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Hot Emission Model for Mobile Sources: Application to the Metropolitan Region of the City of Santiago, Chile

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ABSTRACT

Depending on the final application, several methodologies for traffic emission estimation have been developed. Emission estimation based on total miles traveled or other average factors is a sufficient approach only for extended areas such as national or worldwide areas. For road emission control and strategies design, microscale analysis based on real-world emission estimations is often required. This involves actual driving behavior and emission factors of the local vehicle fleet under study.

This paper reports on a microscale model for hot road emissions and its application to the metropolitan region of the city of Santiago, Chile. The methodology considers the street-by-street hot emission estimation with its temporal and spatial distribution. The input data come from experimental emission factors based on local driving patterns and traffic surveys of traffic flows for different vehicle categories. The methodology developed is able to estimate hourly hot road CO, total unburned hydrocarbons (THCs), particulate matter (PM), and NO_x emissions for predefined day types and vehicle categories.

IMPLICATIONS

The impact of road transport on air quality in urban areas makes accurate emission estimation necessary. This paper presents a methodology to calculate real-world hot emissions from different vehicle categories under both spatial and temporal distributions. Examples of the methodology application to the road network in the urban area in the city of Santiago shows its power and resolution when applied by decision-makers and researchers to reliably simulate microscale impact assessment analysis and predict future environmental situations.

INTRODUCTION

Total mobile sources can be calculated as the sum of three specific terms:[1,2] hot emission, cold start, and evaporative emissions. Hot emission corresponds to the exhaust pipe emissions under normal operational conditions, cold starts represent additional emissions due to lower operating engine temperature, and evaporative emissions denote the fuel evaporation during travel under daily temperature fluctuations (diurnal, hot soak, and running losses). Hot emissions are normally calculated by multiplying a speed-dependent emission factor corresponding to the pollutant and vehicle category analyzed by a term representing the activity level of the vehicle category.[3-5] The emission factor represents the emission rate per unit of activity, normally expressed in grams per kilogram, and determined experimentally from chassis dynamometer transient tests, applying driving cycles representing local driving patterns.[6-9] The activity level could be simply represented by total kilometers traveled by vehicle category; however, this approach leads to poor accuracy that prevents any spatial or temporal emission distributions on the traffic network in an urban zone. More adequate approaches consist of traffic characterizations in terms of flow densities and vehicle category compositions. This can be done from traffic surveys, traffic models, or a combination of both.[10,11]

Hot vehicle emissions depend on several parameters, such as traffic conditions (congestion), vehicle-operating conditions (average speed, load, trip length, driving mode, mileage), vehicle technological parameters (model and year, state of maintenance, engine type, control emission system), fuel characteristics (type, chemical composition), and topography. An emission calculating methodology must take into account as many of these parameters as possible. To calculate emissions from mobile sources, several emission models were developed based on different kinds of input data, all of which lead to a wide range of accuracy.[12-17] Accuracy requirements further depend on the field applications of the results being higher when microscale analysis is required. Current trends are based on real-time traffic data taken from direct street observations.

In this paper, a methodology for estimating hot emission from mobile sources is presented. The methodology considers input data from transport modeling and experimental data concerning driving cycles, emission factors, and traffic flow characterization, in terms of vehicle category composition and driving modes. The emission model developed allows hourly street-by-street hot emission calculation of CO, NO_x, and total unburned hydrocarbons (THCs). An application of the methodology for the traffic network of the metropolitan region of Santiago, Chile, is presented.

METHODOLOGY

General Approach

The methodology developed calculates hourly hot emissions at a portion of the street (arc) from each vehicle category present on a traffic network as follows:

$$E_{h,i,j,k} = F_j \, L_j \, EF_{i,k}(v) \, FP_j \, C_{j,k} \qquad (1)$$

where $E_{h,i,j,k}$ is the emission of pollutant i during the hour of the day h on the arc of the traffic network j from vehicle category k expressed in grams per hour; F_j is the total traffic volume at the arc j on-peak traffic hours expressed in vehicles per hour; L_j is the total length of the arc j in kilometers; $EF_{i,k}(v)$ is the emission factor of pollutant i and vehicle category k as a function of average speed v in grams per kilometer-vehicle; FP_j is the hourly traffic flow profile at the arc j for different day types; and $C_{j,k}$ is the fraction of the total traffic volume corresponding to the vehicle category k on the arc j.

Total traffic volume, F_j, corresponds to output data from a transportation model called ESTRAUS,[18,19] with an urban road network comprising 7567 arcs distributed over the greater Santiago area, which is divided into 264 zones. ESTRAUS is one of the fundamental elements of the methodology for urban transport strategic plans evaluation developed by the Chilean government in the mid-1980s. Like most transportation models, ESTRAUS is built on four main stages: trip generation/attraction, trip distribution, modal choice/split, and trip assignment. The last three stages are solved through a simultaneous equilibrium, generating a solution that reflects a dynamic interaction among them, instead of through a sequential modeling approach. This model is used for strategic planning and covers two main weekday periods of time: morning peak hour (typically 7:30–8:30 a.m.) and interpeak hour (typically 10:30–11:30 a.m.).

Regarding emission calculation, the main outputs from ESTRAUS are traffic volume and time needed to drive over a given arc of the urban road network. Because the ESTRAUS model is mainly used for demand analysis, traffic volume is divided only into two types: fix and variable flow. Fix flow represents public transportation (urban buses) and is received as input by the model, but it is modified during certain stages of modeling, especially at peak-time hours. On the other hand, variable flow includes private transportation modes and is associated with variable timing, which allows calculating the average speed while driving over a given arc. Figure 1 shows the traffic network for the metropolitan region of the city of Santiago. To perform emission calculations, this traffic network is complemented with an additional highway network around the metropolitan region.

Traffic flow profiles, FP_j, refer to the daily flow tendencies normalized with respect to on-peak data for each day type considered. Four types of days in a week have been defined: Monday to Thursday, Friday, Saturday, and Sunday. The day-type definition considers homogeneous traffic characteristics such as flow densities and hours when on- and off-peak periods take place.

The transportation model provides traffic volume desegregated only in two kinds of flows (fixed and variable), which involves only two aggregated vehicle types. A characterization of traffic flows by additional vehicle categories is, however, necessary and will be explained in another section of this paper. Vehicle categories were defined taking into account vehicle type, final use, technology, and emission standards. Table 1 shows vehicle categories considered for the emission model.

Emission factors, EF_{ik}, came from experimental programs for gasoline light-duty vehicles and from COPERT II[20] for the remaining vehicle categories. The experimental program for the determination of emission factors for light-duty gasoline vehicles has been previously reported,[6] where nine standard representative driving cycles for Santiago (STD driving cycles) with the same number of average speeds were used.

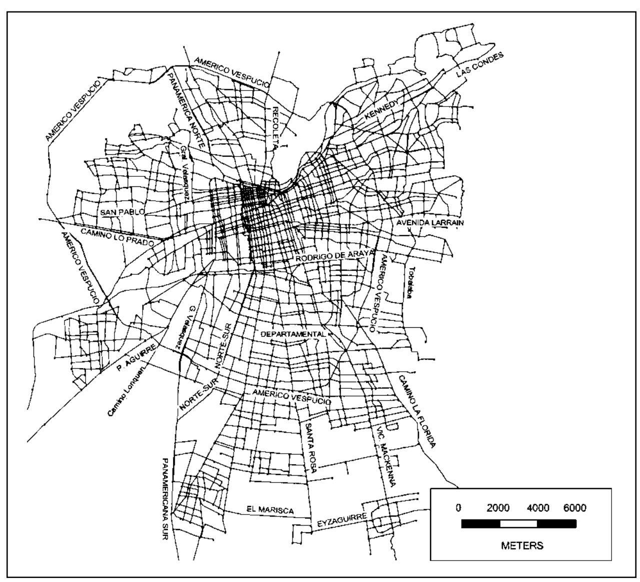

Figure 1. Traffic network of the metropolitan region of Santiago.

Table 1. Vehicle categories.

Vehicle Type	Category	Description
Buses	Bus A	Urban buses pre-EPA-91
	Bus B	Urban buses EPA-91
	Bus C	Urban buses EPA-94
	Bus D	Other buses
Trucks	Truck A	Light- and medium-duty trucks
	Truck B	Heavy-duty trucks
Private vehicles	PPV-CAT	Light-duty catalytic private passenger cars
	PPV-NCAT	Light-duty noncatalytic private passenger cars
Commercial vehicles	CV-CAT	Light- and medium-duty catalytic commercial vehicles
	CV-NCAT	Light- and medium-duty noncatalytic commercial vehicles
	CVD	Light- and medium-duty diesel commercial vehicles
Taxis	T-CAT	Catalytic taxis
	T-NCAT	Noncatalytic taxis
Motorcycles	M-2S	Two-stroke motorcycles
	M-4S	Four-stroke motorcycles

Driving cycles were obtained from an instrumented car running predetermined circuits around the city, as discussed in detail in another section of this paper. A general scheme of the methodology just discussed is described in Figure 2, indicating type and source of the input data.

Driving Cycles

Driving cycles are one of the most important parameters that influence hot exhaust emissions, as reported in previous research.[21-24] To get real-world emission estimates, real-world driving cycles are required that can be obtained from modeling, travel survey data, or measurements taken from an instrumented car. The emission model described in this paper uses driving cycles obtained by on-road measurement methodologies. A vehicle fitted with a data acquisition system for instantaneous engine revolutions per minute and distance driven over a predefined circuit around the city, applying the floating car technique, results in speed-distance plots such as shown in Figure 3. Further acceleration and speed histogram analysis leads to the definition of nine typical driving patterns with average speeds from 3 to 80 km/hr. Figure 4 shows as an example a driving cycle with 30 km/hr average speed (STD30). Table 2 presents the main characteristics of the local driving cycles.

Emission Factors

For light-duty gasoline vehicles, an experimental program was conducted to determine emission factors.[6] This program involved chassis dynamometer transient test using driving cycles described previously. A total of 166 vehicles constituted the sample, including catalytic and noncatalytic cars. Almost 2000 individual emission tests were performed. Equations 2–4 and 5–7 represent the emission factors obtained as a function of average speed, V, in km/hr for catalytic and noncatalytic private light-duty gasoline vehicles, respectively.

$$EF_{\text{PRIVATE CATALYST}}\,(CO) = 20.844 \cdot V^{-0.7656} \tag{2}$$

$$EF_{\text{PRIVATE CATALYST}}\,(NO_x) = 3 \cdot 10^{-6} \cdot V^3 - 3 \cdot 10^{-4} \cdot V^2 + 0.0068 \cdot V + 0.4941 \tag{3}$$

$$EF_{\text{PRIVATE CATALYST}}\,(THC) = 0.3681 \cdot V^{-0.4085} \tag{4}$$

$$EF_{\text{PRIVATE NONCATALYST}}\,(CO) = 0.0243 \cdot V^2 - 2.5613 \cdot V + 76.977 \tag{5}$$

$$EF_{\text{PRIVATE NONCATALYST}}\,(NO_x) = 9.5 \cdot 10^{-6} \cdot V^3 - 0.0016 \cdot V^2 + 0.0738 \cdot V + 1.2586 \tag{6}$$

$$EF_{\text{PRIVATE NONCATALYST}}\,(THC) = 8.8083 \cdot V^{-0.4792} \tag{7}$$

Commercial and private cars have to meet different emission standards; because of this, differentiated emission

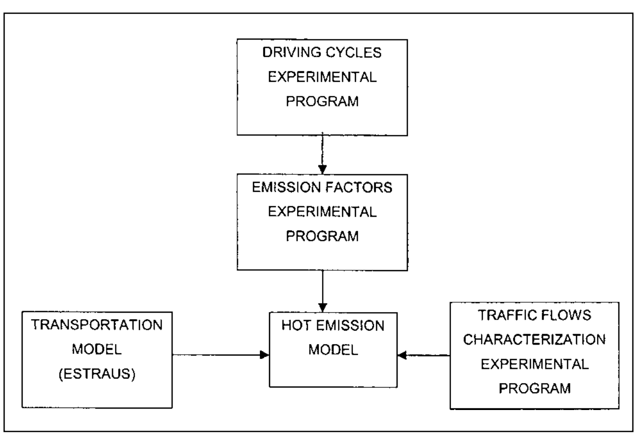

Figure 2. Hot emission model scheme.

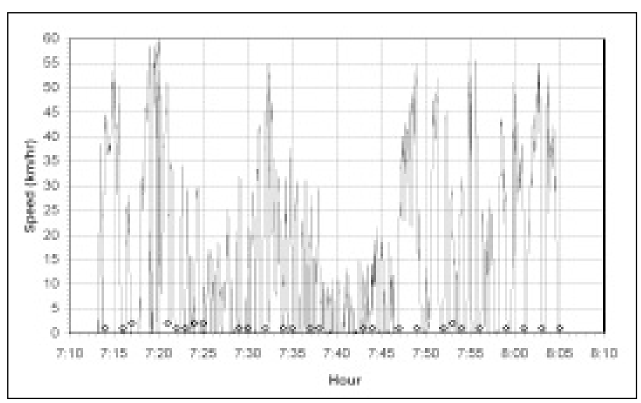

Figure 3. Example of speed-time traces obtained from the instrumented car.

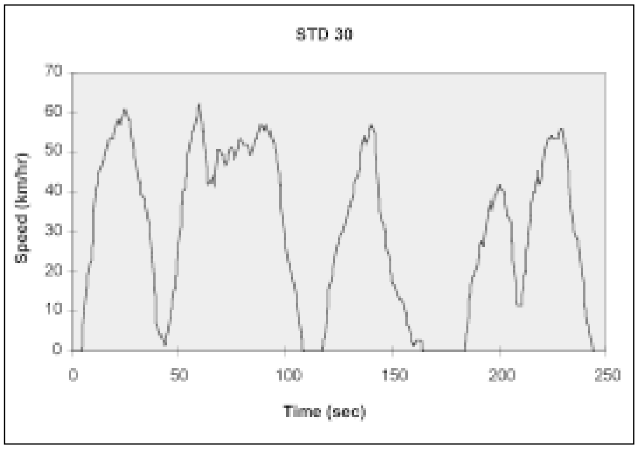

Figure 4. Driving cycle of 30-km/hr average speed.

factors were determined for commercial vehicles. Equations 8–10 and 11–13 correspond to the best fit of experimental data obtained for commercial catalytic and noncatalytic vehicles, respectively.

$$EF_{\text{COMMERCIAL CATALYST}}\,(CO) = -8{\cdot}10^{-5}{\cdot}V^2 + 0.0011{\cdot}V + 0.5633 \tag{8}$$

$$EF_{\text{COMMERCIAL CATALYST}}\,(NO_x) = 8{\cdot}10^{-6}{\cdot}V^3 + 0.001{\cdot}V^2 + 0.03{\cdot}V + 0.4419 \tag{9}$$

$$EF_{\text{COMMERCIAL CATALYST}}\,(THC) = 0.0003{\cdot}V^2 - 0.0277{\cdot}V + 0.7856 \tag{10}$$

$$EF_{\text{COMMERCIAL NONCATALYST}}\,(CO) = 0.0228{\cdot}V^2 - 2.4598{\cdot}V + 79.998 \tag{11}$$

$$EF_{\text{COMMERCIAL-NONCATALYST}}\,(NO_x) = 3{\cdot}10^{-5}{\cdot}V^3 - 0.0042{\cdot}V^2 + 0.1669{\cdot}V + 1.738 \tag{12}$$

$$EF_{\text{COMMERCIAL-NONCATALYST}}\,(THC) = 0.0006{\cdot}V^2 - 0.0891{\cdot}V + 4.5941 \tag{13}$$

Table 2. Characteristics of the nine local driving cycles.

Cycle	Average Speed (km/hr)	Max Speed (km/hr)	Duration (sec)	Acceleration Time (%)	Max Acceleration (m/sec^2)	Idle Time (%)
STD 05	3.0	25.2	239.0	14.2	2.0	67.1
STD 10	11.1	36.0	239.0	32.5	1.5	25.4
STD 20	19.6	57.6	249.0	32.4	2.0	25.6
STD 30	29.7	61.9	244.0	42.9	2.1	14.3
STD 40	38.4	72.1	249.0	48.8	1.8	6.4
STD 50	46.3	73.3	274.0	42.2	2.3	4.0
STD 60	55.3	77.1	274.0	49.1	3.5	1.5
STD 70	66.4	84.7	274.0	38.2	2.3	0.7
STD 80	72.9	94.8	279.0	43.6	2.8	1.8

Emission factors for taxis were assumed to be equal to those of private vehicles because of similar technical characteristics. A comparative analysis of local emission factors (eqs 2–13) with those proposed by other sources, such as COPERT and U.S. Environmental Protection Agency (EPA) AP-42, was presented in a previous paper by the authors.[6] This analysis denotes that local emission factors for private and commercial noncatalytic vehicles forecast higher emissions than AP-42, being closer to COPERT II. Higher speed influence was observed on emission for local results and COPERT II compared with the AP-42 approach, which is more evident for CO and THC. A better agreement was obtained between experimental data and COPERT II and AP-42 for catalytic vehicles. Nevertheless, important discrepancies are noted on low-speed ranges, where CO and THC emissions predicted by models are lower than experimental data.

For diesel vehicles and motorcycles, no experimental facilities were available; thus, emission factors from COPERT II[20] were used (see Table 3). PM emission factors for types A and D buses were corrected by incrementing by ~20% the COPERT proposal, considering the low level of particulates in the maintenance state of these buses in the local fleet. On the other hand, emission factors for type A trucks were obtained from a combination of emission factors for light and medium trucks proposed by COPERT. As an example, emission factors evaluated at 20 km/hr, which should be considered a representative average speed for the city, are presented and compared with emission factors from COPERT II evaluated for the same speed (Table 4).

Traffic Flow Characterization

The hot emission model involves the terms FP_j and C_{jk} (eq 1) representing 24-hr traffic flow profiles and the flow fraction corresponding to the vehicle category *k* at the arc *j*, respectively. As mentioned earlier, output data from the ESTRAUS traffic model include traffic volumes desegregated into fixed and variable flow, with no distinction made for vehicle categories that must be considered for hourly emission calculations for each vehicle category present at the local vehicle fleet, according to eq 1. On the other hand, the traffic model gives data only for 2-day periods (on-peak and off-peak data). Temporal extrapolation of traffic profiles and their desegregation into vehicle categories was needed.

To estimate C_{kj} for field traffic, a characterization of different vehicle categories was carried out using a total of 75 manual measuring points distributed

Table 3. Emission factors for diesel vehicles (COPERT II[24]).

Vehicle Category	Pollutant	Emission Factor (g/km)	Original Source Application
	PM	$0.0000125\ V^2 - 0.000577\ V + 0.2880$	
CVD	CO	$0.00020\ V^2 - 0.0256\ V + 1.8281$	Light-duty diesel
	THC	$0.000066\ V^2 - 0.0113\ V + 0.6024$	vehicles
	NO_x	$0.00014\ V^2 - 0.01592\ V + 1.4921$	<3.5 ton
	PM	$12.09253\ V^{-0.7360}$	
Buses A and D	CO	$59.003\ V^{-0.7447}$	Conventional
	THC	$43.647\ V^{-1.0301}$	buses
	NO_x	$89.174\ V^{-0.5185}$	
	PM	$5.109585\ V^{-0.7360}$	
Bus B	CO	$29.5015\ V^{-0.7447}$	Urban buses
	THC	$32.73525\ V^{-1.0301}$	Stage I
	NO_x	$62.4218\ V^{-0.5185}$	(91/542/EEC)
	PM	$3.14436\ V^{-0.7360}$	
Bus C	CO	$23.6012\ V^{-0.7447}$	Urban buses
	THC	$30.5529\ V^{-1.0301}$	Stage II
	NO_x	$44.587\ V^{-0.5185}$	(91/542/EEC)
	PM	$4.2074\ V^{-0.7174}$	
Truck A	CO	$18.64\ V^{-0.6945}$	Light- and medium-
	THC	$30.09\ V^{-0.8774}$	duty trucks
	NO_x	$46.43\ V^{-0.7535}$ (0–60 km/hr)	
		$0.00077\ V^2 - 0.10045\ V + 5.346$ ($60 < V < 100$ km/hr)	
	PM	$8.712 V^{-0.7105}$	
Truck B	CO	$29.824\ V^{-0.6945}$	Conventional
	THC	$32.096\ V^{-0.8774}$	heavy-duty
	NO_x	$86.688\ V^{-0.6061}$	trucks
	CO	$-0.001\ V^2 + 0.172\ V + 18.1$	Conventional
M-2S	THC	$0.0035\ V^2 - 0.409\ V + 20.1$	heavy-duty
	NO_x	$0.00003\ V^2 - 0.002\ V + 0.064$	trucks
	CO	$0.0123\ V^2 - 1.19\ V + 42.8$	Conventional
M-4S	THC	$0.0022\ V^2 - 0.257\ V + 9.28$	heavy-duty
	NO_x	$0.00005\ V^2 - 0.0008\ V + 0.1$	trucks

Table 4. Emission factors evaluated at 20 km/hr average speed.

Vehicle Type	Local Emission Factors			Copert II Emission Factors[24]			
	CO	THC	NO_x	CO	THC	NO_x	PM
Private-CAT	2.10	0.11	0.53	2.50	0.17	0.42	–
Commercial-CAT	0.55	0.35	0.60	1.51	0.13	0.40	–
Private-No CAT	35.47	2.10	2.64	32.12	3.03	1.76	–
Commercial-No CAT	39.92	3.05	3.64	31.94	3.40	1.82	–
Commercial-Diesel	na	na	na	1.40	0.40	1.23	0.28
Bus A and D	na	na	na	6.34	1.99	18.86	1.33
Bus B	na	na	na	3.17	1.50	13.21	0.56
Bus C	na	na	na	2.54	1.40	9.43	0.35
Truck A	na	na	na	1.28	2.17	4.86	0.49
Truck B	na	na	na	2.05	2.32	7.75	1.04
M-2S	na	na	na	21.14	13.32	0.076	–
M-4S	na	na	na	23.92	5.02	0.104	–

Note: na means local emission factors for these vehicle categories not available.

around the city. On each counting point, traffic flow volumes for 15 vehicle categories were identified through on-peak and off-peak periods (see Table 1). Results were expressed as a fraction of total traffic volume corresponding to each vehicle category, which was calibrated by data collected from automatic total traffic volume counting stations, some of which were placed close to the manual traffic count points. Through data analysis, nine city sectors were defined where vehicle category distributions were homogeneous with a statistical dispersion of less than 10%. On the other hand, as a simplification of the problem, vehicle category distributions were considered constant along the day due to the low variations obtained, as shown in Figure 5. Figure 6 shows a graphical representation of the nine sectors defined and the location of the manual traffic counting points. In each geographical sector, an average vehicle category distribution was assigned.

Temporal extrapolation of traffic profile, represented by FP_j in eq 1, was obtained by mean data collected from continuous 24-hr traffic counting stations. Processing and analysis of this set of data made it possible to generate 24-hr traffic profiles normalized by morning on-peak values, for each one of the four types of day defined. Figure 7 shows an example of traffic profile obtained for sector 3, corresponding to a downtown zone of the city of Santiago. Two types of traffic profiles were used: one for buses and one for the remaining vehicle categories.

MODEL RESULTS

The hot emission model developed is able to calculate hourly CO, THCs, PM, and NO_x emissions on each arc of the traffic network for each vehicle category present in the local vehicle fleet. As an example, Figure 8 shows a graphical representation of PM emissions from buses (kg/hr) in the morning peak period of a working day on each arc of a certain street in a downtown

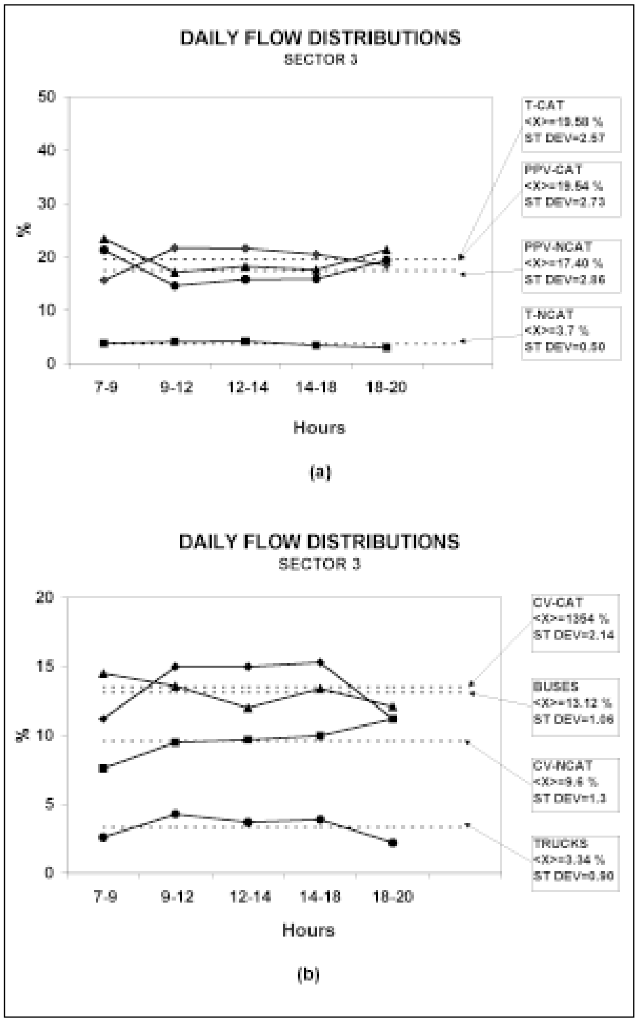

Figure 5. Daily flow distributions in sector 3 (downtown): (a) private vehicles and taxis; (b) commercial vehicles, buses, and trucks.

zone of the city (sector 3). This type of analysis can be made for each vehicle category, hour of the day, and pollutant.

Another result of the model concerns total annual emissions for each sector of vehicle category and pollutant. As an example, NO_x emissions from buses for nine sectors are graphically represented and compared to NO_x emissions of the remaining vehicle categories (Figure 9). The major incidence of emissions from buses is in sectors 3 and 4, where a great activity level of this vehicle category stands out. It is also evident that total emissions, considering all vehicle categories, are greater in sectors 3, 5, and 6, which denotes higher activity levels for older vehicle technologies, corresponding to lower socioeconomic sectors.

Emission scenario analysis permits emission projections from baseline emission inventory. This is normally used for effective evaluation of emission reduction strategies by mean emission estimation forecasting. The model is able to calculate predicted emissions using adequate projection of activity levels

Figure 6. Sectors with homogeneous vehicle category distribution and location of manual counting station.

and emission factors. As an example of this, Figure 10 represents a comparison of 1997 baseline and projected 2005 CO, PM, HC, and NO_x hourly emissions at a microzone of sector 1. Emissions corresponding to 2005 were estimated by means of a projection of traffic flows from the ESTRAUS model, which predicts a 65% total increase of the activity level (vehicle-km/year). In addition, increasing rates of 10% per year for the commercial vehicle fleet and 7–8% for the other vehicle categories were considered. A rate of 2% of withdrawal per year for all vehicle categories was also estimated.

The type of results just discussed corresponds to microscale analysis, which constitutes a powerful tool for sector-scale emission management. Additional macroscale analysis is also possible via integration of hourly street-by-street emission calculations of primary pollutants over the year and the entire traffic network. An example of this analysis is shown in Figure 11, where annual emissions from desegregated vehicle categories and activity levels (ACTs) described by fuel consumption (FC) and vehicle-kilometer

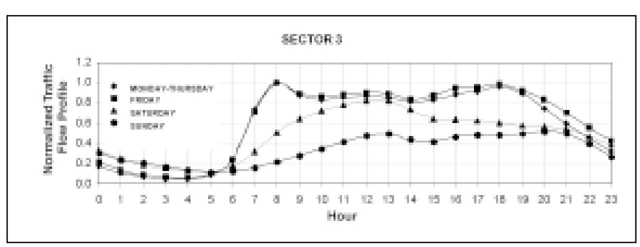

Figure 7. Example of traffic flow profile.

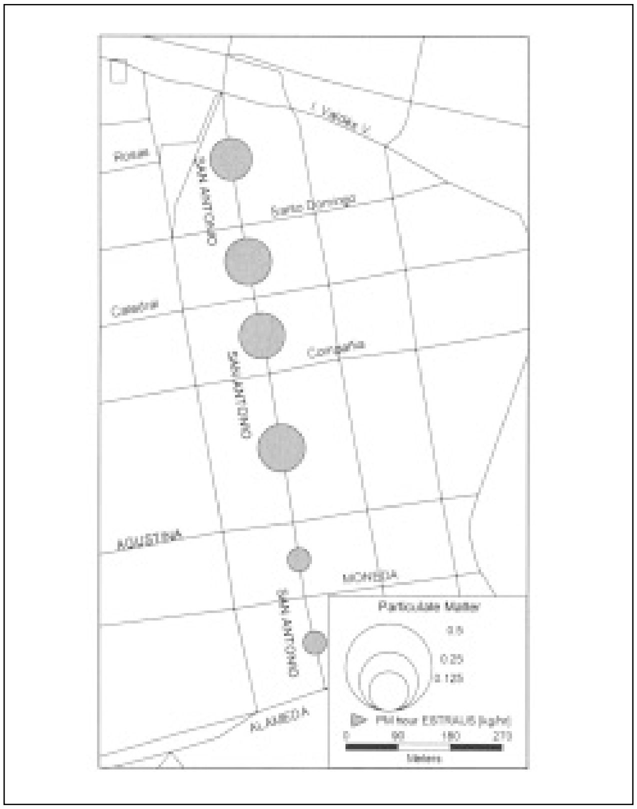

Figure 8. Example of street-by-street hourly emission estimation for vehicle category and pollutant predefined: PM bus emissions (kg/hr) in morning on-peak hour at downtown zone (sector 3).

per year are shown for the entire metropolitan region. This type of analysis allows the identification of major primary pollutant emissions among desegregated vehicle categories.

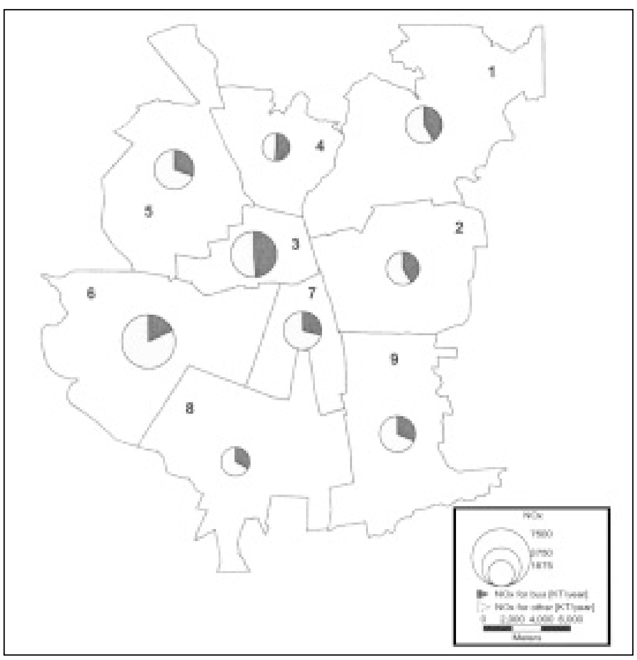

Figure 9. Total annual emissions by geographical sectors: NO_x bus emissions compared with NO_x emissions from remaining vehicle categories.

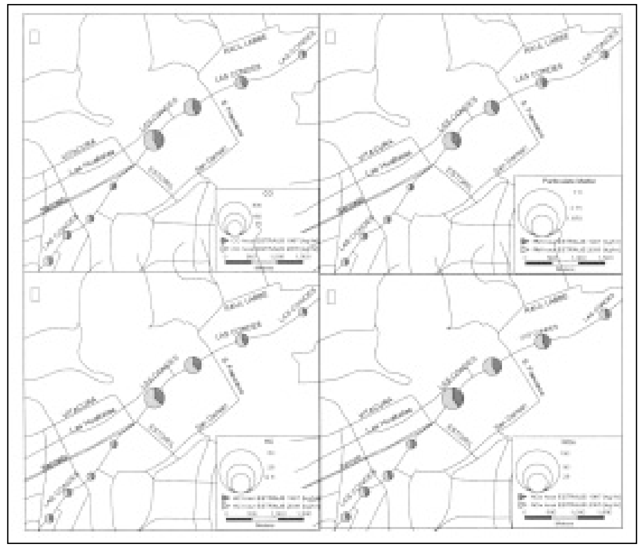

Figure 10. Comparison of 1997 and 2005 CO, PM, HC, and NO_x hourly emissions by arc at a microzone of sector 1.

In the example in Figure 11, it is clear that more than 80% of total annual emissions of PM comes from buses and trucks, despite being lowest in annual mileage. Buses also have an important participation in NO_x emissions. On the other hand, private cars represent the highest contribution to CO and THC emissions. This analysis can be improved by considering more desegregated vehicle categories to allow more specific design strategies in terms of, for example, emission regulation and transportation planning.

DISCUSSION AND CONCLUSIONS

The hot emission model described above renders spatial and temporal high-resolution emission distribution, thus allowing hourly emission estimates for street portions (arcs) defined on a real traffic network for 15 vehicle categories. Input data correspond to real-time traffic data

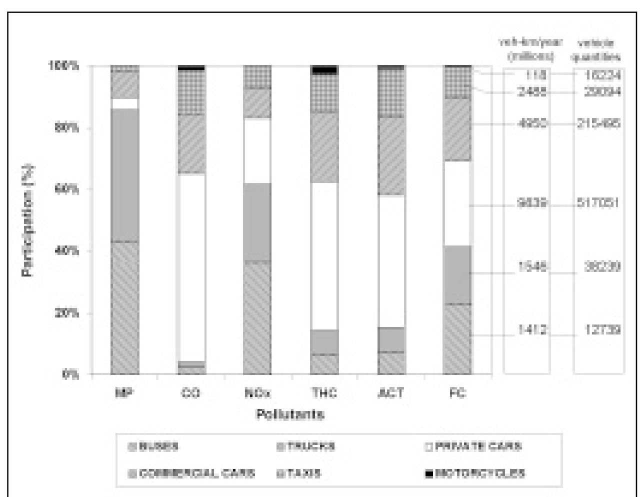

Figure 11. Annual emission, ACT, and FC distributions per vehicle categories.

recollection and, in the case of gasoline light-duty vehicles, emission factors from an experimental program where local driving cycles were used. The complexity of the methodology forces some hypotheses and simplifications to be improved in further research work. An example could be the development of an experimental program to determine emission factors for diesel vehicles, as well as characterization of traffic flows at the urban road network in more detail and, thus, lifting the assumption of constancy along the day. The methodology discussed here only concerns hot emissions, so it must be extended to cold start and evaporative emissions as well. This implies the development of a methodology based on area scale instead of arc scale as done here, which corresponds to the present work being done by the authors.

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