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BOTTOM-UP ROAD TRAFFIC FLOW AND EMISSION CALCULATIONS FOR THE ASSESSMENT OF FUTURE TRAFFIC SCENARIOS AND PUBLIC TRANSPORTATION EXPANSION PLANS IN BUCHAREST

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Abstract*:* The calculation of road traffic emissions to air has been performed in Romania as part of the national emission inventory and for air pollutant dispersion modeling. The project was focused on the city of Bucharest and includes the major urban roads. Road traffic flows were estimated by means of a traffic assignment model, based on traffic counts carried out at a large number of road sections; the model also estimates the vehicle speeds and the origin/destination (O/D) matrix. The calculated traffic volumes and travelling speeds further feed the atmospheric emissions model, based on COPERT4 methodology. Vehicle exhaust gases are estimated from line sources (corresponding to the main roads of the network) and from area sources (zones of aggregation of O/D nodes giving the contribution of diffuse traffic on the secondary roads). In order to determine the emissions from area sources, the average trip length inside each area was estimated according to the geometrical dimension of the zones (represented by the quarter of the length of the circumference of a circle having the same area) and the extension of the secondary road network (represented by the square root of total length of secondary roads inside the area); this method already showed good results in other national and urban contexts (Doha (Qatar), Kaliningrad (Russia) and Tunisia). The modeling results were compared with real fuel consumption data and the methodology showed good correspondence with Bucharest's figures for year 2006, with an error below 20% of the official fuel consumptions. The small differences could be explained by the portion of local travel not considered by the model, the uncertainties in the distribution of the vehicle fleet as well as on the hypothesis made of the trip lengths. The system was finally used to assess scenarios of future emissions due to the increase in circulating vehicles, which is significantly higher in Romania than in Western Europe, and the impact on traffic flows and emissions related to public transportation expansion policies. As a major result, the system showed that in Bucharest also a moderate expansion of public transportation along the most saturated paths could bring to a considerable decrease of total urban traffic emissions (up to 30% and more).

Key words: a*tmospheric pollutant emissions, road traffic, COPERT methodology, traffic modeling, origin/destination matrix, scenario comparison*

INTRODUCTION

Atmospheric emissions fromvehicular traffic were quantified over the Bucharest area through a "bottom-up" approach, starting from traffic flow data available in the transport sector. This method, alternative to a "top-down" approach which starts from aggregated traffic data and proceeds with space and time disaggregation, is based on spatialized data on traffic counting carried out at a large number of road sections. Traffic flow on the remaining road sections need to be assigned by using a transport model that evaluates traffic flows together with speeds on different links of the traffic network, as well as the number of origin/destination trips between different zones. The quantified vehicular activity is then multiplied with proper emission factors, such as the ones given by the EU COPERT methodology for on-road traffic, through an emission model. The emission contribution from secondary roads was further estimated and aggregated into area sources, taking into account the estimated O/D values and theaverage distances travelled on the secondary network. The advantage of a detailed bottom-up approach, compared to a top-down methodology, is the improved knowledge of factors affecting air quality, as the spatial and temporal distribution of different pollution sources can be evaluated.

Finally the validated modeling system could be used as a decision support system to study the effectiveness of different urban management scenarios (such as the increase of public transportation and the renewal of the vehicle fleet over time), in order to help mitigating the urban air pollution levels.

THE ROMANIAN CASE

Romania is a country located at the crossroads of Central and Southeastern Europe,bordering the Black Sea. TheDanubeRivermarks the southwest boundary with Serbia and Bulgaria, while in the north Romania borders with Hungary and Ukraine overthe Carpathian mountain range. The capitalBucharestis located in the southern plainand is the most populous city with over two million inhabitants, which represent around 10% of the total population in Romania. The 1st of January 2007 Romaniabecamea memberof the European Union, which justifies theneed to adapt its legislation to Europeanstandards also with regard to atmospheric pollution. The Romanian road network is more detailed and developed in the Bucharest region but asystem ofrural roadscovers the entire territory, with a total of 64400 km. The evaluation of road traffic emission has been performed over the Bucharest urban area, considering the traffic flow on major urban roads.

THE TRAFFIC MODEL

The traffic data available to feed the models was provided by the Romanian Auto Register (RAR) and correspond to hourly traffic counting at 250 stations obtained from manual counting during year 2006.Traffic flows on road links without existing traffic counting need to be assigned, for example by using a particular category of traffic models which are able to estimate the O/D matrix from traffic counts along with the traffic flows and average speeds on the road network (Van Zuylen H.J., Willumsen L.G., 1980). The traffic simulation was performed by means of an assignment model (CarUSO) including one of the major algorithms (Willumsen's) adapted to non-congested networks using iterative calculations in order to minimize the errors on traffic flows. It is based on the entropy principle and it postulates that, among all the O/D matrixes satisfying the counts of traffic flows (or minimizing the errors, if no solution exists), the best solution maximizes the path entropy, where the entropy is calculated as the product of the O/D matrix elements containing the numbers of travels between each pair of zones. The model also requires a description of the road network as input, including geometrical and functional data related to its elements.

BUCHAREST ROAD NETWORK

The traffic network integrated in the model is an ideal representation of a real road network where roads are symbolized by links (or arcs), cross sections and interchanging points by nodes and traffic sources or sinks by particular nodes, respectively the origin or destination (O/D) zones. Focusing on the Bucharest urban area, the digital road network, provided in GIS format by NEPA ("Romanian National Environment Protection Agency"), was composed of almost 10000 links with a very high degree of detail. The subset selected for the CarUSO simulation included about 950 links chosen according to the hierarchical classification and the availability of traffic measurements. About 25% of the selected urban roads include traffic count sections, corresponding to 250 well distributed road measuring sections, as shown in figure 1.

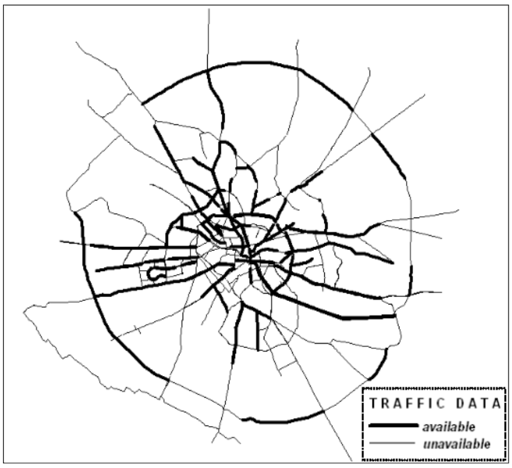


Figure 1. Data availability (hourly average) over Bucharest

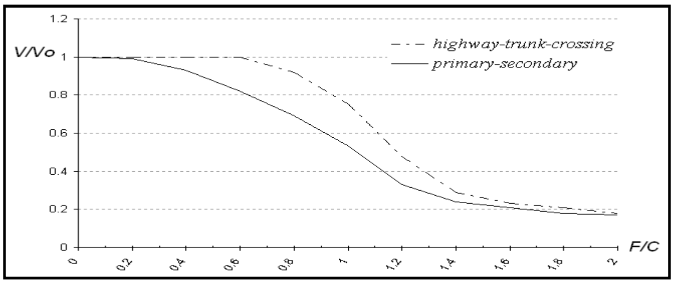


Figure 2. Speed functions (v/v0: real versus free-flow speed ratio; F/C: traffic flow versus road capacity)

The O/D matrix estimation requires that a number of nodes (crossroads) are defined as O/D zones. In principle, the selection of these zones should reflect the real situation (residential districts, business areas, parking lots, modal interchange points,…) with the higher density naturally located in the city center. Furthermore, all the terminal nodes must be treated as O/D zones and certain zones are added or moved in the process of model configuration and optimization; finally a number of 115 O/D zones were selected for the entire road network, from a set of 700 nodes. The estimated O/D values can be used to evaluate diffuse emissions on the secondary traffic network, after aggregation inside consistent areas, giving a picture of diffuse traffic that is realistic enough for the sake of emission calculation as shown both for the Kaliningrad urban network (Calori et al., 2009) and the Tunisia national network (Nanni et al., 2010). In order to complete the network description, the free flow speed and road capacity were defined for each road link according to street hierarchy as shown in Table 1.

Table 2. Free flow speeds and capacities according to road hierarchy for the Romania CarUSO simulation

Road hierarchy level	Free flow speed(km/h)	Capacity (veh/h)
motorway	110	3000
trunk	90	2000
crossing	70	1500
primary	50	1000
secondary	40	1000

The model hypothesis for a non-congested network implies that the trips between origin and destination zones are chosen in order to minimize the path cost, where "cost" stands for the hypothetical time spent to cover the distance or the sum of the ratios between length and free-flow speed of any single link composing the path.

After the assignment of traffic flows, the average speed on each link is estimated by the model through speed functions which relate vehicle speed to link saturation (see figure 2). The functions, definedfor differenttype ofroadways, describe how the real versus free-flow speed relationship decreases while the F/C ratio increase (in both cases the speed does not change significantly for F/C ratios lower than 40%, thereafter it rapidly drops to 30% of the free flow speed to finally decrease slowly).

SETUP AND RESULTS OF THE TRAFFIC SIMULATION

The first CarUSO simulation was based on the average vehicle flow at counting sections during traffic peak hour as well as on the network described above. The peak hour in terms of equivalent vehicles occurs between 9a.m. to 10a.m. and was selected according to the average daily profiles during the autumn season which is the most representative season concerning traffic flows.

The model requires the tuning of some parameters to optimize the results. To better account for situations of congestion, a relative high maximum number of alternative paths (3) were allowed between two different O/D zones as in congested situations vehicles normally tend to change itinerary to avoid queues. At the same time the maximum ratio between the cost of each path connecting a pair of zones and the minimum pair cost is set to 1.2, in order to exclude too expensive (long) paths.

After iterative refinements made on local scale aiming to improve the model performance at the counting sections the output of the simulation in terms of traffic and O/D flows was obtained as shown in figure 3. The map shows that the highest volumes can be found along the main radial connections of the city allowing traffic to travel towards and from the city centre; consequently the zones with higher O/D fluxes are located in the central area. Table 2 presents a summary of the numerical simulation.

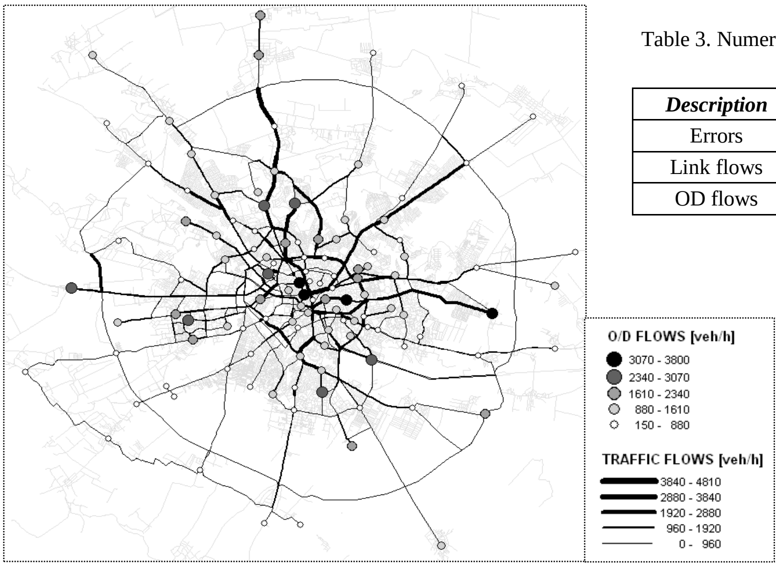


Table 3. Numerical overview of the Romania CarUSO simulation

Description	***Total***	*Network average*
Errors	27.3% RMSE	19.7% MMSE
Link flows	682818 [veh*km/h]	1106 [veh/h]
OD flows	131904 [veh/h]	1157 [veh/h]

Figure 3. Traffic simulation results of O/D flows and traffic volumes on each road

Almost $7 * 10^6$ kilometres are traveled by vehicles during rush hour (1106 veh/h is the average throughput) considering that total length of the simulated network is about 620 km.

A comparison of model vs. measurement results was carried out by calculating the root mean square error(RMSE)and the mean module of relative errors (MMRE) at traffic counting sections. The errorswere further compared with theaverage of measured traffic flow to obtain the percentage shown in the table below. The values 27.3% and 19.7% canbeconsidered satisfactory, as the model does not include human behaviour and the selection of road links included in the simulation is flexible.Figure 4 shows the distribution of the relative errors related to the measured flows on each link.

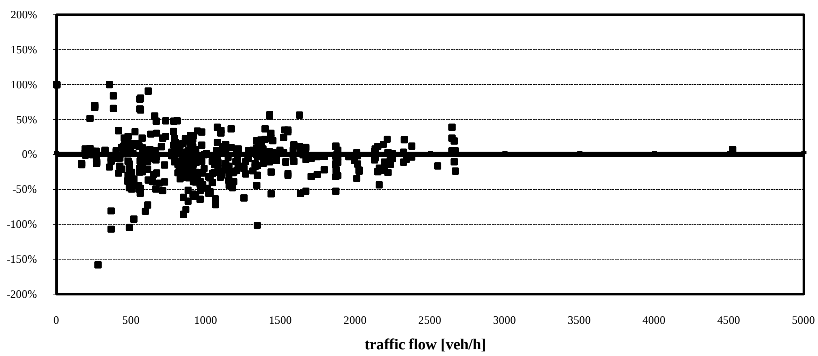
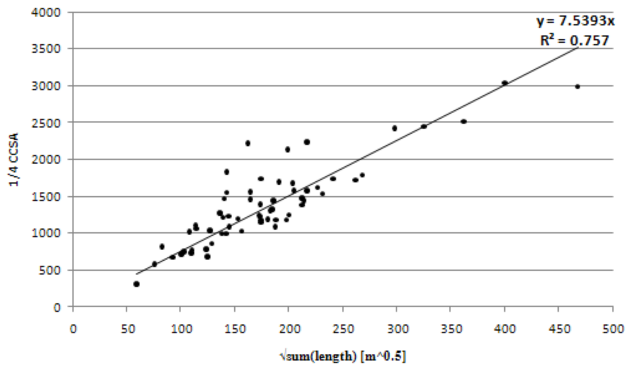


Figure 4. Diagram of relative errors versus measured traffic flows

The diagram showshigher scattering atlow flow values, while for high traffic flowsthe error ismuch smaller.This result is valuable especially in relation to the aims of the project, because it brings to lower emission errors (in percentage) for the majortraffic sources. Thedistribution shows symmetry around the zero error value, the model has no tendency to overestimate or underestimate the total number of kilometers traveled on the road network(and thereby the emissions).

FROM OD ZONES TO AREA SOURCES

The CarUSO network does not consider the traffic contribution on secondary roads although it corresponds to a consistent subset of the urban network (the total lengthof secondary roads is 3600 km). In order to account for the emissions contribution from traffic on secondary roads, the resulting O/D matrix from the simulation for the main road network was processed. The OD fluxes were aggregated into area sources by taking into account the distance that vehicles travel on the secondary network. A set of 63 territorial areas was selected according to the homogeneity of the secondary network texture as well as the number of estimated O/D flows (the major O/D flows were treated as separate sources while for the minor O/D flows the traffic was aggregated). Thereafter each traffic area source was characterized by an internal average trip length and the kilometers driven within each area were calculated as a product of the trip length and the aggregated O/D flows. The average trip length was estimated with an empirical formula which has been validated in previous urban projects, for example in Kaliningrad and in Doha. As observed in these studies a good "conventional" estimation of the average internal trip length is ¼ of the circumference of a circle having the same area (CCSA). This estimation takes into account the zone extent but not the road density inside the area, another property probably influencing the average trip. To account for the road density, a proxy variable corresponding to the square root of the total length of roads was then used. Figure 5 shows the linear correlation between these quantities:



$$L_T = 7.5393(L_{SR})^{0.5}$$

In this equation L_{SR} is the total length of secondary roads while L_T represents the average internal trip length which now includes both extension and road density aspects. The extensions of the defined areas range from 0.12 to 11.6 km^2 and the trip length from 450 to 3500 m.Finally the total number of kilometers run by vehicles on the secondary network according to the O/D matrix was found to be 3 times smaller than the total number of kilometers observed on the main network (24% of the total mileage).

Figure 5. Linear regression model of 1/4 of the CCSA vs. the square root of total length of secondary roads.

THE EMISSION MODEL

The emissions from road traffic have been calculated with the TREFIC model ("Traffic Emission Factor Improved Calculation"), which crosses traffic flow data with emission factors per trip unit (E.F.) and determinates road vehicle emission in terms of pollutant mass per trip unit. The program is based on COPERT IV EU-official methodology (Gkatzoflias D., Ntziachristos L., Samaras Z., 2007) which defines and regularly updates EF values of all major air pollutants (CO, NOx, VOC, PM, NH3, SO2, heavy metals) as well as greenhouse gas emissions (CO2, N2O, CH4) according to different vehicle types, fuels, average traveling speeds and road types. A basic input for the traffic emission calculation is the distribution of the circulating fleet into COPERT vehicle categories, which was provided by NEPA related to reference year of 2006. Figure 6 shows some percentages of vehicles distribution into different emission standards, vehicle categories and fuel use.

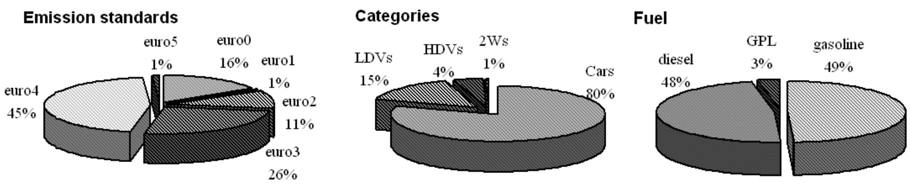


Figure 6. Romania vehicle fleet distribution, year 2006.

The TREFIC model has the double function of feeding emission inventories and atmospheric dispersion models. In Table 3 the sum of emissions from traffic line and area sources in Bucharest can be found for the main pollutants.

Table 4. Road traffic emission calculated for Bucharest city.

Emissions [kg/peak hour]	**CO**	**NOx**	**VOC**	**PM_{10}_LOH**	**CH4**	**Fuel Consumption**
Line sources	6774	790	647	297	15	49130
Area sources	1690	195	175	278	4	12965
Total	8463	985	822	576	19	62096

To check the reliability of the results, a comparison with national fuel consumption from the road transport sector was performed (table 4). The fuel consumption for Bucharest was derived from national data by means of population, (Bucharest corresponds to 9% of the national population). This evaluation shows a slight underestimation of the global emission calculation, presumably because the contribution of trips not intercepted by the main network is not considered and the usage of population to disaggregate consumptions to a major city may bring to overestimations (the average trip length inside a city is shorter than the national one and public transportation is more developed in a large city). Other uncertainties can also be related to the fleet distribution.

Table 5. Fuel consumption: reality vs. model output

FC_Bucharest (measured)	FC_Bucharest (estimated)	Variation
16651686 [GJ/yr]	13404590 [GJ/yr]	-19.5%

SCENARIO COMPARISON

Once set-up and validated, the modeling system was also applied to assess emission scenarios in the transport sector in order to study the efficiency of various emission abatement strategies to reduce air pollution from traffic. In fact, the methodology can reproduce the effects of modifications in the transport system (CarUSO) and the consequences that occur in terms of pollutants emissions (TREFIC). In this project the scenario "business-as-usual"(BAU), accounting for the evolution that can be expected with present regulations without considering any additional policy measure, was compared with a scenario involving expansion in public transportation. Both scenarios were performed for a future situation corresponding to the reference year 2015. The road network was identical to the simulation for year 2006, while the increase in traffic volumes between year 2006 and year 2015 was extrapolated from historical data on registered vehicles in Bucharest. The annual average increase in traffic volumes during the last years corresponds to 8% and was applied to the years between 2006 up to 2010. For the years between 2010 and 2015 the yearly increase was progressively reduced to reach a valueof 2% in year 2015. The lower value of 2 % was applied considering that the current growth rate of 8% should tend to saturate the market (and the street network), in particular in an urban context.The vehicle distribution and fuel characteristics were further updated based on the annual renewal trend of vehicles and the introductionof new standards between year 2006 and year 2015.

The second emission scenario takes into account existing policies regarding the development of public passenger transport in the city aiming to increase the number of buses in areas saturated with traffic. A selection of ten different zones showing the highest vehicular flows in Bucharest were chosen for this scenario. A fraction of the passengers currently traveling along the selected paths by car were moved to buses by multiplying the corresponding traffic flows and the average ratio of passengers transported by car (1.5 passengers per car) versus those carried by bus (90passengers by bus). This action corresponds to a total decrease of 3300 cars on the concerned paths compared to an increase of 55 buses, which is a reasonable modification during peak hour in urban context. The fleet distribution was also modified for the chosen paths, in order to obtain the increase of buses running with clean fuel (CNG) as foreseen by local policies.The impact on emissions of each scenario has been calculated by means of the CarUSO and the TREFIC models and the global output for the complete road network for the different simulationsare summarized in Table 5.

Table 6. Scenario simulation results and comparisons

Description	CO	NO_2	VOC	PM_{10}	CH_4	Fuel Consumption	Kilometers run
1. Business as usual	3740.1 kg/h	835.3 kg/h	396.5 kg/h	826.5 kg/h	8.9 kg/h	87037.8 kg/h	1033549 km/h
2. Public transport increase	2700.0 kg/h	666.4 kg/h	289.4 kg/h	769.3 kg/h	7.5 kg/h	67226.8 kg/h	865016 km/h
Scenario 2 vs. scenario 1	-28 %	-20 %	-27 %	-7 %	-16 %	-23 %	-16%
Scenario 1 vs. scenario 2006	-56%	-15%	-52 %	+ 44 %	-54 %	+40 %	+41 %

The results show that global emissions tend to significantly decrease in scenario 2 as compared to scenario 1, although the proposed action is not significant in terms of global traffic reduction (it only involves the paths between ten major zones). The impactobtained in scenario 1 with respect to the base scenario (year 2006), shows a general increase in traffic mobility, inducing higher fuel consumption and PM_{10}emissions.However, the fleet renewal foreseen in the upcoming years counterbalances the effects of general trafficgrowth for most pollutants, resulting in a reduction of the emissions for NO_X, CO, VOC and CH_4.

CONCLUSIONS

The emissions from the road traffic sector in Bucharest city was evaluated by means of a modeling system including a traffic assignment model and an emission model, fed with urban traffic data at counting sections via a bottom-up approach. This method allows to reproduce transport activity directly on the main network (line sources) through the assignment model and on secondary roads (area sources) by using a semi-empirical formula to estimate the average trip length and the O/D matrix calculated by the assignment model. As expected, the results show that the main trips occur along the major radial connections, therefore the zones with higher O/D fluxes are located in the central area. The activity data were used for emissions estimation by crossing them with emission factors provided by COPERT methodology, together with information concerning Romanian fuels and the age of vehicle fleet. In order to assess the uncertainty, validation was performed comparing the official fuel consumption with the one estimated by the modeling system, with satisfactory results. The modeling tool setup allowed to explore the effects on emission productions due to changes in traffic management; two different scenarios, referring to year 2015, were elaborated (BAU and "public transportation expansion"). Scenario BAU shows how the expected renewal in vehicle fleet can, at least partially for some pollutants, counterbalance the increasing trend in traffic volumes; a demonstrative public transportation expansion action showed high effectiveness even if limited to some central streets. The modeling system proved its capabilities as a decision support system and it is being applied at present to the national road network of Romania to extend atmospheric transportation planning and emission estimation for the whole country.

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