THE RELATIVE CONTRIBUTION OF TRUCKS TO EMISSIONS IN HAMILTON

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By

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Abstract

An origin-destination (O-D) matrix of truck travel was obtained from the City of Hamilton. The concept of Passenger Car Equivalence (PCE) was used to transform this matrix into a passenger car O-D matrix. The integrated land-use and transport model IMULATE has been modified to incorporate the transformed vehicle matrix, along with a matrix for passenger cars. A PCE value of zero implies the total absence of trucks in the network. Reported emission values in this case are attributed to passenger cars alone. PCE values greater than zero indicate the number of vehicles displaced in traffic flow by the presence of a single truck. Reported emissions under such conditions are affected by the presence of trucks.

The results suggest that the estimation procedure is effective. The contribution of trucks to mobile emissions of HC, CO, NOx, and PM has been addressed at the aggregate and link levels. Emission estimates demonstrate sensitivity to the presence of trucks as modeled in this study. The presence of trucks is shown to increase the aggregate level of all pollutants and affect changes in link-based estimates.

While the results are encouraging it has been recognized that the potential of this procedure for generating accurate estimates is limited by the resolution of the observed truck data. It is also recognized that gas PM is emitted at such low rates that it is difficult to measure accurately. Another limitation of the present study is that only trips with origins and destinations within the Hamilton CMA are included. The contribution of trucks passing through the CMA is not dealt with, but warrants future consideration. Also, the reported results refer only to the morning peak period. The contribution of truck emissions during the rest of a typical day is expected to be significant since most freight trips avoid the morning peak period.

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Chapter One

Introduction

Considerable discussion over the last two years within the Hamilton-Wentworth Air Quality Improvement Committee led to the conclusion that little is known about truck mobility in Hamilton-Wentworth. In response to this conclusion, this study was initiated in January 1999 to examine daily traffic volumes and the contribution of trucks to daily emissions from mobile sources in the Census Metropolitan Area (CMA) of Hamilton.

Vehicles are the largest single source of nitrogen oxides (NO_x) and non-methane hydrocarbon (NMHC) emissions (HAQI, 1997). NMHC are often referred to simply as hydrocarbons (HC). NO_x and HC are of concern because of their role in the formation of ground-level ozone. Vehicles are also a major source of climate change gases, such as CO (HAQI, 1997). CO is also of concern because it enters the bloodstream through the lungs and inhibits the blood's capacity to carry oxygen to organs and tissues

In addition to HC, CO and NO_x, there is increasing interest in particulate matter (known as PM or particulates). It is important, when studying PM emissions from mobile sources, to include trucks. The Environmental Protection Agency (EPA) using engine dynamometer tests, have found that a typical light-duty diesel truck emits 30 to 100 times more PM than a comparable catalyst-equipped, gasoline-powered passenger vehicle (USEPA, 1993a). PM_{10} (defined as being 10 micrometers or less) is of particular concern due to its association with cardio-respiratory hospitalisations (Burnett et. al., 1999). In this study, a procedure for estimating emissions of CO, HC, NO_x and PM_{10} has been applied to the Hamilton CMA.

Over the last few years several studies have examined emissions from mobile sources in the Hamilton CMA (see Anderson et. al., 1996, Kanaroglou and Anderson, 1997, Scott et. al., 1997). All of these studies have concentrated on emissions from passenger cars. The objective of the present study is to examine the contribution of trucks to the volume of traffic flow and to emissions from mobile sources. The approach used follows in the footsteps of those used in previous studies. IMULATE, an integrated land-use and transportation simulation model for the Hamilton CMA, is instrumental in generating traffic flow and emissions estimations. IMULATE incorporates the Environmental Protection Agency (EPA) emission model MOBILE 5C. MOBILE 5C has been adapted to Canadian standards from the U.S model MOBILE 5A, used to support air quality planning and emission inventory development.

The remainder of this thesis includes five chapters. Chapter 2 reviews the literature on the techniques used in vehicle surveys and modeling that has been done in North America. This review places emphasis on the cost-effectiveness of vehicle surveys and the completeness of data collected using the various techniques. This chapter is of importance as the studies that have been conducted thus far, including this research, have been limited by the quality and completeness of the data used as inputs into various models. The modeling techniques used are also discussed.

In Chapter 3, the two basic vehicle classification schemes that have been developed are outlined. Also, a brief description of the HC, CO, NO_x, and PM pollutants is given. Data collected in surveys must include some classification of vehicles to help describe the vehicle fleet. Different vehicle classes will emit the various pollutants in different quantities, and emission factors must be assigned to the model output to account for these differences.

Chapter 4 outlines the data and methodology used in this research. Drawing on the literature, as covered in Chapter 2 and 3, a model, classification scheme, and emission factor set are selected. Funding and time constraints omitted the possibility of conducting a vehicle survey to collect a complete origin-destination (O-D) matrix of passenger car and truck travel in the Hamilton CMA. Vehicle survey techniques are reviewed in Chapter 2, and included in this thesis, as direction for future research. It is desirable to complete a survey in the future to increase the accuracy of results generated from the methodology presented here. While an O-D matrix was not collected in this study, one was supplied by the City of Hamilton to be used as input into IMULATE. The classification-by-weight scheme was applied to this matrix, and emission factors generated by the EPA were assigned to the different classes of vehicles.

The empirical findings from the analysis are presented in Chapter 5. Specifically, estimations are made for the emissions from mobile sources of HC, CO, NO_x, and PM_{10}. The relative contribution of trucks to each pollutant is also estimated. Estimates of emissions both at the aggregated regional level as well as at the transportation link level are presented and discussed.

Finally, Chapter 6 summarizes the findings and provides recommendations for future research in the area of truck emission contribution and suggests improvements on this study to further increase the accuracy from the methodology's results.

Chapter Two

A Review of Truck Travel Data Collection and Modeling

2.1 Introduction

To date, very little has been done in the area of truck surveys and truck travel demand forecasting in urban areas. Even less has been done in a Canadian context. This chapter examines the current state of the art in truck data collection and travel demand forecasting. The literature indicates there are three common vehicle survey techniques; a roadside (or intercept) interview, a 'mailback' questionnaire, and a telephone interview of companies using trucks. Case studies that use these techniques in various combinations are reviewed, while other surveys are summarized. Data collected in these surveys is used for a variety of reasons, most commonly in the development transportation models. From the literature, there are three common types of transportation models; Gravity Models, the Stage Model, and Integrated land use and transportation models. Again, case studies of areas where each of these models have been applied are reviewed in detail. Where possible, there is a focus on Canadian efforts, with emphasis on information about Hamilton.

In most instances, the collection of truck traffic data and model development are based on the data collection and modeling being done for passenger vehicles. There have been few efforts treating truck data collection and forecasting as a separate issue. Many planning departments continue to generate their truck trip estimates on out of date origin-destination surveys. The need for current, detailed truck data is crucial in the development and accuracy of models.

2.2 Survey Methods and Empirical Findings

Four case studies of survey techniques and three case studies of transportation models are reviewed in the following chapter. The case studies reviewed here exemplify the particular survey technique or transportation model, and are presented in chronological order from the most recent.

2.2.1 Interview/Mailback: Berks County, Pennsylvania (1994)

When the survey was done:

In 1994, a roadside truck survey was conducted that included vehicle classification count, through-trip, interim origin/destination within the County, and final origin/destination. The survey was done 'within-the-stream' of traffic in conjunction with the distribution of a postcard automobile survey (Matherly, 1996). Over 1000 interviews were conducted throughout the county in five cordons representing key, two-lane and four-lane roads. The sampling rate exceeded 22%, and valid responses were 98%.

The objective of the study was to estimate major internal-external, external-internal, and external-external truck movement patterns in Berks County. Total traffic volumes exceeding approximately 200 vehicles per 15 minutes are likely to lead to unacceptable congestion and low truck survey rates. Research indicated that truck drivers provided very poor response rate on the postcard survey, not exceeding 5-10%, hence the different methods for dealing with trucks and automobiles.

Correlation to actual vehicle counts and flows was an important consideration for model development and lessened the desirability of random phone and mail surveys. Such surveys generally rely on truck registration. They may miss through-trips because of poor response rates from out-of-city trucks, or may introduce bias because of the size and number of firms responding. Errors may be introduced caused by a fleet manager or dispatcher completing the report instead of the actual driver.

Survey Method:

Automated 24-hour traffic counts were conducted at each site before the survey dates. No significant change in traffic volume (i.e. from route shifting) was noted. A limited questionnaire was necessary to meet time constraints and it simply asked "What is (was) your next (last) stop?", and "What route did/will you take?". They considered using palmtop computers coded with appropriate businesses, routes, and addresses, however the pre-test showed that the data could not necessarily be entered in the time available.

Survey Findings:

Across all routes surveyed, 14% of traffic was by trucks. Of that, 53% were composed of heavy trucks (3 or more axles). 'Time of day' truck activity generally conformed to established industry observations. Of all traffic, trucks comprised 9 to 12% during the evening peak (4:45-7:00pm), more than 20% before 2:15pm, and 12-20% from 2:15pm to 4:45pm. They conclude that intercept surveys are important for collecting data on external-external and external-internal trips. The joint automobile/truck survey is feasible, but only on low-volume roads on which moderate truck traffic mixes with automobile traffic. Total traffic volumes exceeding the range of 200 vehicles per 15 minutes per survey lane are likely to lead to unacceptable congestion and delays to low truck and automobile survey rates.

Matherly determined the advantages of their method included; complete information, high response rate, better sampling control, good representative sample of trucks entering and leaving a cordon lines, and easy comparison with mainstream traffic through field counts at survey location. The disadvantages include; potential disruption to traffic, quality and conduct of survey affected by weather, lighting, noise from trucks, hazardous to survey crew, time constraints, no follow-up possible, enforcement problem at the station (drivers avoiding the survey station), and the sample only represents truck traveling on roads along survey stations, not entire region (Matherly, 1996).

2.2.2 Telephone/Mailback: Phoenix, Arizona (1991)

When the survey was done and what data was collected:

In 1991, the Arizona Department of Transportation, Transportation Research Center, funded a commercial vehicle travel survey within the Phoenix metropolitan area. The primary objectives of the study were to collect truck travel data to develop commercial vehicle trip generation, trip distribution, and traffic assignment models (Ruiter, 1992). The models were developed with the intention of being incorporated into the Urban Transportation Planning System-based travel model maintained by the Maricopa Association of Governments (MAG).

The mailout questionnaires were designed to obtain the following data:

- Starting and ending addresses for all trips on the survey day;
- Vehicle type based on number of axles and body style;
- Estimated gross weight;
- Vehicle usage for home-based work and work-related trip purposes;
- Total number of one-way trips on the survey day.

In addition to the above information, the travel diary requested the following information on the first 10 one-way trips made by each vehicle on the survey day:

- Start and stop times;
- Stop odometer readings;
- Name and address of each stop;
- Driver and vehicle activity of each stop;
- Land use at each stop; and vehicle type/total axles for each trip (to determine trailer pick-up and drop-off locations.)

Survey Method:

The survey only included commercial vehicles registered within the MAG study area. The purpose of the survey was to develop new models for internal commercial vehicle trips only. Two sources of data were used to determine the total number of commercial vehicles to be sampled. *The Department of Motor Vehicles (DMV)* produced a digital file of 157,000 commercial vehicles registered in Maricopa County in 1989 (Ruiter, 1991; Ruiter, 1992). The compiled list of commercial vehicles were then stratified by vehicle weight, and sorted by zip code before sample selection. Subsamples were obtained so that vehicle weight categories would be represented for all geographic areas. The sampling strategy was designed to obtain 40% sample of light vehicles (under 8,000 lbs) and 20% for each of the three remaining weight categories (8,000-28,000 lbs, 28,000-64,000 lbs, 64,000+ lbs). The second was a list of 2,300 vehicles garaged in Maricopa County. All of these vehicles were owned by the U.S. Postal Service (USPS) but were not registered in Arizona. The USPS vehicles were sampled by weight and by garaging location. They all fell into the two lightest vehicle weight category (2,180 in the under 8,000 lb category and 101 in the 8,000-28,000 lb. category). The selection process provided 1 in 40 postal vehicles in the light category and 1 in 10 in the next heavier category.

The data collection used a mailback questionnaire, which included a 1-day trip diary. The overall response rate for the mailback survey was 30% with 720 responses, of which 527 vehicles (73%) made trips on the survey day. USPS travel forms, detailing daily itineraries for 62 selected vehicles, were also obtained from the manager of fleet operations. The information obtained was used to fill out the trip diary. A telephone survey to the vehicle owners revealed that only 75.7% of registered vehicles from the DMV data list were available for use for commercial purposes.

Survey Findings:

The Phoenix Commercial Vehicle Survey produced the following conclusions:

- Vehicles in the lighter weight categories made more trips; 96.6% of all commercial trips were made by the two lightest weight categories. The average trips per vehicle for the 8,000-28,000 lb category, for example, was 9.6 trips; whereas, vehicles in the 64,000+ lb category made only 4.0 trips per vehicle.
- Vehicles in the heaviest category made few but long trips. The average VMT per vehicle for the 64,000+ lbs. category was 156.8 miles, compared to 56.2 miles for the 8,000-28,000 lb category. Vehicles in the heaviest weight category averaged 33.4 miles per trip, compared to 11 or less miles per trip for the lighter weight categories.
- A total of 79.4% of the surveyed vehicles were used for commercial purposes.
- Most trucks started their first trip between 6:00am and 9:00am. This pattern, however, varies by weight category. Light trucks were more likely to start their first trip between 6:00am and 9:00am. Heavy trucks (51.8%), started their first trip before 6:00am.
- The peak period for truck travel occurred between 9:00am and 2:00pm. Heavy trucks, however, have a shorter peak period (11:00am-2:00pm). During both of these periods, 13 percent of daily commercial vehicle travel occurred.

- The trucks surveyed made on average 7.7 trips per day. Light trucks made on average more trips (12.1 trips) than heavy trucks (4.7 trips).
- Heavy trucks were found to make high proportion of trips (26.7%) to residential land uses. Analysis showed that the reason could be that heavy trucks, to a large extent, were used to delivery construction materials, including lumber and ready-mixed concrete to residential construction sites.

2.2.3 Interview: Ontario (1988)

When the survey was done and what data was collected:

The Ontario Ministry of Transportation periodically conducts surveys of commercial vehicles based on 5-year intervals for planning and operational purposes. Roadside intercept surveys were completed in 1978, 1983, and 1988. For the 1988 Ontario Commercial Vehicle Survey, 19,000 trucks were surveyed to gather truck travel information (Gorys, 1991). The primary purpose of the 1988 commercial vehicle survey was to provide a current profile of trucking activity in the province for the planning, delivery, and evaluation of Ministry programs. Other than the primary purpose, the survey was also conducted to gather information on the following:

- Nature and extent of dangerous goods movement;
- Structure of the industry between private and for-hire carriers;
- Trans-border goods movement (degree/nature of traffic of other provincial/ U.S. carriers);
- Seasonal variations in transportation and commodity movements;
- Profile of commercial vehicle drivers (demographics and other characteristics);
- Commodity and load characteristics; and
- Measures of efficiency on the basis of empty truck movements and ton-miles transported.

Data was collected on the driver's employment characteristics (age, sex, years of experience, recent training, the number of hours expected to work on the particular trip being surveyed, carrier type, union affiliation, and employee category). Other information on type of commodity hauled, degree of utilization level of the vehicle, and the O-D of the vehicle were collected. The information was cross checked, whenever possible, with photocopied waybills.

Survey Method:

The survey was conducted during a 23-week period, from March to November 1988. Interviews depended on proper lighting, weather, and safety conditions. It was carried out at 57 locations along principal intercity highway inspection stations, rest stops, and at border crossings. Where possible, surveys were conducted at the identical 1983 survey locations. The data collection included carrier information, area of registration, commodity type and weight carried, and trip origin and destination. The station inspectors recorded truck body type, number of axles, vehicle weight, etc. Interviewers recorded vehicle plate numbers and then approached truckers to request approval to go through with the survey. Survey completion lasted between 8 to 12 minutes. During the survey, a vehicle classification count of vehicles passing by the interview location was undertaken. The purpose was to expand the sample data to represent the daily average traffic for the survey location.

Survey Findings:

A total of 19 225 (8.6%) of the total population of commercial vehicles were interviewed over a 1855 hour period, with an overall refusal rate of 3.5%. Another 1363-hour period was used to collect information on vehicle type. The 7-day, 24-hour vehicle classification counts at inspection stations west of Toronto were conducted to obtain data on daily and hourly variations in truck travel.

The limitation of the study was that the data collected was expanded to reflect a yearly flow of truck traffic. Such an expansion would not address seasonal variation in flow. Second, the placement of the interview sites presented a bias towards trucks traveling on the major intercity routes, truck traffic on secondary routes and rural highways were not adequately represented in the sample. Lastly, only a small proportion of weekend truck travel was captured. Week long classification counts at two inspection stations, however, showed that weekend truck traffic was quite low. It was also true that private carriers used lighter vehicles than for-hire carriers. The for-hire carrier industry preferred larger vehicles with 6 or more axles. The survey of on-board monitoring devices found that logbooks were the principal trip recording devices (53% of all vehicles).

An analysis of truck volume by hour in proportion to the total traffic volume, however, revealed that trucks accounted for between 10 and 58 percent of the total traffic, depending on the hour surveyed. The greatest proportions were found in the early morning hours (3:00-5:00am.). Overall, trucks were found to constitute 17 percent of the total vehicular traffic.

2.2.4 Interview/Telephone: Hamilton, Ontario (1973)

When the survey was done and what data was collected:

In 1973 a study was designed to determine the type, volume and variation of trucks traveling in the various parts of the city on a typical weekday, over a 24-hour period. Information was gathered on the classification of trucks traveling within the city, their origins and destinations, trip frequency, trip purpose, and the general route(s) used. The type, weight, origin and destination of all commodity flows into and out of the city were of importance as they are carried by the trucking industry. At the time 'The Traffic By-Law' defined "Heavy Traffic" as any vehicle with a gross weight in excess of 8000 lbs, exemptions made to; buses, fire fighting equipment, public utility vehicles, and emergency vehicles. Also, there were only certain routes south of Barton Street which trucks were allowed to use. North of Barton Street is the industrial area and every street is considered a truck route, unless specifically designated otherwise.

Survey Method:

A roadside interview, combined with telephone interviews were used to gather the data. Two cordons were selected, and screenlines were drawn within each for detailed study. The first, entitled 'External Screenlines', consisted of the access points to the Provincial Highway connections; Red Hill Creek, South City Limits, and Chedoke Valley screenlines. The second, entitled Internal Screenlines, consisted of major crossings within the central lower City. There were the arterial and collector streets crossing Victoria Avenue, the Mountain Brow and Kenilworth Avenue screenlines. Crossing each screenline, thirty-one interview stations were designated at each major roadway with each station having; a Police Officer, one to five interviewers, a recorder, and a roving supervisor. Interviews were conducted over a 24-hour period from Monday 7:00pm to Friday 11:00pm. The inbound direction (towards City Hall) was competed on November 14th to 28th, 1972, and outbound direction was competed December 4th to 20th, 1972. As the study was developed to analyze the truck 'problem' of noise and congestion in the city streets, tractor-trailers, dump truck, and construction vehicles were prioritized, while trucks weighing less then 8000 lbs. were entirely excluded. Interviews lasted about 3 minutes and not all trucks were stopped during peak periods so as not to cause excessive delays or congestion. The survey obtained information on; location, vehicle type and class, trip origin, destination, purpose, and frequency and general routing.

An origin-destination (O-D) survey was created using the collected data. The O-D survey was coded using a detailed traffic zoning system. The zoning system a the time consisted of the following sections; within Hamilton, 114 Neighborhoods (Planning Districts), outside Hamilton, but within TARMS (Toronto Area Regional Municipal Study) study area, traffic zones corresponded to the TARMS zones outside this immediate area either a Provincial or State zoning system was used. A full classification count was taken at each interview station.

In addition, a number of telephone surveys were conducted; of several truck generators to ascertain their methods of operation, assess requirements and service areas; on commercial/industrial establishments, specifically not on the truck routes, to ascertain their night-time truck access requirements, and on leading truck firms, commercial outlets, enforcement agencies and drivers to explore the various problem and solutions.

Survey Findings:

From the classification counts, 26 564 interviewable truck trips crossed the screenlines, 11 077 were interviewed and used to generate the O-D survey (i.e. about 42%). The count also revealed that there were almost twice as many small trucks as there are large trucks. On Nash Road, it was determined that tractor-trailers are not the problem, but rather, a large volume of smaller service and construction vehicles. Overall, they found that truck traffic was not a prime source of congestion. Consequently no effort was made to identify congestion points or any other traffic problems and potential solutions.

The study found that approximately 13 650 heavy trucks, and 18 300 smaller trucks enter and leave the city daily, and estimate there is one truck trip for every 6.5 car trips. Within the city, heavy trucks as a percentage of the total traffic flow varied from 1.1% to 16%. Internal circulation reveals that the volume of small trucks is more than four times that of heavy trucks. Due to its central location and industrial/commercial nature, Hamilton has a high volume of trucks. The smaller vehicles, which make up the majority of the internal flow, had a tendency to be individually owned, as opposed to being controlled by a large fleet. In virtually all areas of the city the volume of tractor-trailers with two trailers is relatively constant over the entire day. This may be due to the fact that a large proportion of these carry steel, steel products, raw materials or liquid fuels, all of which are related to industries working around the clock. These large trucks comprise 5% of the truck traffic and less than 0.4% of the total traffic. Single trailer trucks followed an urban delivery characteristic in that there were a large volume of them during daylight hours, but decreased at night. Mild peaks were shown at 9:00am, 11:30am, and between 1:30pm and 3:00pm. This was credited to characteristics of the delivery and shift schedules of several large delivery and manufacturing industries. The most significant proportion of trucks were single-unit (straight) trucks on local delivery with short trip distances, higher number of trips per day, and smaller payload. These trucks had pronounced peaks at the times indicated above. A very small number of trips used city streets for through trips. Depending on the location of the station, 25 to 40 % of the truck trips used the city streets just to access the highway.

2.2.5 Summary of Survey Methods

In addition to the case studies discussed above, a summary of the characteristics for urban truck travel surveys found in the literature is presented in **Table 2.1.**

Table 2.1. Summary of Truck Travel Survey Characteristics

Location	Year	Method	Surveys completed*	Response rate	Cost (US $)
Berks County, PA.	1994	Interview[2]/Mailback	1000+	.98/.06	NA
El Paso, TX.	1994	Phone[1]	188	0.43	65 000
Houston, TX.	1994	Phone[1]/Mailback	900	0.35-0.40	150 000
New York, NY.	1992-94	Interview[2]	14671	0.38	312 000
Phoenix, AZ.	1991	Phone[1]/Mailback	720	0.30	90 000
Alameda, CA.	1991	Phone[1]/Mailback/Interview[2]	NA/2200/8000+	NA/0.79/NA	NA
Ontario	1988	Interview[2]	19225	0.96	NA
Chicago, IL.	1986	Mailback	3506	0.25	200 000
Hamilton, ON.	1973	Phone[1]/Interview[2]	11077	NA	NA

*denotes approximate number
[1] implies a telephone interview
[2] implies a roadside/intercept interview

The following is a summary of the advantages and disadvantages of different truck travel survey methods.

Telephone Interview

- High response rate
- Easy to follow-up
- Can only call during business hours
- "Phone-tagging" problem
- Limited time on phone if respondent is busy
- Requires access to vehicle registration file

Mailout-Mailback

- Less costly
- Good response rate with certified mail
- Only follow-up of non-responses is necessary
- Low overall, and per item response
- Potential for bias in better response rate from some drivers/owners
- Low response from small truck owners
- Difficult to ensuring driver will fill out form, not owner or fleet manager
- Requires registration file

Combined Telephone-Mailout-Mailback

- Improved response rate over mailout-mailback alone
- Can identify early those owners who agree to participate those who are potential non-responses through phone contact
- Same disadvantages as telephone survey
- High cost of telephone follow-ups
- Need phone reminders for trip diary
- Costly

Roadside Intercept/ Interview

- Complete information
- High response rate
- Better sampling control
- Good representative sample of trucks entering/leaving cordon line
- Comparison with mainstream traffic through field counts at survey location
- Disruption to traffic
- Quality/conduct of survey affected by weather
- Time constraint
- Follow-up impossible
- Avoiding the survey station
- Only represent trucks traveling road along survey station, not entire region

The most common survey method for gathering vehicle travel data in urban areas was the *combined telephone/mailback* method. This method is cost-effective and yields a reasonably high response rate. The second most used survey method was the *roadside interview* method. This method produces very high response rates with complete information. They are ideal for cordon surveys or surveying trucks traveling in from outside the survey area.

2.2.6 Summary of Empirical Findings

Characteristics of Commercial Vehicles

- ***Average Vehicle Weight***: Only the Phoenix survey reported average vehicle weight. The average vehicle weight per commercial trip was 11,870 lbs.
- ***Truck Size***: The share of different truck sizes varied from urban area to urban area.

Characteristics of Commercial Vehicle Trips

- ***Average Trip per Commercial Vehicle***: Light trucks have a higher average trip frequency than for heavy trucks.
- ***Regional and Through Trips***: Most truck trips serve local regional needs. Through trips (usually less than 10%) are mostly made by heavy trucks.
- ***Average Trip Length***: Heavy trucks make longer trips than lighter trucks.
- ***Vehicle Miles Traveled***: Heavy trucks log a higher VMT per day than light trucks.
- ***Time of First Commercial Vehicle Trip***: Most "first" truck trips occur early in the morning (6:00-9:00am). This pattern, however, varies by weight category. Light trucks were more likely to start their first trip between 6:00 and 9:00am. Heavy trucks, however, started their first trip before 6:00am.
- ***Time-of-Day Distribution***: Most truck trips seem to occur during the midday period between 9:00am and 3:00pm. Truck "through" traffic seems to avoid peak periods and tend to travel at night.
- ***Truck Travel During Peak Periods***: The results vary by urban area and by individual locations. In New York, over 35% of trucks made trips during the morning peak period (6:00am to 9:00am). A comparison of morning and afternoon peaks for private vehicle travel found that the morning peak period travel was as important for commercial vehicles as for private vehicles.
- ***Truck Travel During Peak Periods as Percent of Total Vehicular Volume***: Truck traffic range from less than 9 % to as high as 17 % of the total vehicular volume during peak periods.
- ***Day-of-Week Distribution***: Truck traffic typically occurs on weekdays and decreases significantly on the weekends.
- ***Average Trip Duration***: Trip time generally increases with vehicle weight. The Phoenix survey recorded that the overall average trip time for truck travel was 28.1 minutes.
- ***Truck Travel by Facility Type***: Few surveys or studies have attempted to analyze truck trips based on facility types used. Only Ontario used facility types to classify their truck trips.

- ***Route Choice for Return Trips***: The only survey that analyzed route choice for return trips was the New York Truck Commodity Survey. It found that 73% of the truck drivers interviewed in the toll direction indicated that they would use the same route for the reverse trip.

2.2.7 Available Truck Data Sources

The Department of Motor Vehicles

In the U.S, the most common source for drawing a survey sample is the Department of Motor Vehicle (DMV) registration files. The DMV registers vehicles, issues license plates and renewal stickers, licenses vehicle dealers, and maintains vehicle records. Each state has its own DMV that collects and maintains information on the vehicle fleet in that state

R.L. Polk and Company:

This is the only centralized source for US-wide vehicle registration data. *Polk* compiles Department of Motor Vehicle (DMV) registration information from each state into their database on a quarterly basis. These data include, for each vehicle, information describing the make, model, fuel type, gross vehicle weight, and model year.

Vehicle information is stored and manipulated on two databases at *Polk.* The first database records light-duty vehicles and truck registrations according to make, model year, fuel type, and gross weight. Information was available from this database as of July 1, 1996. The second database contains heavy-duty trucks and school buses, again recording make, model year, fuel type, and gross vehicle weight.

Truck Inventory and Use Survey:

The Truck Inventory and Use Survey (TIUS) was conducted during 1992-1993, by the U.S Bureau of the Census. The database compiles statistically significant samples of on-road light duty and heavy-duty trucks. Each record is the equivalent of one vehicle. Data for each record is extensive, and includes the required attributes of age, gross vehicle weight and fuel type. Most importantly, the database records miles driven in calendar year 1992 by these vehicles. The data was used to determine mileage accumulation for light-duty and heavy-duty trucks.

Hamilton and Ontario Commercial Vehicle Surveys:

Major vehicle trip data sources used in the development of origin-destination (O-D) matrices for Hamilton consists of the Hamilton Truck Study (1973), the 1988 Ontario Commercial Vehicle Survey, and the 1998 Hamilton Commercial Vehicle Survey. The sources used to collect data are the 1986 Regional Count Program, the 1986 Regional Cordon Count program, City of Hamilton Traffic Counts and the 1986 Provincial Highway counts. Truck volumes were obtained from the 1986 and 1996 City of Hamilton and Regional traffic counts. The *Emme/2* model produced passenger car volume estimates to which the observed truck volumes were then added. Bi-proportional updating was used to transform tube data and intersection counts into an O-D truck travel matrix. Commercial vehicles include anything identified by an observer as being a vehicle used for commercial purposes. As a result, heavy and light-duty gas and diesel-powered vehicles ranging from pick-up trucks to trucks with six or more axles are included in the matrix. In this study, only data from the 1998 Hamilton Commercial Vehicle Survey was used.

2.2.8 Uses of Truck Data

"Truck travel and goods movement is essential to the economic vitality of an urban area. Trucks not only act as the "supply-line" from warehouses to points of consumption, they connect intermodal freight facilities" (Lau, 1995). As important as truck travel is to regions, it has negative effects such as contributing to traffic congestion, accidents, air pollution, noise, and pavement deterioration. For an urban area to undertake comprehensive truck planning, accurate and reliable truck travel data is needed for analysis. From the literature, truck data gathered from surveys is most commonly used in regional travel model development and route analysis.

Certain regions used the collected data for other purposes. Specifically, Ontario truck data have been used for time series comparisons, evaluation of road design, pavement management planning, truck-related accident analysis, dangerous goods movement regulation and enforcement, understanding truck driver characteristics and for planning truck driver education programs. The El Paso region has mainly used its truck data for regional travel and truck emissions modeling. Similarly, the Southern California Association of Governments (SCAG) has used truck travel data to estimate heavy truck VMT and model truck emissions. The Port Authority (New York) has used its truck data for traffic management purposes during highway and bridge/tunnel reconstructions and freight-economic analysis. While Chicago was able to generate truck activity maps from the data that was collected for that region.

Table 2.2. Summary of Truck Data Applications

Location	Year	Data Application
Berks County, PA.	1994	Estimation of truck movement patterns
El Paso, TX.	1994	Creation of truck travel model, part of regional travel study, truck emissions analysis
Houston, TX.	1994	Freight-economic analysis
New York, NY.	1992-94	Policy evaluation, management for highway reconstruction, freight-economic analysis
Phoenix, AZ.	1991	Time series freight analysis, Freight-economic analysis
Alameda, CA.	1991	Route analysis, create truck travel submodel, Generate 24hr., PM peak volumes by axle
Ontario	1988	Driver education, dangerous goods regulation & enforcement analysis, effects of tolls
Chicago, IL.	1986	Creation of truck travel & speed model, route analysis, effect of tolls, truck activity mapping
Hamilton, ON.	1973	Analyze the truck 'problem' of noise and congestion

Generally truck data has the following application:

Truck travel model development

- Truck trip generation
- Origin and destination analysis
- Local and highway route assignments
- Congestion and speed simulations
- Travel time analysis
- Spatial and temporal (time-of-day, day-of-week, and season) analyses

Corridor/Route analysis

- Evaluate route/corridor traffic management proposals for freight impacts
    - Formulate traffic management plans during roadway reconstructions
    - Assess impact of truck route reassignments or closures
    - Air quality modeling

Truck restrictions and enforcement

- Estimate truck emissions
- Route restriction analysis
- Dangerous goods movement regulation and enforcement analyses
- Truck driver safety programs

2.3 Modeling

2.3.1 Gravity Model: Iowa (1996)

In Iowa, to obtain a statewide truck demand model, the Gravity model was used to distribute the truck tonnage of freight among origin-destination pairs, using travel time as the impedance on highway links (Smadi and Maze, 1996). Estimated truck flows were converted to vehicle trips on least time highway routes using typical vehicle equivalent weights.

The specific steps followed are summarized as follows:

- determine prevailing economic activity by identifying major industry sectors, and locate their activity centres based on the distribution of sectoral employment
- identify major commodity groups produced and consumed by these sectors. Input-output analysis is used to identify other sectors' substantial interactions with major sectors
- estimate the freight tonnage generated (produced and demanded) at activity centres for the major commodity groups using employment, population, and input-output tables
- estimate truck share of total traffic originating in a zone as the freight tonnage produce minus the rail tonnage shipped from that zone. Similarly, destined truck traffic estimated as the attracted freight tonnage minus the rail tonnage shipped to that zone
- identify market location for commodities shipped to and from the state, base on available data. Each location is represented by a node signifying the activity centres. Internal locations represented by internal nodes correspond to counties in Iowa. External markets are represented by the states that have substantial freight shipments with Iowa. These nodes are connected by links representing least-travel-time highway routes between each pair of nodes to form a network model
- apply a Gravity model which uses travel time as the impedance factor to find truck travel distribution. The amount of freight tonnage produced in an origin is distributed among competing destinations within the network

- convert estimates of truck freight tonnage between origin-destination pairs into vehicle equivalents using average commodity truck weights, obtained from Iowa data; and
- determine main highway routes, least travel time links, used by major commodity movement.

2.3.2 Three-Stage Model: Vancouver, British Columbia (1988)

In 1988, the City of Vancouver and the Greater Vancouver Regional District (GVRD) conducted a truck survey. A GVRD Truck Model was developed. It was part of a region wide TRANSPORT 2021 project to recommend a long-range transportation plan for Greater Vancouver with associated policies, demand management measures, and priorities for transportation investment. The GVRD Truck Model was developed to estimate 24-hour light and heavy truck travel demand for current and future years. Light trucks are classified as having a gross vehicle weight (GVW) of 4,500-20,000 kilograms (kg). Trucks over 20,000 kg are classified as heavy trucks. The 1988 Truck Survey origin and destination data was used to calibrate the 1989 GVRD Truck Model. The model was subsequently validated to 1991 conditions using truck screenline data.

The model is broken down as follows:

- Traffic zone system: comprised of 445 traffic zones, based on population and employment densities. There are 11 external zones at entry points to the region to account for traffic entering and leaving the region

- Regional light and heavy truck network: The network is comprised of freeway, arterial and collector facilities. Each roadway link contains information on the number of lanes, posted speed limits, capacity, and turning restrictions, and
- Truck demand modeling procedure: This is a procedure that predicts the number of 24-hour light and heavy truck trips. This is a three-step procedure that includes: 1) trip generation, 2) trip distribution, and 3) trip assignment. The trip generation stage estimates the number of truck trips produced and attracted by each traffic zone based on population, wholesale, manufacturing, and non-wholesale employment for that zone. Modal split, another common stage in this Stage modeling process, is bypassed in this model as the only modes of concern are light and heavy trucks. Proportions of each light and heavy trucks were obtained from the 1991 truck screenline data.

The trip generation equations for light and heavy trucks are:

$$\text{Light}_i = 0.327Wh_i + 0.0213NWh_i + 0.0103Pop_i$$

where,

Light_i = 24-hour light truck trips produced by zone i

Wh_i = wholesale employment in zone i

NWh_i = non-wholesale employment in zone i

Pop_i = population in zone i

and,

$$\text{Heavy}_i = 0.164Wh_i + 0.0665Man_i$$

where,

$Heavy_i$ = 24-hour heavy truck trips produced by zone i

Wh_i = wholesale employment in zone i

Man_i = manufacturing employment in zone i

The trip distribution stage is applied using the "Fratar" modeling technique. Truck trips between origins and destinations are allocated based on the observed heavy and light truck trip distribution patterns. This stage produces a set of 24-hour trip tables for light and heavy trucks. External truck trips are subsequently added to these trip tables.

The final step involves trip assignment (allocating light and heavy truck trips to the digitized network). The network assignment is based on the link travel times derived from the 1991 automobile assignment. The three-step modeling process, together with the traffic zone system and digitized network system, produces estimates of 24-hour light and heavy truck link volumes. These 24-hour link volumes can be factored down to represent travel demands for different time periods during the day.

The GVRD Truck Model results produced the following findings for the base model year 1991:

- Light truck trips outnumbered heavy truck trips by 2 to 1 in the Vancouver region
- The number of daily truck trips in the GVRD exceeded 100,000 trips, and about 15 % of all truck traffic in the region had an origin or destination outside the region
- Truck traffic accounted for 3 % of total daily traffic, with almost 85 % of the truck traffic operating within Greater Vancouver
- External trucks accounted for 15 % of the total volume of goods movement into region
- The modeling effort identified regional roadways that complement primary highways and existing goods movement corridors and that are vital to port and industrial activities
- Significant increase in population, employment along regional roadways were identified
- This assumed growth prompted a need for new/upgraded transportation infrastructure for the movement of goods and passengers within these areas

The GVRD Truck Model results produced the following projections for the model year 2021:

- Total daily truck trips were forecasted to increase by approximately 85 % from 1991 to 2021. Light trucks were forecasted to increase with a faster rate than heavy trucks
- The number of heavy and light trucks entering Vancouver on a 24-hour basis was forecasted to increase by approximately 50 %
- Average truck speed was forecasted to decrease by 8 %
- Average trip distance was forecasted to increase by 6 %

The above forecasts indicated that trucks would experience higher levels of congestion in 2021.

2.3.3 Integrated Land-Use and Transport Model: Hamilton, Ontario (1994)

Integrated land-use and transport models address the relationship between urban land-use and transportation systems. Embedded within the formal structure of these models is the recognition that land-use influences the properties of transport infrastructure and travel behaviour which recursively affect spatial patterns of urban land-use (Miller et. al., 1998). These models can be used to simulate the affect of transport and land-use policies on the characteristics of transportation systems and patterns of urban land-use over time. Detailed reviews of existing operational models and applications can be found in Southworth (1995) and Miller et. al. (1998).

A detailed description of IMULATE, the model used in this study, is found in Anderson et. al. (1994). The general structure of IMULATE consists of four sub-models, and is illustrated in **Figure 2.1**. The first of these, POPMOB, handles intraurban migration and place of work assignment of the resident workforce within a system of 151 census zones. The second sub-model, TRANDEM, handles trip generation, distribution and mode split. TRANDEM estimates the number of work, school and discretionary (i.e. shopping, recreational) trips by mode. The

TRAFFIC ASSIGNMENT sub-model uses a stochastic user equilibrium algorithm to assign interzonal automobile trips (from TRANDEM) to a model of the Hamilton CMA's road network. The road network model consists of over 1100 nodes and 1500 links. The feedback between the transportation model and POPMOB is consistent with other operational models of this kind (Southworth, 1995).

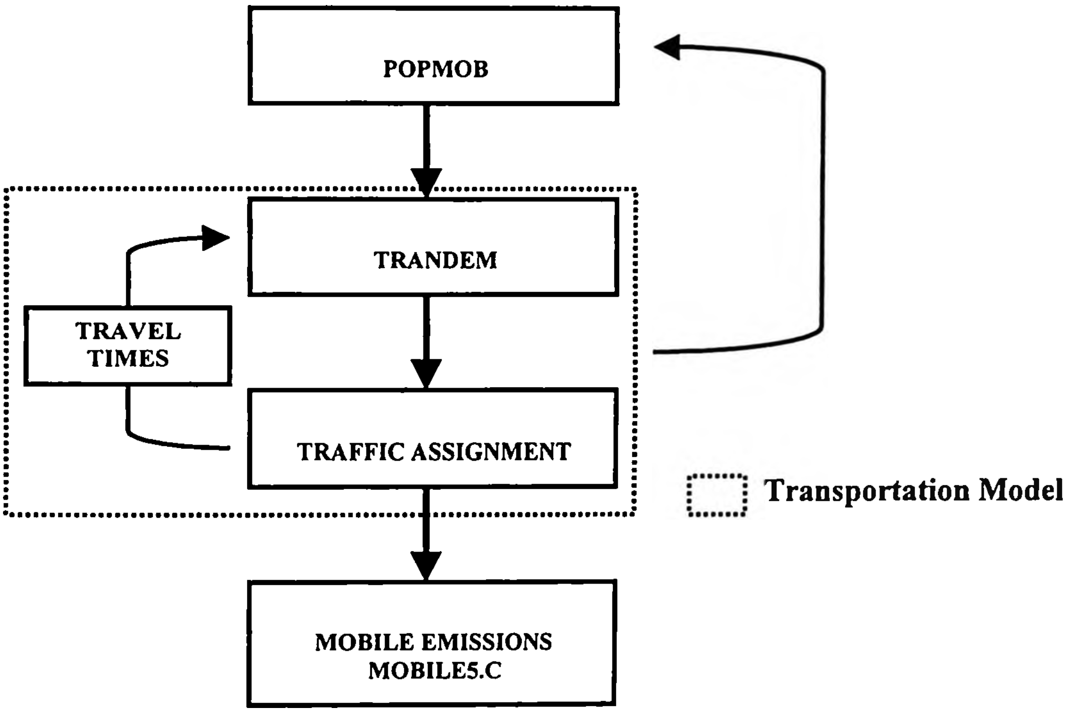

Figure 2.1: IMULATE Model Structure

The MOBILE EMISSIONS extension uses link flows and average speeds from the TRAFFIC ASSIGNMENT sub-model to estimate CO, HC and NO_x for each link. For this purpose, a formal link has been developed with MOBILE5.C, the Canadian version of the U.S. Environmental Protection Agency's (EPA) mobile source emissions model. Average link speeds are used as indicators of roadway congestion. Link speeds lower than those under free flow are considered representative of stop-and-go conditions, commonly associated with congested roadways. Under these conditions tail-pipe emission levels of HC and CO will be higher than under driving cycles associated with higher average speeds.

2.3.4 Summary of Transportation Models

The Gravity Model is the oldest of the models reviewed. A physical analogue model, the Gravity model is used to explain and predict spatial interaction, such as travel demand. The model uses 'mass terms' that indicate the ability of zones in the study area to attract and generate trips. An impedance term (travel time, distance) is used and weighted with a parameter. The next step in the evolution of transportation demand forecasting was the Stage Model. Usually a Four-Stage Model includes; trip generation, trip distribution, modal split, and trip assignment. The Four-Stage Model incorporates different types of Gravity Models in the trip generation and trip distribution stages, but includes a trip assignment stage. The most advanced model for travel demand forecasting is the integrated land-use and transportation model. Integrated land-use and transportation models simultaneously predict land use patterns and transportation system variables. IMULATE is an advanced integrated land-use and transport model that inputs relatively more information, and builds in 'behaviour' characteristics with the use of equilibrium mechanisms. Specifically, a stochastic user equilibrium approach, used in the traffic assignment stage, allocates trips in such a way that no network user believes they can change their travel time by unilaterally changing routes.

2.4 Conclusion

The preferred survey choice combines traffic counts and classifications with intercept interviews. Response rate is usually very high, but often drops slightly during peak hours to relieve delays. Generally, origin-destination (O-D) information is the most important. The benefits of different survey types and models were reviewed and analyzed.

This review indicates that there is information from only a few urban areas with extensive experience in conducting truck surveys and truck travel demand forecasting. Recently, only a few metropolitan areas have made available information on their efforts to collect truck travel data or develop new techniques in forecasting truck traffic. This chapter documented the experiences of a selection of different urban areas in the Canada and the U.S. over the past 20 years, with exception to cases in Hamilton, Ontario.

Chapter Three

Vehicle Classification Schemes, Emissions, and Emission Factors

3.1 Introduction

All travel demand and emission forecasting models use data as input. In some cases surveys are conducted to obtain the data required as input, while other times previously collected data is used. All modeling efforts recognize that different vehicle types emit in different ways. It is desirable, then, to properly classify vehicle type during data collection. From the literature and research, there are two main streams of vehicle classification. The EPA classifies by weight, while the MTO and Region of Hamilton-Wentworth classify by axle. Each method, or scheme, has benefits and drawbacks. Truck classification is usually a function of the available data sources and the desired use of the study.

3.2 Vehicle Classification Schemes

3.2.1 Classification by Weight (EPA)

Classification by weight is the method of classification preferred by the EPA (Environmental Protection Agency) and the developers of the MOBILE emissions modeling program. In the case of the EPA, many data sources were reviewed. The secondary sources of information include industry publications, Gallup Organization Final Report for the Motor Vehicle Manufacturers Association, 1993, 1995 Motor Vehicle Facts and Figures (American Automobile Manufacturers Association), Automotive Fleet 1994 Fact Book (Bobit Publication), 1996 Highway Statistics (Federal Highway Administration). The primary data sources included electronic databases from *R.L. Polk & Company*, the 1992 Truck Inventory and Use Survey (TIUS), and from the Federal Transit Administration (FTA).

Table 3.1 lists the individual vehicle type categories used by the EPA. Registrations and average annual mileage as a function of vehicle age were developed for each of these categories. With respect to registration, the EPA attempted to use 1996 as a base year for characterization. To develop the fleet characterization, they reviewed numerous data sources for relevant and accurate content. There are many uses to the classification in terms of forecasting, not the least of which is assigning emission factors to the various types of vehicles.

Table 3.1. The EPA Vehicle Classification Scheme

Vehicle Class Code	Vehicle Class	Weight (lbs.)
LDGV	Light Duty Gas Vehicles	Up to 6000
LDDV	Light Duty Diesel Vehicles	Up to 6000
LDGT1	Light Duty Gas Trucks	Less than 6000
LDGT2	Light Duty Gas Trucks	6001-8500
LDDT1	Light Duty Diesel Trucks	Less than 6000
LDDT2	Light Duty Diesel Trucks	6001-8500
HDGV (classes 2B-3)	Heavy Duty Gas Vehicles	8501-14000
HDGV (classes 4-8)	Heavy Duty Gas Vehicles	Greater than 14000
HDDV (class 2B)	Heavy Duty Diesel Vehicles	8501-10000
HDDV (class 3)	Heavy Duty Diesel Vehicles	10001-14000
HDDV (class 4-5)	Heavy Duty Diesel Vehicles	14001-19500
HDDV (class 6-7)	Heavy Duty Diesel Vehicles	19501-33000
HDDV (class 8A)	Heavy Duty Diesel Vehicles	33001-60000
HDDV (class 8B)	Heavy Duty Diesel Vehicles	Greater than 60000
HDGB (school)	Heavy Duty Gas Buses	Greater than 14000
HDGB (transit)	Heavy Duty Gas Buses	Greater than 14000
HDDB (school)	Heavy Duty Diesel Buses	Greater than 14000
HDDB (transit)	Heavy Duty Diesel Buses	Greater than 14000

3.2.2 Classification by Axles (MTO and the Region of Hamilton-Wentworth)

Classification by number of axles is the method of classification preferred by the MTO (Ministry of Transportation of Ontario) and the Region of Hamilton-Wentworth. In the case of the MTO, concerns on privacy and misuse of data restrict the amount of information available. **Tables 3.2** and **3.3** show the MTO and Hamilton-Wentworth schemes respectively.

Table 3.2. The MTO Vehicle Classification Scheme

Short Trucks	**Long Trucks**
(Heavy 2 & 3 axle - Single Units)	*(Transports - Combination Units)*
Heavy Truck (dual rear tires)	Combination Unit (3 axles)
Dump Truck	Combination Unit (4 axles)
Stake Truck	Combination Unit (5 axles)
Tractor w/o trailer (2 axles)	Combination Unit (6 axles)
Single Unit Trucks (3 axles)	Combination Unit (7 axles)
Tractor w/o trailer (3 axles)	Combination Unit (8 axles)
Tank Truck (single unit)	Combination Unit (9 axles)
Van (dual rear tires)	
Motor Home	

While similar in characteristic of classification (number of axles), there are differences in **Tables 3.2** and **3.3**. These two tables demonstrate that even similar schemes in similar areas are not always comparable or interchangeable.

Table 3.3. The Hamilton-Wentworth Vehicle Classification Scheme

Vehicle Class	**Vehicle Type**	**# of axles**
2	Car, pick-up, van	2
1	Subcompact	2
3	2-axle light truck	2
6	3-axle single unit truck	3
4	Bus	2
12	3S2 tractor trailer	5
14	6 or more axles	6
11	2S2 tractor trailer	4
5	Car with 1-axle trailer	3
9	4-axle single unit truck	4
13	Other 5 axle	5
8	Car with 2-axle trailer	4
7	2S1 tractor trailer	3
10	3S1 tractor trailer	4

3.2.3 Summary of Classification Schemes

The MTO, the EPA and the Region of Hamilton-Wentworth have developed classification schemes independently, but for similar reasons, to forecast travel demand and emissions. The MTO and Hamilton-Wentworth traffic counts are often done by 'tube' data counts and augmented with human observation of traffic characteristics. Hence, the MTO scheme is based on visual cues, (single versus a combination unit) and on axles (easily counted with the tube). Traffic counts are gathered at point sources and extrapolated to an entire origin-destination matrix. By definition the matrix produced, and results from the matrix are necessarily crude, as crude algorithms must be applied to extrapolate the point-source data to a matrix. The EPA is in a position to draw on more resources (the *Polk*, TIUS, and DMV databases), and produce much more detailed classifications (based on engine type, model years etc.). While the MTO can produce only crude estimates, the cost to the MTO for data collection is considerably less than for the EPA who must commission and purchase databases from for-profit companies. Both schemes are functions of the available data and resources.

3.3 Pollutant Description and Emission Factors

3.3.1 Hydrocarbon (HC)

Hydrocarbon emissions result when fuel molecules in the engine do not burn or burn only partially. Hydrocarbons react in the presence of nitrogen oxides and sunlight to form ground-level ozone, a major component of smog. Ozone irritates eyes, damages lungs, and aggravates respiratory problems. A number of exhaust hydrocarbons are also toxic, with the potential to cause cancer.

3.3.2 Carbon Monoxide (CO)

Carbon monoxide (CO) is a colorless, odourless, poisonous gas. CO is a product of incomplete burning of hydrocarbon-based fuels and is emitted directly from vehicle tailpipes. Carbon monoxide enters the bloodstream through the lungs and inhibits the blood's capacity to carry oxygen to organs and tissues.

3.3.3 Oxides of Nitrogen (NO_x)

Nitrogen oxides (NOx) consist of nitric oxide (NO), nitrogen dioxide (NO2) and nitrous oxide (N2O) and are formed when nitrogen (N2) combines with oxygen (O2). Nitric oxide has no colour, odour, or taste and is non-toxic. In the air it is rapidly oxidized to nitrogen dioxide. Nitrogen oxides, like hydrocarbons, are precursors to the formation of ozone. They also contribute to the formation of acid rain. Nitric oxide by itself is non-toxic, but it is readily converted in the air to nitrogen dioxide. At high concentration levels, nitrogen dioxide is potentially toxic to plants, can injure leaves and reduce growth and yield. In combination with either ozone (O3) or sulphur dioxide (SO2), nitrogen dioxide may cause injury at even lower concentration levels. Nitrogen dioxide is a reddish-brown gas that absorbs light and can lead to a yellow-brown haze. It is one of the important components of smog, and as such, nitrogen dioxide is known to irritate the lungs and increase susceptibility to respiratory infections.

3.3.4 Particulate Matter (PM)

Particulate matter (PM) is the term for solid or liquid particles found in the air. Some particles are large or dark enough to be seen, while others can be detected only with an electron microscope. PM originates from a variety of mobile and stationary sources (diesel trucks, wood stoves, power plants, etc.), and its chemical compositions vary widely. Particulate matter can be directly emitted or can be formed in the atmosphere when gaseous pollutants such as SO_2 and NO_x react to form fine particles. What distinguishes PM from other emission factors, is that particulate emission factors for diesel-powered vehicles are not adjusted for vehicle speed (USEPA, 1995).

The emission factors calculated by the EPA include the particulate pollutant compounds of lead, sulfate, soluble organic fraction particulate, remaining carbon portion particulate, and total exhausted particulate. The lead and sulfate are formed from the lead and sulfur contained in the fuel. The soluble organic fraction consists primarily of hydrocarbons coming from unburned or partially burned fuel and lubricating oil. The remaining carbon portion consists of soot-like carbon (elemental carbon) and trace amounts of other components from the fuel and lubricating oil. The total exhaust particulate is the sum of these four categories. In addition to these categories of exhaust emissions, idle exhaust emissions, brake wear, tire wear, fugitive dust, indirect sulfate, and gaseous sulfur dioxide are also calculated.

The model calculates the emission factors for 12 vehicle classes and a fleet-wide average (estimated by vehicle miles traveled [VMT] weighting of the emission factors for all 12 classes). The vehicle classes include light-duty gasoline vehicles, two classes of light-duty gasoline trucks, heavy-duty gasoline trucks, motorcycles, light-duty diesel vehicles, light-duty diesel trucks, four classes of heavy-duty diesel trucks, and buses. To account for older vehicles on the road, the emission factors reported for each vehicle class are composites of emission factors for vehicles 25+ years old through the calendar year of evaluation (the calendar year of evaluation is provided by the user).

Lead Emission Factors (Gasoline vehicles only)

Lead particulate emission factors are based on the assumption that virtually all the lead in fuel is exhausted. As a result, the emission factors (in units of grams per mile) depend principally on the lead content in the fuel and the fuel economy of the vehicle (in miles per gallon). The lead content of leaded fuel is substantially greater than that of unleaded fuel, so the fraction of vehicles that have had their catalysts removed (and thus are assumed to be using leaded fuel in most cases) can also be an important factor in determining the lead emission factor from a vehicle that is representative of the entire fleet.

Sulfate Emission Factors

The particulate sulfate emission factors consist of direct and indirect sulfate material. The direct sulfate is exhausted as sulfuric acid, and the indirect sulfate is formed later in the atmosphere from exhausted SO_2. The indirect sulfate in the model is calculated based on the assumption that it consists entirely of ammonium sulfate and ammonium bisulfate. The direct sulfate, indirect sulfate, and gaseous sulfur are all computed in the model.

Total Exhaust Particulate

The emission factors for heavy-duty vehicles are expressed in g/BHP-hr, which are converted to g/mi in PART5. The conversion factors (USEPA, 1988b) and emission factors both vary by model year. The emission factors for light-duty diesel vehicles and trucks are in units of g/mi. The total exhaust emission factors given in **Table 3.4** are based on high sulfur fuel. High sulfur is defined as 2500 parts per million (ppm) for diesel fuel prior to 1993, 500 ppm after 1993, and 340 ppm for gas.

Table 3.4. Exhaust Particulate Emission Factors for Diesel Vehicles

Vehicle Type/Model Year Group	**Exhaust Particulate Emission Factor**
Light Duty Diesel Vehicles:	(g/mi)
pre-1981	.700
1981	.259
1982-1984	.256
1985-1986	.255
1987	.134
1988-1990	.132
1991-1993	.131
1994-1995	.128
1996 and newer	.100
Light Duty Diesel Trucks:	
pre-1981	.700
1981	.309
1982-1984	.354
1985-1986	.358
1987	.334
1988-1990	.291
1991-1993	.294
1994-1996	.130
1997 and newer	.109
Class 2B of Heavy Duty Diesel Vehicles:	(g/BHp-hr)
pre-1988	.5156
1988-1990	.5140
1991-1993	.2873
1994 and newer	.1011
Light Heavy Duty Diesel Vehicles:	
pre-1988	.5156
1988-1990	.5140
1991-1993	.2873
1994 and newer	.1011
Medium Heavy Duty Diesel Vehicles:	
pre-1987	.6946
1988-1990	.4790
1991-1993	.2747
1994 and newer	.0948
Heavy Heavy Duty Diesel Vehicles:	
pre-1987	.6444
1988-1990	.4360
1991-1993	.2709
1994 and newer	.0836

The remaining carbon portion consists of soot-like carbon (elemental carbon) and trace amounts of other components from the fuel and lubricating oil.

Table 3.5. Carbon Emission Factors for Gasoline Vehicles (g/mi)

	Leaded	Unleaded		
Vehicle Type/ Model Year Group		**Catalyst (No-Air)**	**Catalyst (Air)**	**Non-catalyst**
Light Duty Gasoline Vehicles:				
pre-1970	0.1930			0.0300
1970-1974	0.0680	0.0060	0.0250	0.0300
1975-1980	0.0300	0.0060	0.0250	0.0300
1981 +	0.0170	0.0043	0.0043	0.0170
Light Duty Gasoline Trucks I:				
pre-1970	0.1930			0.0300
1970-1974	0.0680	0.0060	0.0250	0.0300
1975-1986	0.0300	0.0060	0.0250	0.0300
1987 +	0.0170	0.0043	0.0043	0.0170
Light Duty Gasoline Trucks II:				
pre-1979	0.3700			0.0540
1979-1986	0.0680	0.0060	0.0250	0.0300
1987 +	0.0300	0.0043	0.0043	0.0170
Heavy Duty Gasoline Vehicles:				
pre-1987	0.3700	0.0540	0.0540	0.0540
1987 +	0.1630	0.0540	0.0540	0.0540

3.3.5 MOBILE

The EPA highway emission factor model, MOBILE5 ('a' and 'c'), calculates average in-use emission factors for hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) for numerous vehicle categories of vehicles. These emission factors are expressed in units of grams per mile (g/mi) and are used in combination with data on vehicle miles traveled (VMT) to estimate highway vehicle contributions to mobile source emission inventories.

Since the release of MOBILE5, very little new data on in-use heavy-duty engines, using representative driving cycles, has been produced. In lieu of actual data on in-use engines, the EPA has proposed the use of test data required by the EPA from engine manufacturers for new engine certification as a surrogate for in-use emissions data. Under the EPA certification test procedure, manufacturers are required to submit emissions data on new engines using an engine dynamometer test. The engines are run on a transient engine dynamometer test cycle (developed from in-use data), and emission results are given in grams of pollutant per brake horsepower-hour.

Using this EPA engine dynamometer test cycle in the cooperative test program between EPA and engine manufacturers, the test results indicated that emission-control performance in heavy-duty vehicles does not suffer from significant deterioration. Given that these test data indicate that emission controls on these engines do not deteriorate greatly over time, and because the EPA engine dynamometer test cycle was developed to closely represent the in-use behavior of these engines, the EPA assumed for this analysis that the emission levels produced by the certification test procedure are representative of the average in-use emission levels.

3.4 Conclusion

While there are many possible ways to classify vehicles, two schemes currently dominate the research. Both schemes have merit and are functions of the resources of those that collect vehicle travel data. While the EPA's scheme lends itself to better vehicle description, it is more costly to collect. The classification-by-axle scheme is relatively inexpensive to collect through the use of 'tube' data that simply records the number of axles driving over the tube. The EPA scheme often involves video scans of license plates and draws on DMV files to obtain detailed information about the vehicle. With such information about the vehicle fleet, the matter of selecting and assigning emission factors is efficient and effective. Such resources are not available to the MTO or to the City of Hamilton-Wentworth.

Chapter Four

Data and Methodology

4.1 Introduction

The method used in this study can be divided into four phases **(Figure 4.1)**. In the first phase trucking data was acquired from the City of Hamilton in the form of an origin-destination matrix. Each cell of this matrix records the number of commercial vehicles traveling between two zones located within the City of Hamilton. This matrix is discussed in detail in section **4.3**.

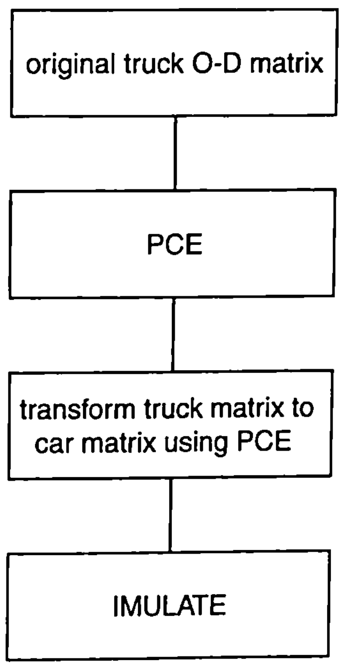

Figure 4.1: General Method Structure

In phase two, the concept of passenger car equivalency was studied and a methodology for its application to this study was developed. The PCE concept is discussed in section **4.4**.

The third phase involved the transformation of the trucking data into a set of passenger car equivalent matrices. In phase four an integrated land-use and transport model, IMULATE, was modified to accommodate transformed truck trip matrices. It was during this phase that estimates of HC, CO, and NO_x emissions were derived. IMULATE was discussed in Chapter 2, section **2.3.3**. In section **4.5** a separate procedure for estimating PM emissions is discussed.

4.2 The Study Area

The CMA of Hamilton is located on the west shore of Lake Ontario approximately 75km from Toronto. It has a population of roughly 500,000 with much of this population concentrated on the southern shore of Hamilton Harbour. Characteristics of site and economics help to explain the current status of urban air quality within the Hamilton CMA (HAQI, 1997).

4.3 Data Collection and Flow Matrix Determination

IMULATE's transportation model has been adjusted to include an origin-destination matrix of morning peak hour (7:00-8:00am) commercial vehicle flows within the Hamilton CMA. Bi-proportional updating was used to transform tube data and intersection counts into this matrix. Commercial vehicles include anything identified by an observer as being a vehicle used for commercial purposes. As a result, heavy and light-duty gas and diesel-powered vehicles ranging from pick-up trucks to trucks with six or more axles are included in the matrix. This matrix was generated from data collected during the 1998 Hamilton Commercial Vehicle Survey.

Trip-ends within certain CMA municipalities (Burlington and Grimsby) have not been included due to incomplete enumeration. The aggregate nature of the commercial vehicle matrix imposes a limitation on this study in that specific vehicle types cannot be extracted.

Empirical evidence suggests that the accuracy of mobile source emission estimates may be affected by the ability to control for road conditions and certain properties of the vehicle fleet (i.e. combustion process, vehicle type etc.). Ideally, a suitable classification scheme of trucks should be established before the assignment of emission factors. A universally acceptable truck classification scheme does not exist. For example, the U.S. EPA classifies trucks by weight, while the Ontario Ministry of Transportation (MTO) and the Regional Municipality of Hamilton-Wentworth classify trucks by axle (Kanaroglou and Taylor, 1999).

4.4 A Passenger Car Equivalency (PCE) Approach

Passenger Car Equivalencies (PCEs) have been used in the past to assess the effects of heavy-duty vehicles such as buses, recreational vehicles and trucks on traffic conditions (Elefteriadou et. al., 1997). PCE values measure the number of base vehicles (usually passenger cars) displaced from traffic flow due to the presence of heavy-duty vehicles (Elefteriadou et. al., 1997). PCE estimation techniques are reviewed in detail in Elefteriadou et al. (1997).

The literature suggests that PCE values vary by truck type, grade, road type, volume and vehicle mix (Elefteriadou et. al., 1997). In this study, a representative PCE value has been derived that controls for road type and access to specific truck routes. Vehicle type and grade are not considered. The aggregate nature of the truck trip matrix does not allow for the estimation of different PCE values for various vehicles types. The grade of the road is ignored as the entire transport network in the study area is characterized by links of moderate to low slope.

4.4.1 Truck Type

Addressing the contribution of trucks to mobile source emissions requires consideration of the type of truck(s) being modeled. Another data source was needed to address truck type due to the lack of detailed information in O-D matrix. At the time of the traffic counts (used to generate the truck O-D matrix), some vehicle classification was done at certain intersections, using a 14-class scheme. To describe the truck fleet, 28 of these intersections were selected at random and class counts for the morning peak hours were calculated **(Table 4.1)**.

Table 4.1. Vehicle classes used in Hamilton-Wentworth

Vehicle Class	Vehicle Type	# of axles	% of peak flow*	Rank**
2	Car, pick-up, van	2	65.63	1
1	Subcompact	2	18.50	2
3	2-axle light truck	2	10.70	3
6	3-axle single unit truck	3	1.39	4
4	Bus	2	1.16	5
12	3S2 tractor trailer	5	0.84	6
14	6 or more axles	6	0.48	7
11	2S2 tractor trailer	4	0.33	8
5	Car with 1-axle trailer	3	0.30	9
9	4-axle single unit truck	4	0.20	10
13	Other 5 axle	5	0.17	11
8	car with 2-axle trailer	4	0.14	12
7	2S1 tractor trailer	3	0.11	13
10	3S1 tractor trailer	4	0.02	14

* refers to the percent of the total vehicle flow at the peak hour that class comprises.

** denotes the order the classes rank in terms of percent of peak flow

Counts were summed for each class over these morning peak hours for each intersection. These sums were divided by the total sum for all vehicle classes at each intersection. The vehicle classes were then ranked based on percentage. The highest ranked class, strictly limited to trucks, was Vehicle Class 3 (2-axle light truck), comprising roughly 10.7% of the total vehicle flow over sampled intersections. Vehicle Class 3 was deemed the 'average truck' in the Hamilton fleet. This can be compared with a 'Single Unit Truck (SUT), with a length of 12.2m and a weight-to-horse power ratio of 300' defined in Elefteriadou et al. (1997). In turn, the EPA defines this SUT as a light duty diesel truck (LDDT) (USEPA, 1993a). It is this truck class that is used to model the presence of trucks in this study. The rationale for not addressing other classes of trucks is that the sparse nature of the O-D matrix would negate the effect of emissions generated by other truck types. The sum of all truck vehicle classes is 14.24% of all vehicles. This is consistent with the percent of trucks in traffic flow found in Elefteriadou et al. (1997).

4.4.2 Road Type and Number of Lanes

Trucks within the Hamilton CMA are restricted, by law, to a subset of links of the entire road network. This truck road network is shown in **Figure 4.2.** Road type and the number of lanes were controlled for by identifying which links on the truck road network were "freeways", "arterials", and "two-lane highways with low flows".

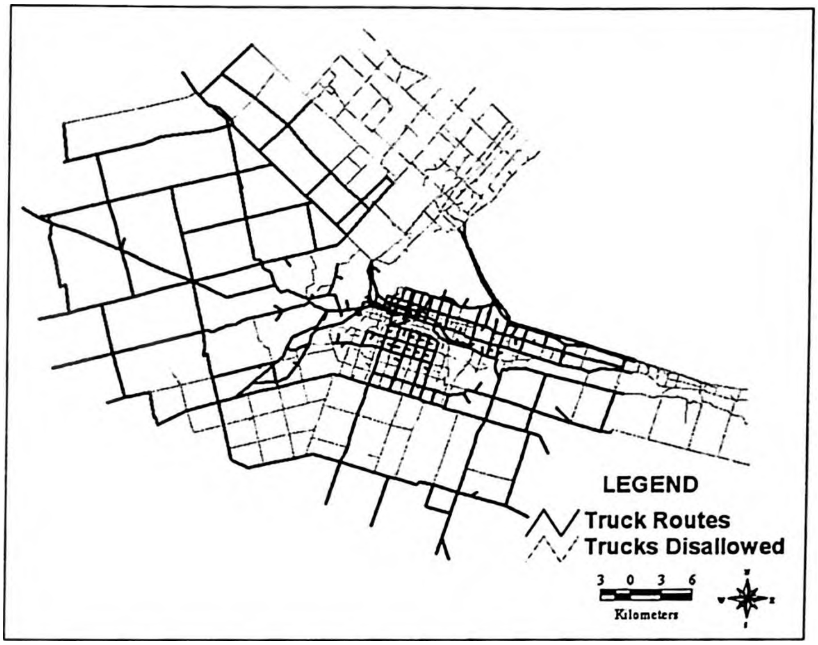

Figure 4.2: Hamilton-Wentworth Trucking Routes

These are the three road types that influence the assignment of PCE values (Elefteriadou et. al., 1997). Tables in Elefteriadou et al. (1997) were used as a guide in determining PCE values. Freeways, two-lane highways, and arterials with four lanes are given a PCE value of 2, while arterials with two lanes are given a PCE value of 5. Arterials do not provide an opportunity for passing, and therefore the impact of heavy vehicles is more pronounced. The mean PCE was found to be 2.48 over 805 truck route links. A PCE of 2.48 implies that roughly two and half passenger cars are displaced from the traffic flow for every individual truck. The upper and lower bounds of a 90% confidence interval were 2.544 and 2.416 respectively. In the interest of sensitivity analysis it was decided that PCE values other than the mean, the lower and upper bounds of the confidence interval were needed. PCE values of 0, 1, 2, 2.42, 2.48, 2.54, 3, 4 and 5 were chosen for the purpose of conducting simulations. The truck O-D matrix was multiplied by each of these scalars, creating six separate PCE matrices. Simulations were run, and emissions recorded for each PCE step and compared. A PCE value of zero, or the 'cars only' scenario, implies the total absence of trucks in the network. Cars are denoted by the EPA, and in this study, as light duty gas vehicles (LDGV). LDGVs in the Hamilton CMA are assumed to be using unleaded fuel and to be catalyst equipped.

4.5 PM Estimation

The MOBILE5C emissions model does not estimate particulates. As a result, a separate methodology for the estimation of link and aggregate levels of PM has been developed. In this section, the methodology will be explained and results will be presented. Particulate emissions come from a variety of sources including combustion exhaust, tire wear, brake wear, idle emissions, and fugitive dust. In this study, IMULATE is used in conjunction with EPA PM emission factors for combustion exhaust, tire wear, and brake wear to generate PM estimates. Due to data limitation, other particulate emissions factors such as idle emissions and fugitive dust are not included.

Literature from the EPA suggests that the total exhaust particulate emission factor for light-duty gasoline vehicles (LDGV) is calculated from the sum of lead, direct sulfate, and a carbon emission factor which includes soluble organics and other remaining carbon (USEPA, 1985a). Carbon is the primary element of diesel and gas powered mobile source combustion. Lack of detailed information on the Hamilton CMA vehicle fleet prohibits the use of lead and direct sulfate emission factors.

4.5.1 Selecting PM Emission Factors

Due to the lack of information on the vehicle fleet in the Hamilton CMA, in this study, the carbon emission factor is used to calculate PM exhaust emissions. Model year and the technology type of trucks and cars affect the carbon emission factor (USEPA, 1985a; USEPA, 1993a). Average age of the Hamilton CMA vehicle fleet (model year) was approximated from U.S. data, collected by Polk (The Polk Data Company, 1998).

The average model year for both the car and truck fleet was found to be 1990. This was an estimate obtained as follows. The simulation that estimated PM ran from 1996 to 2001, as described in the following chapter. The midpoint of this estimation would be half way through 1998. In 1996, the average age of cars was 8.3 years (The Polk Data Company, 1998). Subtracting the average age (roughly eight and a half years) from the year of estimation left a model year of 1990.

The nearest EPA age category for cars (LDGVs) was 1981 and newer. The PM exhaust emission factor for this category is 0.0043 gram/mile. To determine the amount of PM of certain particle sizes, a Particle Size Cutoff (PSC) is applied to this emission factor (USEPA, 1985a). The PSC is defined to be the maximum aerodynamic diameter (between 1.0 and 10.0um) of the particles in the emission factors (USEPA, 1985a). PM_{10} (defined as being 10 micrometers or less) is of particular concern due to its association with cardio-respiratory hospitalisations (Burnett et. al., 1999). In this study a PSC of PM_{10} is modeled as it is harmful to human health (HAQI, 1997) and includes smaller PM sizes such as $PM_{2.5}$. The fraction of particles less than or equal to the PSC is determined from fractions in EPA 1985a. For catalyst equipped LDGVs, 1981 and newer, using unleaded fuel the fraction of particles less than or equal to PM_{10} is 0.98 (USEPA, 1985a).

The flow on each link was multiplied by the length (in miles) of that link in the 'cars only' scenario to get total number of car miles traveled (CMT). CMT was then multiplied by the carbon emission factor for light duty, unleaded gasoline vehicles 1981 and newer. The total amount of particulate matter emitted from combustion exhaust for LDGVs on a typical day from 1996-2001 was 8 kilograms.

For the purposes of this study, it is assumed that the Hamilton truck fleet, and the average truck used to represent the fleet as a whole, is a light duty diesel truck (LDDT). This was necessary to describe the Hamilton CMA truck fleet and attach PM emission factors. In 1996, the average age of trucks was 8.6 years (The Polk Data Company, 1998). Subtracting the average age (roughly eight and a half years) from the year of estimation left a model year of 1990.

The PM exhaust emission factor for this category (LDDT, 1990) is 0.291 gram/mile. Again, to determine the amount of PM_{10} a PSC is applied. For all model years of all diesel vehicles, including 1990 LDDT, the fraction of particles less than or equal to PM_{10} is 1.00 (USEPA, 1985a).

For the purpose of estimating PM, the road network in this study is broken into links that are truck routes and links that are non-truck routes, as described in section 4.4.2. Intersection counts reveal that trucks account for approximately 15% of the volume on truck route links.

4.5.2 PM Estimation Methodology

The PM exhaust (***PME***) estimates for truck route links, *i*, are calculated by:

$$\boldsymbol{PME_i} = (0.15\, \boldsymbol{f_i}\, \boldsymbol{l_i}\, \boldsymbol{EE_{LDDT}}\, \boldsymbol{PSC_{LDDT}}) + (0.85\, \boldsymbol{f_i}\, \boldsymbol{l_i}\, \boldsymbol{EE_{LDGV}}\, \boldsymbol{PSC_{LDGV}})$$

where f_i is the total traffic volume on truck route link i, l_i is the length of truck route link i in miles, EE_{LDDT} is the light duty diesel truck PM exhaust emission factor (0.291 g/mile), PSC_{LDDT} is the fraction of particles less than or equal to PM_{10} for light duty diesel trucks (1.00), EE_{LDGV} is the light duty gas vehicle PM emission factor (0.0043 g/mile), and PSC_{LDGV} is the fraction of particles less than or equal to PM_{10} for light duty gasoline vehicles (0.98).

The PM exhaust estimates for non-truck route links, j, are calculated by:

$$PME_j = (f_j \; l_j \; EE_{LDGV} \; PSC_{LDGV})$$

where f_j is the total traffic volume on non-truck route link j, l_j is the length of non-truck route link i in miles, EE_{LDGV} is the light duty gas vehicle PM emission factor (0.0043 g/mile), and PSC_{LDGV} is the fraction of particles less than or equal to PM_{10} for light duty gasoline vehicles (0.98).

PM from combustion exhaust for the entire system is given by:

$$PME_{total} = \sum_{i=1}^{n} PME_i + \sum_{j=1}^{m} PME_j$$

The PM tire wear and brake wear emission factors for all vehicle categories and model years are 0.002 gram/mile/tire, and 0.0128 gram/mile respectively (USEPA, 1985a). A PSC for PM_{10} is applied to these emission factors as well.

The tire wear emission factor for all vehicle categories and model years ($TWEF_{av}$) in grams/mile is calculated as:

$$TWEF_{av} = (0.002 \; PSCtire_{av} \; ANOT_v)$$

where $PSCtire_{av}$ is the tire particle size cutoff for PM_{10} for all vehicles (1.00), $ANOT_v$ is the average number of tires per vehicle. For both LDDT and LDGV, $ANOT_v$ is 4 (USEPA, 1985a).

The PM tire wear (*PMTW*) estimates for truck route links, *i*, are calculated by:

$$PMTW_i = (f_i \ \ l_i \, TWEF_{av})$$

where f_i is the total traffic volume on truck route link *i*, l_i is the length of a link in miles, $TWEF_{av}$ is the PM tire wear emission factor for all vehicles (0.008 g/mile).

Similarly, the PM tire wear (*PMTW*) estimates for non truck route links, *j*, are calculated by:

$$PMTW_j = (f_j \, l_j \, TWEF_{av})$$

PM from tire wear for the entire system is given by:

$$PMTW_{total} = \sum_{i=1}^{n} PMTW_i + \sum_{j=1}^{m} PMTW_j$$

The brake wear emission factor for all vehicle categories and model years ($BWEF_{av}$) in grams/mile is calculated as:

$$BWEF_{av} = (0.0128 \, PSCbrake_{av})$$

where $PSCbrake_{av}$ is the brake particle size cutoff for PM_{10} for all vehicles categories and model years (0.98).

The PM brake ware (*PMBW*) estimates for truck route links, *i*, are calculated by:

$$PMBW_i = (f_i \, l_i \, BWEF_{av})$$

where f_i is the total volume on truck route link *i*, l_i is the length of a link in miles, and $BWEF_{av}$ is the PM brake wear emission factor for all vehicles (0.0125 g/mile).

Similarly, the PM brake ware (***PMBW***) estimates for non truck route links, *j*, are calculated by:

$$PMBW_j = (f_j\, l_j\, BWEF_{av})$$

PM from brake wear for the entire system is given by:

$$PMBW_{total} = \sum_{i=1}^{n} PMBW_i + \sum_{j=1}^{m} PMBW_j$$

Total PM for the entire system, then, is the sum of the PM from combustion exhaust, brake wear and tire wear.

$$PM_{total} = PME_{total} + PMTW_{total} + PMBW_{total}$$

4.6 Conclusion

Using the concept of passenger car equivalency, the integrated land-use and transport model IMULATE, and emission factors from the EPA, a methodology to estimate the contribution of trucks to PM has been presented. It is recognized that vehicles produce PM from various sources including tire wear, brake wear and exhaust, amongst others. The data source available for this study only allowed for the estimation of the sources named above. A methodology for the estimation of each source, and the total was developed and presented.

Chapter Five

Results

5.1 Introduction

IMULATE was run for passenger cars, starting at base year 1986 and running to 2006 at five-year intervals. The road network was updated at each five-year period as required (i.e. the Lincoln Alexander Expressway was added in 1996). A PCE value of zero, or the 'cars only' scenario, implies the total absence of trucks in the network. Reported emission values in this case are attributed to passenger cars alone. This is the base scenario against which all subsequent scenarios involving trucks with PCE values are compared. Using this methodology, the relative contribution of trucks can be shown at the link level, or aggregated to the regional level.

5.2 Results

5.2.1 Aggregated Regional Results

Table 5.1. Aggregate emissions and trips made for varying PCE values

	HC		CO		NO_x		PM		Trips	
PCE	**Kg**	**%***	**Kg**	**%***	**Kg**	**%***	**kg**	**%***	**trips**	**%***
0.00	12929	0.0	137556	0.0	9476	0.0	47	0.0	174996	0.0
1.00	14035	8.6	149563	8.7	9877	4.2	99	111.3	183452	4.8
2.00	15275	18.1	163174	18.6	10299	8.7	104	121.7	192297	9.9
2.42	15865	22.7	169707	23.4	10478	10.6	106	125.9	195851	11.9
2.48	15955	23.4	170700	24.1	10507	10.9	107	126.5	196396	12.2
2.54	16033	24.0	171560	24.7	10534	11.2	107	127.2	196960	12.6
3.00	16641	28.7	178250	29.6	10733	13.3	109	131.9	200940	14.8
4.00	18071	39.8	193956	41.0	11181	18.0	114	142.4	209798	19.9
5.00	19592	51.5	210879	53.3	11634	22.8	119	152.9	218686	25.0

* denotes percent increase over the 'cars only' scenario

Increasing the PCE value is equivalent to increasing the volume of vehicle traffic that will be loaded onto the network. This serves as a proxy for the presence of truck traffic. The procedure of loading additional base vehicles onto the network leads to increased load on network links. In certain cases (e.g. truck routes) increased link congestion and lower average link speeds result. The relationship between certain mobile source emissions (HC, NO_x, and CO) and average link speed is known to be non-linear (Anderson et. al., 1996). The relationship between PCE values and the percent increase over PCE 0.00 of HC, NO_x, CO, and trips is shown in **Figure 5.1**.

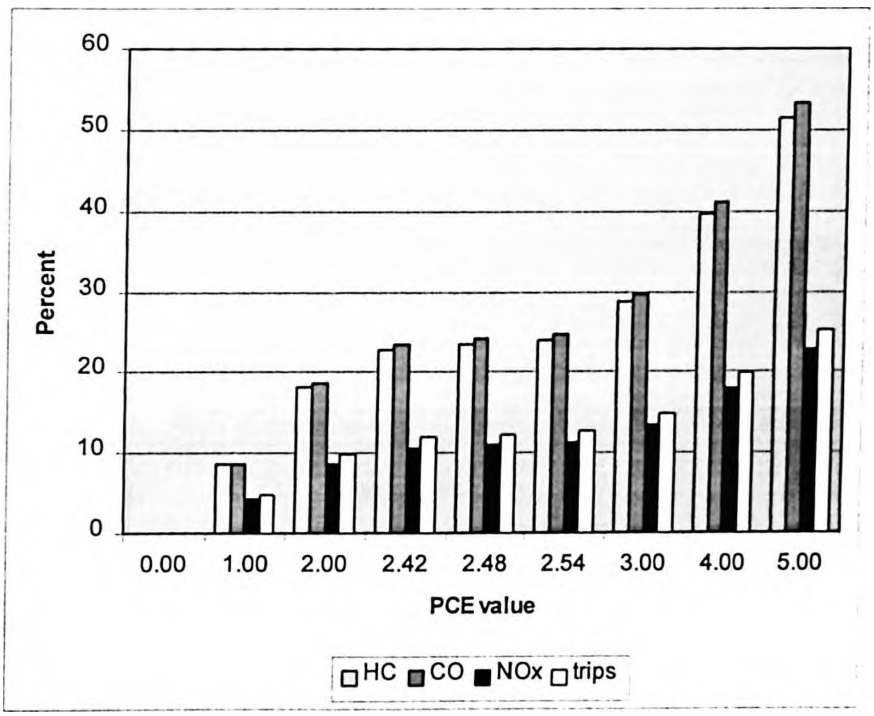

Figure 5.1: Percent increase in HC, CO, NOx, and trips with varying PCE

Particulates behave differently than the other emissions with respect to average link speed. HC and CO in **Figure 5.1** increase non-linearly with decreasing average speeds. PM is not as affected by average speed so much as it is by the number of trips taken **(Figure 5.2)**.

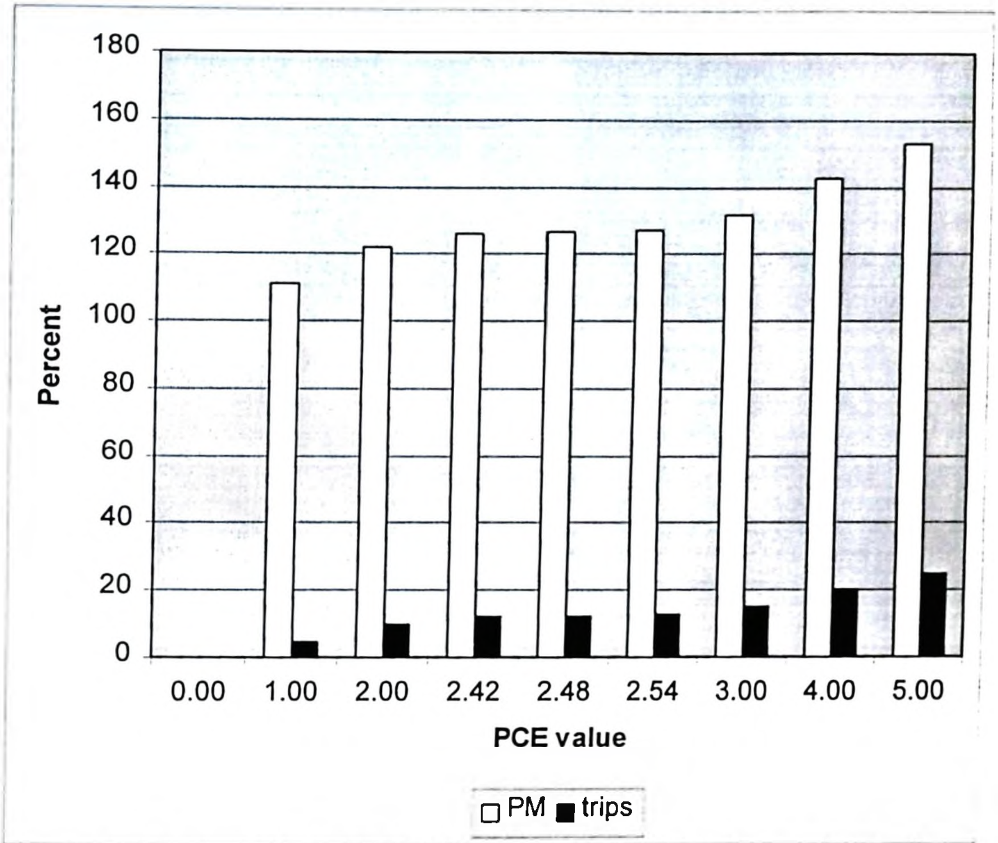

Figure 5.2: Percent increase in PM and trips for varying PCE

Increases in CO and HC for increasing PCE values suggest that emission estimates are sensitive to the presence of trucks and resulting roadway congestion **(Table 5.1)**. Because emissions of CO, HC, and NO_x are dictated by average speed, a meaningful analysis of the contribution of trucks to these emissions is in the comparison of PCE 0.00 and the average PCE value of 2.48. In this comparison, a 12% positive adjustment in base vehicles, to reflect the presence of trucks, yields a 24% increase in CO and a 23% increase in HC emissions. Similarly, accounting for trucks in this way has a positive effect on NO_x (11%) but the effect is not as pronounced. The most dramatic effect is seen in PM, with an 111% increase resulting from a 5% adjustment in base vehicles (PCE 0.00 to PCE 1.00). As PM emissions are not as affected by average speed as they are by vehicle distance traveled, the relative contribution of trucks to PM is found in the investigation of the PCE 1.00 scenario, where the truck O-D matrix is unadjusted. While further study of the results is warranted, these findings are valuable. HC and NO_x emissions are part of the chemical process that generates ground level ozone, while particulate matter is associated with respective increases in respiratory and cardiac hospital admissions (Burnett et. al., 1999). The contribution of trucks to urban mobile source PM emissions cannot be ignored as a typical light-duty diesel truck emits 30 to 100 times more than a comparable catalyst-equipped, gasoline-powered passenger vehicle (USEPA, 1993a).

The total amount of particulate matter emitted by cars and trucks at PCE 1.00 during the morning peak hour (7:00am-8:00am) of a typical day between 1996-2001 was 99 kilograms. **Table 5.2** shows the contribution of brake wear, tire wear, and exhaust emission to the total of PM emissions for cars and trucks at PCE 0.00 and PCE 1.00.

Table 5.2. Aggregate PM emissions from brake wear, tire wear, and exhaust for PCE 0.00 and PCE 1.00

	PCE 0.00			PCE 1.00			% increase in totals from PCE 0.00 to PCE 1.00
	Car	**Truck**	**Total**	**Car**	**Truck**	**Total**	
miles traveled	1900288.4	0.0	1900288.4	1807957.1	175349.8	1983306.9	4.4
brake wear PM (kg)	23.8	0.0	23.8	22.7	2.2	24.9	4.4
tire wear PM (kg)	15.2	0.0	15.2	14.5	1.4	15.9	4.4
exhaust PM (kg)	8.0	0.0	8.0	7.6	51.0	58.6	632.4
Total PM (kg)	47.0	0.0	47.0	44.8	54.6	99.4	111.3

As seen in **Table 5.2** the contribution of trucks to tire and brake wear is only modest. The contribution is directly related to the emission factor for tire and brake wear. This emission factor is more an 'emission multiplier', based on number of tires per vehicle. The largest contribution trucks make is in terms of exhaust particulate matter. This, too, relates to the emission factor being almost ten times larger for light-duty diesel trucks than for light-duty gasoline vehicles. A decrease in the number of car miles traveled coincides with the addition of trucks to the network.

This decrease is attributed to people abandoning passenger cars in favour of public transport options when trucks increase congestion and travel time on certain links. Because of the larger PM exhaust emission factor associated with trucks, however, the PM increase of the trucks overwhelms the PM decrease associated with the decreased car miles traveled.

Describing the vehicle fleet in the Hamilton CMA proved to be difficult with the available data. A typical truck was estimated that would describe the truck fleet as a whole. The estimation methodology is sound, but it is this stage that would most benefit from a complete data set.

5.2.2 Link Level Results

Analyzing the results at the link level reveals the spatial concentration of emissions. The contribution of trucks to all emissions is visible along truck routes. **Figures 5.3** through **5.7** in this chapter, and **Figures A.1** through **A.7** in the **Appendix**, illustrate the spatial pattern of traffic flows, congestion, and emissions and allow for comparison between the cars only scenario and that with trucks at PCE 2.48.

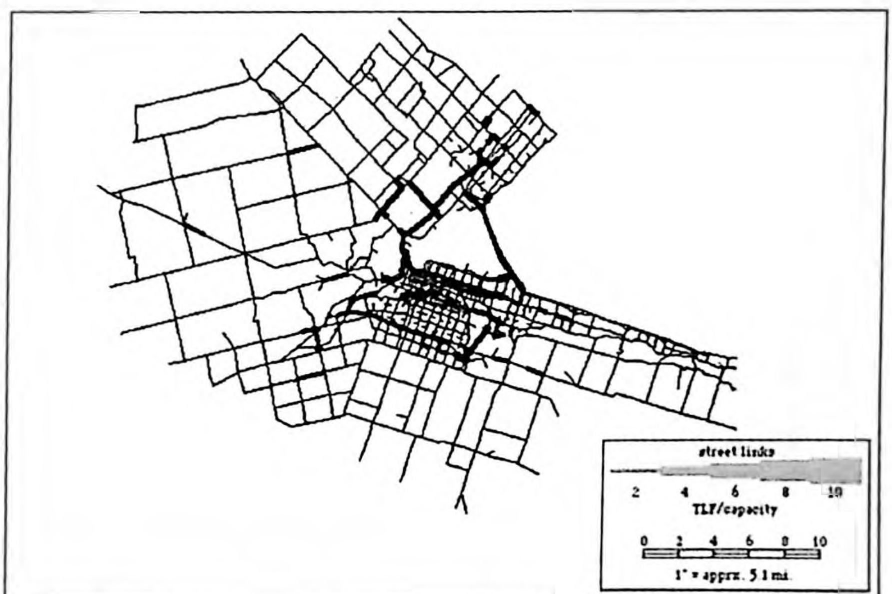

Figure 5.3: Total link flows divided by capacity with trucks at PCE value 2.48

Figure 5.3 is designed to show the spatial pattern of congestion. The total link flow on each link is divided by the capacity of that link. The thickness of the lines demonstrates areas where flow exceeds link capacity. **Figure 5.3** shows the impact on congestion for trucks at PCE 2.48.

Figures A.1 and **A.2,** in the Appendix, show the spatial pattern of link flows without trucks and with trucks at PCE value 2.48 respectively. The pattern of flow is similar in both scenarios, but the thicker lines in **Figure A.2** show the greater impact trucks have on flow. Comparing these figures with **Figure 5.7** and **A.1** through **A.7** shows the association of flow with increased emissions. The thick lines in these figures can be compared with the thick lines in **Figures 5.4** to **5.7** and **Figures A.4** through **A.7.** The spatial pattern in these figures shows that congestion can be associated with increased emissions. **Figure 5.4** and **5.5** show spatial variation in link-based estimates of HC.

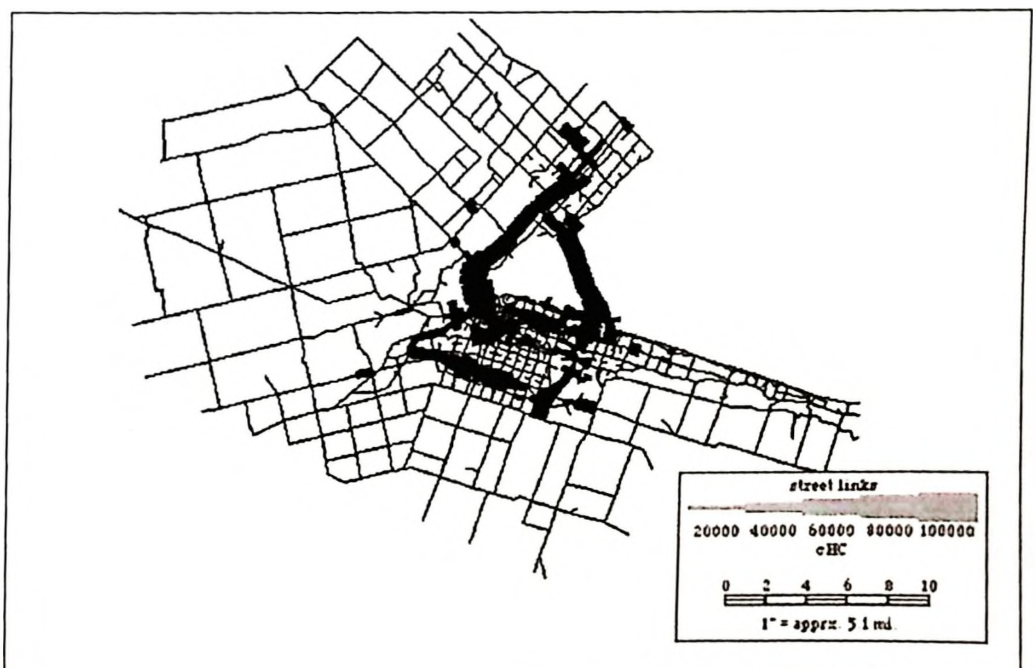

Figure 5.4: Emissions of HC for cars only (PCE 0.00)

The thicker links in **Figure 5.5** are road sections that exhibit large levels of HC as a result of the inclusion of trucks. As expected, the effect appears to be stronger along the truck routes shown in **Figure 4.2**.

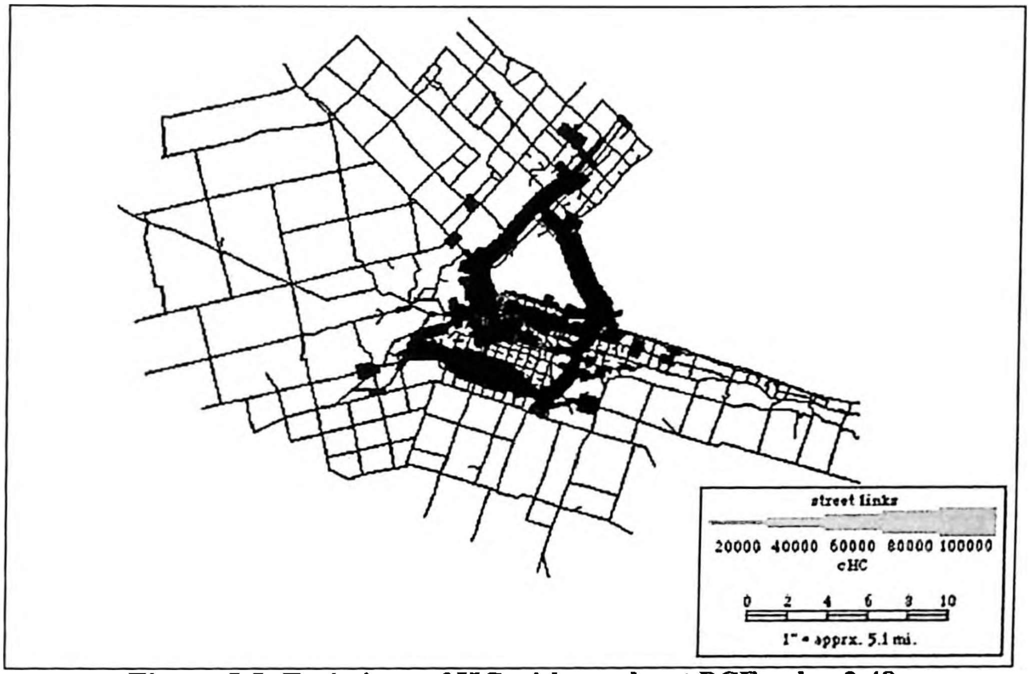

Figure 5.5: Emissions of HC with trucks at PCE value 2.48

Shown in **Figures A.2, A.3** and **A.4, A.5** (Appendix) are similar spatial patterns for the residuals of CO and NO_x. This suggests that not controlling for the presence of trucks results in low estimates of link emissions within certain parts of the Hamilton CMA. Exposure to mobile source pollutants or estimates of ground level ozone would potentially be understated under such conditions.

Figure 5.6 and **5.7** show spatial variation in link-based estimates of PM. Again, the thicker links in **Figure 5.7** are road sections that exhibit large levels of PM as a result of the inclusion of trucks.

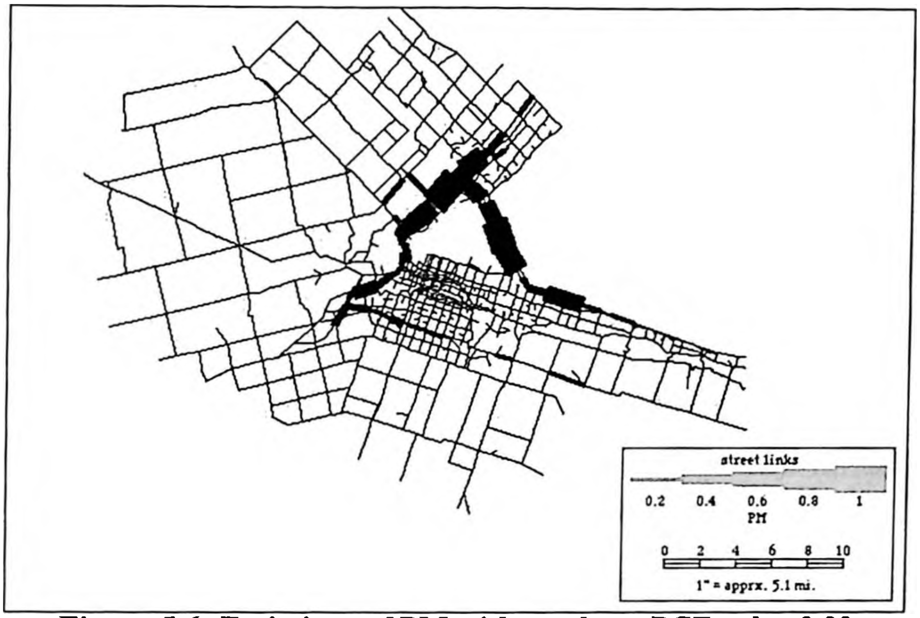

Figure 5.6: Emissions of PM with trucks at PCE value 0.00

From the PM emission factor (given in grams/mile), it was known that PM would not be as affected by average speed so much as it would by the number of trips taken. With trucks, and the trips they contribute, confined only to certain routes, the effect on PM is more pronounced spatially along truck routes than the other emissions.

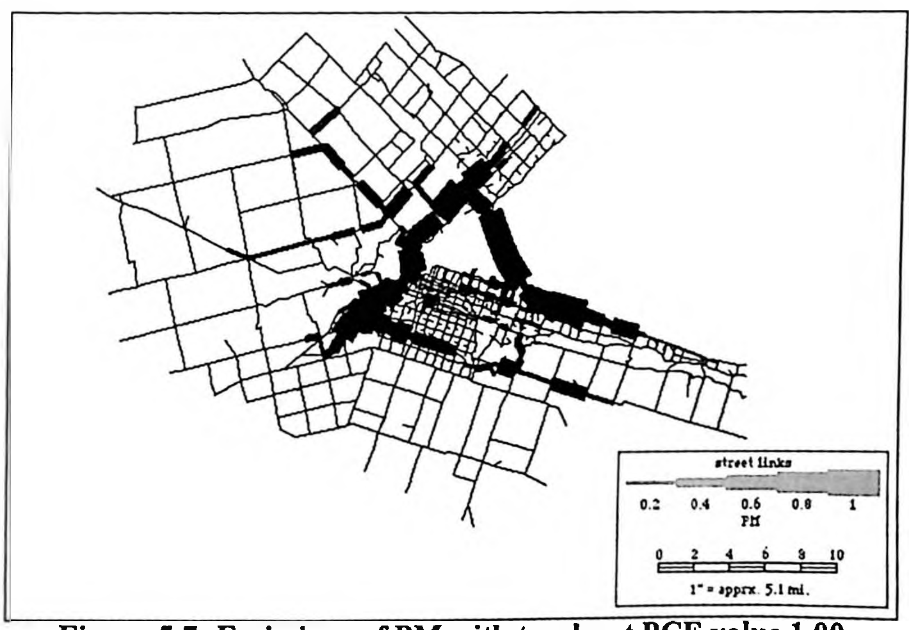

Figure 5.7: Emissions of PM with trucks at PCE value 1.00

5.3 Conclusion

A procedure for evaluating the contribution of trucks to mobile source emissions within urban areas has been presented and tested. The procedure has been applied to the CMA of Hamilton, Ontario. The results suggest that the procedure is effective. The contribution of trucks to mobile emissions of HC, CO, NOx, and PM has been addressed at the aggregate and link levels. Emission estimates demonstrate sensitivity to passenger car equivalency values. The presence of trucks, as modeled in this study, is shown to increase the aggregate level of all pollutants and affect changes in link-based estimates.

While the results are encouraging it has been recognized that the potential of this procedure for generating accurate estimates is limited by the resolution of the observed truck data. The vehicle kilometers traveled, and hence the PM results, are understated due to the sparse nature of the original truck matrix and the aggregate nature of the vehicle classification. Another limitation of the present study is that only trips with origins and destinations within the Hamilton CMA are included. The contribution of trucks passing through the CMA is not dealt with, but warrants futures work. Also, the reported results refer only to the morning peak period. The contribution of truck emissions during the rest of a typical day is expected to be significant since most freight trips avoid the morning peak period.

Chapter Six

Summary and Future Research

The precursor to accurate transportation model development, calibration, and forecast is an appropriate data source. Survey techniques were reviewed in Chapter 2 of this thesis. Any combination of these techniques could be used on the collection of data that could be used to generate a complete O-D matrix and help describe the vehicle fleet for the Hamilton CMA. This research could benefit from a telephone survey of the companies in the Hamilton CMA that use trucks. The telephone survey could be done cost-effectively and could obtain data on the types of trucks used, number of trips made, trip origins and destinations, and route selection. This information could overcome the shortfalls of the data set used in this study, and could be used to construct a complete O-D truck travel matrix for input into IMULATE. Further, the data obtained could help describe the truck fleet in Hamilton, another weakness of the data set used here.

As the municipalities and planning departments are often left to do their own data collection for their own motives, there is no universal truck classification scheme. The idea of establishing one is very appealing so that results from different regions or departments can be compared in a meaningful way. It is recommended that data collected with a phone survey be classified using the EPA classification scheme; by weight and model year. Once a truck classification has been completed, the task of assigning different emission factors to the types of trucks must be addressed. If the classification scheme used is the same as that of the EPA, emission factor assignment is straightforward. In any other case, approximations made between different classification schemes could reduce the accuracy of emission factor assignment, and of the final emission estimations. A description of the many pollutants must be analyzed to formulate the best and most meaningful combination of emission factors to be assigned. In addition to HC, CO, and NO_x, there is an increasing interest in the role of PM, especially with heavy-duty and diesel trucks.

This modeling segment to this research appears to be adequate. IMULATE has proved its robustness as a model and was easily modified to all the input of the truck travel O-D matrix. The methodology, including the PCE approach and emission factor assignment, appears to be reasonable. The range of PCE values used in the approach taken here, acts as a sensitivity analysis for the model. The model has proved sensitive to the addition of trucks to the system, as demonstrated in **Table 5.1**. A sensitivity analysis is typically done when there is uncertainty about the completeness of the input data set. The results revealed that a 12% positive adjustment in base vehicles reflects the presence of trucks. This adjustment yields a 24% increase in CO and a 23% increase in HC emissions. Similarly, accounting for trucks in this way has a positive effect on NO_x (11%) but the effect is not as pronounced. The most dramatic effect is seen in PM, with an 111% increase resulting from a 5% adjustment in base vehicles (PCE 0.00 to PCE 1.00). These results are for a typical day between 1996 and 2001, and only apply to the morning peak period of travel. Establishing a diurnal pattern for truck and car trips, and the corresponding emissions estimation would be a very feasible continuation of the research done here. Again, data collected from a phone survey of the truck-using companies in the Hamilton CMA could be used to generate O-D matrices for different hours of the day and days of the week.

Appendix

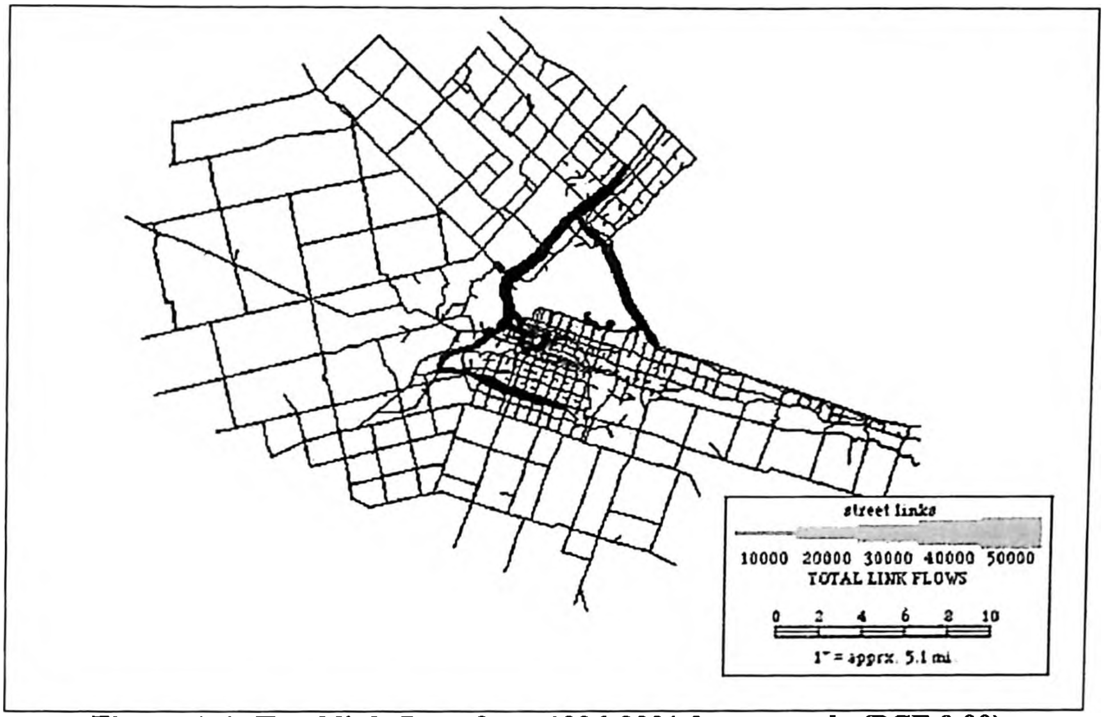

Figure A.1: Total link flows from 1996-2001 for cars only (PCE 0.00)

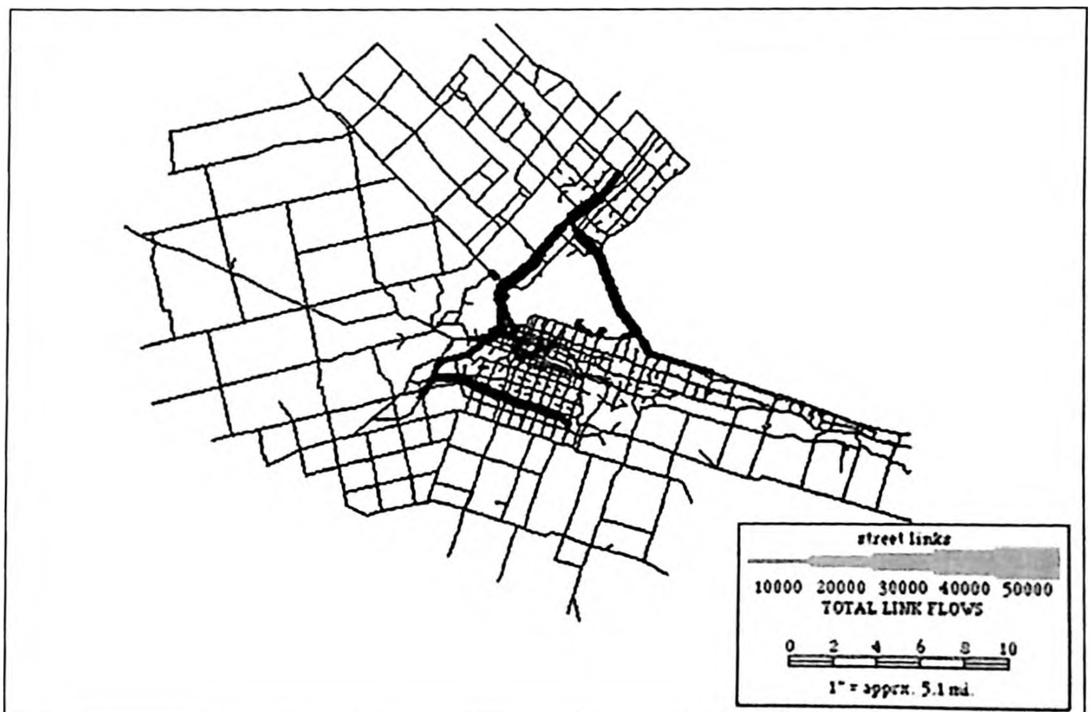

Figure A.2: Total link flows from 1996-2001 with trucks at PCE value 2.48

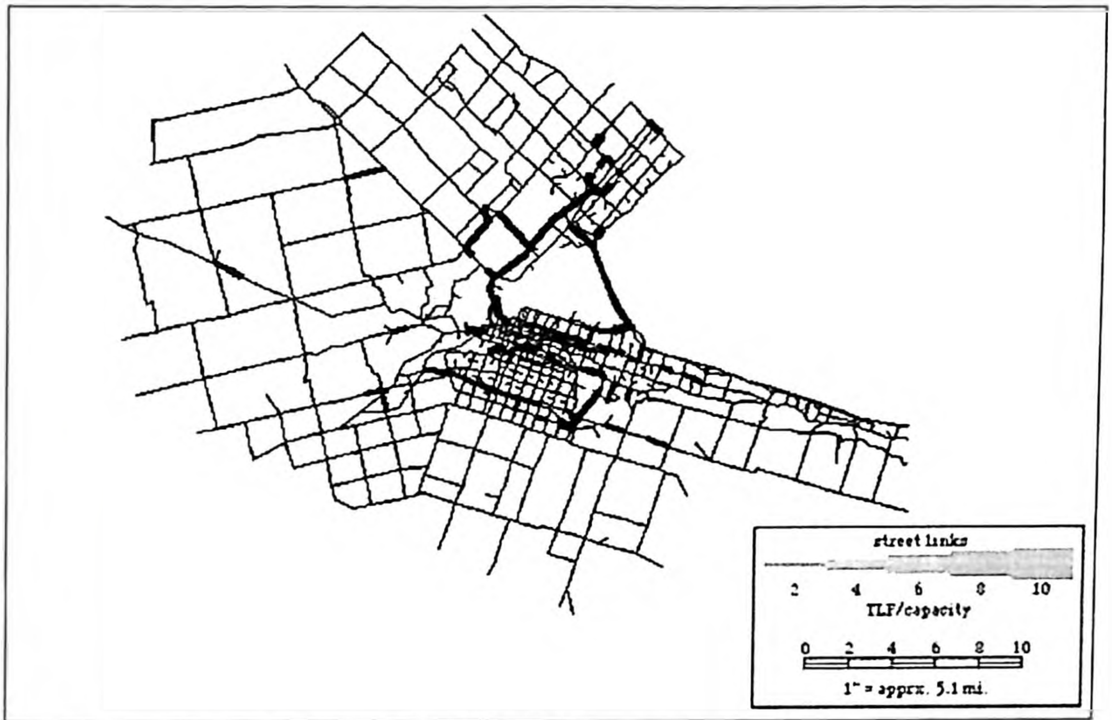

Figure A.3: Total link flows divided by capacity for cars only (PCE 0.00)

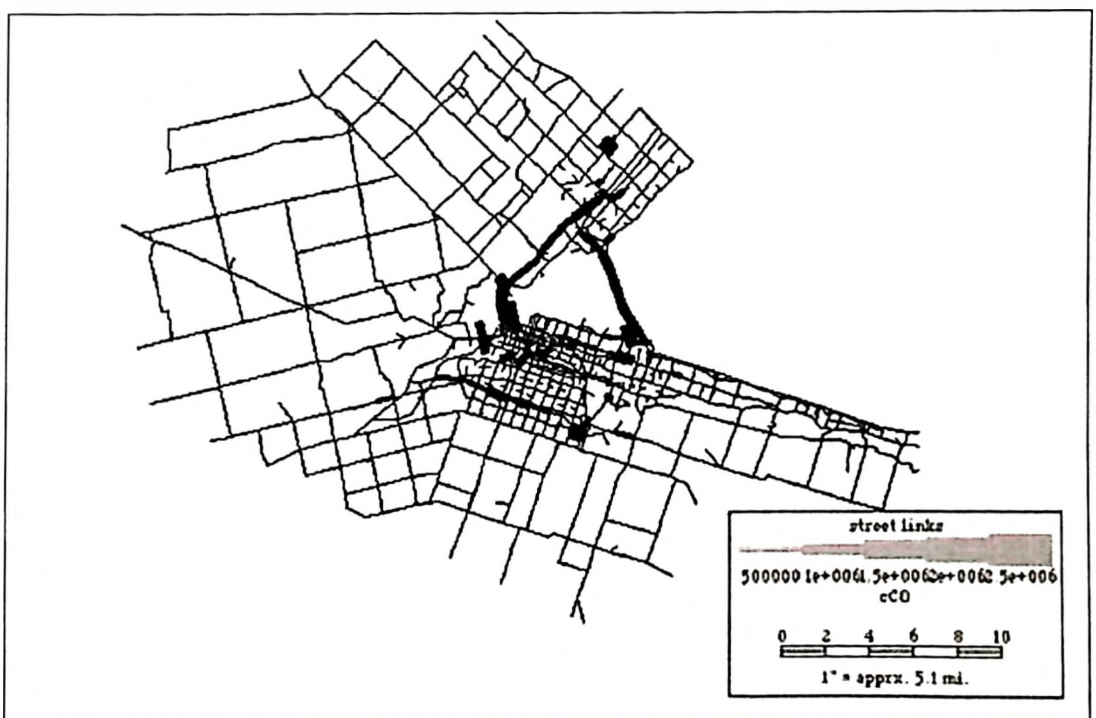

Figure A.4: Emissions of CO for cars only (PCE 0.00)

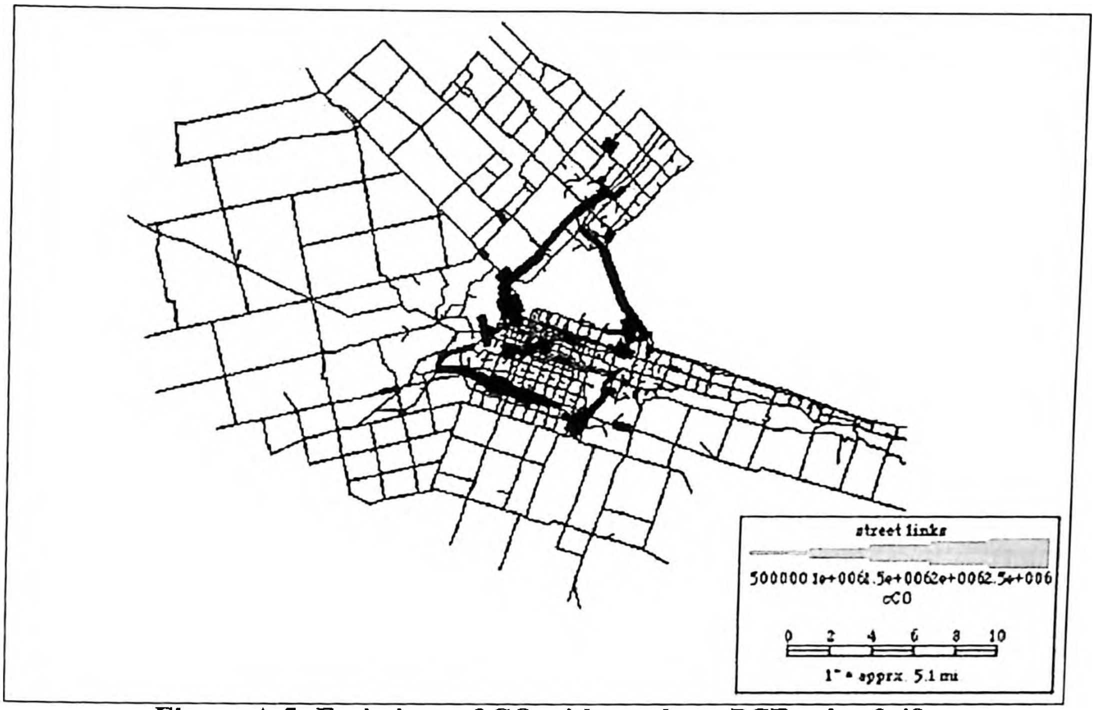

Figure A.5: Emissions of CO with trucks at PCE value 2.48

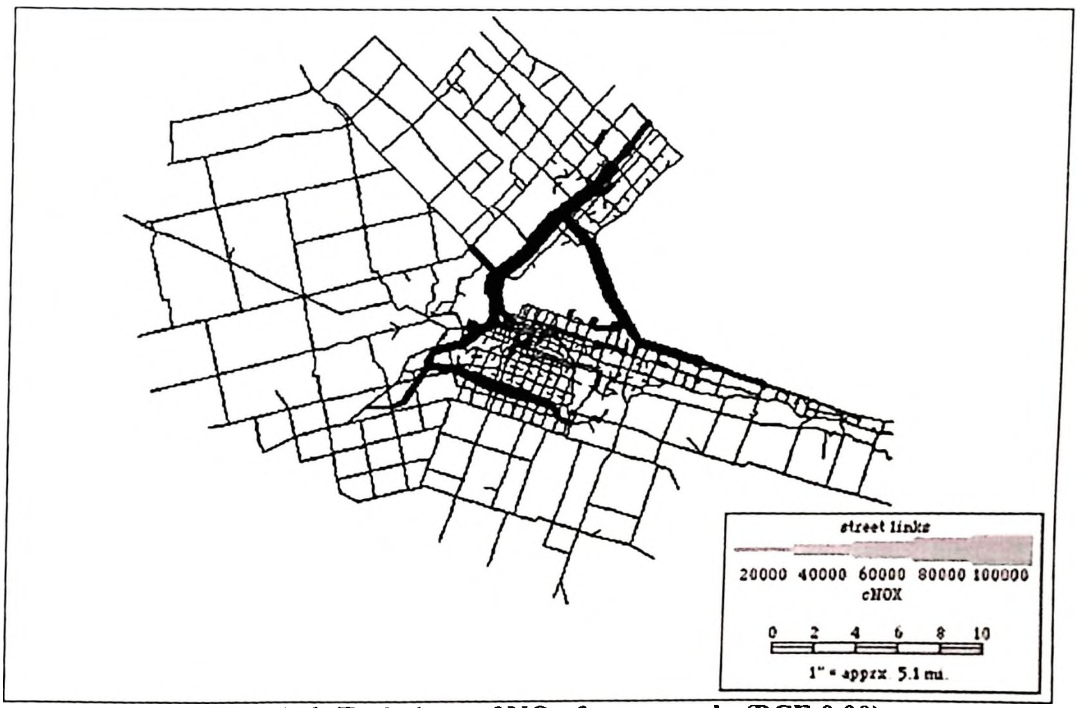

Figure A.6: Emissions of NOx for cars only (PCE 0.00)

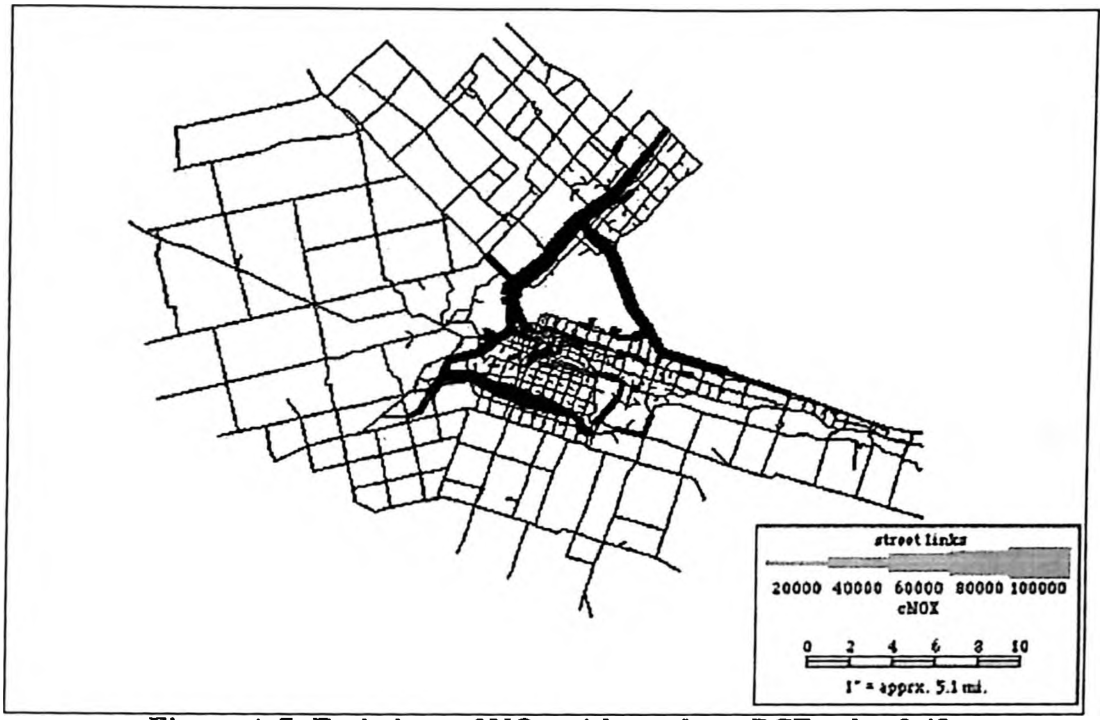

Figure A.7: Emissions of NOx with trucks at PCE value 2.48

References

Anderson W.P., P.S. Kanaroglou and E.J. Miller (1994) *Integrated Land Use and Transportation Model for Energy and Environmental Analysis: A Report on Design and Implementation*, McMaster Institute for Energy Studies, Hamilton, Ontario, Canada.

Anderson W.P., P.S. Kanaroglou, E.J. Miller and R.N. Buliung (1996) Simulating Automobile Emissions in an Integrated Urban Model, *Transportation Research Record*, No. **1520**, pp. 71-80.

Burnett R., M. Smith-Doiron, and S. Cakmak (1999) Effects of Particulate and Gaseous Air Pollution on Cardio respiratory hospitalizations, *Archives of environmental health*, Vol. **54**, No. 2, pp. 131-138.

Elefteriadou L., D. Torbic and N. Webster (1997) Development of Passenger Car Equivalents for Freeways, Two-Lane Highways, and Arterials, *Transportation Research Record*, No.**1572**, pp. 51-58.

Gorys, J. (1991) 1988 Ontario Commercial Vehicle Survey, *Transportation Research Record*, No. **1313**, pp. 20-26.

Hamilton Air Quality Initiative (HAQI) (1997) *Ambient Air Quality & Effects on the Environment in Hamilton-Wentworth*, Regional Municipality of Hamilton-Wentworth.

Kanaroglou P.S. and B.W. Taylor (1999) *Truck Mobility and Emissions: Truck Classification and Emission Factors,* Submitted to the Policy and Research Working Group, Hamilton-Wentworth Air Quality Improvement Committee.

Kanaroglou P.S. and W.P. Anderson (1997) *Emissions from Mobile Sources in Urban Areas: An Integrated Transportation and Land-Use Approach*, Proc. 5th Conference on Environmental Science and Technology, (ed. Th. Lekkas), Molyvos Lesvos, Greece, 1997.

Lau, S. (1995) *Truck Travel Surveys: A Review of the Literature and State-of-the-Art*. Planning Section, Metropolitan Transport Commission, Oakland, CA.

Matherly, D. W. (1996) Stream-Of-Traffic Interview Truck Survey: Methodology And Recommendations On Traffic Volume Thresholds, *Transportation Research Record*, No. **1522**, pp. 18-26.

Miller E.J., D.S. Kriger and J.D. Hunt (1998) *Integrated Urban Models for Simulation of Transit and Land-Use Policies,* TCRP PROJECT H-12. University of Toronto Joint Program in Transportation and DELCAN Corporation.

Ruiter, E.R. (1991) *Development of an Urban Truck Travel Model for the Phoenix Metropolitan Area, Final Report.* Prepared by Cambridge Systematics Inc. for the Arizona Department of Transportation, Phoenix, Arizona.

Ruiter, E.R. (1992) Phoenix Commercial Vehicle Survey and Travel Models. *Transportation Research Record*, No. **1364**, pp. 144-151.

Scott D.M., P.S. Kanaroglou and W.P. Anderson (1997) Impacts of Commuting Efficiency on Congestion and Emissions: Case of the Hamilton CMA, Canada, *Transportation Research-D*, Vol. **2**, No. 4, pp. 245-257.

Smadi, A. and T.H. Maze (1996) Statewide Truck Transportation Planning: Methodology and Case Study, *Transportation Research Record*, No. **1522**, pp. 55-63.

Southworth, F (1995) *A Technical Review of Urban Land Use - Transportation Models as Tools for Evaluating Vehicle Travel Reduction Strategies,* Report ORNL-6881. Oak Ridge (TN): Oak Ridge National Laboratory.

The Polk Company (1998) Transportation energy book, Edition 18, pp. 11.

USEPA (1985a) *Size Specific Total Particulate Emission Factors for Mobile Sources,* U.S. Environmental Protection Agency (EPA-460/3-85-005).

USEPA (1988b) *Heavy Duty Vehicle emission conversion factors II, 1962-2000,* U.S. Environmental Protection Agency (EPA-AA-SDSB-89-01)

USEPA (1993a) *Motor Vehicle-Related Air Toxics Study*, U.S. Environmental Protection Agency (EPA-420-R-93-005).

USEPA (Feb. 24, 1995) *PART 5 Users Guide*, U.S. Environmental Protection Agency (Office of Mobile Sources).