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Evaluation of a simplified top-down model for the spatial assessment of hot traffic emissions in mid-sized cities

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Abstract

Traffic emission estimation in developing countries is a key-issue for air pollution management. In most cases, comprehensive bottom-up methodologies cannot be applied in mid-sized cities because of the resource cost related to their application. In this paper, a simplified emission estimation model (SEEM) is evaluated. The model is based on a top-down approach and gives annual global hot emission. Particular attention is paid to the quality of the input traffic data. The quality of results is assessed by application of the SEEM model in the Chilean Gran Concepción urban area and by comparison with a bottom-up approach that has been led for the year 2000. The SEEM model estimates emissions with an accuracy of about 20% and is related to important resource savings. The results of the SEEM model are then distributed in space with a disaggregation approach and using GIS techniques. The relevancy of the disaggregation approach is evaluated among several possibilities through statistical methods. A spatial disaggregation using principal roads density gives the best results in terms of emissions repartition and gives a globally accurate image of the distribution of hot emissions in a mid-sized city.

Keywords: Traffic; Hot emissions; Top-down models; Data quality; Estimation accuracy; Spatial disaggregation; Chile; GIS

1. Introduction

Today's societies, characterized by industrial growth, mobility boom and disproportioned energy consumption, face serious problems related to air pollution, such as greenhouse or health effects. Among the sources of air pollution, traffic is without doubt one of the most important (Mage et al., 1996; Mayer, 1999).

To establish efficient air pollution reduction strategies, the amount and spatial distribution of the emission sources must be determined. However, for traffic related emissions, this task is far from being trivial. Even if it is possible to measure the concentrations of pollutants in the air, it is difficult

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to measure the emission of pollutants itself, because the sources of emissions are evolving in time and space. For traffic, the most efficient way to assess emission of pollutants is the estimation with mathematical methods.

One of the main applications of traffic emission estimation is the building of an emission inventory, a comprehensive list of sources of pollution, often with spatial resolution (Baldasano, 1998; Friedrich and Reis, 2004; Bellasio et al., 2007). The usual way to build a traffic emissions inventory is to run a traffic model based on origin-destination surveys, to estimate the traffic flow for each road segment, and then to apply on its results an emission model that estimates emissions for every road of the urban area studied. This type of methodology follows a bottom-up approach (Samaras et al., 1995). This method is widely accepted as appropriate for industrialized countries and for megacities (several millions habitants) in developing countries such as Santiago de Chile (Osses and Dursbeck, 2002) or Bogotá (Belalcazar and Zarate, 2004). However, most mid-sized cities of developing countries can hardly implement such traffic models, because they are expensive, time demanding and require high technical skills. For these cities, which are facing uncontrolled urban growth, a lack of planning and an outdated vehicle fleet (Onursal and Gautam, 1997; Tashiro and Taniyama, 2002), the use of simpler methods could be an option. Such methods, called top-down (Samaras et al., 1995), use aggregated traffic data to calculate the amount of emissions of an area, often giving few spatial and temporal detail. Most often, they are used to build national emissions inventories (Sturm et al., 1997). These methods need a widely reduced amount of input parameters when compared to bottom-up methods (e.g., number of cars in the area of interest, average distance driven by vehicle type, etc.) and are therefore more cost-efficient and easier to implement. However the error in the estimation of exhaust emissions by a top-down model is generally expected to be higher than in a bottom-up model and the results often have no spatial distribution and cannot be used for regional planning purposes. Some authors consider the problem of spatial distribution of emissions (Khatami et al., 1998; Brulfert et al., 2005) and a few recent studies show the role of Geographic Information Systems (GIS) to distribute the estimated emissions in high-resolution space (Dalvi et al., 2006; Parra et al., 2006).

The aim of this paper is to develop a simple but efficient top-down method for spatially assessing the traffic-related hot emissions of mid-sized cities in South America. This requires to combine a simplified exhaust emission estimation model with different simplified approaches of spatial disaggregation based on GIS. To estimate the error of the various disaggregation methods considered, the results have been compared with values obtained with a state-of-the-art bottom-up emission model. The main objectives of this paper are to estimate both the impact of the quality of traffic-related input data for the estimation of emissions and the role of the GIS data for their spatial allocation.

The mid-sized Chilean urban area of Gran Concepción (Fig. 1) was chosen for the application. This city of one million inhabitants is considered the

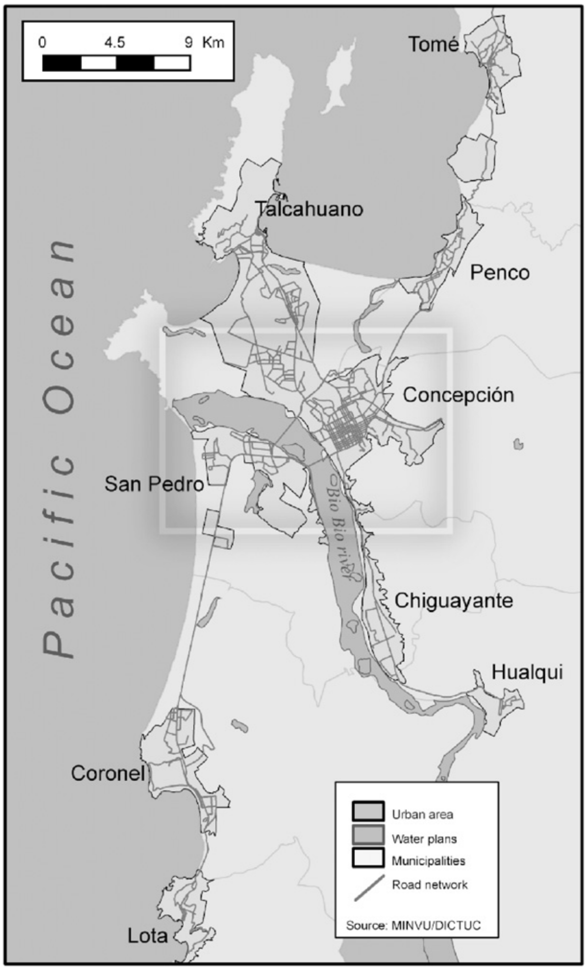

Fig. 1. Gran Concepción urban area (white square: area under study for Fig. 5).

second urban area of Chile, after the Santiago Metropolitan Region. The urban area is divided in nine dense municipalities without urban continuity, linked by connector roads. Half of the population is concentrated in the two largest centres, Concepción and Talcahuano. Most of the economic activity takes place in the same centres, generating the largest part of the traffic flow. Only the centre of Concepción shows a dense road network. Private cars are basically used within the big centres. Therefore, most of the journeys connecting the peripheral settlements are made by public transports. This situation causes the congestion of Concepción and Talcahuano city centres, and involves problems of air pollution.

Even if the Gran Concepción urban area is actually not considered as a contaminated area, the concentrations of pollutants measured are often close to the environmental norm (Oyola, 2004). Therefore, studies have been carried to assess emission inventories in the region. For the traffic-related emission inventory, a bottom-up approach has been used (CENMA, 2001): a traffic model, coupled with the emission model MODEM (Osses, 2003) has been run in the region and is used for the foreseen transport strategy.

The richness of information in the Concepción urban area allows us to use a comparative approach: after building of the simplified model corresponding to the situation of absence of information (typical in cities of developing countries, where the lack of resource impedes the collection of information) the results are compared with the ones obtained by the bottom-up model based on complete and precise information.

2. Methods

The assessment of the quality of the model and of its spatialization has been carried in three principal phases: first (Sections 2.1 and 3.1) the SEEM model has been run with the Concepción data and its estimation of emissions has been compared with the results of MODEM. Then (Sections 2.2 and 3.2), in order to choose the best disaggregation method, the total amount of emissions of MODEM has been disaggregated with 6 GIS-based spatial disaggregation approaches (SDA) and then compared to the output distribution of MODEM (comparing the same amounts of emissions allows to analyze only the quality of the spatial distribution). Finally, the SEEM results have been disaggregated with the best SDA (Sections 2.3 and 3.3), in order to discuss the results of the application of the full methodology in Concepción.

2.1. *The simplified emission estimation model (SEEM)*

2.1.1. *Basic principles*

In order to estimate traffic emissions, a simplified top-down emission estimation model (SEEM) has been developed. The SEEM model only computes the hot emissions, i.e. the exhaust emissions, without taking into account the cold start and the hydrocarbons evaporation emissions. These three types are the components of the total emission and can be described as follows (Costa and Baldasano, 1996):

- Hot emissions: emissions of a vehicle during its normal activity.
- Cold start emissions: additional emissions of a vehicle during the engine-warming process, i.e. when the catalyst is not warm and does not yet work properly. It has been estimated that in the USA between 10% and 30% of traffic emissions come from vehicle starts (Lents et al., 2004).
- Evaporative emissions: they correspond to the emanation of VOC related to the use of gasoline. Evaporative emissions can cover up to 22% of total volatile organic compounds (VOC) emissions (Osses, 2003).

The SEEM model estimates emissions using traffic data (specific for a vehicle category) and emission factors (number of vehicles and vehicle annual activity for vehicle category) and for the pollutant considered

$$Emi_k = \sum_j N_j * M_j * EF_{jk}. \tag{1}$$

- Emi_k is the annual total amount of emission of the pollutant k for an urban area (tons yr^{-1}).
- N_j is the number of vehicles of the category j (N).
- M_j is the vehicle annual activity expressed as amount of kilometres driven per year by a category j (km yr^{-1}).
- EF_{jk} is the emission factor associated to the vehicle category j and the pollutant k taken into account. The factors express the mass of pollutant generated per kilometre driven by a type of vehicle and are speed dependent (g km^{-1}).

2.1.2. Input data

The input data have been carefully chosen in order to avoid overestimations, a problem that often arises when using top-down methods, as stated in literature (Sturm et al., 1997). Following are the inputs of the SEEM model (the information was collected for the vehicle categories of Table 1):

- For the number of vehicles N_j technical inspection data have been preferred to national statistics (available on the WEB) of the vehicle fleet. Global statistics often overestimate the size of the fleet, because they take into account the number of vehicles present into a city and not the fleet in use (Sturm, 1996). For example, global statistics report very old vehicles, which are not used anymore, and cars bought in the city and used elsewhere. Therefore, we used technical inspection data, which report only the fleet in use and are closer to the real fleet information. By technical inspection data, we mean periodical controls done on vehicles which are supposed to cover the whole of the real fleet.
- Information on the vehicle annual activity M_j is often not available in mid-sized cities with limited resources. In order to supply for the lack of information, data coming from another urban area has been used for M_j. The information has been taken from traffic studies done in Valparaiso, a Chilean urban area comparable in size and in traffic activity profile. Nonetheless, according to Chilean traffic experts, the fleet repartition in Valparaiso appears to be slightly different for the share of non-catalytic vehicles.
- Emission factors coming from the COPERT methodology (Kourdis and Ntziachristos, 2000), European reference top-down methodology, have been applied. The suitability of these factors in the Chilean context has been verified by Osses (2003): these factors fit Chilean driving conditions and vehicle technology for a good first approximation when there is no local data available. New factors for nine categories of passenger cars have been defined and tested through local studies. COPERT emission factors for Carbon Monoxide (CO), Nitrogen Oxides (NO_x), VOC and breathable particulate matter (PM 10) have been used for the rest of the vehicle categories.

Table 1
Vehicle categories used for the SEEM

Name	Number of classes	Description
Passenger cars	2	Private passenger cars
Taxis	2	Basic and collective taxis
Commercial vehicles	3	Cars or light commercial vehicles
Motorcycles	2	Motorcycles
Public transport buses	3	Urban buses
Other buses	2	Interurban, interregional, interprovincial and rural buses
Light trucks	2	Light and middle trucks
Heavy trucks	2	Heavy trucks

More specificities can be found in CENMA (2001).

2.1.3. Outputs of the model

The SEEM model delivers as an output an annual and non-spatially resolved value of total traffic hot emissions in the urban area under study. The results have been compared with the outputs of the Chilean emissions model MODEM (Osses, 2003), which delivers values of annual emissions of pollutant per road segment of the Gran Concepción urban area. MODEM uses information derived from a transportation strategic-allocation model and emission mass factors to obtain emissions for several types of pollutants, all of which are determined for 61 categories of vehicles, with high levels of spatial and temporary disaggregation. Results obtained from MODEM include the following pollutants: CO, Hydrocarbons (HC), NO_x and breathable PM 10. Emissions are obtained according to the type of vehicle, distinguishing warm-state, cold-start, and evaporative emissions. The model has been run with the traffic information issued by the governmental bottom-up traffic model ESTRABIO (CENMA, 2001) and only the exhausted hot emissions have been taken in consideration for comparison (Fig. 2).

Both the compared emissions estimations methods, SEEM and MODEM, use the COPERT emission factors described above. The use of the same emission factors allows for the comparison of results in terms of input data quality.

2.2. Evaluation of six simplified SDA

After the total amounts of emissions have been assessed, the results have to be spatialized using a GIS. Practically, that means that the total emissions are distributed over a regular grid with a certain

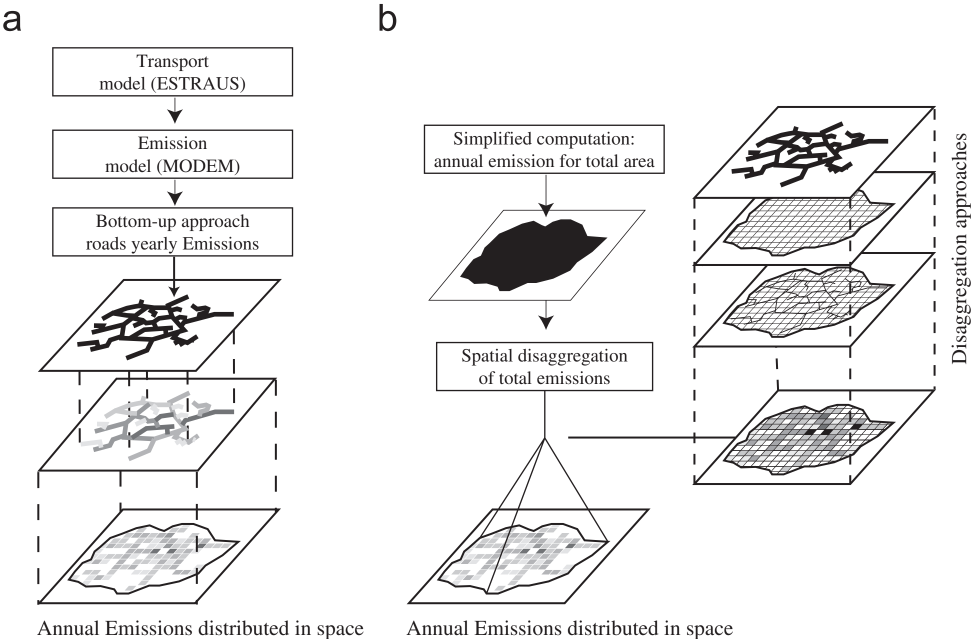

Fig. 2. Distribution of emissions in the bottom-up (left) and top-down (right) case.

spatial resolution (in this study 1 km^2) covering the area under study. Several disaggregation options can be considered to perform this task. Therefore, the emissions maps obtained applying these options have been compared with a reference gridded emission inventory, which is the result of the bottom-up methodology. The reference has been obtained by assigning the emissions values relative to every road segment to each cell of the regular grid (Fig. 2).

CO has been taken as an example. This pollutant is the most suitable for the study, because it is strongly related to car traffic (for whose the ESTRABIO traffic model is particularly well adapted) and to the speed parameter used in the emission factors (contrarily to NO$_x$, which are more correlated to acceleration). Note that in this subsection the total amount of emissions distributed is always the total emission of the MODEM model. By distributing the same amounts of emissions with every approach it has been possible to observe differences related only to spatial factors. Taking MODEM as the most precise SDA we would like to study the impact of the simplified SDAs on the spatial repartition of emissions to build an emission inventory. Six SDAs have been tested on the total annual emissions of CO:

(1) By urbanized area: a binary information has been used. Urban and non-urban areas have been defined and the emission has been disaggregated by the urban area density on the cells of the grid;
(2) By optimized urbanized area: a more precise digitalization of the area based on remote sensing images of the area has been used;
(3) By population density: the population of every cell of the grid has been computed and the total value has been disaggregated following this criteria. This method supposes a linear relationships between population and emission level, which is extremely dangerous and wrong in most cases (for example, the South American slums, even if overpopulated, are not linked to a higher vehicle possession rate);
(4) By principal road network density: the percentage of the total principal roads length per cell has been computed and used for the disaggregation;
(5) By principal and secondary road network density (80% and 20% of emissions, respectively): assumption of proportions between principal and secondary road network emissions is based on discussion with Chilean traffic experts;
(6) By principal road network and estimation of the secondary network: this is an hybrid approach, using the principal road network density for 80% of the emissions and the optimized urban

area density to assign the emissions related to the secondary road network (20%). It is an attempt to optimize the data collection, because the information about secondary road network is often difficult to obtain or to produce.

Each of the cited disaggregation approaches requires the computation of the repartition key of the emission giving the weights w for each of the n cells of the regular grid, as stated in Eq. (2).

$$Emi_i = w_i * Emi_{\text{tot}}, \quad \sum_{i=1}^{n} w_i = 1. \tag{2}$$

GIS procedures to build the repartition keys of this study are discussed in Appendix. Several data preparation techniques are cited (intersect, dissolve, …) and are basic features of GIS packages. A comprehensive explication of these operators can be found in Burke et al. (2004).

The analysis of different disaggregation methods is very important, because it allows to understand the spatial information level required to distribute correctly the emissions on the territory, both in terms of type of information (road network density, land use information or combination of both), and in terms of precision (principal or whole road network, accuracy of land use information, etc.).

Every SDA has been tested first on the bottom-up data in order to compare them against the reference case and thus, choose the best distribution technique. The comparison of the emission inventories obtained with the different distribution techniques is made with a statistical similarity index, namely the *Hellinger distance* d^{HEL} (Malerba et al., 2002), which can be expressed as:

$$d^{\text{HEL}} = \sum_{i=1}^{n} (\sqrt{f_i} - \sqrt{g_i})^2. \tag{3}$$

- f_i is the disaggregation frequency attributed to the cell i by a SDA [0; 1] and
- g_i is the disaggregation frequency attributed to the cell i by the reference case [0; 1].

This index is a similarity coefficient that indicates the correlation between two statistical distributions: the closer the index is to zero, the more the distributions are similar. The Hellinger distance should be interpreted as follows: the simplified approach estimates the repartition of emissions with a certain difference ε (Eq. (4)) with the reference case; this difference is quantified by the index.

$$EMI^{\text{MODEM}} = EMI^{\text{SDA}} + \varepsilon \quad \text{where } \varepsilon\, f(d^{\text{HEL}}). \tag{4}$$

- EMI^{MODEM} is the emissions repartition of the reference case and
- EMI^{SDA} is the emissions repartition of the SDA.

By the application of the square root of the frequency, the index is quite robust to extreme values. Since it works with frequencies, the index is independent of the absolute quantities distributed. The squared power allows for a quantification of the absolute difference. The best SDA is the one that minimizes the Hellinger distance with the reference case, i.e. the one that distributes the total emission in the most similar way compared to the reference case.

2.3. Spatial disaggregation of the total emissions values obtained with the SEEM

The final step is the application of the chosen SDA to the results of the SEEM model. The total emissions have been distributed over the same 1 km^2 regular grid presented above and the results confronted with the reference case. To compare the total differences, it is not possible to use the same index as previously (the Hellinger distance), because it is size independent. In order to allow the index to take into account the differences related to the various totals of emissions distributed, the Hellinger distance has been modified according to Eq. (5). For a given i cell holds:

$$d_i^{\text{modHEL}} = \sum_{i=1}^{n} \left(\sqrt{EMI_i^{\text{SEEM+SDA}}} - \sqrt{EMI_i^{\text{MODEM}}} \right)^2 \tag{5}$$

- $EMI_i^{\text{SEEM+SDA}}$ is the amount of emissions disaggregated by the SEEM methodology for a cell i,
- EMI_i^{MODEM} is the amount of emissions disaggregated by the reference case for a cell i.

3. Results and discussion

3.1. Quality of the emissions estimation of the SEEM model

The application of the SEEM model to the Gran Concepción Urban Area shows a general overestimation of emissions (Fig. 3). The global emissions (i.e. the annual amount of emissions predicted for the whole area) are overestimated by about 20–30% depending on the pollutant.

This difference can be explained by the distribution of errors in the estimation of parameters of the model (cf. Eq. (1)), i.e. the total annual activity (the product $N_j \times M_j$ in the model shown in Fig. 4) used: for instance

- *the quality of* N_j: the number of vehicles in the different categories may have been overestimated: only the technical inspection databases of five out of the nine municipalities composing the urban area were available for our study, although a traffic study of the Transportation Office (SECTRA, 2002) showed that these municipalities were characterized by a higher share of passenger car than the municipalities that were not available. Thus, the integration of the technical inspection data coming from every municipality could improve significantly the results.
- *the quality of* M_j: the use of data coming from another city may be problematic, because

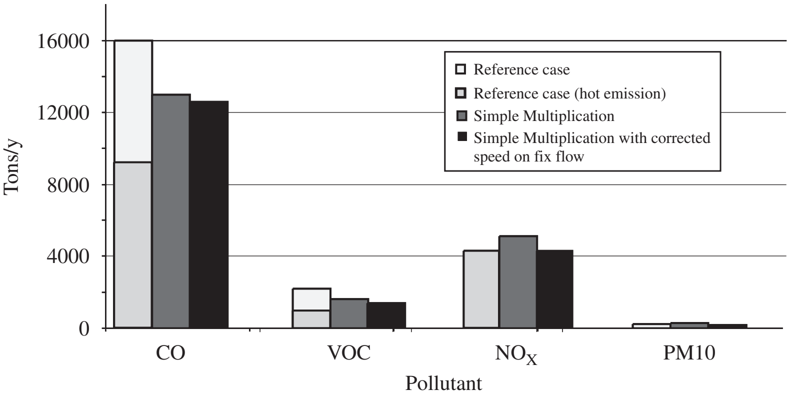

Fig. 3. Estimation of emissions with the SEEM methodology. Differences with the bottom-up reference methodology.

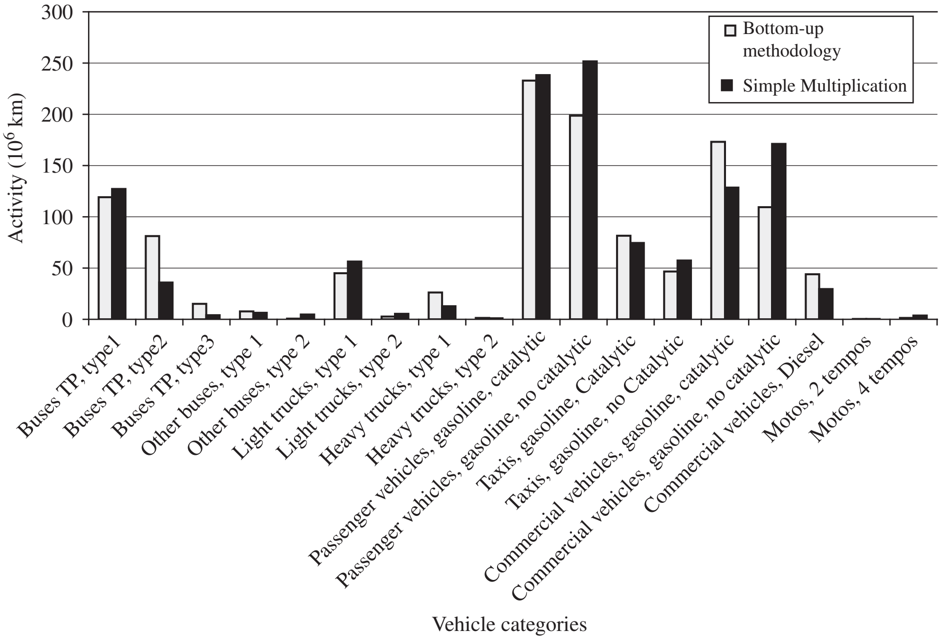

Fig. 4. Estimation of the total annual activity ($N_j \times M_j$) of the SEEM methodology. Comparison with the bottom-up methodology.

Chilean traffic experts confirmed a higher share of non-catalytic vehicles in the fleet of Valparaiso. Therefore, overestimation of M_j may have been important for passenger cars and commercial vehicles. Nevertheless, the activity of fix flow (buses and trucks) is estimated correctly.

The first two considerations explain the general overestimation of the activity, and the fact that the overestimation affects in particular passenger cars and commercial vehicles (Fig. 4). These vehicle categories are particularly relevant in the emission of CO and VOC: in Gran Concepción, passenger cars and commercial vehicles generate 75% of the total emissions of CO and 60% of total emissions of VOC (CENMA, 2001). Subsequently, the estimation of global emissions is affected by different degrees of error: pollutants such as CO and VOC are affected by larger errors than NO_x and PM, which are more related to fix flows (buses and trucks). Despite this, the overestimation of NO_x and PM of Fig. 3 is also relevant, although these pollutants are weakly related to passenger and commercial vehicles. The source of these errors may reside in the parameter governing the third term of Eq. (1), the average speed used within the emission factors $V_{\mathrm{EF}_{jk}}$.

- *the quality of* $V_{\mathrm{EF}_{jk}}$: SEEM uses emission factors related to average speeds of each vehicle category. Errors in the value of the average speed can also partially explain the overestimation of the total emissions, especially for pollutants such as PM and NO_x. These pollutants are mainly related to fix flows and it has been shown above that the total activity of these classes is estimated correctly (Fig. 4). Considering that the emission factors used for both models (MODEM and the SEEM) are the same, we suppose that the errors in the estimation of these pollutants may be caused by wrong speed values. In comparison with the study carried out by the Transportation Office (SECTRA, 2002) it appears that the average speed used was significantly too low. The higher than expected average speed of buses in Concepción is related to the fact that buses and trucks are basically driving between the commercial centre and the peripheral residential areas. By approaching the average speed value of the fix flow to the value proposed by the Transportation Office study, emission values of NO_x, PM and VOC are highly improved (using the COPERT emission factors and for low speed values (below 50 km h^{-1}), an increase of the speed corresponds to a decrease of the emission). The CO estimate improves slightly, because of the weak dependency of CO to fix flow.

3.2. Selection of a spatial disaggregation approach

In Fig. 5 different SDA have been applied to distribute spatially the total emission of MODEM over the urban area of Concepción. The Hellinger distance (Fig. 6) shows the difference between each SDA and the reference distribution.

- *Urban area-based SDA* (1 *and* 2): the approaches using information about the urbanized area give too coarse results. The amount of emission distributed saturates when a cell of the grid is entirely covered by urban area. Therefore, regions characterized by high traffic do not emerge with these types of disaggregation and the global result is a smoothed emission map. Approaches such as these are useless in compact urban areas, where emissions will be distributed equally on the whole urbanized area.
- *Population density-based SDA* (3): disaggregation by population density gives results similar to the landuse disaggregation and the global Hellinger distance is slightly improved.
  We remark that this SDA was expected to give a better result because of the relationship between the possession of vehicles and population density. This assumption of relationship should be verified for developing countries where the areas characterized by the highest densities are often the poorest (slums) and are not related to high vehicle possession. Moreover, some cities have achieved the metropolization process which results in central business districts weakly populated but linked to high traffic profiles.
- *Road network-based SDA* (4, 5 *and* 6): approaches based on network density give the best results. The Hellinger curve of Fig. 6 shows a general improvement related to the use of local information. The resulting maps (Fig. 5) are characterized by smaller local errors. The comparison between the three road network-based methods shows that the injection of secondary road network information (more expensive and difficult to obtain) does not greatly improve the quality of the distribution

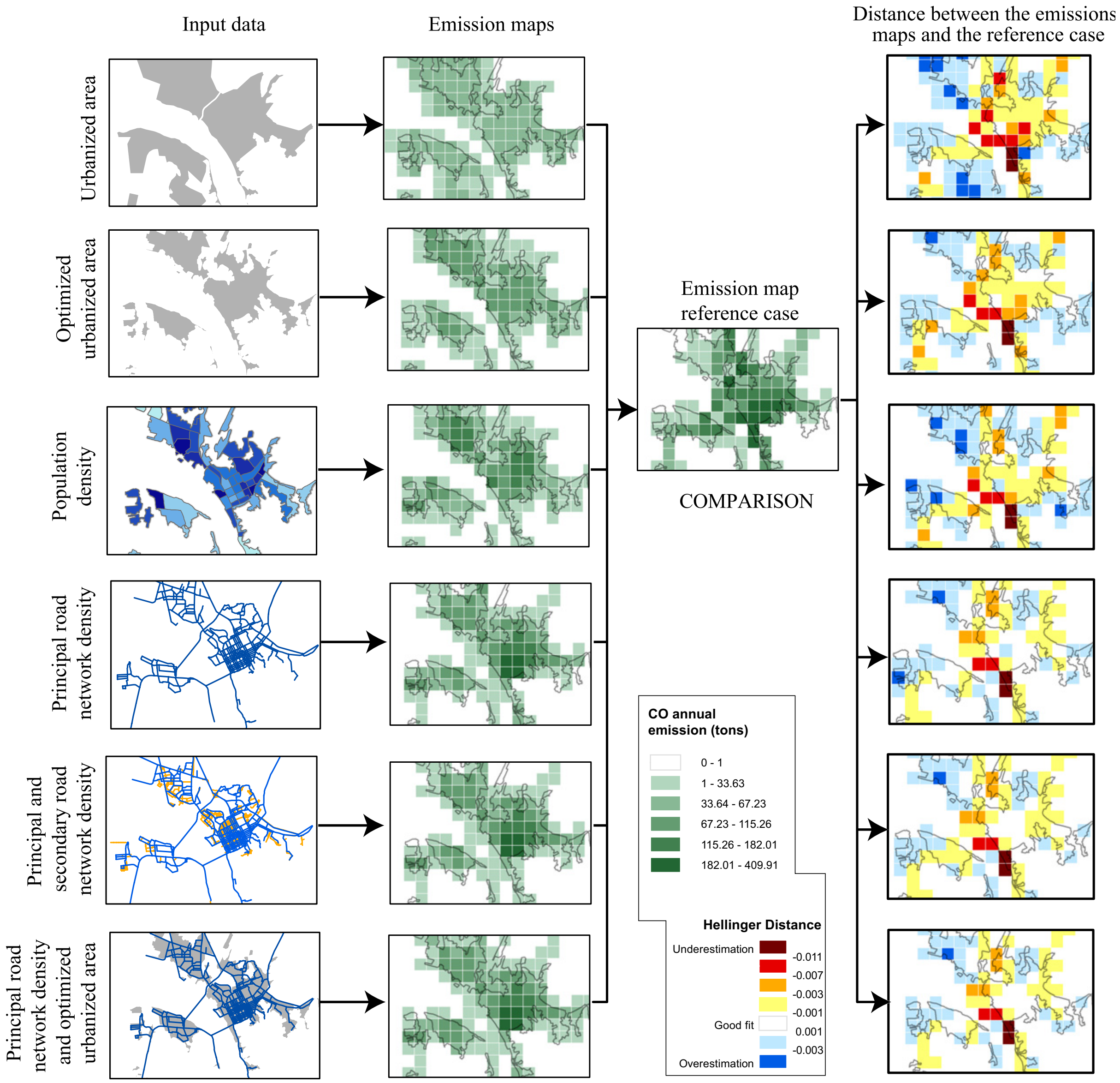

Fig. 5. Comparison of the six disaggregation approaches with the reference (Source of GIS data: SECTRA, MINVU, EULA).

(the global result is statistically the same) and even if this information is required, landuse can efficiently replace the secondary network data.

To sum up, the fourth SDA (i.e. dividing the emissions by the principal road network density) has given the distribution results most similar to the reference distribution of emissions and has been used in the next step as disaggregation approach for the SEEM results.

3.3. *Application of the best spatial disaggregation approach to the SEEM results*

Fig. 7 shows the results for the Gran Concepción urban area, using the modified Hellinger distance (Eq. (5)). The application of the principal road network density SDA to the SEEM shows a generally good repartition of the emissions on the territory. Nevertheless, a general underestimation of CO emission value in congested areas and the compensation of this effect in the urban periphery

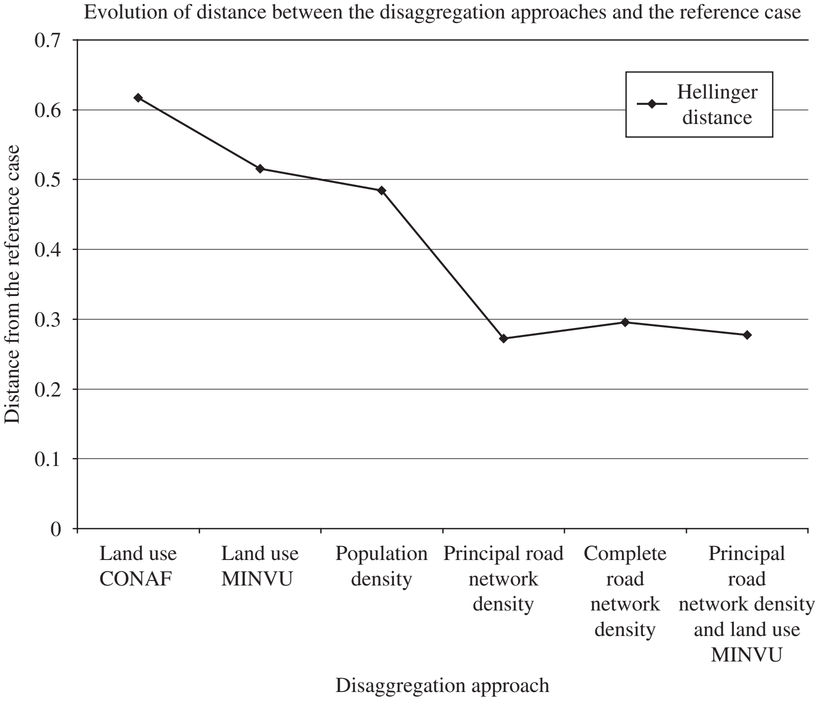

Fig. 6. Dissimilarity between the bottom-up reference case (0 level) and several emissions distribution approaches applied to the results of the SEEM methodology.

are striking. These trends can be explained as follows:

- The model is not able to reproduce the reality because it does not take into account local variations of traffic (every road is considered, in terms of traffic flows, as equal). The most striking examples are the regions characterized by congested traffic. Congested areas, characterized by a traffic flow exceeding the capacity of roads and by higher than typical emissions values, are not detected. The amounts of emissions that have not been distributed to congestioned areas are redistributed on the other cells. The simplified SEEM methodology is not robust enough to reproduce these local effects (Fig. 8a). If this level of detail is required (for example for cities with a denser road network, where the SDA would reproduce an uniform distribution of emissions), a distribution approach that takes into account local traffic conditions would have to be implemented.
- Some design differences between the road network in the reference case and the one of the simplified SDA harm the comparison between the SEEM model and the reference: the main example refers to the bridges crossing the BioBio river: the figure shows an important underestimation area over the BioBio river that is related to the presence of an oversimplificated bridge in the road network of the reference traffic model (Fig. 8b). This imaginary road groups the traffic over two bridges crossing the river. The disaggregation approaches based on the road network is based on digitalization of the real network, so the bridges are located exactly, i.e. in two different cells of the grid. Therefore, the cell containing the reference bridge is underestimated, while the one containing the real one is overestimated. This oversimplification of the reference network creates an artifact that harms the comparison.

4. Conclusions

This study has shown that the accurate choice of traffic input data leads to good global emissions estimations from a simplified top-down model. The simplified emission estimation model (SEEM) developed uses aggregated traffic data in order to give a rough estimation of the total emissions. The application of SEEM in Gran Concepción in Chile assessed the annual traffic emissions with an

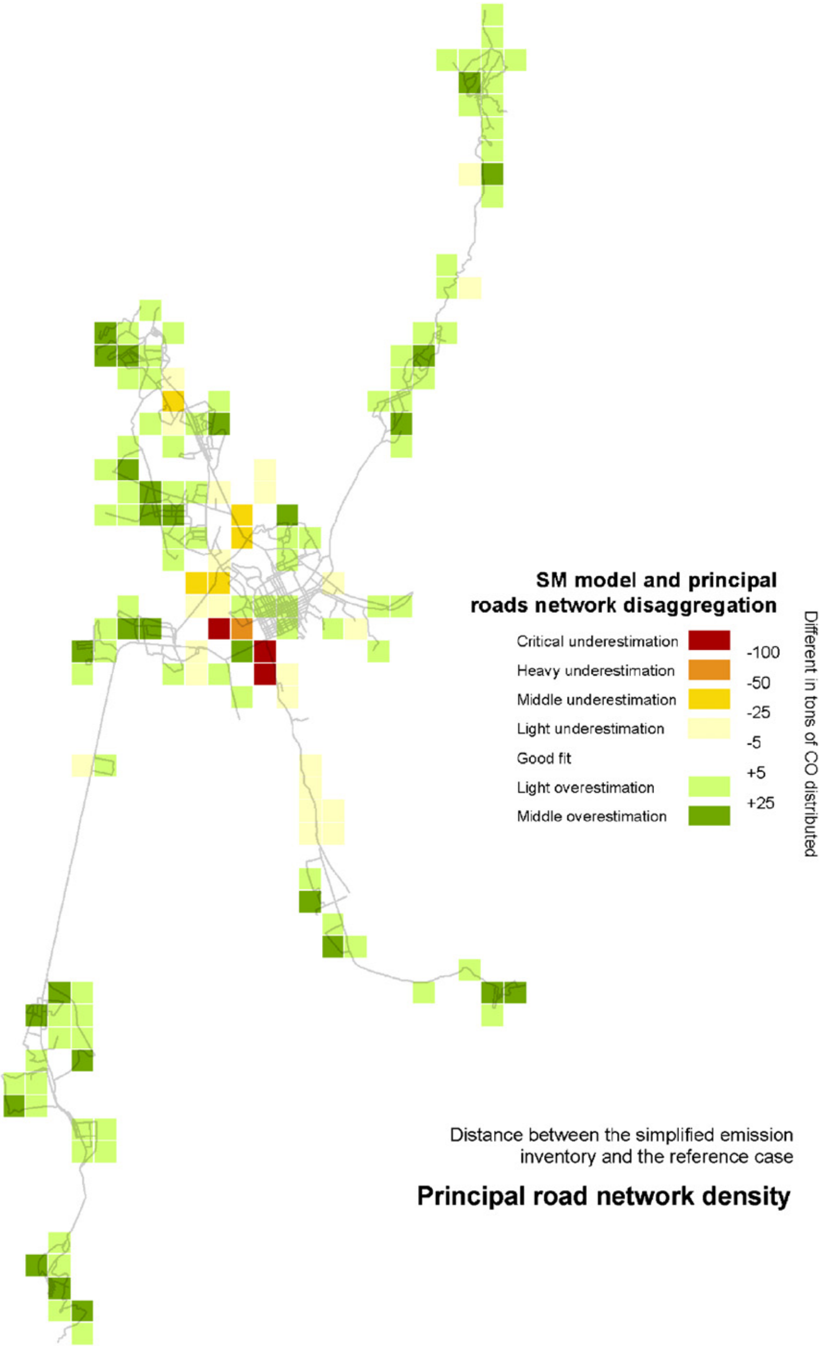

Fig. 7. Comparison between the reference bottom-up approach and the SEEM results distributed by principal road network density (Source of GIS data : SECTRA).

generally good estimation, with an error of 20–30% compared to the reference, the bottom-up emission model MODEM. The SEEM model is highly dependent on input data quality and on the particular characteristics of the area under study. Therefore, these results are only valid for the Gran Concepción study and need to be generalized through application of the model to other urban areas. Two actual studies going in that sense are being led in other cities by the authors' respective groups.

Another important point concerns the present nature of the SEEM model: the simplified approach

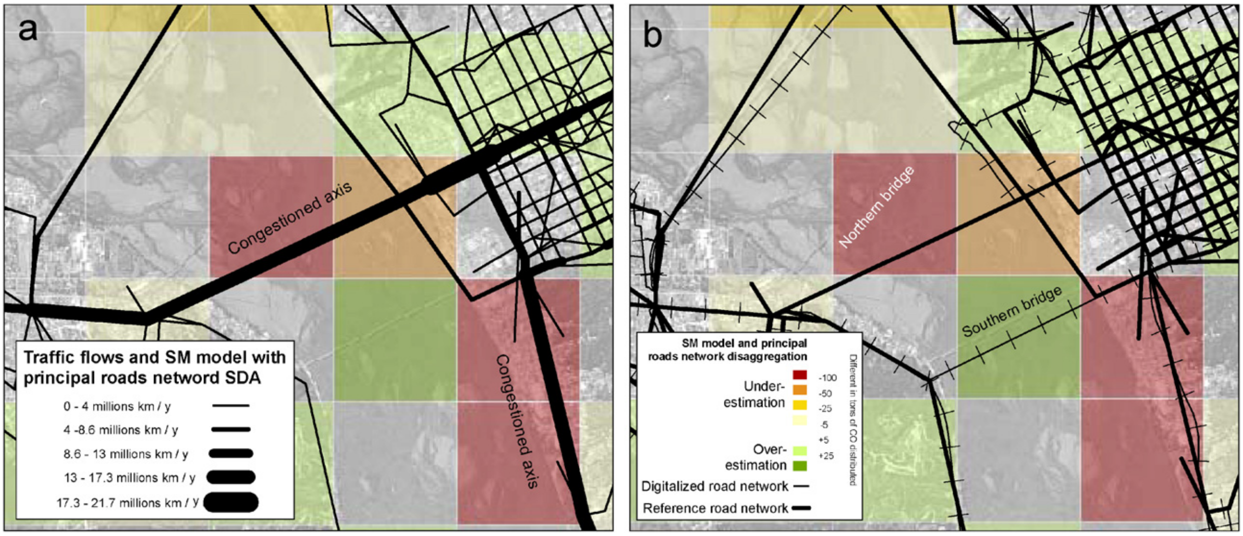

Fig. 8. Main differences between the reference emission inventory and the SEEM, disaggregated with the principal road network SDA (zoom in the BioBio river region of Fig. 7): (a) underestimation related to congestioned areas; (b) underestimation/overestimation related to differences in the design of the reference and digitalized road networks (Satellite image: www.sinia.cl, GIS data: SECTRA).

proposed takes into account only exhaust hot emission, without estimating cold start or evaporative emissions. It is a well-known fact (Lents et al., 2004) that these emissions are relevant especially for CO (cold start) and HC (evaporative) estimation. In order to make the SEEM model operational, the development of a cold start and evaporative emissions estimator module is crucial.

Nevertheless, some observations can already be made: the global results could be highly improved by an accurate choice of input parameters, particularly average speeds and annual vehicle activity. Data collection (e.g. manual short-time traffic counts) can be done with little additional resources and does not imply high technical skills, as has been shown by the IVE model in several cities worldwide (Davis and Lents, 2004). The study of uncertainities in the emission factors is also crucial for the assessment of the absolute quality of the calculated emissions. Input data for the SEEM model are economically accessible in comparison with a bottom-up model, which needs a complex traffic model as source. This kind of model implies information about journeys between areas (origin-destination matrix), as well as other inputs requiring information at the level of households and specialized knowledge about the traffic situation. Therefore, the use of the SEEM model is cost-effective for cities that do not have access to such information.

The SEEM model does not supply spatially resolved information: for that reason, the results have been distributed on the area under study through a GIS-based method and different simplified distribution approaches have been tested. The application has shown that for an urban area such as Gran Concepción, characterized by a spread urbanism and satellite towns, the model can reproduce the repartition of emissions by using road network related information at a reasonably aggregated level (principal road network). The injection of more precise (and costly) information such as detailed secondary road network does not improve the repartition significantly. The precision level reached for Gran Concepción is suitable as a first approximation for applications such as air quality modelling, that most often handles emissions information at an aggregated level (urban air quality models often use information over a 2–4 km^2 resolution, while this study used a spatial resolution of 1 km^2).

Given the need to estimate cold start and evaporative emissions discussed above, it will be important to study the options to disaggregate the cold start and evaporative emissions. These kinds of emissions cannot be disaggregated in the same way as the hot emissions, because they rely on other structural parameters as the origins and destinations of trips or the cars ownership.

The quality of the input data is the key to a relevant simplified emissions model. An accurate choice of input parameters makes a model such as the SEEM particularly attractive for countries with limited resources and restricted data accessibility.

Such models can give a first approximation of the emissions within the cities where economical situation and political awareness of environmental problems do not allow for the implementation of complex models.

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Appendix

(1) By urbanized area
  (a) Intersect the regular gird with the urbanized areas GIS file;
  (b) Join the intersected landuse map with the cells file, in order to have the urbanized surface statistic per cell. Summarize statistics per cell (in case of disconnected objects within the cell);
  (c) Compute the weight of urban covering for every cell (cell urbanized surface area/total urbanized surface of Gran Concepcón);
  (d) Assign to every cell the emissions by multiplying the total CO emission to the weight calculated in (1c).

(2) By optimized urbanized area
  (a) Repeat (1) using the optimized urban area GIS file.

(3) By population density: the population density being given per census units (smaller in Concepción and equal to municipalities' boundaries for the others), the first stage is to homogenize the data set, assigning the densities to the urbanized area: doing this, we assume that the entire population of the census units lives into the urbanized areas.
  (a) Intersect the census GIS file with the urbanized areas GIS file, to create a density per urbanized area GIS file;
  (b) Compute the correct population densities for urbanized census unit taking into account the change of surface;
  (c) Intersect the regular grid with generated file;
  (d) Compute the number of inhabitants per cell using the density statistics per cell and the surface of cell covered by urbanized area (e.g.: if densities are of 100 inhabitants/km^2 on half a cell and of 50 inhabitants/km^2 on a quarter of the cell (a quarter of the cell is non-urbanized), then the population is $100 \times 0.5 + 50 \times 0.25 = 62.5$ inhabitants);
  (e) Repeat (1c)–(1d) using the share of total population per cell and the total population.

(4) By principal road network density
  (a) Intersect the regular gird with the principal roads GIS file;
  (b) Summarize the statistics for a same cell in order to have data corresponding to the total length of principal roads per cell;
  (c) Repeat (1c)–(1d), using the principal road length per cell and the total principal roads length.

(5) By principal (80%) and secondary road network density (20%)
  (a) Repeat (4a)–(4b) for principal roads;
  (b) Use (4a)–(4b) for secondary roads;
  (c) Compute the weights per cell by weighted sum of the percent of principal roads in the cell (weight = 0.8) and of the percent of secondary roads in the cell (weight = 0.2);
  (d) Repeat (1d), using the computed results.

(6) By principal road network and estimation of the secondary network by optimized urbanized area
  (a) Repeat (5), by using (2a)–(2c) to compute the percent of urban covering used to estimate the 20% of emissions (5b).

References

Baldasano, J.M., 1998. Guidelines and formulation of an upgrade source emission model for atmospheric pollutants. In: Power, H., Baldasano, J.M. (Eds.), Air Pollution Emissions Inventory. Southampthon, UK and Boston, USA, pp. 1–51.

Belalcazar, L.A., Zarate, E., 2004. Proyecto Modelo de Calidad del Aire para Bogotá, pp. 44. ⟨http://wwwprof.uniandes.edu.co/~nrojas/Dia_15_ModeloDeBogota/Belalcazar.pdf⟩.

Bellasio, R., Bianconi, R., Corda, G., Cucca, P., 2007. Emission inventory for the road transport sector in Sardinia (Italy). Atmospheric Environment 41 (4), 677–691.

Brulfert, G., Chollet, J.-P., Jouve, B., Villard, H., 2005. Atmospheric emission inventory of the Maurienne valley for an atmospheric numerical model. Science of the Total Environment 349, 232–248.

Burke, R., Napoleon, E., Ormsby, T., 2004. Getting to know ArcGIS Desktop: The basics of Arcview, ArcEditor and ArcInfo Updated for ArcGIS 9 (Getting to Know series). Esri Press, Second Book, 588pp.

CENMA, 2001. Elaboración del Inventario de Emisiones Atmosféricas para la Zona Denominada Gran Concepción, Comision Nacional del Medio Ambiente.

Costa, M., Baldasano, J.M., 1996. Development of a source emission model for atmospheric pollutant in the Barcelona Area. Atmospheric Environment 30 (2), 309–318.

Dalvi, M., Beig, G., Patil, U., Kaginalkar, A., 2006. A GIS based methodology for gridding of large-scale emission inventories: application to carbon-monoxide emissions over Indian region. Atmospheric Environment 40 (16), 2995–3007.

Davis, N., Lents, J., 2004. Comparison of on-road vehicles profiles collected worldwide. Transport and Air Pollution 13th International Scientific Symposium Conference Proceedings. NCA Boulder CO, USA.

Friedrich, R., Reis, S., 2004. Emission of Air Pollutants: Measurements, Calculations and Uncertainities. Springer, Berlin, Heidelberg, 335pp.

Khatami, A., Ponche, J.-L., Jabry, E., Mirabel, Ph., 1998. The air quality management of the region of Great Casablanca (Morocco). Part 1: Atmospheric emission inventory for the year 1992. The Science of the Total Environment 209, 201–216.

Kourdis, C., Ntziachristos, L., 2000. COPERT III—Computer programme to calculate emissions from road transport. European Environment Agency, ⟨http://lat.eng.auth.gr/copert/⟩.

Lents, D., Nikkila, N., Osses, M., 2004. Lima vehicle activity study. International sustainable systems research. ⟨http://www.gssr.net/ive/⟩.

Mage, D., et al., 1996. Urban air pollution in megacities of the world. Atmospheric Environment 30 (5), 681–686.

Malerba, D., Esposito, F., Monopoli, M., 2002. Comparing dissimilarity measures for probabilistic symbolic objects. In: Zanasi, A., Brebbia, C.A., Ebecken, N.F.F., Melli, P. (Eds.), Data Mining III, Series Management Information Systems, vol. 6. WIT Press, Southampton, pp. 31–40.

Mayer, H., 1999. Air pollution in cities. Atmospheric Environment 33, 4029–4037.

Onursal, B., Gautam, S.P., 1997. Vehicular Air Pollution. The World Bank, 282pp.

Osses, M., Dursbeck, F., 2002. Modelo de emisión de contaminantes atmosféricos producidos por transporte urbano: el caso de Santiago de Chile. In: Proceedings of the XI Congreso Latinoamericano de Transporte Público y Urbano. La Habana, Cuba, September 2001.

Osses, M., 2003. Modelo de emisiones vehiculares, MODEM XI, in Congreso Chileno de Ingenieria de Transporte Conference Proceedings. Santiago de Chile.

Oyola, G., 2004. Región del Bio Bio—Contaminación Atmosférica, in Conama Bio Bio 10 años Conference Proceedings, Concepción, Chile.

Parra, R., Jiménez, P., Baldasano, J.M., 2006. Development of the high spatial resolution EMICAT2000 emission model for air pollutants from the north–eastern Iberian Peninsula, Catalonia, Spain. Environmental Pollution 140, 200–219.

Samaras, Z., Kyriakis, N., Zachariardis, T., 1995. Reconciliation of macroscale and microscale motor vehicle emission estimates. Science of the Total Environment 169, 231–239.

SECTRA, 2002. Análisis de la Red Vial Básica del Gran Concepción, I Etapa, Ministerio de Planificación y Cooperación, p. 54. ⟨http://www.sectra.cl/contenido/home/home.htm⟩.

Sturm, P., 1996. Determination of traffic emissions—intercomparison of different calculation methods. Science of the Total Environment 189–190, 187–196.

Sturm, P., et al., 1997. Application of computational methods for the determination of traffic emissions. Journal of Air and Waste Management Association 47, 1204–1210.

Tashiro, Y., Taniyama, T., 2002. Atmospheric NO_2 and CO concentration in Lima. Peru, Environment International 28 (4), 227–233.