Modeling and Experimental Studies of Network Traffic Emissions Using a Microscopic Simulation Approach

by

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ABSTRACT

This thesis describes the design and implementation of a traffic network emissions model, at the heart of which is the integration of a microscopic traffic simulator and a load-based vehicle emissions model. This traffic network emissions model serves as a simulation laboratory of congestion and emissions on traffic networks. The laboratory allows for the evaluation of transportation control measures such as emissions control strategies, and in conducting research to investigate the relationship between traffic congestion and its impact on emissions. The network emissions model operates at a microscale and uses as sub-components, MITSIM, a microscopic traffic simulator, and CMEM, a dynamic vehicle emissions model.

The network emissions model is applied to three networks, two of which model real-world networks. The sensitivity of the model output to stochasticity and temporal and spatial averaging intervals is tested using the small real-world network. Additionally, the emissions inventory on a medium-sized urban arterial is modeled. The computational requirements of the model are assessed using a model of the Central Artery/Tunnel of Boston.

The laboratory is applied to assess the effectiveness of the following emission control strategies: traffic signal timings, Inspection/Maintenance (I/M) programs, and demand management through peak spreading. The effect of the level of total demand on emissions is also assessed. These strategies are evaluated individually, and in groups of combined strategies. It is shown that the relative improvements for different emission species varied with the emission control strategy. The effectiveness of the strategies for reducing emissions were found to not be additive.

The capabilities of the model to perform detailed spatial analysis are illustrated by evaluating the emissions at a large-size urban intersection. Using a meter-by-meter representation of emissions, the laboratory results indicate that emissions at the center of an intersection are two to three times higher than on the rest of the network. Topics that need further research are suggested.

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Chapter 1

Introduction

Air pollution is a major externality of transportation causing health problems, crop damage, and visibility problems in cities. But transportation is important to the well being of humans. Economic development and our quality of life are dependent on mobility. Excessive traffic congestion and the accompanying air quality problems are making it necessary for cities to be more creative in managing traffic as populations grow. The traditional method of "building out" of traffic congestion, such as adding new lanes and new roads, cannot keep up with the rate of population growth. Space for new roads is limited in developed cities and even if space is available, the construction time for adding on roads capacity is lengthy and expensive. Often, a capacity expansion project takes so long to complete that the capacity of the new roadway is reached soon after it is opened.

Concurrently, the public is demanding cleaner air, yet unwilling to change their travel behavior. On one hand, there is an increasing focus around the world on air quality, while automobile ownership numbers continue to rise (MIT and Charles River Associated, 2002). The demand for increased mobility with less environmental impacts is a difficult one to satisfy. Many mechanisms are being used to control vehicle emissions including vehicle technology regulations, city parking policies, and traffic management. Car manufacturers, the energy industry, and policy makers are beginning to address these issues, which are complex and the tools needed to understand them are limited.

The introduction of more sophisticated modeling tools could help improve the understanding of the relationships between automobile emissions, traffic congestion, and air pollution. Such tools can be used to evaluate and support decisions regarding the mechanisms used to combat emissions, to contribute to the understanding of how changes in traffic conditions translate into changes in air quality, and assist in designing emissions minimizing networks which still demand levels. This knowledge would help pinpoint the areas where technology, management, and policy can be improved. Increasing the general knowledge within the field of transportation could eventually translate into better laws as this knowledge makes its way to the lawmakers and the general public.

1.1 The Mobile-source Air Pollution Problem

According to the California Air Resources Board, the first episode of "smog" occurred in Los Angeles in 1943 (CARB, 2002). Visibility was reduced to three blocks resulting in people suffering from smarting eyes and vomiting. Since then, episodes of extremely high levels of pollution, e.g. "Killer Fog" in London, and wide-spread studies show that constant exposure to pollution have been directly linked to serious health problems and pre-mature deaths. The magnitude of the problem has led to many regulations and air pollution control measures, which have successfully decreased pollution levels in many cities.

The main generators of air pollution are industrial processes, heat and energy generation, and transportation. Of these, highway vehicles are the largest source of transportation-related emissions for nearly every type of pollutant (TRB, 1995, p. 39). They contribute 30-60% of emissions of carbon monoxide (CO), nitrogen oxides (NOX), hydrocarbons (HC), and particulate matter (PM) (Howitt and Altshuler, 1999, p. 228) in the United States. These pollutants are criteria pollutants, regulated in each region of the United States by the Environmental Protection Agency (EPA), the agency responsible for protecting the natural environment and controlling pollutants that affect human health.

HC and NOX are volatile organic compounds (VOC) that react with sunlight to produce ground-level ozone, a primary component of smog. They are by-products of the combustion engine or are directly released as fuel evaporates. Ozone harms the lungs, creating respiratory problems, and causes damage to trees and crops. Furthermore, NOX itself can irritate lungs and lower resistance to respiratory infections and contributes to acid rain. CO is part of the engine exhaust and essentially reduces the delivery of oxygen through the bloodstream. PM from engine exhaust, tire and brake wear, and dust stirred-up by auto operations causes respiratory problems. All of these pollutants not only affect people with pre-existing respiratory problems, but also healthy people (Howitt and Altshuler, 1999, p. 226).

1.2 Fuel Consumption

Emissions generally increase with increasing fuel consumption. Thus, it is important to track fuel consumption. Reducing fuel consumption directly reduces emissions. In addition, fuel consumption is an important issue by itself; fuel is expensive to distribute and causes additional emissions in the process of its distribution. Because the transportation sector is essentially wholly dependent on oil, fuel greatly influences any nation's security and economic stability. The great dependence on foreign fuel means that its availability directly affects the world economy. Due to its importance and its fundamental relationship with emissions, the research documented in this thesis includes fuel consumption in the analysis of emissions.

1.3 Air Pollution Control Legislation

Two legislations have played major roles in keeping air quality under control in the United States: the Clean Air Act Amendments (CAAA) and Intermodal Surface Transportation Efficiency Act (ISTEA). The Clean Air Act (CAA) was passed in 1963 to address the worsening air pollution problem by giving the federal government the responsibility to set air pollution criteria. It outlines the National Ambient Air Quality Standards (NAAQS) that must be met by each state. Eventually, after many amendments, the federal government was also given the power to enforce these standards. The Clean Air Act first began to develop auto emissions regulations in 1965. Since then, tailpipe emissions regulations have continually become more stringent. The

CAAA also includes provisions for auto Inspections and Maintenance (I/M) programs. The most recent amendments in 1990 include tailpipe standards to be phased in for passenger vehicles, light-duty trucks and SUVs. The first set of standards, Tier 1 standards were fully implemented in 1997. Tier 2 standards is planned to begin to be phased-in in 2004 (Arizona Dept. of Environmental Quality, 2000). The National Low Emission Vehicle (NLEV) program provided a schedule for manufacturers to certify a percentage of their vehicle fleets to standards during the period between the two tiers. Additionally, stricter testing processes outlined in the CAA have enabled more effective and longer lasting vehicle emissions technologies requirements. The new laws require that emissions components fulfill performance requirements for 150,000 miles or 15 years of operation. Manufacturers, driven by these tightening regulations, are researching and producing lower emitting vehicles.

ISTEA has also been instrumental in reducing motor vehicle pollution. The legislation provided funds for Congestion Mitigation and Air Quality (CMAQ) programs. The CMAQ funds, currently $8.1 billion for 1998-2003, are tied to the NAAQS, creating a major incentive for cities to meet the standards. This is one method for the U.S. Federal Government to motivate the states to implement effective emissions reduction programs. States are also allowed to use CMAQ funds to make transportation improvements that also reduce emissions. Currently, reducing vehicle kilometers traveled (VKT) and improving traffic flow are automatically considered as emissions reducing projects.

Together, the CAAA and ISTEA keep transportation focused on air quality. Going beyond the Federal regulations, some states are actively spearheading their air quality problems. The California Air Quality Board has been a national leader in the effort to address air quality through regulations (that are even more stringent and aggressive than the federal laws), research, and other policies.

Over the last 25 years, regulations and vehicle technology improvements have reduced the in-use emissions of HC and CO by one-fifth and NOX by one-half to one-third. But at the same time, urban miles traveled have doubled, canceling the effect of approximately one-fourth of the HC and CO reductions and two-thirds of the NOX reductions achievements. Mobile emissions are still responsible for 35-70 percent of ozone-forming emissions (HC and NOX) and 90 percent or more of carbon monoxide (CO) (Calvert et al., 1993).

Mobile emissions are comprised of evaporative emissions and on-road exhaust emissions. Evaporative emissions are released by a vehicle throughout the day as fuel temperature changes after engine shutdown, during vehicle operation, and due to daily ambient temperature variations. Evaporative losses can be eliminated by more effective control systems, fuel volatility controls, inspection procedures, and attention to fuel-delivery systems. On-road exhaust emissions, on the other hand, have been more difficult to regulate. Policies addressing on-road exhaust emissions, mostly stricter federal standards for new vehicles, have been only half as effective as expected (Calvert et al., 1993).

New solutions are needed to compensate for the increasing emissions as VKT increases. So far, the public in the United States is still unwilling to accept emissions pricing to improve air quality (Howitt and Altshuler, 1999). The auto manufacturers are turning out emissions control technology as quickly as they can. Inspection and Maintenance (I/M) programs and remote sensing are being implemented by states to weed out the high emitters. Traffic network management can also be used to address emissions. Under the Clean Air Act, the air quality impact analysis of new infrastructure is required, but consideration of alternative options for minimizing emissions is not currently required. Neither does traffic management take air quality directly into account. Emissions are considered an additional benefit of improving traffic congestion, rather than a criterion of traffic management. Historically traffic management has focused on keeping traffic congestion and safety to an acceptable level. There is an emerging belief that untapped potential exists for improving air quality through the use of better traffic signal timing, ramp metering, and other mechanisms to smooth traffic flow. Accurate modeling tools are lacking for evaluating emissions on a network and for identifying effective methods of emissions management.

1.4 Objectives

While many relationships between emissions and general traffic parameters such as speed and acceleration have been developed for regional air quality analysis, these simple relationships have been shown to be inadequate for more detailed evaluation of emissions on a traffic network (Guensler et al., 1999). The need for a tool that can model the impact of local traffic changes on emissions has been identified. As it becomes more challenging to improve air quality, the ability to perform cost-benefit analysis for comparing potential Transportation Control Measures (TCMs) is needed to prioritize projects and funding. The cost of analyzing and optimizing traffic systems and network design can be minimized when assisted by simulation tools. Such tools can also be used to conduct research on vehicle emissions and air quality.

The objective of this research is to design and implement a network emissions model for the evaluation of TCMs, profiling emissions on a network, or for further research of traffic-emissions relationships. A framework is proposed for the integration of a traffic micro-simulator and a modal emissions model. A laboratory, Microscopic Integrated Traffic Network Emissions Model (MITNEM), is developed within this framework, using two existing state-of-the-art models, MITSIM and CMEM. MITSIM, developed at MIT, simulates the movements of vehicles on a road network. CMEM, developed at U.C. Riverside, models the emissions from vehicle trajectories resulting from MITSIM.

MITNEM is applied to two real networks. It is used to study the sensitivity of the model to stochasticity and temporal and spatial averaging intervals is tested using a small real-world network. Also, computational requirements of the model are assessed using a model of the Central Artery/Tunnel of Boston. Two experimental studies are conducted on the Hornstull network. The first study evaluates and compares the effectiveness of emissions control strategies on a real road network. The second studye analyzes the profile of emissions generated at and around intersections. Recommendations for future topics of study and implementation are also given.

1.5 Thesis Outline

The thesis is organized as follows. Chapter 2 gives an overview of the different types of traffic models, emissions models, and integrated network traffic-emissions models. A literature review of the existing integrated models and their applications is also presented. Chapter 3 proposes a framework for, and details the design process of a network emissions model developed in this thesis. Chapter 4 uses MITNEM for three case studies. The case studies include exploring result analysis using different emissions measures; a sensitivity study of the model to stochasticity, and temporal and spatial averaging intervals; and the use of MITNEM to model the emissions inventory of a major artery in Boston. Chapter 5 presents the application of MITNEM to three experimental analyses. Finally, Chapter 6 concludes the thesis and offers lessons learned and suggestions for future work.

Chapter 2

Background and Literature Review

Advanced models have been developed by researchers in the disciplinary fields of traffic, emissions, and air quality modeling. Traffic models are used to analyze traffic networks, emissions models are used to model the emissions from new and old vehicles, and air dispersion models are used to assess air quality in a city. Many types of models exist in each of these fields. An appropriate combination of a model from each of the fields can be used to simultaneously model traffic flow on a road network, the emissions the vehicles generates on the network, and the resulting air quality.

This thesis is concerned primarily with network emissions modeling at a local level, as opposed to regional or city-level network emissions modeling or emissions modeling of a single street or intersection. Emissions models intended for these purposes will be referred to as local network emissions models. The specific implementation of a local network emissions model, described in this thesis, is a microscopic network emissions models. Local network emissions models are predominantly used for assisting with the evaluation of the emissions resulting from different traffic control mechanisms.

This chapter begins with an overview of the each of the three components of network emissions models: traffic models, emissions models and air dispersion models in Sections 2.1 - 2.3. This is followed by a discussion of general integrated model applications in Section 2.4. The chapter concludes with a literature review of existing local network emissions models and their applications to evaluating transportation control measures (TCM) in Section 2.5.

2.1 Traffic Models

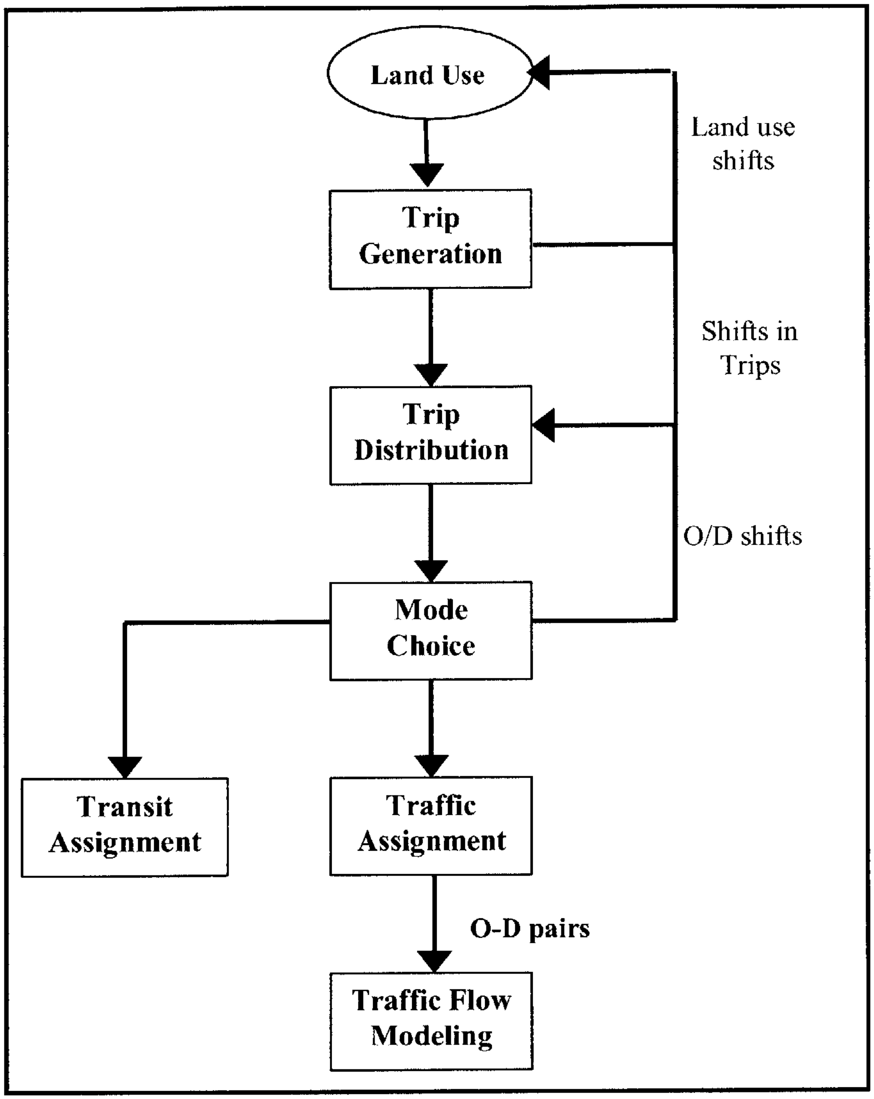
Traffic models use travel demand information to predict future traffic conditions. A typical traffic demand model includes the following components: trip generation, trip distribution, mode choice, traffic assignment, and a traffic flow model. A diagram of a traffic demand model is shown in Figure 2.1. We are interested mainly in the traffic flow modeling component in this section. Traffic flow modeling is typically a part of the traffic assignment model for modeling route choice, but it can also be used independently if provided a pre-determined O-D matrix, as we will be doing in this thesis. Assuming a relatively stable demand, we would like to understand how to manage emissions most effectively.

This section gives a brief overview of traffic flow models with a focus on micro-simulation, since the model to be established in the following chapters will use a micro-simulator. The reader is referred to Hoogendoorf and Bovy (2001) for a more detailed description of traffic flow models.

Traffic models can be classified by five characteristics:

- Representation of traffic (continuous vs. discrete)
- Traffic flow variables (aggregate vs. disaggregate)
- Representation of the processes (deterministic vs. stochastic)
- Operationalization (analytical vs. simulation)
- Scale of application (intersections, links, stretches, and networks)

The representation of traffic can be continuous or discrete in time. Models using continuous representation treats traffic as individual vehicles moving on a roadway. Discrete representation moves vehicles together in groups. Traffic flow variables can be aggregate or disaggregate. Aggregate variables characterize the network in macroscopic traffic parameters such as flow and density, and speed is calculated using its relationship with density. Disaggregated variables move each of the vehicles individually using driver behavior models such as car-following and lane-changing models, mimicking interaction between vehicles.



Adapted from: US EPA, 1998, p. 9

Figure 2.1: Travel modeling

The representation of the processes can also be deterministic or stochastic. A deterministic model does not include variances in the model parameters, therefore two runs of the model using identical parameters will reproduce identical results. A stochastic model includes variances in sub-points of the system such as from driving behavior, fleet mix, and vehicle flow in its parameters. The effects of the variances in the sub-points in a stochastic model will cause differences in the outputs for each simulation run, resulting in a variance in the system outputs. Traffic models can be either analytical or a simulation. Analytical models capture relationships between variables through sets of mathematical equations, while simulations can be used to test relationships in complex problems with many system components which cannot be readily described in analytical terms (Hoogendoorn, 2000).

The level-of-detail of a model is determined by a combination of the first two characteristics, the representation of traffic and traffic flow variables. Table 2-1 shows three resulting model types, macroscopic, mesoscopic, and microscopic. Macroscopic models assume that the driving environment affects the aggregate behavior of vehicles, which can be characterized by vehicular flow and density. Mesoscopic models use less aggregated variables at the vehicle level to give more detailed vehicle trajectories. Vehicles are discrete and therefore behavior rules are specified, but still in a generic fashion, such as through probability distribution functions of capacity and density relationships. Microscopic models use disaggregated variables and a discrete representation of traffic to give the most detailed vehicle trajectories with speed and acceleration values.

Table 2-1: Traffic model types

		Flow Variables used for Moving Traffic	
		Aggregate variables (capacity, density, etc...)	Disaggregate variables (vehicles move using car-following and lane changing models)
Representation of Traffic	Continuous (flow-based)	**Macroscopic**	-
	Discrete (at the vehicle level)	**Mesoscopic**	**Microscopic**

Microscopic traffic flow modeling simulates detailed vehicle movements by specifying car-following, lane-changing, and route-choice behavior. Other rules can be specified such as intersection behavior, merging behavior, response to traffic control systems (rules and compliance level), and overall acceleration/deceleration logic. The intention is to simulate the actual decisions, conscious or unconscious, being made on the road by drivers as they react to the driving conditions. These models can operate at various resolutions (deci-seconds to few seconds).

Car-following models calculate the distance a driver will keep between himself and the vehicle in front of him. It is a function of multiple parameters such as the current driving speed, the difference in speeds between the two vehicles, and driver aggressiveness. More complex car-following models such as the psycho-spacing model, take into account the current headway, so that at large distances, drivers are less sensitive to the difference in speeds (Hoogendoorn and Bovy, 2001).

Lane changing models simulate the driver's decision to change lanes and gap acceptance behavior. Lane changing occurs to fulfill destination goals, speed goals, or the desire to pass slower vehicles. Gap acceptance models the willingness of a driver to change lanes into available gap sizes. This is usually a function of the speed, driver aggressiveness, and the amount of time left for the maneuver to be completed.

For any type of model, the inputs and the sub-model parameters usually need to be calibrated for each network. Traffic characteristics can vary from local area to local area and depending on network geometry. Driver behavior parameters (e.g. aggressiveness and fleet mix) vary from one city to another. In macroscopic models, speed-flow-density relationships vary across links. It has been shown that macroscopic models are relatively easy to calibrate (Hoogendoorn, 2001). However, the calibration process can be very data intensive and time-consuming for micro-simulation. Additionally for both models, origin-destination pairs must be calibrated carefully. This can be done using the output of a regional travel demand model, using vehicle registration plate sampling, or estimated from surveys.

2.2 Vehicle Emissions Models

Vehicle emissions modeling estimates emissions based on vehicle operating conditions. A variety of approaches exist for vehicle emissions modeling. This section begins with a description of the principal vehicle emission species and the conditions under which they are generated.

2.2.1 The Pollutants

The pollutants that are typically modeled by vehicle emissions models are hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOX). Detailed particulate matter (PM) models are still being developed in the literature. Today, the emissions being emitted at the engine output (EO), which are relatively well described by fuel consumption, are being modeled with relative accuracy. But, after the engine, the exhaust goes through the catalyst, which filters out much of the pollutants, while the remaining emissions are emitted at the tailpipe. The tailpipe emissions are much more difficult to estimate, since the catalyst behaves non-linearly.

This section describes some of the driving conditions under which each of the pollutants is created. An understanding of these concepts can help identify the traffic conditions that will affect emission levels. For more details on the processes which cause the pollutants, the reader is referred to Cappiello (2002) where simple, but thorough descriptions of each of the pollutants are provided.

Fuel Consumption

All pollutants are emitted as a function of fuel consumption. In general, the less fuel burned, the less pollutants are emitted. Many models exist for modeling fuel consumption, which can be done relatively accurately. Therefore, many emissions models are based on fuel consumption. The load-based emissions model (see Section 2.2.4), in particular, relies upon an accurate fuel consumption prediction. In terms of fuel, there are three conditions under which an engine operates: stoichiometric, enleanmeant, and enrichment. Stoichiometric means that the engine is operating at the optimized air-to-fuel ratio of approximately 14.5. There is a very small window for what is considered stoichiometric in engines, but with the current technology, the conditions are controlled very carefully. Enleanment is when the engine is operating with less fuel or more air. Under certain conditions, such as during deceleration, the vehicle will operate under enleanment, since less power than usual is required, less fuel and more air is provided to the engine. Enrichment occurs when the vehicle is operating with more fuel or less air than required. This can occur when the driver is accelerating. To provide as much power as possible, the engine is provided more than enough fuel. Under high accelerations, the amount of air available is not sufficient to burn the additional fuel. Under certain conditions, it is desirable for the vehicle to operate enriched. Additional fuel during high power demand cools off engines and additional fuel during cold starts, when a vehicle is operating cold, causes engines to heat at a faster rate. Vehicles operating in cold-start require much more fuel initially than a vehicle with a warm engine (Barth et al., 2000, p. 80).

Carbon Monoxide

Carbon monoxide (CO) results from incomplete combustion which occurs during enleanment. Rapid accelerations and deceleration produce unburned CO due to the inability of the engine to fully use all of the available fuel. CO production is also especially high during cold-starts when vehicles operate enriched to heat the engine faster in the attempt to raise the exhaust temperature so the catalyst can operate efficiently (Cappiello, 2002).

Hydrocarbons

Hydrocarbons (HC) can increase during enleanment, resulting from abrupt high load demands (accelerations) and long decelerations, or when an engine is not fully warmed up (Barth et al., 2000, p. 79). These conditions occur over several seconds; therefore it is essential to take operating history into account for estimating HC. Long periods of deceleration cause HC "puffs". Rapid speed fluctuations, acceleration, and deceleration result in HC emission spikes, caused by unburned HC from rapid throttle closing. If a model does not take these into account, but is calibrated on cycles which include such driving cycles, it would most likely result in HC over-predictions during normal operation and under-predictions during these special operating circumstances.

Nitrogen Oxides

Nitrogen oxides (NOX) are very sensitive to peak temperatures in the cylinder whereas it is not usually affected by enrichment, since the extra fuel actually cools down the engine temperature (Barth et al., 2000, p. 84). High levels of NOX can be produced during even several seconds of catalyst inefficiency (CMEM Final Report, p. 79). NOX can travel hundreds of miles from their origin.

Ozone

Ozone is formed in a chemical reaction involving NOX, HC, and sunlight. Ozone at the ground level is harmful to humans. It is a key ingredient of smog. The chemical equation below shows that when NOX or NO_2 is in the presence of oxygen and sunlight, it forms ozone and NO. If any volatile organic compounds (VOCs) are available, NO is recycled back into NO_2. HC is a VOC.

$$NO_2 + O_2 + sunlight \rightarrow O_3 + NO$$
$$VOC + NO \rightarrow NO_2$$

This process can occur very rapidly in hot weather. Industrial processes, gasoline vapors, and chemical solvents produce VOCs. VOCs are also produced by natural sources such as trees.

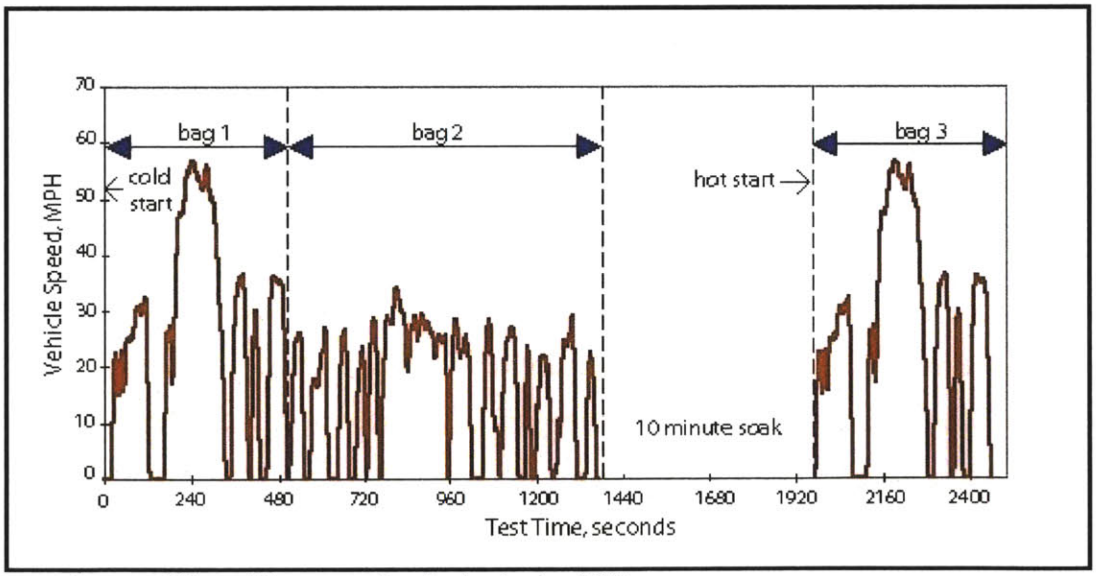
For optimal emissions management, it is crucial to monitor the local background levels of VOCs and NOX. In most regions, the amounts of NOX and HC are not balanced. If one chemical is limiting the reaction, it is called the limiting factor. For example, if a region has very little VOC, that region is VOC-limited. This means that additional NO_2 will not lead to more ozone. The chemical reaction above is limited by the amount of VOCs available. In a VOC-limited region, the marginal cost to society of each additional gram of VOC is very high because it creates more ozone, whereas the marginal cost of NOX is much lower. Though NOX and HC alone can cause health problems, ozone is a more serious concern. Rather than trying to reduce both pollutants, a cost-effective ozone strategy would be to try reducing the limiting species.

Carbon Dioxide

Carbon Dioxide (CO_2) and other green house gases are widely believed to contribute to global warming. Carbon dioxide accounts for more than half of the green house gases. The total life cycle of the transportation sector is responsible for 30% of CO_2 emissions (Weiss et al., 2000). The evidence for this theory is not conclusive, yet there is global concern that if the connection is indeed true, there are serious consequences (rising sea levels, climate change, etc.) to continued green house gas pollution. For the same type of fuel, CO_2 emissions tracks fuel consumption closely.

2.2.2 Vehicle Emissions Data Collection

Vehicle emissions data are usually based on chassis dynamometer testing. A driving cycle is developed to represent typical driving conditions. In the United States, the standard regulatory driving cycle is the 3-bag Federal Test Procedure (FTP), shown in Figure 2.2. The cycle attempts to represent arterial road and highway driving. Humans, or a machine, drive the vehicle as close as possible to the specified speeds. Each "bag" of emissions is collected separately to allow comparison of different operating modes such as cold start and hot start.



Source: Office of Transportation Technologies, 2002

Figure 2.2: FTP urban driving cycle

Research shows that the FTP cycle does not represent many driving patterns (Barth et al., 2000). Typical vehicle activity can spend a large fraction of time outside of the FTP range (Hallmar, 1998). An additional driving cycle, the US06, is an aggressive regulatory cycle, which targets high emission operation, meant to supplement the 3-bag FTP regulatory cycle. The emissions collected from these driving cycles are used for most vehicle emissions model calibration and validation.

2.2.3 *Factors Affecting Vehicle Emissions*

The emissions produced by a vehicle are very dependent on the driving cycle on which it is tested. This is because of several reasons. First, emissions are very dependent on the starting temperature. Second, some pollutants are dependent on the history of the drive cycle, for example, longer accelerations and decelerations. Finally, the performance of the catalyst may be dependent on the amount of emissions it is required to handle. This is one reason emissions models are calibrated using a data set where the emissions are measured using the same driving cycle for all vehicles. This method allows comparability among different vehicle categories.

One drawback of this method is that it has been found that emissions models are usually only good at predicting emissions for drive cycles that are similar to the ones they were calibrated on. When the validation drive cycle is different from the calibration drive cycle, the error grows as the difference in drive cycles becomes larger (Hickman, 1999). Therefore, since it would be impossible to design a driving cycle that covers all the different combinations of speed, acceleration, and history conditions, it is essential that the appropriate driving cycle, representative of the conditions of interest, be used. A good driving cycle should cover a wide variety of accelerations, decelerations, cruise speeds, and length of speed fluctuations. Three additional factors which are known to significantly affect emissions are discussed below:

Aggressiveness

Aggressiveness is a measure of how frequently a driver accelerates/decelerates and the magnitude of the acceleration/deceleration. Aggressive drivers may follow vehicles ahead of them closer, change lanes more often, and wait for the last minute for mandatory maneuvers. High-aggressiveness may be more frequent for certain cities. Higher aggressiveness creates more time lags, or "jittering", in the dynamometer measurements. Older vehicles can limit the manifestation of the aggressiveness of a driver due to the deterioration of power and braking.

Air-conditioning

Air-conditioning increases the power requirements during vehicle operation. It specifically increases NOX. Air-conditioning is very difficult to model (Nam, 2000), but during the summer or in warmer cities, this is a major cause of emissions and should be modeled.

Cold-start

A vehicle is operating under cold-start when the engine is not at operating temperature yet. All emissions are higher during a cold start because the combustion is not as efficient and also the catalyst has not warmed up yet, and is therefore also not operating optimally. The vehicle start-up can contribute up to 1/3 of total VOC emissions (TRB, 1995, p. 48).

2.2.4 Dynamic emissions models

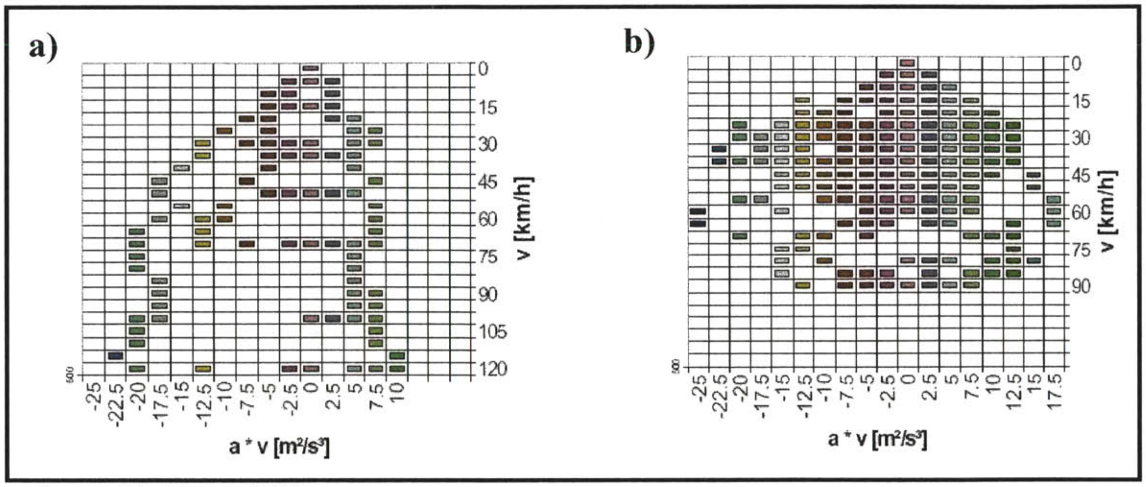
Not only is a wide variety of driving conditions needed, but once obtained, driving cycle data cannot be used directly. The data needs to be cleaned and there are usually lags of varying lengths between the trajectory data and the emissions data. There are many dynamic methods for modeling emissions calibrated using dynamometer data. Dynamic models use the instantaneous speed and emissions data from the dynamometer tests to model instantaneous emissions. This is opposed to the static emissions models that describe the emissions per distance traveled as a function of average speeds for trips or links. Though static models can approximate emissions for a region, they are not able to model emissions at a local level. The models described below are all dynamic emissions models. There are two types of dynamic models, statistical models and load-based models.

Statistical Models

The dynamometer data can be described statistically for use in estimating emissions under similar conditions. Two types of models exist: emissions matrices and regression models.

The data can be separated into individual bins characterized by instantaneous operating mode, typically speed and acceleration, to derive the average emissions under the specified operating mode. This method creates an ***emissions matrix***, commonly referred to as an emissions map or look-up table. When only speed and acceleration are used, it is called an acceleration-velocity (a-v) map. Additional parameters can also be used to create multi-dimensional bins, such as level-of-service, operating temperature, etc. One matrix is needed for each pollutant for each vehicle category. The drawback of this method is the amount of data required to populate an entire matrix. Figure 2.3 exemplifies this problem. Matrix a) shows a European regulatory driving cycle. Matrix b) shows the typical urban driving range. It is difficult to design a driving cycle that populates all of the desired cells. Additionally, multiple occurrences of each cell are required to have statistically significant results. The data for each cell may be affected by the previous few seconds of activity. Therefore, ideally, the cell would be populated with values averaged from conditions with different history (the preceding seconds were for the different samples were under different operating conditions).

Though the use of emissions matrices may seem straightforward, it requires a great deal of data and data manipulation effort for its implementation. The user is referred to Pischinger (1998) for a more detailed review of emissions matrices.



Source: Pischinger, 1998

Figure 2.3: Emissions matrix: a) European driving cycle b) Emissions matrix needed for typical urban driving

The other type of statistical models are ***regression models***. A regression on explanatory variables can be used to capture the trends in vehicle emissions. Some models, such as the Virginia Polytechnic model, use a combination of acceleration and velocity to different powers (e.g. $a^x v^y$) as explanatory variables (Rakha et al., 2000). Other models, such as MEASURE (see Section 2.5.1), use a wider array of explanatory variables including power, acceleration, and dummy variables such as odometer reading, vehicle and emissions technology type, to fit the emissions data (Bachman et al., 2000). The benefit of the regression model is the ability to extrapolate (within reason) and interpolate the values of emissions that were not part of the driving cycle. The downside of this is the lack of reasoning in the final explanatory variables. It has been found that after being fit, the combination of the explanatory variables found to be significant for each vehicle category and the estimated parameters results in different equations for different vehicle categories. Some of the models require such a large number of variables that it results in an over-fit of the data and a large reliance on the driving cycle on which it was calibrated (Cappiello, 2002). These characteristics make it difficult to model changes that affect driving cycle or new technology.

Load-Based Models

Load-based models represent each of the physical components of the vehicle. From the vehicle trajectory, the engine load is calculated, which has been found to be an effective method for estimating fuel consumption. The emissions can then be calculated as a function of the fuel consumption and engine operating conditions. Up to the engine out emissions, load-based models typically have a satisfactory accuracy. The effect of the catalyst, between the engine out to the tailpipe out, is still challenging to accurately describe. This accuracy has its trade-offs. Load-based modeling is data intensive. To model a vehicle category, certain vehicle parameters such as the engine maps need to be defined. These values can be determined through calibration, manufacturer specifications, or literature values. Often, each module which models a physical part in the vehicle, such as the power demand or the catalyst pass fraction needs to be calibrated separately. CMEM (see Section 2.2.4) is well-known load-based emissions model developed by University of California Riverside which groups similar vehicles together into vehicle categories to calibrate the physical model parameters.

Figure 2.4 summarizes the range of dynamic emissions models discussed. The models are of different processing complexities and require a range of processing times. The emissions matrix is the simplest and requires only a look-up table, and therefore an algorithm using this method would run quickly. Statistical regressions may comprise of a few modules, but are essentially a few analytical equations; therefore they also run rather quickly. The load-based approach requires many more calculations and is therefore the slowest of the three types of models.

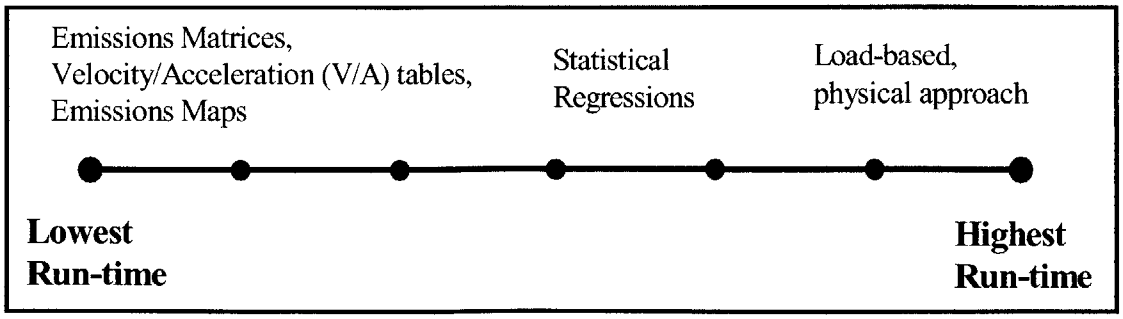


Figure 2.4: Spectrum of dynamic emissions model run-speed

2.3 Air Dispersion Models

Air dispersion models are used to model air quality from emissions data. Though this thesis does not address air dispersion modeling, a brief overview of air dispersion modeling is provided here due to its important role in extending emissions results to air quality results.

Air quality is not directly proportional to emissions. Air quality depends on numerous factors including the background concentrations, chemical reactions, and the meteorological conditions. Pollution from other industries and naturally occurring sources create the background concentration, which affects the dispersion of the emissions generated by on-road vehicles. Additionally, chemical reactions will change the concentrations. Different chemical reactions occur depending on the levels of other gases/pollutants in the vicinity. The chemical reaction that forms smog involves NOX and HC, which form ozone. CO does not go through chemical changes.

The human exposure to all pollutants depends on the concentration of the pollutant, not their emission rates. The concentration is affected by the wind and weather conditions. Locally, cars on the street create wind and buildings act as wind tunnels, which mix the emissions. These winds take the emissions away from the city, and higher into the atmosphere to create smog. Rain, on the other hand, captures many of these large smog particles and "washes" it away.

There are different complexities of air dispersion or air quality models. Models used to simulate transportation related emissions usually treat on-road emissions as line sources emitted along the roads. Other models include area-sources, point-sources, and pollutant plumes. At the street level, urban canyon models can be used to model the concentrations. At the regional level, meteorological models are used to calculate the regional air quality. CALINE, developed by the California DOT, is a widely used air dispersion model for areas around highways and arterial streets. The interested reader is referred Hanna (1981).

2.4 Integrated Models

The traffic, emissions, and air dispersion model types described in the previous sections have been used in a variety of combinations for modeling traffic emissions around the world. Some models have been combined with or compared to real-world measured data. The models have been applied to modeling emissions inventories, transportation control measures, and other vehicle emissions scenarios.

The models within each of the fields are based on sophisticated theories and decades of research. Yet, the inter-related inputs and outputs are simplified. For instance, the traffic modelers have very detailed models for trajectories on roadways, the emissions modelers usually use standardized driving cycles as their inputs. Furthermore, while emissions modelers are able to model emissions along a roadway over time, air dispersion modelers use static emission rates along the road segments of a network.

Simplifications must be made in modeling, but clearly, integration of these models into a comprehensive traffic-emissions-air quality model is logical. Doing so would allow for cause and effects to be associated and studied. Ultimately, more accurate emissions and air quality estimation can be developed through these integrations.

In the United States, MOBILE and its modules, HERS[1] and PART5[2], are the standard models used by engineers at federal and state transportation agencies. It is the model used for all California Clean Air Act Amendments (CAAA) related emissions modeling, including emissions inventories. MOBILE5 and the soon to be release MOBILE6 use speed based emissions factors (grams/mi) for different vehicle categories on different road types. Correction factors and offsets are used to adjust the emissions factors for high speeds, extreme temperatures, extra loads, tampering, and other parameters that affect emissions. MOBILE was originally designed for regional air quality modeling. Its emission factors are adequate for approximating the emissions on a link using average

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[1] The Highway Economic Requirements Systems (HERS) model is used to perform cost-benefit analysis of traffic improvements. It includes the cost of the construction, travel delays or improvements, and emissions.

[2] PART5 is the particulate emission factor model that supplements MOBILE.

speed, road type, and a generic vehicle fleet mix for its air dispersion modeling, but it has been shown that emissions factors based solely on speed are inadequate for modeling emissions at a finer spatial scale (Latham et al., 2000). Emissions are highly dependent on modal changes and cannot be captured by an average speed descriptor.

Great progress in regional vehicle emissions modeling has been achieved using MOBILE. Yet, there is no widely accepted tool for modeling the emissions impacts of traffic control measures. A more refined traffic and emissions model would bring more insight to the on-road emissions problem. Traffic engineers and planners could simulate emissions due to road design and flow management. Regulators and auto manufacturers could simulate the behavior of vehicle technologies on a real network and study the effect of the different technology components. The addition of an air quality model would enable regulators to go beyond the technology and study larger scale, more comprehensive solutions including the effect of urban planning or ITS on air quality.

As discussed in Section 2.2, in addition to speed, emissions are affected by operating history, acceleration, engine dynamics, air to fuel ratio, temperature of the catalyst, grade, and the use of accessories such as air conditioners. The effects of these additional variables can be dependent on the ambient weather conditions, such as temperature, humidity, and wind and also on driver behavior and are also specific to vehicle type, age, mileage, and mechanical condition (Cappiello, 2002). Including these additional modal and operating parameters increases the complexity of the models. With increasing computational ability, recently, many integrated models have been developed which include the effects of more of these variables.

The literature indicates that in the past five years, modal emissions models has increasingly been used to research traffic control measures. The studies show that the modal activity resulting from transportation control measures, such as intersection traffic signals and ramp metering, covers a wide range of accelerations and decelerations which is difficult to capture in a single average speed value. As mentioned before, the modal activity is difficult to capture even for a given driving cycle. A few studies have been conducted by various groups to study 1) the applicability of traffic micro-simulators to traffic emissions modeling, 2) the impact of traffic control measures on traffic emissions, and 3) the use of combined traffic micro-simulators and modal emissions models to assess the impact of traffic control measures. The rest of this section reviews existing integrated model research, their applications, and the lessons learned from these experiences. Results from these studies are described.

Models can be integrated at different levels. Some models take the output of the first model (e.g. a traffic model) and formats it properly as an input to the next model (e.g. emissions model). Other models have been joined so that the combined model is seamless to the user. Because these distinctions do not affect the result, as long as the joining of two models is performed using consistent assumptions, for the purposes of this thesis, all types of model combinations are referred to as "integrated models". The term "integrated" captures the idea that the joined model uses the modeling concepts embodied in each of the individual models to create a single internally consistent model system.

2.4.1 Model Applications

There are many applications for an integrated traffic and emissions model. Different types of applications require different foci and different capabilities. Model assumptions define the achievable levels of detail, realism of simulated conditions, and required run-times. Table 2-2 lists some of the possible applications for an integrated model.

Each of the applications may involve analysis of traffic and emissions on different scales. The model application determines the requirements for the model. For example, for regional air quality modeling, mobile emissions are an input, amongst many other stationary emissions sources, to modeling air quality of a region. Consequently, fine precision in the emissions results for the individual segments on the link is not necessary as long as the magnitude of the regional air quality can be estimated.

Table 2-2: Possible applications of integrated models

	Description/Example
Daily Traffic Management	▪ Traffic operator managing daily traffic, incidents, congestion
Operational Planning	▪ Ramp metering, signal coordination schemes/timings ▪ Scheduling, e.g. construction, large events
Network/System Design	▪ New technology evaluations ▪ Network design: new roads
Local Air Quality Analysis/Planning	▪ Local air quality compliance, identification of "hot spots", signal timing changes
Regional Air Quality/ Urban Planning	▪ Zoning, traffic routing/calming, transit planning, emissions regulations, general air quality
Research/ Policy	▪ Optimization (e.g. travel time, emissions) ▪ Traffic Emissions/Travel Cost Trends ▪ Identifying technology weaknesses/areas for funding ▪ Improve emissions and mobility models

Regional modeling mostly uses average speed emissions factors for estimating emissions on a network links. Local network emissions models operate at a finer scale. A local network denotes networks of smaller sizes, from a few intersections to a medium-sized city. Local network emissions models are typically used to evaluate the effect of management strategies on emissions, as opposed to air quality, which is usually the final objective of regional emissions modeling. Precision in the emissions results is more important for local network emissions modeling. Accordingly, more complex emissions models are typically used for local network emissions models.

For example, a traffic network can vary in size from 50 vehicles in an intersection, to 10,000 vehicles in a region. Figure 2.5 gives an idea of the number of vehicles that need to be simulated for analysis of different network sizes.

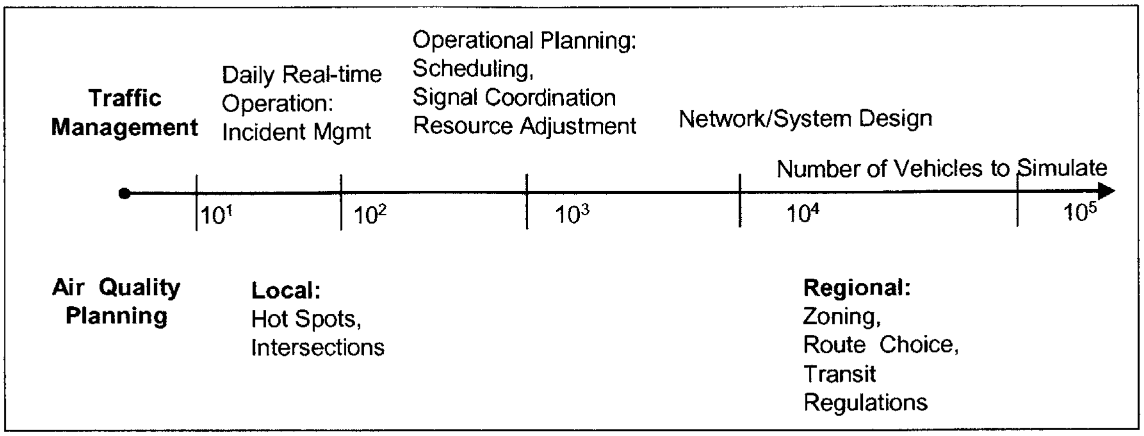


Figure 2.5: Number of vehicles under consideration

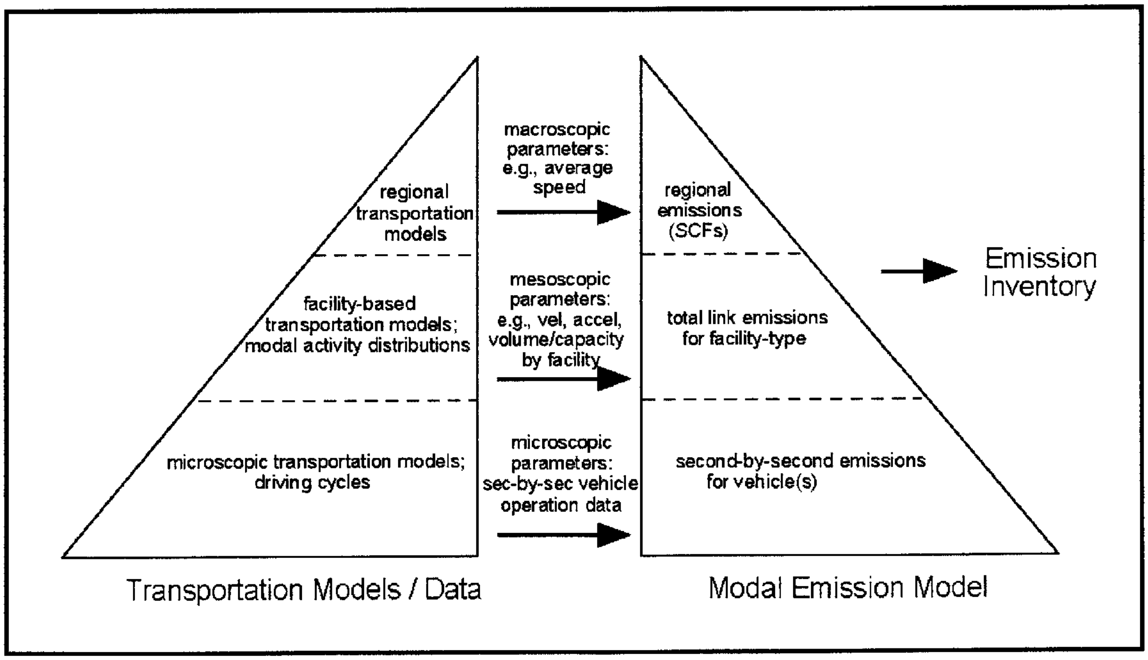
In addition to the number of vehicles under consideration, there are forecast periods and computation time requirements for different applications. Real-time traffic management would require short run-times, faster than real-time, for short forecast periods, since frequently updated data will change the forecast. On the other hand, researchers desiring vehicle-by-vehicle details probably would not mind if a program took several hours to run, as long as the results are detailed. If longer run-times are acceptable, longer forecast periods can be used. Table 2-3 lists the applications described in Figure 2.5 and shows reasonable expectations of forecast periods and computation times for each.

Table 2-3: Application specific computation time

	Forecast Period	Allowable Computation Time
Traffic Management (Real-time)	½ hour	Faster than Real-time
Operational Planning using ITS	24 hours	Few days
Local Air Quality Analysis/Planning	12 hours	Few hours – 1 day
Regional/ Urban Planning	24 hour	1 day
Research/Policy	24 hour	Longer time periods acceptable

2.4.2 *Model Resolution*

The range of integrated models work at different temporal and spatial scales. The resolution is driven by the nature of the component models. Both traffic and emissions models come in different levels of detail. The finest vehicle emissions models calculate emissions second-by-second and the finest traffic micro-simulator operates at the deci-second level. A combination of two such models, where emissions are calculated for every vehicle during every second of the simulation, would be considered a micro-scale integrated model. Figure 2.6 defines other possible resolutions for integrated models. In the literature, the level-of-detail categorization of the integrated model is loosely determined by the lowest level of traffic data detail exchanged between the models. Therefore a microscopic traffic simulator that is used to provide link-based modal parameters to an emissions model is a mesoscopic integrated model.



Adapted from: Barth et al., 2000

Figure 2.6: Model resolution for integrated traffic emissions models

In general, macroscopic models use average speed, flow, and density relationships to describe traffic conditions. Mesoscopic models are based on facility-based, link parameters. Microscopic models operate on second-by-second vehicle data. It is possible to use a microscopic traffic model with a mesoscopic or macroscopic emissions model by aggregating the results from the microscopic model.

Similarly, the results of a macroscopic or mesoscopic traffic model can be disaggregated by using statistical distributions to generate inputs to a second-by-second emissions model. In general, the most straightforward way to combine two models is to use models that work at the same level-of-detail, for example, using a second-by-second traffic model and a second-by-second emissions model to produce second-by-second emissions along a network. This ensures that the input details are carried across from beginning to the end and computation time is not spent on processing data that will be discarded later. Table 2-4 below shows the different applications for the range of level-of-details.

Table 2-4: Integrated model types

Model Type	**Description**	**Application Example**
Microscopic	Second-by-second modeling of emissions	Detailed study of relationships
Macroscopic	Emissions by congestion level and macroscopic traffic parameters over time and space	Travel time and emissions optimization
Mesoscopic	Combination of both	Real-time predictions

The microscopic scale is chosen for this study in order to first understand the fundamental relationship of traffic and emissions. A microscopic model allows observed behavior to be studied in detail. As the relationship between traffic and emissions is better understood, macroscopic models can be used to approximate the behaviors observed in the microscopic model in order to perform large-scale optimizations. Mesoscopic models, which are not cumbersomely detailed but enough to be situation specific, can then be created based on the findings from the microscopic and macroscopic models to make real-time predictions.

Microscopic models are more appropriate for studying network emissions. They directly simulate the vehicle maneuverings that result in the acceleration, decelerations, and speed trajectories needed for emissions modeling. This method departs from the conventional method of using driving cycles or average speed to represent the driving of all vehicles on a network. Aggregate variables usually need to be calibrated for new roadways or different conditions that might arise from new traffic control management. Disaggregate variables, since they are dependent on driver behavior (not roadway layout), once calibrated for drivers of a region, should not need to be calibrated for future changes on the same roadway. When evaluating future improvements, this is a large benefit.

The model developed in this thesis is meant for operational planning, network/system design, local emissions evaluation, and for studying the relationships between traffic and emissions at a local scale (small networks or intersections). It is not meant for real-time traffic management or regional air quality modeling. A major constraint is the availability of computing resources. The amount of detail required in local network emissions modeling is not necessary for real-time traffic management objectives nor even desired.

2.5 Local Network Emissions Modeling

The traditional method for modeling local emissions is to derive a driving cycle from traffic measurement equipment on roads, to which emissions factors can be applied. More recently, on-board vehicle monitoring equipment has been developed to record multiple vehicle trajectories from which a driving cycle can be formed (see Cicero-Fernandez and Long, 1996). For more comprehensive studies, driving cycles are used to generate emissions profiles for vehicles on a dynamometer in a laboratory environment.

Figure 2.7 shows the typical process for local network emissions modeling. Vehicles equipped with on-board measurement equipment drive the routes of interest. The vehicle position and the necessary modal data (i.e. velocity and acceleration) are recorded. From this data, driving cycles are developed to represent the driving profile to be simulated. Various types of representative vehicles (e.g. passenger vehicles, trucks, heavy-duty trucks, high emitters) are then tested on the dynamometer using the driving cycle developed. The emissions results from the dynamometer test are then weighted by each vehicles respective parentage in a fleet mix and summed to derive the corresponding fleet emissions for the driving cycle.

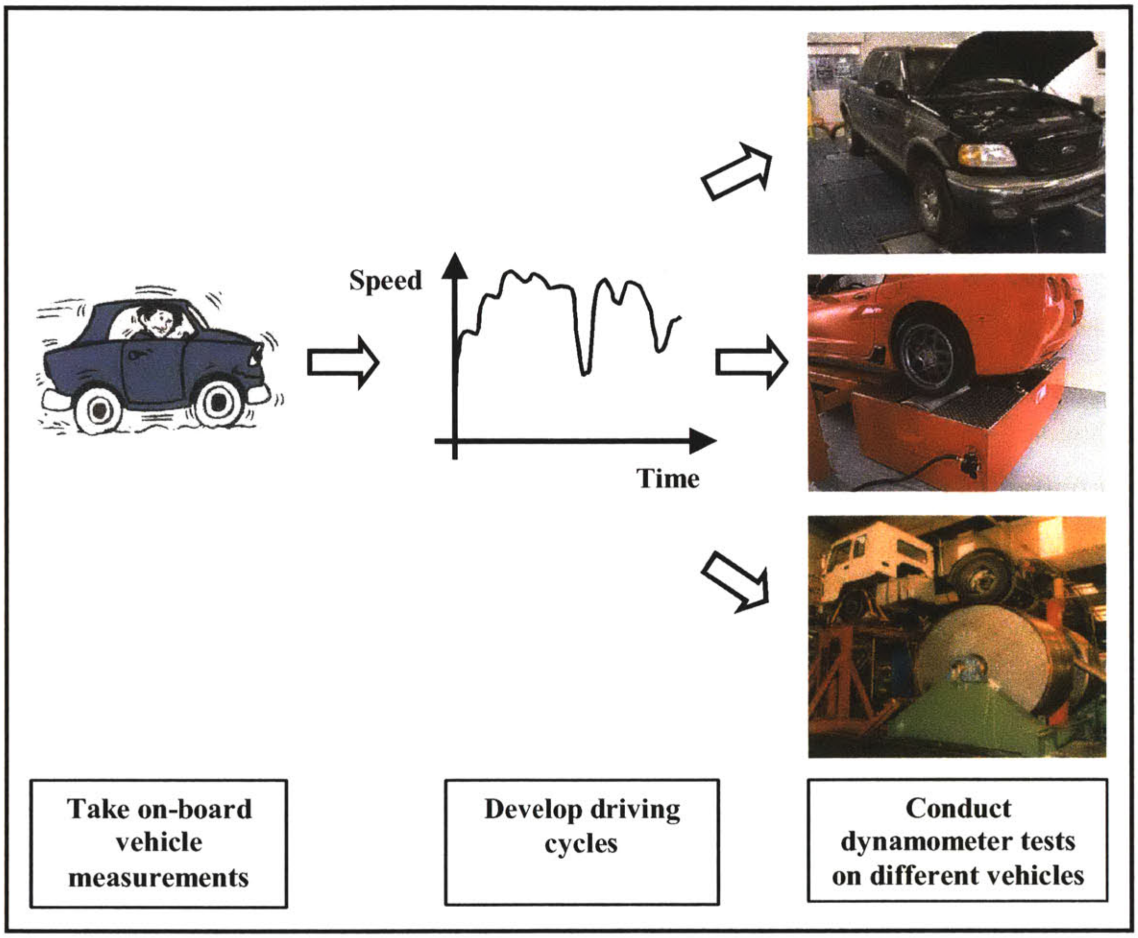


Figure 2.7: Traditional local network emissions modeling method

These methods require a single driving cycle to represent all the vehicles on the road. Studies have shown that modal behavior varies by vehicle queue position (defined as the number of cars between the car of interest and the stoplight) (e.g. Hallmark et al., 1998 and Hallmark, 2000). Recently, research has advanced the on-board measurement technology to include tail pipe emissions monitoring (Rouphail et al., 2000). However, equipment is still in development stage and difficult to transfer from vehicle to vehicle. Currently, the method for using these vehicles is to drive the vehicle over the route before and after the implementation of a TCM, which does not help in TCM design and implementation, but the potential exists for using this data to calibrate and validate network emissions models in the future. This addresses concerns about nonrepresentative driving cycles, but has the limitation that emissions can only be estimated for existing routes. Currently, the equipment for on-board emissions measurement is also very expensive. For designing and planning future local improvements or for studying the emissions resulting from a fleet of vehicles, simulation is a useful approach. A variety of models have been developed to address this issue.

2.5.1 Existing Models

This section offers a review of existing models, which have been used for network emissions modeling (at both the local and regional level) and their applications to different scenarios. The component models are described as well as the application methodology. Table 2-5 lists the existing integrated models discussed in this section, their traffic and emissions models, the data set used for their development and any applications of the models.

Microscale Models

DIANA – Finland/Helsinki University of Technology (Niittymaki et al., 1999)
DIANA (Development of Integrated Air Pollution Modeling Systems for Urban Planning) calculates air pollution created in urban areas. Its strength is its traffic flow and dispersion model. The traffic model used is HUTSIM, a stochastic micro-simulator that uses discrete speed steps of 2.5 km/hr. HUTSIM does not calculate acceleration directly. It is derived afterwards from the speed data. The emissions sub-program, EMCA, is based on speed and acceleration look-up tables for cars, vans, and heavy vehicles. Emissions are input as an area source to OSPM, an urban street canyon flow, and a Gaussian dispersion model developed by the Finnish Meteorological Institute, is used to calculate the final air pollution levels. OSPM uses a plume and box model, with urban background concentrations and a photochemical reactions model. Ambient temperature and re-circulation are taken into account. DIANA operates on a 0.1 second time scale.

DIANA was used to model pollution in downtown Helsinki. For two months, hourly street level measurements were taken along with roof-level measurements for the background concentration levels. Electronic traffic counts were taken for one year. Three days of these measurements were used for validation. Their results showed good correlation for NOX, NO_2' and CO.

VISSIM and Emissions Maps – PTV AG, Germany

VISSIM is a discrete, stochastic, time step based microscopic model. The finest time-step is 0.1 seconds. It uses psycho-physical car following, lane changing, and gap acceptance models. It requires iterated simulations to calibrate the dynamic assignment module. Fellendorf and Vortisch (1999) designed an integrated model that simulates demand, traffic flow, emissions and air quality. The emissions were calculated using dynamic emissions maps. VISSIM is also currently being integrated with CMEM by Nam (Cappiello, 2002).

TRANSIMS – Los Alamos National Laboratory (U.S. EPA, 1998)

TRANSIMS is under development as part of a large-scale integrated simulation effort. The model is currently under-development with funding from the FHWA, FTA, and the EPA, to be released in 2003. The model is designed with many modules to simulate the details that affect the use of transportation systems. It is planned that the model will include representation of demand generation by individual traveler behavior and freight movements; simulation of traffic, transit, bike, and pedestrian activity over different periods of the day, week, months, and seasons; and vehicle characteristics. Currently, TRANSIMS uses a cellular automata traffic micro-simulator, which uses car-following and lane-changing models with statistical speed distributions to generate micro-scale traffic data. The emissions are calculated using speed and acceleration based emissions maps. The environmental impacts include estimates of evaporative emissions. The integration of the traffic micro-simulator with CMEM is underway at U.C. Riverside (US EPA, 1998). The model has been applied to conceptual networks to analyze simple networks (William et al., 1998).

INTEGRATION – Virginia Polytechnic Institute and State University, Center for Transportation Research (Rakha et al., 2000)

INTEGRATION is a dynamic traffic assignment micro-simulator. An emissions regression model developed at the Oak Ridge National Laboratory (ORNL) was integrated with it to evaluate fuel consumption and network emissions. The model was used to compare the effect of different control strategies (variable speed, stop sign, traffic signal coordination) on a long link. The model has since been used to study the combined effect of route choice and traffic signals on a conceptual network (William and Yu, 2001).

CORSIM and **Emissions Rates - North Carolina State University** (Rouphail, 2000)

CORSIM is a traffic microsimulator, which is a combination of two sub-models: FRESIM, which simulates freeway components, and NETSIM, which simulates arterial streets. It has also been integrated with unpublished vehicle emissions rates from dynamometer tests based on speed and acceleration.

Mesoscopic Models

MEASURE – Georgia Institute of Technology (Bachman et al., 2000)

MEASURE (Mobile Emissions Assessment System for Urban and Regional Evaluations) is a mesoscopic, statistical aggregated modal traffic emissions model. The model is geographically based (using GIS) with respect to vehicle activity and emissions rates. Statistical distributions of vehicle activity are assigned geographically. The emissions rates are calibrated based on data used to develop MOBILE and from CARB dynamometer tests. It was originally integrated with a statistical categorization of vehicles by facility type and traffic roadway conditions. The emissions modal model considers engine power, kinetic energy, speed, and acceleration parameters. Results in MEASURE are currently being adapted to estimate microscopic emissions rates.

CORSIM + MEASURE – Georgia Institute of Technology (Guensler et al., 2001)

MEASURE (see above) has been integrated with CORSIM (see above), both microscopically and mesoscopically. The mesoscopic version of the model was applied to analyze the effect of signal coordination on 17 signalized intersections in Atlanta (Hallmark et al., 2000). In another study, attempts to validate the model using a total of 30 intersections found that field data demonstrates much greater distribution of speeds and accelerations than that seen in the model (Hallmark and Guensler, 1999). The model has also been used to analyze the effect of ramp metering on several ramp meters on the I-75 in Atlanta. This project included comparing CORSIM to driving cycles generated from the trajectories of probe vehicles. It was found that the micro-simulator accuracy not modeling the driving conditions accurately enough for local emissions analysis.

Dynamic Traffic Model + EMIT – Massachusetts Institute of Technology (Cappiello, 2002)

An instantaneous modal emissions model, EMIT, was integrated with a mesoscopic dynamic traffic model (Bottom, 2000). EMIT is calibrated on NCHRP dynamometer data. It has been calibrated only for a few vehicle categories, but with very positive fitting results. The model was used to test the effect of route guidance on emissions, fuel consumption, and travel time on a small hypothetical network.

Other Models

ITEM – U.C. Riverside (Barth et al., 1999)

ITEM (Integrated Transportation/Emissions Model) is a hybrid macro/micro-scale model for modeling both regional and local emissions. It uses a macroscopic traffic assignment model for its wide area transportation model, and one of many microscopic sub-models for the local emissions modeling. The sub-models are models of: freeways, freeway ramps, signalized intersections (TRAF-NETSIM), and rural highways. The traffic models use a time-step of 0.1 seconds. CMEM (Comprehensive Modal Emission Modal) is used directly to provide second-by-second emissions estimates. The model has been applied to a case study of the Inland Empire in Southern California.

Table 2-5: Summary of existing integrated traffic flow and emissions models

Model Name	Traffic Flow Model	Emissions Model	Data set	Application
DIANA Finland/Helsinki Univ. of Technology	Stochastic microsimulator (HUTSIM)	▪ V/A look-up tables (EMCA) ▪ Flow and dispersion in urban st. canyons (OSPM)	Downtown Helsinki: street- and roof-level concentrations, traffic counts	
ITEM Univ. of California Riverside	▪ Macro. traffic assignment model ▪ Microsimulator sub-models (Fwys., On-Ramps, Signalized Intersections, Rural Hwys., etc.)	CMEM		Inland Empire in Southern California
MEASURE and CORSIM Georgia Institute of Technology	Statistical distributions of vehicle activity	Statistically based emissions using aggregate Modal Model (MEASURE)	CO: EPA and CARB	
MEASURE and CORSIM Georgia Institute of Technology	Microsimulator (CORSIM - combination of FRESIM and NETSIM)	Statistically based emissions using aggregate Modal Model (MEASURE)	CO: EPA and CARB Traffic Flow and Pollutant Concentrations: Atlanta I-75	(1) 17 signalized intersections in Atlanta (2) Ramp meters
VISSIM PTV, Germany	Dynamic assignment microsimulator (VISEM)	(1) V/A look-up tables (2) CMEM in progress ▪ Includes a Dispersion model		
TRANSIMS Los Alamos National Laboratory	▪ Cellular automata microsimulator ▪ Demand generation	(1) V/A Look-up tables (2) CMEM (in the future) ▪ Incl. Evaporative Emissions		Hypothetical Networks
INTEGRATION Virginia Polytechnic Institute and State University	Microscopic (INTEGRATION)	Speed and acceleration regressions developed at Oak Ridge National Laboratory		(1) Long segment (constant speed, stop sign, signalized, etc) (2) Hypothetical netwrk w/ route choice and traffic signals
EMIT + Dynamic Traffic Model	Mesoscopic	Instantaneous regression emissions model (EMIT)	Emissions: NCHRP data	Route guidance on a small hypothetical netwrk

2.5.2 *Literature Review on the Evaluation of Transportation Control Measures*

Each of the traffic, emissions, and air dispersion models alone is complex and time consuming to develop, learn, and apply. When cross-field studies are done, to streamline the process, average results are used between the models instead of spatially and temporally detailed information. The traditional method of evaluating emissions changes due to traffic changes is to model the traffic conditions due to the change, and then to summarize the resulting traffic conditions from these changes as average speeds. Some studies have also used before and after average speed conditions from measured data. The modeled or collected average speed data are used with an emissions model, or emissions look-up table, to estimate the changes in emissions. The emissions changes are summarized as static average numbers, and can then fed to an air quality model, which estimates the changes in air quality using wind speed and dispersion models. The complexity and accuracy used in each of the models may be lost as the data is averaged when passed between these models.

Many traffic models have been developed to evaluate traffic control strategies for their ability to improve traffic conditions. But considering the strong belief in the transportation community that traffic control management (TCM) results in emissions benefits, very few methods exist for evaluating the performance of TCMs from the point of view of emissions impacts. A limited number of studies have been conducted to model the effects of ramp metering, signalized arterials, and traffic calming techniques on traffic emissions. Methods that have been used include remote sensing, equipping vehicles with emissions sensors, and traffic emissions modeling. The literature review of this subsection focuses on the models that have been used to evaluate traffic and emissions control strategies.

The most comprehensive study of modeling air quality impacts of a traffic control measure was conducted by the ***Georgia Institute of Technology*** on several ramp meters on the Atlanta I-75 (Guensler et al., 2001). The study sampled traffic data by simultaneously using probe vehicles and laser range finders on the ramp and mainlines of the ramp meters. The MEASURE aggregate modal model is used to predict the emissions that are generated on the mainline and the ramps. These emissions results were compared to those that are produced by MOBILE5. Using MEASURE, it was found that for the observed demand levels, ramp metering led to a minimal decrease in HC of 1%, accompanied by a larger NOX increase of 4%. MOBILE, on the other hand, predicted *increasing* HC and a smaller NOX increase. The amount of emissions in the system predicted by MOBILE was also very different from that predicted by MEASURE.

The I-75 network was also coded into the CORSIM traffic microscopic simulation model and calibrated on the traffic data. The network was then simulated in CORSIM and the traffic modes were run through MEASURE to predict the emissions for higher demand and also with incident management. The emissions results differed from the MEASURE-only results, which the GeorgiaTech team believes was due to the inability of CORSIM to reproduce the same traffic conditions as those observed. Some other key results of the study include:

- The discovery that though onramp emissions estimates are important, the mainline segments for the studied system accounted for 96 to 98 percent of the system wide emissions.
- Ramp metering provides greater mainline freeway time savings under heavier traffic flow conditions.
- The identification of the top five factors which affect vehicle emissions for the studied system (cited in order of influence): age of vehicles, fleet composition by vehicle type, change of traffic patterns, changes in fleet composition throughout the day, and changes in fleet composition from day to day.
- The estimated emissions increase due to ramp metering on the portion of the corridor accounted for less than 0.005 percent of the daily regional budget.

In another study by the same group from the Georgia Institute of Technology, field data versus simulated speed-acceleration profile data were compared for a multiple intersections (Hallmark and Guensler, 1999). It was shown that NETSIM (the urban traffic microscopic simulator used) did not produce as wide a range and variety of speed-acceleration activity as observed in the field. Also, when the vehicle profiles were run through MEASURE and MOBILE5, the simulated data resulted in higher emissions than those measured in the real world. Hallmark and Guensler concluded that NETSIM would have to be adjusted before it could be used for emissions predictions.

The same approach, as described above, was used to evaluate the effect on carbon monoxide of signal coordination at a group of intersections (Hallmark et al., 2000). The entire spectrum of level of services (LOS) of congestion was observed, indicating that modal activity level was continually changing. One observation made in the paper was that modal activity varied greatly by queue position. They show that well coordinated signals can significantly improve CO emissions over uncoordinated signals. The study indicates that the ability of a model to take modal activity into consideration can significantly affect the emissions estimates. MEASURE predicts more than twice the emissions benefits that MOBILE5 does. Although neither of the models has been validated for local network emissions modeling, MEASURE has been shown to perform equally well or more accurately than MOBILE and though MEASURE was shown to overpredicts emissions for the validation sample, the overprediction was only slightly (Fomunung et al., 2000). The discrepancy in the emissions predictions of the two models for the intersection suggests that modal activity should be included in TCM evaluation.

Another study, conducted at the University of California Riverside, uses CMEM and PARAMICS to model vehicle activity and the resulting emissions in the Caldecott Tunnel, a two-lane tunnel (Hill et al., 2001). Emissions measurements, vehicle speeds, and fleet mix were taken during afternoon rush hours for four summers (Kirchstetter et al., 1999). The tunnel has a 4.3% grade and is 1.1 km long. The average simulated speeds and NOX using the integrated model were higher.

These studies conducted by GeorgiaTech and UC Riverside show that it is important to validate traffic models specifically for emissions before relying on their predicative capabilities. Most traffic models are validated with respect to flow and other more aggregate parameters, but not on individual vehicle speed and acceleration distributions. Microscopic simulators usually use car-following, lane changing, and gap acceptance models, to predict the speed and accelerations of the vehicles. These models are usually calibrated using speed and acceleration data, but the validation is done on the aggregate level only.

No microscopic traffic models have been reported to have been successfully validated for emissions purposes (validating speed and acceleration distributions and profiles). Macroscopic models such as DIANA (emissions for concentration levels) had more success (Niittymaki et al., 2001). The process of validation requires a great deal of effort and time. A detailed set of traffic and emissions parameters needs to be collected to capture the traffic conditions of an entire local area. Therefore, second-by-second combined models have mostly been studies of the effect of traffic control measures on emissions on hypothetical cases, with no validation.

The studies using hypothetical networks have employed various emissions modeling methods. The simplest method is to apply regional emissions factors to vehicle activity data. This was done on the A9 autobahn in Germany (Metz et al., 1997) for estimating the emissions before and after traffic control. Due to its simplicity, this method is the traditional and most widely used by policy makers. The method is still supported by many in the field to be as accurate as modal emissions modeling methods (Zachariadis and Samaras, 1997). This method depends heavily on the emissions factor being used. It also cannot capture the effects of traffic control strategies that do not change the average speed of a section, but changes the mode in which the vehicles are operating. Studies have shown that even for runs with the same average speed or over a narrow range of average speeds, the emissions can vary by 100% (Latham et al., 2000).

To study a specific traffic control method in greater detail, driving cycles have been developed to represent different driving conditions, such as ramp metering, which are then used on the dynamometer to test the emissions for a larger set of vehicles (Cicero-Fernandez and Long, 1996). The drawback of this method is that strategies can only be estimated after their implementation. Without simulation, it is difficult to design driving cycles that are representative of potential improvements and changes. The small fluctuations and various driver reactions arising from new technologies are difficult to place.

More recently, instrumented probe vehicles have been used to collect emissions and traffic data. These vehicles are driven on the routes of interest allowing the emissions and traffic data to be collected simultaneously for real driving conditions. This method was used to evaluate the effect of signalized arterials (Rouphail et al., 2000) and traffic signal coordination and timing (Frey et al., 2000). The on-road vehicle data measurement device used is the OEM 2100, designed by Vojtisek-Lom and is now marketed by CleanAir Technologies International, Inc. The device simultaneously measures tailpipe and engine out emissions and gathers data from the On-Board Diagnostic (OBD). This instrumentation has shown to be accurate in laboratory tests. Similar to the driving cycle method, the limitation of this method is that it is only suitable for improvements that have already been made. It is difficult to test multiple scenarios unless they are deployed in the field

In order to model hypothetical situations such as future demand, different signal timings, or other ITS technologies, integrated microscopic traffic emissions models are required. These have been used to evaluate TCMs including using different traffic signal controls on a simple network (Rakha et al., 2000) and the effect of traffic signal cycle lengths (Williams and Yu, 2001) (see Section 5.1.2). Development of more comprehensive models, which include mobility demand modeling, route choice, emissions, and air dispersion models have been proposed, but only limited results have been published on these models. It is the opinion of the author that ITEM (Barth et al., 1999) and VISSIM (Fellendorf and Vortisch, 1999) are two promising efforts underway.

An example of a TCM that may improve travel times, without much emissions benefits is ramp metering. Several studies have been conducted to evaluate the effect of ramp metering on emissions. Ramp metering is considered one of the most effective methods for improving traffic flow on freeways. By delaying the entry of a small set of additional vehicles onto the highway, ramp meters allow the mass of vehicles already on the freeway to move more efficiently. This is based on the fundamental traffic theory that on a given freeway segment the average speed is a function of the density on the roadway. Ramp meters keep the density on the main freeway branch lower and allow the average speed of the freeway to be higher than if there were no ramp meters. Consequently, ramp meters may also cause higher emissions generation by the vehicles encountering the ramp meters on entering the network, due to the high levels of acceleration required to reach cruising speed from complete stop before the ramp meter.

Currently, studies show that ramp metering does not provide significant emissions benefit, but can provide significant time savings. Additionally, it has been shown that if demand is too low, ramp metering is not effective at either reducing delay or reducing emissions (Cambridge Systematics, 2001 and Guensler et al., 2001). It is possible that a "smarter" ramp metering system could both reduce travel delay while reducing emissions.

Evaluating the impact of a coordinated ramp metering system requires the modeling a stretch of the main freeway section, the ramp, and the roadway that leads onto the ramp, because ramp metering can impact the traffic in these areas. The CA/T network includes a coordinated ramp metering strategy called FLOW. The ramp metering system includes three ramp meters. Two vehicle release strategies can be simulated on the CA/T, single release and platoon release.

There are two conflicting factors that affect the emissions consequences of ramp metering. On the main freeway section, ramp meters increase the average speeds which increases emissions, yet accelerations and deceleration events are reduced, if flow is improved, which would reduce emissions. On the ramps, adding the stops and hard accelerations could increase emissions, yet the modal activity observed during merging from the ramp onto the main section should be smoother, which could reduce emissions.

These trade-offs may be different at different speeds and using different ramp metering algorithms.

2.5.3 Summary and Conclusions

Network emissions models are being developed for air quality analysis as a tool to help address mobile emissions, which are a major source of air pollution. From a political standpoint, technological improvements such as vehicle technology improvements and TCMs are more acceptable ways of dealing with emissions, in lieu of travel demand management. It has yet to be proved, though, that TCMs in general can significantly decrease on-road emissions, even though the federal government encourages its use for Clean Air Act compliance. It has been shown that TCMs can potentially provide emissions benefits if implemented in correct situations. This is also true for the traffic congestion benefits that TCMs can offer, but the difference is that the emissions benefits are difficult to measure, whereas the congestion benefits are comparatively easier to measure. It would be beneficial, to have tools available to transportation engineers and policy makers which evaluate the effectiveness of TCMs and other measures, with proven acceptable accuracy and reliability.

Average speed emissions models are currently the most widely used models for estimating mobile emissions. However, they may not be appropriate for TCM modeling. TCMs can dramatically change the local modal activity profile, such as speed fluctuations and the length of accelerations and decelerations. Average speed emissions models do not consider modal activity. To address this deficiency, integrated traffic and emissions models are being developed for modeling both the changes in modal activity and the resulting emissions changes.

Ramp metering and signalized intersections have been studied often because vehicles exhibit the most extreme vehicle activity (acceleration and decelerations) in these situations. The traffic management capabilities of these two technologies have been proven, and have been considered for their air quality benefits too, under the assumption that improving traffic conditions also benefits emissions. This has been shown to be an invalid assumption, where the increase in emissions generated by higher speeds from effective traffic management is greater than the emissions reduction resulting from smoothing traffic (Guensler, 2001).

The concept of local network emissions modeling using integrated traffic and emission models is still in its infancy. One main obstacle is the difficulty of validating both the speeds, accelerations, and the resulting emissions on the network. Another modeling limitation is the available computing power. Local network emissions modeling requires both spatial and temporal detail. The ability to simulate larger networks in more detail continues to progress as computing power enhances.

Chapter 3

Design and Implementation of Network Emissions Models

As evidenced in the literature review in Chapter 2, a model with fine spatial and temporal accuracy is useful for analyzing the emissions consequences of transportation control measures. The model should be able to simulate the effect of changes in traffic control measures on traffic flow and their effect on emissions. One framework for this model would be to keep track of individual vehicle trajectories resulting from traffic conditions and to then calculate the emissions resulting from these trajectories using a dynamic emissions model. Such a model could also be used for various other local network emissions modeling purposes such as simulating emissions control strategies, modeling emissions inventories, and studying emissions characteristics.

We have developed a microscopic network emissions model that can serve as a laboratory. This laboratory is called MITNEM (Microscopic Integrated Traffic Network Emissions Model). MITNEM uses two existing models as its sub-components, MITSIMLab, a traffic micro-simulator and CMEM, a load-based dynamic modal emissions model. The two models are state-of-the-art and implement the latest research developments in their respective fields. MITSIMLab includes detailed driving behavior models and is designed specifically for testing traffic control technologies. CMEM takes operating history into account and can model numerous parameters which have been found to affect emissions, including cold starts, grades, air-conditioning, ambient temperature, and humidity.

This chapter is organized as follows. Sections 3.1 and 3.2 describe the development process and the framework for a general microscopic network emissions model. Section 3.3 presents the structure and some intended applications of the MITNEM laboratory created using the framework. Potential applications for MITNEM are also discussed in this section. Sections 3.4 and 3.5 describe the sub-component models MITSIMLab and CMEM, respectively, in the context of their use in MITNEM.

3.1 Development Process

Figure 3.1 depicts a single iteration of the process for designing a traffic-emissions model. The development process is iterative because each of the decisions relies partially on the decisions made in the other boxes. For example, the choice of models depends on the level-of-detail desired, the input and outputs desired and needed from the other models, and finally, the data that is available.

The framework is used to design the model structure, identify the components of the model, define the input and output data and parameters, and determine the interfaces required for data flow. A well-designed framework is likely to be able to accommodate sub-models designed in the future.

Part of the development process is to determine the level-of-detail of the included parameters, which include the number of vehicle categories and the time and geographic scales. The decisions made here will affect the amount and complexity of calibration and validation required.

A survey and evaluation of the current sub-models, such as performed in Chapter 2 is required to determine whether new models must be designed or if existing models are to be used. As the framework and level-of-details change, the scope of the model evaluation may change. Some modifications to existing models may be necessary before integration into the framework is possible.

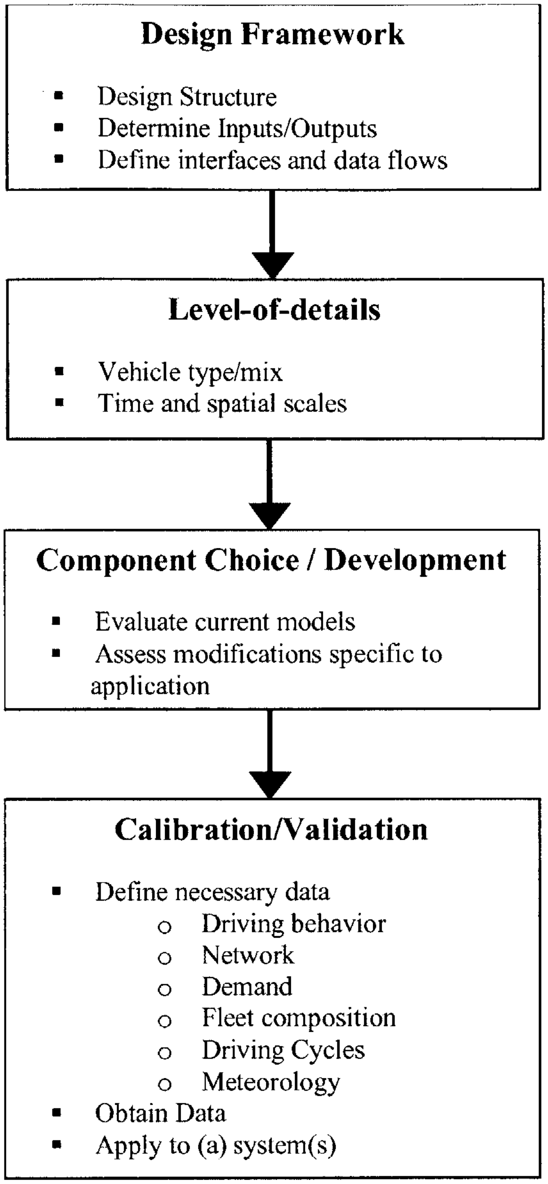


Figure 3.1: A design process for general local network emissions models

Finally, the ease of calibration and validation will determine the applicability of the final model. A simple model may be calibrated as a whole, but a calibration of a model with complex sub-models requires individual calibration of the sub-models. Microscopic traffic model calibration includes the optimization of driving behavior parameters, network layout and right-of-way rules, the demand, and the fleet mix (acceleration capabilities, size, etc.). The resulting driving trajectory is typically calibrated and validated macroscopically (flow and average speed are calibrated). Emissions models require vehicle fleet mix data, including emissions category and percentage of vehicles operating in cold-start. Air quality models require as input background pollution concentrations and meteorology data. Health consequence models require population density data. Often, calibration of all parameters is not possible, so default values or calibrations from similar networks are used. For the entire model to be calibrated, data needs to be collected for the entire process. The amount of data required is so large that it has not been done to date. Attempts at calibration have been unsuccessful on local network emissions models, mostly due to the difficulty of validating traffic models at the level of time-dependent speeds and accelerations, and the difficulty of modeling air quality to the necessary accuracy for validation.

3.2 Framework

Many microscopic traffic simulators and emissions models have been described in Chapter 2. Because they operate on similar time scales, on the order of seconds, they are relatively straightforward to integrate. The framework depicted in Figure 3.2, may be applied to the integration of most microscopic traffic models and dynamic emissions models. The framework contains the following components:

- A microscopic traffic simulator;
- A dynamic micro-scale emissions model;
- Data post-processing tools; and
- Visualization and analysis tools.

The conventional microscopic traffic model requires the following to be defined either using default values or the user input values of variables such as:

- Demand;
- Vehicle type;
- Network
    - Physical layout,
    - Traffic rules of the network,
    - Technology; and
- Driver behavior parameters.

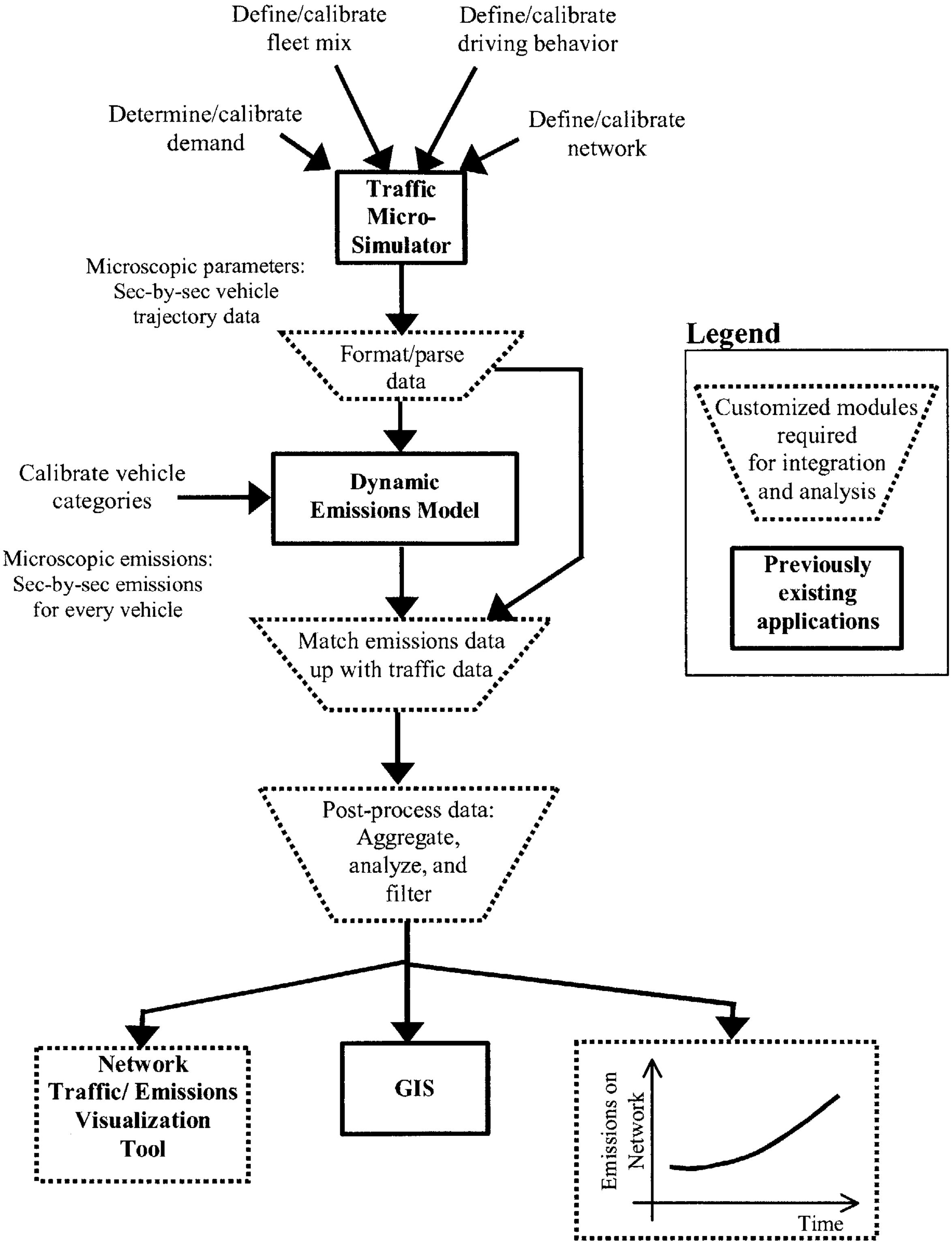


Figure 3.2: Microscopic network emissions model framework

The demand is often specified in the form of origin-destination (O-D) trip tables, which are used to assign vehicles to paths and then move them throughout the road network. The demand can be deterministic or stochastic, constant over time or varying as a function of time. The vehicle type specification includes vehicle size and the maximum acceleration and speeds achievable by vehicles. The physical network specifies the roads connect, the number of lanes, and how the roads are divided into links and segments. Geographical features, such as roadway grade,which impact vehicle movement can also be represented. The driving rules of the network include speed limits, traffic light rules, definition of carpool and high-occupancy vehicle lanes, and merging and intersection right-of-way rules. The technology covers traffic light timings, ramp metering strategies, variable message signs, traffic condition feedback loops, and other Intelligent Transportation Systems (ITS) .

Emissions models have their own vehicle categories based on the data on which the model was calibrated. Each vehicle in the model must be assigned an emissions category. This can be done at the beginning of the simulation, as the vehicle is introduced onto the network by the microscopic traffic simulator, or the assignment can be performed after the traffic simulation. If the assignment is performed after the traffic simulation, then the vehicle type used in the traffic simulation for each vehicle must be consistent with the emissions category. For example, if the microscopic traffic simulator vehicle types are old passenger vehicles and heavy-duty trucks then it should be ensured that only passenger vehicle emissions types are assigned to vehicles modeled as passenger vehicles and only heavy-duty truck emission types are assigned to the heavy-duty trucks.

Some dynamic emissions models take into account modal operation history, such as time spent in acceleration, cruise, or idle. These emissions models cannot run concurrently with a traffic microsimulator. They must be run slightly lagging or in serial with the traffic microsimulator.

The data flow begins with the traffic simulator calculating micro-scale (exact time-scale is application specific) vehicle acceleration, speed, and/or position data, which constitute the vehicle trajectories. This data is formatted, and the speed and/or acceleration, and vehicle categories are fed to the dynamic emissions model. Formatting entails converting time-scales, calculating accelerations, converting units, changing data file formats, or any number of data conversions.

The dynamic emissions model uses this information to calculate the emissions at every time step (also application specific). If the emissions model is running within the traffic model, the trajectory data and emissions data can be matched instantaneously to be written to a file during or after the simulation. If the emissions model is external to the traffic simulator, the emissions data is written to a file and needs to be "matched" with the position data in the trajectory file. This "matched" file can then be post-processed (e.g. spatially or temporally aggregated, filtered using spatial or temporal qualities, or averaged) for visualization or further analysis.

Visualization tools can include customized application, specific to traffic and emissions modeling and analysis, and Geographical Information Systems (GIS) such as ArcView. Analysis tools include spreadsheets, graphing and statistical packages such as Excel, Access, and Minitab.

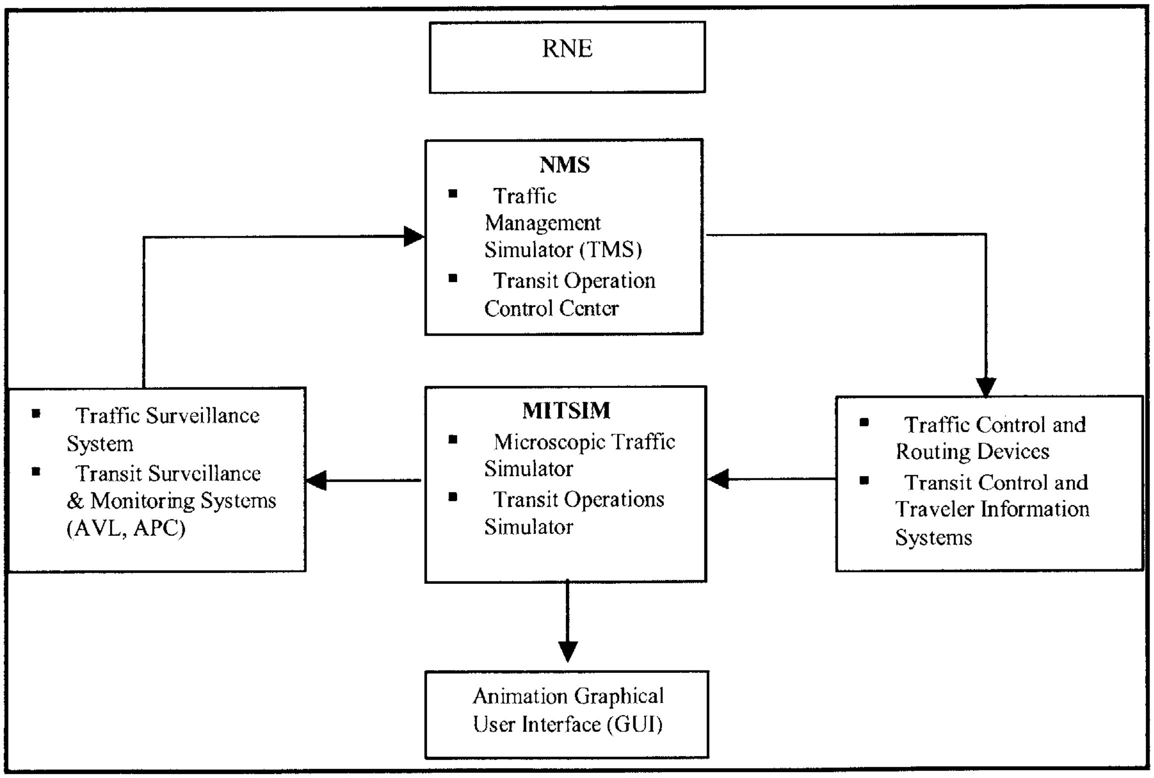
The framework allows substitution of sub-models so that different combinations of models can be used in order to calculate the consequences of different modeling assumptions. Modules such as air dispersion models and travel demand models can be added for additional insight. Additionally, the framework is designed to allow transfer of a high-level of detail between the models so that the user can conduct experiments with maximum flexibility.

3.3 Implementation of a Local Network Emissions Model

The framework described in the previous section is used to develop a laboratory called MITNEM. This section describes its structure and some of the intended applications.

The two sub-models in MITNEM are MITSIMLab, a traffic micro-simulator laboratory and CMEM, a modal vehicle emissions model.

As shown in Figure 3.3, MITSIMLab includes: the Road Network Editor (RNE), a graphical interface which facilitates input of network information, a MIcroscopic Traffic SIMulator (MITSIM), a Network Management Simulator (NMS) which "operates" the traffic control and routing devices including transit operation and devices, and finally a graphical user interface for displaying the simulation, and related data during run-time or as a post-runtime animation. CMEM is a second-by-second modal emissions model which calculates HC, CO, NOX, fuel consumption, and CO2.



Adapted from: Morgan, 2002

Figure 3.3: Elements of MITSIM

The modules of MITNEM are shown in Figure 3.4. The format for the names of the files in which the output or interface data is stored at each phase, are shown next to the arrows.

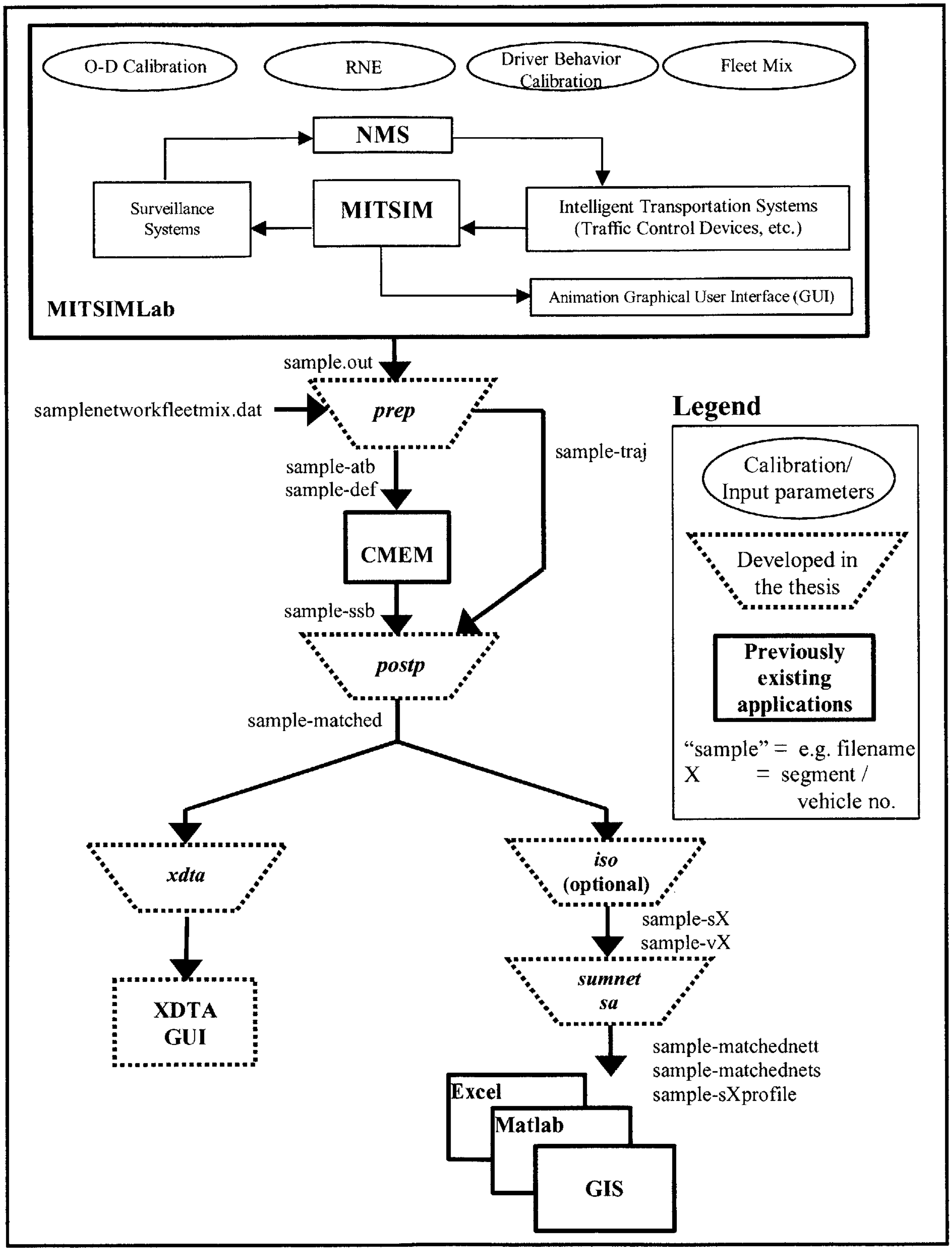


Figure 3.4: MITNEM

The figure uses "sample" as the filename. This would be substituted with the filename of the simulation run. Programs written specifically for MITNEM are *italicized.* Detailed description of all MITNEM files (executables, C++ code, and data files) can be found in Appendix A. The format of all input, output, and interface files are listed in Appendix B.

Some model preparation is required for MITSIMLab. Typically, for a real network in MITSIMLab, the demand, vehicle fleet mix, and driving behavior are calibrated using measurements and historical data. This is a lengthy process that requires data collection from the field. For experimental networks, literature values can be used along with MITSIMLab default values. With these parameters defined, MITSIMLab simulates the traffic on the network for the specified demand profile for a specified time period.

The output is the vehicle trajectory data, which is written to a file with the extension "*.out" (sample.out). This data is formatted by *prep*, a C++ program, for CMEM, by creating the vehicle activity file (sample-atb) and the vehicle definition file (sample-def) from the MITSIM output. *Prep* randomly assigns CMEM emissions vehicle categories to each vehicle ID number in the proportion specified in the fleet mix data file (samplenetworkfleetmix.dat, e.g. CATfleetmix.dat) and writes the vehicle ID number, corresponding CMEM category number, and vehicle operating conditions (engine temperature, humidity, etc) to the vehicle definition file. *Prep* also creates an interim trajectory file, sample-traj which is used later in *postp*, the post-processing program written in C++. An additional control file (sample-ctb) is required to run CMEM. CMEM uses these files to calculate the second-by-second vehicle emissions and writes the emissions data to the second-by-second batch output file (sample-ssb).

The second-by-second batch output file is used in conjunction with the trajectory file (sample-traj) to match the emissions data back up with the trajectory data. Each vehicle is assigned a unique ID number when entering MITSIM, which in conjunction with the time entry forms a unique record, which appears once each in the trajectory file and the CMEM batch output file. This matched data is written to a single file called a "matched file" (sample-matched), that includes all the necessary information for visualization or data analysis of the emissions and traffic conditions on the network. The matched file includes the following second-by-second data: Vehicle ID, Segment, Lane, Position, Speed, Acceleration, Vehicle Type, HC for this second, CO, NOX, Fuel consumption, and CO2.

The output data still needs to be post-processed before analysis can be performed. Post-processing tasks include:

- Filtering the data of unwanted data (temporal, spatial, vehicle category, etc.) or extracting specific sub-sets of data,
- Aggregating the data into spatial and/or temporal values and,
- Normalizing the data for comparison purposes.

For example, filtering could be used to filter out all non-passenger vehicles (buses and heavy-duty trucks) from the data set. Aggregating data includes aggregating all of the HC emissions released during the entire simulation. And an example of normalizing the data is to divide the total aggregated emissions by the simulation run time, to obtain emissions/hr.

Several post-processing tools have been written, in C++, to perform some of these tasks, *iso*, *sumnet*, and *sa*. *Iso* is an optional filter program which can be used to extract the data on a single network segment (*-sX) or vehicle (*-vX) from the matched file. *Sumnet* takes the matched file or the filtered files as input to perform aggregation by time (*-matchednett), by segment (*-matchednets), or over the entire network. *Sa* takes the file filtered by segment (*-sX) and aggregates the emissions along the segment meter by meter to create a segment profile (*-sXprofile).

These output files are text files. They then can be opened or formatted for spreadsheets, mathematical programs, or visualization application, such as Excel, Matlab, or ArcView. Customized displays can also be used to display or analyze results. An example of a customized application is XDTA, which was originally designed to animate traffic flow variables (such as speed, density, and flow) around the network by segment. A C++

program, *prexdta*, was written to aggregate the matched file into the input required by XDTA.

3.3.1 GIS Graphical Display

If a map or digital photo of the network is available, it can be loaded into ArcView. The emissions results can then be charted as an overlay on this GIS-based map. Examples of GIS-based charts are shown in Figure 3.5. Visualization helps engineers and policy makers to more rapidly identify existing or potential problem areas. GIS is a method for organizing data. GIS display can assist in analysis such as spotting spatial emissions shifts created by TCMs or identifying emissions generation patterns. Section 5.2 uses GIS to show the emissions changes due to signal timing and to show detailed emissions patterns around an intersection.

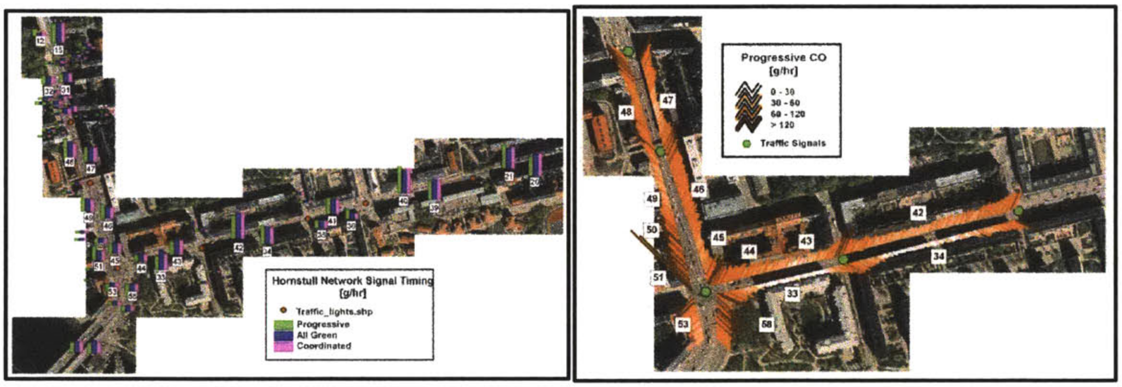


Figure 3.5: Examples of GIS graphical display of emissions

3.3.2 MITNEM Capabilities and Limitations

MITNEM is designed to be used for multiple purposes. There are also situations which to which MITNEM should not be applied. It is just as important to understand the limitations of the model as its strengths. This section lists the intended applications for MITNEM and some of its limitations.

- MITSIMLab is currently used for operational planning. MITSIMLab was designed to test the effectiveness of ITS technologies, therefore it has many built-in tools, such as sensors, incident generators, and error simulators, which can be used to test the effectiveness of traffic management technology and schemes. The addition of CMEM adds the ability to include emissions results in the planning process.

- Combined with simple air quality models MITNEM could be used for local air quality analysis and planning, analyzing roadside air quality and quantifying mobile emissions sources.
- In its current format, or combined with more sophisticated air quality models, MITNEM can address numerous research questions. Some research questions include the study of effects of driving behavior on emissions, methods to optimize emissions reductions using ITS, and the impact of air quality to different TCMs.

MITNEM has the following limitations:

- It can take a few days to process simulation runs. Because of the details used in the model, MITSIMLab roughly runs real-time and CMEM runs much slower. And the because MITNEM is a stochastic model, several simulation runs must be made for the same conditions before a conclusion can be made. For a medium sized network, several days may be required to obtain emissions results.
- The simulation requires a lot of memory and hard-disk space. For medium sized networks, a few gigabytes of space are needed for a simulation run. Many of the interim files used in the simulation can be deleted after the simulation has been completed.
- Parts of the model can only be run on a Sparcstation or a Silicon Graphics (SGI) workstation. The batch-processing version of CMEM is currently available only as executables for these two Unix platforms.

3.4 MITSIMLab

MITSIMLab is a micro-simulator tool that simulates the conditions on a network by modeling the driving behavior of individual vehicles dynamically interacting with the network geometry, other vehicles, and any traffic control mechanisms (signals, speed limits, ramp metering, etc). The model is one of the most sophisticated traffic micro-simulators in the field. It has been successfully calibrated, validated, and applied to several networks around the world (Ahmed, 1999, Yang, 1997, and Davol, 2001). This section gives an overview of the details of MITSIMLab.

Two modules of MITSIMLab are used in MITNEM:

- Traffic Flow Simulator (MITSIM),
- Network Management Simulator (NMS),

MITSIM calculates the driving behavior and travel behavior on the road network in reaction to the control information (speed limits, routing, signals) provided by TMS. In turn, the sensors placed throughout MITSIM monitor the network conditions (for instance, flow, density, and speed) and pass the information to TMS, similar to the feedback on real networks. TMS then calculates the new control settings using the logic that it has been programmed to simulate. Separating the control from the driver behavior into these two modules realistically keeps the driver behavior separate from the traffic management control. TMS can simulate failing signals and MITSIM can simulate driver non-compliance to traffic controls and sensor failure.

The logic behind MITSIMLab was developed in multiple steps. More information can be found on MITSIMLab in the theses referenced in this paragraph. The original framework of MITSIM was developed in Yang (1997). Ahmed further refined the models used for driver behavior and lane changing (Ahmed, 1999). Additional modeling features such as the ability to simulate ramp metering (Hasan, 1999), signal priority strategies (Davol, 2001) and public transit operatiosn modeling (Morgan, 2002) have been added since.

MITSIMLab has a graphical user interface, called the Road Network Editor (RNE), for inputting the geometry of a network and for specifying placement of surveillance and control devices. Networks in MITSIMLab can be drawn graphically in RNE, and these the graphic files are translated into a text file with nodes, links, segments, and signal locations. Roads are broken down into links, which consist of segments. Segments are composed of lanes. Because segments have unique ID numbers in MITSIMLab, only segment and lane information is used in MITNEM and link information is not included in the data. Segments are defined as uniform sections of road with the same number of lanes, speed limits, and roadway geometry along the entire stretch. Figure 3.6 shows how a roadway would be broken into segments in MITSIM. MITSIMLab keeps track of the position of a vehicle in a lane on a segment.

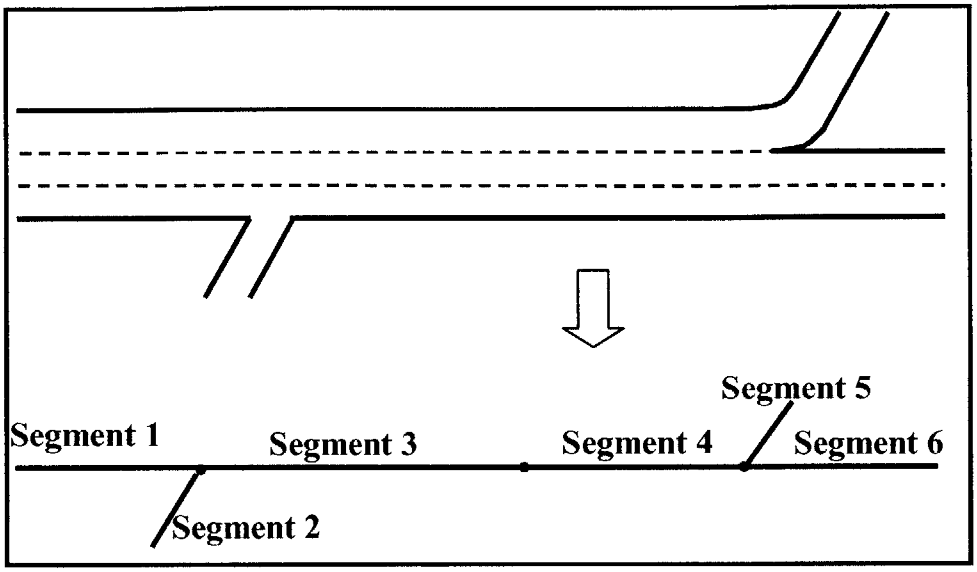


Figure 3.6: MITSIMLab network representation

MITSIMLab's major strength is the stochastic microscopic traffic simulation models used to produce the second-by-second trajectories of vehicles over the network. These include:

- A route-choice (route-generation) model
- Driving behavior models
    - Acceleration (car-following, free-flowing) models
    - Lane changing models

The authors of MITSIMLab have further refined many of the models for implementation in MITSIMLab. Typically, in microscopic traffic modeling, realism is sacrificed for simplicity. For example, the simpler acceleration models used in most simulators are usually memoryless, reactive, and independent of the driving "neighborhood" (Toledo, 2002b). MITSIMLab uses several models to comprehensively address these issues. Driving is divided into three regimes, free-flowing, car-following, and emergency. The car-following model and free-flowing models, developed by Ahmed (1999) and implemented in MITSIMLab, are improvements on existing models in the literature and have been estimated using real-world data. The car-following model allows for the non-linearity observed in real driving. Similarly, the lane changing model developed by Ahmed is much more comprehensive than a simple gap acceptance model. The different situations that lead to lane changing are modeled individually. Mandatory and discretionary lane changing have separate binary logit models (a decision-making model) and forced merging has its own model. The gap acceptance model is estimated using second-by-second vehicle trajectory data. The parameters for all of the models are jointly estimated during calibration, since changing the value of one parameter may affect the fit if the other parameters are left constant.

3.4.1 Origin-Destination Matrix

The orign-destination (O-D) matrix specifies the input flows and the destination proportions (proportion of vehicles aimed for each exit) at all the entrances of the network. These flows can vary by time. For example at 7:00 am, the O-D flow could be 700 vehicles/hr from a point A to a point B (entering the network at point A and exiting the network at point B), and at 8:00 am, the flow could be changed to 1000 vehicles/hr from point A to point B. MITSIM will introduce vehicles onto the network stochastically in this proportion with a statistical "error term" (with a given variance). The O-D matrix can be determined from multiple sources of data, including actual flow measurements at the entrance points or extrapolations from flow measurements around the network. The O-D matrix can be calibrated along with other parameters of the driving behavior models using the observed traffic variables (flows and velocities). Additionally, MITSIM has a parameter which can be used to scale the O-D matrix. This parameter can be used to study the effect of increases or decreases in demand.

In specifying an O-D matrix, there is one condition that must be met for traffic emissions modeling. It is important that traffic does not back up at the entrance of the network. If vehicles are beginning to back up at the entrance points, then the specified entrance flow will be invalidated. Though MITSIM does queue these vehicles to be introduced onto the network until space becomes available, their trajectory is not included until they actually enter the network. These vehicles are continually emitting pollutants, but the pollution emitted cannot be accounted for, since their trajectories before entering the network are not being modeled (see Section 4.1).

3.4.2 Vehicle and Driver Categories

As each vehicle enters the network in MITSIM, it is assigned a vehicle category and a driver category. The driver category specifies whether the driver is aggressive or conservative. Aggressive drivers are more likely to change lanes often, follow other vehicles closely, drive above the speed limit, and can run red lights. The proportion of aggressive to compliant drivers is specified as an input parameter. Additionally, MITSIMLab uses, in general, five vehicle categories: new cars, old cars, heavy-duty trucks, buses, and semi/combination trucks. The vehicle adheres to these characteristics the entire time it is on the network.

Any number of additional vehicle type categories can be defined. The information required for each vehicle category is: vehicle length, percentage of fleet, and a breakdown of the vehicle's maximum acceleration at various speeds between 20-80mph. There are other optional parameters for the vehicle type, such as average normal deceleration, maximum deceleration, and maximum speed, which are usually set to default values. Table 3-1 and Table 3-2 are examples of fleet definitions from case studies which are presented in the following chapters.

Table 3-1: Percentage of MITSIM vehicle types on networks

Vehicle Type	**Central Artery/Tunnel (CA/T)**	**Hornstull**
New cars	50%	51.9%
Old cars	48%	41.6%
Buses	1%	1%
Trucks	1%	5.5%
Trailer trucks	0%	0%

Table 3-2: Maximum acceleration of vehicles (at 24.4 m/s or 80 ft/sec) in m/s^2 (ft/sec^2)

Vehicle Type	CA/T	Hornstull
New cars	1.22 (4)	1.22 (4)
Old cars	0.61 (2)	0.61 (2)
Buses	0.30 (1)	0.30 (1)
Trucks	0.15 (0.5)	0.30 (1)
Trailer trucks	0.12 (0.4)	N/A

In the simulation, the driver and vehicle type are assigned randomly. The flexibility to stochastically assign vehicle mixes using a user-specified proportion makes MITSIMLab amenable to combination in a straightforward manner with emissions models, which categorize emissions behaviors by vehicle type. To obtain a realistic fleet mix, the fleet mix of Riverside, California as categorized in Barth et al. (1999), was adapted for use. Each MITSIMLab vehicle type was mapped to one or more CMEM vehicle categories so that the accelerations and velocities of a vehicle are consistent with the CMEM vehicle category being assigned to it. The five vehicle types in MITSIM were mapped to a fleet containing twenty-eight (28) CMEM vehicle categories. Any change in vehicle mappings (additional vehicle categories) would have to be changed in both MITSIMLab and the fleet mix data file (see Appendix A). The MITSIM-CMEM vehicle mappings for the networks tested in this thesis are defined in Appendix C.

3.4.3 Network Calibration

Typically, micro-simulators which incorporate driver behavior models are calibrated with limited field data or use literature values for driver behavior parameters. The networks modeled in MITSIM are calibrated and validated with local data to capture the real driving behavior on the networks that are being modeled. This subsection describes the networks that are used in the case studies in the following chapters.

Each real-world network is calibrated in MITSIM such that the parameters are statistically significant. A range of driving behavior parameters has been observed on different networks. Using non-calibrated parameters can significantly affect the traffic and trajectory results.

The following models and parameters are calibrated in MITSIM:

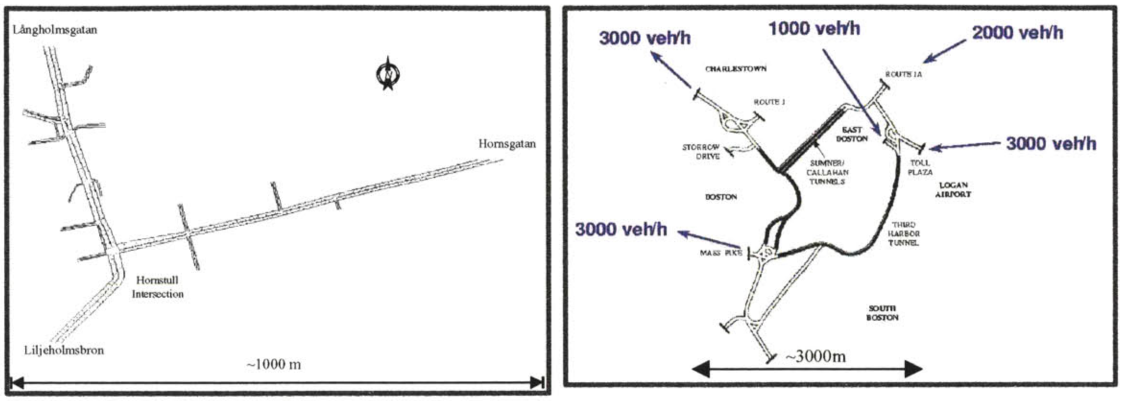
- Driving behavior;
- Route choice;
- O-D matrix (match counts, assignment matrix and original matrix); and
- Traffic control mechanism.

The driving behavior is calibrated using data along a small road section of the network where speed measurements have been taken. The O-D matrix can be obtained from historical network demand data. If this data does not exist, methods to estimate O-D matrices from sparsely measured data. An important part of emissions modeling is the speed and acceleration profile. For calibration of speed to a finer detail could result in more accurate emissions results. Work is currently underway at MIT to calibrate speed at closer intervals by taking speed measurements at closer data collection points and automating the calibration process (Deepak, 2002). These parameters are calibrated in parallel to achieve the best fit.

3.4.4 MITSIMLab Network Library

The library of validated and calibrated networks is available in MITSIMLab. The process of validation and calibration includes gathering traffic counts, flow rates, vehicle type distributions and average speed data around the network. Typically, data is divided in multiple parts. Parts are used to calibrate the parameters in the driver behavior models and the rest is used to validate. The networks in the library are models of real networks from the United States (Irvine, California and Boston, Massachusetts) and Europe (Stockholm, Sweden). The networks used in the case studies and experimental studies of Chapter 4 and Chapter 5 are described below. Thumbnails of the networks are shown in Figure 3.7, more detail about the networks is provided in Chapter 4.

The **Hornstull, Stockholm** network is a Y-shaped urban network with coordinated traffic signals and optional bus priority signaling (Davol, 2001). It is comprised of three major streets connecting at one intersection. The cross streets carry low traffic flows. The network is small and covers an area of one square kilometer. This network is used to study the emissions patterns resulting from different traffic signal settings on an arterial.



Source: Davol, 2002 and Hasan, 1999

Figure 3.7: MITSIMLab networks: Hornstull and CA/T

The **Central Artery/Tunnel (CA/T), Boston** is a network currently under construction. It is approximately 3 km x 4 km. It is a freeway network for which multiple ramp metering strategies options are available (Hasan, 1999). It is considered a large network in terms of micro-simulated traffic networks. Data was collected for the driver behavior observed for the region in the present day. The traffic demand used on the network is an estimated O-D matrix for the year 2010. The CA/T network will be used to test the computation limits of the traffic emissions model.

3.4.5 Integration Implementation Issues

In designing MITNEM, several integration issues arose. This section provides a discussion of these issues and how they were resolved.

The passing of data from MITSIM to CMEM is done via files. The following data is needed by CMEM for each vehicle on the network at every second: vehicle ID, segment the vehicle is on, vehicle position on the segment, lane where the vehicle is, speed of the vehicle, and the acceleration of the vehicle. This set of data is referred to as the vehicle trajectory data. MITSIM calculates these values every tenth of a second. CMEM, on the other hand, only processes emissions once every second. Therefore, MITSIM writes the vehicle trajectory data to the output file only once every second, on the second. Thus, the acceleration and speed reported by MITSIM at each second is actually the driver's acceleration during the next tenth of a second, not the average acceleration during the entire next second.

The acceleration is calculated by MITSIMLab dependent on the gap in front of that particular vehicle, the gap acceptance of the driver, and the speeds of the vehicle and its neighbors, while being limited by the acceleration capabilities of the vehicle. This process mimics the real driver decision-making process. The calculated "desired" acceleration is applied and the resulting speed and position of the vehicle are reported by MITSIMLab. It was found that these accelerations differ significantly from the second derivative of the position, $\frac{d^2x(t)}{dt^2}$, which is the *average* acceleration applied by the vehicle over the last second, where $x(t)$ denotes the position of the vehicle at time t.

The acceleration being reported by MITSIMLab consistently has a larger amplitude than the acceleration derived from the second derivative of position, as illustrated in Figure 3.8 a). Often, the signs of the accelerations are even opposite. Since acceleration is a key parameter in emissions production, it would be expected that these differences would affect the emissions results. Simulation trials on the simple network (see Section 4.1.1) showed that the total emissions values calculated using the MITSIM acceleration compared to the acceleration calculated from the first derivative of speed resulted in differences of approximately 0 to 10% more HC, 15 to 40% more CO, 2 to 40% more NOX, and 0 to15% higher fuel consumption. This makes sense, since acceleration is a significant explanatory variable for emissions.

The consistently larger amplitude and the occurrences of values which are opposite in sign, shows that the differences between the two methods for calculating acceleration are not simply because MITSIM is reporting instantaneous acceleration values and that the second derivative of position is the acceleration value averaged over one second. If this were the only factor, the differences in the instantaneous value of the acceleration should be evenly distributed with respect to the average value over one second. The derivatives of position are the most accurate speed and acceleration information because the position, unlike the MITSIM reported acceleration and velocity, is not the "desired" position; it is the true position of the vehicle at each second. The acceleration is different because the reported acceleration is the "desired acceleration" as determined by the different component models (car-following, lane changing, etc.). However, since all the vehicles are moved at the same instant, the resulting traffic conditions may not actually allow for the "desired" acceleration to be achieved. Therefore, in theory, the true acceleration can be slightly lower than the "desired" acceleration.

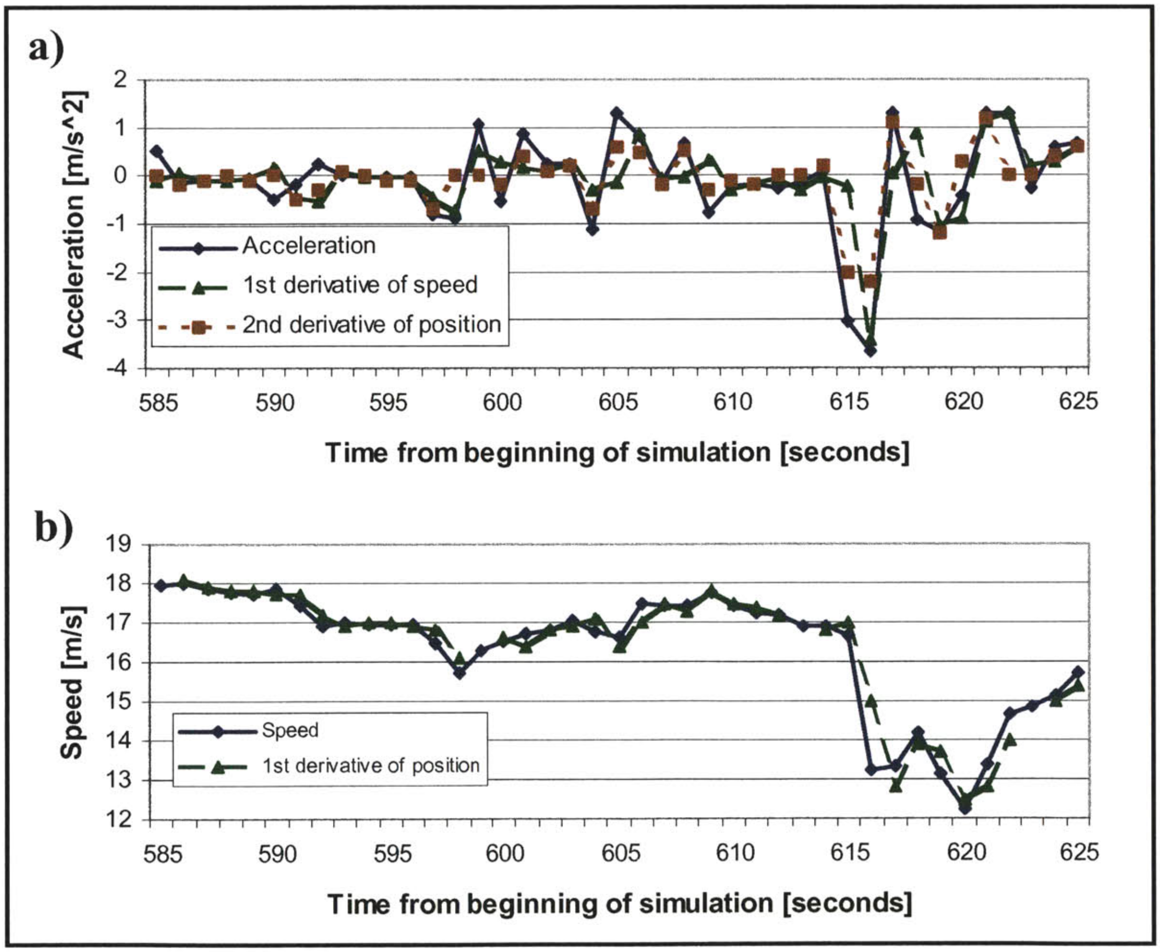


Figure 3.8: MITSIM reported trajectory values vs. derivative values on the simple network: wa) acceleration, b) velocity

In MITNEM, the acceleration was calculated using the first derivative of the MITSIMLab reported velocity. Since the velocity reported by MITSIMLab correlates well with the second derivative of position as shown in Figure 3.8 b), using the velocity should not produce the bias in the magnitude seen in the MITSIM reported acceleration values. Note that CMEM automatically calculates the acceleration from the speed data if no acceleration data is provided. The problem with calculating the acceleration from the second derivative of velocity is that the magnitude of the accelerations and decelerations will always be less than the maximum instantaneous acceleration of the last ten 0.1-second long intervals.

A second integration issue is the **simulation initialization period**. MITSIM is initialized by running it at least as long as the longest free flow trip on the network. Simulation results after this initialization period can be assumed to be representative of real traffic conditions. This same rule is adopted by MITNEM.

A third integration issue is the treatment of **intersections** in MITNEM. MITSIMLab does not explicitly model what happens to traffic inside intersections. As vehicles approach an intersection, they do not see the vehicles that are approaching the intersection from other directions. The vehicle continues on its path into the intersection. Somewhere in the middle of the intersection, the vehicle transfers from one segment onto a new segment. On this new segment, if another vehicle reaches the same segment at the same time, it is possible for both vehicles to be present at the same position. This conflict is resolved by allowing one vehicle to progress as the other vehicle waits until the gap ahead of it is large enough for it to resume motion.

An intersection can be modeled more realistically in MITSIMLab by specifying the traffic rules at the intersection. For example, if there are traffic lights, vehicles will only move on their turn, and conflict rules are specified. Turning speeds can also be user defined. The simple network used in Section 4.1 does not have these parameters defined. For studying the emissions on networks with intersections, it is mandatory for these parameters to be defined, since they affect the trajectories of the vehicles in the intersection area. The Hornstull network, which is used in Section 5.2 for studying intersections, has definitions for all of the parameters.

3.4.6 XDTA Graphical User Interface

MITSIMLab has a viewer for post-processed MITSIMLab data. This viewer is called XDTA. It takes segment information (flow, average velocity, density aggregated at every minute), and displays it on the network or on a graph, over time for each segment. XDTA has been modified to display emissions over the network. The input format for the emissions data is aggregated by segment for the correct time interval (one minute). This information can be displayed in XDTA. The visualization of both time-dependent traffic and emissions data helps determine the causes and effects of emissions around the network, and assists with locating areas where emissions and/or traffic conditions are adverse.[3] A second method for viewing data graphically is by using GIS software, described in Section 3.3.1.

3.4.7 MITSIMLab Limitation

One limitation of MITSIMLab should be noted. At the current time, MITSIMLab application is not straightforward, as currently documentation is not available. A lot of expertise is necessary to run such a micro-simulator. It generally takes a person one year to learn the program well enough to conduct experiments.

3.5 CMEM

Recent studies have shown that the simpler emissions models based on speed and/or acceleration alone, cannot fully explain the emissions being observed on the road. One drawback of the speed-acceleration matrices used in many models is that due to the difficulty of fully populating matrices, they should only be applied to driving situations, which are similar to the driving cycle on which they were calibrated. This makes their application limited. Also, it has been found that the history in driving cycles (the operating conditions of the vehicle in the last few minutes) can affect the emissions being

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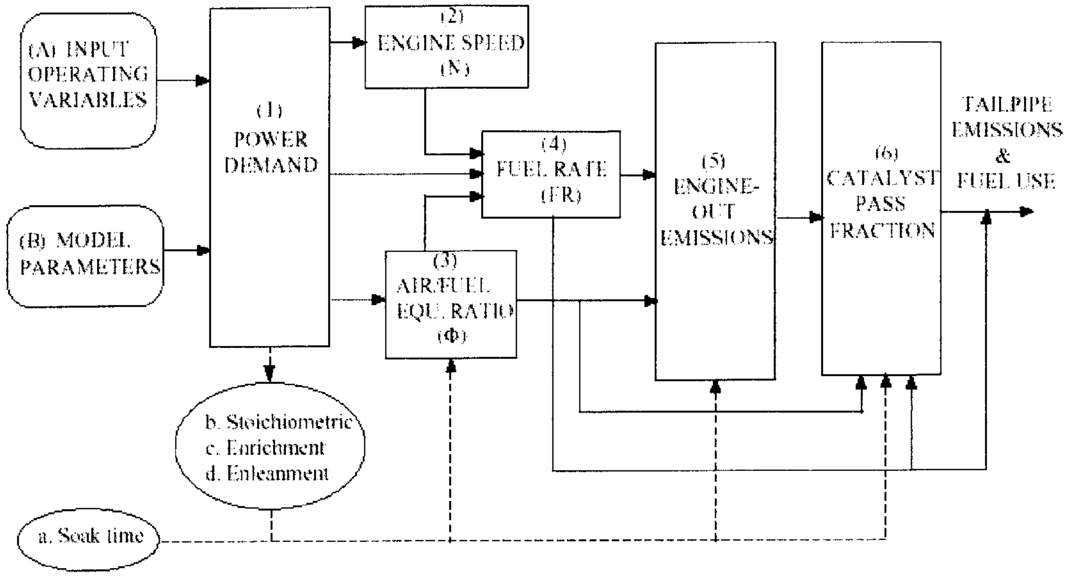
[3] MITSIMLab has a graphical interface for its traffic portion of the simulation, but since the emissions is post-processed using CMEM, we cannot view emissions in real-time at this point.

produced. Other operating conditions such as air-conditioning and vehicle load also play a large role in emissions production. CMEM was designed to address such limitations. It is based on the physical behavior of the vehicle including the dependence of emissions on extraneous load. If the fundamental physical response functions of the vehicle are modeled well, CMEM is in principal able to model the emissions resulting from driving cycles, beyond the operating conditions under which emission tests were conducted.

CMEM was calibrated and validated on 350 vehicles. The interested reader is referred to Barth et al. (2000) for more detail on CMEM model development, validation, uncertainty, and sensitivity. In designing the model, UC Riverside focused on high-emitting vehicles since it has been shown that the few high-emitting vehicles (older vehicles, vehicles with malfunctioning or missing catalysts, vehicles which have been tampered with, and malfunctioning vehicles) can produce a large portion of on-road emissions. All of the 350 vehicles were driven through three driving cycles on a dynamometer: 3-bag FTP, US06, and MEC. MEC is a modal driving cycle developed by UC Riverside to complement the FTP and US06 driving cycle, for testing specific, “clear-cut” modal emissions conditions (Barth et al., 2000, p. 57). CMEM is calibrated on the FTP and MEC01 driving cycles, and validated on the US06 driving cycle.

CMEM models the emissions creation process in three parts. First, it models the power demand, engine speed and the air-fuel ratio to calculate the rate at which fuel is consumed. Then, the engine out emissions are calculated using emission rates per fuel consumption for each emission species. The last step models the catalyst pass fraction to determine the tailpipe emissions from the engine-out emissions. Figure 3.9 shows a schematic of the CMEM load-based model. Between the engine-out emissions and the catalyst pass fraction, there are a few modules, which model the known emissions producing phenomena, such as long decelerations and rapid speed fluctuations for HC, high engine temperatures for NOX, and cold starts.



Source: CMEM Final Report, p. 74

Figure 3.9: CMEM schematic

Using a load-based model allows engine operating conditions to be determined without direct measurement. For example, engine speed can be calculated using an engine map. Calculating these engine parameters can substitute for additional instrument readings during vehicle emissions testing, simplifying the vehicle emissions testing process. Using physically based variables also meaningfully constrains the calibration parameters which is more important than achieving the best fit of a regression equation. Most importantly for emissions the fuel/air ratio can then be modeled, and the operating condition of the engine (lean, enriched, or operating within stoichiometry) is determined. CMEM models all of the main factors that are known to affect emissions.

3.5.1 CMEM Vehicle Categories

CMEM categories were chosen carefully to allow for the best representation of the emissions being produced by the real-world fleet. Vehicles were grouped into categories that are as similar as possible. In order to be able to distinguish cars with emissions malfunctions from normally emitting vehicles and model the normal vehicles without bias, gross emitters were not included in their regular vehicle technology category, but in a "high-emitting" category. Five categories of high-emitters were separated, each with a different signature emissions characteristic: Vehicles that run lean, run rich, misfire, have bad catalysts, and vehicles that run very rich. A very simple preliminary diesel model is also included with its own category. Table 3-3 presents the CMEM emissions vehicle categories.

CMEM categories are differentiated somewhat by specific vehicle properties such as power-weight ratio and age of vehicle. These properties limit the acceleration of the vehicle. If a vehicle is reported to have accelerated beyond its maximum, CMEM just uses the maximum acceleration of the vehicle instead of the real acceleration to calculate emissions.

MITNEM assigns each vehicle (identified by its Vehicle ID) a CMEM vehicle category in the program *prep* (see Appendix A). Each MITSIM vehicle type is mapped to one or more CMEM vehicle categories. *Prep* reads the mappings from the fleet mix data file and randomly assigns the CMEM emissions category in the specified proportions.

Two vehicle fleet categorization studies, which categorize an observed fleet mix into CMEM vehicle categories, have been performed in the literature. The traffic in the Caldecott Tunnel in the San Francisco bay area was categorized in a study conducted at CE-CERT (Hill et al., 2001). Another categorization was performed for the Riverside region (2000). Since fleet mix data was not available for the CA/T or Hornstull networks, a vehicle fleet mix was assigned to the networks for use in MITNEM. The assigned fleet mixes were adapted from the fleet mix determined by the vehicle categorization study of the Riverside region. The rest of this subsection describes the adaptations made to apply the Riverside fleet mix to the CA/T and Hornstull networks. The categorizations from the study and the adjusted fleet mixes are provided in Appendix C.

Table 3-3: CMEM vehicle categories

#	CMEM Vehicle Emissions Category
	Normal Emitting Cars
1	No Catalyst
2	2-way Catalyst
3	3-way Catalyst, Carbureted
4	3-way Catalyst, FI, >50K miles, low power/weight
5	3-way Catalyst, FI, >50K miles, high power/weight
6	3-way Catalyst, FI, <50K miles, low power/weight
7	3-way Catalyst, FI, <50K miles, high power/weight
8	Tier 1, >50K miles, low power/weight
9	Tier 1, >50K miles, high power/weight
10	Tier 1, <50K miles, low power/weight
11	Tier 1, <50K miles, high power/weight
24	Tier 1, >100K miles
	Normal Emitting Trucks
12	Pre-1979 (<=8500 GVW)
13	1979 to 1983 (<=8500 GVW)
14	1984 to 1987 (<=8500 GVW)
15	1988 to 1993, <=3750 LVW
16	1988 to 1993, >3750 LVW
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)
25	Gasoline-powered, LDT (> 8500 GVW)
40	Diesel-powered, LDT (> 8500 GVW)
	High Emitting Vehicles
19	Runs lean
20	Runs rich
21	Misfire
22	Bad catalyst
23	Runs very rich

Source: adapted from Barth et al., 2000, p.183

As discussed in Section 3.4.2, by default, MITSIM has five vehicle categories: old vehicles, new vehicles, trucks, buses, and trailer-trucks. These five vehicle types were mapped to the 28 CMEM vehicle categories. The current version of CMEM does not provide emissions modeling for heavy-duty vehicles (HDVs). The fraction of HDVs of all vehicles are small, but their effect on traffic is significant due to their size, acceleration limits, and driving behavior. In order to retain the calibrated traffic conditions on the networks, heavy-duty vehicles (the tracker-trailer and bus vehicle types in MITSIMLab) were kept on the Hornstull and CA/T networks in the MITNEM simulations. Heavy-duty vehicles and buses were all mapped to the CMEM diesel vehicle category (category 40) in MITNEM. Old vehicles, new vehicles, and trucks were each mapped to multiple CMEM vehicle categories. The detailed fleet mixes and MITSIM vehicle type to CMEM vehicle category mappings are listed in Appendix C.

CMEM emissions vehicle categories were kept as consistent as possible with the MITSIM vehicle types so that the maximum acceleration used in MITSIM would be similar to the maximum acceleration cut-off point used in CMEM. If an acceleration is higher than the cut-off point assigned for the vehicle category, CMEM uses the maximum acceleration to calculate the emissions. If the maximum acceleration used for MITSIM and CMEM are very different, then inconsistencies will arise. The vehicle trajectories will be different from the trajectory being used to calculate the corresponding emissions results. This would mean that the network conditions would not really match the emissions calculated.

3.5.2 CMEM Limitations

The batch version of CMEM comes as a UNIX executable. It is a relatively simple program to learn using its accompanying user manual. There are still some drawbacks to CMEM which are described in this section.

First, there is a trade-off between the level of detail of the CMEM model and its simplicity. Calibrating the CMEM model requires a solid understanding of vehicle mechanics and the emissions generation process. The model is also data intensive since each module of the CMEM model must be carefully calibrated. This means that extensive data collection, including dynamometer testing and definition of average vehicle parameters, needs to be preformed for the addition of each new vehicle category. Some information about vehicle parameters such as vehicle mass, the number of gears, and the maximum torque are publicly available, but others such as the engine friction factor and power threshold factor are much more difficult to obtain (Barth et al., 2000), sometimes because car manufacturers do not provide this data. For the parameters that are not available, estimated values from testing measurement data are used. Unfortunately, this makes it difficult to go back and calibrate the models with new vehicle parameters as they become available.

On the other hand, unlike models where the effect of these components are only taken into account indirectly, such a detailed model allows the emissions contribution to be traced back all the way to the physical components so that future technological improvements can be estimated without having to perform dynamometer tests. Yet, it is not simple to change CMEM to model new components, due to the difficulty of calibrating a new category of vehicles. At this point in time, new categories can be added in the Microsoft Access version of CMEM. For the UNIX version, only executables are available publicly. To add additional categories in its UNIX version, CMEM would have to be reprogrammed by the user. The current model includes vehicles up to 1999.

A few errors and discrepancies between the UNIX version and the Microsoft Access version have been found while performing the work of this thesis. Unfortunately, these issues cannot be resolved because CMEM is not an open-code software. The results from MITNEM are from the latest UNIX version of the CMEM code, version 2.01.

Another limitation of using CMEM is that an estimate of the fleet composition in terms of the CMEM defined categories may be needed for each region. A categorization process must be performed using registration databases or data collection to determine the vehicle fleet for the area to be modeled.

The last limitation of CMEM is that as a consequence of the level-of-detail used in the model, the computation time required by CMEM can be significant. Because it analyzes the emissions for every second using results for several previous seconds, CMEM's run-time is much larger than a simple look-up table. The computation time is further discussed in Section 4.3.3.

Chapter 4

Studying Emissions Using a Microscopic Network Emissions Model: 3 Case Studies

The microscopic network emissions model, MITNEM, described in Chapter 3, was used to analyze emissions on three networks, which have different size and complexities. They were used to verify the reasonableness of the results, explore the sensitivity of model output to different input parameters and post-processing parameters, and to study the effect of using different analysis variables on the result.

Section 4.1 presents a simple hypothetical network which is used to study the effect of different analysis variables for expressing the results. An example of time-dependent emissions along road segment is presented in this section. The other two networks are models of real-world networks. The real-world networks have been calibrated with measured speed and flow data, and origin-destination matrices. Different traffic signals and ramp meters, and a vehicle fleet with multiple vehicle types are analyzed. The Hornstull network, presented in Section 4.2, is a small urban network. It is used to conduct sensitivity tests of MITNEM output data to the size of time and spatial averaging intervals. The Central Artery/Tunnel, presented in Section 4.3, is a larger urban freeway network. It is used to test the computational requirements of the model and assess the effect of ramp metering on vehicle kilometers traveled (VKT) and emissions results.

Each section in this chapter is dedicated for one network. The sections are organized as follows: a network description is given, the simulation details are described, and finally, the results are presented and analyzed.

4.1 Result Analysis Using Different Measures on a Simple Hypothetical Network

The simple network described in this chapter was used in the development of MITNEM. Its simplicity facilitated the debugging of integration issues. The network was used for a preliminary study of the effect of increasing demand on network emissions. It was used to illustrate the importance of understanding the appropriate emission measures for result analysis. The emissions profiles for two segments on the network are also shown as an example of the analysis that can be performed using MITNEM.

4.1.1 Network Description

The simple network is composed of five 1-lane segments. Figure 4.1 depicts the network.

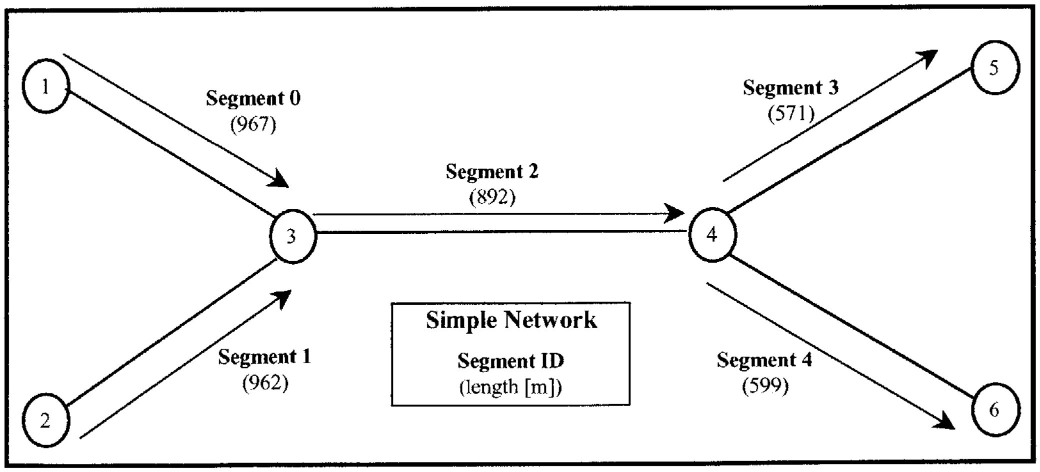


Figure 4.1: Node-segment representation of simple network

Traffic on the network flows from left to right. This simple network has four origin-destination (O-D) pairs. Table 4-1 shows the demand for each O-D pair.

Table 4-1: Simple network baseline O-D

O-D pair	Demand [vehicles/hr]
1-5	20
1-6	25
2-5	30
2-6	25
Total	100

An increased level of vehicle interactions is caused by the junction at node 3, where the two single-lane segments, 0 and 1, join to form a single-lane. The vehicles reduce their speed as they merge onto segment 2, and then accelerate to regain their speed. The maximum speed allowed on the network is 35 km/hr (21.7 mph). To introduce some variation, a mix of four MITSIM vehicle categories was used on the network. Each of these categories was mapped to a CMEM category. No traffic control technologies are available on the network. Run time is short due to the small size of the network and the interval during which there is demand. Table 4-2 summarizes he characteristics of the network.

Table 4-2: Simple network statistics

Network Description	
Area covered	2km x 1km (1.2 mi x 0.6 mi)
Type	Conceptual urban roads
Length of roadways	4000 m of 1 lane roads
Traffic control	None
Simulation Description	
Number of segments	5
Max. speed on network	35 km/hr (21.6 mph)
Max. flow on network	~1300 vehicles/hr
Total demand	100 vehicles/hr
Vehicle mix	5 MITSIM categories: old car, new car, heavy-duty truck, combination trucks, buses

The vehicle mix used on this network is hypothetical in the sense that it is not representative of a real world vehicle mix. The CMEM vehicle categories used here were chosen by their congruence with the MITSIM vehicle categories (old cars were older, new cars were newer, etc.) and respective representation in the real world. Table 4-3 shows the MITSIM to CMEM vehicle mapping for the simple network.

Table 4-3: MITSIM vehicle type and corresponding CMEM vehicle categories for the simple network

Vehicle Type	Percentage of fleet	MITSIM Type	CMEM Category
New car	20%	0	5
Old car	20%	1	21
Buses	20%	2	40
Heavy-duty Trucks	20%	3	16
Trailer Trucks	20%	4	22

4.1.2 Simulation Description

After MITNEM was verified to be working reasonably, an experiment was designed for the simple network to test the relationship between the traffic demand and resulting emissions. The data generated from this experiment is used in Sections 4.1.3 and 4.1.4 as examples of how MITNEM can be used for analysis.

It is not intuitive how total emissions will behave with increasing traffic demand. There are two factors that influence emissions. As more vehicles are introduced onto the network, speeds on the network decrease. And as the velocities decrease from free flow speed, the emissions from each individual vehicle per unit time will also decrease. On the other hand, as speeds decrease, vehicles on the network will travel a shorter distance per unit of time. Let e_{ri} denote the VKT-respective emissions rate (emissions per VKT) of an emission species *i*, or the total fuel consumption, for a given area (region, city, or network). e_{ri} can be expressed as:

$$e_{ri} = e_{ti} \div vkt_t$$

where: e_{ti} is the emissions rate (emissions per unit of time) for species *i*, and vkt_t is the VKT accrual rate. If the time-respective emissions rate and the VKT accrual rate move in the same direction (increasing or decreasing), the VKT-respective emissions rate will move the same direction, but if the direction of the two parameters move in opposite directions, the VKT-respective emissions rate depends on the rate of emissions decrease and the change in vehicle velocities.

Demand was scale up to produce higher levels of demand. Table 4-4 describes the traffic demand levels used in the simulations and the corresponding traffic conditions.

Table 4-4: Demand levels on the simple network

Demand [vehicles/hr]	Description of Resulting Network Condition	Average Speed on Network [kph] (mph)		
		Network	Segment 0	Segment 2
100 - 200	Free-flow	89 (55)	89 (55)	87 (54)
500	Interactions between vehicles observed	83 (52)	89 (55)	77 (48)
800	Somewhat congested	72 (45)	80 (50)	63 (39)
1,000	Somewhat congested	78 (48)	52 (52)	70 (43)
1,100	Congested	55 (34)	69 (43)	53 (33)
> 1,500	Extremely congested (moving a few meters in 15 minutes)	17-18 (11)	8-9 (5 - 6)	43 (27)

Each demand was run five times for a period of 60 minutes each. The first 10 minutes of each run were used as an initialization period and are not included in the results.

4.1.3 Result Analysis Using Different Variables

The availability of detailed time and spatial trajectory and emissions data is useful. The emissions can be expressed in terms of varying time and spatial intervals (e.g. g/s/km, g/hr for the entire network), different traffic parameters can be calculated (e.g. flow, density, average velocity, and VKT), and the data can be organized into a wide range of categories and sub-categories (e.g. by individual vehicles, vehicle type, segment ID). The wealth of data provides flexibility for a wide array of research and emissions evaluation applications.

This subsection discuses the applicability of different emission measures for analysis. Many different emissions measures (g/vkt, g/s, g/veh/hr, etc.) are used in literature, but a review of the literature performed by the author did not reveal any organized discussion of the various uses of different emissions parameters. An analysis of the emissions created on the simple network at different demand levels is used as an example to demonstrate the uses of different emission measures.

The determination of the appropriate measure for expressing the result is the first step to analyzing emissions on a network. The appropriate parameter depends on the objectives of the analysis. Table 4-5 lists the goals and the respective units that would useful for expressing the results of an analysis for each goal. Many of the objectives are measured with an implicit "frame of reference" which are also shown in the table. The vantage point from the frame of reference enables different types of analyses to be performed on the network. One frame of reference is to view the area under consideration as a whole. Another option is to follow a vehicle around the network. Yet another option is to monitor the emissions and traffic conditions at one point on the network.

Table 4-5: Emisisons parameters for different modeling objectives

Example of analysis objective	Emission measure	Constant variable	Example units
Reduce total emissions on network	Emissions over entire region and a time period	Area of consideration	g/km^2/day
Eliminate/reduce hot spots (emission flow rate)	Emissions over one or multiple segments during a time period	Roadway position	g/s/km of roadway
Reduce emissions "intensity" of transportation	Emissions per trip Emissions per distance traveled	Vehicle --	g/trip g/veh-km traveled

A commonly used measure of emissions on a network is the emissions generated per area. Different traffic management strategies result in moving the emissions to different areas on a network. As long as the area is large enough, the measure of emissions per area ensures that any changes in emissions due to changes in traffic between two different scenarios are captured. Emphasis should be placed on defining the appropriate area. For example, if a ramp meter causes traffic to back up onto side streets, these should be included in the analysis to capture the overall effects of changes in traffic.

Another measure is emissions per time per distance of roadway. This measure is useful for looking at a given spot on the roadway or comparing two different spots on a roadway, mainly for hot spot identification. This locates positions where high levels of emissions are being generated. Also used in the literature is the measure, emission per time (emission flow rate). This parameter is an output of vehicle emissions modeling and an input to air quality modeling, to estimate the concentration of pollution in an area. It is however not an effective parameter for comparing different emissions control or traffic management strategies. If the only measurement of effectiveness of a strategy were emissions per time, then the optimal strategy would be to reduce traveling speeds as much as possible, to the point where no vehicles are moving! A vehicle traveling slowly or is stopped emits less per second. What is needed is a measure of effectiveness that takes into account the demand for travel.

The answer to this problem may be found in a commonly used measure in the power industry, referred to as an emissions intensity. This parameter is used to measure the CO_2 emitted per kWh of power generated. Emissions intensity captures the concept that a primary goal of the power industry is to provide power to their customers. A secondary goal of the power industry is to reduce emissions. However, the demand for power varies throughout the year and from region to region and because power sources also vary, the CO_2 emissions also fluctuate. Therefore normalizing the emissions by the demand allows for a measure of effectiveness towards both goals. The concept behind this parameter can be extended to transportation. Similarly, a primary goal of the transportation industry is to move vehicles from one place to another, or serve a vkt demand. A secondary goal of the transportation industry is to reduce emissions. Therefore, the emissions per vkt would measure the emissions intensity of a transportation network. The goal of both industries is to serve as much demand as possible (or needed) while keeping the emissions as low as possible. And that external influences may constantly change demand, the measure of emissions intensity allows for performance comparison under different circumstances.

Emission intensity measures *system* traffic and emissions performance. It is possible for the emissions of a few vehicles to increase or the VKT on the network for some vehicles to decrease, while the emissions per vkt decreases. When appropriate, an alternative measure is emissions per trip which can be used to measure the emissions intensity of individual users given a constant vkt for a trip. This measure does not represent the total emissions intensity for the network if the travel demand changes or the particular trip is not representative of all vehicles on the network.

These concepts are illustrated in the rest of this section using the HC data generated from the simulations of different demand levels on the simple network as an example. The total network HC as a function of total demand desiring to enter the network, the numbers of vehicles which actually enter the network, and network VKT are shown in Figure 4.2 (graphs for CO, NOX, and fuel consumption looks similar). The HC emissions as a function of demand increases linearly up to 1500 vehicles per hour and then stays constant. By watching the MITSIMLab simulation GUI, one can see the traffic build up on segments 0 and 1 caused by congestion resulting from the merging at the junction. The vehicles desiring to enter the network begin to back-up beyond the network at high demand.

Vehicles that do not make it onto the network are not included in the MITSIMLab trajectory output; therefore the emissions of the demand higher than the network capacity (~1,300 veh/hr) are not being included in the total emissions. This over-flow is an important concern when evaluating on-road emissions. It is critical that the correct network size and simulation period is delimited. If emissions are physically displaced off of the network instead of being reduced through better management, reducing emissions in one local area may actually increase total regional emissions. Similarly, emissions can be temporally displaced. The emissions per time may be reduced (e.g. through flow reductions) but drawn out over a longer period, resulting in the same amount of total emissions being produced in a day.

This is the reason Figure 4.2 a) may be misleading, since not all the demand is satisfied, therefore the emissions of those vehicles are not being included in the analysis of the impact of increasing demand levels. For example, if the goal of the analysis was to evaluate different traffic control strategies at the junction, then there is no ability to recognize in the measure that there is unsatisfied demand not being included in the analysis. One solution to this problem is to define a larger network area. Suppose this cannot be done, then a second solution is to substitute "vehicles that enter the network" for demand.

Figure 4.2 b) counts only the vehicles that enter the network. This graph gives us additional insight about the emissions behavior. First, it is observed that emissions continue to increase with the number of vehicles that have entered the network. The emissions in Figure 4.2 a) can be seen to level off because the network can no longer accept additional vehicles beyond the first 1,000 vehicles (in the 50 minute simulation period) due to the congestion at the first node. The second observation is that as more vehicles are introduced, the HC does not increase linearly. This means that at a certain point, around 1,000 vehicles for this simple network, the marginal cost of an additional vehicle begins to increase with the number of vehicles that enter the network. The addition of every vehicle adds not only its own emissions but also causes other vehicles on the network to emit more emissions.

Both Figure 4.2 a) and b) show that total emissions has a higher variance from run to run at higher demand levels. Although the "number of vehicles introduced" vary little between each run (the horizontal variation is small), the variation in the amount of emissions for the runs with the same demand increases as the demand increases. This suggests that traffic conditions are becoming less stable. As demand increases, it is easier for the network to become congested and it takes longer for the network to recover from congestion. Small deviations in traffic conditions are easily exacerbated. The emissions become more difficult to predict for these situations because the network could be in one of multiple conditions, from slightly congested to very congested.

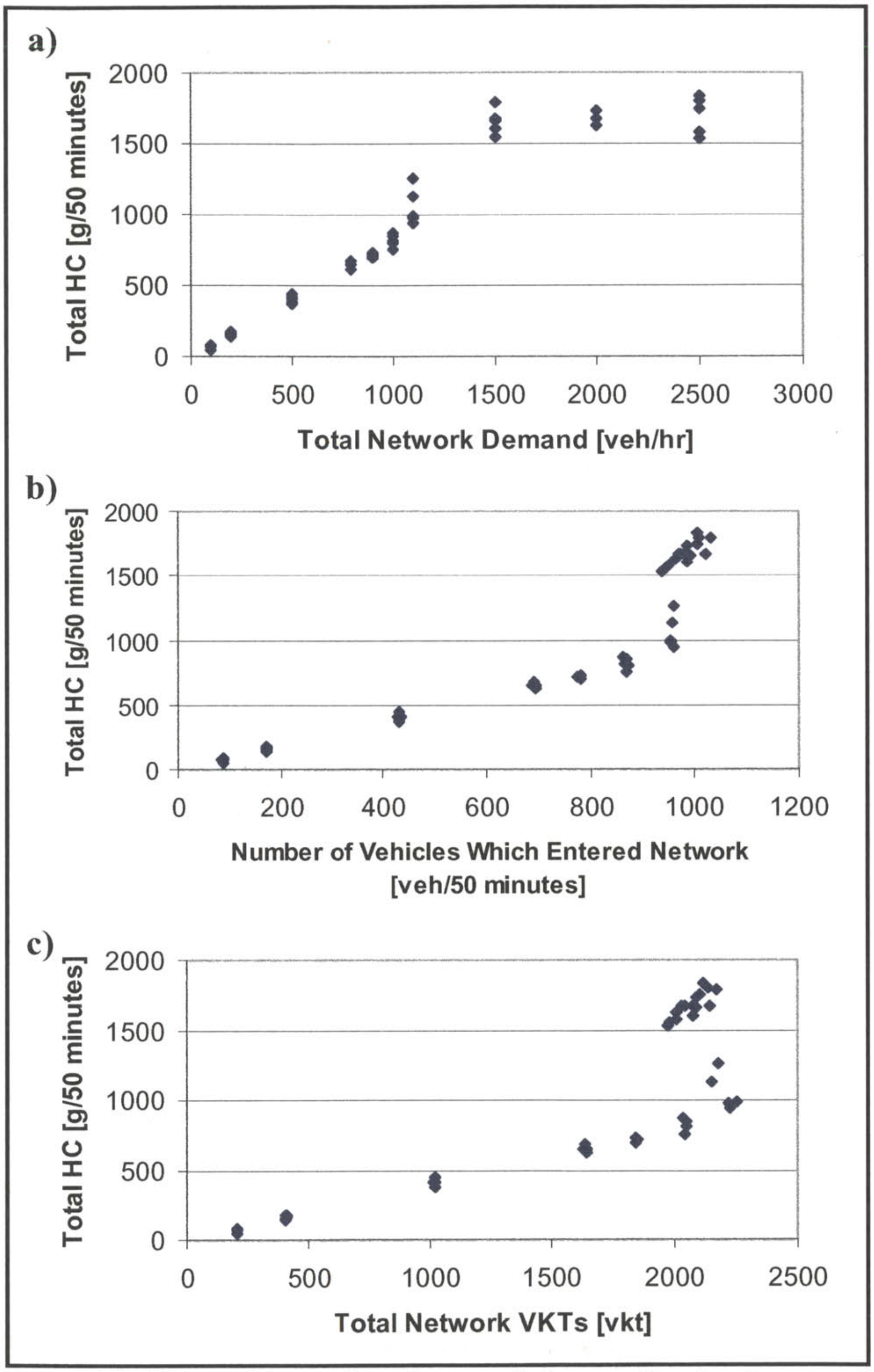


Figure 4.2: Effect of demand levels on emissions on the simple network

The total emissions graphed against VKT best captures the emissions results of increasing demand on the network. Figure 4.2(c) shows that at high demand, not only is the HC double that of the lower demands which serve approximately the same VKT, but the VKT also decreases. Figure 4.2 b) is unable to show this decrease in traffic performance because the introduction of additional vehicles onto the network actually decreases the traffic flow rates served. Since the fundamental goal is to achieve the most travel for the least emissions. The difference between the two graphs is that there is a differentiation between an increase in emissions which is accompanied by higher VKT served and higher emissions which does not satisfy any extra demand. Some authors argue that increasing emissions slightly is economically worthwhile if additional productivity (measured in VKT) is gained. Environmentalists argue that no amount of increase in VKT can be worth additional emissions. The later case, where emissions increases with no additional VKT gains, is what everyone, environmentalists and traffic specialists want to avoid. Therefore, there should be no debate that conditions where both emissions are increased and less VKT are served, should be vigorously avoided.

The example of using different measures for analysis on the simple network shows that there are clear benefits of choosing the appropriate parameter for an analysis objective. Different measures are used throughout this thesis to display different results and conclusions.

4.1.4 Spatial Variation of Emissions on a Segment at Varying Demand Levels

This section analyzes the results of the simulation experiment described in Section 4.1.2 as a function of the position on a segment.

The average velocity along segments 0 and 2, at every meter, is depicted in Figure 4.3. As vehicles approach the junction, they begin to slow down, and then approximately 75 meters after the junction, vehicles are able to begin accelerating.

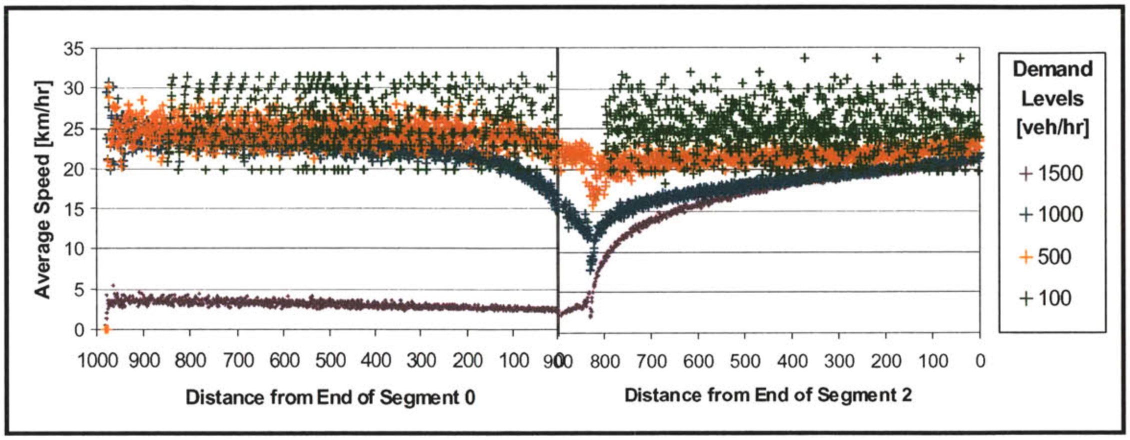


Figure 4.3: Time-average speed along segments 0 and 2

On segment 0, a large difference in speed is observed on the network when the demand increases from 1000 vehicles per hour to 1500 vehicles per hour. This is where the network suddenly experiences severe congestion. The demand also affects the accelerations that are observed on segment 2. The simulation runs corresponding to higher demand recovers less rapidly after the junction, whereas the runs with lighter traffic only slows down slightly at the junction.

The graphs in Figure 4.3 can be used in conjunction with plots of the emissions around the network to identify and diagnose areas corresponding to bad traffic and emissions. Figure 4.4 shows the HC emissions per hour-meter for segments 0 and 2, at the different demand levels. A distinctly higher amount of emissions is generated at demands greater than 1500 vehicles/hour. As the vehicles merge onto segment 2, the emissions roughly doubles for all of the demand scenarios. This is because merging rules for this junction (discussed in Section 3.4.5) have not been defined in MITSIMLab. Essentially, vehicles may be physically overlapping on the network. This shows the importance of properly defining intersections and merging areas.

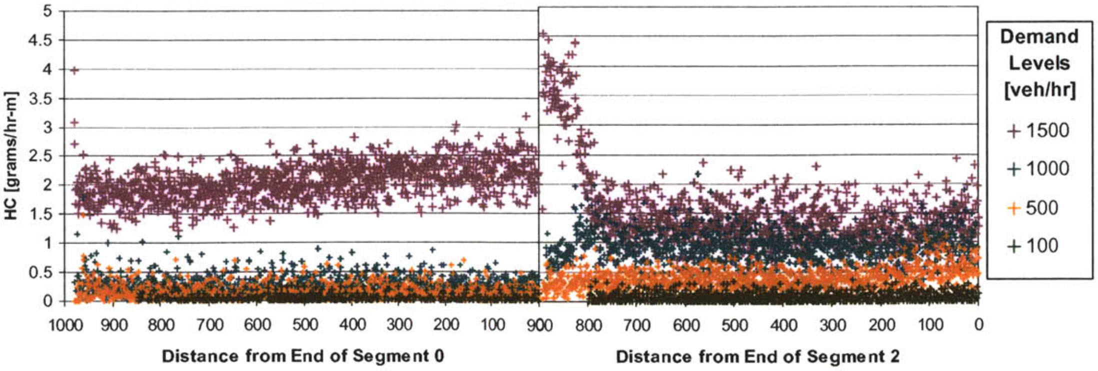


Figure 4.4: HC emissions along segments 0 and 2

4.1.5 Conclusions

The following results were arrived at using the simple network. MITNEM was applied to simulating a simple hypothetical network. The use of different measures for analyzing emissions on a network were compared. The use of the emissions intensity measure allowed situations where both VKT decreases and emissions increases can arise were identified from the simulation results of the simple network. Such situations should be carefully avoided in traffic management. Average speed and emissions as a function of the position on a segment were analyzed to study the effect of demand levels on both traffic conditions and emissions. The results showed the consequence of not defining merging areas in MITSIM. Real intersections and merging must be well-defined in MITSIM for emissions data to be useable.

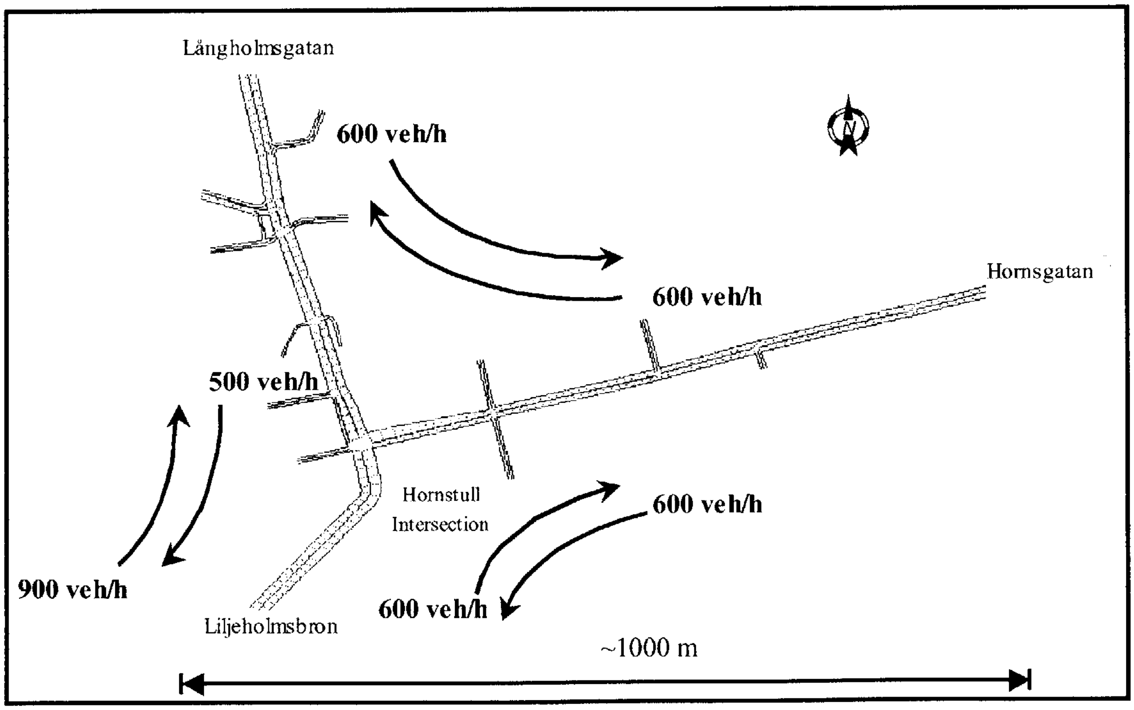
4.2 Sensitivity Analysis using the Hornstull Network

The stochastic nature of MITNEM requires multiple runs under the same conditions to be made for modeling a network. Additionally, there is spatial and temporal variation within each run. First, the run-to-run emissions variation of MITNEM is tested. Next, different temporal and spatial averaging intervals are used to analyze data on the Hornstull network.

The Hornstull network is comprised of three large arterials that join at the Hornstull intersection. The small size of the network makes it manageable in MITNEM. The simulation runtime is approximately 1 hour and the sizes of the generated files are not too large (approximately 6 files of 50 to 100 megabits each). The Hornstull network is a real-world network with simulation of coordinated traffic lights, the presence of pedestrians, and optional bus priority timing. These properties of the network make it a practical choice for sensitivity analysis testing.

4.2.1 Network Description

The Hornstull network has been used to test the effect of different bus priority strategies on traffic conditions. It is an urban network with cross streets that feed traffic on and off the main streets. The Hornstull intersection is where the three major arterials meet. The traffic lights are coordinated along the corridor that runs east of the Hornstull intersection through to the corridor that runs north from the main intersection. The network and calibrated demand levels are shown in Figure 4.5.



Adapted from Davol, 2001

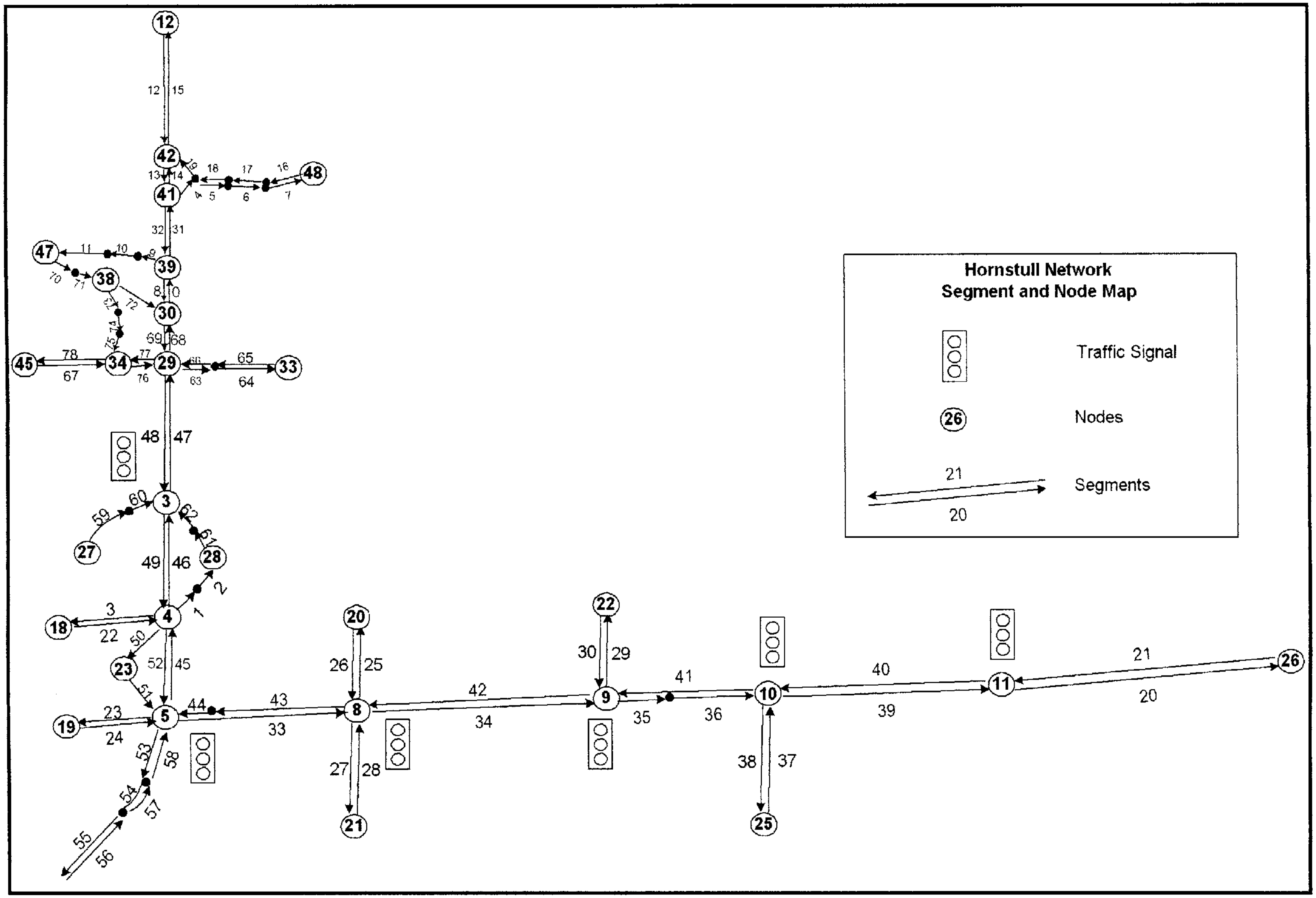
Figure 4.5: Depiction of the Hornstull network and its associated origin-destination flows, 7:30 AM – 8:30 AM

Table 4-6 summarizes some of the characteristics of the Hornstull network.

Table 4-6: Hornstull network statistics

Network Description	
Area covered	1 km x 1 km (0.6 mi x 0.6 mi),
Type	Urban Arterial
Length of roadways	4,990 m of 2-3 lane roads
Traffic control	8 signalized intersections, coordinated with bus priority option
Simulation Description	
Number segments	79
Maximum speed	50 km/hr (31 mph)
Demand period	7:30am – 8:30am
Total demand	~38,000 vehicles/hr
Vehicle mix	Adjusted Riverside (described in Appendix C)

The node-segment representation of the Hornstull Network is shown Figure 4.6.



Note: Some segments (e.g. 52) are for specialized traffic only, such as buses. Passenger traffic will not be observed on these segments because they are not allowed on these segments.

Figure 4.6: Nodes-segments representation of Hornstull network

4.2.2 Stochasticity

Various model components in MITSIMLab contain stochastic terms and variables to reflect variability that exist in driving behavior among drivers, daily variation in traffic demand, vehicle fleet mix, frequency of pedestrian crossings, and other simulated elements. Each simulation run of MITSIMLab can be interpreted as a possible realization of traffic conditions. The range derived from simulation runs can be as important as the average, particularly in cases when small deviations in demand, driving behavior, and other simulated elements lead to congestion. This is observed in Figure 4.2, where as network capacity is reached, the simulation gives a larger range of different traffic conditions from run-to-run. Because of this stochasticity, multiple runs of MITSIMLab are required before any conclusions can be drawn from simulation results.

The effect of the stochasticity on network emissions is tested on the Hornstull network. Five simulation runs in MITNEM were made using identical input data and parameters. The duration of the simulation is 65 – 70 minutes long, with demand beginning at 7:30 and ending at 8:30; a progressive signal timing is used (see Section 5.1 for more description); and the fleet mix is the adjusted Riverside fleet mix. Figure 4.7 a) shows the number of vehicles on the network over a one-hour period for five simulation runs. Four of the five runs look similar during the whole hour. One of the runs gives number of vehicles consistently higher than the number of vehicles corresponding to the other runs. This result shows that a multiple runs must be made for any scenario, since one run is not always representative of all other runs. For example, if the run that lead to the highest number of vehicles is only used to calculate the emissions for the network, the average emissions would be over-estimated. If only one of the runs were used, it would not capture the range of possible emissions being generated on the network.

The values of the VKT, traffic emissions, and fuel consumption rates using a one-minute aggregation interval corresponding to the four different runs are shown in Figure 4.7 b) – f).

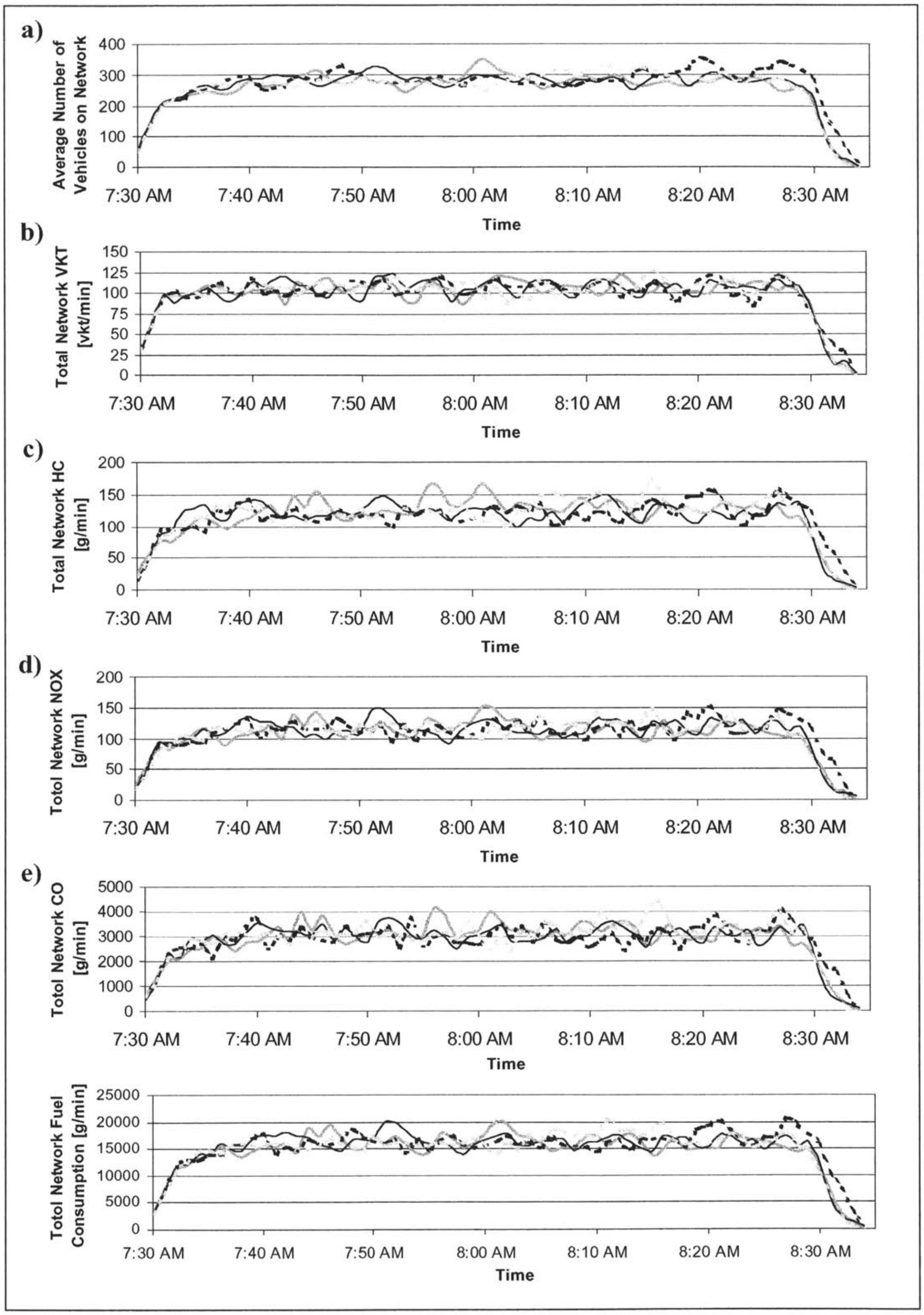


Figure 4.7: Variation over multiple runs using: a) Average number of vehicles on the network, b) Total network VKT per minute, c) Total network HC per minute, d) Total network NOX per minute, e) Total network CO per minute, f) Total network fuel consumption per minute

Figure 4.8 a) – e) reports the cumulative VKT, emissions, and the fuel consumed. The differences between the four runs are less noticeable than in Figure 4.7 c) – f) where rates of emissions and fuel consumption are reported.

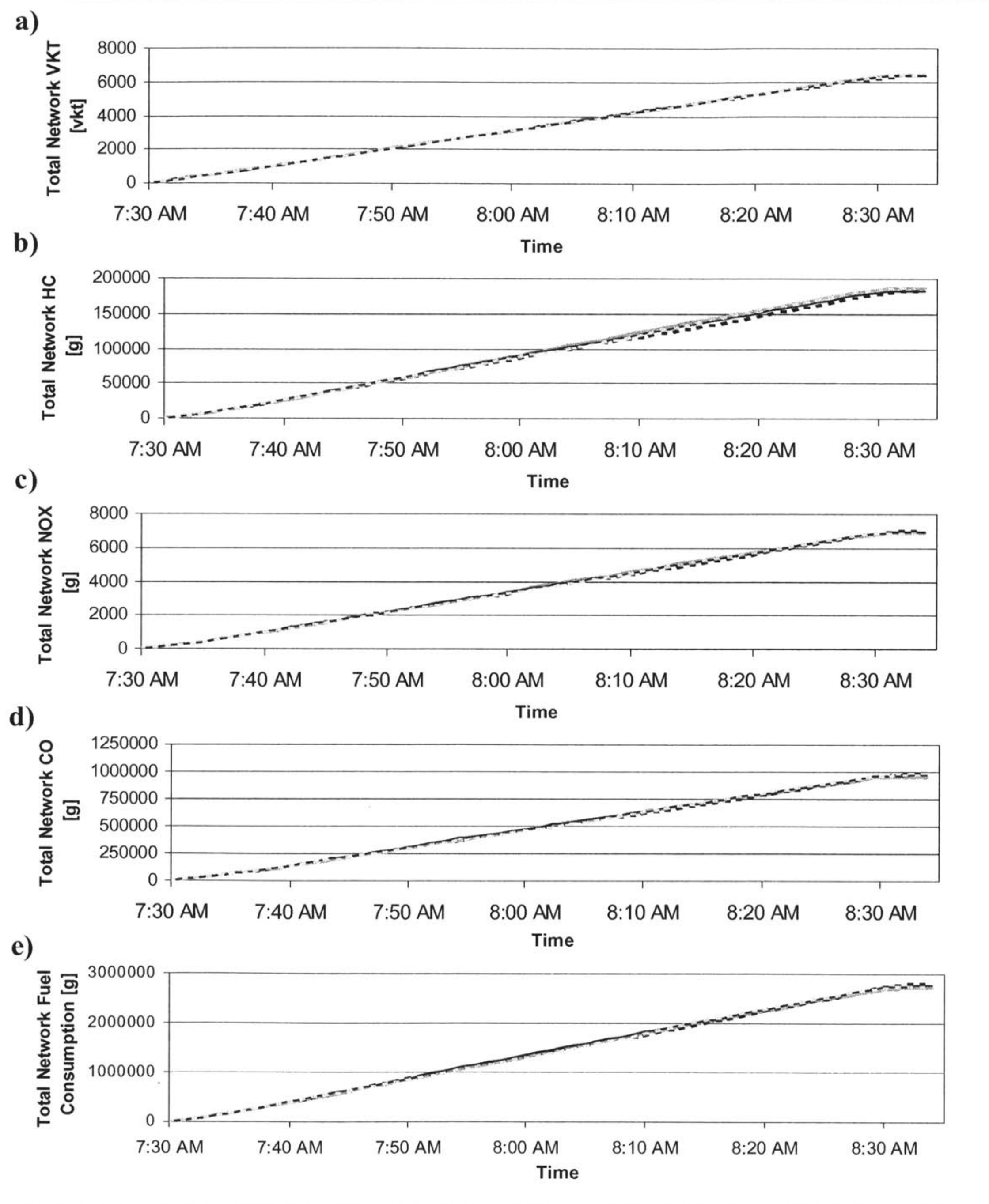


Figure 4.8: Cumulative variation over multiple runs: a) Total network VKT, b) Total network HC, c) Total network NOX, d) Total network CO, e) Total network fuel consumption

4.2.3 Effect of the Size of the Length of Temporal and Spatial Averaging Intervals

Different temporal and spatial intervals can be used to calculate emission rates. The results may be different depending on the size of the intervals used to analyze the data. In this section, the average emissions rates of a segment of the Hornstull network are analyzed using different spatial and temporal averaging.

Figure 4.9 shows the average emissions and fuel consumption rates in grams per meter per hour, using spatial average intervals of 1, 2, 5, and 10 meters. The segment analyzed is segment 33. The curve of the average emissions over the simulated period smoothens out as the spatial averaging interval is increased.

Figure 4.10 shows the time-average total emissions and fuel consumption rates in grams per min on the entire segment. The averaging intervals vary from 60 seconds to 300 seconds. As the averaging interval is increased, the average emission smoothens out as the temporal averaging interval is increased.

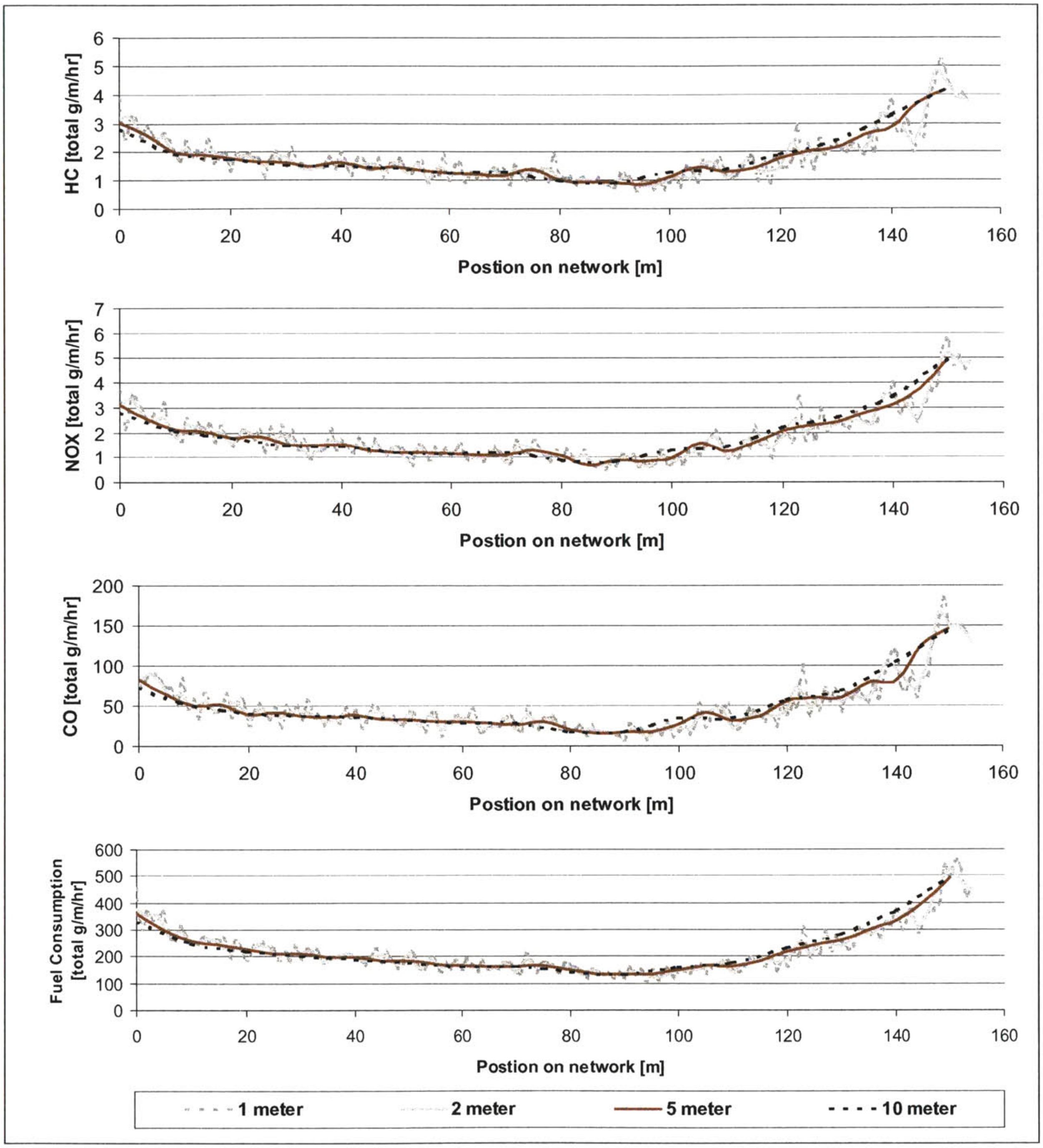


Figure 4.9: Effect of spatial averaging interval sizes on emissions and fuel consumption rates

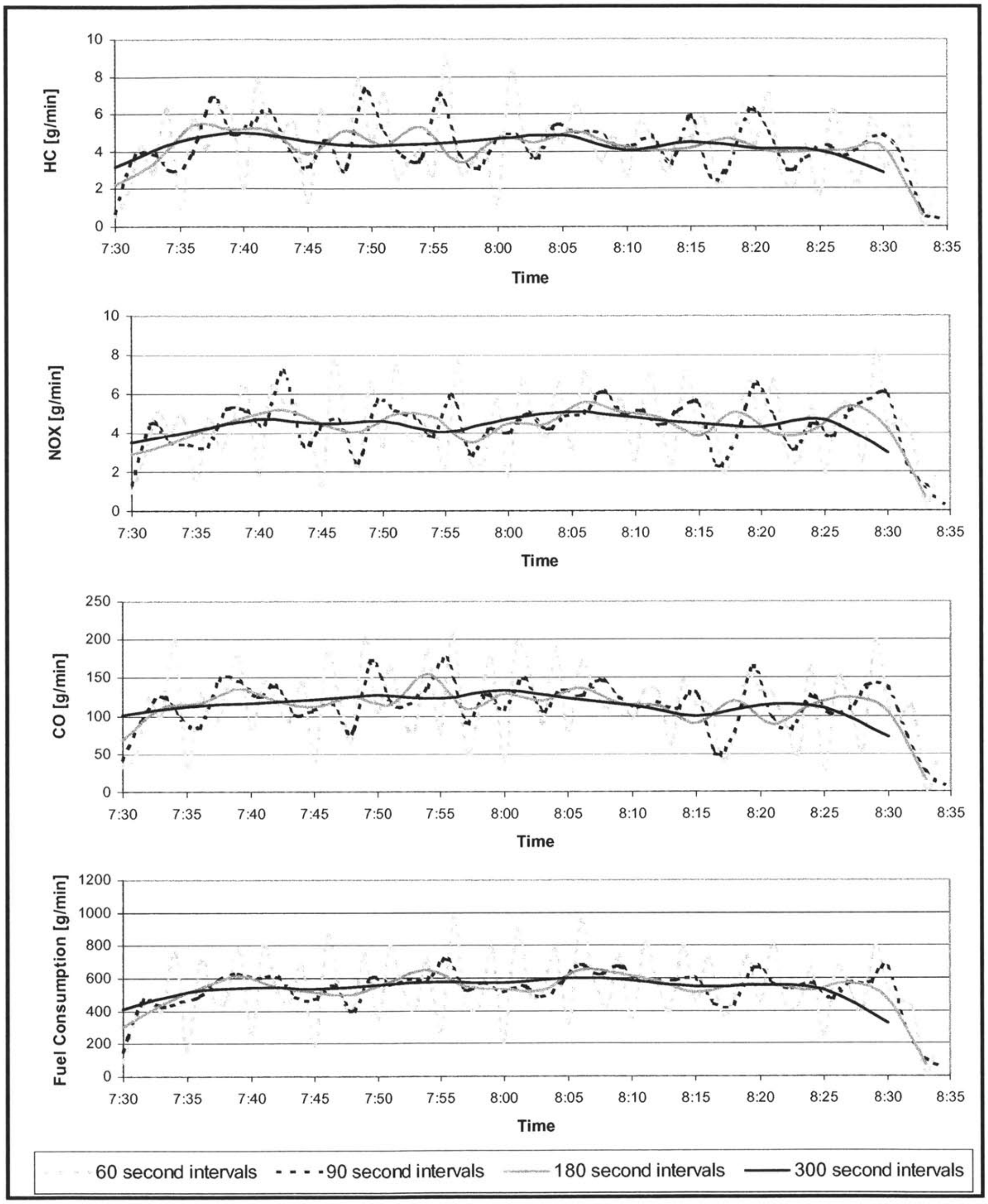


Figure 4.10: Effect of the size of temporal averaging interval on total segment emissions and fuel consumption

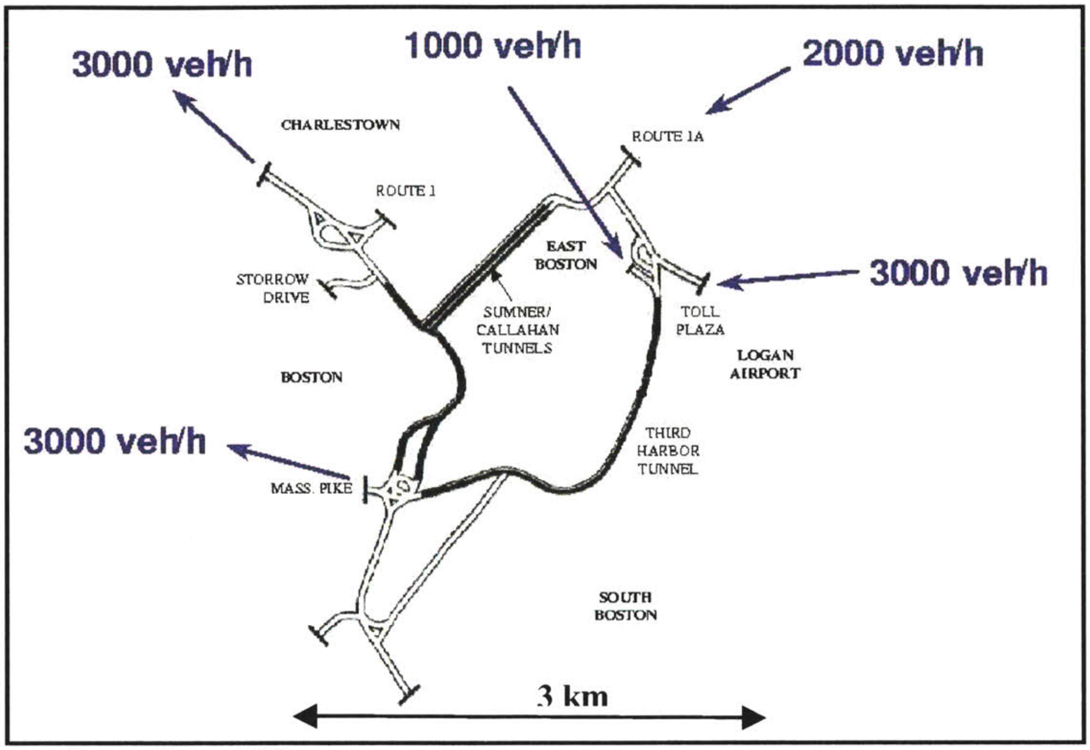
4.3 Quantifying the Emissions Inventory, Computational Requirements, and the Effect of Ramp Metering on the CA/T Network

Compared to the networks studied earlier in this chapter, the Central Artery/Tunnel is a larger network. It is the largest in the MITSIMLab Network Library. It models a major artery in the Suffolk County area in Boston, Massachusetts. The emissions inventory of the network was calculated and compared to the emissions in Suffolk County. A simulation run of the network initially took approximately two days to run and the output files require approximately 2 gigabytes of space in total. Some methods were found to shorten the run time and reduce the size of the storage files.

4.3.1 Network Description

The Central Artery/Tunnel network is a highway network. It is a major congested network in the City of Boston, including commuter traffic, commercial traffic and through traffic. It serves the inner city business district, the airport, and the suburbs. The total demand on the network is approximately 20,000 vehicles per hour. Figure 4.11 shows the areas the CA/T serves and the main entry and exit points of the demand.

The CA/T network was coded in MITSIMLab to evaluate the effectiveness of different ramp metering strategies on the Central Artery Tunnel. Origin-destination values were estimated for the year 2004, given the historical growth patterns and past traveler choices in Boston. Two ramp-metering strategies have been implemented in MITSIMLab: single-vehicle release and platoon release. Single-vehicle release metering allows one vehicle at a time to pass from the on-ramp to the freeway, while platoon-release metering allows multiple vehicles to enter the freeway from the ramp. Ramp metering uses sensors which measure density on the main line of the Central Artery. If congestion reaches a certain level the ramp meters are activated to limit the flow on the highway and prevent congestion from building up. Table 4-7 lists some of the characteristics of the CA/T network.



Source: Hasan, 1999

Figure 4.11: Physical CA/T network

Table 4-7: CA/T network statistics

Network Description	
Area covered	3 km x 4 km (1.9 mi x 2.5 mi)
Type	Urban Freeway
Length of roadways	81,611 m
Traffic control	3 ramp meters, with single release or platoon release options
Simulation Description	
Number of segments	637
Average speed	50 – 60 km/hr (31 – 37 mph)
Demand period	Morning peak
Total demand	~20,000 vehicles/hour
Vehicle fleet mix	Adjusted Riverside (described in Appendix C)

4.3.2 Base Case Emissions Inventory

Table 4-8 gives the emissions generated on the highway in Suffolk County in 2001. This is compared to the average total network emissions obtained from five simulation runs of the CA/T using MITNEM for the year 2004. No ramp metering was used for the simulation. The CO_2 generated on the network is responsible for approximately 10% of the emissions in the county and the HC is responsible for 2.2% of the emissions in the county. This shows that optimizing a network of this size can be significant enough to be beneficial to the emissions inventory of the area.

Table 4-8: Suffolk County and CA/T emissions inventory

	HC (Tons/yr)	**CO** (Tons/yr)	**NOX** (Tons/yr)	**Fuel** (Tons)	**CO2** (Tons/yr)	**PM10** (Tons/yr)	**PM2.5** (Tons/yr)	**SOX** (Tons/yr)
Suffolk County (2001)	18,938	141,309	42,677	N/A	N/A	12,284	4,593	10,135
Highways of Suffolk County (1999)	9,185	90,718	14,456	N/A	N/A	450	330	713
Simulated CA/T (2004)	145.5	4359.6	161.6	18670.6	52822.4	N/A	N/A	N/A
% of Suffolk Co.	**1.58%**	**4.80%**	1.12%	--	--	--	--	--

Source: EPA website, AirData, http://www.epa.gov/air/data/emisdist.html?st~MA~Massachusetts

4.3.3 Computational Requirements

The size of the CA/T required long running times to process the data. The output size of the simulation runs also required large amounts of storage space. The run-time of a one-hour simulation of traffic with 40,000 vehicles/hour on a Sparcstation is summarized in Table 4-9.

Table 4-9: Run-times for the CA/T network

Processing	**Computation time**
Generate the trajectory file using MITSIMLab	1 hour
Process the MITSIMLab data into CMEM input format	3 hours
Calculate the emissions using CMEM	30 hours
Post-process the data sets generated by CMEM	1 hour
Total for one run	**35 hours**
Five runs required for statistical significance	**175 hours**

Each simulation run described above generated 6 files (MITSIM output file, trajectory file, CMEM batch activity file, CMEM second-by-second data, CMEM summary file, and matched file). Each file requires approximately 500 megabytes (MB) of storage space. Only one file (the matched file) is required for further analysis, so all the rest of the files can be deleted at the end of each simulation run. The data analysis time is not included in these estimates. Files of this size are time consuming to manipulate and cumbersome to store, especially since the stochastic nature of MITSIMLab requires multiple runs for each simulation.

To reduce the run-times and file sizes, a few methods were used. First, even though MITSIMLab includes the trajectory files during the initial loading period (10 minutes), this data does not need to be processed for emissions. Second, parts of the network can be studied separately. The MITSIMLab trajectories can be generated for the entire network, but the segments of interest can be extracted from the trajectory file and then processed in CMEM. Extracting data from a MITSIM simulation of the entire network ensures that the conditions across the network are consistent. An alternative method is to run just a small portion of the network. By considering the network as a whole, the interactions of the different areas are modeled, whereas simulating only the subparts of interest may not capture the traffic effects the from other parts of the network.

At the current state of computing technology, studying traffic networks at the microscopic level has only been practical in research facilities and at private organizations with specialized computing resources. Advances in computation technology will make it possible to study larger size networks in the future.

Chapter 5

Experimental Studies

MITNEM was used to characterize emissions in two experiments: a study of the effectiveness of Emissions Controls Strategies (ECSs) and a study of the emissions generated at intersections and along segments. These studies are intended to answer complex questions about network emissions behavior, which are difficult to assess without simulation tools.

The chapter is organized as follows. Section 5.1 describes the use of MITNEM to model different emissions control strategies. The effectiveness of the different methods is compared. Additionally, the simultaneous application of multiple strategies is also studied. Section 5.2 uses the data generated in the models developed in Section 5.1 to study emissions profiles at intersections, with a focus on carbon monoxide. The range of modal activities around an intersection makes it an interesting focus for study using micro-simulation. The emissions profile of the Hornstull network is mapped using GIS software first by segment then along the roadway for more detailed analysis of emissions along a segment and around the intersections. These maps are used to determine whether emissions at an intersection are significantly higher than along the segment.

5.1 Experiments with Traffic Emissions Control Strategies

Many traffic management strategies can be used to control emissions in addition to improving traffic flow. The Clean Air Act Amendments of 1990 (CAAA) allows certain transportation control measures (TCMs) to be considered as potential air quality improvements. In some cases, CAAA mandates some TCMs for areas which are in nonattainment status (Cambridge Systematics, 2001). Due to the lack of simulation tools to assess the impact of traffic improvements on emissions, the actual effectiveness of most TCMs on reducing emissions have not been quantified. The basic assumption behind the CAAA regulations is that if flow is improved, emissions intensity is also reduced. For many cases this assumption is true (US DOT, 1996), but some cases have been identified where it is not true (e.g. Guensler et al., 2001). This indicates that the effect of individual TCMs on emissions should be studied before the TCM can be claimed to improve emissions.

In this section, four traffic and emissions control strategies (ECSs), some of which are also TCMs, are modeled to estimate the potential benefit that can be realized. The strategies modeled are: vehicle technology improvements, signal timing, traffic management through demand spreading, and changing demand levels.

Each subsection includes an introduction to the ECS considered and a review of the existing literature concerning its emissions reduction ability, a description of the experiment, and a presentation of the results obtained. The relative benefits of the management strategies are also compared to each other in Section 5.1.5. Though the accuracy of MITNEM has not been validated, the relative benefits predicted by MITNEM can be used for comparison.

Combinations of management strategies are also modeled. Most likely, the benefits of using a combination strategy will be less than the sum of the reductions achieved through the application of the strategies independently because as emissions are reduced, it becomes difficult to further reduce emissions. Finally, dollar values are assigned to each pollutant to translate the emissions benefits into economical benefits using monetary benefits found in the literature for the case of the United States of America.

All test results are the average of five (5) runs of each scenario on the Hornstull network using MITNEM. Unless otherwise specified, the base case uses the adjusted Riverside fleet mix (see Appendix C), the progressive signal timing (see Section 5.1.2), and a constant one-hour demand level as shown in Figure 5.1. This base case will be the reference with which all other ECSs will be compared. The origin-destinations (O-Ds) are shown in Figure 4.5. The base case simulation is run for one hour plus a five to ten minute "wind-down period," totaling a simulation period of 65 to 70 minutes. The wind-down period is meant to provide the different demand profiles a chance to serve the demand which entered the network within the last few minutes. The different profiles have a different number of vehicles entering within this time period; therefore this does not disadvantage the profiles which have more vehicles entering within the last few minutes. Additionally, some of the scenarios have different simulation periods (185 minutes) due to different demand profiles.

All of the scenarios serve roughly the same VKTs because the total demand level is the same (except where the ECS is a change in total demand level). The scenarios do have slightly different values of VKT due to stochasticity in the demand and also due to the different introduction rates of the demand profiles, hence, the average VKT in each scenario is also shown for the concerned ECSs. Because of the different simulation periods, reporting the results in grams of emissions per hour would not be effective. Instead, the results are reported in grams per VKT. This is desirable because a network which serves more vehicles in the hour will most likely have produced more emissions, but consequently, it has served more VKT which will not need to be served later.

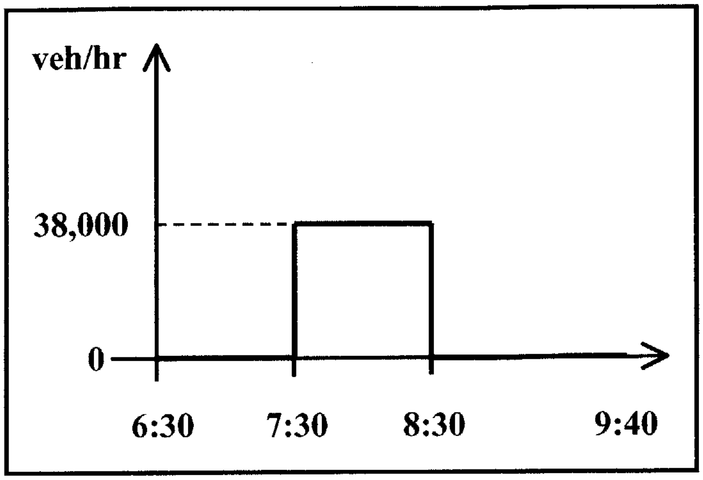
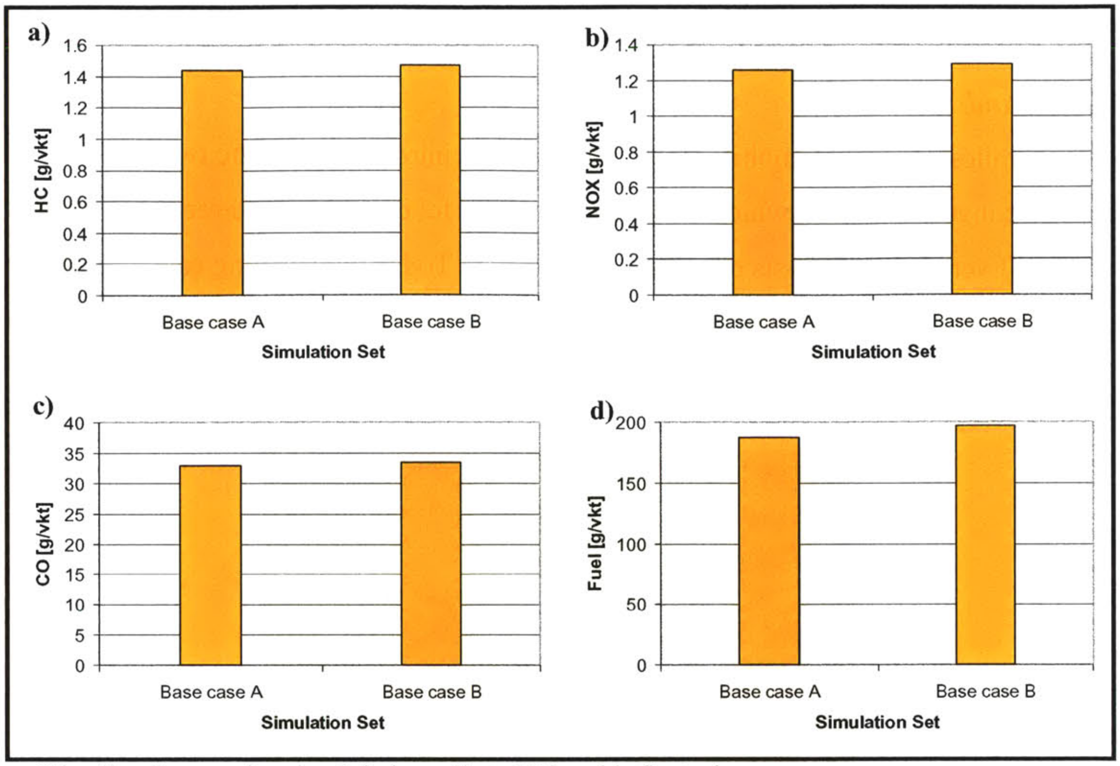


Figure 5.1: Base case Hornstull demand profile

It should be noted that the models described here do not simulate induced demand. This is realistic for I/M programs, which do not in principle, impact on an individual's daily travel decisions. On the other hand, demand management ECSs and changes in traffic signal timing may affect people's travel behavior, including route choices and origin-destination pairs, thereby producing network conditions and demand slightly different from those simulated in this section.

To test the variability of the simulation, two sets of five runs (base case A and base case B) using the base case scenario were compared. The two sets of runs are shown in Figure 5.2 and Figure 5.3. The variability between these two sets of runs is 2% for HC intensity, CO intensity, and VKT Total; 3% for NOX intensity; and 5% for fuel consumption per vkt. Hence, variations do exist between results averaged from multiple runs, but the magnitude of the variation is small.



*Baseline: Progressive signal timing, adjusted Riverside fleet mix

Figure 5.2: Variability of emissions and fuel consumption in two sets simulation runs: a) HC intensity, b) NOX intensity, c) CO intensity, d) Fuel intensity

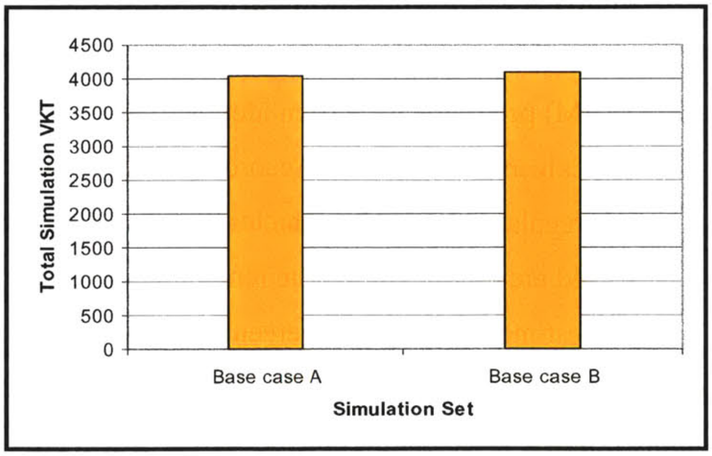


Figure 5.3 Variability of Total VKT in two sets of simulation runs

5.1.1 Vehicle Technology Improvements

Background

A major milestone in automobile technology was the introduction of the two-way catalytic converter in cars, which took place in 1975, followed by the three-way catalyst in 1976. Ever since, catalysts have been improving. Today, all gasoline cars are required to have a catalyst, without which automobiles would not pass current emissions inspection tests.

Source: CARB, 2002

Figure 5.4: Improperly discarded catalysts

Inspection Maintenance (I/M) programs have been identified as a cost effective method for combating emissions (Calvert et al., 1993). According to the EPA, since CAAA has been tightening emissions regulations for new vehicles, the emissions being generated by vehicles less than 7 years old are diminishing. The remainder of vehicles includes very heavy polluters. The EPA estimates that 10-30 percent of vehicles in the United States are responsible for more than 50% of the emissions (EPA Fact Sheet, 1993). These vehicles are commonly referred to as "high-emitters." High-emitters are vehicles that are malfunctioning, operating lean (air to fuel ratio is too high), rich (air to fuel ratio is too low), or are misfiring. Some vehicles have had their emissions control technologies tampered with (e.g. the catalyst is removed) to increase driving performance. I/M programs are targeting a sub-class of these vehicles, the "super-emitters." Yearly, or roadside, emissions testing is used to identify vehicles which need emission service or need to be replaced. Evidence shows that super-emitters are responsible for 50% of CO emissions and 10% of HC emissions (Calvert et al., 1993).

In addition to I/M programs, current Federal regulations require automobile manufacturers to gradually transition to Tier I vehicles, which have stricter emissions standards. The combination of I/M programs and improving technology is simulated in MITNEM by replacing all high-emitters by equivalent Tier I vehicles.

Experimental Setup

Vehicle technology improvements are currently being achieved through emissions technology regulations and inspection maintenance (I/M) programs. These two methods are modeled using MITNEM. The modeling is performed by assigning a different fleet mix of vehicle categories to the same MITSIM simulation runs, thereby using the exact same vehicle trajectories for different fleet mixes. The baseline mix is the adjusted Riverside vehicle fleet mix, derived from the CMEM User Manual (Barth et al., 1999) and described in Appendix C.

As shown in Table 5-1, the high-emitting vehicles, CMEM categories 19 through 23, comprise 24.8% of the Hornstull adjusted Riverside fleet mix. To simulate I/M programs, all high-emitting vehicles (categories 19 through 23) are replaced with equivalent Tier 1 vehicles (categories 8 through 11, and 24).

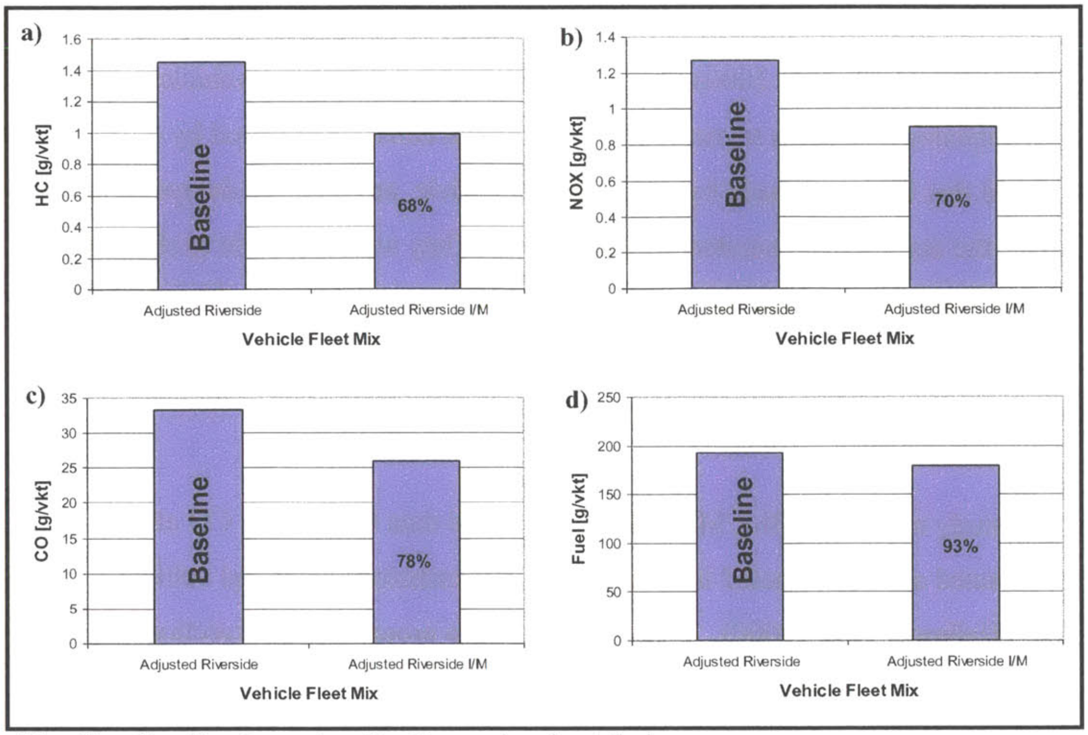
Table 5-1: High-Emitters in Hornstull fleet mix

High-Emitter Category	**CMEM Vehicle Category Number**	**I/M Vehicle Tier 1 Category Number**	**Percentage of Hornstull Fleet**
Runs Lean	19	10	4.6%
Runs Rich	20	9	1.7%
Misfires	21	8	9.8%
Bad catalyst	22	11	6.9%
Runs very rich	23	24	1.8%
Total			**24.8%**

Experimental Study Results

Figure 5.5 shows the emissions reduction that can be achieved by replacing high-emitters with Tier 1 vehicles. In all simulation runs, approximately 6000 vkt were served. The HC and NOX emissions intensities are reduced by a third and the CO intensity is reduced by about 22%. The fuel consumption improvement is smaller because the only improvement is in the vehicle technology, hence the VKT and the modal activities are exactly the same in both scenarios. The reductions in fuel consumption intensity are achieved by the re-optimization of stoichometry in vehicles operating rich and very rich.

The high-emitting vehicles in this experiment are responsible for less of the fleet emissions than the estimates given in the literature review, which stated that high-emitters were responsible for 50% of CO emissions and 10% of HC emissions. The magnitude of these reductions is still significant. It is possible that other conditions such as freeway or city driving may change the proportion of emissions for which high-emitters are responsible. Although this "I/M fleet mix" is optimistic, since vehicles would not always be replaced with Tier I vehicles in the real world, it indicates what emissions savings can be obtained if high-emitting vehicles are replaced by Tier I vehicles.



*Baseline: Baseline demand profile, Progressive signal timing

Figure 5.5: Effect of vehicle technology on emissions: a) HC intensity, b) NOX intensity, c) CO intensity, d) Fuel intensity

5.1.2 Signal Timing

Background

Several studies have simulated the effect of traffic signals on emissions. Traffic signals and traffic signal timing improvements are commonly used by traffic engineers for reducing travel delay and fuel consumption. Since emissions are significantly correlated to fuel consumption, it is reasonable to believe that traffic signals and improved timing can also reduce emissions.

Introducing improper timing can actually increase emissions by increasing the number of stops vehicles have to make, resulting in more acceleration events. On the other hand, signals can improve the flow of traffic and optimize system travel time by introducing some delays at intersection to a few vehicles, in order to minimize the total delay on the network.

Field data has been used to study the effect of delays resulting from traffic signals on emissions (Rouphail et al., 2000). In this study, three instrumented vehicles were driven through signalized arterials to estimate the additional emissions created by delays. First, they found that for a trip made by an individual vehicle, any stops or delays significantly increases the emissions generated during the trip. They were also able to show that emissions from accelerations are at least an order of magnitude more than emissions during idling. This is contrary to the popular belief in traffic engineering that idling causes the bulk of emissions (Frey et al., 2000).

Another study uses CORSIM, MEASURE, and field data to estimate CO at uncoordinated and coordinated intersections using emissions rates and vehicle activity profiles (Hallmark et al., 2000). The immediate area around the intersection (500 feet upstream and downstream of the intersection) was studied. They observed a 9% reduction of emissions using coordination at the intersection of study. They show that a larger reduction was observed using modal modeling as compared to MOBILE5, which bases emissions on average speeds. MEASURE predicted at least 100% more emissions at this intersection for both scenarios than did MOBILE5.

Table 5-2: Results of CORSIM/MEASURE signal coordination study

Timing Plan	**Average Speed (kph)**	**MEASURE Emissions for Peak Hour (g)**	**MOBILE5a Emissions for Peak Hour (g)**
Uncoordinated	47	5,130	2,016
Coordinated	60	4,680	1,878
Difference	**-13**	**449**	**138**

Source: Hallmark et al., 2000

Another study used DYNAMIC, a modal-based traffic and emissions model, to analyze the difference in independently optimizing fuel consumption, emissions, and travel time on a hypothetical network using traffic signals (Williams and Yu, 2001). The study found that for the network used, optimizing travel time resulted in a 2 to 5 % increase in emissions, while if environmental objectives (emissions or fuel consumption) are optimized, higher travel times resulted.

In general, due to the spatial and temporal detail required for TCM modeling, microscopic approaches were predominantly used. In one study, INTEGRATION and a simple regression models of emissions were used to study the effect of three equally spaced signal timings along a conceptual arterial without cross streets (Rakha et al., 2000). Both travel delay and emissions were improved by 40 to 55% using signal coordination. Another 40 to 50% improvement was achieved using adaptive signal control.

One important point emphasized in Guensler et al. (2001) is that the simulation model must include the entire relevant network, not just the intersection of concern. This is because the emissions due to changes in traffic control could be displaced onto other parts of the network. If traffic control strategies such as ramp metering and signal timings change the flow of vehicles that pass through the intersection, the entire area where flows have changed needs to be modeled.

Experimental Setup

The Hornstull network uses a coordinated signal timing. Two additional signal timings were created for this experiment: a progressive signal timing and an all-green signal timing. The progressive signal timing is used as the base case scenario throughout this section. The three traffic signal timing schemes are summarized in Table 5-3. The progressive signal timing is often used in cities, where signals along a street progressively turn green. The all-green signal timing, also common practice, has all of the lights along a street turn green at once. Finally, the coordinated signal timing is a signal timing which is optimized for the network to minimize travel time.

These three signal timings were implemented on the Hornstull network using MITNEM. To verify that the total flow served has not been changed significantly due to the signal timings, VKT are presented. VKT do not measure travel delay, but since there is no induced demand in MITNEM, VKT can be used as a measure of system travel time.

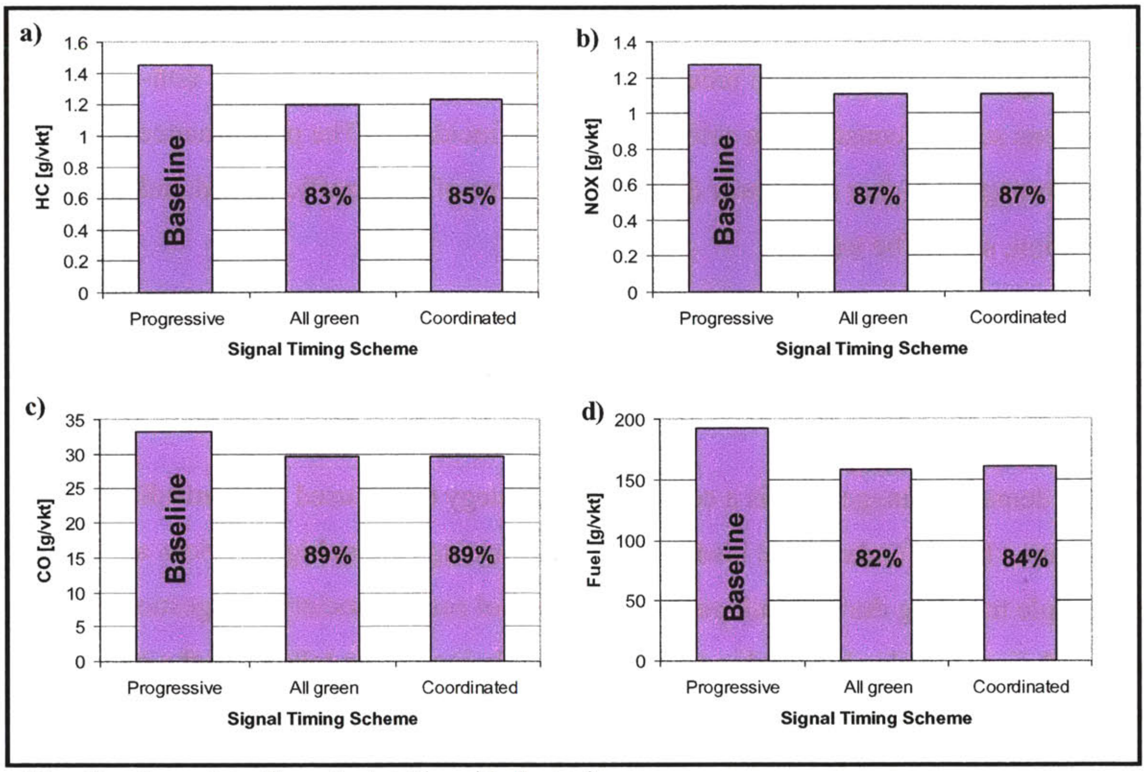
Table 5-3: Hornstull signal timing descriptions

Signal Timing	**Description**
Progressive	Every intersection along the main arterials turns green 50 seconds after the previous one. The cycle time of all intersections is 100 seconds.
All-green	When the light for one direction turns green at the Hornstull intersection, all of the traffic lights leading up to it turn green.
Coordinated	Optimized signal timings for the Hornstull network for the calibrated demand. The Hornstull intersection allocates a high green time split to vehicles in the Northeast-bound and Southwest-bound directions with the objective to maximize the amount if flow served at this intersection.

Experimental Study Results

It was found that for the given fleet mix, demand and network combination, the all-green, and coordinated signal timings performed similarly. Compared to the progressive signal timing, the emissions intensity of HC is reduced by 15 to 17%, the NOX by 13%, and the CO by 11%, compared to the progressive signal timing. The fuel consumption per VKT was reduced by 16 to 18%. The results for each pollutant are shown in Figure 5.6.

The VKT for each of the signal timings are shown in Figure 5.7. The all-green signal timing serves the most traffic in the course of one hour while the progressive signal timing serves the least. The all-green signal timing and the coordinated signal timing results clearly perform better than the baseline, progressive signal timing. But the difference between the two signal timings is within the variability range, so a conclusion cannot be drawn about their respective performance.



*Baseline demand profile, adjusted Riverside fleet mix

Figure 5.6: Assessment of signal timings on emissions: a) HC intensity, b) NOX intensity, c) CO intensity, d) Fuel intensity

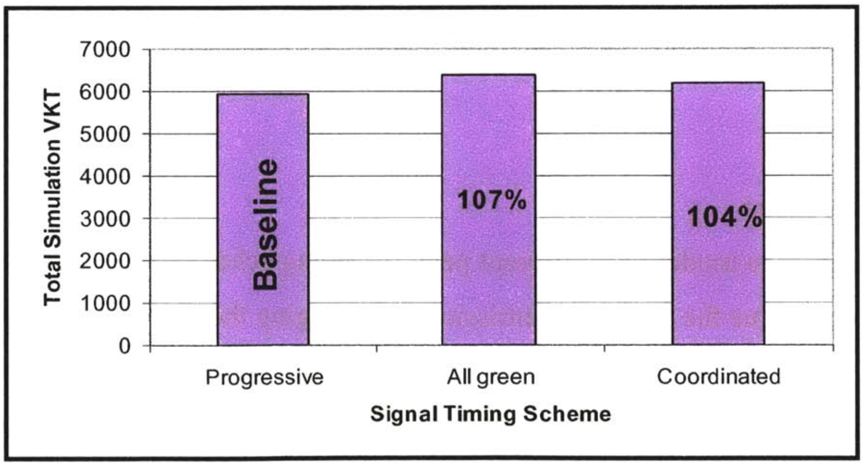


Figure 5.7: Effect of signal timing on total VKT served

In conclusion, the all-green signal timing and the coordinated signal timing are able to serve more traffic while generating less emissions per VKT. It should be noted that the signal timings results are only valid for the base case demand profile shown in Figure

5.1. A scheme's ability to address variations in traffic load is important, since demand can change slowly over time in recurrent conditions or abruptly in case of non-recurrent conditions such as construction activities or traffic incidents. The performance of the signal timings at higher and lower demands, in terms of both traffic served and emissions generation, should be tested.

5.1.3 Traffic Demand Management: Peak Spreading

Background

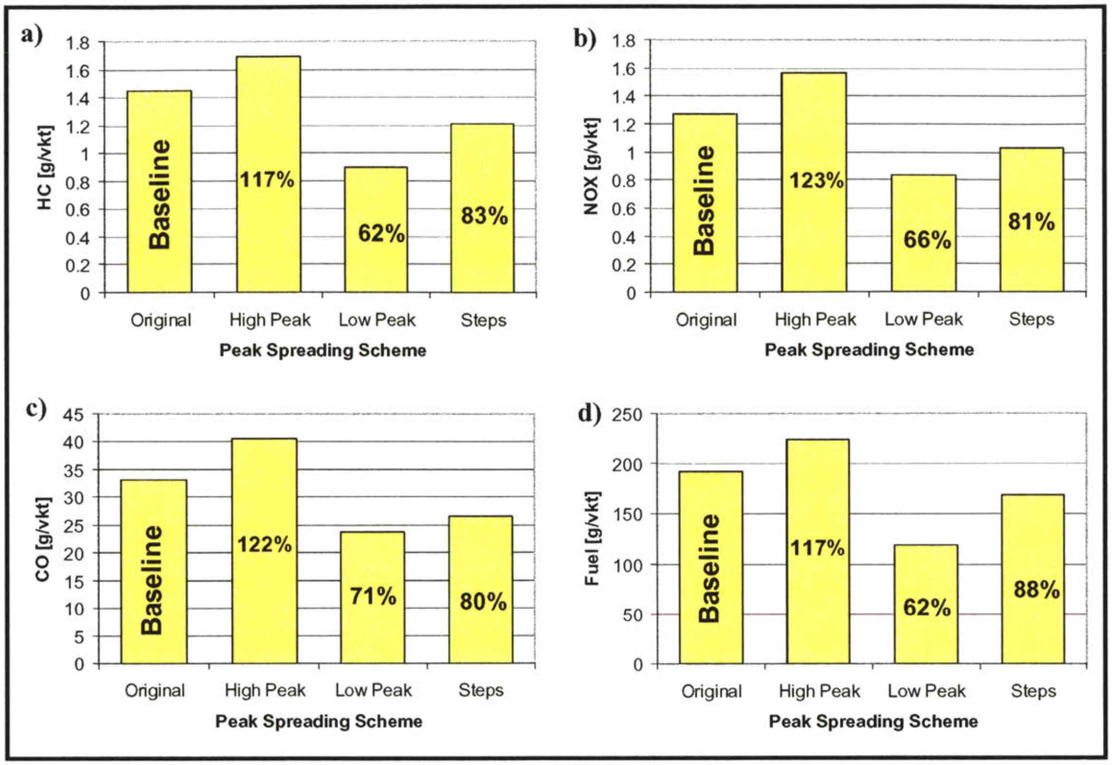
Traffic demand management is a controversial strategy that is used for controlling emissions. It is a fundamental idea behind value pricing, where higher prices are charged for people traveling during peak periods when travel costs to society (congestion, noise, and pollution) are also higher due to congestion. By increasing tolls on highways and bridges during peak hours, automobile travel is penalized during the peak hours and part of the demand is moved to earlier or later time periods. This particular scheme is called peak spreading because the peak demand is reduced by spreading the traffic over a longer time period. Another example of managing peak demand is seen in cities with large industrial labor forces. Employers often stagger the time their employees start and finish work, leading to a potential reduction in the congestion created on the roads from a spike in demand.

Experimental Setup

MITNEM is used to model four different peak spreading schemes on the Hornstull network to determine the impact on emissions of changing the demand profile. The total travel demand for all of the scenarios is maintained constant. To include the effect of the vehicles introduced in the last few minutes of the simulation, all runs include a 10-minute wind-down period in which no additional demand is introduced, but the trajectories are still recorded. The baseline scenario, shown in Figure 5.9 a), is the baseline demand profile used in the other scenarios. This demand is constant during one hour from 7:30 AM to 8:30 AM. There is no demand before 7:30 AM and after 8:30 AM. The second scenario, shown in Figure 5.9 b), has the demand ramping up more smoothly, but with a higher peak. This demand represents what might be seen at the end of a sporting event such as a major ball game. The demand period is the same as the baseline, which is one hour. The third scenario, shown in Figure 5.9 c), also has a smooth increase in demand, but is spread out over three hours, from 6:30 AM to 9:30 AM, therefore the demand rate at all times is lower than the baseline demand. This profile can be achieved through continuous traffic management controls such as ramp metering, which limit the number of vehicles entering the network. An implementation of the low peak profile on a larger scale is an ideal. A technology to produce such a smooth demand profile would require continuous feedback from around the network, accurate traffic prediction algorithms, and a variable pricing mechanism. The last scenario, shown in Figure 5.9 d), is a step function, also spread over three hours, where a quarter of the original demand is spread out over the first and last hour, leaving only half the demand for the peak hour of 7:30 AM to 8:30 AM. This profile may arise as a result of congestion pricing implemented currently in the practice, where higher tolls are charged for the peak period and lower tolls are charged for adjacent periods.

Experiment Study Results

Figure 5.8 shows the emissions results from the different demand profiles. The simulation results show that the low peak profile is the most effective among the profiles tested to reduce emissions for the Hornstull network, reducing emissions intensity and fuel consumption by 29 to 38%. The step function profile also shows an improvement to the baseline, reducing emissions intensity by approximately 20% and fuel consumption by 12%. These results are achieved from simply redistributing the demand and avoiding profiles with high peak and/or profiles which cause sharp congestion. On the other hand, demand profiles such as the high peak demand profile simulated, can cause significant increases in emissions although the total demand is the same as in all of the other peak spreading schemes.



*Progressive signal timing, adjusted Riverside fleet mix

Figure 5.8: Effect of peak spreading on emissions: a) HC intensity, b) NOX intensity, c) CO intensity, d) Fuel intensity

The VKT for each of the peak spreading schemes are shown in Figure 5.10. The high peak scheme serves the same amount of VKT as the baseline scenario. The low peak scheme, possibly due to improved traffic conditions, increases the VKT on the network. Therefore though the demand is the same, it is served faster. The step function profile serves slightly less VKT than the other profiles. A possible reasons for this is because of the sudden increase of demand one hour into the simulation. Sudden perturbations can cause congestion. Though the step function may increase travel delay it is effective in decreasing emissions. In cities with major pollution problems, it may be a viable strategy.

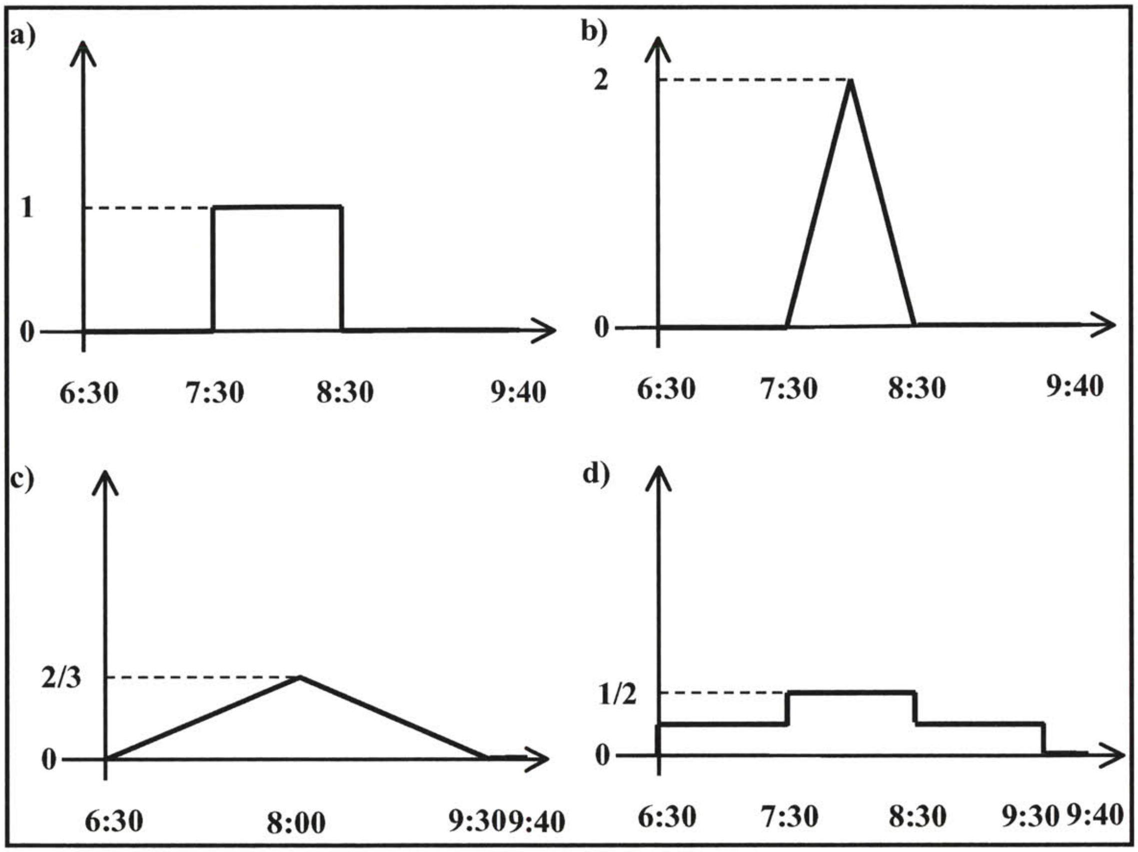


Figure 5.9: Demand profiles: a) Base case Hornstull demand, b) High peak demand, c) Low peak demand, d) Step demand

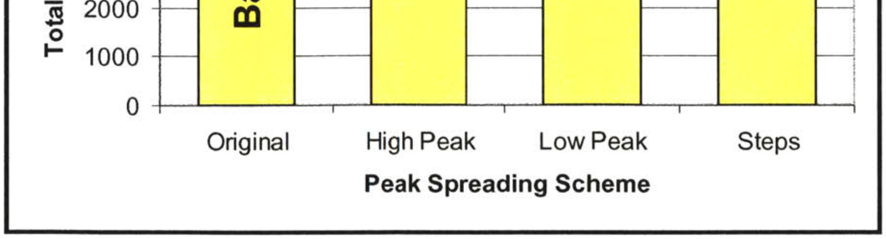


Figure 5.10: Effect of peak spreading on VKT

These scenarios give a general idea about the improvements that can be achieved through traffic demand management. The actual magnitude of change will depend upon the capacity of the network and the ratio of the current load compared to the capacity. If the demand to capacity ratio is low, then peak spreading may not offer any benefit because queues will not be formed. The greatest benefit for any scheme should be observed when the baseline scenario is operating above capacity and the peak spreading scheme is able to keep the demand well below the capacity.

These results are specific to the Hornstull network for a given demand level. The specific implementation details of a peak spreading scheme should impact the emissions results. For example, as discussed in Section 2.5.2, though ramp metering smoothes out traffic flow, it causes modal changes in the traffic pattern. This can lead to changes in acceleration patterns, which affect the emissions. Hence an improvement in traffic flow may not lead to emissions improvement.

5.1.4 Traffic Demand Management: Changing Demand Levels

Background

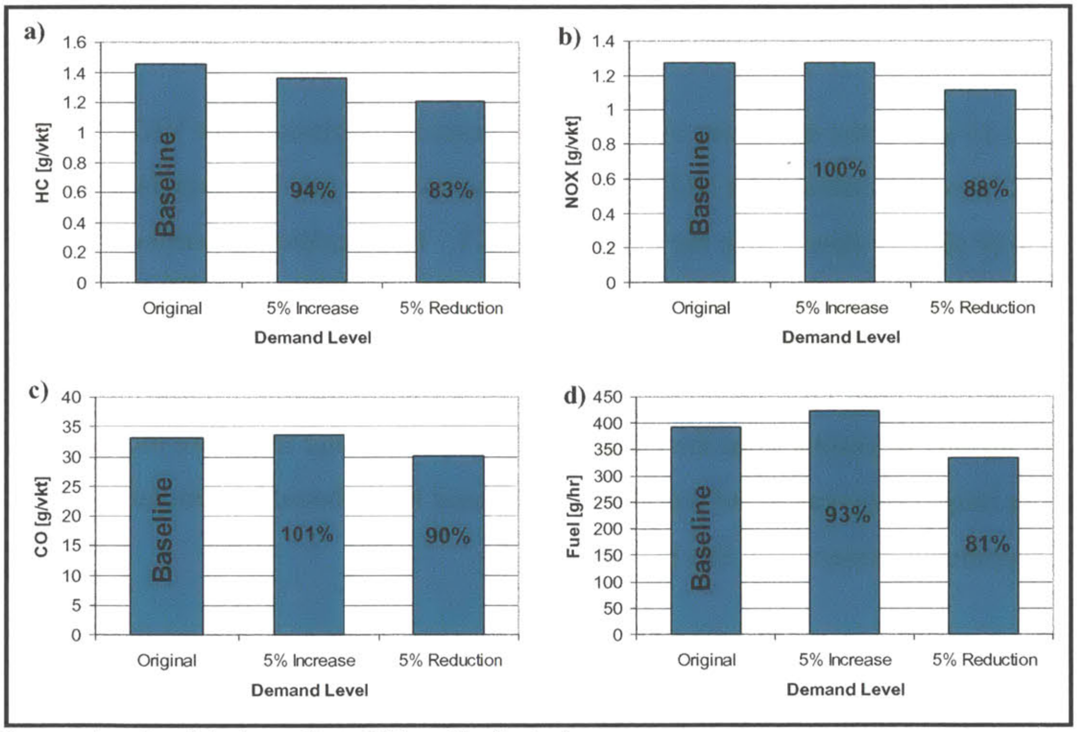
Various traffic and emissions control strategies aim to decrease the total traffic demand. This can be achieved through programs that promote and/or improve alternative transportation modes such as transit, biking, and walking; increasing the average riders per vehicle through carpooling or ride sharing; and other methods such as educating the population about trip chaining. A demand reduction over a few years of 3 to 5% in VKT is reasonable using an integrated transportation plan (Hillsborough County, 2001). The yearly VKT growth in the United States in the last decade was 2 to 4% per year (FHWA, 2000).

Experimental Setup

The effects on the Hornstull network of a marginal reduction of 5% in demand, and of a 5% increase in demand are simulated. The demand is increased and decreased proportionately at all of the O-Ds. The progressive signal timing and the adjusted Riverside fleet mix are used.

Experimental Study Results

The results are shown in Figure 5.13. The reduction of demand reduces HC, NOX, and CO intensities by 17%, 12%, and 10%, respectively. It also reduces fuel consumption by 19%. Surprisingly, increasing the demand from the base case does not affect CO and NOX intensities and. It even decreases HC intensity and the fuel consumption. Yet an effect is observed when if comparing the 5% reduction scenario to the base case! This phenomenon is studied in more detail.



*Progressive signal timing, adjusted Riverside fleet mix

Figure 5.11: Effect of total demand level on emissions: a) HC intensity, b) NOX intensity, c) CO intensity, d) Fuel intensity

Figure 5.12 shows that the additional demand introduced onto the network indeed increases the VKT. A 5% demand increase increased the VKT by 13%. A 5% decrease in demand also increases VKT by 2%, which may result from either better flow or MITNEM variability.

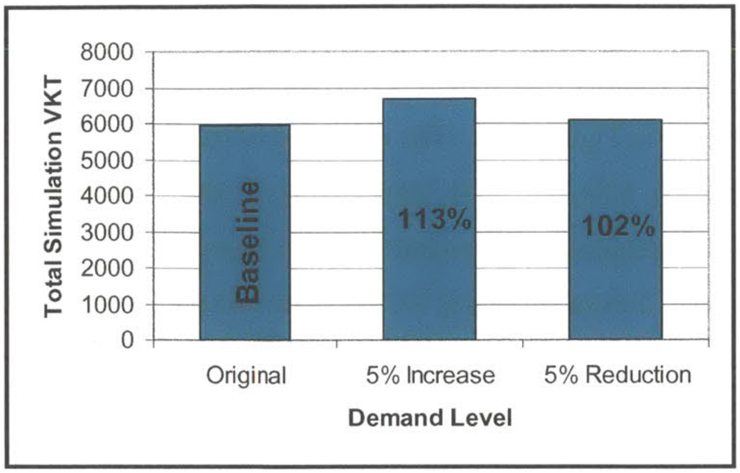
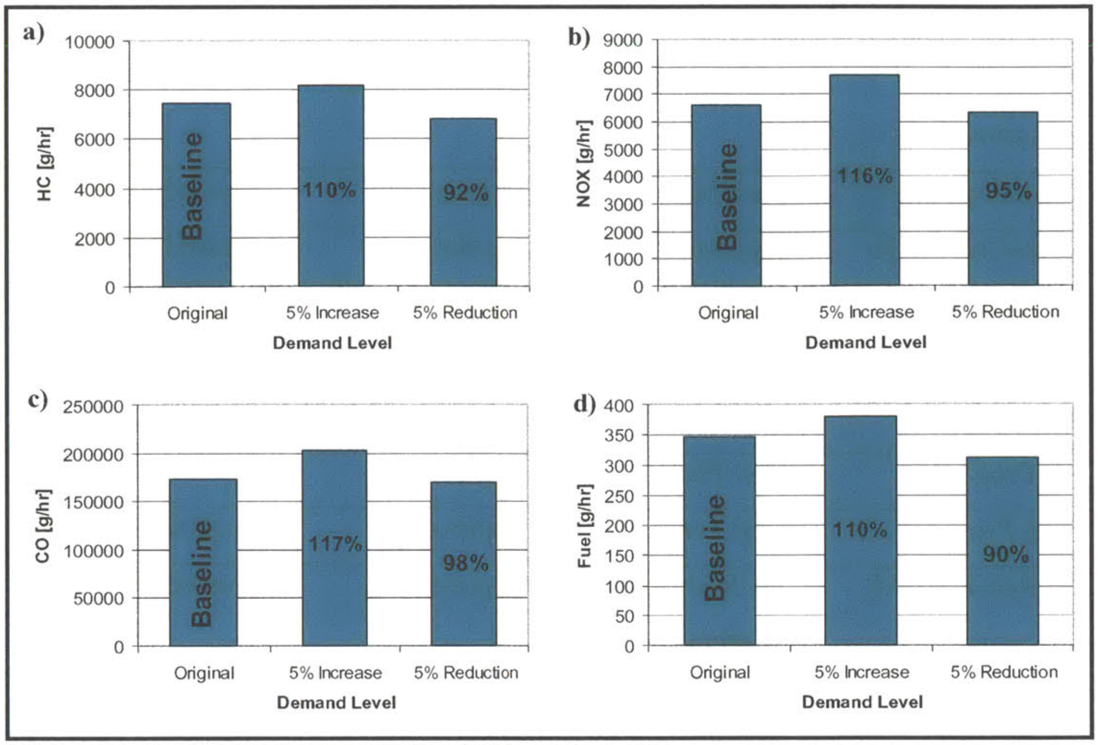


Figure 5.12: Effect of total demand level on VKT

Figure 5.13 shows the emissions over one hour instead of emissions per VKT. In the 5% demand increase scenario, the NOX and CO emissions flow rate has increased roughly equal to or slightly slower than the increase in VKT. This explains the emissions intensity results which show no change. The 5% reduction in demand shows a clear reduction of HC and NOX emissions and fuel consumption.

In conclusion, the results from the marginal changes in demand levels are inconclusive. A wider range of increases and reductions in demand level should be simulated to study the phenomenon observed in this experiment.



*Progressive signal timing, adjusted Riverside fleet mix

Figure 5.13: Effect of total demand level on emissions: a) HC flow rate, b) NOX flow rate, c) CO flow rate, d) Fuel flow rate

5.1.5 Comparison of Emissions Control Strategies

The previous sections have described and quantified the emissions benefits and/or disbenefits that can be achieved on the Hornstull network using different emissions control strategies. In this subsection, we compare the relative benefits of the different strategies. All strategies which were tested for emissions reductions are included except the all-green signal timing because its results were similar to the coordinated signal timing. The coordinated signal timing is included instead because it is the signal timing currently implemented on the Hornstull network. The scenarios included, along with the notation used to refer to each ECS, are shown in Table 5-4.

Table 5-4: Single-Strategy ECS Summary Table

ECS Strategy Notation	Demand Profile	Signal Timing	Fleet Mix
Base-Prog-AR	Baseline	Progressive	Adjusted Riverside
Base-Coord-AR	Baseline	Coordinated	Adjusted Riverside
Base-AG-AR (not included in Figure 5.14)	Baseline	All-Green	Adjusted Riverside
LP-Prog-AR	Low Peak	Progressive	Adjusted Riverside
Step-Prog-AR	Step Function	Progressive	Adjusted Riverside
5%Red-Prog-AR	5% Reduction of Baseline	Progressive	Adjusted Riverside
Base-Prog-I/M	Baseline	Progressive	I/M

Figure 5.14 summarizes the effect of the studied ECSs for the Hornstull network. All strategies serve about 6000 vkt. The VKT is expressed in total VKT for the simulation (rather than VKT/hr) because the simulation time period for all scenarios is 65 to 70 minutes, except LP-Prog-AR and Step-Prog-AR which is 185 to 190 minutes (see Section 5.1.3). Overall, for all pollutants and fuel consumption, the most effective emissions control strategy is the LP-Prog-AR strategy. If one does not consider fuel consumption, the I/M program is the second best ECS. For fuel consumption, reducing demand is the second best method. As for the other ECSs, the emission species are impacted differently by the different ECSs. This is an important point, that a blanket ECS should not be used for every locale. The appropriate ECS will be dependent on the air quality of a given area.

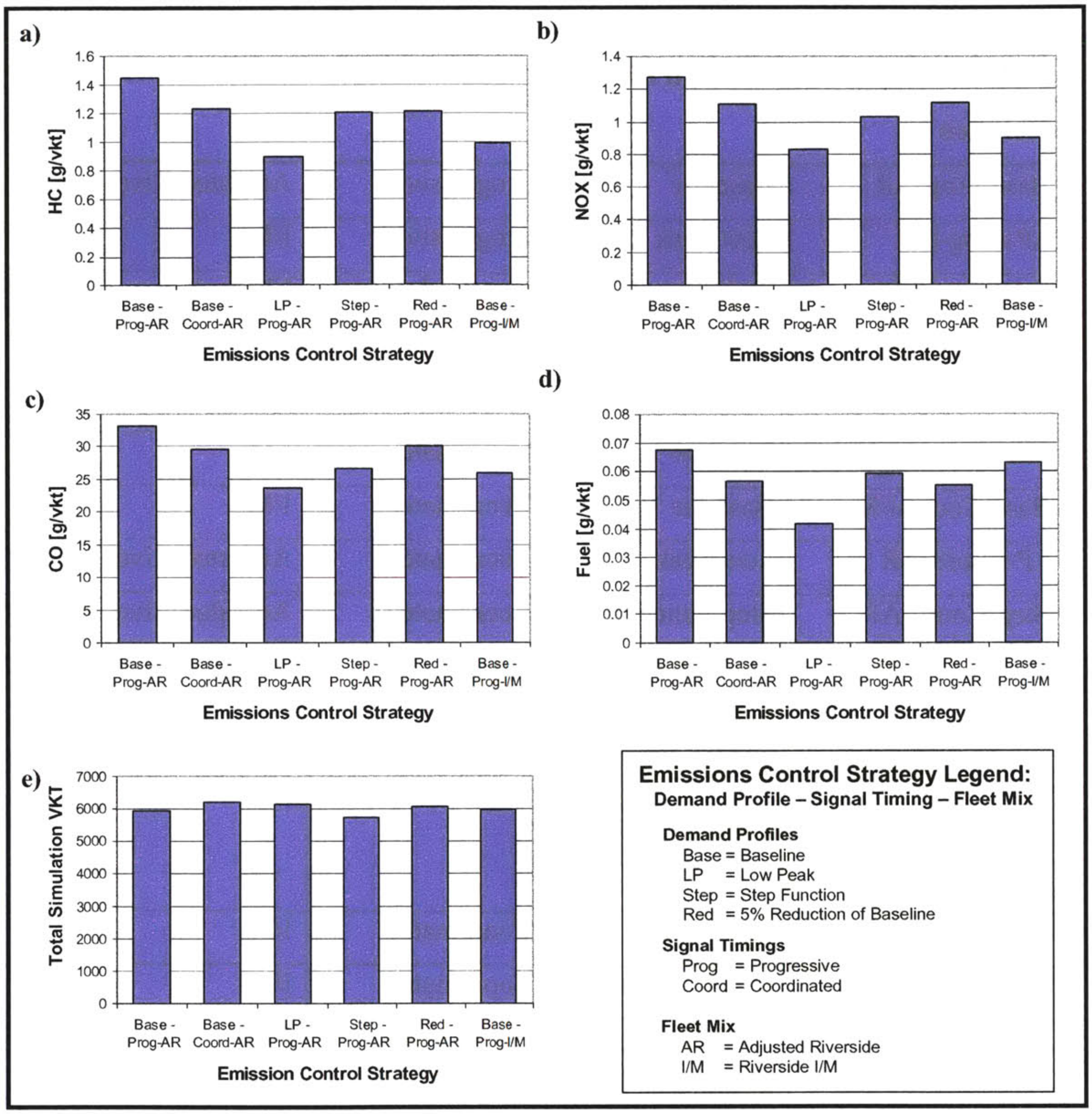


Figure 5.14: Comparison of single-strategy effect on emissions: a) HC intensity, b) NOX intensity, c) CO intensity, d) Fuel intensity, e) Total VKT

5.1.6 Combination Emissions Control Strategies

The improvements from the individual emissions control strategies shown in the previous sections are not necessarily additive. One reason is because as vehicle technologies improve, it becomes increasingly difficult to reduce emissions intensity. MITNEM is used to study the effect of combination strategies on emissions, fuel consumption, and VKT. The strategies simulated and the notations used to refer to the ECSs are shown in Table 5-5.

Table 5-5: Summary of combination-ECSs tested

ECS Strategy Notation	Demand Profile	Signal Timing	Fleet Mix
Base-Prog-AR	Baseline	Progressive	Adjusted Riverside
LP-Prog-I/M	Low Peak	Progressive	I/M
Step-Prog-I/M	Step Function	Progressive	I/M
Red-Prog-I/M	5% Reduction of Baseline	Progressive	I/M
Base-Coord-I/M	Baseline	Coordinated	I/M
Base-Coord-I/M	Baseline	Coordinated	I/M
LP-Coord-AR	Low Peak	Coordinated	Adjusted Riverside
Step-Coord-AR	Step Function	Coordinated	Adjusted Riverside
Red-Coord-AR	5% Reduction of Baseline	Coordinated	Adjusted Riverside
Inc-Prog-I/M (not included in Figure 5.15)	5% Increase of Baseline	Coordinated	Adjusted Riverside
LP-Coord-I/M	Low Peak	Coordinated	I/M
Steps-Coord-I/M	Step Function	Coordinated	I/M
Red-Coord-I/M	5% Reduction of Baseline	Coordinated	I/M

Figure 5.15 compares the effectiveness of some combination strategies. The most effective strategies for the Hornstull network are the LP-Prog-I/M and the Step-Coord-I/M combination strategies which reduce emissions by 40 to 60% and fuel consumption by 40 to 43%. For fuel consumption, the Step-Coord-AR is also relatively effective, reducing fuel consumption by 40%. The least effective strategies of those tested are the LP-Coord-AR and Red-Coord-AR which are only able to reduce emissions by 17 to 30%. This is probably due to the fact that at lower demand levels with smoother demand profiles, the congestion is not severe enough to take advantage of the coordinated signal timings.

Figure 5.15 e) shows the VKT for each of the combined strategies. The highest VKT correspond to the strategies which use coordinated signal timing (Prog-Coord-I/M, Step-Coord-AR, and Steps-Coord-I/M). Note that at higher congestion levels, additional demand may reduce total VKT.

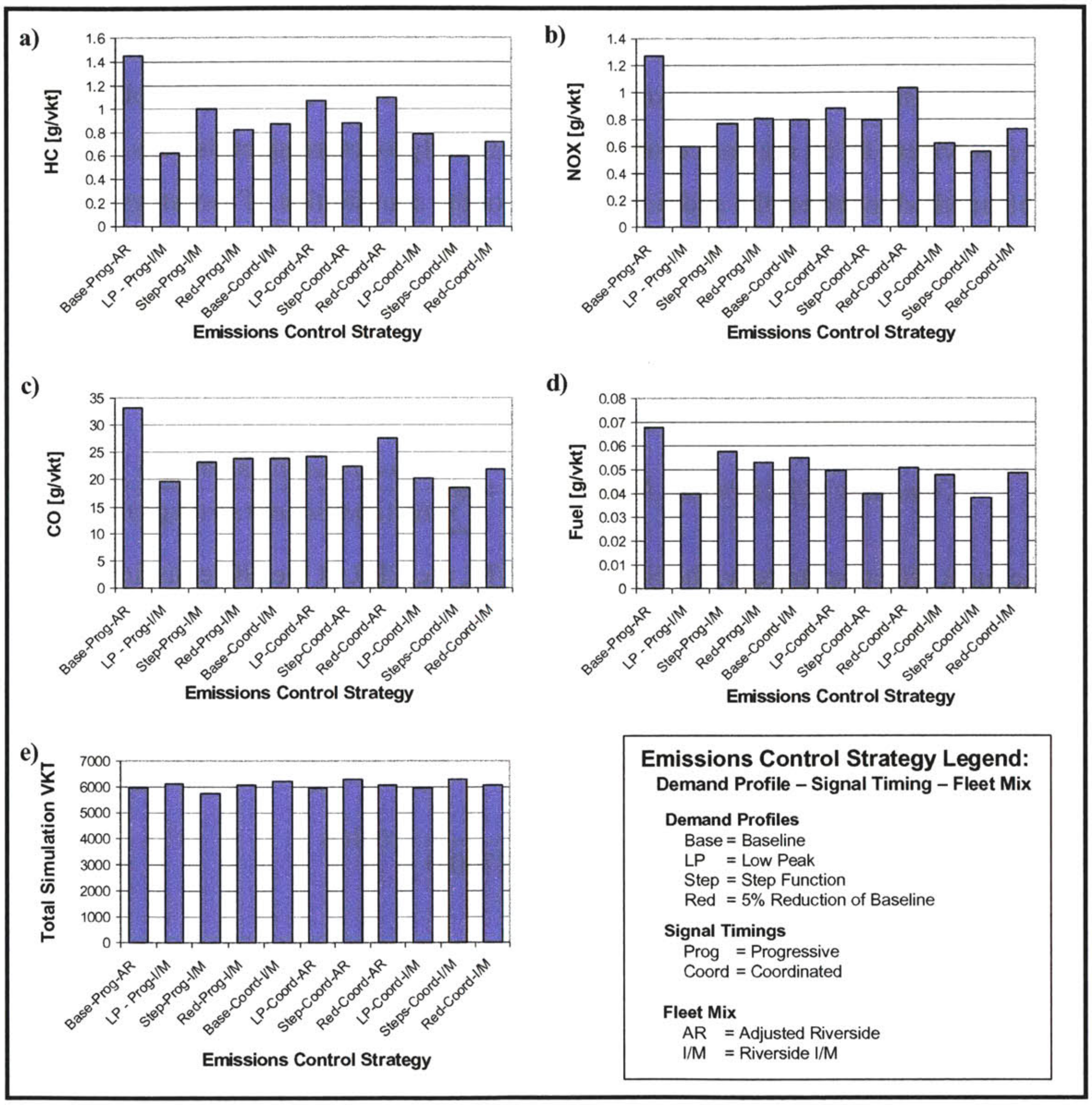


Figure 5.15: Effect of combination ECSs on fuel and emissions: a) HC intensity, b) NOX intensity, c) CO intensity, d) Fuel intensity, e) Total VKT

Table 5-6 summarizes the emissions and fuel consumption results corresponding to all ECSs tested on the Hornstull network. The total emissions are for the entire simulation run (approximately 65 to 70 minutes for all ECSs except the models which model the step function or the low peak demand profile each of which are approximately 185 to 190 minutes). To account for the different level of demand served for each scenario, the "difference between the scenario and the base case total emissions" is calculated by multiplying the difference of the emissions rate by the VKT corresponding to each scenario.

Some combination strategies are more effective than others. In some combinations, one of the component ECSs may not contribute significantly to lowering emissions. As a possible method to reflect the additional change of the contribution of a strategy to lowering emissions, a ratio, called the "combined effectiveness ratio" (CER) is introduced. The CER is the total emissions changes corresponding to a combination strategy, over the sum of the emissions changes corresponding to the component strategies. The changes are with respect to the base case (Base-Prog-AR).

$$Combined\ Effectiveness\ Ratio\ (CER) = \frac{\Delta E(combination\ strategy)}{\sum \Delta E(component\ strategy)}$$

For the most effective strategy, the Step-Coord-I/M, the CER of the HC emissions compared to the component single-strategy ECSs is:

$$\frac{\Delta E(Step-Coord-I/M)}{\Delta E(Base-Coord-AR)+\Delta E(Step-\mathrm{Pr}og-AR)+\Delta E(Base-\mathrm{Pr}og-I/M)}$$

$$=\frac{5340.0}{1356.7+1410.4+2760.0}=0.966$$

Table 5-6: Emissions obtained for all emissions control strategies tested

Scenarios	**Average Total VKT, Emissions, and Fuel Consumption over Five Simulations**[a]						**Emissions Intensity**				**Difference of Total Emissions**[b] **relative to the base case**			
	VKT (km)	**HC** (g)	**CO** (g)	**NOX** (g)	**Fuel** (L)	**CO2** (g)	**HC** (g/vkt)	**CO** (g/vkt)	**NOX** (g/vkt)	**Fuel** (L/vkt)	**HC** (g)	**CO** (g)	**NOX** (g)	**Fuel** (gal)
Baseline	5951	8451.5	195571	7481.4	1487.3	3205622	1.4527	33.2376	1.2739	0.2563	--	--	--	--
Traffic Signals														
All-green	6382	7665.1	188818	7085.8	1346.8	2884590	1.2010	29.5845	1.1102	0.2108	1606.7	23315.0	1044.3	288.4
Coordinated	6193	7576.6	182731	6850.9	1320.0	2830988	1.2336	29.5988	1.1108	0.2150	1356.7	22533.5	1009.6	255.5
Peak Spreading														
Hi Peak	5971	10087.3	241339	9327.9	1783.3	3830938	1.6922	40.4522	1.5634	0.2990	-1430.0	-43081.1	-1728.8	-255.5
Low Peak	6126	5493.2	144726	5115.9	964.9	2049184	0.8967	23.6254	0.8351	0.1575	3406.2	58885.2	2687.8	604.5
Steps	5734	6682.6	150255	5739.5	1237.8	2687306	1.2068	26.6067	1.0296	0.2252	1410.4	38021.0	1400.8	177.5
Demand Management														
5% Increment	6697	9106.8	225469	8545.7	1601.6	3427785	1.3598	33.6674	1.2761	0.2392	622.0	-2878.3	-14.8	114.3
5% Reduction	6070	7353.7	182170	6774.1	1267.0	2704678	1.2114	30.0104	1.1159	0.2086	1464.7	19589.8	958.6	288.4
Vehicle Technology														
Riverside I/M	5969	5835.6	154596	5315.7	1410.4	3091448	0.9904	26.0389	0.8963	0.2392	2760.0	42971.7	2254.1	101.8
Combination Strategies														
LP-Prog-I/M	6126	3798.3	120876	3685.9	931.6	2012150	0.6200	19.7319	0.6017	0.1522	5101.3	82737.2	4117.9	638.2
Step-Prog-I/M	5734	5379.7	130460	4255.5	1202.2	2631762	0.9924	23.2983	0.7678	0.2192	2639.6	56991.5	2901.5	213.1
Red-Prog-I/M	6069	4978.9	145142	4892.5	1219.3	2656324	0.8204	23.9155	0.8061	0.2010	3837.7	56574.8	2838.5	335.8
Inc-Prog-I/M	6694	6238.1	176904	6066.6	1531.6	3344168	0.9319	26.4267	0.9063	0.2286	3486.6	45593.7	2460.8	183.6
Base-Coord-I/M	6193	5319.3	147369	4919.1	1274.5	2783548	0.8689	23.8993	0.7979	0.2074	3615.1	57828.7	2947.3	300.9
LP-Coord-AR	5975	6290.3	144388	5203.5	1102.3	2377255	1.0700	24.3286	0.8788	0.1878	2286.6	53230.9	2360.6	409.6
Step-Coord-AR	6300	5549.5	141427	4982.3	954.3	2028373	0.8814	22.4540	0.7911	0.1514	3599.5	67941.3	3041.5	659.4
Red-Coord-AR	6071	6673.7	167950	6269.2	1165.1	2486380	1.0992	27.6635	1.0326	0.1919	2146.1	33841.6	1464.6	390.3
LP-Coord-I/M	5975	4577.8	120636	3678.7	1060.3	2314748	0.7830	20.3528	0.6215	0.1806	4001.5	76985.9	3897.5	452.0
Steps-Coord-I/M	6300	3809.8	117013	3542.3	913.8	1975810	0.6052	18.5771	0.5625	0.1450	5340.0	92367.8	4481.9	700.0
Red-Coord-I/M	6071	4387.1	132250	4432.3	1119.3	2440252	0.7226	21.7831	0.7300	0.1843	4432.7	69543.0	3301.6	436.1

Baseline: Progressive signals, One-hour Flat demand, Riverside fleet mix

[a] All scenarios simulations are 65 – 70 minutes long except step function and low peak demand profile scenarios which are 185 –190 minutes long

[b] Both the scenario total emissions and base case total emissions have been normalized by the average VKT for the scenario

The CER can also be used to compare the effectiveness of a combination strategy with sub-combination strategies. For example, the Step-Coord-I/M is compared to the Base-Coord-I/M strategy (a sub-combination strategy) and to the Step-Prog-I/M strategy:

$$\frac{\Delta E(Step-Coord-I/M)}{\Delta E(Base-Coord-I/M)+\Delta E(Step-\Pr og-AR)}=\frac{5340.0}{3615.1+1410.4}=1.06$$

$$\frac{\Delta E(Step-Coord-I/M)}{\Delta E(Base-Coord-AR)+\Delta E(Step-\Pr og-I/M)}=\frac{5340.0}{1356.7+2639.6}=1.34$$

These CERs are greater than 1, which means that the combined strategy is more effective than the sum of the emissions reductions achieved by its sub-component strategies independently. This can happen when there is a synergy between two or more component strategies. For example, if congestion is backing traffic up into a signalized intersection, potentially decreasing the effectiveness of a signal setting, a synergistic strategy could reduce congestion so that the intersection is freed up enough so that the signal timings can be adhered to again.

Table 5-7 shows the CERs of all of the combined strategies. A high CER does not mean that the ECS is the most effective strategy, but low CERs suggest that the combination under consideration contains one or more redundant component strategies, which can be eliminated. The Step-Coord-I/M strategy both reduces the emissions rate effectively and has a CER close to 1, therefore it is a good ECS candidate for the Hornstull network.

Table 5-7: Combined Effectiveness Ratios (CER) with respect to single-strategy ECSs

	CER of HC	CER of CO	CER of NOX	CER of Fuel
LP-Prog-I/M	0.83	0.81	0.83	0.90
Step- Prog-I/M	0.63	0.70	0.79	0.76
Red-Prog-I/M	0.91	0.90	0.88	0.86
Base-Coord-I/M	0.88	0.88	0.90	0.84
Base-Coord-AR	0.48	0.65	0.64	0.48
Step-Coord-AR	1.30	1.12	1.26	1.52
Red-Coord-AR	0.76	0.80	0.74	0.72
LP-Coord-I/M	0.53	0.62	0.65	0.47
Step- Coord-I/M	0.97	0.89	0.96	1.31
Red- Coord-I/M	0.79	0.82	0.78	0.68

It is also possible for a combination strategy to consist of antagonistic strategies, where the two scenarios make the other strategy less effective. This was not seen in the set of ECSs simulated, but this could happen if the flow of traffic is changed to disrupt the original coordination of a coordinated signal timing.

5.1.7 Emission Control Strategy Health and Visibility Costs

It is useful in cost-benefit analysis to have emissions reduction benefits translated into dollar amounts. This allows different objectives to be compared. Doing so allows, for instance, travel time and emissions benefits to be compared. If one ECS slightly increases travel time, but reduces emissions, one may want to compare this to a strategy that leads to a larger travel time reduction and a small emissions increase. Dollar costs may not fully capture the trade-offs between emissions and travel time, but they do provide a means for comparison. Dollar amounts also allow for different pollutants to be weighted, since one gram of CO does not have the same health costs as one gram of NOX.

Table 5-8 shows high and low costs for each of the ECSs, using values from a study conducted by McCubbin and Delucchi (1999). Costs vary by region, but the values used here are average emissions costs for the United States. Additional details about the emissions costs used are in Appendix D. McCubbin and Delucchi also included the cost of PM and SOX, not included here, which they indicate are responsible for approximately

90% of health costs in most cities. The table shows a high estimate and a low estimate. These estimates are based on the range of values which studies have assigned different health effects. As noted by McCubbin and Delucchi, it is best to always use the range of values when citing the results since there is a great deal of uncertainty in the single dollar values. Using the high or low estimate alone may be misleading.

Though health costs are based on morbidity and mortality rates, they usually comprise a small fraction of total costs in a cost-benefit study. In one study using HERS (see Appendix D), health benefits accounted for only about 1-2% of the benefits of highway improvements (US DOT, 2000).

When converted to dollar amounts, the Step-Coord-I/M combination strategy provides the most emissions benefits with a low estimate of $197/hour to a high estimate of $530/hour. This is followed closely by the LP-Prog-I/M (ranging from $180/hour to $485/hour) and Step-Coord-AR (with a cost estimate ranging from $182/hour to $458/hour) strategies. Though the emissions benefits are smaller, in terms of total cost, the low peak demand strategy (with a cost estimate ranging from $167/hour to $417/hour) alone can achieve most of the benefits of the LP-Prog-I/M and Step-Coord-AR combination strategies. In a cost-benefit analysis, the low peak demand may be a preferable choice to the LP-Prog-I/M and Step-Coord-AR strategies.

Table 5-8: Health and visibility savings compared to base case in 2001 US Dollars corresponding to the emissions control strategies tested using the Hornstull network

Strategies	High Estimate					Low Estimate				
	HC	CO	NOX	Fuel	Total	HC	CO	NOX	Fuel	Total
Traffic Signals										
All-green	$3.04	$3.03	$32.27	$152.41	$190.74	$0.27	$0.23	$2.35	$76.20	$79.06
Coordinated	$2.56	$2.93	$31.20	$135.04	$171.73	$0.23	$0.23	$2.27	$67.52	$70.25
Peak Spreading										
Hi Peak	-$2.70	-$5.60	-$53.42	-$134.94	$196.66	-$0.24	-$0.43	-$3.89	-$67.47	-$72.03
Low Peak	$6.44	$7.66	$83.05	$319.43	$416.58	$0.58	$0.59	$6.05	$159.72	$166.93
Steps	$2.67	$4.94	$43.28	$93.86	$144.75	$0.24	$0.38	$3.15	$46.93	$50.70
Demand Management										
5% Increment	$1.18	-$0.37	-$0.46	$60.47	$60.81	$0.11	-$0.03	-$0.03	$30.23	$30.28
5% Reduction	$2.77	$2.55	$29.62	$152.44	$187.37	$0.25	$0.20	$2.16	$76.22	$78.82
Vehicle Technology										
Riverside I/M	$5.22	$5.59	$69.65	$53.84	$134.30	$0.47	$0.43	$5.07	$26.92	$32.89
Combination Strategies										
LP-Prog-I/M	$9.64	$10.76	$127.24	$337.18	$484.82	$0.87	$0.83	$9.27	$168.59	$179.55
Step-Prog-I/M	$4.99	$7.41	$89.66	$112.67	$214.73	$0.45	$0.57	$6.53	$56.34	$63.88
Red-Prog-I/M	$7.25	$7.35	$87.71	$177.32	$279.63	$0.65	$0.57	$6.39	$88.66	$96.26
Incr-Prog-I/M	$6.59	$5.93	$76.04	$96.96	$185.52	$0.59	$0.46	$5.54	$48.48	$55.07
Base-Coord-I/M	$6.83	$7.52	$91.07	$159.07	$264.49	$0.61	$0.58	$6.63	$79.54	$87.36
LP-Coord-AR	$4.32	$6.92	$72.94	$216.34	$300.52	$0.39	$0.53	$5.31	$108.17	$114.40
Step-Coord-AR	$6.80	$8.83	$93.98	$348.38	$458.00	$0.61	$0.68	$6.84	$174.19	$182.33
Red-Coord-AR	$4.06	$4.40	$45.26	$206.25	$259.96	$0.36	$0.34	$3.30	$103.13	$107.12
LP-Coord-I/M	$7.56	$10.01	$120.43	$238.76	$376.77	$0.68	$0.77	$8.77	$119.38	$129.60
Step- Coord-I/M	$10.09	$12.01	$138.49	$369.75	$530.35	$0.91	$0.92	$10.08	$184.88	$196.79
Red-Coord-I/M	$8.38	$9.04	$102.02	$230.39	$349.83	$0.75	$0.70	$7.43	$115.20	$124.07

Base case: Progressive signal timing, one-hour constant demand, and adjusted Riverside fleet mix
Costs include health and visibility costs. Health effects of PM, air toxics, SOX, and road dust are not included.

5.1.8 Summary and Conclusions

Several types of ECSs were modeled using MITNEM. It was observed that ECSs could be used to significantly reduce emissions on the Hornstull network. Among the strategies modeled, two were found to be the most effective. The first of these strategies, using a low peak demand profile, keeps the peak demand comparatively low to other demand profiles. The second strategy corresponds to replacing high-emitting vehicles with less emitting (Tier 1) vehicles, which can be implemented through I/M programs and new vehicle regulations. Numerical results indicate that both strategies could reduce emissions by about 20 to 30%. Peak spreading had the advantage of also reducing fuel consumption by a similar margin. It was found that these two strategies could be combined to obtain further improved benefits of 40 to 60% in emissions reductions and 40 to 43% reduction in fuel consumption.

An important result was that in most cases, an ECS affects different emissions species, fuel consumption, and VKT differently. Therefore the choice of the best ECSs for each city would depend on the regional air quality and emissions goals. For example, if a city is NOX limited (see Section 2.2.1), then it is crucial to not increase HC so that ozone is not formed. On the other hand, a different city may be exceeding CO levels; therefore this city would want to chose an ECS which reduces CO effectively.

The combined effectiveness ratio, CER, was introduced to compare the effectiveness of combination strategies to their component strategies. Some combinations of peak spreading and I/M programs were found to have high CERs. It was found that the Step-Coord-I/M strategy both reduces the emissions rate effectively and has a CER close to 1, therefore it is a good ECS candidate for the Hornstull network. The same conclusions are reached when the cost of all emissions is translated into health and visibility in dollar amounts. The best performing ECS in economic benefit was the Step-Coord-I/M combination strategy.

5.2 Modeling Intersection Emissions: Point source or line source?

The large range of modal activity that occurs around intersections makes them an appropriate focus for micro-scale emissions modeling. Frey et al (2000) found that "spikes and peaks in emissions occur during the acceleration from a full stop...with emissions rates much larger than during most of the rest of the trip." The wide range of modal activity that can be observed at signalized intersections make characterization of emissions using average-speed models not an adequate approach.

In many cities, higher emissions rates are typically found in corresponding lower income areas, compared to higher income areas. This is because neighborhoods which abut freeways or large arterials (typically lower income areas) carry the brunt of transportation externalities. This discrepancy is also a side effect of the common practice of diverting traffic to larger streets, and traffic calming lobbied by certain neighborhoods. Not only is the noise of traffic moved to these other streets, but the emissions are also displaced. The inability to model the emissions and consequently the air quality at the street level prevents regulations to be formulated and implemented to protect residents from exposures to high levels of CO, PM, and air toxins.

In this section, emissions on the Hornstull network are analyzed at a more spatially detailed level. The network is broken down into segments to identify those responsible for higher emissions. A few of these segments are then analyzed meter-by-meter to study the spatial variation of the emissions along the segments.

Background

As discussed in Section 5.1.2, several micro-simulators have been applied to analyze emissions at intersections. Most of the studies reported in the literature analyzed the emissions for an intersection as a whole. When the intersection is modeled spatially at a scale of meters, the spikes in emissions that occur due to the modal activity must be spatially accurate. Although MITNEM has not been validated for such detailed emissions analysis, the trajectories generated by MITSIM are consistent with average velocity and flow relationships. Until a validation at a disaggregate level can be performed, the results of this section should be viewed as preliminary. They can, however, be useful to gain general understanding of vehicle activity and emissions at intersections and the potential changes that can arise when there are changes in conditions or controls at intersections.

The current practice in air quality modeling represents roads as emission line sources, with emissions equally spread out along segments of roads. But intuitively, pollution should be concentrated at intersections or junctions. Two reasons for this are: a) there is generally a higher density of vehicles around intersections; and b) there are typically more accelerations and decelerations caused by discontinuities in traffic speeds (stop and go driving). Data gathered from instrumented vehicles have shown that the accelerations after a traffic light produce much more emissions than the idling and decelerations upstream of the traffic light (Frey et al., 2000). If emissions generation is equally distributed along road segments, the current modeling techniques would be correct, but if emissions are concentrated around intersections, then it may be more appropriate to model the intersections as point sources. This could lead to large differences in the results from air quality models. The question of whether to model an intersection as a point source or as part of a line source is particularly important for CO which can directly affect humans near the source of generation (within a few feet). This is in contrast with NOX and HC which go through a chemical reaction to form ozone. The assumption that on-road generated CO is distributed evenly along a segment can lead to significant under-estimation of the human exposure to CO around intersections.

Experimental Setup

For this section, the Hornstull intersection is defined as the segments that leads directly up to the intersection of the three arterials, segments 33, 43, 44, 45, 51, 53, and 58 (segment 43 is included to keep segment 44/43 the same length as segment 33). A few additional segments are also studied, segments 34, 42, 46, and 47. The Hornstull intersection including these additional segments will be referred to as the extended

Hornstull intersection. These segments lead up to and from other signalized intersections, providing more insight to the behavior of emissions around intersections.

The Hornstull intersection (see Figure 4.5) is well-suited for this study. It is a high flow intersection, with a large number of vehicles passing through it during the studied 7:30 AM - 8:30 AM period. Intersection conflict and speed rules in the simulation are well defined. The rules for the Hornstull intersection are as follows:

- Vehicles continue to adhere to car following rules inside intersections when driving straight,
- Turning vehicles check for gaps and pedestrians before making turns,
- Left turns are made at a "desired" speed of 32.3 kph (20mph), and
- Right turns are made at a "desired" speed of 16.1 kph (10mph).

The data generated from a few of the simulations of signal timing ECSs described in Section 5.1 (Base-Prog-AR, Base-AG-AR, Base-Coord-AR, and Base-Coord-I/M) are analyzed in more detail in this section. First, the Hornstull network is studied at the segment level. The emissions generated around the network for the progressive, all green, and coordinated signal settings are plotted by segment on a map of the Hornstull network. This shows how the different signal timings affect the emissions on different parts of the network, especially around the Hornstull intersection. Next, the area around several intersections, including the Hornstull intersection is studied at the scale of a meter. The results are plotted on a map of the area around the Hornstull intersection. Finally, three segments are chosen for study at a finer spatial detail and an analysis of the emissions in the Hornstull intersection is performed.

The meter-by-meter distribution of emissions described in this section is generated by assigning the emissions to the position each vehicle was sighted at the beginning of each second. Because the time resolution of the emissions model is one second, the emissions per second modeled by CMEM is assigned to the location at which MITSIM reports this vehicle's position for that second, x(t), as shown in the bottom of Figure 5.16. In reality, emissions are generated and distributed on the space interval [x(t), x(t+1)].[4] Most likely, the emissions would not be evenly distributed between the x(t) and x(t+1). The number of vehicles sighted at each one-meter-long portion of road over one hour is relatively large (greater than 100). Therefore, although the emissions calculation is not allotted appropriately for a single vehicle, theses errors cancel out when one considers the total emissions that takes place over one hour at a given one-meter-long subpart of a segment.

In summary, the assumptions we make for the meter-by-meter emissions analysis are:

- The emissions (g/s) reported by CMEM are the total emissions generated by the vehicle over the next one second.
- There are a large enough number of vehicles sighted at every position (every meter) of the network. Hence, possible errors resulting from assigning all the emissions during one second to the position the vehicle is sighted at a time *t*, will practically even out in computing the emissions of all vehicles.

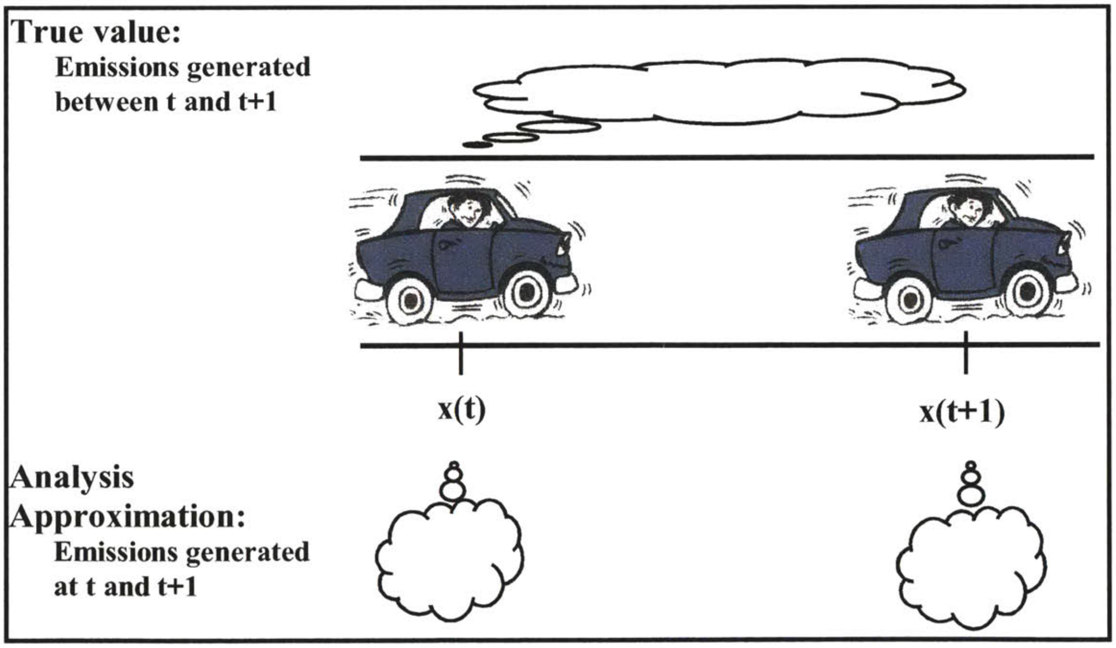


Figure 5.16: Meter-by-meter emissions representation

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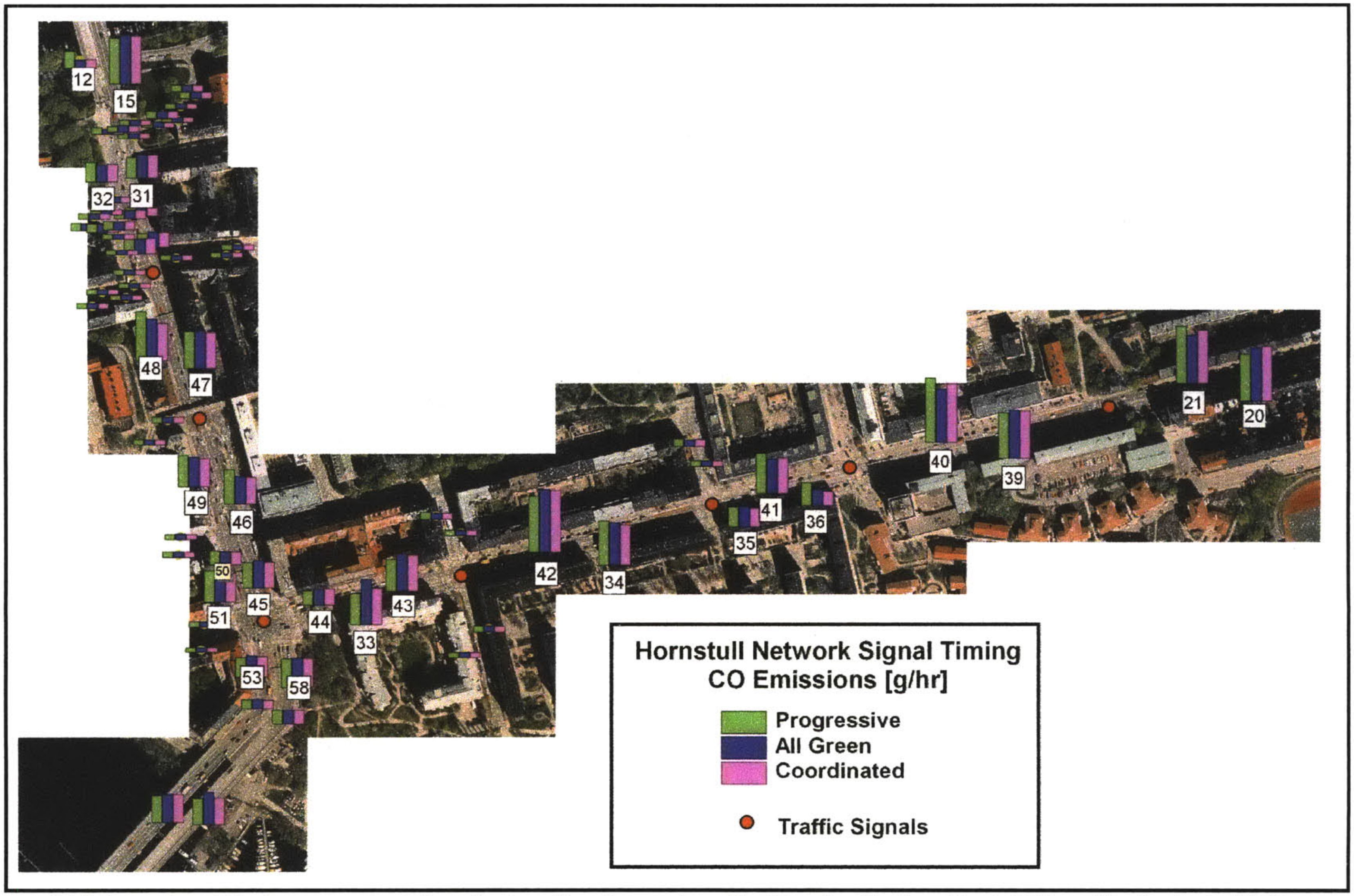
[4] The path of the vehicle is not kept track of directly in MITNEM, therefore it would be difficult to assign the emissions appropriately when vehicles cross segments and change lanes.

Experimental Study Results

Figure 5.17 shows the CO emissions on each of the segments on the Hornstull network. The three bars show the emissions generated from the three signal timing scenarios described in Section 5.1.2. The figure indicates the spatial distribution of emissions for the different signal timings. Although it was shown that the Base-AG-AR and the Base-Coord-AR signal timings generate approximately the same total amount of emissions, the figure indicates that the emissions from these two signal timings can be significantly different at the segment level. The all-green signal timing generates much more emissions around the Hornstull intersection, while the coordinated signal timing generates about the same amount of emissions around the intersection as the progressive signal timing. It is important, when minimizing total network emissions, that CO emissions spikes are not created.

Table 5-9 summarizes the emissions contribution of each segment in the extended Hornstull Intersection. The results from MITNEM indicate that the Hornstull intersection generates approximately 20% of the emissions on the Hornstull network even though it consists of only about 10% of the roadway surface. The extended Hornstull intersection is responsible for approximately a third of the emissions on the entire network even though it consists of only about 23% of the roadway surface.



*All three signal timings were tested on the baseline demand profile (Base) with the adjusted Riverside fleet mix (AR)

Figure 5.17: Spatial distribution by segments of CO generated during one hour corresponding to three signal timings

Table 5-9: CO Emissions per one hour around the Hornstull intersection

	Segment Properties		Emissions Control Strategies [g/hr]			
	Segment Number	Segment Length [m]	Base-Prog-AR	Base-AG-I/M	Base-Coord-AR	Base-Coord-I/M
Hornstull Intersection	51	47.97	5,726.5	5,889.5	5,236.9	4392.1
	45	73.56	4,315.2	4,706.1	4,406.8	3481.1
	53	48.29	3,126.5	3,502.5	3,319.5	2763.6
	58	48.33	5,029.1	5,191.2	5,131.5	3947.0
	44	29.61	2,329.3	2,653.1	2,794.5	2078.2
	43	125.29	5,612.4	6,793.9	6,453.6	4780.2
	33	154.78	5,769.7	8,775.5	6,924.7	5463.8
Additional Segments included in the Extended Hornstull Intersection	42	211.39	10,468.2	11,845.6	11,681.6	9060.2
	34	211.24	8,158.2	7,790.9	7,338.5	5965.3
	49	89.55	5,567.5	5,174.7	4,845.6	3796.6
	46	91.93	6,099.6	4,666.7	4,496.9	3311.2
Hornstull Intersection Only CO Subtotal VKT Subtotal		527.83	31,908.7 888.3	37,511.6 952.6	34,267.4 952.9	26906.0 952.9
Extended Hornstull Intersection CO Subtotal VKT Subtotal		1,131.94	62,202.2 1870.7	66,989.5 2015.8	62,630.0 2017.4	49,039.3 2017.4
Network CO Total VKT Total		4,990.34	175,838.4 5970.5	175,075.8 6384.2	169,094.1 6386.8	135,428.2 6386.8
Hornstull Intersection Only CO % of Network Total		10.6%	18.1%	21.4%	20.3%	19.9%
Extended Hornstull Intersection CO % of Network Total		22.7%	35.4%	38.3%	37.0%	36.2%

It was shown in Section 5.1.2, that the all-green and coordinated signals improved the emissions per vkt on the entire network. But the subtotals shown in Table 5-9 for both the "Hornstull Intersection Only" and the "Extended Hornstull Intersection," indicate that the signals do not reduce the total CO emissions in the vicinity of the intersection. The CO emissions in the Hornstull intersection corresponding to Base-AG-AR and Base-Coord-AR, actually increase during one hour. The lower CO emissions intensity [grams of CO per vkt] observed in Section 5.1.2 results from an increase in VKT. To achieve lower emissions around the intersection, an additional ECS would be needed. The Base-Coord-I/M ECS serves an equal amount of VKT in an hour while reducing total emissions. Table 5-9 shows that Base-Coord-I/M can reduce emissions by 16% and 28% compared to the baseline, Base-Prog-AR, in the Hornstull intersection and the extended Hornstull intersection, respectively.

Figure 5.18 through Figure 5.21 respectively depict the meter-by-meter emissions around the extended Hornstull intersection for the following ECSs: Base-Prog-AR, Base-AG-AR, Base-Coord-AR, and Base-Coord-I/M. For all signal timings scenarios, the highest peaks (greater than 120 grams of CO per hr) are seen around the intersections. The CO emissions distribution around the intersection for the three signal timings is different. Of the three ECSs, Base-Prog-AR has the highest CO emissions where segments 58 and 33 intersect, while it has the lowest emissions along segment 46. The Base-AG-AR ECS has high CO emissions where segments 33, 34, 43 and 42 intersect, while it has significantly lower emissions where segments 46,47, 48, and 49 intersect. Additionally, Base-AG-AR minimizes the CO emissions along segment 48. Base-Coord-AR has the lowest CO emissions along segment 33 and high emissions along segment 46. But a general decrease of emissions around all five intersections is only achieved in Base-Coord-I/M.

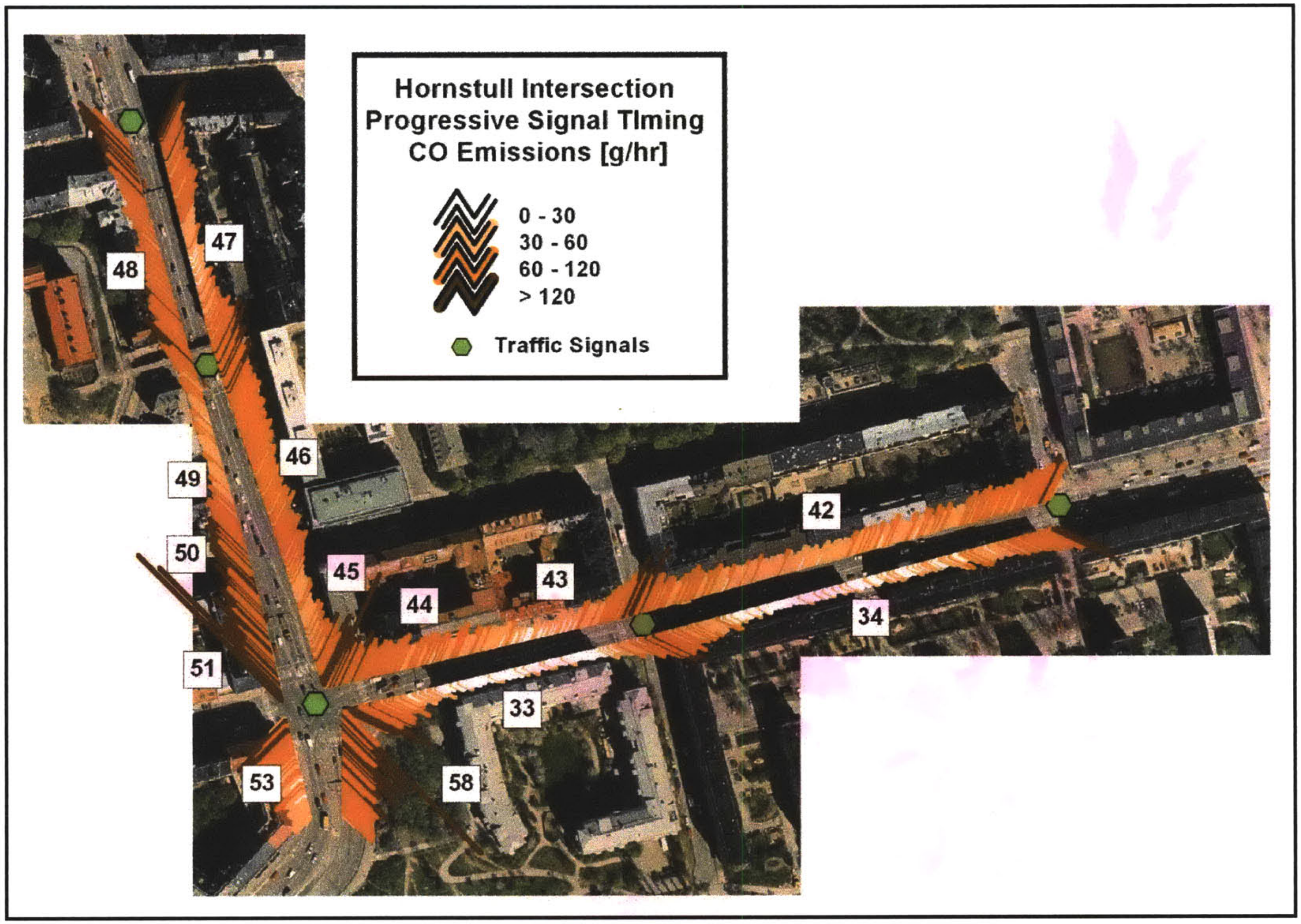


Figure 5.18: Spatial distribution of CO generated during one hour corresponding to the Base-Prog-AR emissions control strategy

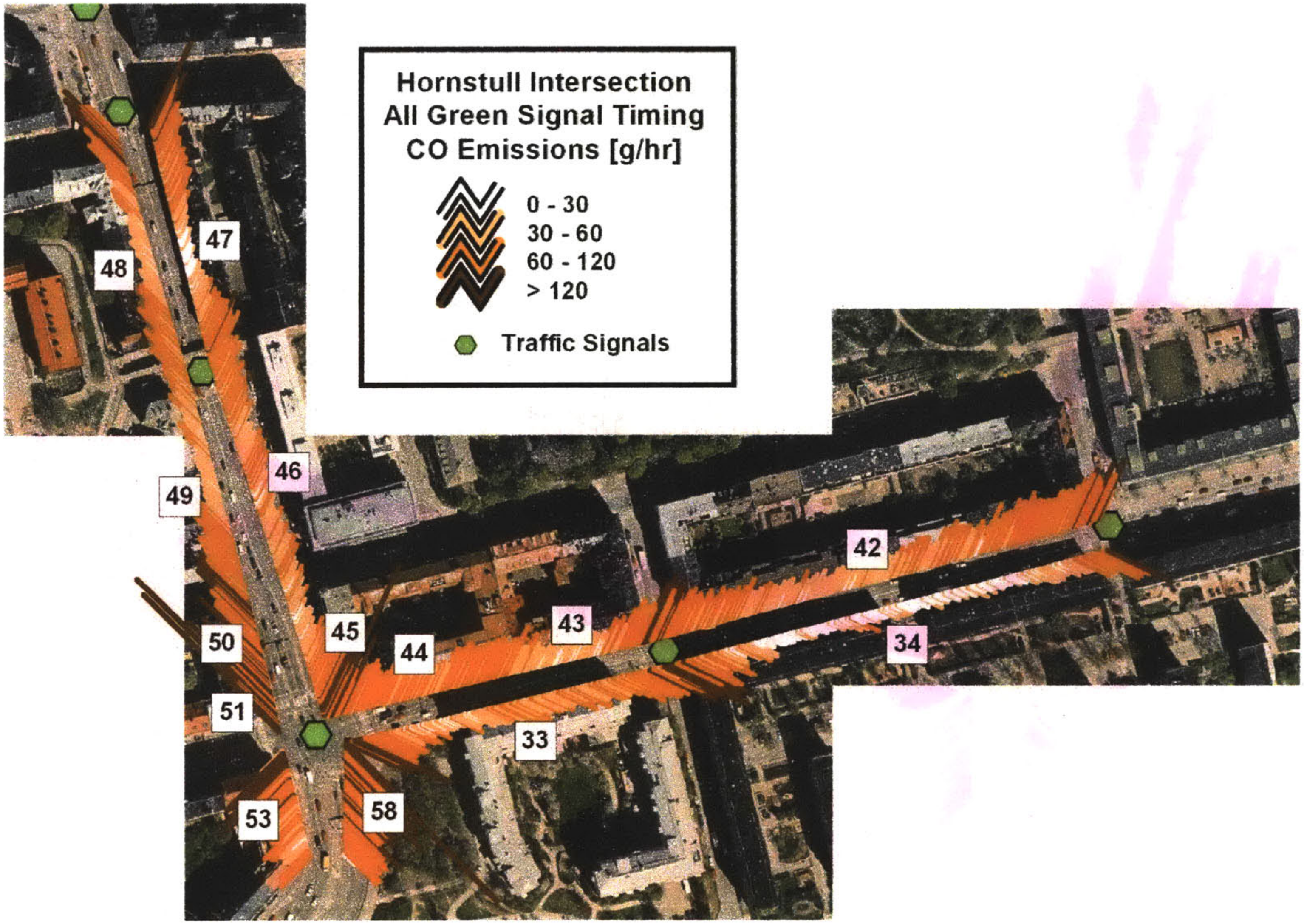


Figure 5.19: Spatial distribution of CO generated during one hour corresponding to the Base-AG-AR emissions control strategy

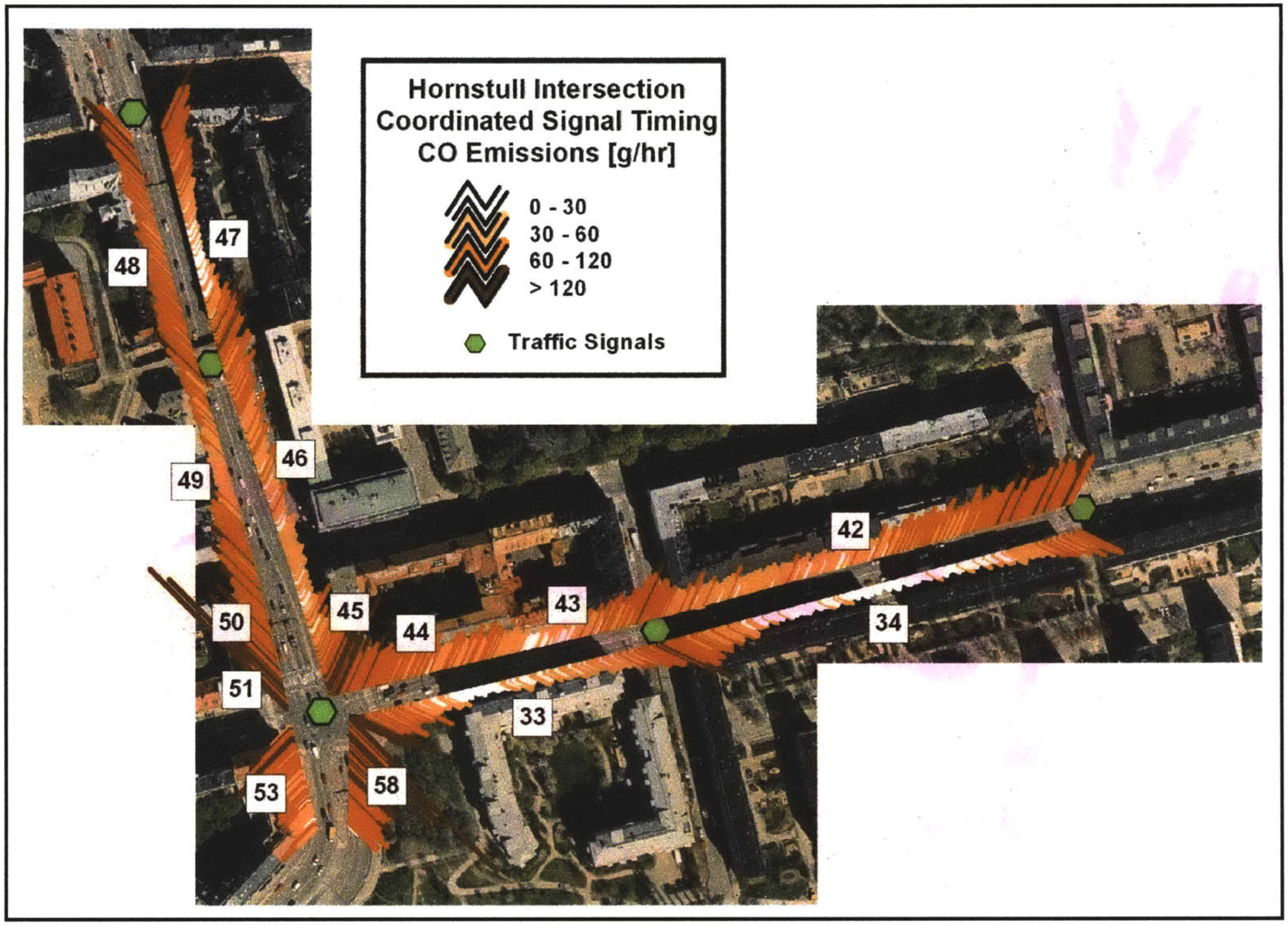


Figure 5.20: Spatial distribution of CO generated during one hour corresponding to the Base-Coord-AR emissions control strategy

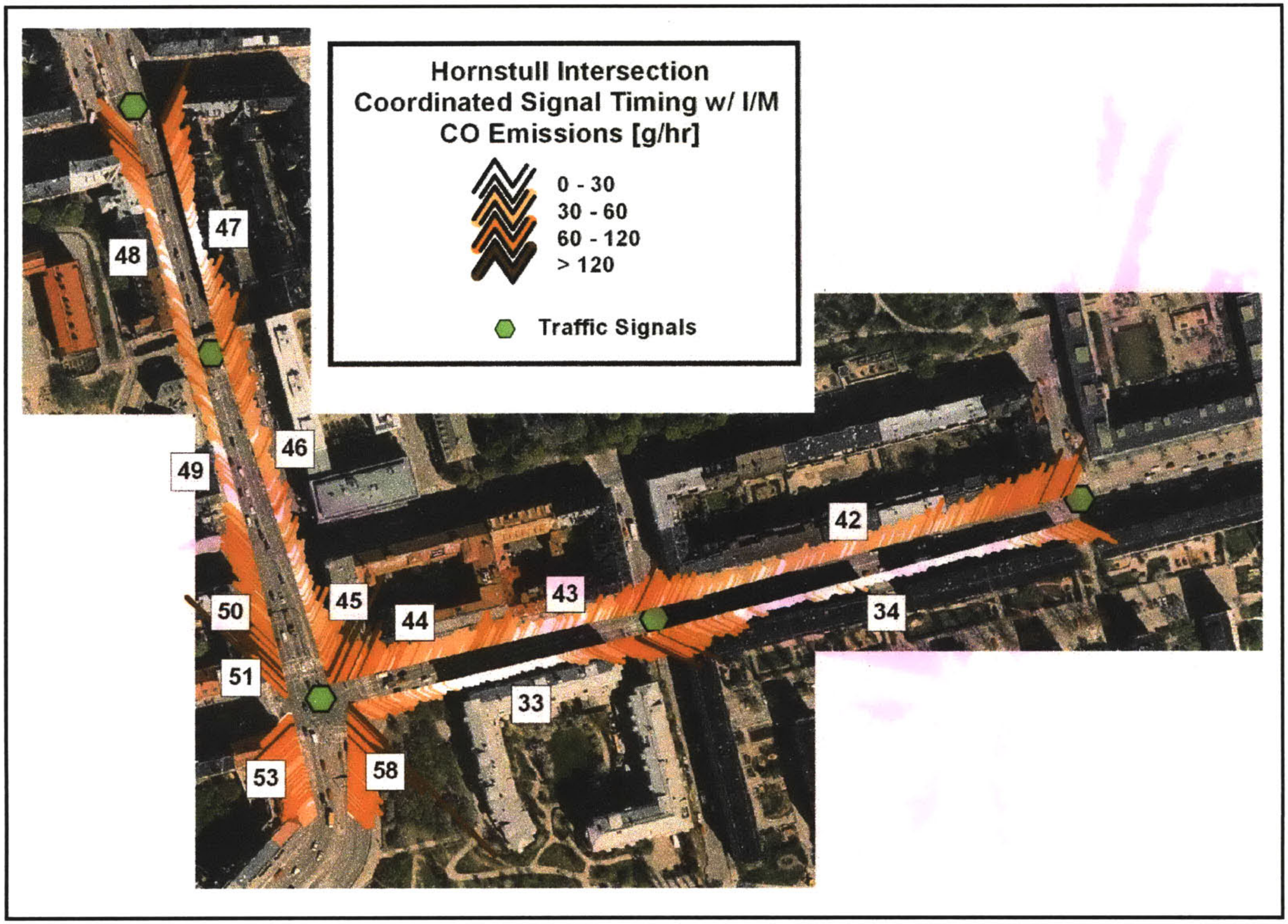


Figure 5.21: Spatial distribution of CO generated during one hour corresponding to the Base-Coord-I/M emissions control strategy

Figure 5.22 and Figure 5.23 depict the spatial variation of HC, NOX, and CO emission rates and fuel consumption rate along segment 33, and the geographical area covered by segments 45 and 46 (denoted 45/46), near the Hornstull intersection. Traffic on both segments 33 and 45/46 follow one direction, away from the Hornstull intersection and ending at stoplights. Traffic flows from the beginning of segment 45 (node 5 in Figure 4.6) and most of the traffic continues on through node 4, to segment 46 and towards node 3. In the charts, position 0 indicates the end of a segment (e.g. for segment 46, position 0 is at node 3).

The emissions are higher towards the ends of the segments, due to vehicles accelerating away from the intersection on the left side of the graph, and a higher traffic density would be observed due to vehicles stopped by the traffic light on the rights side of the graph. As shown in Figure 5.17, the all-green signal timing (Base-AG-AR) produces the highest emissions on segment 33, while the progressive signal timing (Base-Prog-AR) produces the highest emissions on segments 45/46.

The effect of cleaner vehicle fleet mixes can be seen by comparing Base-Coord-AR with Base-Coord-I/M. The U-shaped behavior of the CO emissions of the Base-Coord-AR is more exaggerated at the ends than Base-Coord-I/M in Figure 5.22 and Figure 5.23. This might be due to lower efficiency of the engine during vehicle accelerations and also during idling of the high-emitters as compared to the Tier I vehicles. Tier I vehicles operate more efficiently because they operate for more time at or nearer to stoichometry.

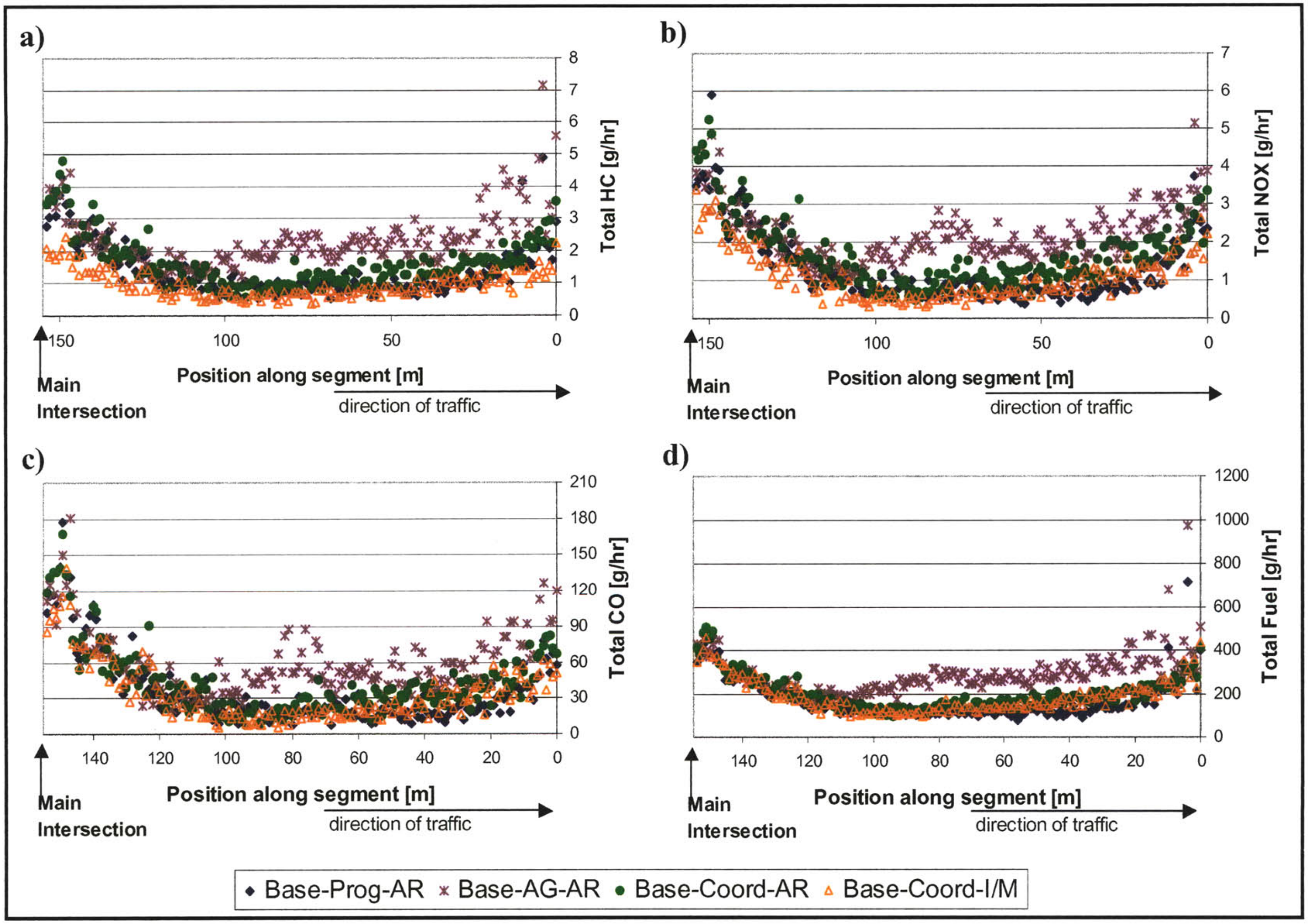
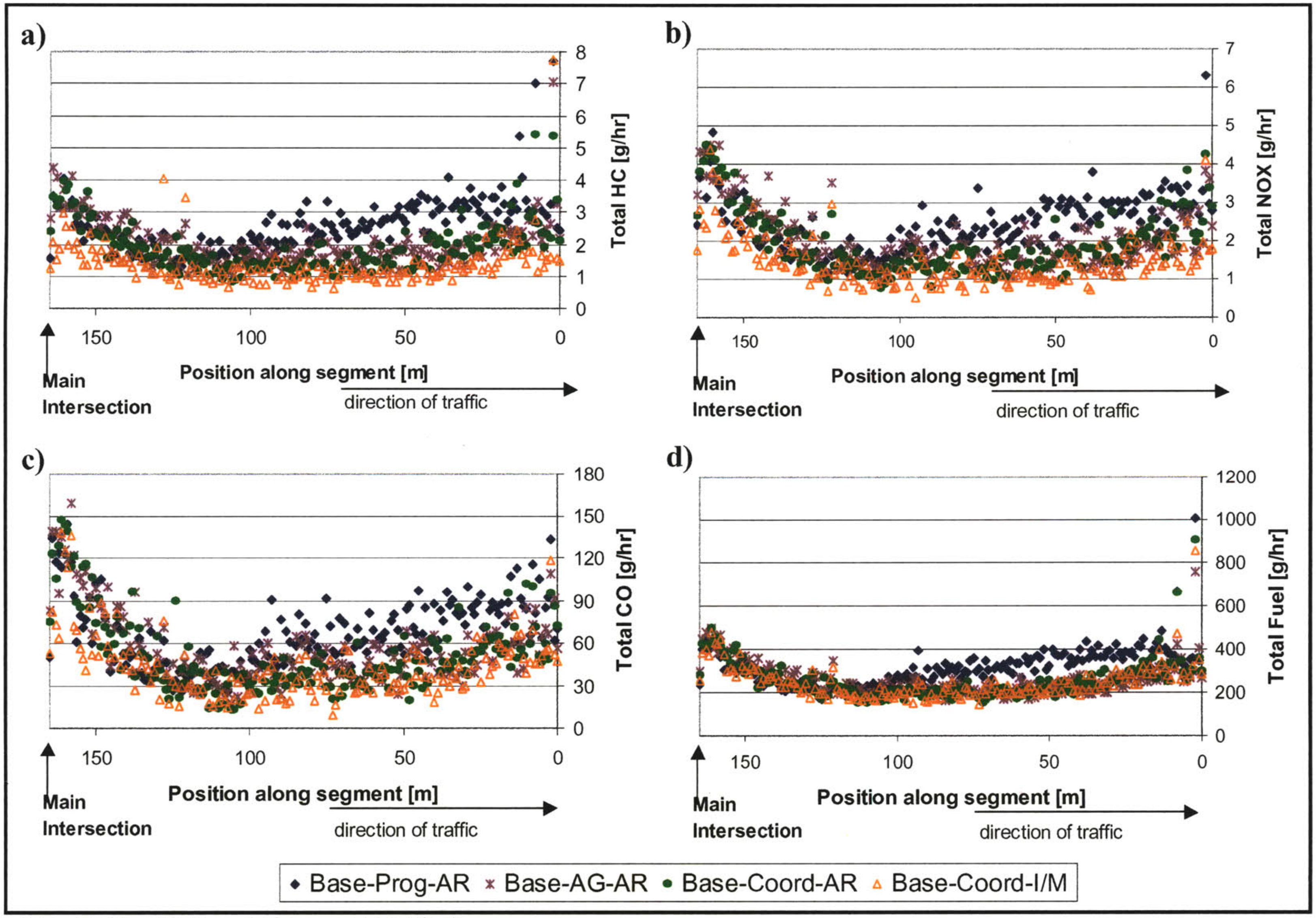


Figure 5.22: Total emissions (in g/hr) on segment 33 over the one-hour simulation period: a) HC, b) NOX, c) CO, d) Fuel



Note: Position 0 is the end of segment 46 (node 3).

Figure 5.23: Total Emissions (in g/hr) on segments 46 and 45 over the one hour simulation period: a) HC, b) NOX, c) CO, d) Fuel

Each emission species shows distinct behaviors. Table 5-10 summarizes the ratio of the minimum and maximum emissions on each segment for Base-Prog-AR, Base-Coord-AR, and Base-Coord-I/M strategies. Whereas NOX and fuel consumption is approximately 6-8 times higher near the intersections on segments 45/46 than in the middle of the segment, CO and HC can be 6-15 times higher near the intersections than in the middle of the segment. On segment 33, CO immediately around the intersection is up to 23-28 times higher than in the middle of the intersection. The fuel consumption for the Riverside fleet mix and the I/M fleet mix are very similar, indicating that the emissions improvement can be obtained if one fixes improperly functioning vehicles or improves emissions control technology in newer vehicles, even fuel efficiency of newer vehicles is not increased.

Table 5-10: Ranges of emissions rates along segments 45/46 and 33

		Segment 45/46				**Segment 33**			
		HC	**CO**	**NOX**	**Fuel**	**HC**	**CO**	**NOX**	**Fuel**
Base-Prog-AR	Minimum Value of Emissions Rate [g/hr]	1.29	25.91	1.07	168.0	0.52	7.61	0.38	77.5
	Maximum Value of Emissions Rate [g/hr]	7.70	144.21	6.31	1004.6	4.89	177.20	5.89	719.2
	(Max. Value)/ (Min. Value)	**6.0**	**5.6**	**5.9**	**6.0**	**9.4**	**23.3**	**15.3**	**9.3**
Base-Coord-AR	Minimum Value of Emissions Rate [g/hr]	0.84	12.81	0.77	150.9	0.55	7.35	0.47	96.5
	Maximum Value of Emissions Rate [g/hr]	5.41	146.93	4.48	904.6	4.78	167.25	5.22	508.8
	(Max. Value)/ (Min. Value)	**6.5**	**11.5**	**5.8**	**6.0**	**8.7**	**22.8**	**11.2**	**5.3**
Base-Coord-I/M	Minimum Value of Emissions Rate [g/hr]	0.61	9.03	0.52	146.0	0.37	5.06	0.29	96.8
	Maximum Value of Emissions Rate [g/hr]	7.75	137.44	4.39	853.5	2.43	140.10	3.37	461.3
	(Max. Value)/ (Min. Value)	**12.8**	**15.2**	**8.4**	**5.8**	**6.6**	**27.7**	**11.5**	**4.8**

Further analysis of the main intersection is conducted as a function of the distance from the center of the Hornstull intersection for each of its constituting segments using 10-meter interval sizes. Figure 5.24 shows the results of this analysis. Segments exhibit similar trends. The emissions generated per 10 meters decrease as a function of the distance from the center of the Hornstull intersection.

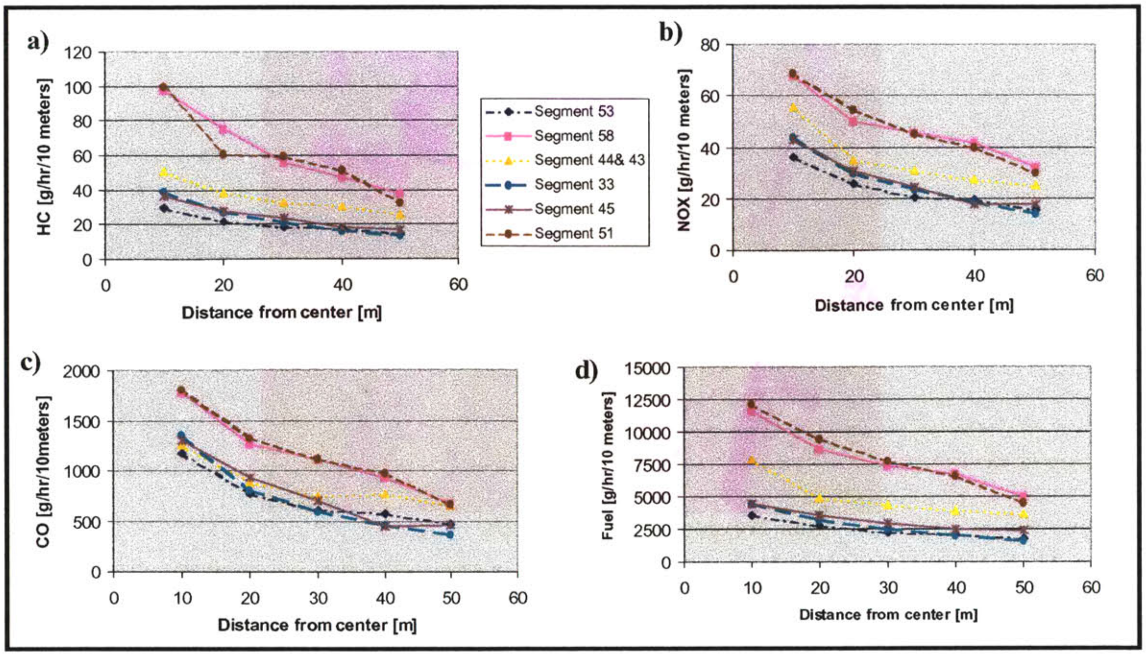
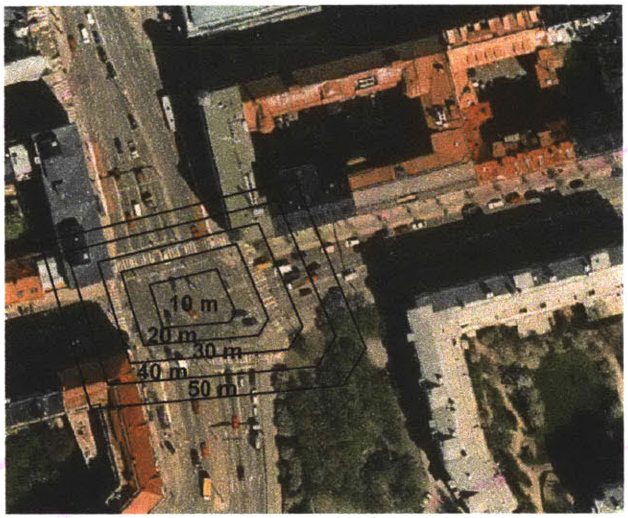


Figure 5.24: Emissions and fuel consumption of segments at different distances from the center of the Hornstull intersection for Base-Coord-AR: a) HC, b) NOX, c) CO, d) Fuel Consumption

The emissions on the segments leading into the intersection are summed by distance from the center of the intersection. Using a ten-meter spatial interval for summing the emissions, ten-meter wide rings are formed around the center of the intersection. Figure 5.25 depicts a graphical representation of these 10-meter rings. The first 10-meter ring forms a 10-meter polygon in the center of the intersection, in which all the emissions of a given species, inside the area is summed. The second 10-meter ring includes all the emissions of a given species between 10 meters and 20 meters from the intersection, and so forth.

The first 10-meter ring generates 2.6 times more CO emissions than a 10-meter ring 40 meters away. Segments follow a similar trend. The amount of emissions generated in each ring decreases as a function of the distance from the center of the intersection. Other pollutants generated 2.3 to 2.5 times more emissions in the first 10 meters. Figure 5.26 shows the total emissions generated in each 10-meter strip as a function of the distance from the center of the intersection.



Note: Polygons not drawn to size

Figure 5.25: Distance from center of Hornstull intersection

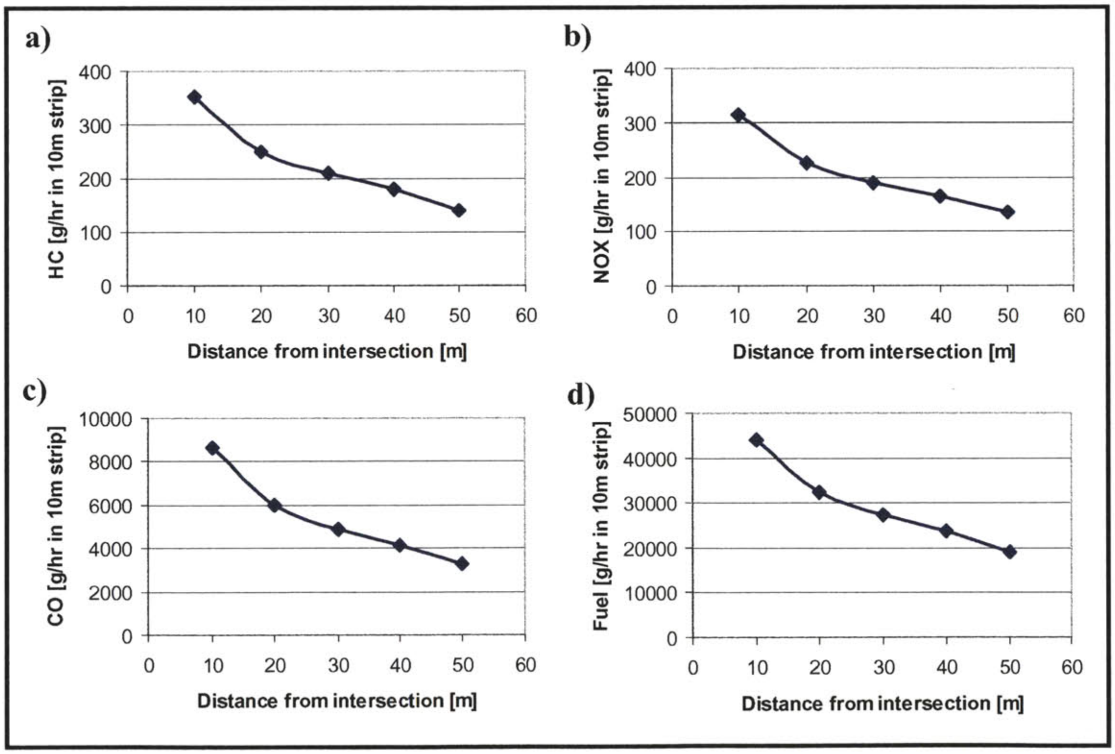


Figure 5.26: Emission and fuel consumption at different distances in the Hornstull intersection Base-Coord-AR: a) HC, b) NOX, c) CO, d) Fuel consumption

Figure 5.27 depicts the emissions and fuel consumption for both Base-Coord-AR and Base-Coord-I/M. The addition of I/M and clean technologies reduces the emissions around the network. The emissions are reduced uniformly in the intersection.

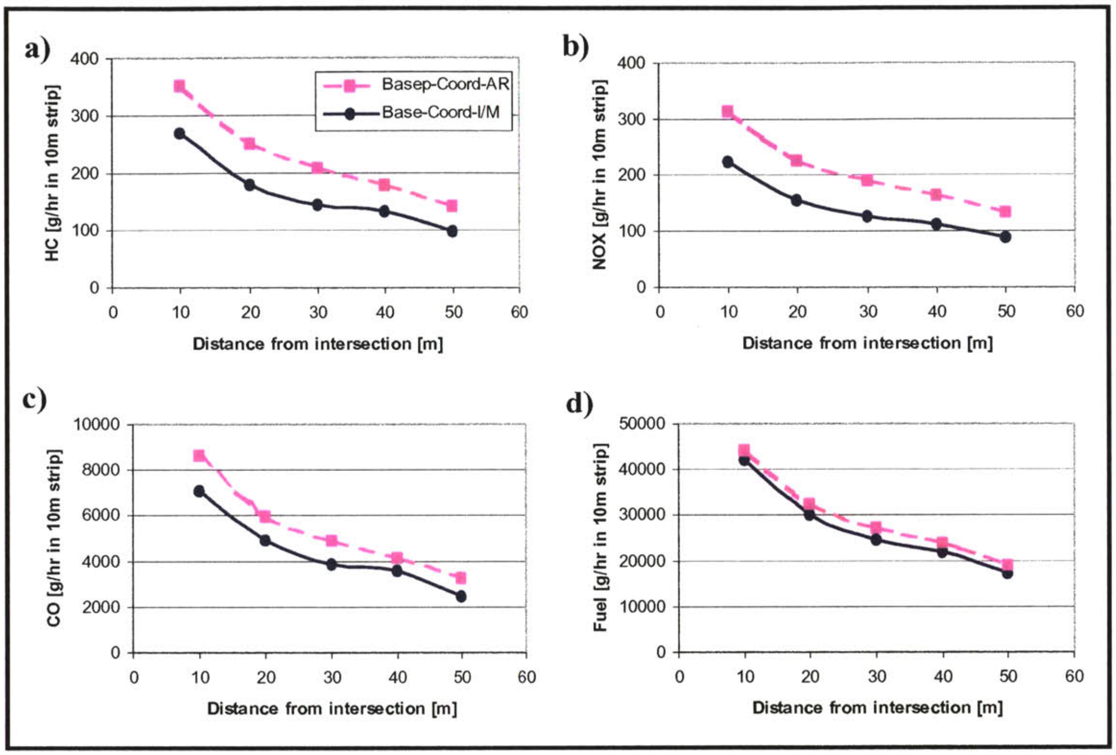


Figure 5.27: Comparison of emissions and fuel consumption at different distances in Hornstull intersection for Base-Coord-AR and Base-Coord-I/M: a) HC, b) NOX, c) CO, d) Fuel consumption

The phenomenon of higher emissions near intersections might result in higher pollutant concentrations near intersections. The resulting concentrations would depend on the weather conditions, background pollutant concentrations, and other factors. Higher CO concentrations result in higher human exposure to CO. The pedestrians who pass through the intersection and the people who spend prolonged time periods such as residents and workers at businesses located in the intersections would be affected more than others. Hence, pedestrians who pass through intersections have short exposures to higher CO concentration levels, whereas individuals working in areas near major intersections for prolonged hours would have a higher exposure. Over multiple days, the overall exposure may lead to negative health consequences.

1.1.1 Conclusion

While total CO emissions on the network were reduced by 23% using the all-green or the coordinated signal timings when compared to the progressive signal timing, emissions on individual segments were reduced by an average of 20%, and spot emissions were reduced on average by 19%. In general, larger improvements were observed where emissions were higher.

Table 5-11: Coordinated I/M improvement over base case

	Emission Improvement of Base-Coord-I/M over Base-Prog-AR
Network VKT	7%
Intersection VKT	7%
Total mass of CO on Network	23%
Total mass of CO in Hornstull Intersection	16%
Total mass of CO in Extended Hornstull Intersection	21%
Total mass of CO on an intersection segment	Range: 5-46% Average: 20%
Spot CO mass within 20 meters of center of intersection (using 10 meter resolution)	Range: 5-39% Average: 19%

The NAAQS regulation for CO is 9 parts per million (ppm) over an 8-hour average, and 35 ppm over an hour average. This means that over any 8 consecutive hours of the day, the average CO concentration may not exceed 9 ppm. Additionally, over any one hour of the day, the average CO concentration may not exceed 35 parts per million (see Appendix E). These levels are typically monitored at selected locations around a city. In the year 2000, the average Boston metropolitan area CO concentration was 8 ppm (over any 8-hour period) (US EPA, 2001). The results obtained using MITNEM indicate that air quality readings may be sensitive to the placement of the monitoring stations. One would then recommend that monitoring stations be located as close as possible to major intersections to truly compare the carbon monoxide levels to the maximum levels given in NAAQS regulations.

Chapter 6

Conclusions and Future Research

In this chapter, we summarize the results of this thesis. Ideas for future work and research, of questions which were raised during the work on this thesis, but were not addressed, are also presented.

6.1 Summary of Results

A framework for the design of a microscopic traffic network emissions model was presented and used to develop an actual network emissions model called MITNEM. MITNEM uses two sub-models, MITSIMLab, a microscopic traffic simulator, and CMEM, a load-based emissions model. MITSIM provides vehicle trajectories and CMEM estimates the corresponding vehicle emissions. MITNEM serves as a simulation laboratory for studying congestions and emissions. Tools for data processing and analysis were developed for spatial and temporal analysis. The model gave reasonable results on three networks of varying sizes and complexity. The sensitivity of the model output to stochasticity and temporal and spatial averaging intervals was tested using a small network. Additionally, the emissions inventory on a medium-sized urban arterial is modeled.

MITNEM was applied to two experimental studies. The first set of experiments assesses the effectiveness of different emissions control strategies (ECSs) to reduce emissions on a small-size urban network (the Hornstull network). Four strategies were modeled: vehicle technology and fleet improvement through a hypothetical Inspection/Maintenance (I/M) program, signal timing selection, management of traffic demand through peak spreading, and marginal changes in traffic demand levels. Combinations of these individual strategies were also modeled. The effectiveness of the strategies for reducing emissions were found to not be additive. Overall, it was found that the more effective strategies for emissions control for the Hornstull were managing traffic demand through peak spreading and the implementation of an I/M program. It was also found that different strategies affected emission species differently. Therefore, the choice of the most effective ECS for a given city may depend on the air quality objectives of the city rather than the overall performance of ECSs for all emission species.

In the second experiment, the spatial distribution of emissions was studied around an intersection. It was found that the emissions in the center of the intersection are two to three times higher than the emissions elsewhere. It was found that the traffic signal timings modeled did not change the amount of emissions being released in the intersection. As expected, the I/M program reduces the emissions in the intersection in addition to other parts of the network.

6.2 Future work

During the writing of this thesis, various issues related to the topics addressed were noted for future research. Some of these issues may be relatively straightforward to address, such as the modeling of cold starts and the effect of road grade. Other questions may involve more efforts. A first example of this concerns the addition of an air quality model to MITNEM. A second example concerns the calibration and validation of traffic and emissions models of MITNEM using real-world data. This section documents these issues for future work and research.

Modeling of Cold Start

If the vehicle is cold when driven, the HC and CO emissions are much higher than when the engine is warm. NOX can also increase if the engine is operating cold instead of warm. This can affect the geographical distribution of emissions on the network. For example, freeways should have a smaller proportion of vehicles operating cold than in an urban area. CMEM takes the vehicle temperature into consideration. One needs to estimate the fraction of vehicles operating in cold start and determine the engine temperature of these vehicles based on values of appropriate variables (i.e. current travel duration and fuel consumed) since the departure of these vehicles from their origin.

Modeling of Road Grades

Studies have shown that grade can increase emissions by a factor of two on ramps (Cicero-Fernandez and Long, 1996). Grades also affect the maximum acceleration of vehicles and consequently the traffic conditions on a network. The networks coded into MITSIM did not include grade information, though it can be introduced rather easily. Since no grade information is provided, no grade was entered into CMEM either.

Detailed Modeling of Vehicle Acceleration

Currently the only vehicle types available in MITSIM are new cars, old cars, buses, trucks, and trailer trucks. The description of the acceleration capabilities of the vehicles is only available at a few speeds. Because acceleration significantly affects emissions, the acceleration capabilities should be more detailed. A few studies (Abou Zeid et al., 2002 and Kleeman, 1998) have been conducted using acceleration data obtained from real-world driving.

Freight and Heavy Duty Vehicles

Freight accounts for a large percentage of the criteria pollutants in the United States. Heavy-duty vehicles (HDVs) affect both traffic conditions and emissions. Currently, MITSIM model HDVs, but no emissions model exists in CMEM. A separate HDV emissions model could be applied to the trajectories of HDVs generated by MITSIM.

Air Quality Modeling

Dispersion models could be applied to the emissions rates obtained from MITNEM. This would allow for the regional/local meteorological conditions and other air dispersion factors such as the wind created by moving vehicles, to be modeled.

PM

PM has become recognized as extremely hazardous to health. It is one of the criteria pollutants regulated by CAAA. According to the health costs estimated by McCubbin and Delucchi (1999), PM represents approximately 90% of health costs in many cities. Models are being developed to estimate PM, though its chemistry may not be as well understood as the chemistry of CO, NOX, and HC. Its behavior is somewhat different from the other pollutants and should be considered in parallel to better understand the conditions under which pollutants are generated.

Updated Vehicle Categories and Fleet Mixes

The CMEM vehicle categories correspond to an older vehicle fleet. Since it was developed in 1999, older vehicles have been retired and replaced by vehicles which have more advanced emissions control technologies. These include Tier II vehicles. Emission models need to be updated to accurately reflect new vehicle types in the fleet.

MITSIM Validation and Calibration for Emissions Purposes

Validation studies of microscopic traffic models have not been done at the level of trajectories (particularly acceleration) of vehicles. Such validation is important for emissions modeling due to the important role speed and acceleration combinations play in determining emissions.

Glossary

A/C – Air Conditioning
CAAA – California Air Act Amendment
CA/T – Central Artery Tunnel
CMEM – Comprehensive Modal Emission Model (designed by U.C. Riverside)
CO – Carbon Monoxide
ECS – Emissions Control Strategy
EPA – Environmental Protection Agency
FTP – Federal Testing Procedure
HC – Hydrocarbons
HDV – Heavy-Duty Vehicle
HERS – Highway Economic Requirements System software (FHWA)
I/M – Inspection/Maintenance
ITS – Intelligent Transportation Systems
LDV – Light-Duty Vehicle
LOS – Level-of-Service
MITSIM – MIcroscopic Traffic SIMulator
NOX – Nitrogen Oxides
PM – Particulate Matter (PM10 = Particulate matter less than 10 microns, PM2.5 = Particulate matter less than 2.5 microns)
TCM – Traffic Control Management
VKT (vkt) – vehicle kilometers traveled (vehicle miles traveled)

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Appendix A – MITNEM File Descriptions

The following table lists all of the files used in MITNEM, (excluding the files used in MITSIMLab). The name of the file or the extension of the file is listed in the first column. The file type (data file, C++ code, and executable file) is listed in the second column. The files required for running, the output files, and the executable which generated file are listed in the third column. And a description of the file, with any special instructions, is listed in the fourth column.

Table A-1: Summary of MITNEM Files (Listed in order of use)

Name of file/file extension	**File type**	**Associated files**	**Description**
***.out**	Data file	Required for running (prep)	This file is the MITSIM output trajectory file.
iMITSIM.C **prep** **Variations:** **IMiMITSIM.C** **cleaniMITSIM.C** **dirtyiMITSIM.C**	C++ code Executable file	Required input files: *.out *fleetmix.dat Output files: *-traj *-def *-atb Required for compiling: trajdata.h	Prepares the MITSIM trajectory file for cmemBatch processing. The variations map the MITSIM vehicle types to CMEM vehicle categories. prep takes 3 arguments: 1: *.out filename without ".out" extension 2: number of minutes to remove from beginning (beginning from the first second of the simulation) 3: number of minutes to remove from end (the end being the last second of the simulation) e.g. prep sample1 0 0

Name of file/file extension	**File type**	**Associated files**	**Description**
***fleetmix.dat**	Data file	Required by: prep	**Vehicle category fleet mix file** This file defines the mapping of the MITSIM vehicle types to the CMEM emissions vehicle categories. One MITSIM vehicle type can be split into multiple CMEM emissions vehicle categories. The proportion in which to split the vehicles is specified here.
***-def file**	Data file	Generated by: prep Required for running CMEM (cmemBatch)	**Vehicle definition file** This file has a unique entry for each vehicle that enters the network. A CMEM vehicle category is assigned (through a mapping) to the vehicle with default category characteristics and soak times.
***-atb file**	Data file	Generated by: prep Required for CMEM (cmemBatch)	**Vehicle activity file** This file is a reformatted trajectory file, it is a list of the vehicle speeds and acceleration for every vehicle on the network for each second of the run.
*-traj file	Data file	Generated by: prep Required for post-processing (postp)	**Vehicle trajectory file** This file is an interim file created from the *.out file. It converts the MITSIM units into CMEM units and is used later for post-processing.
*-ctb file	Data file	Generated by: User Required for CMEM (cmemBatch)	**Batch control file** The user needs to make a ctb file to accompany each set of -atb and -def file for CMEM. This file specifies the input and output units (English or metric) of the files and whether CO2 should be an output. The format is specified in the CMEM User Manual (Barth et al., 1999). Note: The author found that CMEM does not take every combination of input/outputs. It takes only metric as input and all outputs are in English.

Name of file/file extension	File type	Associated files	Description
cmemBatch	Executable file	Required input files: *-atb *-def *-ctb Output files: *-ssb *-smb	This is the emissions calculation module. It takes the vehicle trajectories, vehicle types, and the control file and calculates the emissions generated by each second by each vehicle. (See the CMEM User Manual for more detailed information.)
***-ssb**	Data file	Generated by cmemBatch	This file contains the second-by-second emissions generated by each vehicle as calculated by CMEM. (See the CMEM User Manual for more detailed information.)
***-smb**	Data file	Generated by cmemBatch	This file contains summary information about each vehicle from the CMEM calculations. (See the CMEM User Manual for more detailed information.)
post_match.C **postp**	C++ code Executable file	Required input files: *-traj *-ssb Output files: *-matched Required for compiling: trajdata.h ssbdata.h vehdata.h	**Post-processing file** This file takes the original MITSIM trajectory file and CMEM emissions output file and matches each second-by-second emissions value to each second-by-second trajectory (speed and acceleration) entry to make one all-inclusive matched second-by-second file. postp takes one argument: 1: *.out filename without the ".out" extension e.g. postp sample

Name of file/file extension	**File type**	**Associated files**	**Description**
***-matched**	Data file	Generated by postp	This file contains speed and acceleration values that are matched up with the emissions values for each entry.
mksumnet.C **sumnet**	C++ code Executable file	Required input file: *-matched Output file: *-matchednett OR *-matchednets	This file calculates the total emissions on the network either over time or by segment.
mkseglengths.C	C++ code Executable file	Required input file: *.out	This file makes the seglength file for any network from a *.out file which is long enough so that at least one vehicle has probably appeared on every spot on the network where vehicles will appear. The longer the *.out file, the better.
*lengths **simplelengths** **hornlengths** **CATlengths**	Data file	Required for: Segment analysis (sa)	**Segment length files** These files are needed by sa (seganal.C), to analyze the emissions on along a segment.
mkxdta.C **ppp**	C++ code Executable file	Required input file: *-matched	This file makes the xdta files, which are for the graphical display of minute-by-minute emissions on each segment and node. One file for each pollutant is created: -HC, -CO, -NOX, -Fuel, -CO2.

Name of file/file extension	**File type**	**Associated files**	**Description**
isolate.C **iso**	C++ code Executable file	Required input file: *-matched Output file: *-sX OR *-vX Required for: Segment analysis (sa)	This file takes the -matched file and isolates a single trajectory or segment as specified by the user. This allows the user to look at the emissions of a single trajectory or to use this file as an input to usematrix.
***-sX**	Data file	Generated by: iso Required for: Segment analysis (sa)	This file is a parsed version of the *-matched file. It has only the entries which occur on the segment X.
***-vX**	Data file	Generated by: Iso	This file is a parsed version of the *-matched file. It has only the entries associated with vehicle X. Essentially, it is the vehicle trajectory for this vehicle.
seganal.C **sa**	C++ code Executable file	Required input file: *-sX Output file: *-sXprofile	This program takes the isolated post-processed segment file and figures out the emissions distribution along the segment

Note: When compiling some of the C++ code, the error: "warning: assignment to `int' from `double'" may appear. This is normal.

Note2: File formats are listed in Appendix B.

Appendix B – Data Formats in MITNEM files

This section lists the formats for all input, output, and interface files used in MITNEM. A description of the file is followed by the file extension [e.g. -traj]. A description of the data by columns is listed following the first line.

MITSIM output [.out] & sorted trajectory file [-traj]:
time • VehID • segment • lane • position • speed [m/s] • accel [m/s^2] • MITSIM VehTyp

CMEM activity file [-atb]:
time • VehID • speed [km/hr]
OR
time • VehID • speed [km/hr] • accel [km/hr*s]

CMEM definition file [-def]:
VehID • CMEM VehType • Soak Time • SH

CMEM sec-by-sec output file [-ssb]:
time • VehID • speed [km/hr] • HC • CO • NOX • fuel • CO2

Matched file [-matched] AND [-s33] (sorted by VehID then by time):
time • VehID • segment • lane • position • speed [km/hr] • accel [km/hr*s] • VehTyp [MITSIM] • HC • CO • NOX • fuel • CO2

Network file summed over time [-matchednett]:
time interval segment [time/interval] • num veh (each vehicle counted once every second) • avg velocity in interval [km/hr]• total km's traveled in interval• HC [g/time interval] • CO • NOX • Fuel • CO2

Network file summed by segment [-matchednets]:
segment• num veh (each vehicle counted once every second) • avg velocity on segment [km/hr]• total km's traveled on segment• HC [total g over run] • CO • NOX • Fuel • CO2

Segment analysis file[-s33profile]:
position [along segment] • average velocity[at that position] • number of vehicles counted at that position • min velocity • max velocity • HC • CO • NOX • Fuel • CO2

Segment analysis file[-s33profile3D]:
position [along segment] • time[minutes] • average velocity[at that position] • number of vehicles counted at that position • min velocity • max velocity • standard deviation of speed • HC • CO • NOX • Fuel • CO2

Appendix C – Fleet Mix

The fleet mixes used for both the Hornstull and CA/T network were each adapted from the Riverside fleet mix described in the CMEM User Manual. The changes were that trucks and buses were added to the fleet. The Riverside fleet mix was scaled down from 100% (to 93.5% for Hornstull, and to 98% for CA/T) to accommodate these additional categories. Some manual adjustments were required to round the final percentages off to 1/10th of a percentage while keeping the sum of the fleet to 100%.

The Caldecott Tunnel categorization is another example of a real fleet mix.

Table C-1: Fleet Mixes and MITSIM Vehicle Type to CMEM Vehicle Category Mapping

						Categorization %			MITNEM Fleet Mixes	
	Description	CMEM Category	I/M to CMEM Mapping	MITSIM Category	Examples	Riverside Proper (Barth, 2000)	Riverside region (Barth, 2000)	Caldecott Tunnel (Malcolm, 2000)	Adjusted Riverside	CA/T
Normal Emitting Cars		1	1	1	Honda Civic 76, Datsun 240Z 73, Ford Mustang 67	5.18%	4.68%	0.34%	4.60%	5.20%
		2	2	1	Honda Prelude 82, Oldsmobile 98 79	7.68%	7.41%	2.08%	7.10%	7.70%
		3	3	0	Honda Accord 85, Nissan Sentra 86	5.12%	5.26%	3.38%	4.80%	4.80%
		4	4	0	Honda Civic 91, Buick Century 8, Nissan Sntra 90,	10.51%	10.99%	15.25%	10.10%	10.20%
		5	5	0	Oldsmobile 89, Honda Accord 90, Toyota Camry 92,	14.16%	14.12%	20.04%	13.20%	12.90%
		6	6	0	Dodge Spirit 91, Mazda Protégé 90,	1.08%	1.16%	1.80%	1.00%	1.00%
		7	7	0	Nissan 240SX 93, Mazda Protégé 94, Mercury Tracer 81, Suzuki Swift 92	1.68%	1.67%	3.83%	1.60%	1.60%
		8	8	0	Honda Civic 95(2) & 94, Toyota Camry 94,	1.45%	1.54%	3.27%	1.40%	1.40%
		9	9	0	Jeep Cherokee 95, Saturn SL2 93,	2.67%	2.65%	5.76%	2.50%	2.40%
		10	10	0	Toyota Tercel 95, Honda Civic 95,	1.30%	1.44%	2.13%	1.30%	1.30%
		11	11	0	Cadillac NS 96, Buick Lesabr 96, Honda Civic 95 & 96, Infinity G20 95, Plymth Breeze 96, Chevy Capri 94,	2.68%	4.68%	7.35%	3.40%	2.50%
		24	24	0	Ford Escort 95 & 96, Chevy S10 95, Jeep Cherokee 95	0.09%	0.10%	0.09%	0.10%	0.10%
Normal Emitting Trucks		12	12	1	Ford F150 75, Chevy Camin 78, Ford F250 72,	5.24%	4.96%	0.30%	4.50%	5.20%
		13	13	1	Ford E_150 83, Ford F150 Van 83, Ford Bronco 82, Ford Superwagon 80	2.01%	1.96%	0.43%	1.80%	2.00%
		14	14	1	Chevy Suburban 87, Ford Aerostar 14, Ford Bronco 86, Ford Pickup 81, Chevy C10 81	2.62%	2.60%	0.63%	2.30%	2.60%
		15	15	0	Toyota PU 90 & 88, Ford Mini 93, Plymouth Voyager 91, Toyota X Cab 92	3.87%	3.96%	4.23%	3.50%	3.80%
		16	16	0	Chevy Suburban 94, GMC Sonoma 91, Chevy Atrovan 94, Ford Explorer 92	3.64%	3.52%	4.45%	3.10%	3.20%
		17	17	0	GMC Safari 96, Plymouth Voyager 94, Jeep Wrangler 95, Ford Explorer 97	0.29%	0.30%	0.30%	0.30%	0.30%
		18	18	0	Ford Van 95, GMC 1500 95,	0.43%	0.43%	0.79%	0.40%	0.40%
		25	25	1	Ford F350 96 & 92 & 87, Dodge Ram 97, GMC Sierra 89, GMC 3500 88,	1.79%	1.86%	2.67%	1.60%	2.70%
	Diesel	40	40	1	Ford F350 95, Ford F250 87 & 86, Dodge 250 90 & 92 & 97	0.07%	0.06%	0.06%	0.10%	0.10%
High Emitting V	Runs Lean	19	10	1	Plymouth MV 88, Dodge Minivan 95, Honda Civic 89,	4.88%	4.90%	4.36%	4.60%	4.90%
	Runs Rich	20	9	1	Cadillac 84, Ford Windstar 95, Toyota Camry 98	1.82%	1.83%	1.79%	1.70%	1.80%
	Misfire	21	8	1	Chevy Van 86,	10.45%	10.53%	8.02%	9.80%	10.50%
	Bad catalyst	22	11	1	GMC S15 Truck 85, Nissan Truck 84, Pontiac 90, Dodge Truck 91, Cad Eldorado 82	7.40%	7.46%	5.04%	6.90%	7.50%
	Runs very rich	23	24	1	Mazda 626 83	1.89%	1.91%	1.62%	1.80%	1.90%
		40	40	2	Trucks	0.00%	0.00%	0.00%	5.50%	1.00%
		40	40	3	Bus	0.00%	0.00%	0.00%	1.00%	1.00%
Total %						100.00%	100.00%	100.00%	100.00%	100.00%

Appendix D – Literature Review of Health and Visibility Costs of Emissions

Many studies have attempted to assign health costs to emissions. McCubbin and Delucchi conducted the most comprehensive study. Their initial report, "The Social Cost of the Health Effects of Motor-Vehicle Air Pollution" was the 11th report of a 20 part report *The Annualized Social Cost of Motor-Vehicle Use in the United States, based on 1990-1991 Data.* They collected air quality data from monitors around the United States and used EPA county-level emissions inventories to estimate the air quality around the country. Dose-response functions were used to calculate the occurrences of health consequences for given air quality levels. Finally, by applying per-incident health costs, these health consequences were translated into dollar figures for emissions health costs in the nation. Regional health costs for select metropolitan areas, urban areas, and many large cities were also estimated. A well-written summary of their methodology and conclusions was published in McCubbin and Delucchi (1999).

The high estimates give an upper bound to the range of values while the low estimates give the lower bound. The high estimates of emissions are not necessarily meant to be compared to the high estimates of fuel or travel time. The ranges are independent of each other. In one region, for example in a rural area, emissions costs may fall in the lower range, while fuel costs may be closer to the high estimate.

Table D-1 lists the health costs estimated in the report. The McCubbin and Delucchi estimates are made in 1990 dollars. The GDP deflator is used to convert these figures into 2001 dollars. This is the same method the Office of the Secretary of Transportation uses to update their value of life estimates, from which a majority of health costs are derived. The GDP deflator for 1990 to 2001 $1.26. This is compared to the CPI inflator, also a commonly used dollar adjustment ratio, which is $1.36 for the same time period.

Examples of travel delay costs are from a literature review performed by Ghosh, 2000. Fuel costs are base on current (2002) fuel prices. Property damage costs (crop damage), costs associated with environmental damage to natural resources (forests, water, etc.) were not included. It should be noted that PM10 health costs are much higher than that of HC, CO, and NOX, but are not included in the cost estimates in this report because PM10 emissions is currently not being modeled.

Table D-1: Emissions health costs ranges (U.S. Urban Averages)

		HC 2001 $ (1990 $)	**CO 2001 $ (1990 $)**	**NOX 2001 $ (1990 $)**	**PM10 2001 $ (1990 $)**	**Fuel 2001 $**	**Travel Time 2000 $**
	Unit	Per kg	Per kg	Per kg	Per kg	Per gallon	Per hour
Health	**High Estimate**	$1.83 ($1.45)	$0.13 ($0.10)	$29.50 ($23.34)	$200.00 ($158.23)	$2	$30
	Low Estimate	$0.16 ($0.13)	$0.01 ($0.01)	$2.01 ($1.59)	$15.40 ($12.23)	$1	$5
Visibility	**High Estimate**	$0.06 ($0.05)	N/A	$1.40 ($1.11)	$4.93 ($3.90)	N/A	N/A
	Low Estimate	$0.01 ($0.01)	N/A	$0.24 ($0.19)	$0.51 ($0.40)	N/A	N/A

Source: Delucchi, 2000 and Ghosh, 2000

One concern about these health cost figures is an issue of whether the average costs should be used or marginal costs. There are two reasons for this concern. First, because dose response functions are not linear. It has been shown that there can be a tolerance level, where up to a minimum concentration level, additional emissions do not result in a linear increase in health consequences. On the other hand, above a certain threshold, certain pollutants can become more dangerous. McCubbin and Delucchi used their model to estimate both health cost savings associated with a 100% reduction in vehicle emissions and health cost savings associated with a 10% reduction in vehicle emissions.

The second reason is that background pollution concentration levels determine the impact of additional emissions. Specifically, ozone is formed during the chemical interaction of HC, NOX, and sunlight. If a region has low HC and high NOX, then additional NOX will not increase the ozone in the area because the area is "HC limited," HC limits the amount of ozone that can be formed, not NOX. On the other hand, additional HC will react with the readily available NOX and form ozone. Therefore, the marginal cost of each gram of HC in this region will be very high, whereas the marginal cost of NOX will be low. One solution to this problem is by using different health costs for different cities, which McCubbin and Delucchi have done. Their results show that the health costs can be vary by a factor of more than 20 from city to city.

Other recent studies which have conducted emissions costs include: a study conducted at Argonne National Laboratory (Wang et al., 1994), which also estimates emissions cost values in the U.S. by region; and a report by the EPA in *The Benefits and Costs of the Clean Air Act.*

The largest uncertainty in economic valuation for emissions related health costs is mortality. The valuation of mortality in literature ranges from $0.6 - $13.5 million per death. The DOT uses $3 million[5] for a highway accident mortality and the US EPA uses a value of $4.8 million (US EPA, 1997). Mortality from emissions exposures are usually assigned a similar value. These values are typically from labor market studies, where pay is correlated with risk associated with high-risk jobs. Experts question whether these values are applicable for emissions related deaths because most emissions related mortality victims are the elderly or people who are in weak health. The sudden exposure to high levels of pollution (elevated ozone levels due to extreme temperature conditions) results in a pre-mature death, which is not equivalent to a death from a car accident, where the person is of random age and health.

Another method of valuing emissions related mortality is to use the "life-years lost" approach, where the value of life is translated into years. The DOT estimated that using this method, a premature death would average $2.6 million. After evaluating the two

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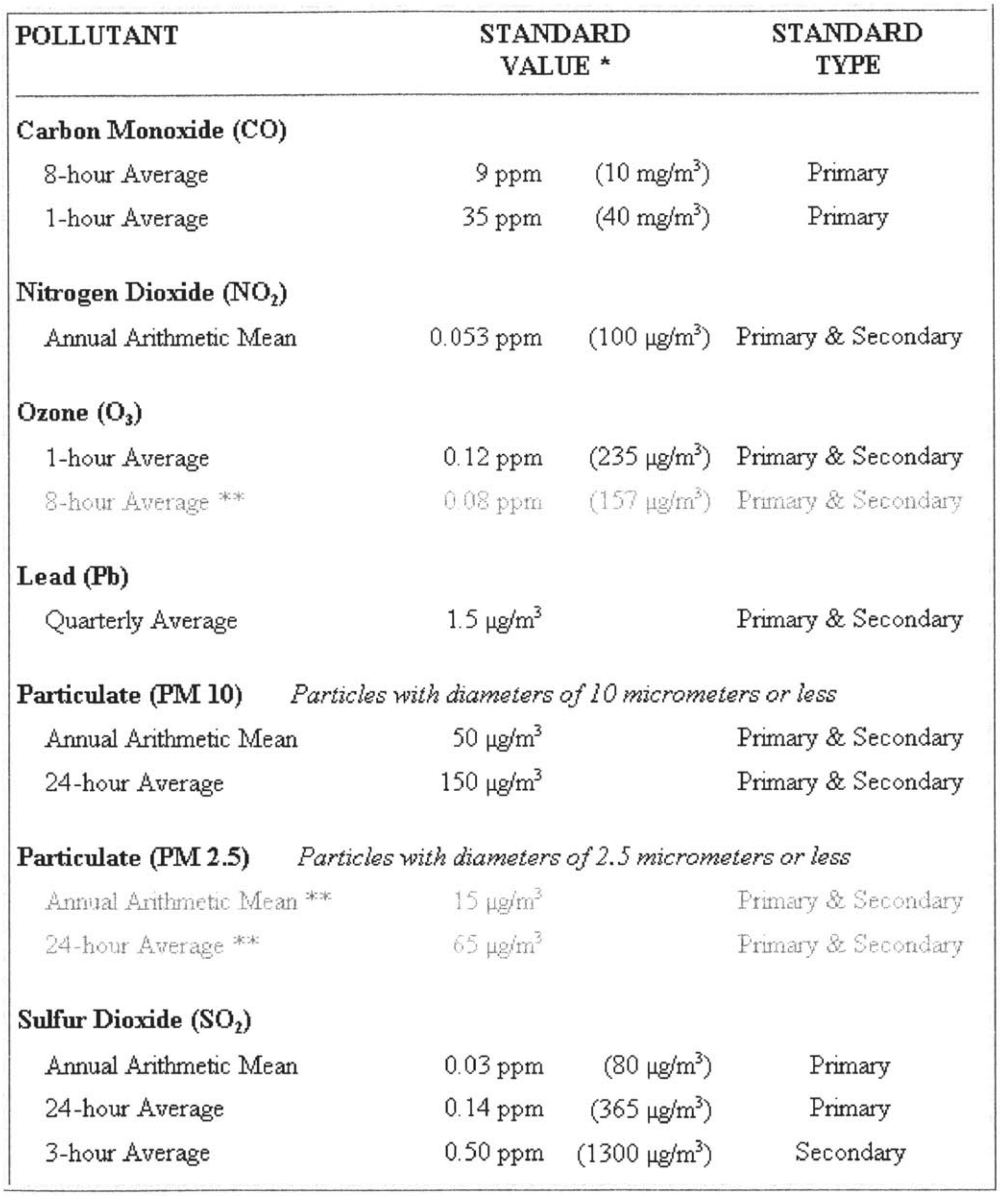
[5] The Office of the Secretary of Transportation issues from time to time a guidance on the value of life estimate to be used for economic valuations of car accident related mortality. The latest figure from year 2002 is $3 million. (U.S.DOT, 2002).

methods, the DOT preferred not to use the life-years lost approach because they felt that this devalued the value of life of the elderly and those in weak health.

It is not clear from the studies exactly which health consequences are taken into account. For example, it is still under debate whether ozone directly leads to mortality. Some cost studies include mortality as a health consequence of ozone and others do not. Since the value of life is the dominant factor, this makes a large difference in the final health cost numbers. Some of this uncertainty is captured in the high and low estimates given by McCubbin and Delucchi. Their report emphasizes the importance of using the range of their values and not either of the actual values.

Appendix E – National Ambient Air Quality Standards (NAAQS)

Table E-1: Current National Ambient Air Quality Standards



POLLUTANT	STANDARD VALUE *		STANDARD TYPE
Carbon Monoxide (CO)			
8-hour Average	9 ppm	(10 mg/m^3)	Primary
1-hour Average	35 ppm	(40 mg/m^3)	Primary
Nitrogen Dioxide (NO_2)			
Annual Arithmetic Mean	0.053 ppm	(100 µg/m^3)	Primary & Secondary
Ozone (O_3)			
1-hour Average	0.12 ppm	(235 µg/m^3)	Primary & Secondary
8-hour Average **	0.08 ppm	(157 µg/m^3)	Primary & Secondary
Lead (Pb)			
Quarterly Average	1.5 µg/m^3		Primary & Secondary
Particulate (PM 10)	*Particles with diameters of 10 micrometers or less*		
Annual Arithmetic Mean	50 µg/m^3		Primary & Secondary
24-hour Average	150 µg/m^3		Primary & Secondary
Particulate (PM 2.5)	*Particles with diameters of 2.5 micrometers or less*		
Annual Arithmetic Mean **	15 µg/m^3		Primary & Secondary
24-hour Average **	65 µg/m^3		Primary & Secondary
Sulfur Dioxide (SO_2)			
Annual Arithmetic Mean	0.03 ppm	(80 µg/m^3)	Primary
24-hour Average	0.14 ppm	(365 µg/m^3)	Primary
3-hour Average	0.50 ppm	(1300 µg/m^3)	Secondary

* Parenthetical value is an approximately equivalent concentration.

Source: US EPA website, http://www.epa.gov/airs/criteria.html, 2002