Estimating the Contribution of Commercial Vehicle Movement to Mobile PM Emissions in Urban Areas

Pavlos S. Kanaroglou, McMaster University, and Ronald N. Buliung,
University of Toronto at Mississauga
(e-mail: pavlos@mcmaster.ca)

1. INTRODUCTION

Empirical data suggest that urban commercial vehicle movements (UCVM) account for roughly 6-18% of total urban travel (Cambridge Systematics, 2004; Hunt and Stefan, 2004; Stefan et al., 2005). UCVM, however, exert substantial influence on traffic flow, road surface conditions, and environmental emissions (Hallmark and Isebrands, 2005; Kanaroglou et al., 2000; Stefan et al., 2005). Recognition of the contribution of UCVM to local and regional economies, the impact of UCVM in cities, and the unique set of conditions and behaviours that facilitate and characterize UCVM have lead to increased research activity over the last decade.

With these issues in mind, this study uses an integrated urban land use and transport model (IMULATE), developed for the CMA of Hamilton to examine the contribution of UCVM to PM emissions in urban areas. There is increasing interest in particulate matter (PM), associated usually with heavy-duty gasoline and diesel trucks. Research suggests that PM can be detrimental to human health (Burnett et al, 1999).

2. IMULATE – GENERAL STRUCTURE

The Census Metropolitan Area (CMA) of Hamilton with a population of 600,000 is separated by the Niagara escarpment into the lower and the upper part (known also as the mountain). Both the lower and upper city is relatively flat, with access from one to the other provided by five major transport links. IMULATE is an integrated transport and land use model designed to predict traffic loads on links of the transport network for the morning peak period (7:00 to 8:00am) in the Hamilton CMA. The initial conception and operationalization of the model are described in detail in Anderson et al (1994). IMULATE consists of three main modules. The first is the land-use module, made up of two sub-modules that take account of population and firm mobility to determine a place of residence to place of work matrix within a system of 151 zones (census tracts). Second is the transport module, which determines the number of motorized work, school and discretionary (i.e., shopping, recreational) trips and uses a stochastic user equilibrium algorithm to assign interzonal automobile trips to the CMA's road network. The latter consists of about 1100 nodes and 1500 links. The feedback between the transport and land use modules ensures that land use changes are reflected in estimated traffic volumes. The third module of IMULATE uses link flows and average link speeds produced by the transport module to estimate emissions of 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.

3. METHODOLOGY AND DATA

This study proceeds in four steps. First, an origin-by-destination matrix of commercial vehicle trips, **C**, at the census tract level was acquired from the City of Hamilton. Second, the concept of passenger car equivalency (PCE - number of passenger cars that correspond to a typical truck) is discussed and a method is developed for the determination of representative mean PCE value, E, for the study area. In the third step, we scale the origin-by-destination matrix of commercial vehicle trips **C, using the** estimated E value to produce an origin-by-destination matrix of passenger cars that is equivalent to a commercial vehicle matrix. Since E is a scalar, the matrix sought is the product E**C.** In step four the derived matrix is added to the passenger cars origin-by-destination matrix **P**, estimated within the TRADEM module of IMULATE to produce **T** = **P**+E**C**, which is used as input to a stochastic user equilibrium routine that determines the traffic flow on the network. After equilibrium is achieved, estimated traffic flows are passed to the emissions sub-module, producing estimates of HC, CO, and NO_x emissions by link, and for the entire study area. Since emission factors for the determination of PM emissions are not included in IMULATE, a separate procedure has been developed and is discussed later in this section. One can examine several scenarios by varying the passenger car equivalency scalar value of E. The simulation period for this study is 1996 to 2001.

3.1 The Commercial Vehicle Trips Matrix (C)

During the 1998 Hamilton Commercial Vehicle Survey, tube data and intersection counts were collected. Bi-proportional updating was used to transform the count data into the matrix **C** for the morning peak hour (7:00-8:00am). Commercial vehicles in this context 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. It is also important to note that trip-ends within the municipalities of 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.

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 (for example, combustion process and vehicle type). 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).

3.2 Passenger Car Equivalency (PCE)

Passenger car equivalencies were introduced to the literature in the *Highway Capacity Manual* (HCM) of 1965, and defined as: "The number of passenger cars displaced in the traffic flow by a truck or a bus, under the prevailing roadway and traffic conditions". In other words, PCEs measure the number of base vehicles (usually passenger cars) removed from traffic due to the presence of heavy vehicles (Al-Kaisy et al., 2005; Elefteriadou et al., 1997; Sumner et al., 1984). There has been little change to the PCE definition since the 1960s (see TRB, 2000), and PCE values are still used to evaluate the impact of heavy vehicles on traffic operations under free-flow conditions (Al-Kaisy et al., 2005; Elefteriadou et al., 1997).

PCE estimation procedures can be distinguished by the travel characteristic used to define an equivalency criterion. Past research has used vehicle headway, delay, platoon formation, speed, vehicle hours, travel-time, density, and queue discharge flow (QDF) (see Al-Kaisy et al., 2005; Elefteriadou et al., 1997). While the HCM publishes PCE measures for various facility-types (e.g., 2-lane and multilane highways and freeways), classified by grade and heavy vehicle type (Truck, RV), it assumes free-flow operating conditions. Buses are treated the same as trucks. Traffic simulation studies provide some contrast to the HCM approach, indicating variation in PCEs by heavy vehicle type, road grade and facility type, volume, vehicle mix, and traffic conditions (Al-Kaisy et al., 2002; Al-Kaisy et al., 2005; Elefteriadou et al., 1997; TRB, 2000). For example, Webster and Elefteriadou (1999) found increases in PCE values with traffic flow, free-flow speed, and segment length/grade, and decreasing PCEs with number of lanes and truck percentage.

Since we use an integrated model, and congestion is estimated by link, it is conceivable to take account of congestion, provided one accepts a functional relationship between the two. In the absence of such a relationship, we assume that PCE values are invariant to congestion, implying a potential underestimation of emissions. Using the speed-flow PCEs estimated by Elefteriadou et al. (1997), we assign representative PCEs to network segments according to link type. Commercial vehicles within the Hamilton CMA are restricted, by law, to a subset of links in the road network (Figure 3.1).

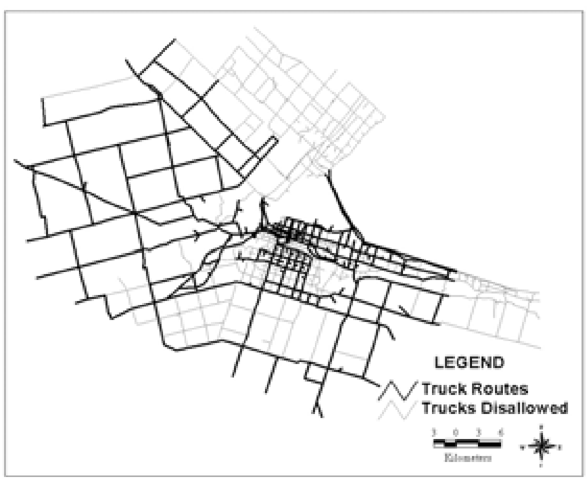

Figure 3.1: The Hamilton CMA Trucking Routes (805 links)

Values are assigned to links by type according to the following scheme: 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. The latter type of arterial facility does not provide opportunities for passing, making the impact of heavy vehicles more pronounced. The mean PCE value over the 805 truck route links was found to be 2.48. The upper and lower bounds of a 90% confidence interval were 2.54 and 2.42, respectively. Since our estimate of PCE is rather crude, we perform some sensitivity analysis by allowing PCE to attain the values 0, 1, 2, 2.42, 2.48, 2.54, 3, 4 and 5. The value of 0 implies absence of commercial vehicles in the network, corresponding to the "passenger cars only" scenario.

In the determination of PCE values, we ignore the grade of the links. As discussed earlier the upper and lower parts of the Hamilton CMA are relatively flat, justifying this assumption. There are five links, however, that connect the lower with the upper part, for which the grade is substantially different than zero. Trucks are allowed to use three of those links. Given, however, that those links are arterials with four to six lanes, we felt that ignoring link grade is justified.

3.3 PM Estimation

Since MOBILE5.C does not estimate particulates, we now discuss a methodology for the estimation of PM at the link and aggregate levels. Particulate emissions come from a variety of sources including combustion exhaust, tire wear, brake wear, idle emissions, and fugitive dust. We combine IMULATE with EPA (PART 5) PM emission factors to generate PM estimates from the first three sources. Idling and fugitive dust are not dealt with due to data limitations.

The total exhaust particulate emission factor 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.

To address the contribution of UCVs to PM emissions, we require vehicle type and emissions data. Since these data are not available for Hamilton, we resort to evaluating the average type of UCV and the frequency of its appearance in links within the Hamilton network during the morning peak period. At the time of data collection a vehicle classification was done at 28 randomly selected intersections of the network. The classification scheme employed is shown in Table 3.1, along with the percentage frequency of appearance of the different vehicle types. Interestingly, these data substantiate results reported for other cities (e.g., Calgary, Edmonton), with light vehicles taking up the largest percentage of observed commercial vehicle types during the peak period (e.g., Stefan et al., 2005).

Table 3.1: Vehicle classes used in the CMA of Hamilton

Class	Type	Axles	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	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 1-axle trailer	3	0.30	9
9	4-axle single unit	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

* Percent of total peak hour vehicle flow by class.
**Denotes the order the classes rank in terms of percent of peak flow

The highest ranked class, strictly limited to trucks, was Vehicle Class 3 (2-axle light truck), comprising 10.7 percent of the total vehicle flow over sampled intersections. On this basis, we considered for our purposes Vehicle Class 3 the average or representative type of commercial vehicle for the Hamilton fleet. Class three approximates a 'Single Unit Truck (SUT), with a length of 12.2m and a weight-to-horse power ratio of 300' (see Elefteriadou et al., 1997). Based on the USEPA schema, SUTs are essentially light duty diesel trucks (LDDT) (USEPA, 1993a). The sum of all truck vehicle classes represents 14.24 percent of all vehicles. This is consistent with the percent of trucks in traffic flow reported in Elefteriadou et al. (1997). For our purposes, in what follows, we consider a rough estimate of 15 percent of commercial vehicles, including buses.

3.3.1 Selecting PM Emission Factors

As discussed earlier, this study is limited to estimating PM exhaust emissions through the application of a carbon emission factor. 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 the Polk Data Company (1998).

The average model year for both the car and truck fleet was estimated to be 1990 as follows. As mentioned earlier, the simulation period for this study was 1996 to 2001. The midpoint of this period 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 midpoint of the year 1998 provides a model year of 1990.

The nearest EPA age category for passenger cars (LDGVs) was 1981 and newer. The PM exhaust emission factor for this category is EE_{LDGV} = 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 as the maximum aerodynamic diameter of the particles in the emission factors (USEPA, 1985a). PM_{10}, includes particles of 10 micrometers or less in aerodynamic diameter, and is of particular concern due to its association with cardio-respiratory hospitalisations (Burnett et. al., 1999) and other health effects (HAQI, 1997). In this study a PSC for PM_{10} is determined from tables provided by the USEPA (USEPA, 1985a). For catalyst equipped LDGVs, 1981 and newer, using unleaded fuel the fraction of particles less than or equal to 10 micrometers in diameter, PSC_{LDGV} = 0.98.

To determine the exhaust emissions factor and the PSC for light duty diesel trucks (LDDT), we follow the same procedure reported for passenger cars. In 1996, the average age of trucks was 8.6 years (The Polk Data Company, 1998). Subtracting the average age from the year of estimation left a model year of 1990. The PM exhaust emission factor for this category is EE_{LDDT} = 0.291 gram/mile. To determine the PSC for particles less than 10 micrometers in diameter we note that for all model years, and for all diesel vehicles, including 1990 LDDT, the value is PSC_{LDDT} = 1.00 (USEPA, 1985a).

3.3.2 Estimation of PM Emissions

For the purpose of estimating PM, the road network in this study is broken into links that are part of truck routes and links that are not part of truck routes. The PM exhaust (PME) estimate for a truck route link *i*, is calculated as:

$$PME_i = 0.15 f_i l_i EE_{LDDT} PSC_{LDDT} + 0.85 f_i l_i EE_{LDGV} PSC_{LDGV}$$

Where, f_i is the total traffic volume on link *i*, and l_i is the length of link *i*. The factors .15 and .85 reflect our estimate that 15 percent of the flow on a truck route link *i* is from trucks and the remainder 85 percent from passenger vehicles.

The PM exhaust estimate for non-truck route link *j*, is calculated as:

$$PME_j = f_j l_j EE_{LDGV} PSC_{LDGV}$$

Where, f_j is the total traffic volume on link *j*, and l_j is the length of link *j*. Assuming that we have *n* truck route links and *m* non-truck route links, 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 emission factor for all vehicle categories and model years is E_{tire} = 0.002 gram/mile/tire, while the particle size cut-off for all vehicles is PSC_{tire} = 1.00 (USEPA, 1985a). Since the emission factor is per tire, one needs the average number of tires per vehicle, which is $ANOT_v$ = 4 (USEPA, 1985a). Obviously, the tire wear emission factor does not vary by link type. As a result, the tire-wear emission $PMTW_k$ for any link *k* is given by:

$$PMTW_k = f_k l_k E_{tire} PSC_{tire} ANOT_v ,$$

and the PM tire wear emissions for the entire system is expressed as:

$$PMTW_{TOTAL} = \sum_{k=1}^{m+n} PMTW_k$$

The PM brake wear emission factor for all vehicle categories and model years is E_{brake} = 0.0128 gram/mile, while the average particle size cut-off over all vehicles and model years is PSC_{brake} = 0.98. Since there is no variation by link type, the PM break wear emission $PMBW_k$ for any link k is given by:

$$PMBW_k = f_k l_k E_{brake} PSC_{brake} ,$$

and the PM break wear emissions for the entire system are given by:

$$PMBW_{TOTAL} = \sum_{k=1}^{m+n} PMBW_k$$

Total PM for the entire system, then, is the sum of PM emissions from all sources (combustion exhaust, brake wear, and tire wear).

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

4. RESULTS AND DISCUSSION

Establishing the contribution of commercial vehicles to mobile emissions requires an initial estimation of network flows from passenger vehicles only (E = 0). This is followed by a series of estimations, where **T** = **P** + E**C**, with E > 0, as discussed earlier.

4.1 Aggregate Level Results

In Table 5.1, increasing the PCE value (column 1) is equivalent to increasing the volume of vehicle traffic in the network. This additional traffic serves as a proxy for the presence of UCVs. Loading additional base vehicles onto the network leads to increased traffic on network links. For certain links, especially those on truck routes, the result is increased congestion and lower average speeds. Unlike other mobile pollutants, PM emissions are less affected by congestion and the average speed on a link, but by vehicle-miles traveled (strictly speaking this might not be true -congestion and stop and go will augment brake-use, and brake dust emissions). This is evident in the PM emission figures shown in Table 4.1. What is important is the increase in PM emissions when commercial vehicles are introduced at all, that is, when the PCE value changes from 0 to 1. For a 4.8 percent increase in trips, PM emissions increase by 111.3 percent. To better understand this relationship, it is important to examine the source of emissions. Table 4.2 provides a breakdown of emissions by type for this particular case.

Table 4.1: Aggregate Emissions and Trips by PCE Value

PCE	**PM**		**Trips**	
E	kg	%*	*n*	%*
0.00	47	0.0	174996	0.0
1.00	99	111.3	183452	4.8
2.00	104	121.7	192297	9.9
2.42	106	125.9	195851	11.9
2.48	107	126.5	196396	12.2
2.54	107	127.2	196960	12.6
3.00	109	131.9	200940	14.8
4.00	114	142.4	209798	19.9
5.00	119	152.9	218686	25.0

* Denotes percent increase over the ‘passenger cars only’ scenario

The first striking result in Table 4.2 is that the introduction of commercial vehicles causes roughly a 5% decrease in passenger vehicle miles traveled (VMT). This decrease is likely the response of passenger car drivers to the disutility of the extra congestion introduced by commercial vehicles, causing mode switching or trip reduction during the a.m. peak-hour. Perhaps the most important result reported in Table 5.2 is that the exhaust system represents the primary source of PM emissions introduced by commercial vehicles. Out of the 54.6kg of particulate matter produced by commercial vehicles, 51kg (93%) originates at the tailpipe. These results indicate that to reduce particulate matter emissions in urban areas, one has to pay close attention to UCV exhaust systems.

Table 4.2: Aggregate PM Emissions by Type and PCE Value

Scenario	Car	Truck	Total
PCE (E=0.00)			
VMT	1900288	0.0	1900288
Brake wear (kg)	23.8	0.0	23.8
Tire wear (kg)	15.2	0.0	15.2
Exhaust (kg)	8.0	0.0	8.0
Total (kg)	47.0	0.0	47.0
PCE (E=1.00)			
VMT	1807957	175350	1983307
Brake wear (kg)	22.7	2.2	24.9
Tire wear (kg)	14.5	1.4	15.9
Exhaust (kg)	7.6	51.0	58.6
Total (kg)	44.8	54.6	99.4
Increase (%)			
VMT			4.4
Brake wear (kg)			4.6
Tire wear (kg)			4.6
Exhaust (kg)			632.5
Total (kg)			111.5

4.2 Results at the Link Level

In this sub-section we focus on the spatial concentration of congestion and emissions through a selected set of figures. Figure 4.1 depicts the ratio of flow to capacity when PCE is E = 2.48. Thicker link lines are associated with ratio values greater than 1, meaning that traffic flow exceeds capacity (volume to capacity ratio), rendering the link congested. A comparison with Figure 3.1 indicates that congestion emerges primarily on truck routes.

Figures 4.2 and 4.3 show emission results by link in grams/mile. From our earlier discussion, we know that the number of trips per link, rather than congestion, affects the level of PM emissions. With the inclusion of commercial vehicles in the network, and the trips they contribute confined only to certain routes, the effect on PM is more pronounced particularly along trucking routes. The results obtained suggest that not controlling for the presence of commercial vehicles results in low estimates of link emissions within certain parts of the Hamilton CMA.

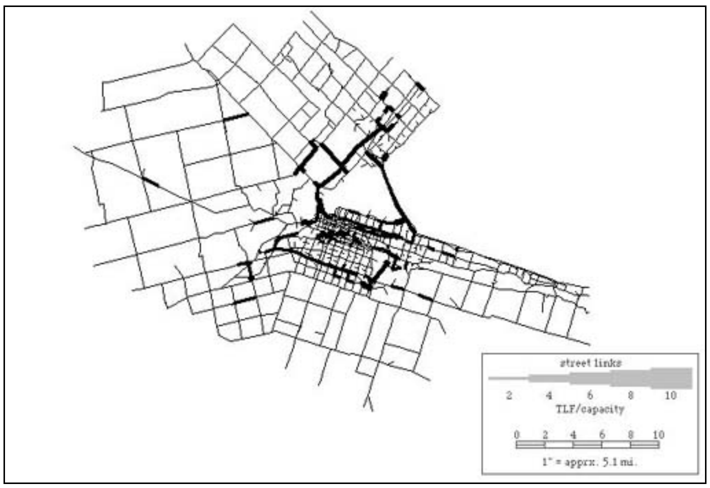

Figure 4.1: Ratio of link flows to link capacity, PCE value E=2.48

CONCLUSIONS

A procedure for evaluating the contribution of trucks to link and system wide PM emissions from mobile sources within urban areas has been presented and applied to the Census Metropolitan Area of Hamilton, Canada. We demonstrate that the application produces plausible results. Emission estimates demonstrate sensitivity to passenger car equivalency (PCE) values. The presence of trucks is shown to produce a dramatic increase in particulate matter emissions. The analysis indicates that this increase is mainly due to combustion exhaust emissions, as opposed to other sources (e.g. tire and break wear). Overall, a 4.4 percent increase in vehicle miles traveled because of the presence of trucks can produce a 111 percent increase in PM emissions. For all pollutants link level changes tend to be focussed along trucking routes.

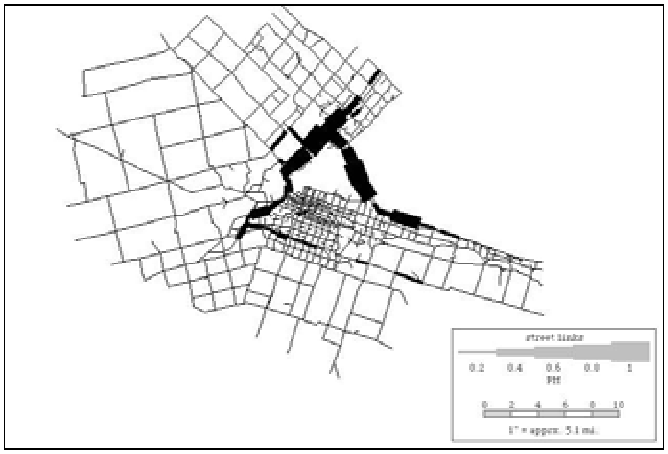

Figure 4.2: Emissions of PM for Passenger Cars, E = 0

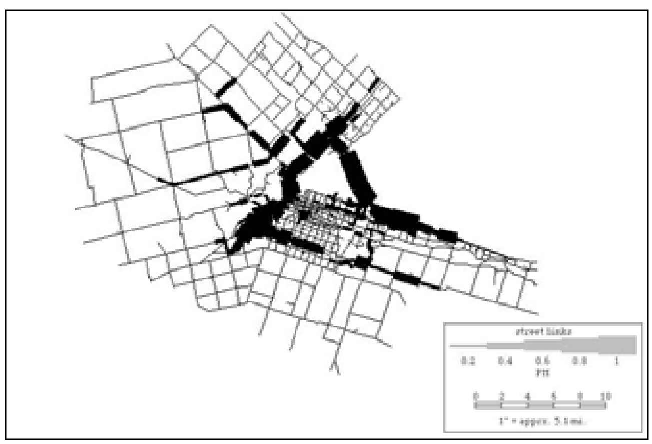

Figure 4.3: Emissions of PM with Commercial Vehicles, E = 1.00

While the results are encouraging, the potential of this procedure for generating accurate estimates is limited by the resolution of the observed trucking data. Another limitation 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. In the presence of current data on inter-city trucking, we anticipate that the contribution of external flows to emissions could be relatively small (e.g., City of Calgary, 2001). To be certain of this, data for the Hamilton CMA need to be collected. Furthermore, the current focus of the model is the morning peak period traffic volumes and related emissions, while the majority of truck trips in urban areas take place outside this period. Overall, our experience to date suggests that detailed analysis of UCVM emissions in urban areas requires a concerted effort by stakeholders to engage in the regular collection of data describing heterogeneity in fleet characteristics and behaviours.

REFERENCES

Al-Kaisy, A.F., Hall, F.L., Reisman, E. (2002) Developing passenger car equivalents for heavy vehicles during queue discharge flow, *Transportation Research Part A*, 36, pp. 61-78.

Al-Kaisy, A., Jung, Y., Rakha, H. (2005) Developing passenger car equivalency factor for heavy vehicles during congestion, *Journal of Transportation Engineering-ASCE*, 131, pp. 514-523.

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.

Burnett, R., Smith-Doiron, M., Cakmak, S. (1999) Effects of particulate and gaseous air pollution on cardio-respiratory hospitalizations, *Archives of Environmental Health*, Vol. 54, No. 2, pp. 131-138.

Cambridge Systematics. (2004) Accounting for commercial vehicles in urban transportation models, Available from: http://tmip.fhwa.dot.gov/clearinghouse/docs/accounting/ [Accessed, December 2005].

City of Calgary. (2001) Calgary Region External Truck Survey Study, City of Calgary, Available from: www.calgary.ca [Accessed, November 2005].

Elefteriadou L., Torbic, D., Webster, N. (1997) Development of passenger car equivalents for freeways, two-lane highways, and arterials, *Transportation Research Record*, 1572, pp. 51-58.

Hallmark, S.L., Isebrands, H. (2005) Evaluating speed differences between passenger vehicles and heavy trucks for transportation-related emissions modelling, *Journal of the Air and Waste Management Association*, 55, pp. 1441-1450.

Hunt, J.D., Stefan, K.J. (2003) Calgary Commercial Movement Model, *Paper presented at the 17th International EMME/2 Users' Conference*, Calgary, AB, October.

Kanaroglou P.S., Taylor, B.W. (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., Buliung, R.N., Taylor, B.W. (2000) Mobile source emissions in urban areas: the relative contribution of trucks. *Proceedings of the 5th International Conference on Protection and Restoration of the Environment*, Thassos, Greece.

Stefan, K., Brownlee, A.T., McMillan, J.D.P., Hunt, J.D. (2005) The nature of urban commercial movements in Alberta, Available from: http://www.calgary.ca [Accessed, December 2005]

Sumner R., Hill, D., Shapiro, S. (1984) Segment passenger car equivalent values for cost location on urban arterial roads, *Transportation Research Part A*, 18, pp. 399-406.

Transportation Research Board (TRB) (2000) Highway Capacity Manual, 4th ed., Washington, DC: National Research Council.

Webster, N., Elefteriadou, L. (1999) A simulation study of truck passenger car equivalents (PCE) on basic freeway sections, *Transportation Research Part B*, 33, pp. 323-336.