ASSESSING THE EFFECT OF TRAFFIC CONGESTION ON GREENHOUSE GAS EMISSIONS

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Polytechnic University of Bucharest
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Florin Valentin Rusca
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INTERNATIONAL CONFERENCE ON TRAFFIC AND TRANSPORT ENGINEERING

ictte

ISBN 978-86-916153-1-4

Belgrade 2014

- ICTTE Belgrade 2014 -
Proceedings of the Second International Conference on Traffic and Transport Engineering

ICTTE Belgrade 2014 has been jointly organized by the City Net Scientific Research Center Ltd. Belgrade, University of Belgrade, Faculty of Transport and Traffic Engineering and "Kirilo Savić" Institute. ICTTE Belgrade 2014 is co-hosted by the AIIT (Associazione Italiana per l'Ingegneria del Traffico e dei Trasporti) Research Center, Rome, Italy. The conference is supported by the EA SEA WAY project (Adriatic IPA, Cross Border Cooperation 2007-2013), and is held in Belgrade, Serbia, from 27th to 28th November 2014.

The conference covers a wide range of topics related to traffic and transport engineering, with the aim of representing the importance of all modes of traffic and transport, especially the importance of improving these industries, and their compliance to one of the most significant principles nowadays, sustainable development. ICTTE Belgrade 2014 gathers researchers, scientists and engineers whose fields of interest are traffic and transport engineering, and should provide them a good platform for discussion, interactions and exchange of information and ideas. ICTTE Proceedings have been indexed within Thomson Reuters's CPCI – Conference Proceedings Citation Index accessed via Web of Science.

For publisher:	Prof. Dr Srećko Žeželj
Editor in Chief:	Assist. Prof. Dr Olja Čokorilo
Publisher:	City Net Scientific Research Center Ltd. Belgrade Uzun Mirkova 10/I 11000 Belgrade, Serbia Phone: (+381 11) 26 23 895 Cell: (+381 63) 28 12 55 Fax: (+381 11) 32 82 076 e-mail: office@city-net.rs / office@ijtte.com www.citynetsrc.com / www.ijtte.com

ISBN 978-86-916153-1-4

CIP - Каталогизација у публикацији - Народна библиотека Србије, Београд

656.07(082)(0.034.2)
711.73(082)(0.034.2)

INTERNATIONAL Conference on Traffic and Transport Engineering (2nd; 2014; Beograd)
[Proceedings of the Second] International Conference on Traffic and Transport Engineering ICTTE, [November 27-28], 2014, Belgrade [Elektronski izvor] / [organized by the City Net Scientific Research Center, Belgrade ... [et al.] ; editor in chief Olja Čokorilo]. - Belgrade : City Net Scientific Research Center, 2014 (Belgrade : City Net Scientific Research Center). - 1 elektronski optički disk (CD-ROM) ; 12 cm

Sistemski zahtevi: Nisu navedeni. - Nasl. sa naslovnog ekrana. - Tiraž 200. - Napomene uz tekst. - Bibliografija uz svaki rad.

ISBN 978-86-916153-1-4
1. Čokorilo, Olja [главни уредник], 1977- 2. City Net Scientific Research Center (Beograd)
a) Саобраћај - Зборници b) Транспортни системи - Зборници c) Роба - Превоз - Зборници
COBISS.SR-ID 211435020

Transport Logistics

Sustainable Transport

ASSESSING THE EFFECT OF TRAFFIC CONGESTION ON GREENHOUSE GAS EMISSIONS

Eugen Roșca[1], Dorinela Costescu[2], Florin Ruscă[3], Ștefan Burciu [4]
[1,2,3,4]University Politehnica of Bucharest, Faculty of Transports, 313 Splaiul Independenței, 060042 Bucharest, Romania

Abstract: Transport activities are among the greatest contributor to greenhouse gas (GHG) emissions and despite other economic sectors the trend is still positive. Using the latest European Environment Agency guidelines in estimating vehicles emissions, the paper presents a methodology for assessing GHG emissions integrating exhaust emission factors, geographic information system (GIS) data, traffic composition surveys, and road traffic simulation. According to EU recommendation for reporting national gas inventories, the estimation of GHG emission factors based on the average speed is adopted. The computer simulation of road traffic allows tracing individual car driving cycles and computing emissions based on average speed, mileage, fuel, and engine emission standards. The main advantage when using the computer traffic simulation is to reduce the amount of measurements which have to be performed in the field. Also the computer models have the ability to evaluate the effects of different traffic patterns (free flow, car following flow and traffic jam) and the future traffic scenarios. The carbon dioxide, methane, and nitrous oxide emissions are equated by their global warming potential. The case-study done in Carpathians outlines the way the superposition of the specific land use policy, transport network characteristics and road traffic patterns generated by the variability of human activities (the leisure-time and business tourism) can cause road congestion that increases vehicles emissions. The study presents aggregated emissions evolution by time periods and comparative values to European average levels and targets.

Keywords: traffic congestion, greenhouse gas emission, traffic simulation

1. Introduction

The most important source of greenhouse gases (GHG) emissions in the EU-28 was fuel combustion of energy industries, transport, manufacturing and construction industrial activities. Transport sector was the only source that presented an increase between 1990 and 2011 (19%), having a share of 20.2% from total emissions (EC, 2013). The GHG emissions of Romania are still below the target established in the Kyoto Protocol (-50%), allowing the trade of the emission rights on the European Trading Scheme. Despite the general favorable situation, the GHG emissions in the Romanian transport sector have been growing from an amount of 5.97 Mt in 1989 to 11.15 Mt in 2010, showing a high growing dynamic due to a constant increasing of the motorization rate and the dominant position of the road transport mode versus rail and inland water transport. Policy makers should take into consideration new ways to promote an efficient transport system that provides accessibility, satisfies the economic and social needs, and minimizes the negative external effects on the environment.

2. Assessment methodology for the road traffic GHG emissions

Across Europe, the most pertinent emission estimation tools that have been used are CORINAIR (Eggleston et al., 1992), DRIVE (Jost et al., 1992), COST 319 (Joumard, 2009) and HBEFA (Hausberg et al., 2009). The European Commission, through the European Environment Agency (EEA) issued the Emission Inventory Guidebook (EEA, 2013) that covers a high range of exhaust emissions (GHG, acidifying substances, ozone-precursors, particulate matters, heavy metals, toxic and carcinogenic substances). Also, the EEA methodology consists in the thoroughly classification of the emission factors according to a large variety of vehicles technical characteristics. The EEA guidelines have been also incorporated into the software tool COPERT 4 (Ntziachristos et al., 2009), which allows the compilation of the national emissions inventories on a yearly basis. Still, COPERT 4 uses traffic patterns and average traffic flows characteristics, which are not suitable for thorough details on local areas.
The following methodology for evaluating GHG emissions combines field recorded traffic data, computer traffic simulation using VISSIM software and emission factors estimated through Tier 3 approach of the EEA guidelines. The flow chart for the GHG emissions assessment is depicted in Fig. 1.

[4]Corresponding author: florin_rusca@yahoo.com

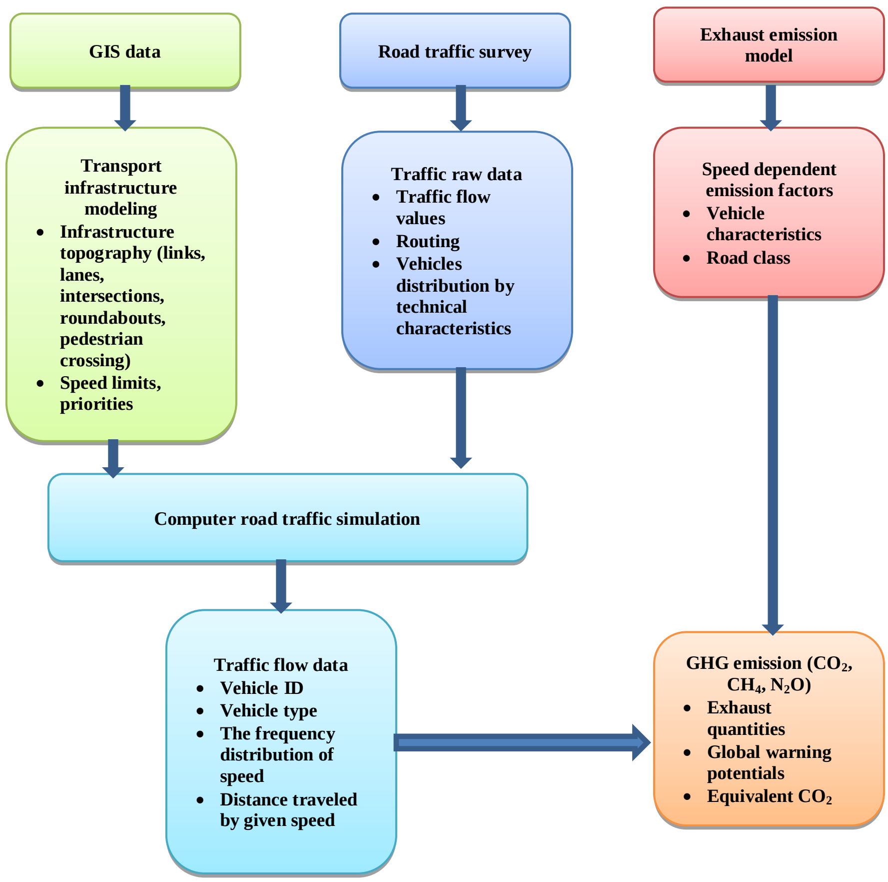


Fig. 1.
GHG emission evaluation flow chart

2.1. Transport infrastructure modeling

The Geographic Information System (GIS) base software provides scalable geographic maps and detailed transport network data used further into traffic simulation programs. Using real world coordinates, the transport network topology is described in terms of links, lanes, connections, roundabouts, public transport terminals/stations, speed limit areas, priority rules, signaling systems.

2.2. Traffic raw-data

This module considers survey data obtained in the field. The car traffic flow is recorded separately for each individual vehicle type (passenger car, LDH, HDV, bus/coach). Traffic flow variation has to be considered. The daily peak-hours, weekends or seasonal variations influence the exhaust emissions due to changes in the car driving cycles (e.g. speed, acceleration, and number of stops). The vehicles are classified according to their fuel type (gasoline, diesel, LPG, CNG, hybrids), technology/standards (pre ECE, Euro 1-5) and engine capacity. Other traffic participants (pedestrians, cyclists) have to be included as long as they interact with the car traffic flows.

2.3. Computer traffic simulation

The traffic raw-data and the transport infrastructure model represent inputs for the traffic simulation software. The main advantage when using the computer traffic simulation is to reduce the amount of measurements, which have to be performed in the field. Also the computer models have the ability to evaluate the future traffic scenarios based on various traffic management schemes. The traffic micro simulation models are able to describe a complete driving cycle including free-flow, car following, overtaking and interactions in junctions. Boulter and McCrae (2007), Tate et.al (2005), Panis et al. (2006), Jayaratne et al. (2009) provide relevant descriptions of the nowadays traffic simulation models and how they are implemented in assessing vehicle emissions using different emission factors databases.

2.4. Traffic flow characteristics

Traffic simulation allows getting the basic outputs used in GHG emission assessment:
- the vehicle ID;
- the vehicle type;
- the frequency distribution of the mean speeds of each vehicle along the route;
- the car mileage of each vehicle at a given mean speed.

The driving cycle contains free-flow, car following, acceleration/deceleration or queue waiting periods specific for each road segment. As flow increase, the traffic density increases too, while the average speed decreases. The flow is getting a maximum at a specific speed and density, according to traffic conditions, road topology, and cars interactions. Then the flow starts decreasing with increasing density and decreasing speed (congestion pattern), going towards zero at jam density.

2.5. Emission factors

The car traffic emissions with the highest greenhouse effect are CO_2, CH_4 and N_2O. CO_2 emissions are estimated based on the fuel consumption, while CH_4 and N_2O are directly estimated, based on the specific emission factors covering different traffic situation (urban, rural, highway) and engine characteristics.

- **Carbon dioxide (CO_2) emission**

Considering an oxygenated fuel with the generic chemical formula $C_xH_yO_z$, the end of pipe mass of CO_2 emitted by vehicles with the engine technology *k*, combusting the fuel *m* is:

$$E_{CO_2,k,m} = 44.011 \times \left(\frac{FC_{k,m}}{12.011 + 1.008 r_{H:C,m} + 16 r_{O:C,m}} - \frac{E_{k,m}^{CO}}{28.011} - \frac{E_{k,m}^{VOC}}{13.85} - \frac{E_{k,m}^{EC}}{12.011} - \frac{E_{k,m}^{OC}}{13.85} \right) \quad (1)$$

where:

$E_{CO_2,k,m}$ - CO_2 exhaust emission [g/km];

$FC_{k,m}$ - the fuel consumption of the vehicles [g/km];

$EC_{k,m}^{CO}$ - carbon monoxide exhaust emission [g/km];

$EC_{k,m}^{VOC}$ - volatile organic components exhaust emission [g/km];

$EC_{k,m}^{EC}$ - elemental carbon exhaust emission [g/km];

$EC_{k,m}^{OC}$ - organic carbon exhaust emission [g/km];

$r_{H:C,m}$ - the ratio of hydrogen to carbon atoms in the fuel;

$r_{O:C,m}$ - the ratio of oxygen to carbon atoms in the fuel.

Eq. 1 takes into consideration the emission of carbon (C) atoms in the form of carbon monoxide (CO) and volatile organic components (VOC). EEA (2013) offers generic functions for estimating the fuel consumption (FC), CO and VOC emissions in relation to the vehicle type, fuel, engine capacity, engine emission standards and vehicle mean speed. These functions having quadratic, power, polynomial form or a combination of them, have been estimated through statistical analysis of the empirical data, providing for most of them coefficients of determination higher than 0.9.

- **Methane (CH_4) emission**

The CH_4 emission factors are directly estimated and not computed based on fuel consumption. The emission factors are discriminated according to vehicle type, fuel, engine technology and road category. The limits of the variation of CH_4 emission for different car/traffic characteristic are presented in Table 1.

Table 1
Limits for CH4 emission factors

Vehicle type	Fuel	CH_4 emission factor [mg/km]		
		Urban	Rural	Highway
Passenger car and light-duty vehicle	Gasoline	2 - 131	2 - 86	0 - 41
	Diesel	0 - 28	0 - 12	0 - 8
	LPG	80	35	25
Heavy-duty vehicle, bus and coach	Diesel	85 - 175	23 - 80	20 - 70
	CNG	980 - 6800		
Two-wheels vehicle	Gasoline	150 - 219		

Source: (EEA, 2013)

- **Nitrous oxide (N_2O) emission**

Based on the complementary studies done by Riemersma et al. (2003), Papathanasiou and Tzirgas (2005), EEA estimated the N_2O emission factors by vehicle type, fuel, and engine technology.

Table 2
Limits for N_2O emission factors

Vehicle type	Fuel	N_2O emission factor [mg/km]
Passenger car	Gasoline	5 - 23
	Diesel	0 - 10
	LPG	0 - 24
Light-duty vehicle	Gasoline	10 - 28
	Diesel	0 - 9
Heavy-duty vehicle	Diesel	7 - 53
Bus and coach	Diesel	1 - 40
	CNG	0
Two-wheels vehicle	Gasoline	1 - 2

Source: (EEA, 2013)

The N_2O emissions are not strongly dependent on vehicle average speed as CO_2 emissions are, but mainly on fuel and engine type. Diesel vehicles have lower N_2O emissions than catalyst equipped cars.

2.6. CO_2 equivalence

The emissions of GHG can be aggregated into CO_2 equivalent taking into consideration the relative effect to the climate change determined by the global warming potentials (GWP). Table 3 presents GWP for methane and nitrous oxide.

Table 3
Global Warming Potentials relative to CO_2

Gas	Radiation efficiency [Wm^{-2}/ppbv]	GWP (20 years time horizon)
Carbon dioxide CO_2	1.8×10^{-5}	1
Methane CH_4	3.7×10^{-4}	62
Nitrous oxide N_2O	3.1×10^{-3}	275

Source: (IPCC, 2001)

The equivalent CO_2 emissions of vehicles crossing a specific area during a given time interval should be computed as:

$$E_{eq.CO2} = \sum_{i=1}^{N} d_{i,k,m,r} \times (GWP_{CO2} \times e_{CO2,k,m,r} + GWP_{CH4} \times e_{CH4,k,m,r} + GWP_{N2O} \times e_{N2O,k,m,r}) , \quad (2)$$

where:

$E_{eq.CO2}$ is the equivalent exhaust emission of CO_2;

N - number of vehicles [veh] crossing the study area;

$d_{i,k,m,r}$ - mileage per vehicle [km] driven on road r by vehicle i of technology k and fuel m;

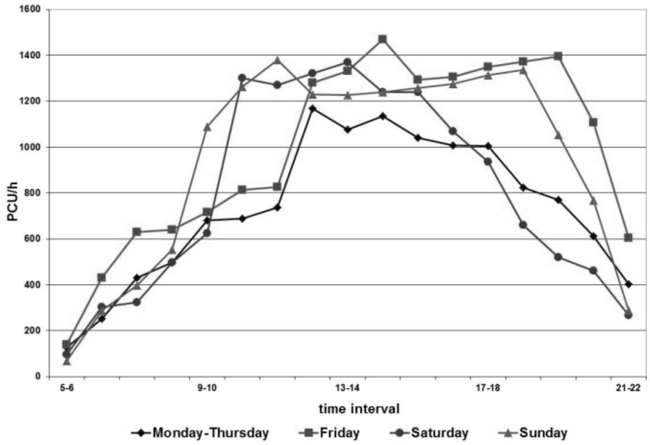
$e_{j,k,m,r}$ - emission factor [g/km] for pollutant j (CO_2, CH_4 or N_2O) by vehicle of technology k, fuel m on road type r;

GWP_j - global warming potential for pollutant j.

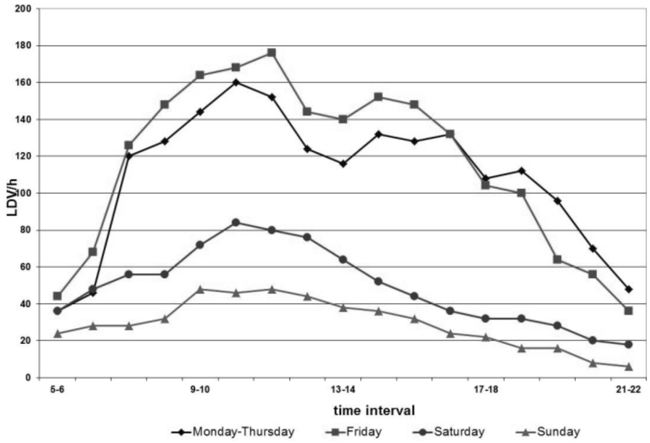
3. Case study. Assessing the GHG emissions on Prahova Valley (Carpathians)

The route E60 along Prahova Valley, situated in the Meridional Carpathians, is one of the most transited routes connecting the southern and the central part of Romania. The transit route passes alongside the Bucegi Massif that is classified as a type B site (medium influence environment) by the European Network of Protected Areas – Natura 2000. Downhill of this massif there are a couple of mountain resorts transited by the route E60, among them Buşteni standing out as the main bottleneck of the road traffic. Due to the transport infrastructure characteristics (single lane, intersections, dense pedestrian crossing) and the traffic increasing during weekends and tourist seasons, the road traffic congestion is often presented in the area, reducing the level of performance of the network and increasing the car exhaust emissions.

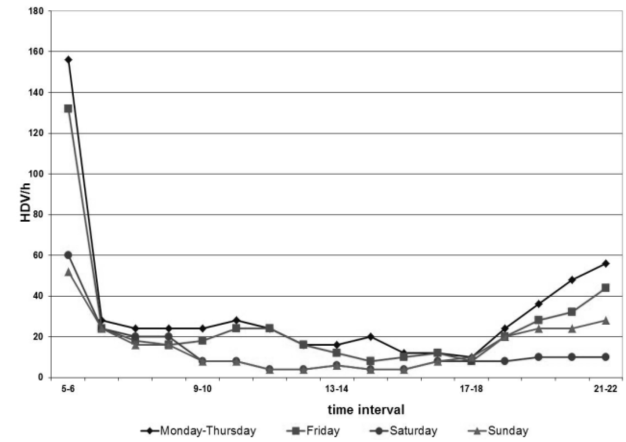
For assessing the GHG emissions, the road traffic in Buşteni mountain resort is modeled using the VISSIM traffic simulation software, implementing the Wiedemann (1974) car-following model. The transport infrastructure layout is completed by the traffic rules (vehicles speed limits, priority rules in intersections and pedestrian crossing) and by the public transport elements (stations, stop times distribution). The traffic survey was conducted during May-June, period providing high traffic intensity and non-uniformities mainly during weekends. The traffic flows are recorded separately by vehicles type: passenger car (PCU), light-duty vehicle (LDV), heavy-duty vehicle (HDV), bus/coach (B/C). The data are differentiated by the days of the week (Monday-Thursday, Friday, Saturday and Sunday), taking into consideration the traffic pattern according to the socio-economic activities cycle and the leisure-time travels (Holden, 2007). The average traffic flows (cumulative both ways) are shown in Fig. 2.



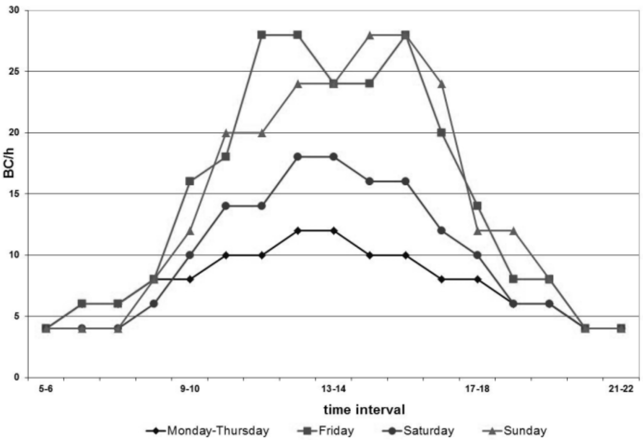
(a) Passenger cars



(b) Light-duty vevicles



(c) Heavy-duty vehicles



(d) Busses and coaches

Fig. 2
Daily average road traffic flows

The survey also included the structure of the vehicles flow according to their fuel type, technology/emission standards and engine capacity. The data have been collected through a systematic sample scheme for each vehicle category, using a sample interval of 10 vehicles. The data structure based on vehicle type, fuel and emission standard is shown in Fig. 3.

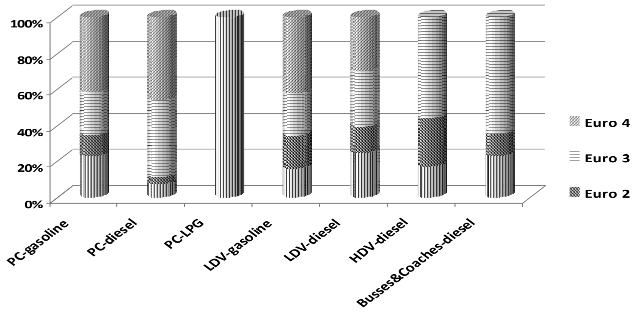


Fig. 3
Statistical structure of the vehicles flow

The traffic simulation outputs have been obtained for different daily time intervals and for working days/weekends. Each vehicle entering the simulation process has allocated individual ID number and characteristics concerning its type, fuel, engine capacity, emissions standard and maximum speed allowed.
The plot of the average speed to the traffic flow volume resulting from simulation is shown in Fig. 4. The total traffic flow volume is expressed in equivalent passenger car units (PCU) using the equivalent factors proposed by Hobbs (1979).

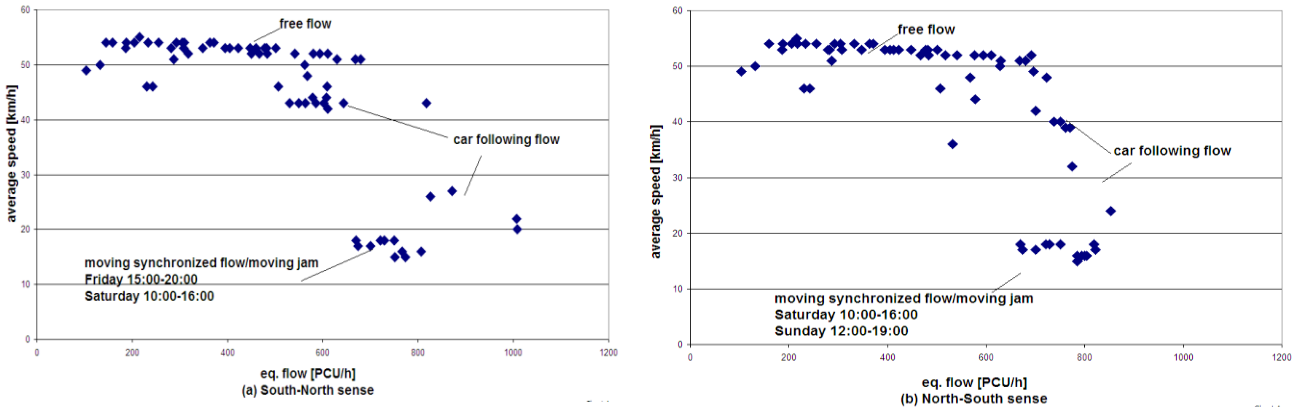


Fig. 4
Traffic volume vs. average speed diagram

The traffic situation creates specific congested phases characterized by a moving synchronized flow pattern that turns during some periods to a moving jam phase. The congestion appears on different traffic ways on Friday and Sunday and on both ways on Saturday.
Following the assessment methodology described in the paragraph 2, the average equivalent CO2 emission per unit of time and distance and by day of the week is depicted in Fig. 5.

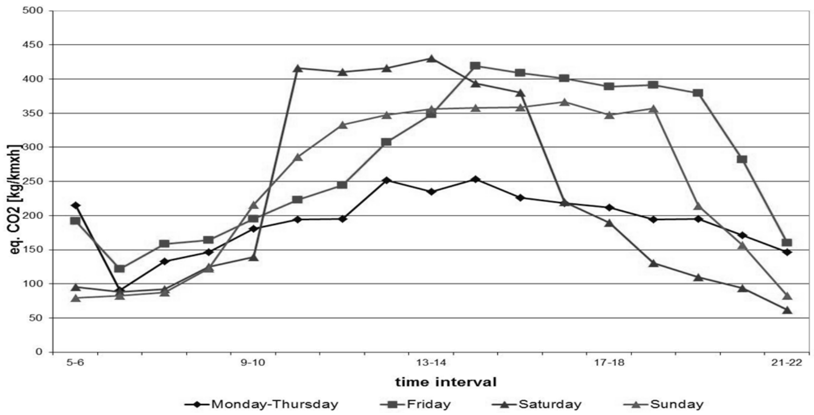


Fig. 5
Equivalent CO_2 emission

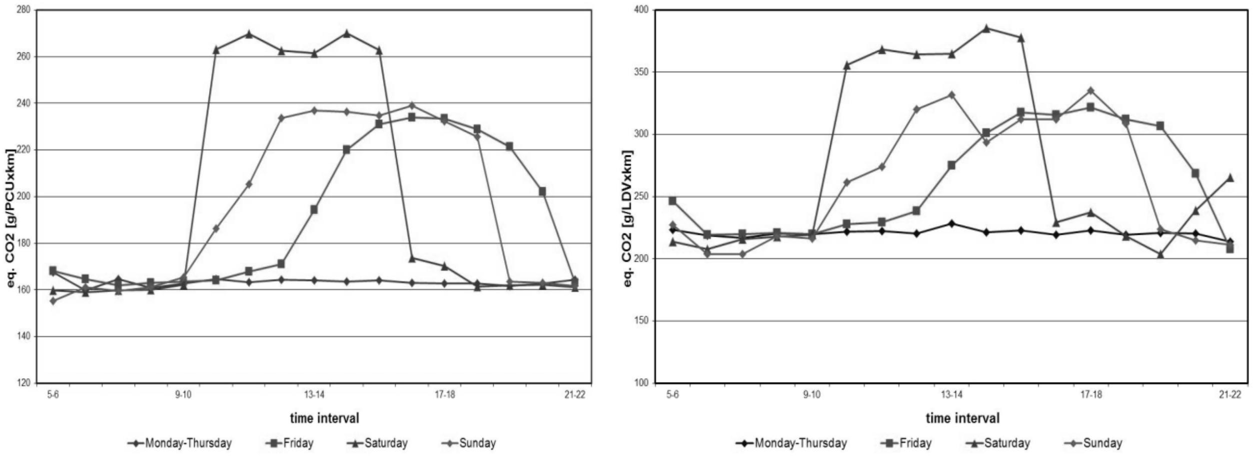
Also, the daily average emissions of GHG in the area are shown in table Table 4.

Table 4.
Daily average GHG emissions from road traffic

Day of the week	Emisions [kg/day]						
	CO_2 full combustion process	CO	VOC	CO_2 end of pipeline	CH_4	N_2O	Equivalent CO_2
Monday-Thursday	3301.83	57.49	5.09	3195.33	0.49	0.12	3258.33
Friday	4898.50	103.86	9.48	4705.20	0.60	0.15	4784.67
Saturday	3908.96	93.83	8.61	3734.16	0.45	0.11	3792.87
Sunday	4272.65	101.19	9.23	4084.32	0.53	0.13	4152.37

Analyzing the equivalent CO_2 emission in Fig. 5, some remarks are issuing:

- The morning emissions are greater during the working days due to the heavy-duty vehicles circulation. These are restricted to circulate on Prahova Valley during 06:00-22:00, unless a special transport toll is paid.
- The mid-day and the afternoon emissions are highly raised during weekends, due to increase in car traffic volume and the resulting decrease of the average speed. As depicted also in Fig. 4., the congestion phenomena are presented during these time intervals of the weekends. The rising of the traffic flow and the decrease of the speed is turned in a higher increasing of the eq. CO_2 emission.



(a) Passenger cars (b) Light-duty vehicles

Fig. 6.
Average equivalent CO_2 emission per vehicle

The average eq. CO_2 emissions for passenger cars and light-duty vehicles are depicted in Fig. 6. During the working days and the out-of-peak time intervals of the weekends, the eq. CO_2 average emissions for passenger cars are very closed to the average value recorded at European level – 150g/PCU×km, but also superior to the aim established –

140g/PCU×km (EEA, 2010). During congested periods, the average passenger car emission values increase between 40 – 60%. For light-duty vehicles, the eq. CO_2 average emissions overpass 200 g/LDV×km and are higher to those recorded at European level – 170g/LDV×km (EEA, 2010). This situation reflects the aged LDV fleet in Romania. The average emissions per LDV are up to 70% greater during the congested periods of the weekends compared to the working days.

4. Conclusions

The use of the traffic simulation is highly benefic for assessing vehicles emissions. It allows a detailed computing at individual vehicle level, and also could be used in evaluating the influence of the infrastructure modernization or traffic reorganization. The case study outlines that the weekend leisure-time and the business tourism are among the most responsible human activities for road traffic congestion and therefore for the GHG emission. The rising of the car ownership, the poor public transport services and the land use policies allowing the spread of the residential areas in the former restricted areas are translated into a high growth of the passenger car use with negative external effects on the air pollution.

Acknowledgements

The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/132397.

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ISBN 978-86-916153-1-4
9 788691 615314