Pergamon

Atmospheric Environment Vol. 27B, No. 4, pp. 435–446, 1993.

0957-1272/93 $6.00+0.00

MODEL FOR TRAFFIC EMISSIONS ESTIMATION

A. ALEXOPOULOS and D. ASSIMACOPOULOS
Department of Chemical Engineering, Section II, National Technical University of Athens, Zographou 157 73, Athens, Greece

and

E. MITSOULIS*
Department of Chemical Engineering, University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada

(*First received* 15 *December* 1991 *and in final form* 25 *April* 1993)

Abstract—A model is developed for the spatial and temporal evaluation of traffic emissions in metropolitan areas based on sparse measurements. All traffic data available are fully employed and the pollutant emissions are determined with the highest precision possible. The main roads are regarded as line sources of constant traffic parameters in the time interval considered. The method is flexible and allows for the estimation of distributed small traffic sources (non-line/area sources). The emissions from the latter are assumed to be proportional to the local population density as well as to the traffic density leading to local main arteries. The contribution of moving vehicles to air pollution in the Greater Athens Area for the period 1986–1988 is analysed using the proposed model. Emissions and other related parameters are evaluated. Emissions from area sources were found to have a noticeable share of the overall air pollution.

Key word index: Traffic emissions, traffic pollution, urban emission modelling.

1. INTRODUCTION

In recent years, urban pollution has emerged as the most acute problem, because of its negative effects on health and deterioration in living conditions. To prevent further exacerbation, a thorough environmental policy is required based on scientific planning of pollution control. Within this framework it is necessary:

— to analyse and specify all pollution sources and their contribution to air pollution;
— to study the different factors which cause the phenomenon;
— to develop tools to reduce pollution by introducing control measures and alternatives to existing practices.

An appraisal of the existing pollution sources constitutes the first step of tackling the problem. A precise knowledge of their location, temporal distribution, level of activity and their interconnection with the massive flow of pollutants in the atmosphere, comprise the most crucial elements in the overall formulation of a model, which can be used for quantitative predictions concerning real situations (Claggett *et al.*, 1981; Matzoros, 1990).

Estimates of emissions from traffic (moving sources) is a demanding problem. It requires coordination of a large number of data and measurements in the area of interest. This work presents a model, which evaluates the pollutant emissions from traffic in urban areas in a detailed manner. In our attempt to model the emissions, we have tried to make as much as possible use of existing raw data. The present model is flexible enough so that it can be used in cases where raw data are not complete and a network/trip matrix is difficult to generate.

Special attention has been paid to the evaluation of traffic area sources, i.e. to those emissions which do not originate in the big arteries and for which traffic load data are usually missing. Modelling of these sources presents major difficulties and is possible only when detailed data are available. Such an example was given by Psaraki-Kalouptsidis (1976) in the case of St Louis, U.S.A. This model is based on a special probability law which is assumed to govern traffic, when the latter has as a determining parameter the average travelled distance. Different routes are grouped into categories with common traffic characteristics and emission factors.

In the present work there are no such data available. The proposed method groups together small line sources into area sources. For area sources, fuel consumption is estimated from an overall balance in the study area and according to data for population density and local traffic intensity. The structure of the model is independent of the time period of its implementation and it can be updated with new traffic data. Thus, in connection with similar emission models for central heating (Kozaris *et al.*, 1984) and for industrial emissions, it can be used as a tool for pollution control policies.

* To whom correspondence should be addressed.

The implementation of the model refers to the prediction of CO emissions in the Greater Athens Area in Greece (see Fig. 1). The raw data used refer to traffic conditions during the period 1986–1988. Thus, the analysis takes into account the influence of partial restriction of automobile traffic in the Athens city centre enforced in 1983 (establishment by the government of an *internal ring* where half of the private vehicles and taxis are prohibited from entering, see shaded area of Fig. 1). Also, comparisons are made with results based on raw traffic data of 1982, whenever possible.

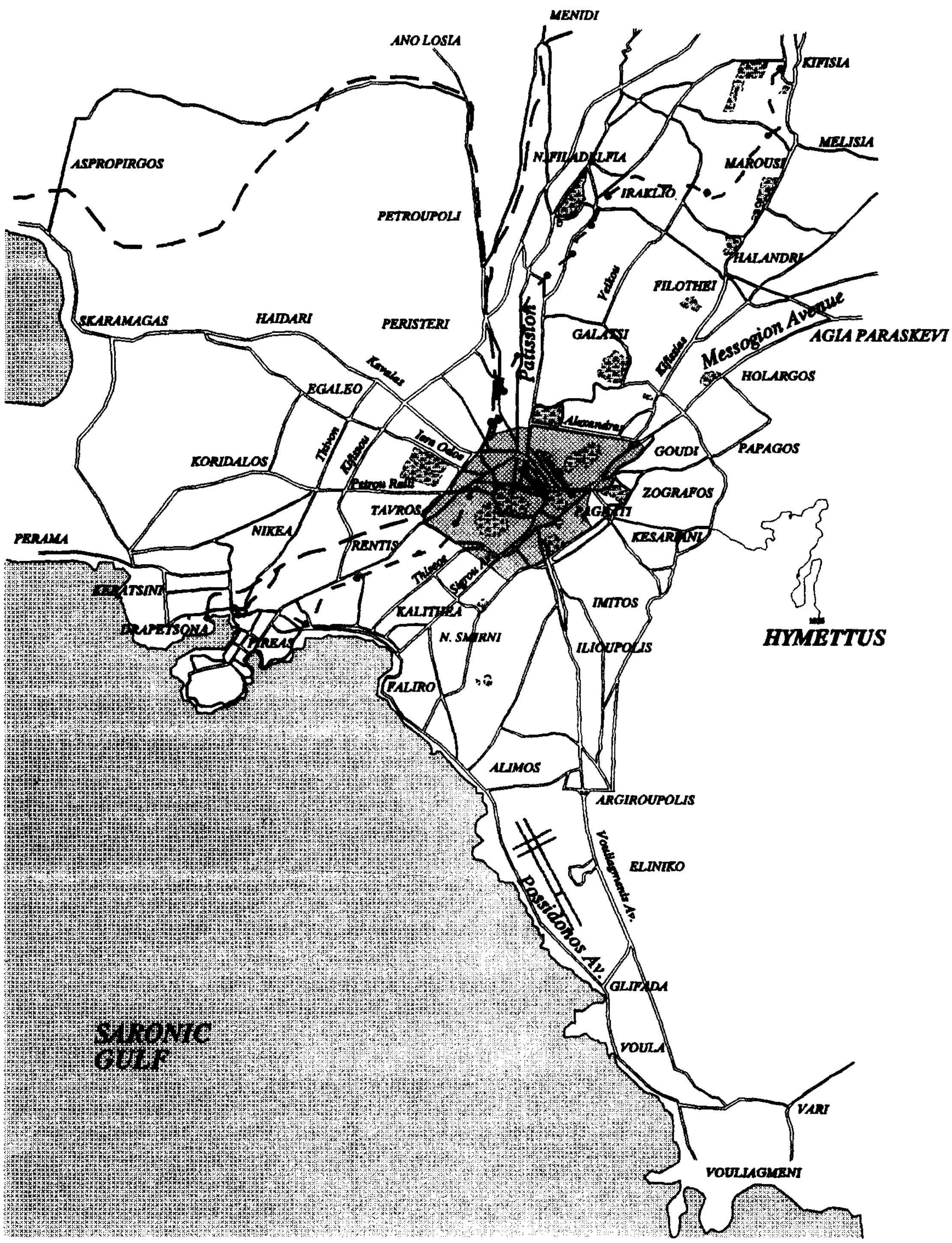

Fig. 1. Map of Greater Athens Area with key arteries and regions. Shaded area represents the traffic restriction zone (Internal Ring).

2. MODEL FORMULATION FOR EMISSIONS EVALUATION

2.1. *Emissions evaluation*

Pollutant emissions at a point of a traffic artery is a function of many variables, which can be grouped into two categories: (a) traffic variables (x_n), such as traffic load, traffic composition, speed, driving model, etc. and (b) vehicle variables (y_n), related to vehicle engine and its driving conditions. The emission of a pollutant p during the time interval t will be:

$$E_{pt} = \mathscr{F}_{pt}(x_1, x_2, \ldots, x_n; y_1, y_2, \ldots, y_n). \quad (1)$$

The spatial and temporal distribution of traffic load is an essential factor in the emission model. In most cases there is a total lack of data for arteries of light traffic, and the evaluation of their contribution to air pollution is based on simplifying assumptions (Roth and Roberts, 1974).

Traffic composition, i.e. the percentage distribution of traffic load per vehicle category, differs from the corresponding composition of vehicle fleet due to different usage of various vehicle categories. In cases where data on traffic composition are missing or inadequate, vehicles are grouped into two categories according to fuel type used. In the case of a total lack of data on traffic composition, some information can be obtained from the relative consumption of gasoline and diesel in the area or from literature sources (EPA Report, 1979).

Simulation of the motion of a certain vehicle category leads to the driving model and gives the average operating times of the vehicle engine while stationary, in constant speed, acceleration, or deceleration for a typical route of constant distance. The emission factors used for the calculation of vehicle emissions depend on driving conditions (EPA Report, 1978). Road driving conditions can be expressed, apart from the driving model, as a function of the average speed of the vehicles during the time period under consideration (Roth and Roberts, 1974).

The pollutant vehicle emissions also depend on several engine parameters, the most important of which are the engine volume (cc) and age, the ratio air/fuel, the ignition procedure, the ratio area/volume of the cylinders, the compression ratio, etc. Emissions are also sensitive to a large number of parameters concerning driving conditions such as engine charge and temperature.

It is evident that in a large-scale model it is impossible to take into account all different parameters. For simplification, we proceed with the following categories:

— vehicles with similar engine parameters,
— arteries with similar traffic conditions.

Such categories can be expressed by the parameters referred to as "traffic composition" and "traffic artery category" and be taken into account as such in the model.

2.2. *Line sources modelling*

In order to implement Equation (1), some approximations should be made such as that all variables therein are kept constant along distance l of the route and during the time period under consideration. Practically this is impossible to achieve since traffic arteries transverse areas with different urban activities and cross many smaller roads.

In the present model, the arteries for which traffic data exist are divided into small linear segments (corresponding to measurements). These, in turn, are considered as independent line sources with constant traffic variables. Under these assumptions, the pollutant quantity E_p emitted from a segment of an artery (hence line source) of length l during a time period t is given by:

$$E_p = \sum_{i=1}^{N} Q \cdot \sigma_i \cdot l \cdot e_{pi}. \quad (2)$$

The quantity $Q \cdot \sigma_i$ expresses the traffic load of vehicles of category i in the time period studied. The quantity $Q \cdot \sigma_i \cdot l$ represents the number of vehicle-kilometres that were travelled by the vehicle category i during time t and along distance l of the line source.

In the emission model of line sources all roads for which traffic data are available, are taken into account. Line sources are divided into appropriate linear segments for which traffic load, traffic composition and emission factors of the pollutants are assumed constant. Road splitting is made according to changes in traffic load along its length. The line segments derived this way are studied as independent line sources with a traffic composition corresponding to the category which each line source belongs to.

Raw data collected on traffic load present many shortcomings, either because of bad scheduling practices or because of problems during measurement or because of lack of adequate technical equipment. In order to resolve better these inadequacies, the following submodels for handling traffic data were developed.

(*a*) *FILL*. Submodel FILL fills up missing data in traffic load files. The method used averages data of similar road categories with complete data records. The averaging procedure generates non-dimensional values for traffic loads of each line source (using the average value). Then, it applies a curve fitting procedure in order to find suitable adjusting factors expressing the traffic load variation in the time period under examination.

(*b*) *EXTEND*. The duration of measurements is usually one week and the data collected refers either to weekdays or to weekends. The number of traffic load data related to weekends is significantly lower than that related to weekdays. It is essential to extend the traffic load data, so that they can cover the same number of weekend periods as that of weekdays. Submodel EXTEND creates weekday/weekend proportionality factors for the roads, for which data from

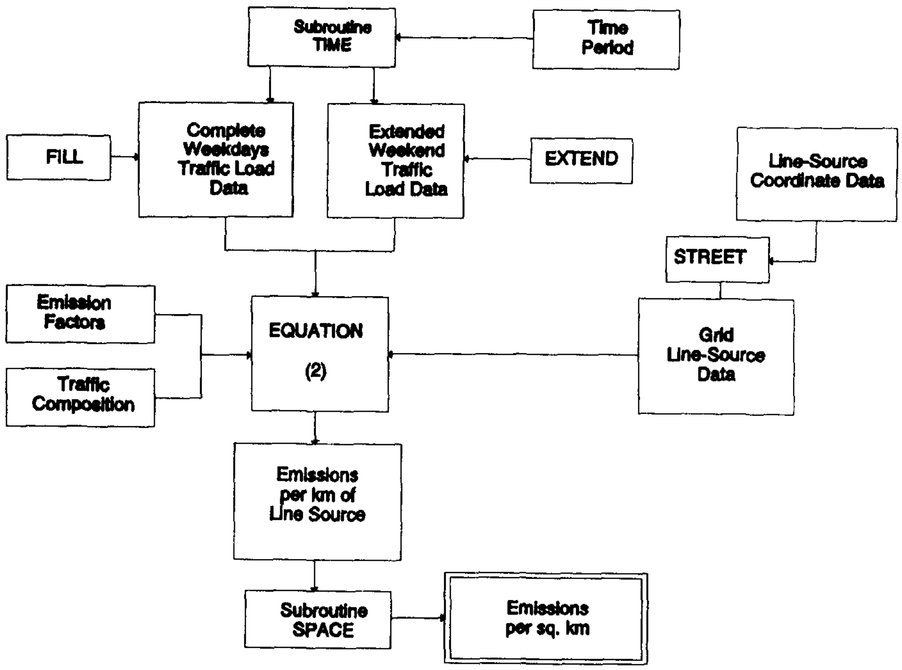

Fig. 2. Structure of the model estimating line-source emissions (LINE-S).

both categories are available and provides an estimation of the weekend traffic load values.

(*c*) *STREET*. Estimation of emissions, in the form of pollutant quantity per unit area, can be achieved if all partial emissions from the line sources are added in each grid cell. For this, it is necessary to locate the line sources on the grid, so that their contribution to each cell can be identified. Then, the intersections of line sources with grid lines are determined and the intercepted lengths of line sources are calculated and enter the corresponding grid cell.

Figure 2 shows the structure of the overall model for calculating emissions from line sources, called LINE-S. The user initially chooses (with subroutine TIME) the time period for which emissions are to be calculated. Then subroutine SPACE determines whether the results will be emissions per unit length of line source or emissions per unit area. In the second case it is necessary to handle the output files from submodel STREET. Necessary input data also comprise: the coordinates of line sources, the emission factors, and the traffic composition for each vehicle category.

2.3. *Area sources modelling*

It is evident that the previous modelling procedure does not take into consideration that part of the traffic which occurs in secondary roads and for which there are no data available. Depending on the density of measurements, the traffic percentage which is not considered as line sources may be quite important. This shortcoming can be surmounted, to a degree, by introducing the concept of *mobile area source*. In fact, it is a grouping of disperse small line sources transformed into an area source having as emission point the centre of the corresponding cell.

The model of line sources (which is solved first) estimates fuel consumption (gasoline and diesel) of vehicles, using the consumption factors for each vehicle category. Then from the overall fuel consumption in the area, the extra fuel quantities are distributed to that part of traffic (small roads without traffic data) not processed in the line-source model.

The distribution procedure should discriminate among different urban activities. For the proposed model, these are divided into:

— activities that lead to vehicle traffic in the grid cell under consideration;

— activities that lead vehicle traffic to big arteries.

The first type of activity is usually proportional to the urban activities of the area, which as a first approximation can be assumed to be in direct proportion to the population of the area under consideration. The second type has an intensity proportional to the traffic load of local line sources.

For the implementation of the above traffic model, a percentage a of the fuel consumed in the area-traffic sources, is distributed to all grid cells and in proportion to their local population density. This fuel quantity corresponds to all constant traffic activities of the area. The remaining fuel $(1-a)$ is distributed proportionally to the corresponding vehicle-kilometres travelled by each vehicle category in the neighbouring line-traffic source.

The fuel quantities (gasoline and diesel) annually consumed in the line sources of the area of interest are calculated using the consumption factors for each

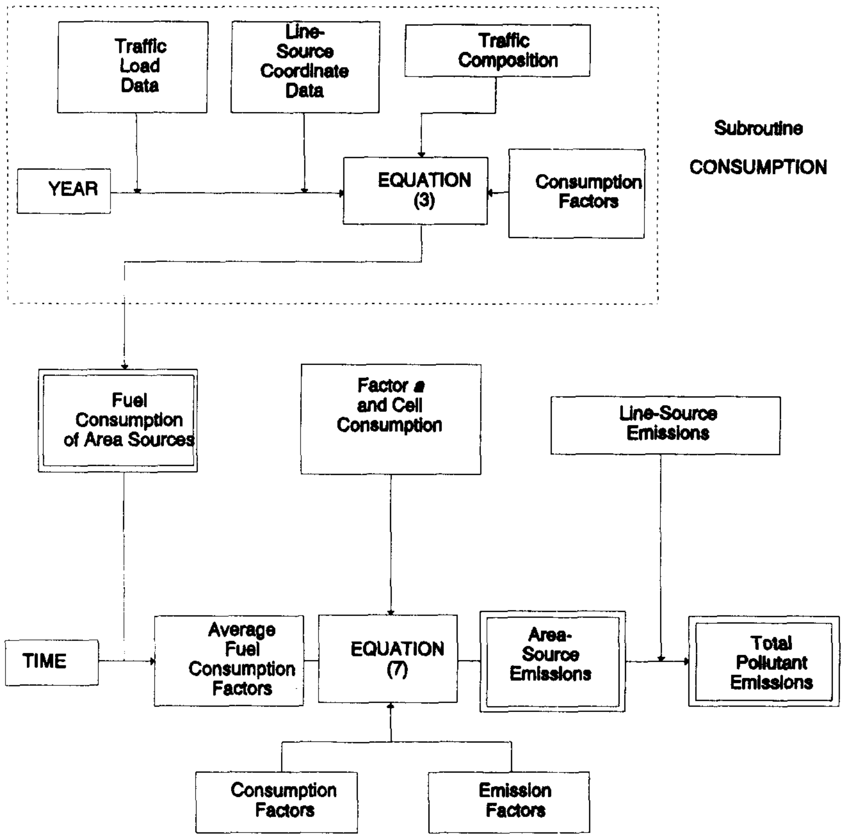

Fig. 3. Structure of the model estimating area-source emissions (AREA-S).

vehicle category. The calculation is carried out in submodel CONSUMPTION (Fig. 3), which determines fuel consumption according to:

$$K_j=\sum_i Q\cdot\sigma_i\cdot C_i\cdot l. \tag{3}$$

Upon setting as an input the time period, the appropriate traffic load data file is opened along with the corresponding coordinate data file of the line sources. It calculates the total length of each line source and by using the traffic composition data determines according to Equation (3) the fuel consumption for that period of time. The relations for distributing the fuel quantities are then:

$$B=\sum_j K_j^1+\sum_j K_j^2 \tag{4}$$

where B is the total fuel quantity consumed in area sources. For each cell j of the grid the following relations hold:

$$K_j^1=\frac{a\cdot B\cdot(\text{population in cell } j)}{\text{population of area}} \tag{5}$$

$$K_j^2=\frac{(1-a)\cdot B\cdot(\text{vehicle}\cdot\text{km in cell } j)}{\text{total vehicle}\cdot\text{km}}. \tag{6}$$

The relation which transforms a fuel quantity into the corresponding emissions quantity using consumption and emission factors is:

$$E_p=\sum_i\left[\frac{K_i^1\cdot e_{pi}}{C_i}+\frac{K_i^2\cdot e_{pi}}{C_i}\right]. \tag{7}$$

The model AREA-S implements the above described procedure and finally adds the emissions from area sources to those caused by line sources. Schematically, the model structure is given in Fig. 3.

3. A CASE STUDY: THE GREATER ATHENS AREA

3.1. *Introduction*

Smog in Athens exhibits a strong photochemical character and the contribution of automobiles to its formation is without question. About 5,100,000 passenger trips are made in Athens on a daily basis. From these only 38% make use of public transportation, while 35% use private automobiles and 6.2% taxis (Klidonas, 1986). Automobile traffic through the centre for non-business purposes accounts for 40%, and the total taxi-travelled distance without passenger reaches 900,000 km day^{-1}. Furthermore, vehicles with high emissions reach about 80% of the total fleet (Klidonas, 1986).

In recent years, there has been a number of publications with pollutant emissions data for the Greater

Athens Area. According to PERPA (1990), vehicle traffic is responsible for 64% of smoke, 8% of SO_2, 67% of NO_x, 68% of HCs and almost 100% of CO. Based on this evidence, the Greek State introduced at the end of 1982 traffic restrictions prohibiting half of the fleet of private automobiles to enter the city centre. The area of restricted circulation is demarcated by the Internal Ring road (see Fig. 1). It is clear that emissions from moving sources are of great interest, and therefore a precise analysis of their contribution to overall air pollution as well as their spatial and temporal distribution is necessary.

The relation between emissions and automobiles for the Greek capital has been the subject of some studies by Pattas and co-workers (1983, 1985a, b, c). However, a thorough model for emissions prediction based on traffic sources has not been developed as yet. Dracopoulos (1986) attempted a determination of the mean yearly pollutant emissions in the Greater Athens Area for traffic conditions prevailing in 1982. In a similar study, Bonazoundas and Tsibidis (1987) determined the lead emissions from gasoline-employing vehicles moving in the main arteries of the Greater Athens Area according to traffic data of 1983.

3.2. *Input data*

3.2.1. *Model geometry.* The area under consideration corresponds to a surface of 693 km^2 (21 km × 33 km), which is covered with an evenly distributed square grid of 1 km^2 unit cells. The limits of the study area extend to mountains Egaleo, Parnitha, Penteli, Hymettus and the Saronic Gulf. The axes of the coordinate system used coincide with geographical directions of North–South (y) and East–West (x), respectively. This coordinate system was also the basis for the calculation of the coordinates of main arteries used in the present model.

3.2.2. *Traffic load data.* The case study was based on traffic data for years 1986 and 1987, as well as the first 9 months of 1988, and concerns calculation of CO emissions from traffic in the Greater Athens area. The choice of CO was based on two reasons: (a) CO is relatively inert and (b) CO may be considered as the best tracer for determining the traffic contribution to the overall atmospheric pollution of the area since it is almost solely emitted by vehicles (PERPA, 1990).

The traffic data used were collected by the Ministry of Environment with the purpose of regulating traffic lights by using pneumatic-type devices. They have already been partially processed (Christou, 1989). Traffic load is given as a monthly average. The number of data-collection stations is given on a yearly basis in Table 1. For every station there are detailed data, such as codification, exact location of measuring devices, etc. Data collection has a duration of about one week. In the raw data there is discrimination between weekdays and weekends, and this procedure will also be followed in this study.

3.2.3. *Traffic composition.* The Ministry of Environment has also undertaken measurements of traffic composition for certain time periods during a day. For the years 1986–1988 there is little information available on the subject and only for a limited number of arteries. Data collection has been carried out in such a way that it does not allow for definitive conclusions about monthly, daily or hourly variations. Therefore, in what follows only average values of traffic composition for typical vehicle categories have been used. The vehicle subdivision consists of five categories, each of which emits and contributes to pollution in a different manner (Table 2).

Line sources in the Greater Athens Area were classified into seven categories as shown in Table 3. This classification was based on the concepts of *big* and *small* arteries, their location inside or outside the *Ring* of the down-town area, and finally coastal roads which lead traffic to resort places away from the city. This last classification is due to the different contribution of these roads to the emissions problem and it will be further explained later in the analysis of the results.

The traffic composition measurements of the Ministry of Environment were used to extract some representative values of each category of line sources in the Greater Athens Area. Then some adjustment (with polynomial curve fitting) was carried out for the values of road composition, for which complete (or adequate) data existed. This resulted in the percent-

Table 1. Stations measuring traffic load (Christou, 1989)

Day	Year		
	1986	1987	1988 (first 9 months)
Weekday	436	611	559
weekend	26	91	104

Table 2. Vehicle categories

Category	Vehicle type
1	Motorcycles
2	Automobiles
3	Taxis
4	Buses
5	Trucks

Table 3. Categories of line sources

Category	Type
1	Big arteries within the Ring
2	Small roads within the Ring
3	Arteries at the Ring boundaries
4	Big arteries outside the Ring
5	Small roads outside the Ring
6	Big coastal arteries
7	Small coastal roads

Table 4. Percentages of traffic composition for line-source categories (processed data)

Category	Motorcycles	Automobiles	Taxis	Buses	Trucks
1	12.2	46.6	32.7	7.2	1.3
2	12.8	47.7	33.2	5.0	1.3
3	10.2	60.2	21.9	3.5	4.2
4	6.8	64.7	17.9	3.9	6.7
5	9.8	71.7	12.5	2.0	4.0
6	7.5	72.8	12.3	3.0	4.4
7	9.8	78.3	8.6	1.5	1.8

Table 5. Average CO emission and fuel consumption factors (processed data of Pattas, 1981)

Vehicle category	CO emission factor ($g\,km^{-1}$)	Fuel consumption factor ($\ell\,km^{-1}$)
Motorcycles	18.8	0.035
Taxis	2.83	0.115
Buses	19.2	0.4
Trucks	18.56	0.3
Automobiles		
Category 1 (av. speed 21 $km\,h^{-1}$)	45.6	0.07
Category 2 (av. speed 17 $km\,h^{-1}$)	49.8	
Category 3 (av. speed 17 $km\,h^{-1}$)	49.8	
Category 4 (av. speed 42 $km\,h^{-1}$)	33.5	
Category 5 (av. speed 30 $km\,h^{-1}$)	36.2	
Category 6 (av. speed 42 $km\,h^{-1}$)	33.5	
Category 7 (av. speed 30 $km\,h^{-1}$)	36.2	

ages given in Table 4 for each of the seven categories of line sources and five categories of vehicles.

3.2.4. *Average speed—driving model—emission factors.* Spatial and temporal variation of vehicle speed has a considerable effect on the evaluation of emission factors, since *speed, driving model* and *emissions* are interdependent. Subdivision of line sources into categories allows for groupings with common characteristics so that it is possible to create a driving model with a corresponding average speed.

The Ministry of the Environment has recently initiated speed measurements in various roads, but data have not been processed as yet. Similar measurements have been made in the studies by Pattas *et al.* (1985a, b) for a total road distance of 1300 km. The driving model derived ("Athens '84") describes the average situation of driving conditions in the Greater Athens Area. The average speed according to this model was found to be 21 $km\,h^{-1}$, but it should be noted that spatial variation of traffic conditions in Athens is particularly uneven. For roads inside the *Ring* the measured average speed was in the range of 15–17 $km\,h^{-1}$, whereas for roads outside the ring boundaries this value was around 30 $km\,h^{-1}$. For large arteries in the suburbs the average speed reached the value of 42 $km\,h^{-1}$ (Messogion Avenue, in the suburb of Agia Paraskevi, see Fig. 1).

As far as emission factors are concerned, the value of 18.8 $g\,CO\,km^{-1}$ for motorcycles was used. For taxis the value of 2.83 $g\,CO\,km^{-1}$ was used, which is the weighted average between 1.34 and 11.8 (under the assumption of a proportion of 12,000 diesel-taxis and 2000 taxis using liquified propane gas [LPG]). The value of 19.2 $g\,CO\,km^{-1}$ and that of 18.56 $g\,CO\,km^{-1}$ was used for emissions caused by buses and trucks, respectively. For automobiles a more detailed model was assumed. For each road category a different speed was assigned (according to the average speeds measured by the "Athens 84" driving model) with the appropriate emission factor. The above are summarized in Table 5, where values for fuel consumption factors are also given (Pattas, 1981).

3.3. *Fuel balance in the Greater Athens Area*

Fuel quantities consumed in line sources of the Greater Athens Area (for which traffic data were available) were calculated with submodel CONSUMPTION (see Equation 3 and Fig. 3). The results of the calculations are presented in Table 6. The percentages of gasoline consumption corresponding to contributions from automobiles and motorcycles are 96% and 4%, respectively. Taxis, buses and trucks contribute 28%, 35% and 37%, respectively, to the total diesel consumption.

The actual fuel consumption in the Greater Athens Area during 1982 and in the period 1986–1988 is given in Table 7 (PERPA, 1990). Comparing the values of Table 6 with the respective values of Table 7, it is evident that the calculated fuel quantities appear lower than the total actually consumed quantities. This is mainly due to fuel consumption outside the Greater Athens Area (despite the fact that purchase is done in Athens) as well as to fuel consumption due to traffic on small roads (which are not included in the line-sources model).

In order to balance the fuel consumption, the extra fuel quantities were distributed to the grid cells used in the model. According to PERPA (1990) estimations, from the 15,000 km travelled yearly by the average automobile in the Greater Athens Area, 6000 km are travelled outside the area (long-distance professional activities, excursions, etc.). Under the assumption of "9/15", which refers to all vehicle categories, the new differences between calculated and consumed fuel quantities (to be used as an input to the area-source model) are given in Table 8. These differences are also given as percentages of the total actually consumed fuel.

Table 6. Calculated fuel consumption in line-source in Greater Athens Area (in metric tons)

Category	1986	1987	1988 (Jan–Sept)
Motorcycle	6324	7987	6442
Automobiles	181,821	223,420	178,469
Taxis	35,562	43,380	35,287
Buses	42,151	54,304	43,886
Trucks (diesel)	45,795	56,771	45,771
Trucks (gasoline)	97,031	106,734	88,056
Total gasoline	285,176	338,141	272,967
Total diesel	121,508	154,455	124,944

4. RESULTS AND DISCUSSION

4.1. *Spatial and temporal emissions variation*

A parametric study of CO emissions for several time periods was carried out using the model described above. A typical example of results is shown in Fig. 4, in the form of an emission density map. It presents average daily CO emissions (in $kg\,km^{-2}$) during a July 1987 weekday. Figure 5 shows the corresponding contours of CO emissions. An examination of the emission density maps shows that the maximum of emissions occurs in almost all cases (winter or summer, weekday or weekend) in the centre

Table 7. Actual fuel consumption in Greater Athens Area (in metric tons, PERPA, 1990)

Year	Regular	Premium	Total	Diesel	Auto Diesel
1982	—	—	608,000	—	406,000
1986	104,262	578,175	682,437	1,387,074	401,390
1987	94,047	624,474	718,521	1,097,013	329,104
1988 (Jan–Sept)	62,479	513,903	576,382	885,371	265,611

Table 8. Differences between calculated and consumed fuel (in metric tons)

Year	Fuel	Calculated	Consumed	Difference
1982	Gasoline	229,220	364,800	135,580 (37.2%)
	Diesel	200,750	243,600	42,850 (17.6%)
1986	Gasoline	285,176	409,462	165,715 (30.4%)
	Diesel	121,508	240,834	119,326 (49.5%)
1987	Gasoline	338,141	431,113	123,963 (21.6%)
	Diesel	154,455	197,462	43,007 (21.8%)
1988 (Jan–Sept)	Gasoline	272,967	345,829	97,149 (21.1%)
	Diesel	124,944	159,367	34,423 (21.6%)

of Athens. Another point of emission accumulation is the port of Piraeus and neighbouring areas.

Figure 6 shows the corresponding contours for the excess CO emissions of July over January. It is seen that in July the areas around the Saronic Gulf as well as those traversed by arteries which lead to north-eastern shores, show increased emissions compared with January. On the contrary, Fig. 7 shows that

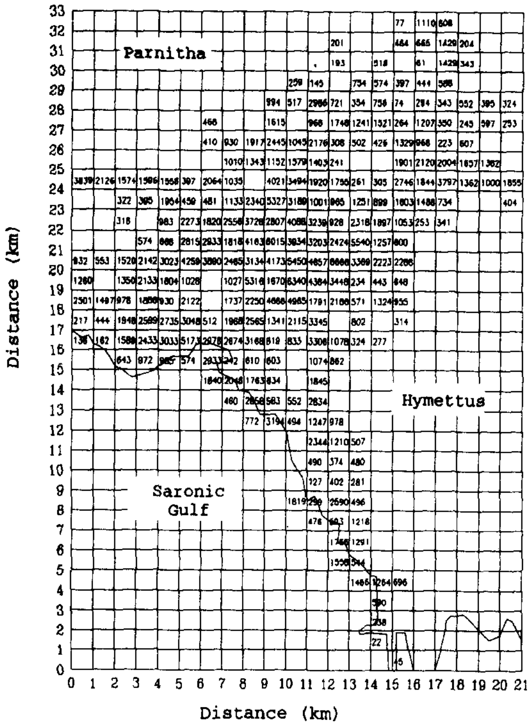

Fig. 4. Daily average CO emissions ($kg\,km^{-2}$), July 1987.

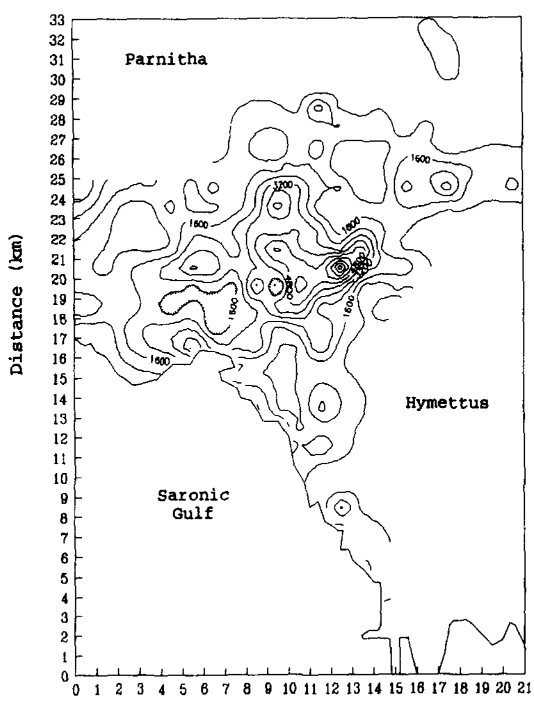

Fig. 5. Contours of equal CO emissions ($kg\,km^{-2}$), July 1987.

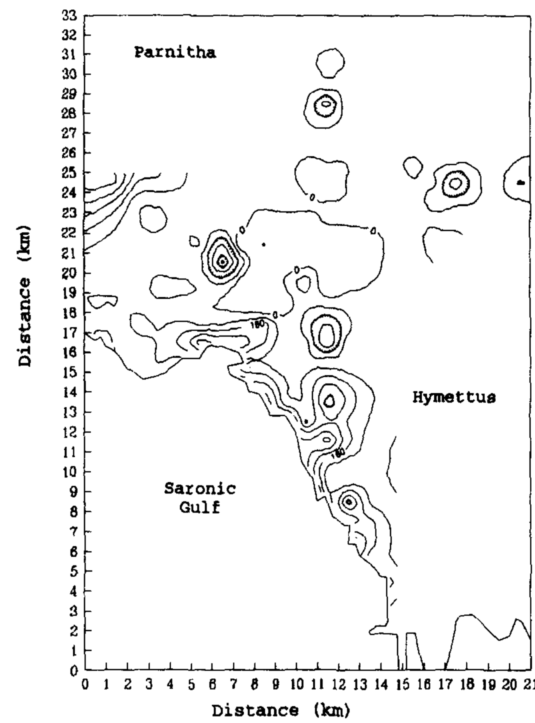

Fig. 6. Excess emissions (July over January 1987).

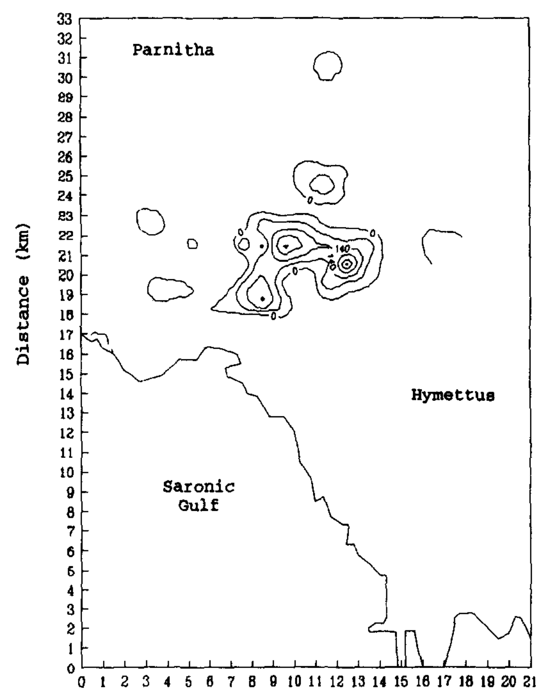

Fig. 7. Excess emissions (January over July 1987).

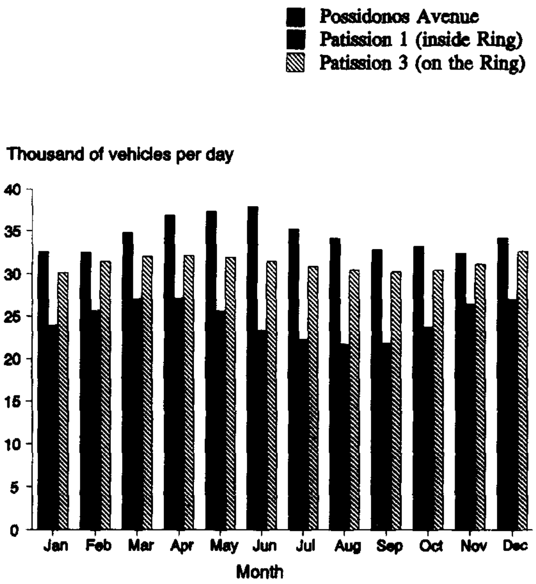

Fig. 8. Traffic load variation in three different line-source categories (weekend, 1987).

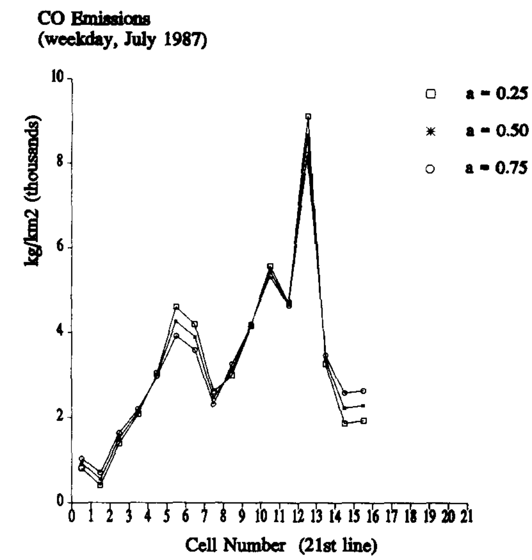

Fig. 9. Sensitivity analysis of fuel amount a in Equations (5) and (6).

Table 9. Calculated CO emissions ($kg\,d^{-1}$)

Year	January	July
1982	Typical day: 513,899	
1986	372,660	382,998
1987	391,623	406,074
1988	395,597	430,582

emissions in January are highest in the city centre, compared with that of July.

Traffic load data reveal an important monthly variation mainly in roads with high summer activity. Figure 8 shows the monthly variation in traffic load for all vehicles moving on the coastal Possidonos Avenue connecting the port of Piraeus to the coastal suburb of Glyfada, and Patission Street (Patission 3 on the Ring boundaries and Patission 1 inside the Ring). The data are of weekends of 1987. An increased traffic variability is observed on the roads leading to summer resorts and inside the Ring. On the contrary, roads on the Ring boundaries show a smaller fluctuation of traffic load, since they "operate" almost always under conditions of traffic saturation. There is also a difference in the period when the maxima appear (March to May for down-town roads while June for roads leading to sea-side resorts). The monthly variation of emissions follows the monthly fluctuation of the corresponding traffic load.

Table 9 shows the total CO emissions for 1986–88. It is evident that during this period (data for 1988 refer to the first 9 months), the emissions show an upward trend, which can be explained by an increase in the number of vehicles and the resulting increase in fuel consumption. For comparison reasons, data of year 1982 (before the implementation of restrictive measures of partial traffic circulation in the centre of Athens) presented by Dracopoulos (1986) were reprocessed. The observed reduction in CO emissions could be attributed to traffic restriction measures implemented after 1983, but the inadequacy of the raw data may make this not a totally unambiguous conclusion.

4.2. *Approximation of the coefficient* a

In the present study, fuel consumption proportional to the population density $a = 50\%$ was assumed, since there were no data or estimates of a network/trip matrix. This percentage is an estimate deemed adequate as a first approximation to the real situation. Figure 9 gives a sensitivity analysis of CO emissions, calculated along the 21st row of cells of Fig. 4, and for different values of the factor a. It is evident that the change of emission values is minimal in the interval $0.25 < a < 0.75$. This finding must be checked and the model must be adjusted accordingly after a series of comparisons of its predictions with pollution measurements.

4.3. *Contribution of vehicle categories in the* CO *emissions*

With regard to the contribution of each vehicle category to the total CO emissions, the results show that private automobiles are the main source of pollution responsible for about 85% of CO emissions, followed by motorcycles with 6.4%. Automobiles are the main offenders because they consume gasoline, have high emissions factor and constitute the highest percentage of traffic composition (45% in the centre). Figure 10 shows CO emissions per vehicle category on a typical weekday in January 1987.

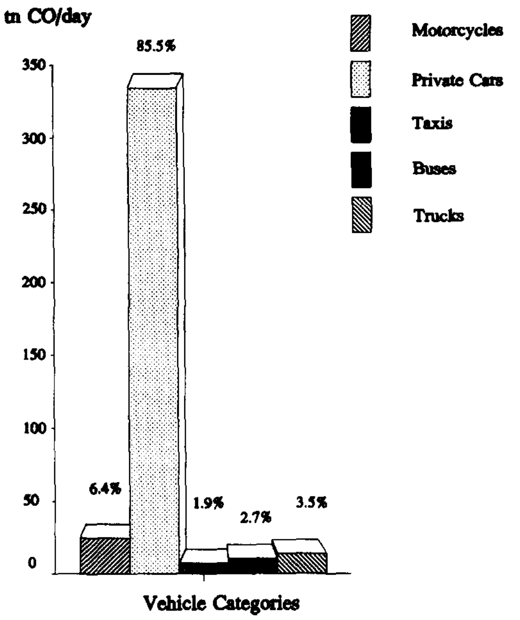

Fig. 10. Contribution of each vehicle category in CO emissions.

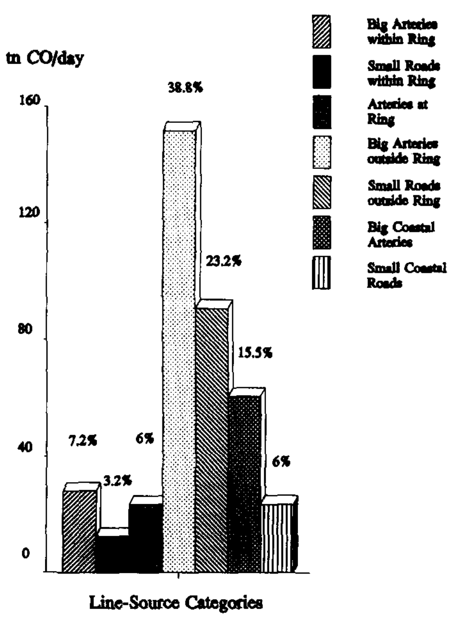

Fig. 11. Contribution of line-source categories in CO emissions.

4.4. *Contribution of line source categories in the* CO *emissions*

Another interesting point concerns the distribution of CO emissions in the seven categories of arteries of the Athens basin. Figure 11 shows emissions for January 1987. It is evident that almost 17% of the total CO emissions take place within the Ring. This percentage, despite its decreasing trend in recent years, continues to be considered high, if one bears in mind that a typical inhabitant moving in the city and working 8 hours per day next to big arteries, is directly exposed to high concentrations of pollutant emissions, which are detrimental to health.

5. CONCLUSIONS

The methodology presented in this work has been implemented in an easily applicable model, which estimates in a detailed manner the pollutant emissions from traffic sources in urban areas. It has been built on an open architecture structure allowing rapid and flexible modifications as well as easy updates with new traffic data.

The model was used for the prediction of CO emissions in the Greater Athens Area during the year 1982 and 1986–88 period. Because of a severe shortage in raw data, simplifying assumptions were introduced in a very straightforward way. Estimations of the spatial and temporal distribution of traffic emissions (monthly averages) have been found. Qualitative estimations of spatial seasonal variations of emission load have been obtained.

In order to derive more precise predictions regarding the evolution of pollutant emissions, it is essential to implement the model with more complete traffic data. As soon as adjustments according to pollution measurements have been made, the model can be used for pollution control policies related to vehicle circulation.

Acknowledgements—We would like to thank the personnel of the Department of Traffic Research and Statistics of the Ministry of Environment, Planning and Public Works and particularly the director Mr N. Christou for giving us the raw data upon which this work is based. Financial support for one of the authors (E. Mitsoulis) during his sabbatical leave at NTUA by the Natural Sciences and Engineering Research Council of Canada (NSERC) is gratefully acknowledged.

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