Vehicle emission model of air pollutants from road traffic: Application to Catalonia (Spain) for 1994

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Abstract

A vehicle emission model has been developed in order to estimate spatially desegregated emissions (highway, roads and streets) from road traffic using the ARC/INFO geographic information system (GIS), with a spatial resolution for each cell of 1x1 km², and a temporal time-scales for the calculation of emissions on an annual, monthly, daily and hourly basis. The model takes into account the hot, cold and evaporative emissions and uses CORINAIR’s emission factors. It considers the following pollutants: CO, NOₓ (NO and NO₂), SO₂, particles and several VOC. This model has been applied to obtain the emission inventory for Catalonia (Spain) for year 1994 from this source. The total amount of pollutants emitted is 407,309 tones/year: 69.6% of total emissions correspond to CO, 19.11% to NOₓ, 8.61% to VOC’s, 1.65% to SO₂ and 1.03% to TSP.

1 Introduction

Emission models are essential tools to estimate the emissions of atmospheric pollutants in a given area and they are a fundamental component of air quality management plan. Besides, they are required in order to provide inputs to air quality modeling and to assess the potential impacts of future programs and policies. Uncertainty in emission inventories for different pollutants is an important source of error in Air Quality Models. For this reason, research in the last years on this subject has increased. Nowadays, any air quality model should include, apart of a meteorological model and a chemical transport model, an emission model that will provide input for the estimation of final emission concentrations.
According to the results obtained by Lübbert and Tilly (1989) for 12 European OECD countries for 1980, traffic is the major source of NOx (on average 44%) and of anthropogenic VOC (42%). More updated estimates (EEA 1998) give a contribution from traffic of 60% of NOx (1994) and 44% of anthropogenic VOC (1990). A study of national air pollutant emission estimates published by the U.S. Environmental Protection Agency (EPA) indicated that in 1993 road traffic contributed 62% of all CO emissions, and 26% of all VOC emissions in the United States (Brett and Harley 1996). Evers (1994) showed that traffic is the major source to NOx and NMVOC emissions in the Netherlands in 1990. In the Barcelona area for year 1990, according to Costa and Baldasano (1996), emissions of road traffic represented 76% of the total amount of pollutants emitted and it is the main emission source of VOC, NOx and CO (55.92%, 74.08% and 98.52% respectively).

Currently, there are three principal methods to estimate traffic emissions, which vary mainly in the way that they treat the interaction between vehicle operation and the corresponding emissions (MEET 1999). The first one is the simplest and only takes into accounts the total number of kilometres driven by the whole fleet. The second method is an average speed-dependent approach and exploits the fact that average emissions over a trip vary according the average speed of the trip. The third approach, more complex, is called instantaneous vehicle emissions (modal modeling) and takes into account the speed variation along the trip. For an extensive discussion about vehicle emission models see the final report COST 319 (1999).

The vehicle emission model presented in this contribution follows the second methodology described above for obtain an emission inventory of emissions from road traffic for 1994 in Catalonia (Spain). The area under study is the Catalonia region located in the Northeast of Spain. It covers an area of 31.895 km\(^2\) and its population is 6.059.494 inhabitants. It includes the Barcelona geographical area, which is one of the major urban conglomerations in the Mediterranean (4000000 inhabitants, 2 million vehicles and important industrial activities).

### 2 Main characteristics of the vehicle emission model

Emissions from road traffic are calculated using CORINAIR emission factors (Eggleston et al., 1992) in order to make European inventories more homogeneous and easily comparable. For some vehicle categories we have used the emission factors defined by Veldt and Bakkum (1988). Necessary input data for the calculations are: traffic intensity for each roadway in the area (number of vehicles for each category and road class), their monthly, daily and hourly variation, classification of vehicles by size, age, type of fuel used and existence or not of catalytic convertors and their main usage patterns (average speed and distance driven with cold engines).

The roadways are divided in three types according to the driving type (average circulating velocity and continuous or not circulation): highways, roads and streets.
The main highways are the A-7, A-2, A-19, A-18 and A-16; the main roads are the N-II, N-340, N-152, N-420, C-246 and N-260; and the streets considered in this study are the streets in the cities of Barcelona, Terrassa and Sabadell. Traffic data were available from state authorities for the main highways, roads and streets. However, it has been difficult to find appropriate local data because some data are of poor quality or unexistent. Being the most difficult data to find that from the streets, we have only been able to consider those from three cities. For the set of roadways from which we have found information, we have selected the roads and highways whose Annual Average Daily Traffic-AADT (traffic over a seven day week) exceeds 5,000 vehicles/day, and the streets whose AADT exceeds 30,000 vehicles/day. The results of this selection are 6 highways (631 km), 84 roads (2908 km) and 105 streets (186 km).

For operating purposes, the work area has been divided into 1x1 km² cells. For each one of the cells we have determined the annual, monthly, daily (weekday or holiday) and hourly emissions of carbon monoxide (CO), nitrogen oxides (NOx), sulphur dioxide (SO₂), particles (TSP) and volatile organic compounds (VOC). The main characteristic of vehicle emission model used to estimate emissions from road traffic in Catalonia are described below. The methodology used is general, but adopted to availability of data.

3 Methodology for the calculation of road traffic emissions

Emissions from road traffic are divided into three types. First type is hot emissions, which are the main emissions from road traffic, these are emissions from vehicles after they have warmed up and they have their engines thermally stabilized (water temperature over 70 °C). Second type is cold start emissions, which are produced while the vehicle is warming up. Third type is evaporative emissions, these emissions are the evaporation of fuel from its circuit, in this case the emission are only VOC. Total traffic emissions lead to the first basic relationship used: $E = E_{hot} + E_{cold} + E_{evap}$. Temporal emissions are computed by a traffic fluctuation factor.

Although the model developed includes the possibility to calculate evaporative emissions, they have not been included in this particular application for Catalonia, and therefore their methodology is not included in this section.

3.1 Methodology for cold start emissions

Hot emissions from road traffic of pollutant $i$ in a stretch of a roadway $s$ (piece of a roadway with a constant AADT) per time units $(t)$, $E_{i, hot}^s(t)$ are computed according:

$$E_{i, hot}^s(t) = \sum_{j=1}^{J} AADT_{js}(t) L_x F_{jp}^{i, hot}$$  (1)
Where $L_s$ is the length of the stretch; $F_{ij}^{\text{hot}}$ is the hot emission factor a pollutant $i$, vehicle category $j$ in road type $p$ (highway, road or street).

Necessary data for the calculation of hot emissions are traffic data (number of vehicles that drive along a roadway, fluctuations around AADT, etc.) and the emission factors for each pollutant, given a vehicle category and a type of roadway. They are a function of the type of pollutant (CO, NO, SO$_2$, particles and VOC), average speed, driving mode (highways, roads and streets) and vehicle categories.

We have used CORINAIR (Eggleston et al., 1992) emission factors for four vehicle categories (light and heavy gasoline vehicles and light and heavy diesel vehicles) and have used the emission factors described by Veldt and Bakkum (1988) for three other categories (mopeds, motorcycle 2-stroke and motorcycle 4-stroke).

### 3.2 Methodology for cold emissions

Cold emissions start from the moment the vehicle’s engine is turned on until it is thermally stabilized. Therefore, they most likely will take place under urban driving conditions (urban trips are usually between 2-4 km). Furthermore, these emissions occur for all vehicle categories, but emission factors are only available for gasoline and diesel light vehicles. So the methodology covers only these light vehicles categories and in urban driving conditions (streets).

Following the methodology proposed by CORINAIR (Eggleston et al., 1992), the calculation of cold emissions in stretch $s$ from road traffic of pollutant $i$ and per time units $(t)$ is:

$$ E_{si}^{\text{cold}}(t) = \sum_{j=1}^{J} \left[ \frac{E_{si}^{\text{hot}}(t)}{F_{ij}^{\text{hot}}} \right] \beta \left( \frac{F_{ij}^{\text{cold}}}{F_{ij}^{\text{hot}}} - 1 \right) $$

where $E_{si}^{\text{cold}}(t)$ is the cold emitted pollutant $i$ in a stretch of a roadway $s$ per time units $t$; $E_{si}^{\text{hot}}(t)$ is the hot emitted pollutant $i$ in a stretch of a roadway $s$ per time units $t$ and per vehicle category $j$; $\beta$ is the fraction of mileage driven with cold engines; $F_{ij}^{\text{hot}}$ is the hot emission factor for each pollutant $i$, vehicle category $j$ in streets; $F_{ij}^{\text{cold}}$ is the cold emission factor for each pollutant $i$, vehicle category $j$ in streets.

In this methodology we need to know: hot emissions, the parameter $\beta$ and the hot and cold emission factor ratios. CORINAIR’s hot and cold emission factor ratios have been used to compute these emissions. They are a function of the type of pollutant, the ambient temperature and the different light vehicle categories.

Parameter $\beta$ is the fraction of mileage driven with cold engines. It depends on ambient temperature and the average trip length. To calculate it we have used the methodology described by CORINAIR:
\[ \beta = 0.647 - 0.025 L_{\text{trip}} - \left( 0.00974 - 0.000385 L_{\text{trip}} \right) T_{\text{amb}} \]  

(3)

where \( L_{\text{trip}} \) is the average trip length; and \( T_{\text{amb}} \) is the ambient temperature in °C. For \( L_{\text{trip}} \) we are use a estimate value proposed for Spain (Eggleston et al. 1992): 6.31 km.

4 Treatment of the input traffic data

Estimation of emissions from road traffic needs to know an AADT flow to the road network. It is also necessary to determine the distributions of different vehicle type and fuel-use classes for each roadway category, to associate road lengths, average speed and appropriate emission factors, to determine the monthly and daily fluctuations around AADT and to establish the daily cycle of traffic intensities.

4.1 Assessment of monthly and daily fluctuations around AADT

An AADT flow was assigned to each stretch in the network, but this value has been averaged for the year. To estimate monthly or daily emissions we need to know the fluctuations around that average. Monthly emissions are calculated in order to know the differences between seasons emissions, and daily emissions are computed in order to know the weekday-to-holiday variability. We had detailed information in 47 control points (11 in highways, 26 in roads and 10 in streets). Figure 1 (left) shows two examples of monthly fluctuations in a control point in highway A-7 and in a Barcelona street. This figure shows the differences between the highways and streets traffic conditions. In highways number of vehicles increases during summer because this highway is the one connect the city with the coast of Catalonia, where a lot of people go during their summer holidays period. In contrast with this situation, in the streets of Barcelona number of vehicles decreases during the summer.

![Figure 1](image-url)

Figure 1. Monthly fluctuations in the highway A-7 and one street of Barcelona city (left) and daily cycle in the highway A-7 (right).
Regarding to the rest of the stretches where data was not available, it was assigned to each of them the fluctuations around AADT from the 47 data set. The assignment criterion was the geographical proximity between the stretch and the control point, and in some cases, the similarity of driving patterns (type of road). Factors are then available to translate AADT flows into average flows specific to each month and each day (weekday and holiday). These flows allow estimating for the different days of the week and month of the year.

4.2 Assessment of the daily cycle

We are used data from 20 control points (8 in highways, 2 in roads and 10 in streets) to calculate hourly traffic intensities. With the data available, daily variation for each roadway were derived with an assignment by proximity and type of road, as was done in the case of the monthly and daily fluctuations. We have established two different daily cycles: one for weekdays and another one for holidays.

Figure 1 (right) gives an example of the daily cycle in one point in the highway A-7, this figure shows the differences between a weekday and a holiday. During a weekday, characteristic daily cycle is a gradual decrease of the traffic intensity from 1 a.m. to 4 a.m., after 5 a.m. there is an increase up to a maximum around 9 a.m. Later, traffic decrease from 2 p.m., to increase again until reaching another peak around 6 p.m. On a holiday the first peak appears later at 11-12 a.m.

4.3 Vehicle category classification in Catalonia

It was needed to determine the detailed traffic composition (proportions of different vehicle type and fuel-use classes) for each roadway category. The AADT must be divided into different vehicle-type groups in order to use the appropriate emission factors. Vehicle fleet has been classified into 7 main groups: gasoline cars < 3.5 t; diesel cars < 3.5 t; heavy-duty gasoline vehicles > 3.5 t; heavy-duty diesel vehicles 3.5-16 t; heavy-duty diesel vehicles > 16 t; mopeds and motorcycles.

Gasoline cars < 3.5t are subdivided in 8 antiquity categories according to the different European Directives of emissions from vehicles and their respective periods of application: pre-ECE, ECE 15/00-01, ECE 15/02, ECE 15/03, ECE 15/04, Improved Conventional, Open Loop and Closed Loop. Vehicles belonging to each of these categories are again divided according cylinder capacity (< 1400cc, 1400cc - 2000cc and > 2000cc). Diesel cars < 3.5t are subdivided in: less and more than 2000cc. And motorcycles are divided according to their engine type: 2 or 4-stroke.

We have used the composition of the Catalonia region fleet according to the Dirección General de Tráfico (1994) and have adapted these proportions to every type of roadway according to MOPTMA (1992).
4.4 Accounting for driving average speeds

Average speed for each type of roadway was determined from real available data. We have determined a single average speed for the highways (108.5 km/h) and for the roads (71.4 km/h). But 14 different speeds were determined for streets because we had measured real data for them. These average speeds ranges from 13.9 km/h to 34.0 km/h. Furthermore, we have determined another speed for the external ring roads of the city of Barcelona (Ronda de Dalt and Ronda del Litoral), which average speed is 62.7 km/h.

5 Emissions from road traffic in Catalonia

Catalonia annual emissions estimated for each species for 1994 from road traffic are given in the Table 1.

Table 1. Estimates of annual emissions from road traffic in Catalonia for 1994 (tones/year).

<table>
<thead>
<tr>
<th>Pollutant (t/year)</th>
<th>Hot emissions</th>
<th>Cold emissions</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon monoxide (CO)</td>
<td>271014 (68.8%)</td>
<td>12493 (91.8%)</td>
<td>283507 (69.6%)</td>
</tr>
<tr>
<td>Nitrogen oxides (NOx)</td>
<td>77771 (19.8%)</td>
<td>61 (0.5%)</td>
<td>77832 (19.1%)</td>
</tr>
<tr>
<td>Volatile Organic Compounds (VOC)</td>
<td>34080 (8.7%)</td>
<td>974 (7.2%)</td>
<td>35054 (8.6%)</td>
</tr>
<tr>
<td>Sulphur dioxide (SO2)</td>
<td>6659 (1.7%)</td>
<td>53 (0.4%)</td>
<td>6712 (1.7%)</td>
</tr>
<tr>
<td>Particles</td>
<td>4173 (1.1%)</td>
<td>31 (0.2%)</td>
<td>4204 (1.0%)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>393697 (100%)</td>
<td>13612 (100%)</td>
<td>407309 (100%)</td>
</tr>
</tbody>
</table>

In the whole study area, the road traffic during 1994 emitted 407309 tones/year of the considered pollutants: 69.6% of the total emissions correspond to CO, 19.1% to NOx, 8.6% to VOC, 1.6% to SO2, and 1.0% to particles. Hot emissions represent 96.6% of the total emissions, while cold emissions only represent 3.34%. It is important to point out here that this high percentage is due to the fact that hot emissions are estimated for all Catalonia while cold emissions are estimated only for Barcelona and its surroundings. If we only consider this reduced area for both hot and cold emissions, then hot emissions represent 85.4% and cold emissions 14.57%. This smaller share of cold emissions is explained due to the higher average temperature for this region as compared to other European regions.

With regards to the annual hot emissions according to the different vehicle categories, estimations have shown that gasoline vehicles mainly emit CO, NOx and VOC: 87.14% of the total CO emissions, 72.15% of the total NOx emissions and 71.3% of the total VOC emissions. Diesel vehicles mainly emit particles and SO2, despite of the fact that this vehicle category only represents 18% over the total fleet. Their emissions are 51.42% of the total SO2 emissions and 57.41% of the total particle emissions. As far as the differences according to the weight of vehicles, light vehicles are the main source of emissions of CO (54.03%), NOx (57.42%) and VOC (48.95%), whereas heavy vehicles mainly emit SO2 and particles (55.57% of the total SO2 emissions and 67.7% of the total particle emissions).
Figures 2 presents the spatial distribution of CO (left) and NO\textsubscript{x} (right) annual hot emissions. Emissions are expressed as kg/km\textsuperscript{2}/year. Emissions of CO vary considerably across the Catalonia road network, ranging from 231 kg per km\textsuperscript{2} and per year to 2104279 kg per km\textsuperscript{2} and per year. They are associated with major road routes and large urban areas. Emissions of NO\textsubscript{x} display similar spatial variation and range from 74 kg per km\textsuperscript{2} and per year to 423666 kg per km\textsuperscript{2} and per year. In these two figures it can be observed that the highest CO and NO\textsubscript{x} emissions (the rest of pollutants follow the same pattern) are found in the area of Barcelona where population density and the traffic flow are the highest in Catalonia. But there is a difference between these pollutants. The cell with the highest CO emission (the same cell where there are the maximum emissions of SO\textsubscript{2}, VOC and particles) is located in the middle of Barcelona, where driving speeds are relatively low. While the maximum emission of NO\textsubscript{x} is located in a point with fast highways and roads (driving speeds are higher).

Time evolution of the emissions is strongly influenced by the behavior of the road traffic. Table 2 shows the monthly percentage of the total emissions in Catalonia. We can see that total emission increase during summer (in July and August emissions are approximately 10% of total annual emissions) while for the rest of the months emissions range from 7-8%. However, this increased during summer is not general.

Figure 2. Total traffic annual emissions of CO (left) and NO\textsubscript{x} (right) in t/year.
Table 2. Monthly percentage of total traffic emissions in Catalonia for year 1994.

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>NO\textsubscript{x}</th>
<th>VOC’s</th>
<th>SO\textsubscript{2}</th>
<th>TSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>7.25</td>
<td>7.06</td>
<td>7.45</td>
<td>7.21</td>
<td>7.35</td>
</tr>
<tr>
<td>February</td>
<td>7.58</td>
<td>7.42</td>
<td>7.73</td>
<td>7.55</td>
<td>7.57</td>
</tr>
<tr>
<td>March</td>
<td>7.94</td>
<td>7.85</td>
<td>8.02</td>
<td>7.93</td>
<td>7.93</td>
</tr>
<tr>
<td>April</td>
<td>7.92</td>
<td>7.86</td>
<td>7.98</td>
<td>7.91</td>
<td>7.92</td>
</tr>
<tr>
<td>May</td>
<td>8.19</td>
<td>8.15</td>
<td>8.22</td>
<td>8.18</td>
<td>8.19</td>
</tr>
<tr>
<td>June</td>
<td>8.29</td>
<td>8.28</td>
<td>8.28</td>
<td>8.29</td>
<td>8.28</td>
</tr>
<tr>
<td>July</td>
<td>10.30</td>
<td>10.62</td>
<td>10.01</td>
<td>10.37</td>
<td>10.34</td>
</tr>
<tr>
<td>August</td>
<td>9.68</td>
<td>10.15</td>
<td>9.28</td>
<td>9.78</td>
<td>9.74</td>
</tr>
<tr>
<td>September</td>
<td>8.26</td>
<td>8.27</td>
<td>8.22</td>
<td>8.26</td>
<td>8.25</td>
</tr>
<tr>
<td>October</td>
<td>7.97</td>
<td>7.95</td>
<td>7.99</td>
<td>7.97</td>
<td>7.96</td>
</tr>
<tr>
<td>November</td>
<td>8.24</td>
<td>8.12</td>
<td>8.37</td>
<td>8.21</td>
<td>8.22</td>
</tr>
<tr>
<td>December</td>
<td>8.36</td>
<td>8.26</td>
<td>8.47</td>
<td>8.33</td>
<td>8.35</td>
</tr>
</tbody>
</table>

6 Conclusions

The emissions inventory of CO, NO\textsubscript{x}, SO\textsubscript{2}, VOC and particles in Catalonia for 1994 described in this paper provides the first one for this region with a spatial resolution of 1x1 km\textsuperscript{2} and it includes a temporal variation (monthly, daily and hourly). The methodology followed in order to estimate these emissions is based on the data of the traffic and the fleet in Catalonia for 1994 and the emission factors proposed by CORINAIR (Eggleston et al., 1992) and Veldt and Bakkum (1988). However, the lack of data produced some adjustments in the application of the methodology proposed by CORINAIR.

Results obtained in this application show relatively large variations in the emissions between different areas of Catalonia. Highest emissions are located in the Barcelona area, which may be attributed to the high-density population and the high level of economic activities in this region. Emissions also present some important differences along months of the year. In cities emissions decrease during the summer period, while outside cities (especially in the coastal regions) emissions increase. The analysis of the daily cycle of emissions has allowed the identification of the hours with maximum emissions and differences between weekday and holiday hourly patterns. Major contributors of the CO, VOC and NO\textsubscript{x} are gasoline and light vehicles, while diesel and heavy vehicles mainly emit SO\textsubscript{2} and particles.
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