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Spatial disaggregation of traffic emission inventories in large cities using simplified top–down methods

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ABSTRACT

Simple, inexpensive and accurate methods for assessing the spatial distribution of traffic emissions are badly needed for the environmental management in South American cities. In this study, various spatial disaggregation methods of traffic emissions of carbon monoxide are presented and evaluated for a large city (Santiago de Chile). Previous methods have used a simplified road network as a proxy for deriving spatial patterns of emissions. However, these approaches resulted in underestimation of emissions in urban centers, industrial zones and highly loaded roads, as well as overestimation in residential zones. Here we modify these methods by adding data correlated with the emissions (e.g. traffic counts, vehicles mean speed, road capacity) solving partially or completely the indicated problems. After an accuracy-simplicity analysis two methodologies stand out over the others: using traffic count classification and using a land use map, both combined with a simplified road network. Both are top–down approaches that correlate well (∼0.9) with the reference emissions and capture emission peaks (within 30% relative error). Hence the proposed changes allow an improved balance between accuracy and costs (monetary, availability of data and time to obtain data).

1. Introduction

Emission inventories (EIs) should consider three main components: total amount of emissions, spatial distribution and temporal disaggregation. EIs in developing countries are scarce and usually they only report total amount or magnitude of emissions. Just in few Latin American cities data on temporal distribution is available, while spatial distribution is not reported (e.g. IVE (International Vehicle Emissions) model, Davis et al., 2005). Therefore, it is necessary to develop simple methodologies capable to distribute emission inventories data over a certain urban area, in order to find hot spots of emissions and also to provide accurate data for air quality forecasting.

In Winiwarter et al. (2001) and references therein spatial distribution is assessed for several European cities and for different sources (traffic, industrial and domestic), using satellite land use data, street networks, traffic counts and vehicle registration. Other studies have made comparisons between spatial distribution of emission inventories computed with different levels of information. Kühlwein et al. (2002) showed that a big source of uncertainty is encountered when only considering distribution using population while Lindley et al. (2000) found discrepancies between inventories generated with road networks at different levels of detail and different sources of digital data.

There are studies in South America (Chile specifically) oriented to obtain traffic emissions. In Tuia et al. (2007) simple methodologies for the spatial distribution/disaggregation of CO emissions are developed on a medium sized city (Gran Concepción area, approximately 800 000 inhabitants). In that study the most accurate results were obtained when using road density obtained from a simplified road network. In a later study this approach was applied in 7 small and medium sized Chilean cities, in order to make a sensibility analysis when changing the city and the pollutant (Ossés de Eicker et al., 2008). Main conclusions from both works are that emissions are underestimated in urban centers, industrial zones and highly loaded roads and, on the other hand, traffic emissions are overestimated in residential zones. Also, the spatial accuracy of the method tends to decrease with size and complexity of the city. Until now, this methodology has been only applied for small and mid-sized cities (100.000–800.000 inhabitants). However, it is yet unknown if simplified methods for disaggregation of traffic emissions could also be applied in mega-cities, which exhibit a more complex settlement structure.

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The main goals of this study are (i) to apply existing simplified approaches in the large city of Santiago de Chile (6 million inhabitants), (ii) to further optimize these simplification methods with respect to the conditions of a large city and (iii) to evaluate the most suitable approaches regarding accuracy and simplicity. Methods with different data inputs are applied so it could be adapted to other cities depending on data availability.

2. Study system

Santiago, the capital city of Chile, concentrates more than 30% of the population of the country, which leads to intense industrial and traffic activity resulting in severe pollution problems. Also, Santiago de Chile is located on a complex topography, where the average altitude in the city is around 500 m.a.s.l with mountain chains surrounding it, reaching from 1500 to over 4000 m.a.s.l. Topography plus meteorological conditions (temperature inversion and coastal lows) bring down the base of the subsidence inversion, which are unfavorable for the dispersion of air pollutants in the basin (Rutllant and Garreaud, 1995; Gallardo et al., 2000).

Given the pollution problems of Santiago de Chile, authorities have generated detailed emission inventories and environmental data, making this city a good study site to test emission distribution methodologies given the availability of reference inventories. Therefore, several methods can be implemented and tested, giving flexibility when applying the method over other cities.

An objective of the present work is to use only available information, and not to generate additional data to apply the methodologies. The information used can be divided into four categories: emission inventories, road network maps, population density maps and land use maps, which are described below.

2.1. Reference emission inventory

Spatial distribution will be estimated only for CO since small differences have been obtained when changing pollutants (Ossés de Eicker et al., 2008), and for mobile sources. The results are compared with an official emission inventory map of CO for year 2002 provided by CONAMA (National Environmental Commission of Chile) which is used as a reference. It has a spatial resolution of 2 × 2 km^2 and 1 h temporal resolution. The official inventory is divided into mobile and stationary sources (see Table 1). Mobile sources (approximately 90% of total CO emissions) are computed with the bottom–up methodology MODEM (Emission model, Corvalán and Osses, 2002) which considers official traffic modeling results (ESTRAUS model, see Section 2.2), comprehensive traffic counts, analysis of databases for vehicle technology distribution and emission factors from COPERT III model (Ntziachristos and Samaras, 2000) and also from local measurements. This emission inventory was evaluated in Saide et al. (2009) using inverse modeling.

In Tuia et al. (2007) and Ossés de Eicker et al. (2008) emissions were given for each segment of the ESTRAUS network, thus the emission inventory could be built for any grid. In the present work this is not the case, and the emissions are provided in a fixed grid. Also, the ESTRAUS network used for building the disaggregation methodologies is not the same (but similar) as the one used for building the reference inventory, which can cause additional discrepancies.

Table 1
Total emissions for Santiago de Chile for year 2002. Units in Tons of pollutant per year.

	CO	VOC	NOx
Traffic emissions	167 000	20 000	35 000
Stationary sources	12 000	55 000	10 000
Total emissions	179 000	75 000	45 000

2.2. Road network maps

Two road networks are available for the city under study:

- ESTRAUS: this road network is used by the strategic traffic model of urban transport system for the city of Santiago de Chile, ESTRAUS (De Cea et al., 2003), which provides vehicular fluxes for the principal streets of the city of Santiago de Chile (see Fig. 6). It is built by "arcs" (or segments) where each one has information on vehicular fluxes, street's capacity, vehicular categories, length and commuting time. This study uses the results of ESTRAUS for the year 2001. The traffic network provided by ESTRAUS is the baseline used to compute the official emission inventory of mobile sources for the city of Santiago de Chile. The ESTRAUS network is a simplification of the real road network and has geo-referencing problems described in Tuia et al. (2007) and Ossés de Eicker et al. (2008).
- Complete road network: it comprises all the streets in the city of Santiago de Chile and its surroundings. It is a comprehensive digital network but there is no additional information for each street as in the ESTRAUS network.

2.3. Population density maps

Two population density maps were compiled and an additional one was built with the available information:

- High resolution population density map: 120 × 120 m^2 grid with population density in each cell, generated with 2002 census information.
- Population density by sectors ("Comunas"): official map for the year 2002.
- Improved population density map: in order to address areas where no people live (green areas, mountains, agriculture, etc.) a land use map was combined with the population density map by sectors to obtain an improved population density map. The new map was validated using as reference the high resolution density map.

2.4. Land use maps

Two land use maps were compiled containing different type of data and structure:

- Land use from the Geography Department of the University of Chile (LUGDUC). Consists of a 30 × 30 m^2 grid-cell indicating the land use of the cell obtained by manual photo-interpretation following Pauleit (Pauleit and Duhme, 1995), Anderson (Anderson et al., 1976) and CORINE (CEC, 1993) typologies for a LANDSAT image of 31st December of 2004, using MSS and TM sensors.
- MUSSA (Land use model for Santiago, MIDEPLAN, 2008). It's a map with information of the percent of area occupied by different kinds of land use for the year 2001. The categories are more specific than the ones in LUGDUC, having information about commercial, industrial, public administration, residential and offices zones between others, but the spatial resolution is lower (bigger areas, not in a regular grid).

3. Simplified disaggregation methods

Different simplified methods have been applied for disaggregating the traffic emissions. The basic methodology can be found in Tuia et al. (2007). Consists in finding weights for each cell, which are normalized in a scale from 0 to 1 (these factors will be called Normalized Emission). Also, as mentioned before, better results were obtained using a simplified road network as a base of the estimation, that's why in the present work the approaches will start from principal road network and adding information.

3.1. Using road density (B1 and B2)

Spatial distribution of mobile emissions is bounded to the geographic location of the roads. For this reason one can attribute emissions to the roads weighting with the length (Tuia et al., 2007; Ossés de Eicker et al., 2008). A road density can be obtained for each cell:

$$E_j = \frac{\sum\limits_i l_{ij}}{\sum_{j=1}^{M} \sum\limits_i l_{ij}} \tag{1}$$

where l_{ij} is the length of the segment i in the cell j, M the total number of cells and E_j the normalized emission in the cell j. A physical meaning can be given to Eq. (1): Normalized emissions assuming the same traffic counts and vehicular speed in all the network (see Eq. (2)). The main problems of this approach reported in Tuia et al. (2007) and Ossés de Eicker et al. (2008) are that the method is not able to properly asses urban areas with high traffic intensity like urban centers, main roads (accesses to the city, principal avenues and highways) and industrial zones. However, these limitations were obtained for small and medium sized cities, and the city under study is considered a large city, so the limitations must be checked. This method can be applied with both road networks, the ESTRAUS (B1) one and the complete one (B2).

3.2. Using information directly obtained from a transport model (F, V, F + V)

In order to obtain better results, the same information used in computing the inventory is used. This information comes from the transport model ESTRAUS and it consists in mean vehicle speed and traffic counts (vehicle fluxes) for each segment of the simplified road network. The basic formula to estimate hot emissions with the MODEM methodology (Corvalán and Osses, 2002) is the following:

$$Em_{ijk} = F_j \cdot l_i \cdot EF_{ijk}(v) \cdot PF_{jk} \cdot C_{jk} \tag{2}$$

where Em_{ijk} are the emissions for a given pollutant i in the segment j for the vehicular category k, F the total traffic counts in each segment for the morning peak, l the segment lengths, EF an emission factor dependent on the mean speed, PF a pattern to normalize the traffic counts for the rest of the hours, and C the fraction of the counts from the corresponding category. The implemented methods consist in applying parts of the main formula. Traffic counts can be used directly, but it is necessary to choose a representative emission factor for the speed. Osses et al. (2002) reported that around 90% of the total mobile emissions of CO are produced by private vehicles, and 80% of those are produced by vehicles without a catalyst. From Osses et al. (2002) the following emission factor (in g. of pollutant km^{-1}) is used for that category, which was obtained using local measurements:

$$EF(v) = 0.0203 \cdot v^2 - 2.2662 \cdot v + 77.661 \tag{3}$$

Finally, three methods are presented using traffic count information (F), speed information (V) and both ($F + V$), as shown in the following equations:

$$E_j = \frac{\sum\limits_i F_{ij} l_{ij}}{\sum_{j=1}^{M} \sum\limits_i F_{ij} l_{ij}} \tag{4}$$

$$E_j = \frac{\sum\limits_i EF(v_{ij}) l_{ij}}{\sum_{j=1}^{M} \sum\limits_i EF(v_{ij}) l_{ij}} \tag{5}$$

$$E_j = \frac{\sum\limits_i F_{ij} EF(v_{ij}) l_{ij}}{\sum_{j=1}^{M} \sum\limits_i F_{ij} EF(v_{ij}) l_{ij}} \tag{6}$$

where i represents the segments and j the cells. A physical meaning can be given for all three equations: Eq. (6) computes emissions as such, Eq. (4) computes emissions assuming the same vehicular speed in the entire network and Eq. (5) computes emissions assuming the same traffic counts in each segment. The results are expected to be improved using this method compared with the basic one that only uses the lengths. However, it is not the purpose of this work to encourage the use of this method, because a transport model is needed to obtain the fluxes, which is expensive (see Section 3.2). The reason of showing these methodologies is to see which information is more relevant in the estimation of the spatial distribution and then see how close other methods' results can get to these estimations when using information that is not coming from the transport model. Also, if a transport model is available the computation of spatially resolved inventories using a bottom–up model is straight forward (i.e. ESTRAUS-MODEM system) and the application of disaggregation methodologies it is not necessary.

3.3. Using traffic counts classification (FC1, FC2)

As it was said before, a transport model is needed to obtain the fluxes in every segment. Trying to avoid the use of the transport model one can categorize the streets of a simplified road network in levels, e.g. high, medium and small fluxes (FC1). The categorization between the classes is made using real flux measurements from campaigns such as IVE (Davis et al., 2005). Roads without information can be included in the categories using different methods such as road similarity, in situ observations or satellite images.

Since information for all segments is available for the case of study the total traffic counts of the ESTRAUS network is used for the classification. To establish the categories the method of the natural breaks will be used (Jenks, 1963) since categories with big intern homogeneity and maximum differences between them are obtained. The factors to be used for each category are the mean value inside the category normalized by the mean value of the smaller count category. Finally, they were rounded to the nearest natural number (see Table 2 for values of each category).

Then, the methodology is the following:

$$E_j = \frac{\sum\limits_i f_{ij} l_{ij}}{\sum_{j=1}^{M} \sum\limits_i f_{ij} l_{ij}} \tag{7}$$

with f_{ij} the factor used depending on the category of the segment. The simplified road network used in the present work has more

Table 2
Categories limits and factors obtained for the traffic count classification approach FC1.

Category	Lower Limit [veh h^{-1}]	Upper Limit [veh h^{-1}]	Mean [veh h^{-1}]	Factor (f)
Small	0	855	352.5	1
Medium	856	2261	1360.6	4
High	2262	6447	3189.5	9

than 6000 segments. Trying to test the results of the present method for more simplified networks a factor equal 0 can be used for the Small Fluxes category, reducing the number of segments of the network by 63% (FC2).

3.4. Using road capacity (C)

The capacity of the road (maximum vehicles per hour) is much easier to determine than the traffic counts in each segment. Based on the road capacity, emissions can be estimated with the following approach:

$$E_j = \frac{\sum\limits_i c_{ij} l_{ij}}{\sum_{j=1}^{M} \sum\limits_i c_{ij} l_{ij}} \tag{8}$$

with c_{ij} the capacity of each segment obtained from the ESTRAUS network. This method can be interpreted as computation of emissions assuming the same vehicular speed everywhere and approximating the traffic counts by road capacity.

3.5. Using land use classification (LU1, LU2, LU3)

Tuia et al. (2007) and Ossés de Eicker et al. (2008) reported underestimation in urban centers and industrial zones, and overestimation in residential zones. As seen in the results, this is fixed by using traffic counts. This method uses MUSSA land use to weight in different ways the latter land uses in order to approximate the spatial distribution of traffic counts. Since MUSSA map has percentages of area used for each type of land use in every zone, the percentage can be used directly to compute the factor. The industrial (*%I*) and residential (*%R*) percentages can be obtained directly, and for the Urban Centre (*%UC*) the sum of the percentage of area occupied by public administration, commerce and offices has been considered.

Three different methods have been used that consider different types of information where LU1 uses all three land use classes (*%UC*, *%I* and *%R*), LU2 uses *%UC* and *%I* percentages and LU3 only uses *%UC* percentages, as shown in the following equations:

$$E_j = \frac{\sum\limits_i \left(0.25 + \%UC_{ij} + \%I_{ij} + \left(1 - \%R_{ij}\right)\right) l_{ij}}{\sum_{j=1}^{M} \sum\limits_i \left(0.25 + \%UC_{ij} + \%I_{ij} + \left(1 - \%R_{ij}\right)\right) l_{ij}} \tag{9}$$

$$E_j = \frac{\sum\limits_i \left(0.25 + \%UC_{ij} + \%I_{ij}\right) l_{ij}}{\sum_{j=1}^{M} \sum\limits_i \left(0.25 + \%UC_{ij} + \%I_{ij}\right) l_{ij}} \tag{10}$$

$$E_j = \frac{\sum\limits_i \left(0.25 + \%UC_{ij}\right) l_{ij}}{\sum_{j=1}^{M} \sum\limits_i \left(0.25 + \%UC_{ij}\right) l_{ij}} \tag{11}$$

The factor 0.25 in Eqs. (9)–(11) accounts for the land use not considered in each method, because if a segment is located in a zone where the percentages of the categories used is 0 or near 0, this segment is not considered which is wrong. Thus this factor can be interpreted as the minimum weight for each segment. The value of the factor was obtained by doing a sensibility analysis using factors between 0 and 1, where 0.25 resulted as the optimum.

3.6. Combine principal road network and complete road network (P + C)

The methods based on a simplified road network (ESTRAUS) do not account for spatial distribution of emissions produced in roads that are not in the network. Even if the vehicle fluxes are small, these streets still contribute to the total emission. The ESTRAUS network will be used as the principal one and the complete road network will be used for the rest, similarly to Tuia et al. (2007):

$$E_j = W \cdot Ap_j^k + (1 - W) \cdot B2_j \tag{12}$$

where Ap_j^k can be any of the approaches that use the road network ESTRAUS for the lengths ($B1$, F, V, $F + B$, FC1, FC2, C, LU1, LU2, LU3), $B2_j$ the approach that uses the road density of the complete road network ($B2$) and W a weighting factor that ranges between 0 and 1. For the present study we choose Ap_j^k as FC1.

W represents the emission produced in the principal road network compared with the rest of the streets. In Section 4 it can be seen that the method that multiplies the length with the fluxes is a good estimator of the spatial distribution of the emission. Based on this idea, the normalized multiplication of the total length of the roads by a representative value of the fluxes was obtained for each network. The representative value of the fluxes was obtained using traffic counts of a measuring campaign, taking the mean of a representative group. To decide whether the streets were considered into the principal road network or not the name of the street was retrieved in the ESTRAUS network. If the street wasn't on the ESTRAUS network it was considered secondary. The length for the secondary road network was obtained subtracting the length of the complete one with the principal one. The results of applying the previous methodology to obtain W can be found in Table 3.

If a complete road network is not available the road density corresponding to this network can be approximated by the normalized population in each cell. To obtain the normalized population the following method must be applied (Tuia et al., 2007):

$$P_j = \frac{\sum\limits_i \frac{\rho_{ij} a_{ij}}{A_j}}{\sum_{j=1}^{M} \sum\limits_i \frac{\rho_{ij} a_{ij}}{A_j}} = \frac{\sum\limits_i \rho_{ij} a_{ij}}{\sum_{j=1}^{M} \sum\limits_i \rho_{ij} a_{ij}}$$

where ρ_{ij} is the population density of the i polygon of area a_{ij} in the cell j, A_j the area of each cell (constant) and P_j the normalized population in each cell. Fig. 1 shows the dispersion graph comparing the map of normalized population (P_j) with the map of road density for two types of population density maps: High resolution density map (D1) and Improved population density map (D2) (see Section 2.3), both showing good correspondence with the road density obtained from the complete road network (see Section 2.2).

4. Methods for accuracy analysis

The accuracy of the results is analyzed with different quantitative and qualitative approaches according to Winiwarter et al. (2003). Correlation coefficient and acceptation percentage (% of cells falling within a certain threshold of absolute and relative error) have been calculated with a relative factor of 0.3 and an absolute threshold of 10% of the mean value (as in Winiwarter et al., 2003). Additionally, the results are displayed with emission maps, differences maps, dispersion graphs and scanning series graphs.

Table 3
Data from traffic count campaigns to obtain the weighting factor W for the approach that combines a principal and a complete road network ($P + C$).

	Mean flux [veh h^{-1}]	Total length [m]	$(1 - W)$, W
Secondary Net.	12.21	8 772 548	0.11
Principal Net.	248.51	3 347 896	0.89

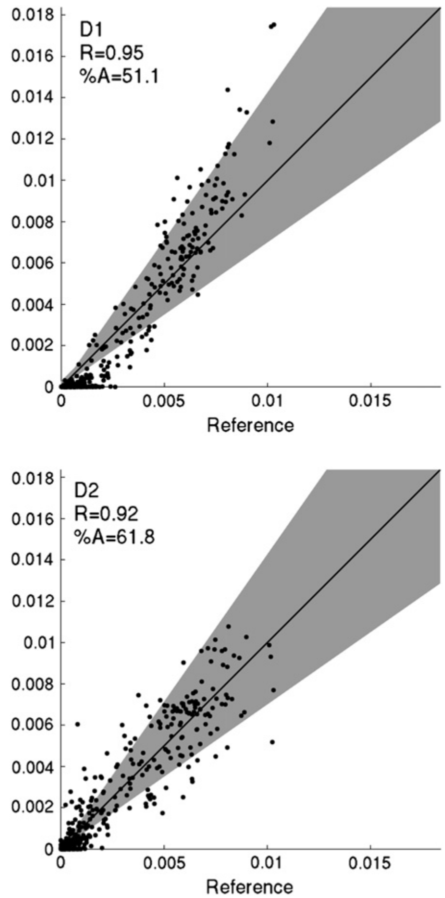


Fig. 1. Dispersion graph comparing road density from the complete road network with an estimation of it using two kinds of population density maps: high resolution density map (D1) and Improved population density map (D2).

In order to classify the different methods, two perspectives must be taken into account: accuracy and simplicity. Accuracy takes into account the quality of the results in quantitative and qualitative ways and simplicity considers costs of the information used in each approach (by cost we mean monetary costs, availability and time required to obtain the information). We establish three levels of accuracy:

- Accuracy level 1: Represents results similar to the base methodology, where the maximums of emission are underestimated and the base problems still remains.
- Accuracy level 2: Maximums of emissions are represented roughly and secondary problems remain.
- Accuracy level 3: Maximums of emission are represented in a very accurate way and a good percentage of the cells are well estimated.

On the other hand, we define the following levels of simplicity:

- Simplicity level 1: Represents expensive and hard to get data where the cost of the information is similar to build the inventory from the beginning. This category comprises simulations of a transport model for the whole city that requires expensive surveys and campaigns.
- Simplicity level 2: Data with a medium level cost. Here the data is still expensive but the cost is not comparable with Level 1 costs. In this category can be included short measurement campaigns (e.g. IVE) or the obtaining of a complete road network for the city.
- Simplicity level 3: Represents low cost data. Data included here is usually owned by government institutions and it was obtained for other purposes (e.g. land use maps, population density maps) or is data that is not hard to build (e.g. simplified road network).

Given the classification, each methodology can be included in one of the levels of each perspective, resulting in a matrix of nine possibilities that can be summarized in a plot as shown in Fig. 7. In this matrix, as far from the origin is the method, the better the method is.

5. Results and discussion

Figs. 2 through 5 show a summary of the results. Fig. 2 shows quantitative comparisons between approaches by computing correlation and percentage of acceptation. Figs. 3–5 show emissions and difference maps, scatter plots and scanning series in order to perform qualitative comparisons.

5.1. Using road density (B1 and B2)

When using the two road density methodologies B1 and B2 it can be seen that both represent in a similar way the reference (using Section 3.2 criterion). The method with the complete network (B2) tends to present more disperse results and an inferior representation of the peaks. Fig. 6 shows that the general problems stated in Tuia et al. (2007) and in Ossés de Eicker et al. (2008) still remain. It can be seen that there is underestimation in the main urban center zone (A), in some industrial zones (e.g. B) and in high loaded streets (e.g. *C*). However, not all industrial zones show this behavior (north-west of the map). Also, some residential zones (e.g. east-north side of the city) show overestimation. The underestimation in urban centers is the most critical, representing only half of the emission of the reference state (see Fig. 5).

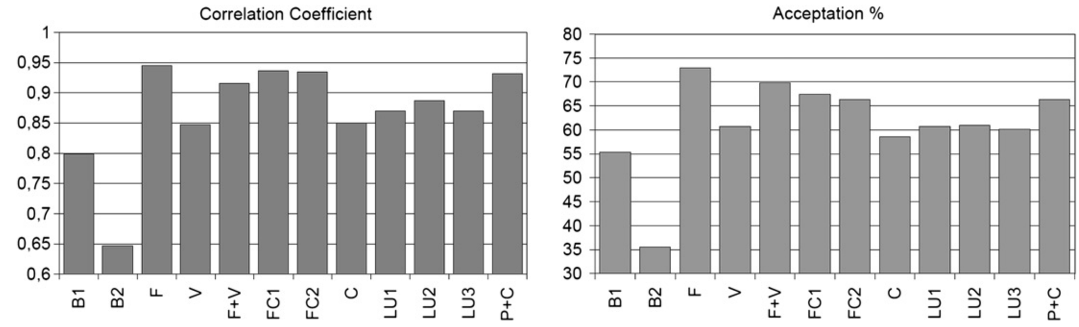


Fig. 2. Correlation coefficient and percentage of acceptation for all approaches applied.

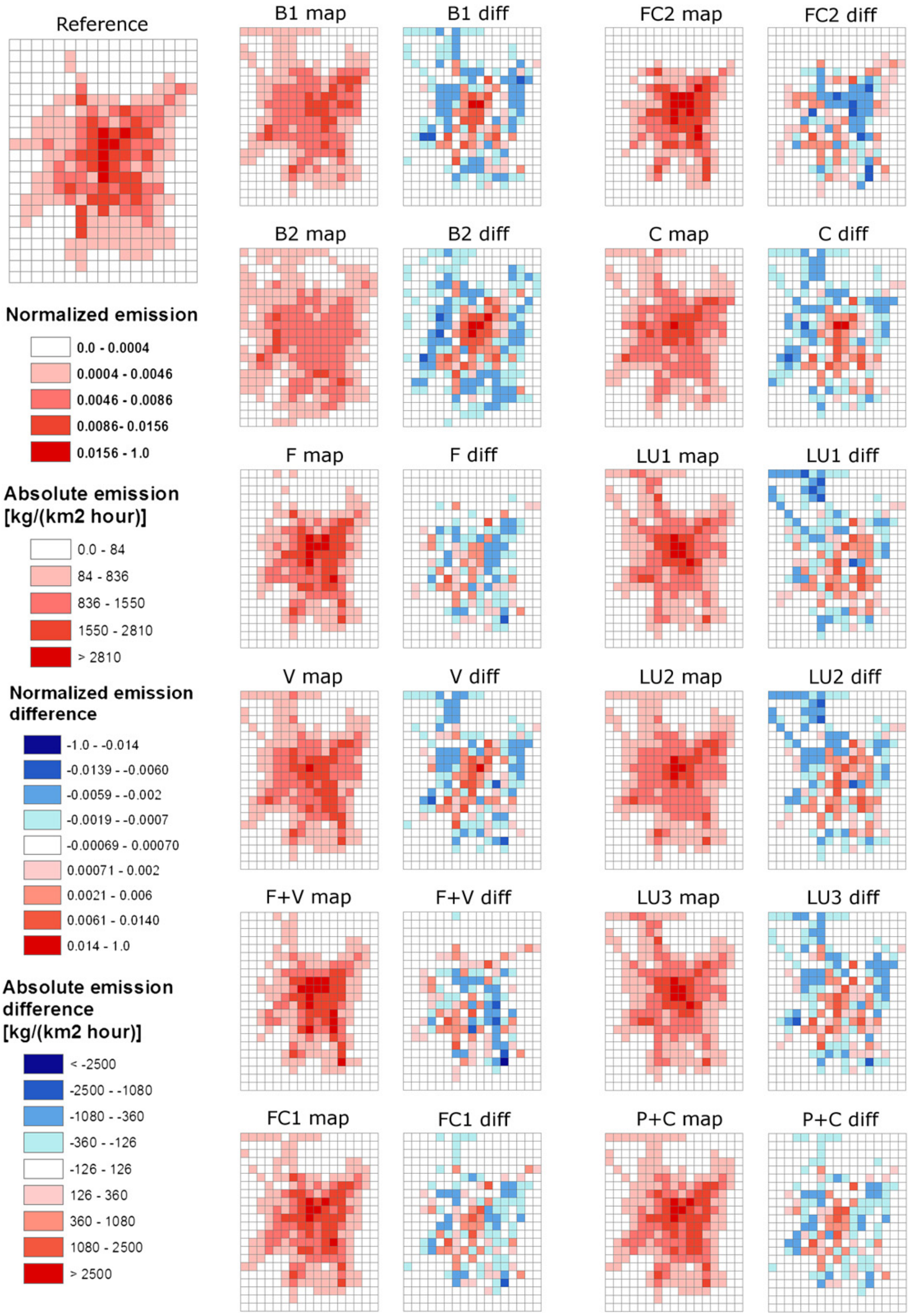


Fig. 3. Normalized and absolute emissions and differences maps for the reference and all the approaches applied.

5.2. Using information obtained directly from a transport model (F, V, F + V)

A high correlation with the reference case and a high acceptation rate was achieved when using traffic counts (*F*) (Fig. 2). The peaks are well represented since almost all maximum points fall in the acceptation area (Fig. 4) and the dispersion of the medium and low values decreases. Fig. 5 shows that scanning series are really close and the % of acceptation and correlation coefficient increase widely. On the other side, when using the mean velocity (*V*) results in an improvement compared with the base case, but the main problems remain. When combining traffic counts and mean velocity (*F* + *V*) results are still good, but not better than the traffic counts case (*F*). This can be explained

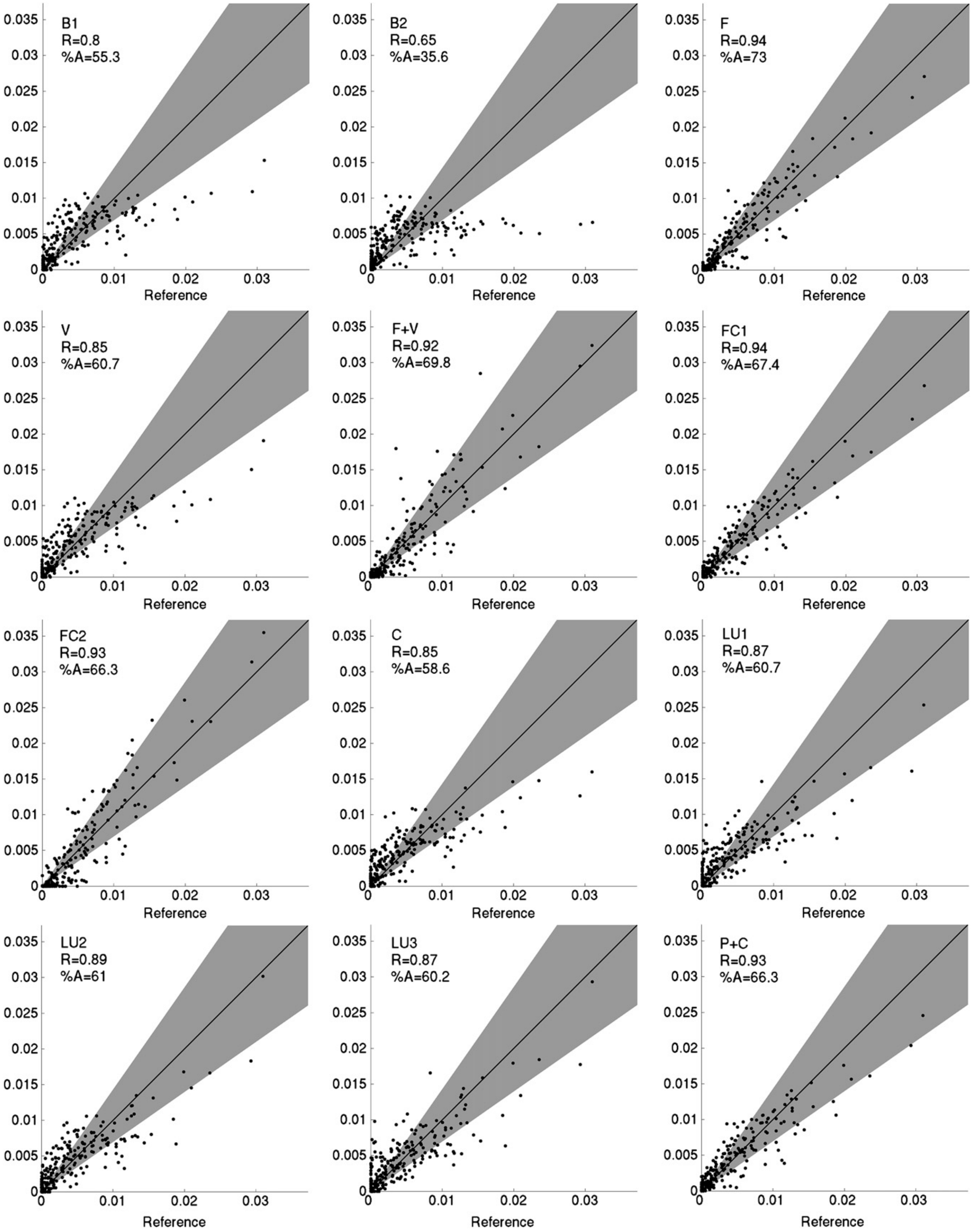


Fig. 4. Dispersion graph comparing the normalized reference inventory with the normalized emissions from the approaches applied. The grey area represents the acceptation zone. Values are normalized (unitless).

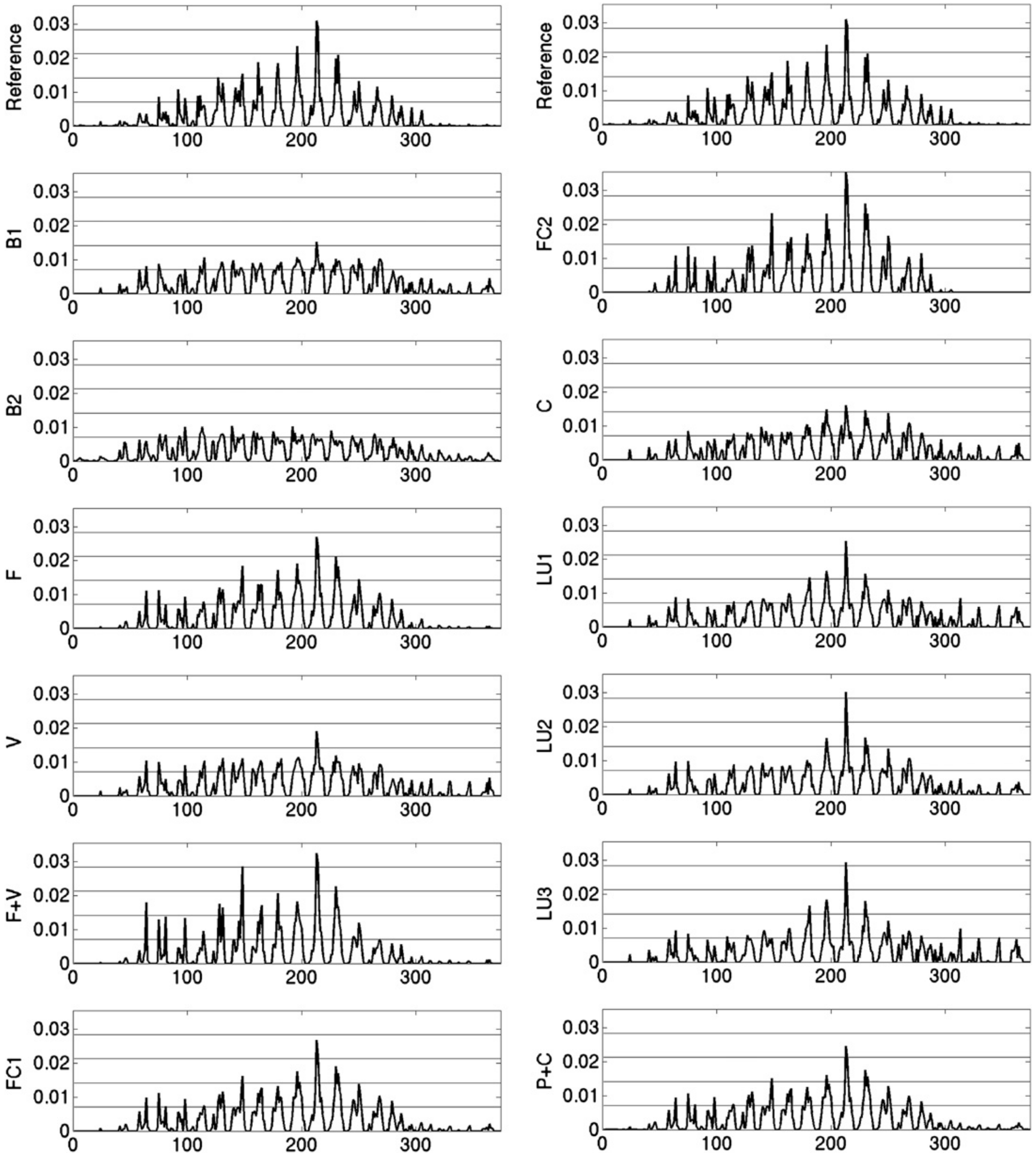


Fig. 5. Scanning series for the normalized emissions of the references and all the cases applied. The numbers on the bottom denote the grid-cell ID. Values are normalized (unitless).

by the simplification made when not considering vehicular categories, and the selection of one emission factor. It can be concluded that the problems of the base methodology are solved, when using traffic counts.

5.3. Using traffic counts classification (FC1, FC2)

Figs. 3–5 show similarity between the approach that uses traffic counts (*F*) and the one that uses classification of fluxes in three categories (FC1). Also, the quantitative indexes show only a small decrease in the quality of the results. The approach that classifies in two categories (FC2) delivers a poorer representation in the city boundaries because of the elimination of these segments, producing a decrease in the percentage of acceptation. The correlation coefficient remains close to the one of the FC1 case because the representation of the maximums is similar. In conclusion, passing from a full range of fluxes to only three categories (or two in the second case) results only in a slightly degraded correlation and the problems of the base methodology are kept solved.

5.4. Using road capacity (C)

When looking at qualitative results it can be observed that the capacity approach (*C*) shows similar results with the base methodologies (*B*1 and *B*2), with a slight improvement when looking at the indexes (Fig. 2). As for the speed approach (*V*), the problems remain unsolved. However, since the information is easy to get, the approach might be applied if no other data is available.

5.5. Using land use classification (LU1, LU2, LU3)

Using land use information results in an improvement of the results with respect to the base method (*B*1) for all the three approaches (LU1, LU2 and LU3) obtaining a relatively good representation of the emission peaks. For the approaches that use industrial and residential maps (LU1 and LU2) there is an improvement in some areas and a decrease in the accuracy in others compared with the approach that use only the urban center map (LU3). This might be explained by the fact that in

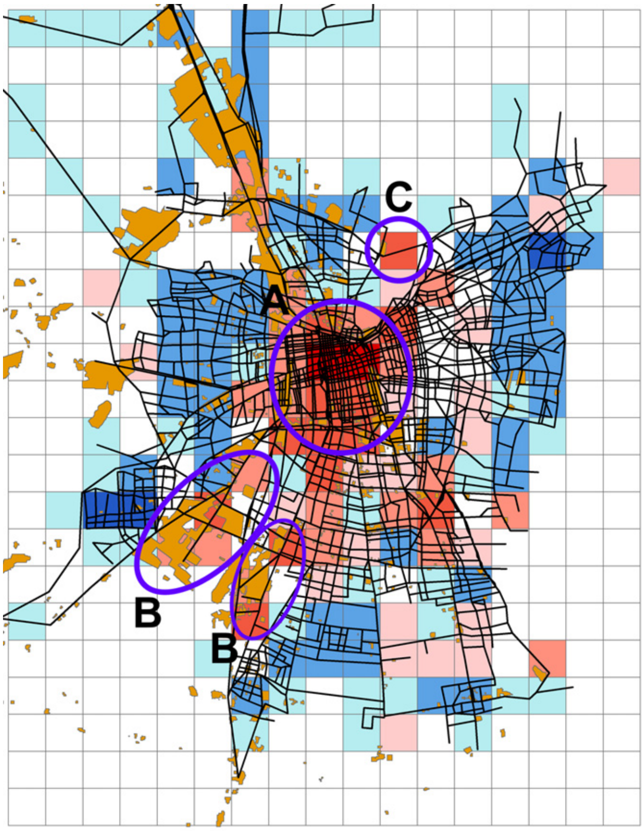


Fig. 6. Difference map between the reference emission inventory and the road density approach using the ESTRAUS network (B1), which is represented in black lines. Dark yellow areas represent industrial zones obtained from LUGDUC land use map. A is an example of urban center, B of industrial zones and C of highly loaded segment. For colors and color scale refer to Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

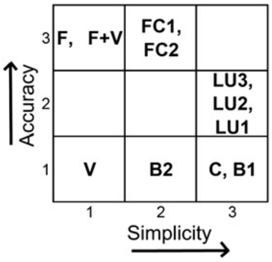
some industrial zones there is no underestimation of emissions and in some residential zones there is no overestimation of emissions. Thus, this approach is not as accurate as the ones that use fluxes (F, FC1, FC2) but it solves the main problem of underestimation in urban centers, resulting in good quantitative indices (Fig. 2).

5.6. Combine principal road network and complete road network (P + C)

The results of the combined approach depend mainly on the approach used for the principal road network, because the weight of the complete road network tends to be small. Then the results obtained with this methodology are quite similar to the approach used in the first term (Eq. (12)). A slight decrease in accuracy is observed because the reference inventory doesn't consider the emissions outside the principal road network.

5.7. Accuracy – simplicity analysis

With the objective to summarize all the previous results and in order to obtain conclusions, the matrix shown in Fig. 7 is built using the categories explained in Section 3.2. When several methods are in the same cell, they are arranged from higher to smaller accuracy considering the correlation coefficient and % of acceptation. The method that combines a principal road network with the complete road network ($P + C$) is not included in this analysis because its results depend on the methodologies chosen to build it (see Section 3.6).



	1	2	3
3	F, F+V	FC1, FC2	
2			LU3, LU2, LU1
1	V	B2	C, B1

Fig. 7. Matrix of simplicity vs. accuracy. The higher the level the better accuracy or simplicity.

There is a tendency that simple methods are in the first level of accuracy and complex methods have higher accuracy. Given our classification, none of the methods achieved the highest level of accuracy and simplicity at the same time, but two methodologies reached good levels: traffic counts categories (FC1, FC2) and classification through land use maps (LU1, LU2 and LU3). It depends on the available data which methods should be applied. The recommendation when applying methods to distribute emissions over a city is trying to collect the information from the higher levels of accuracy, and if it's not possible, then pass to the lower levels and so on. In this case, if traffic counts measurements are available, then this should be the methodology used (assuming that a transport model is not available) considering that the cost of classifying the segments into the categories can be assumed.

5.8. Extension to other species

The presented methods don't make any assumption on the pollutant to be estimated. Thus, the same methodologies can be applied to other pollutants. Ossés de Eicker et al. (2008) showed that, for mid-sized cities, small differences in accuracy are obtained when changing pollutants for the base methodology (B1). Hence, the accuracy of the presented methods is expected to be similar than CO. Nevertheless, further testing with other pollutants must be conducted to completely probe this hypothesis for a large city as Santiago.

6. Conclusions

Several methods have been presented to spatially distribute emissions over a city of considerable size as Santiago de Chile. The methods applied are based on the road density methodology presented in Tuia et al. (2007), trying to solve the problems found when using the base methodology: underestimation in urban centers, industrial zones and highly loaded streets and overestimation in residential zones (Tuia et al., 2007; Ossés de Eicker et al., 2008). The disaggregation methods evaluated in this study used two types of data, namely indirect data (population density, land use) and direct data (road networks, traffic count data, road capacity and information from transport models) related to vehicle activity. It was found that using mean speed or road capacity approaches had results similar to the base methodology without solving the problems of underestimation and overestimation. Using land maps solved the problems partially while using traffic counts data solved them almost completely. A categorization scheme was developed to classify methods by accuracy and simplicity, i.e. the ability of the method to reproduce the reference and the cost of the data required to implement the method respectively. Two methods (traffic count and land use maps) obtained the higher scores combining simplicity and accuracy. It is recommended to use the first one if traffic counts are available and if the cost of classifying the segments is accepted. Otherwise it is recommended to pass to the next lower level of accuracy.

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