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METHOD FOR INVENTORYING CO EMISSIONS FROM ROAD TRAFFIC IN URBAN AREAS THROUGH TRANSPORT MODELING

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Abstract

Carbon monoxide (CO) is a gas obtained both from natural sources (bush fires, volcanic emissions and electric discharges) and by anthropogenic processes (incomplete combustion of fossil fuels). Together with particulate matter, nitrogen oxides and hydrocarbons, it is part of the air pollutants associated with the transport sector, which have a negative impact on human health, animals and vegetation. In this paper the authors propose a methodology for assessing CO emissions from road traffic in urban areas, created by harmonization between a *traffic estimation model*, which takes into account the land use functions and the user behavior, and a *CO emissions estimation model*, which takes into consideration the average travel speed and the engine type of each motor vehicle from the traffic flow. Within the case study in which this methodology is applied we have estimated a reduction in the CO emissions produced by road traffic in the city of Pitesti, as a result of the fact that the existing road network was completed with a bypass road. It is highlighted that for the internal network of the city, in the peak traffic interval in the morning, the level of emissions in the atmosphere is 30% lower than in the case in which the transit traffic would use the urban network instead of the bypass road. The presented methodology is a very useful tool in quantifying the environmental impact produced by road traffic, specific to different situations of land use and transport networks.

Key words: air pollution, carbon monoxide, road traffic, traffic model, urban area

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1. Introduction

The change in the physical characteristics of the atmosphere by the action of chemical, physical or biological agents is called air pollution (WHO, 2013). The polluting substances with significant impact on human health are: particulate matter (PM), carbon monoxide (CO), ozone (O_3), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and hydrocarbons (HC). As in the case of noise pollution (Petrescu and Borza, 2013), when these substances reach the limit values settled by law, they become dangerous for the living organisms.

The accumulation of carbon monoxide can reach dangerous levels, especially under atmospheric calm conditions in winter and spring (being more chemically stable at low temperatures) when the burning of fossil fuels reaches the maximum level. It should also be mentioned that the concentration of CO in the atmosphere depends heavily on local and atmospheric conditions (Baldauf et al., 2009; Meng, 1998; Ştefan et al., 2013). In the urban environment in particular, high concentrations of CO are present in the atmosphere in the morning, on the one hand due to the high amount of emissions produced by road traffic at peak intervals and on the other to the conditions of atmospheric stability specific to this time of day (Azmi et al., 2010; Li and Liu, 2011). This substance enters the body through the lungs, and in the blood it creates a strong bond with hemoglobin.

Breathing air containing a large amount of CO reduces the ability of the blood to carry oxygen, this way reducing the amount of oxygen received by the

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tissues and organs of the human body. People exposed to affections caused by CO suffer from cardiovascular diseases. At extremely high levels, CO can cause death (EEA, 2012a).

The preoccupations with the assessment of the CO amount in the atmosphere and its effects on human health have appeared since 1945 (Roughton and Root, 1945). Over the time they have intensified, leading to estimates of the costs generated by the effects of such pollutants on human health (VTPI, 2013). According to the data published by the *European Environment Agency (EEA)* in the report called "The contribution of transport to air quality" (EEA, 2012b), at the level of the 32-EEA member states, road transport is one of the major sources of CO production, with a share of 27%, the other transport modes contributing only 3% of the total amount of CO discharged into the atmosphere. Although at the average level in the EEA-32, between 1990 and 2010, this pollutant recorded a dramatic reduction of 76%, Romania recorded a decrease of only 20%, a fact that recommends the development of policies and the adoption of measures meant to reduce the amount of CO that reaches into the atmosphere. In Romania the road network is made up of local, county and national roads. Local and county roads are intended for local traffic while national roads are used for long - distance travels. Statistics published by the Ministry of Transport and Infrastructure of Romania show that about 36% of the total length of national roads is situated in inhabited areas, sometimes passing through the center of the localities in the absence of bypass roads. Thus, the population is exposed not only to the emissions produced by the local traffic, but also to those generated by the transit traffic.

Taking into account that good information about emissions can be used to develop necessary emission inventories and transport plans, in this paper the authors propose a methodology for estimating the CO emissions from road traffic in the urban area, based on a transport model.

2. Methodology proposal for estimating CO emissions from road traffic

In this paper the authors propose a methodology for assessing the CO emissions from road traffic in urban areas, created by harmonizing a *traffic estimation model*, which takes into account the land use functions and the user behavior, with a *CO emissions estimation model*, which takes into consideration the average travel speed and the engine type of each motor vehicle from the traffic flow (Mitran, 2012). The harmonization of the parts of the two models is shown in Fig. 1.

The traffic estimation model that we used is the one known in literature as the "four-step model" – *trip generation, trip distribution, mode choice* and *trip assignment* (Ortuzar and Willumsen, 2011). Each stage is based on mathematical models whose results offer information regarding the number of travels, their origin and destination, the mode of transport and the chosen route.

The estimate of the total number of travels generated by each traffic area is obtained by applying mathematical models relying on socio-economic and demographic data specific to the area under analysis.

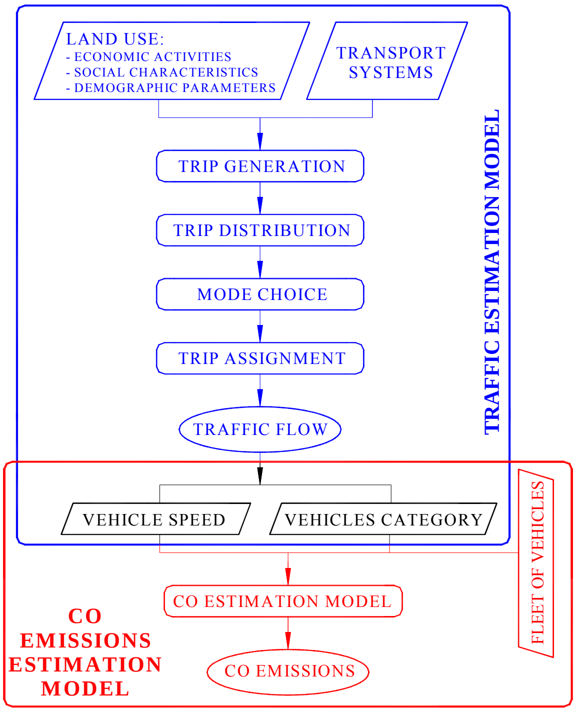

Fig. 1. Methodology diagram for the inventory of CO emissions from road traffic

The mathematical model that integrates such data in order to estimate the number of generated travels is the model of multiple linear regression. By means of this model we emphasize the relation between the dependent variable – the number of travels, and a series of independent variables. The equation of multiple linear regression may be expressed through the relation (1):

$$Y = a + \sum_i b_i \cdot X_i \quad (1)$$

where: Y is the dependent variable;

X_i are independent variables;

a is the free term;

b_i are the regression coefficients of the model.

The X_i attributes are the socio-economic variables (the intensity of economic and social activities in the territory under analysis), but they can also be attributes of the transport offer, such as the variables that measure the accessibility of the area or of the transport service, namely the value attached to the utility corresponding to the level of "successive" choices made by the person who travels. The number of travels generated by and attracted into each traffic area offers an idea about the level of travels in an area of study, but this aspect is insufficient for modeling and taking decisions regarding the transport activity.

Clarifications concerning the areas of origin and destination of travels are obtained at the second stage of the estimation process for the transport demand, that is the *trip distribution*. The best known model used for this stage is the gravitational model, formalized by analogy with *Newton's Law of Universal Gravitation*. By means of this model, we can estimate the travels for each pair of areas Origin - Destination (a cell from the matrix O-D), without using data resulting from measurements. Consequently, these models are also known as synthetic models. Generally, the gravitational model may be written as Eq. (2):

$$t_{ij} = g_i \cdot a_j \cdot f(d_{ij}) \quad (2)$$

where:

$g_i = \sum_j t_{ij}$ represents the "generation" of the demand in the i area;

$a_j = \sum_i t_{ij}$ represents the "attraction" of the demand in the j area;

$f(d_{ij})$ is the function of the difficulties encountered when travelling between i and j areas: distance, travel time or travel cost.

The simplest models of *modal choice* are those applied to choose between two modes of transport, most of the times between private and public transport. The complexity of the models increases with the number of modes of transport available for the person who travels. The *Multinomial Logit Model* is used to find out the probability for a person to choose a mode of transport *i* from the set *C,* based on the relation (3):

$$P_C(i) = \frac{e^{\mu \cdot V_i}}{\sum_{k \in C} e^{\mu \cdot V_k}} \quad (3)$$

in which: μ is a parameter of the model, $\mu \in R$;

V_1, V_2, ..., V_k are the utilities of the possible alternatives.

The last stage within this "four-step" transport demand forecasting model, aims at finding a balance between transport demands and offers. Over time various mathematical models have been studied with a view to determine the most appropriate transport demand assignment model. Within the transportation models for the urban environment, it was established that the assignment of demand is such as to ensure a balance for the user.

The results of the traffic model are represented by traffic flows which are estimated for each element of transport infrastructure (a segment of the considered road network), according to their characteristics (number of vehicles per category, average speed and total length of routes). These characteristics of the traffic flows constitute the input data for the CO emission calculation model. To assess the CO emissions, the variation functions were used in relation to the average travel speed specific to each category of vehicles, specified in the *"EMEP/EEA air pollutant emission inventory guidebook - Technical guidance to prepare national emission inventories"*, available for all the EU-27 member states (EEA, 2009; Ntziachristos and Samaras, 2012).

The guidebook specifies the variation functions of polluting factors such as CO, HC, NO_x, PM and of fuel consumption dependent on travel speed, taking into account the exhaust emissions from road transport for each class of vehicles (passenger cars; light-duty vehicles – with a mass of less than 3.5 tones; heavy-duty vehicles – with a mass of more than 3.5 tones and buses), emissions standards (conventional/ECE; Euro 1 to Euro 5), engine capacity and fuel (gasoline; diesel; LPG).

Considering the probability that a vehicle from one of the above-mentioned categories appears in the traffic flow composition as being directly proportional to the share that certain category holds of the total motor vehicle fleet in the research area, the variation function of CO emissions in relation to the average speed of travel for each class of vehicles is GIVEN BY Eq. (4):

$$E^a_{CO} = \sum_{i=1}^{m} P(i) \cdot e^i_{CO}(v) \left[\frac{g}{km}\right] \quad (4)$$

in which:

i is the type of motor vehicle;

m is the total number of motor vehicle types from the "a" category;

v is the average travel speed specific to the "a" category;

e^i_{CO} is the variation function of CO in relation to the average speed of travel for the established "i" type of motor vehicles from "a" category;

$P(i)$ is the share of the "i" type in the total motor vehicle fleet from the "a" category.

In the proposed methodology both the effect of the transient thermal engine operation regime (termed "cold-start") and the influence of the ambient temperature on the amount of emissions generated were neglected.

The tool for computing and representing the results obtained by harmonizing the two models was *Visum* software (PTV AG, 2010), dedicated to demand modeling and planning in transports. The modules of this software allowed us to develop a calculation programme, which takes data from the transport model (the average travel speed for each class of motor vehicles, the number of vehicles from each class that are part of the traffic flow composition) and calculates the amount of CO produced by the flow of motor vehicles at each point in the transport network according to the motor vehicle category from each class.

The developed methodology offers the advantage of detailing the analysis regarding the CO emissions generated by road traffic at the level of research area, both from the perspective of the travel behavior of the transport system users (the spatial and time distribution of the traffic flows, the average speed of travel), and from the perspective of the technical characteristics of the motor vehicles that preponderantly use the transport system (vehicle class, emissions standards, engine capacity and fuel). The utility of this approach is ensured by its capacity to point out the impact of different solutions of traffic management, urban management, and land use planning in an attempt to reduce CO emissions produced by the mobile source – the road traffic at the level of the whole transport network under research.

By applying the methodology we can determine the sensitivity of the amount of CO emissions in relation to the independent variables taken into consideration: socio-economic and demographic data, characteristics of the transport network (average speed, traffic capacity, number of lanes), travel behavior, technical characteristics of the motor vehicle fleet etc.

3. Case study

In order to demonstrate the utility of this methodology for estimating the CO emissions associated to road traffic, we developed a case study in which we evidenced the reduction of the CO emissions in Pitesti municipality, a medium-sized city in Romania located on the Pan European Corridor IV - North branch (Fig. 2) (MTI, 2009). The emissions were recorded from the moment the bypass road of the city was completed and available for use. The bypass road of Pitesti Municipality has been operational since 2007, taking over the transit traffic.

Fig. 2. The Pan - European corridor no. IV along the Romanian territory, crossing Pitesti city

According to the document *"TEM and TER Revised Master Plan, Final Report, Volume II Annexes"*, prepared by the *Economic Commission for Europe* (ECE, 2011), significant traffic values at the level of the *Annual Average Daily Traffic* (AADT) (Table 1) were registered and predicted on the Corridor No. IV, between the nodes Pitesti North and Pitesti South. If the bypass had not been built, these traffic values would have been added to the local traffic, which uses the road network.

Table 1. Transit traffic volumes on Pitesti road network

Road network section	***Year***	***Traffic volume, AADT [vehicles]***	***Road network***	***Observation -traffic volume***
Pitesti North – Pitesti South	2005	10 300	Urban network	observed
	2010	13 400	bypass	observed
	2015	16 500	bypass	forecasted
	2020	18 100	bypass	forecasted

In this case study we applied the methodology presented at point 2. Starting from the socio-economic and demographic data we built a transport model for the influence area of Pitesti municipality, which was calibrated and validated for the peak traffic interval in the morning. Based on traffic measurements, this interval at the level of AADT for the year 2012 is between 8 a.m. and 9 a.m. The transport network was calibrated and validated based on travel time measurements performed in practice. The regulated maximum speed in the streets from the urban environment is 50 km/h and on the bypass it is 130 km/h (as it has a transverse profile similar to that of a motorway).

In Fig. 3 we presented the graph of the transport network under research, in which we pointed out the actual travel speed at peak hour in the morning. The average travel speed in the urban network resulted after modeling, without the bypass, is 36 km/h. It can be observed that within the urban area there are a few streets with a travel speed less than 30 km/h.

According to Fig. 4, in which we represented the functions of land use, the arcs of the network with a low travel speed are located in the central area (due to its administrative functions – which represent attraction poles inducing traffic) and in the residential neighborhoods (especially where there are collective dwellings, a fact that implies a high population density). If we study the functions of land use, we can observe that the bypass is adjacent to some traffic areas in which the activities performed are mostly related to services, industry, agriculture and there are very few inhabited areas (where there are individual dwellings, and therefore we have a low population density). Consequently, the number of persons exposed to the emissions generated by the motor vehicles that use the bypass is very small, compared with the number of persons exposed to the emissions produced when these vehicles use the urban road network.

In 2011, the annual mean concentrations of CO in Romania, extracted from the European database, relied on maximum eight-hour averages daily with at least 75% valid measurements, in mg/m^3, are indicated in Fig. 5. We can remark that Pitesti is one of the cities that received a warning (in orange colour) for these high values, a fact that underlined the necessity of taking steps to reduce this polluting factor.

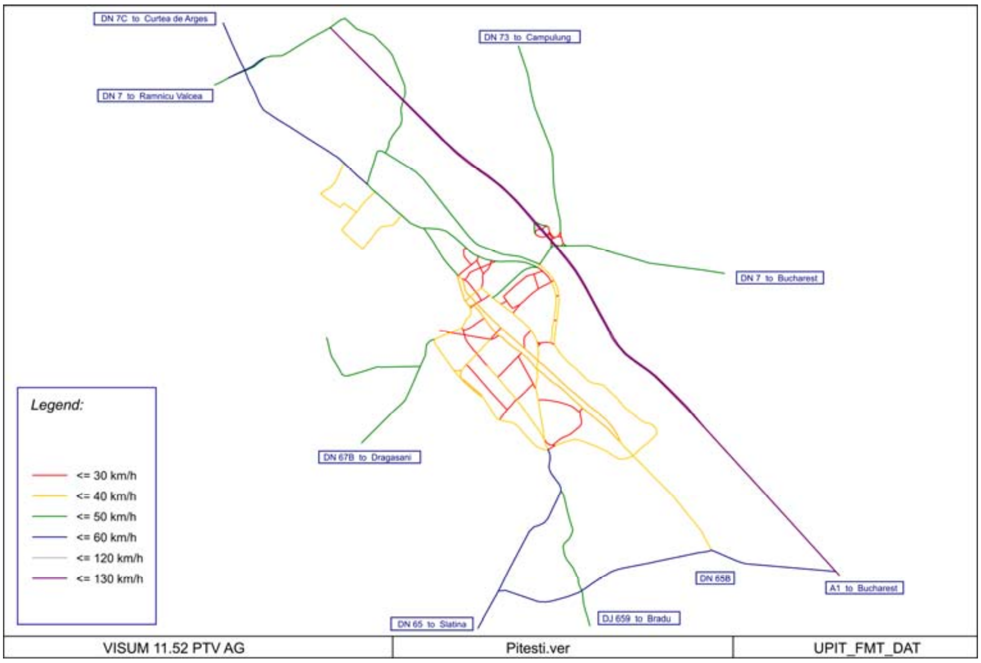

Fig. 3. Network graph – average travel speeds on the segments of the network

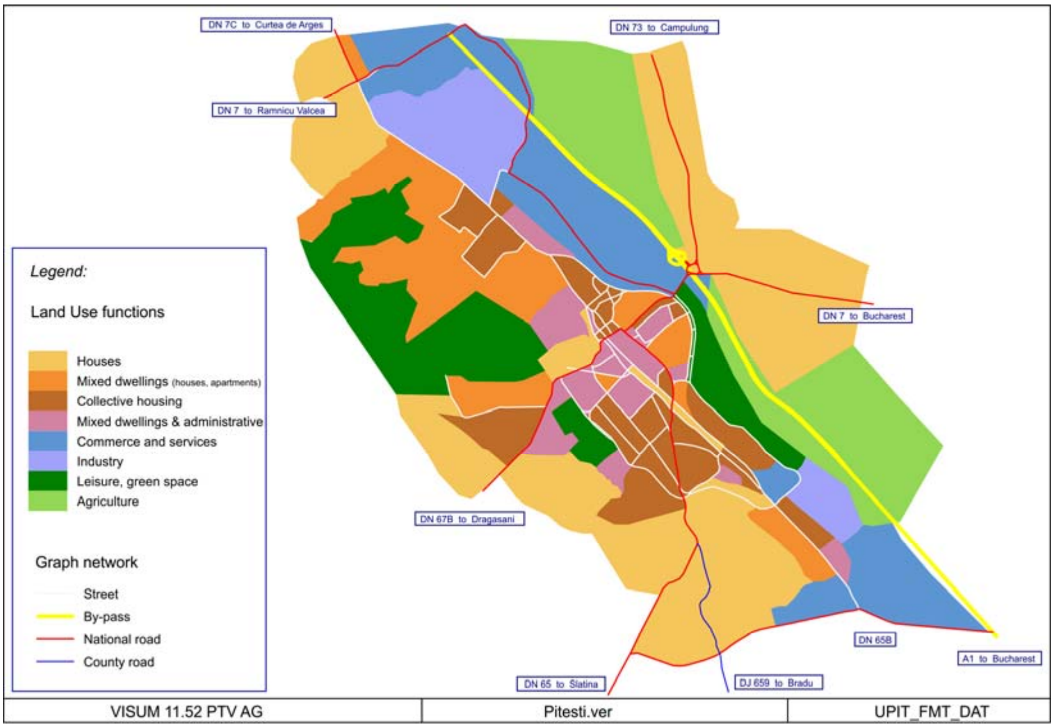

Fig. 4. Functions of land use specific to the traffic zones within the transport model

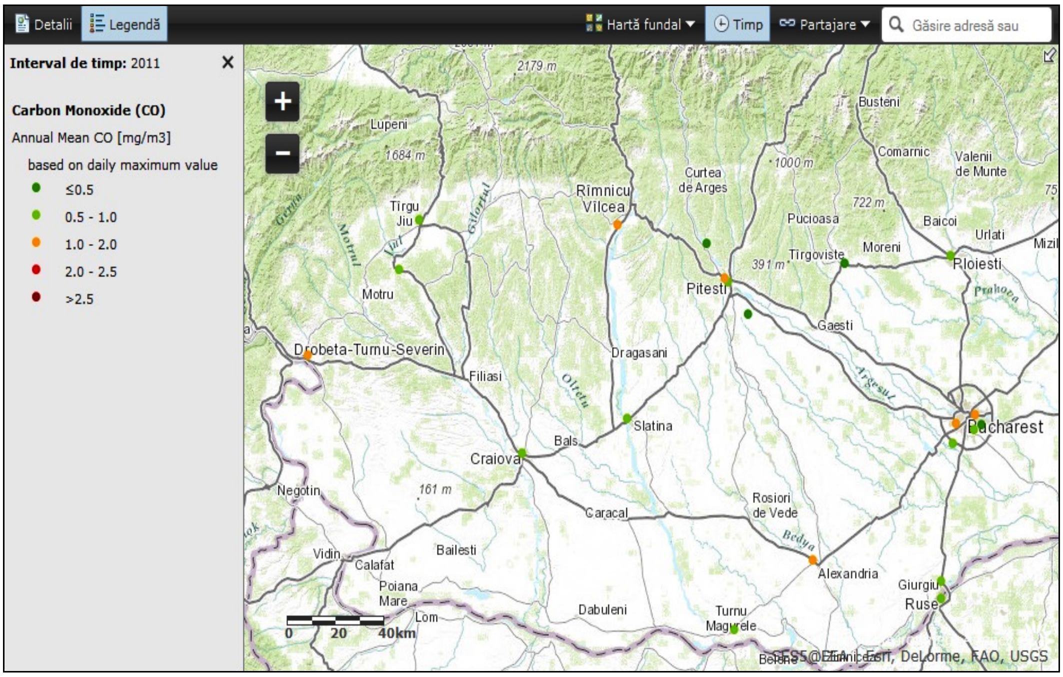

Fig. 5. The annual mean concentration of CO in the Pitesti area (EEA, 2013)

In this case study we determined the variation curves dependent on the travel speed for the CO emissions generated by the vehicles registered in the city, for each category for which there are variation curves of CO emissions dependent on the travel speed validated by the *European Environment Agency* for the EU-27 member states: passenger cars, light duty vehicles, heavy duty vehicles and buses. These data were published in the report included in (EEA, 2009).

4. Results and discussions

By applying the methodology for the estimation of CO emissions described in the second chapter to the case study for Pitesti city, in the first stage we estimated the traffic flows for the peak traffic interval in the morning, from 8:00 to 9:00 a.m., calibrated and validated according to the traffic surveys at the level of year 2012. The results (traffic flows – number of vehicles) are presented in Fig. 6 –

for *passenger cars*, and in Fig. 7 – for *light duty vehicles, heavy duty vehicles* and *buses.*

In the second stage of the presented methodology based on (Eq. 4) we determined the variation curves of CO emissions dependent on the average speed for each category of vehicles specific to the vehicle fleet inventory of Pitesti city (Fig. 8). Thus, we could particularize the model for the area under research. For all the categories of motor vehicles, the global variation functions are sextic polynomial functions.

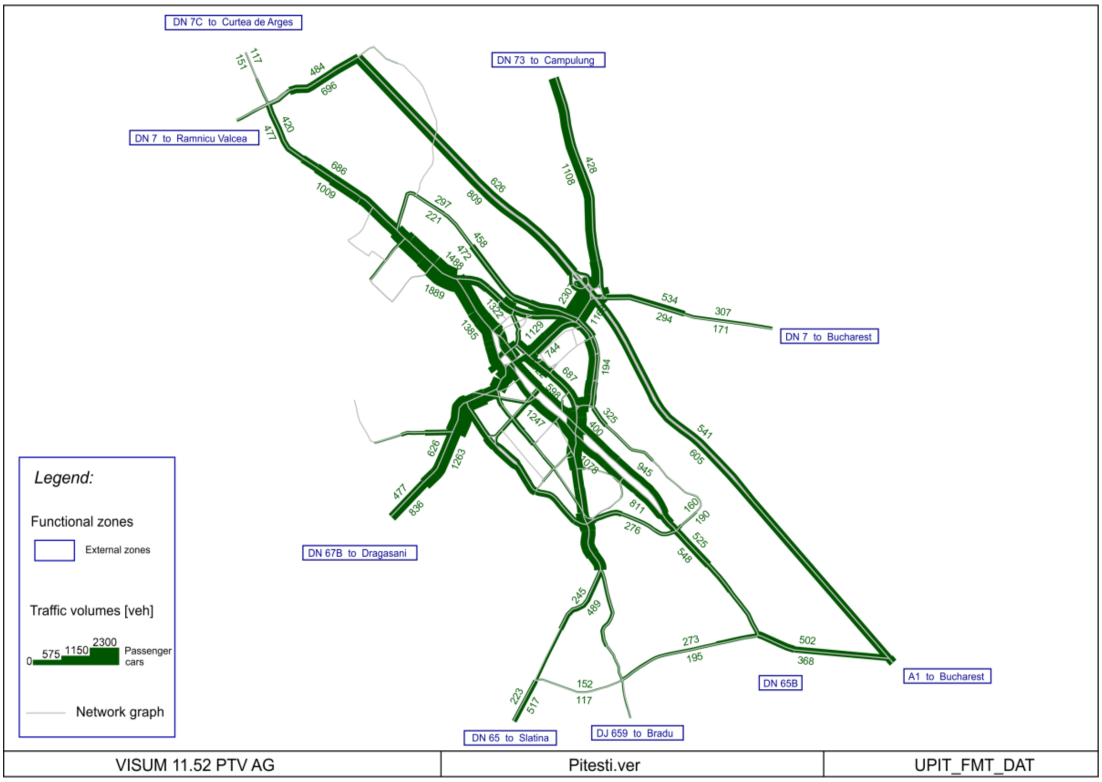

Fig. 6. Traffic flows – passenger cars

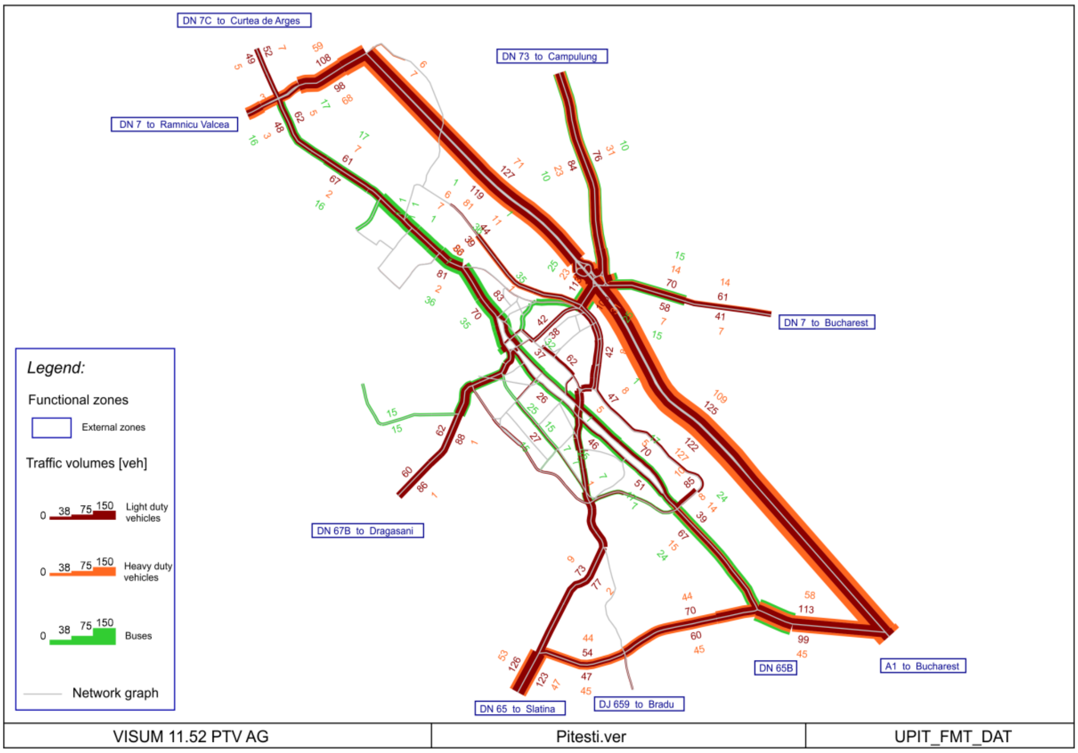

Fig. 7. Traffic flows – light duty vehicles, heavy duty vehicles, buses

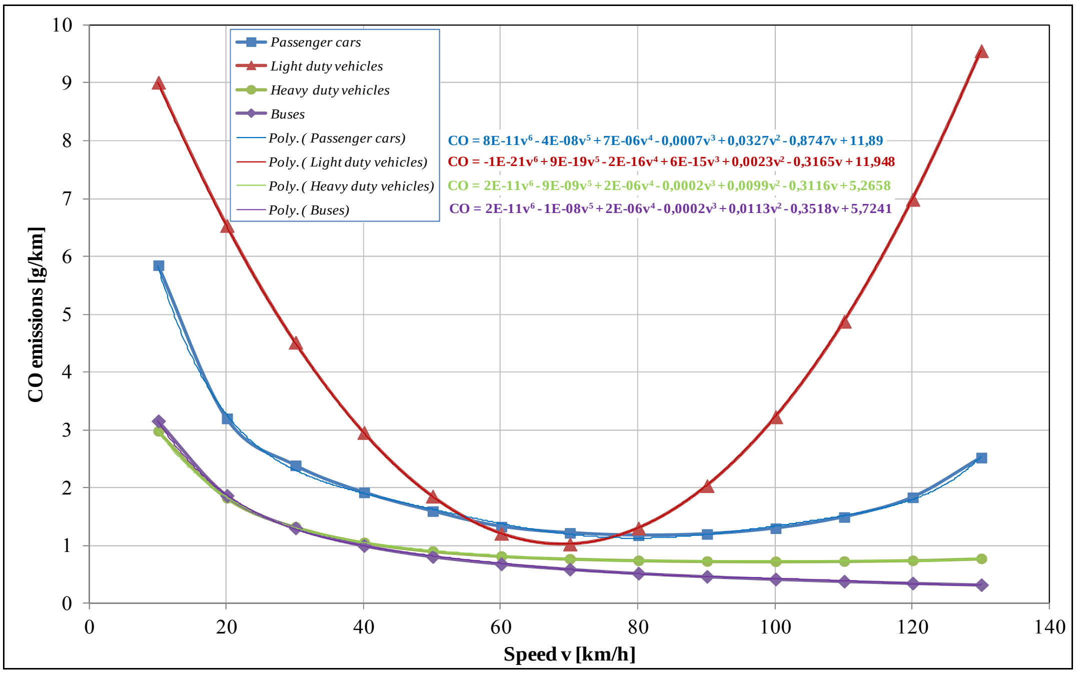

Fig. 8. CO variation functions in the Pitesti area for passenger cars, light duty vehicles, heavy duty vehicles and buses

The interpretation of the graphic representation offers us the following information:

- *Passenger cars:* the minimum level of emissions is obtained at a travel speed of 80 km/h; at higher speeds, the amounts increase slightly;
- *Light duty vehicles (LDV):* the minimum level of emissions is obtained at an average travel speed of 70 km/h; any deviation from this value leads to a rapid increase of CO emissions;
- *Heavy duty vehicles (HDV):* the minimum level of emissions is obtained at an average travel speed of 100 km/h, with a gentle slope both in the descending and in the ascending areas;
- *Buses:* the amount of emissions decreases as the travel speed increases; the minimum value is reached at a travel speed of 130 km/h.

If we compare the data within the analysis of the transport network conducted in the case study, in which the average travel speed in the urban environment varies between 20 and 50 km/h, we can conclude that the displacement of the traffic flows of heavy duty vehicles on to the bypass leads to a substantial reduction in the emissions produced by this class of vehicles. With regard to the passenger cars and the light duty vehicles, the main advantage results from the removal of emissions to the outskirts of the inhabited area and the reduction of their contribution in the urban environment. Simultaneously, is obtained reduction of contribution of the two categories of vehicles in urban environment that still use the internal network, through the increase of average travel speeds as a result of congestion reduction. The bus routes are not altered after the construction of the bypass, because the buses serve the local public transport, but the reduction of traffic congestion at the level of the internal network leads to an increase in the instantaneous speed and to a decrease in the emissions generated by buses.

Within the proposed methodology created by harmonization of the two modeling stages presented above, using the average speed of the vehicles from each category at the levels of the transport network sectors as input data in the function for CO estimation, we obtained the amount of pollutant emitted into the atmosphere at any point of the transport network, distributed according to the four main categories of vehicles: *passengers cars, light duty vehicles, heavy duty vehicles* and *buses.* By summing up the obtained values, we identified the total amount of CO generated by road transport and involved in the dispersion process at the atmospheric level in the influence area of Pitesti city road network. The results obtained in the case in which the bypass road is functional or closed are shown in Figs. 9 and 10.

The transport network considered for the case study was formalized through a graph with 297 links. To exemplify the relation between the characteristic values of the network, of the transport demand and of the CO emissions, we selected ten major links illustrated in the following Fig. 11 and Table 2, for which we compared the values specific to the two cases: *with* or *without* the bypass road. The differences between the amounts of CO emitted when the bypass is in operation and when there is no a transit traffic road, estimated for peak traffic hour between 8:00 and 9:00 a.m., are shown in Fig. 12.

The reduction in CO emissions is marked in green colour and the increase in red colour. In the graphical representation the actual amounts of CO which decrease, respectively appear (indicated along the network), are directly proportional with the width of the lanes represented along the roads.

We can notice a significant decrease in the CO emissions at the level of the internal network and an increase on the bypass, with only one exception – the link between the center of the city and the bypass, where, as a result of the increase in traffic flows (drawn in by the bypass), we recorded increases in the level of CO emissions.

A significant reduction of CO emissions with the construction of the bypass road occurs, especially in the northwest of the city, which is the area with the highest residential density. These differences appear due to the re-routing of traffic flows, but are also caused by the increase in speed in the network as a result of the reduction in traffic congestion.

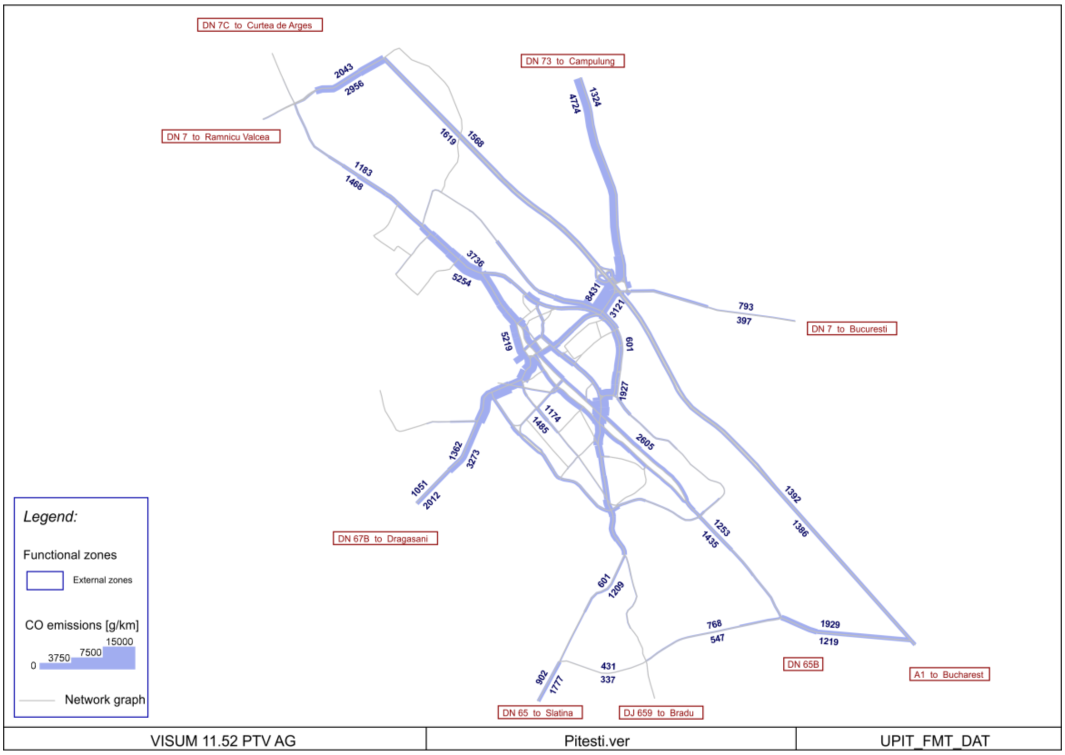

Fig. 9. Total CO emissions – Pitesti road network *with* bypass road

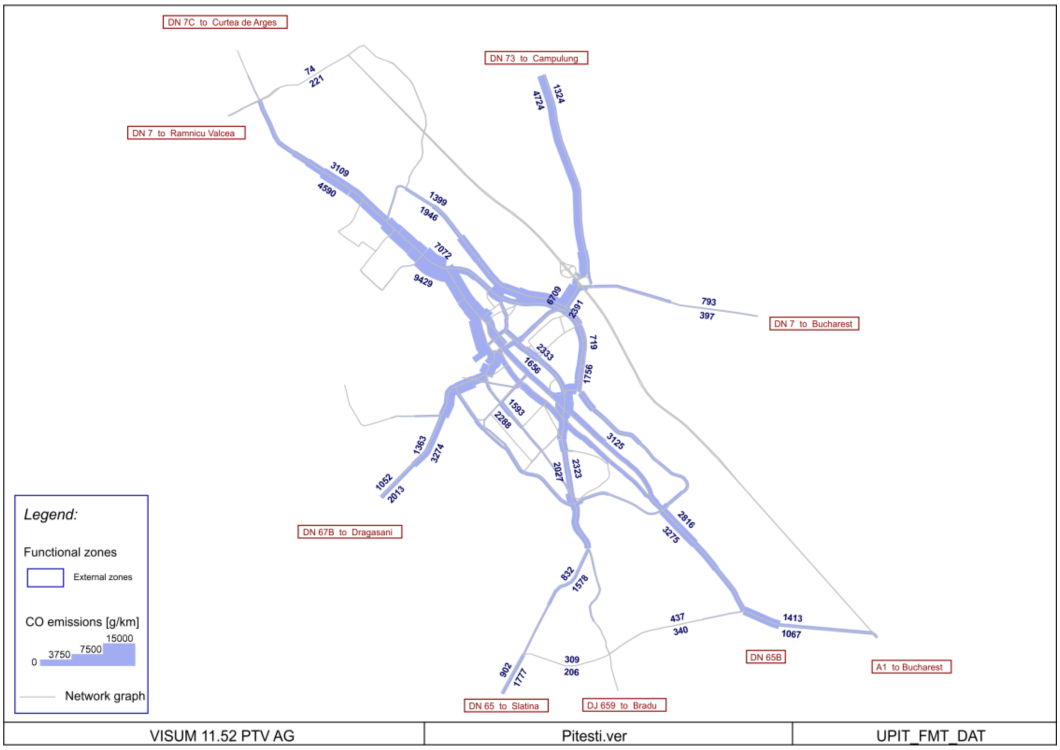

Fig. 10. Total CO emissions – Pitesti road network *without* bypass road

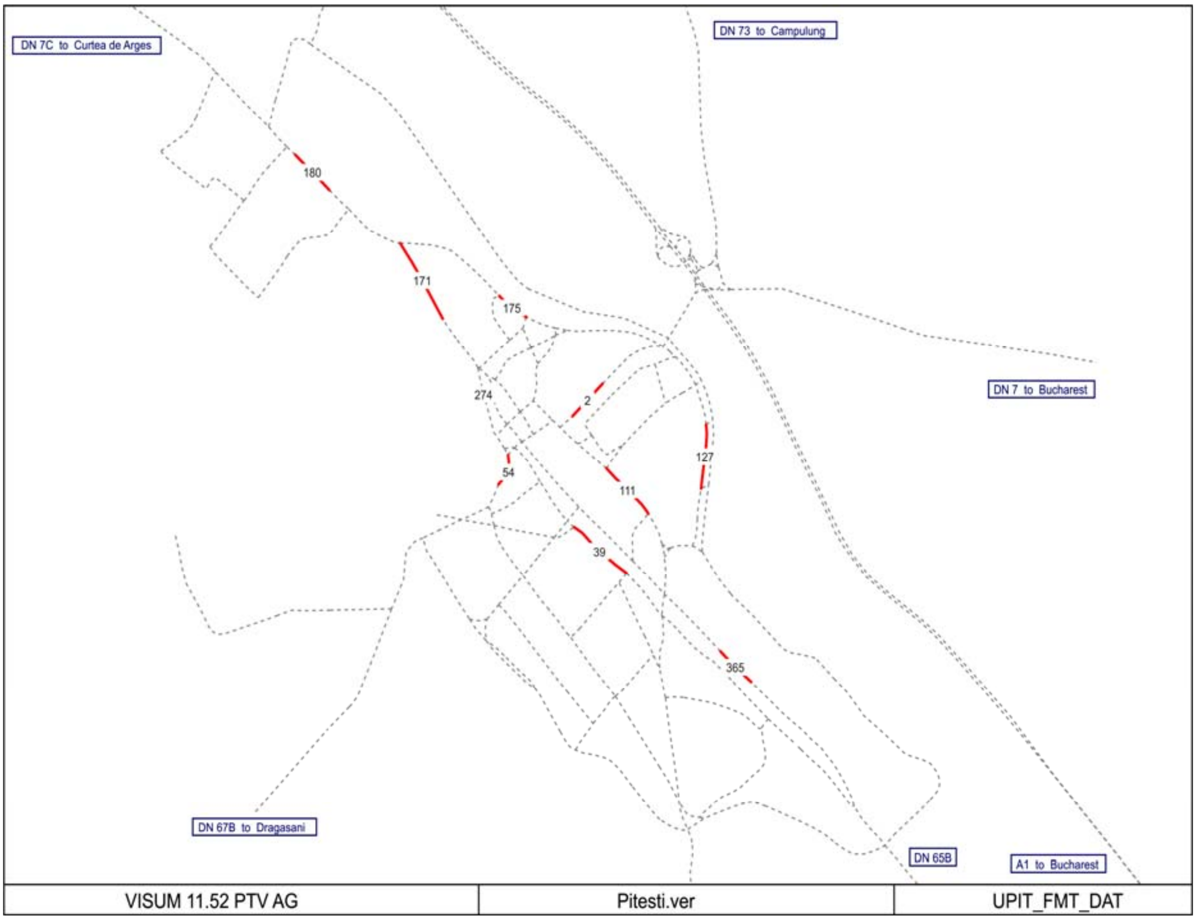

Fig. 11. Selected links with corresponding traffic volumes and emissions

Table 2. The characteristics of selected links and the differences in CO emissions

Link no.	*Case**	*Length [km]*	*Speed [km/h]*	*Cars [veh.]*	*LDV [veh.]*	*HDV [veh.]*	*CO [g/km]*	*Difference between "1" and "2" [%]*
2	"1"	0.282	38	1593	51	0	3316	27%
	"2"	0.282	36	1873	80	0	4213	
39	"1"	0.45	21	1478	44	0	4817	-25%
	"2"	0.45	24	455290	9628	0	3632	
54	"1"	0.208	18	2631	162	4	10016	-13%
	"2"	0.208	20	2475	137	1	8763	
111	"1"	0.393	29	1479	97	0	3989	-18%
	"2"	0.393	31	1285	71	0	3269	
127	"1"	0.389	31	1491	172	76	4358	-8%
	"2"	0.389	33	1591	120	0	4001	
171	"1"	0.54	23	3410	296	4	11573	-42%
	"2"	0.54	31	2608	153	1	6719	
175	"1"	0.224	18	2100	83	12	7910	-32%
	"2"	0.224	23	1799	30	10	5370	
180	"1"	0.313	25	3632	333	10	11783	-43%
	"2"	0.313	34	2813	139	9	6739	
274	"1"	0.08	16	1901	137	2	8452	-40%
	"2"	0.08	21	1509	73	0	5112	
365	"1"	0.277	26	1259	114	0	3918	-34%
	"2"	0.277	31	990	71	0	2605	

** "1" - with bypass; "2" - without bypass.*

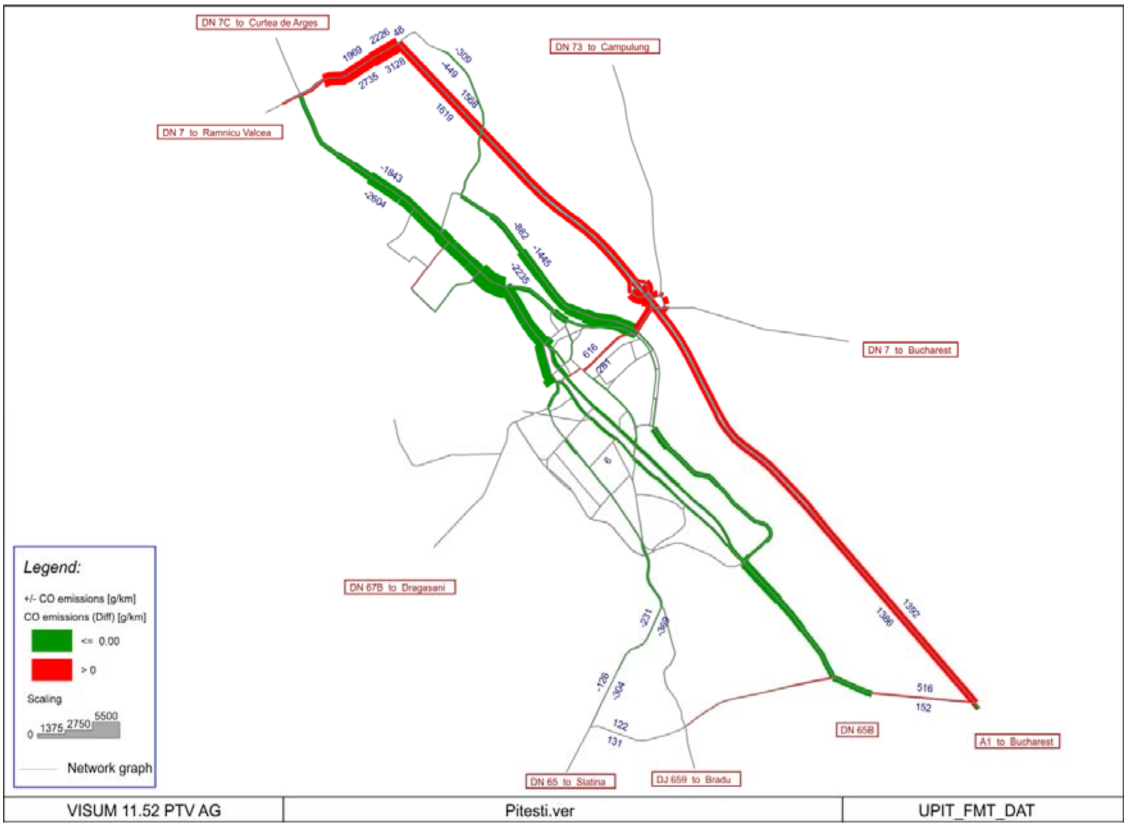

Fig. 12. The differences in the amounts of CO: situations *with* and *without* the bypass road

5. Conclusions

The aim of this paper was the presentation of a methodology which allows us to emphasize the interdependence between road traffic and air pollution by inventorying carbon monoxide emissions produced by the road vehicles that make up the traffic flows in urban areas. The exclusivity of the results obtained by applying this methodology is given by the fact that both the model for estimating traffic flows and also the one for estimating the emissions allow the absolute particularization of the considered area of influence.

The case study in this paper shows the spatial distribution of CO emissions in the area under research as a consequence of road network restructuring. We underlined the advantages of introducing a bypass road with a view to reduce CO emissions in the areas with high residential density and in the central areas of the cities, contributing in this way to the improvement of air quality in the urban environment. Thus, the paper highlights the importance of assessing the environmental impact of road transport in the planning of transport networks.

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