UNIVERSITY OF NIS FACULTY OF MECHANICAL ENGINEERING

THE SIXTH INTERNATIONAL CONFERENCE
TRANSPORT AND LOGISTICS

til 2017

ESTIMATION OF FUEL CONSUMPTION-DEPENDENT EMISSIONS OF PASSENGER CARS IN THE CITY OF NIŠ

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Abstract

Estimation of vehicles consumption and associated emissions within urban zones is an important issue in sustainable transport. For a given vehicle type fuel consumption and emission of fuel consumption-dependent emissions is affected by a number of variables such as vehicle type, vehicle age and class, traffic conditions, driver behavior, climate conditions, etc. This paper was aimed at development of mathematical models for estimation of fuel consumption-dependent emissions of passenger cars in the city of Niš. The experimental and methodological approach combines the use of on-board equipment for fuel consumption measurements and mathematical model development with the application of COPERT and artificial neural network (ANN). A given city zone, day in the week and the hour of day were used as input parameters and basis for estimation of fuel consumption-dependent emissions such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and lead (Pb).

Key words: *fuel consumption, emissions, mathematical models, estimation.*

1 INTRODUCTION

The combustion of fossil fuels which are predominantly used in transport sector generates a set of environmental problems. Combustion of a liter of fossil fuel produces about 100g of carbon monoxide (CO), 20g of volatile organic compounds (VOC), 30g of nitric oxide (NO_x), 2.5 g of carbon dioxide (CO_2) and many other harmful and toxic substances such as compounds of lead, sulfur and solid particles [1]. All these emissions have global effects to climate changes and acidity concentration as well as local effects leading to air pollution. Gasoline-fuelled passenger vehicles with conventional engines comprise a significant share of transport modes in many countries [2], thus represent the major air-quality concerns. Assessment of the impact of road transportation on the environment (noise and air pollution, i.e. emissions) is becoming an integral part of all traffic analysis. This assessment is based on the use of emission models representing upgrade of transport models which are widely represented in the planning and management of transport systems [3].

Till date, researchers have developed several algorithms for modeling automotive emissions with various approaches and spatial scales [2]. Eglese and Black [4] analyzed emissions arising in vehicle routing in consideration to relevant factors such as speed, distance travelled, load weight and distribution, vehicle engine, driving style and road gradient. Bokare and Maurya [5] studied CO, HC and NO_x emissions of small passenger cars in India. De Haan and Keller [6] discussed the use of instantaneous high-resolution emission data for the estimation of passenger car emissions during real-world driving. Rakha et al. [7] described how on-road emission measurement (OEM) data can be utilized to develop HC, CO and NO_x emission models that are suitable for estimating instantaneous mobile source emissions. Ahn et al. [8] developed several hybrid regression models for the prediction of emission rates for light-duty vehicles and light-duty trucks. Cappiello [9] developed dynamic emissions model for CO_2, CO, HC and NO_x for light-duty vehicles. The model was derived from regression-based and load-based emissions modeling approaches and effectively combines their respective advantages. Borge et al. [10] compared two approaches to estimate road traffic emissions in Madrid (Spain): the Computer Programme to calculate Emissions from Road Transport (COPERT4) and the Handbook Emission Factors for Road Transport (HBEFA), representative of the 'average-speed' and 'traffic situation' model types, respectively.
The motivation of this study was to develop mathematical models for estimation of fuel consumption-dependent emissions of passenger cars in the city of Niš. Like other developing countries, the vehicle characteristics, road features and driving conditions in the city of Niš are specific and different than reported in literature. More specifically, based on experimentally measured data recorded through on-board equipment, as well as the use of the COPERT model, three mathematical models based on the use of artificial neural networks (ANNs), were developed. The traffic conditions for a given city zone, day in the week and the hour of day were used as input parameters upon which the mathematical models were able to estimate fuel consumption-dependent emissions such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and lead (Pb).

2 EXPERIMENTAL DETAILS AND DATA COLLECTION

For the purpose of the fuel consumption measurment a set of data instances were collected from vehicle's ECU using OBD-II scanner via CAN bus interface. The passenger car used in the present study was a second generation (make 2010 with 40000 km traveled) Toyota Yaris powered by a EURO 4 1.33 l petrol engine with 74 kW engine power and six-speed manual transmission. Over the period of 30 days the vehicle running parameters were collected for each day of week, hour of day (h) and city zone. For the purpose of the analysis the entire city area was divided into three city road zones: narrow city center (zone 1), inner city zone (zone 2) and wider city zone (zone 3). Parameters day of week and city zone are categorical (nominal) variables, whereas hour of day (h) is represented in discrete domain from 08:00 to 23:00 h with interval of 1 h.

3 VEHICLE EMISSIONS

3.1. Environmental impacts of vehicle emissions

In the Republic of Serbia gasoline, diesel, liquefied petroleum gas (LPG) and compressed natural gas (CNG) are predominantly used as motor fuels for passenger cars. Combustion of these fuels generates exhaust emissions. The most important pollutants which are emitted by road transport vehicles are [1]: ozone precursors (CO, NO_x, $NMVOC_s$), gases that produce the greenhouse effect (CO_2, CH_4, N_2O), acid compounds (NH_3, SO_2), solid particles (PM), carcinogenic compounds (PAH_s and POP_s), toxic substances (dioxins and furans), heavy metals. In this study fuel consumption-dependent emissions such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and lead (Pb) are given consideration.

Carbon dioxide (CO_2) is a colorless and odorless gas, the principal product of complete combustion. Although it is naturally present in the atmosphere and it is not considered a pollutant, it is a greenhouse gas that contributes to the potential for global warming [9]. Typically, more than 99% of the carbon in a fuel is emitted as CO_2 when the fuel is burned. Sulphur dioxide (SO_2) originates directly from burning sulfur-containing fuels, especially diesel and lubricant combustion. It easily dissolves in water to form weak sulfuric acid, the main ingredient in acid rain. SO_2 and its secondary products (sulfuric acid and sulfides) can cause serious health problems. Lead (Pb) was originally introduced into petroleum products as an 'anti-knock' additive to improve combustion in a spark-ignition engines. High levels of lead are still of concern in urban areas with high levels of traffic. However, emissions of lead have been significantly dropped in Europe, as a result of unleaded gasoline introduction already from the early 1990s [11].

3.2. Factors affecting vehicle emissions

Emissions of CO_2 are directly related to the fuel consumption. Emissions of the remaining gases depend on the amount of fuel used but are also affected by the way the vehicle is driven (e.g. the speed, acceleration and load on the vehicle), the vehicle type, the fuel used and technology used to control emissions (e.g. catalysts) [12]. The primary factors affecting emissions that result from transportation sources can be classified into four categories [13]: travel-related factors, driver-related factors, road-related factors, and vehicle characteristics and other factors.

3.3. Mathematical models for emission's estimation

For emission estimation of road transportation vehicles a number of mathematical models were proposed. In general most of the developed model fall into the following four categories: (1) modal emission models (MEM), (2) models based on average vehicle speed such as MOBILE6 and COPERT models, (3) microscopic emission models that estimate emissions in hot stabilized conditions using instantaneous vehicle speed and acceleration levels as input variables (VT-micro emission model), (4) fuel consumption based emission models.

COPERT (Computer Program to calculate Emissions from Road Transport) is the mathematical model for calculation of air pollutant emissions from road transport. It calculates emissions of all regulated air pollutants produced by different vehicle categories (passenger cars, light duty vehicles, heavy duty vehicles, mopeds and motorcycles), and greenhouses gases (i.e. CO_2) emissions based on fuel consumption [14].

The primary objective of this study was to develop mathematical models to estimate estimate fuel consumption-dependent emissions such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and lead (Pb) by using the measured fuel consumption rate of the passenger car in the city of Niš. By the COPERT model the estimation of emissions for Toyota Yaris 1.33l gasoline engine (EURO4) are calculated as follows. For gasoline ($[CH1.8]_x$), the mass of CO_2 emitted by vehicle due to fuel combustion can be calculated as:

$$E_{CO_2} = 44.011 \cdot \frac{FC}{12.011 + 1.008 \cdot r_{H:C} + 16 \cdot r_{O:C}} \tag{1}$$

where E_{CO2} [g/km] is emission of CO_2, FC [g/km] is the vehicle fuel consumption, $r_{H:C}$ is the ratio of hydrogen to carbon (=1.8) and $r_{O:C}$ is the ratio of oxygen to carbon (=0).

The emissions of SO_2 are estimated by assuming that all sulphur in the fuel is transformed completely into SO_2, using the formula [11]:

$$E_{SO_2} = 2 \cdot k_s \cdot FC \tag{2}$$

where E_{SO2} [g/km] is emission of SO_2 and k_s [g/g] is the weight related sulphur content in the fuel.

The average value for fuel sulphur content of the gasoline of k_s=0.00035 [g/g] is derived from the fuel analysis conducted by the Jugoinspekt [15].

The total lead emitted to the atmosphere due to fuel combustion of unleaded gasoline with traces of lead can be calculated according to:

$$E_{Pb} = 0.75 \cdot k_{Pb} \cdot FC \tag{3}$$

where E_{Pb} [g/km] is emission of P_b and k_{Pb} [g/g] is the weight related lead content of gasoline.

The maximal value for fuel Pb content of the gasoline of k_s=13 [mg/l] is derived from the fuel analysis conducted by the Jugoinspekt [15].

4 RESULTS AND DISCUSSION

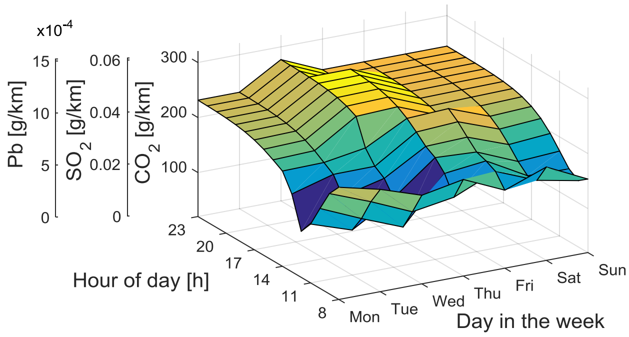
4.1. ANN models for emissions estimation

The main focus of study was estimation of fuel consumption-dependent emissions, such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and lead (Pb), of passenger car in city of Niš. To this aim three mathematical models considering day of week, hour of day and city zone as input parameters were developed by the application of artificial neural networks (ANNs). Estimation of emissions was based considering experimental results of passenger car fuel consumption in the city of Niš and the use of afore-given equations derived from the COPERT model.

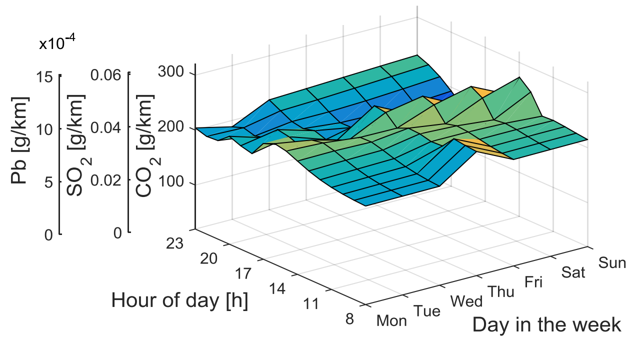
ANN architecture of the proposed models, i.e. number of layers and associated neurons and transfer functions were set after initial comprehensive analysis. It has been observed that Levenberg-Marquardt algorithm with Nguyen-Widrow initialization provided best experimental data fitting in least number of iterations. The statistical method of mean absolute percent errors of 8.85 and 12.53 on data used for mdoel develpment (training) and testing confirmed the validity for the use of the developed models for estimation of fuel consumption-dependent emissions.

4.2. Analysis of car emissions in the city of Niš

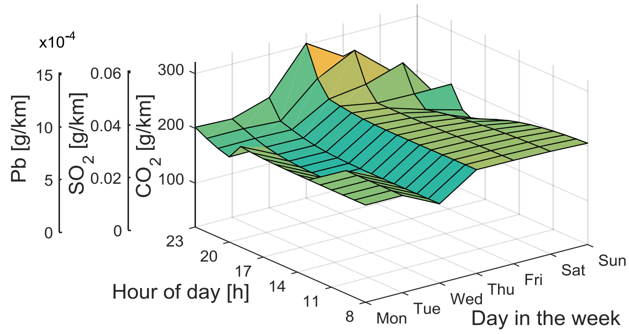
Analysis and discussion of passenger car emissions in the city of Niš was performed by means of twelve 3D surface plots showing the interactions effects of hour of day and day in the week for city zones (Fig. 1).



a) Zone 1



b) Zone 2



c) Zone 3

***Fig. 1** Emissions of CO_2, SO_2 and Pb within Niš city zones*

From Fig. 1 one can observe that for a given day the emissions of CO_2, SO_2 and Pb decreases from zone 1 to zone 3 as a result of less traffic and congestions. Given average emissions of CO_2, SO_2 and Pb, there are reduction of these emissions in zones 2 and 3 for about 1 and 10 %, respectively.

Because of increased traffic higher level of CO_2, SO_2 and Pb emissions occur in the early morning hours and afternoon hours between 14-17h both on weekend and days of week. This could be clearly observed in Fig. 1a,b. On average, emissions of CO_2, SO_2 and Pb are slightly decreased for weekend but do differ drastically in comparison to other days of week.

It has to be noted that response surfaces for emissions of CO_2, SO_2 and Pb generated by ANN models follow the same pattern as the consequence of Eqs. (1), (2) and (3).

5 CONCLUSION

Among transportation means, passenger cars are the main sources of emissions in the urban areas. With ever increasing city population and number of passenger cars, the prediction of passenger car emissions in the urban areas is very important environmental issue. Because vehicle emissions are closely related to the specific traffic conditions which characterize a given city, the present study was aimed at development of mathematical models for estimation of fuel consumption-dependent emissions of passenger cars in the city of Niš.

It has been observed that average emissions for all days and all three city zones for CO_2, SO_2 and Pb are 208.1, 0.0458 and 0.00085 g/km, respectively. Given these average emissions, there are decreases of these emissions in wider city areas up to 10 %. As these emissions are in direct relationship with fuel consumption, higher level of these emissions occur in the early morning hours and afternoon hours between 14-17h both on weekend and days of week.

Implementation of the developed emission models for eco routing planning is future research scope.

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