DEVELOPMENT OF A MODEL FOR ESTIMATING COMMERCIAL VEHICLES' FUEL CONSUMPTION AND EXHAUST EMISSIONS

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Abstract: *In this paper, an estimation model of fuel consumption and exhaust emissions of commercial vehicles in different operating conditions is developed. Depending on vehicle's average speed, road slope and vehicle's load/capacity utilization, the model determines the fuel consumption and emissions of harmful gases for the observed vehicle type and category. In order to validate the model, recordings on actual commercial vehicles were made in real operating conditions on two urban public transport bus lines in Belgrade. Obtained fuel consumption in real operating conditions and estimated fuel consumption by the developed model were compared. Deviations of the estimation model from the real consumption values are on average about 5%. After a successful fuel consumption validation, the emissions of the most common harmful gases by the model are estimated.*

Keywords: *estimation model, validation, fuel consumption, GHG emissions*

1. INTRODUCTION

If a transport operator wishes to become sustainable, it has to operate efficiently by reducing transport costs, maintenance costs and/or by increasing the fleet energy efficiency (Kamakaté and Schipper, 2009; Ruzzenenti and Basosi, 2009; Vujanović et. al., 2018). Since fuel consumption represents a major operating cost for transport companies (Gohari et. al., 2018; Kot, 2015; Kovács, 2017) and they mostly operate heterogeneous vehicle fleets (Hoff et. al., 2010), adequate vehicle selection for existing transport volumes represents one of fleet management's key activities. By selecting a more fuel-efficient vehicle, lower fuel costs and greater vehicle autonomy will be achieved (Lin et. al., 2009). Additionally, one of the parameters that represents sustainable fleet management is the reduction of harmful gas emissions (Ansaripoor et. al., 2014). Reduction of fleet's harmful gas emissions and increase of its energy efficiency can be achieved through the selection of vehicles of appropriate type and category (Liimatainen and Pöllänen, 2010), as well as through increasing their load/capacity utilization index (Vujanović et. al., 2010).

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Based on all previously mentioned, this paper presents a model allowing fuel consumption and harmful gases emissions estimation on the observed transport routes depending on following vehicle and road characteristics:

- commercial vehicle category,
- commercial vehicle emission standard,
- speed profile,
- road slope and
- load/capacity utilization index.

The aim of this paper is to develop an estimation model which will make it possible to quickly and easily determine the fuel consumption and GHG emissions for different commercial vehicles in dominant actual operating conditions. The model was developed in Matlab 2018, and its validation was performed on data obtained by recordings in real-world operating conditions of standard buses deployed on lines 53 and 83 of urban public transport in Belgrade, Serbia.

The paper is structured as follows. In the second section, one of the most commonly used models for determining fuel consumption and exhaust emissions is described, after which the third chapter provides a step-by-step overview of the developed model for fuel consumption and exhaust emissions estimation. Afterwards, in the fourth chapter, the model validation was performed on buses operating on two urban public transport lines in both directions, at different measured speeds, road slopes and capacity utilization indices. Finally, in the fifth chapter, some concluding remarks, as well as main directions for future research are suggested.

2. MODELS FOR FUEL CONSUMPTION AND EXHAUST EMISSIONS DETERMINATION

By conducting a literature review the authors found that EMEP/EEA air pollutant emission inventory guidebook represents the referent source for determining fuel consumption and emission factors for various exhaust gases (European Environment Agency, 2019). Its “road transport appendix 4 emission factors” (Ntziachristos and Samaras, 2021) is the database that shows the average fuel consumption and exhaust emissions expressed in grams per kilometer (g/km), which allows determining the exhaust emissions before reaching the regular engine operating temperature (i.e., cold emissions) as well as after (i.e., hot emissions). The exhaust emissions are determined for different: speed profiles, gear shifting strategies, vehicle capacity utilization indices, road slopes, vehicle characteristics, etc. Exhaust emissions data contained in the model were obtained on the basis of a large number of measurements performed both in laboratory conditions and in real operating conditions using a Portable Emission Measurement System (PEMS). (ERMES - European Research on Mobile Emission Sources, 2020; Hausberger et al., 2019)

The reference database of road transport related emission factors contains a very large set of data on fuel consumption and exhaust emissions for each vehicle type and category. These values were obtained based on vehicle measurements at different segmented load/capacity utilizations (0%, 50% and 100%), road slopes (-6%, -4%, -2%, 0 %, 2%, 4% and 6%), as well as at different speeds. The main disadvantage of this database is that it does not provide values of fuel consumption and exhaust emissions for other load/capacity utilization indices and road slopes that are in-between intervals of predefined and previously shown values (e.g., capacity utilization of 37% and road slope of 2.42%).

In that sense, the following chapter gives a brief explanation of the model developed in Matlab, which estimates fuel consumption and emissions for different vehicle types and categories, for any value of vehicle speed, road slope and vehicle capacity utilization index.

3. ESTIMATION MODEL DEVELOPMENT

Within this chapter, the steps of the model for fuel consumption and exhaust emissions estimation for different vehicle types and categories are presented. The proposed model is supplied with data from the reference database of fuel consumption and exhaust emissions for different vehicle types and categories.

Within the first step, all necessary technical characteristics of the vehicle are defined, such as type (e.g. heavy duty vehicle or bus) and vehicle category (e.g. heavy rigid vehicle 7.5 - 12 t, heavy articulated vehicle 20 - 28 t, urban bus articulated >18 t, urban bus standard 15-18 t, urban bus midi ≤15 t, etc.), as well as vehicle Euro standard (Conventional, Euro I - Euro VI).

In the second step the following operating conditions are defined: average speed (km/h), vehicle load/capacity utilization (%), longitudinal road slope (%) and trip distance (m).

After the vehicle technical characteristics and operating conditions are defined, in the third step, presented model estimates output parameters: fuel consumption (FC) and emissions of carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbon (HC), and particulate matter (PM). The model compares imported values with existing discretized data from reference database and estimates output values based on bilinear interpolation (Press et. al., 1992). The model is designed to take any value of vehicle speed, load/capacity utilization and road slope, and based on bilinear (repeated linear) interpolation of existing discretized values estimates desired output parameters. For example, if the observed speed is 15 km/h, the road slope is 2.8% and the vehicle load/capacity utilization is 75%, the model takes left and right boundary values of reference database discretized data. These four values for vehicle speed of 15 km/h, are denoted as follows (Figure 1):

1) Q_{11} - value when the road slope is 2%, the vehicle load/capacity utilization is 50%;
2) Q_{12} - value when the road slope is 2%, the vehicle load/capacity utilization is 100%;
3) Q_{21} - value when the road slope is 4%, the vehicle load/capacity utilization is 50%; and
4) Q_{22} - value when the road slope is 4%, the vehicle load/capacity utilization is 100%.

The R_1 value is found by first linear interpolation of the values Q_{11} and Q_{21} in the road slope axis direction, and R_2 from Q_{12} and Q_{22}. After obtaining the values of R_1 and R_2, repeated linear interpolation is performed to obtain the point P (Figure 1) which represents the final result of the observed parameter for road slope of 2.8% and vehicle load/capacity utilization of 75%.

As the values of fuel consumption and exhaust emissions from the reference database are presented in g/km, the total trip distance is calculated in order to determine the total fuel consumption/exhaust emissions at the observed bus line. When calculating fuel consumption, it is necessary to take into account the specific density of the observed fuel to obtain the consumption in liters. In this paper, the average density of diesel used in calculations is 830 g/l.

Presented model is validated in real-world operation conditions on public transport buses in Belgrade.

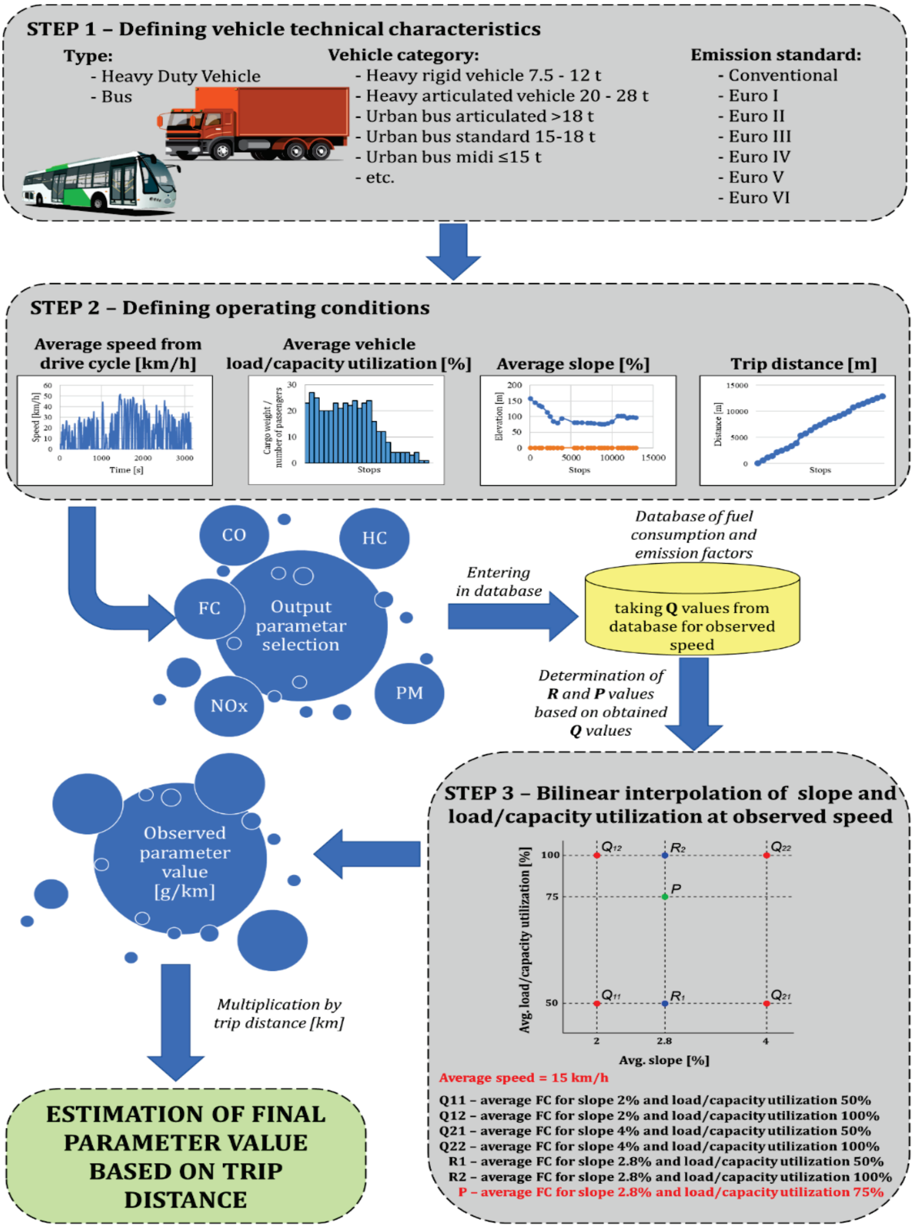

Figure 1. Schematic representation of the model

4. MODEL VALIDATION

The model validation was performed on recorded data of buses' operation on lines 53 and 83 of Belgrade public transport, in both directions. Data were recorded on a HIGER standard diesel bus, type KLQ6129GQ2 manufactured by Chariot Motors, shown on Figure 2. The observed buses meet the emission norms set by Euro VI standard. The maximum capacity of the buses is 100 seats (29 seats and 71 standing places).

Figure 2. Diesel bus Higer KLQ6129GQ2

Data recording on line 83 was performed on February 14, 2020 from 9 AM to 11.45 AM, while data recording on line 53 was performed six days later (February 20, 2020) from 9 AM to 10.45 AM. Each data recording was preceded by equipment mounting and testing. Data on actual vehicle speed and current fuel consumption were collected using PCAN-USB Pro - PEAK (Figure 3 - left), while Garmin GPSMAP 62s (Figure 3 - right) was used to collect altitude data used for average road slope determination. The percentage of bus capacity utilization was determined by systematic passenger counting.

Figure 3. The Appearance of PEAK (left) and GARMIN (right) devices

Line 83 is a moderately difficult diametrical line connecting two peripheral settlements (Crveni krst) and (Zemun) through the central city core. The length of the line in the direction from Crveni krst to Zemun (direction A) is 12,914 m, while in the opposite direction (B), the length is 13,624 m. Unlike line 83, 53 is moderately heavy radial line connecting the central city zone (Zeleni venac) with the peripheral settlement (Vidikovac). The length of this line in both directions (A and B) is about 12,925 m. The position of these bus lines, as well as the start and end terminal stations are shown in Figure 4.

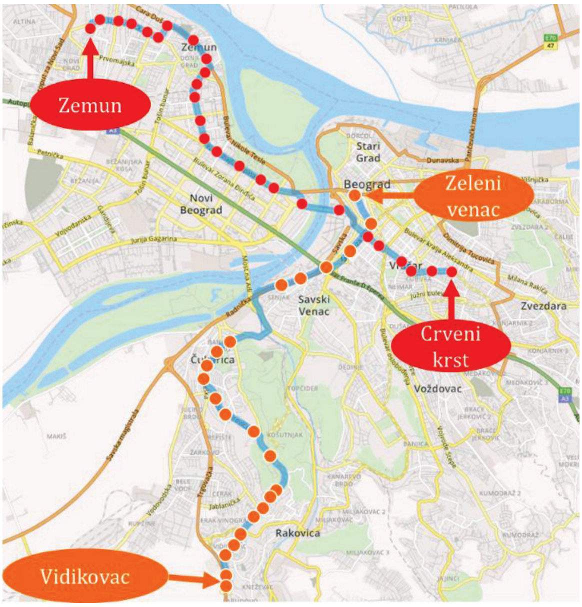

Figure 4. Position of bus lines and start and end terminal stations

The longitudinal road slope of the observed lines in the direction A is given in Figure 5.

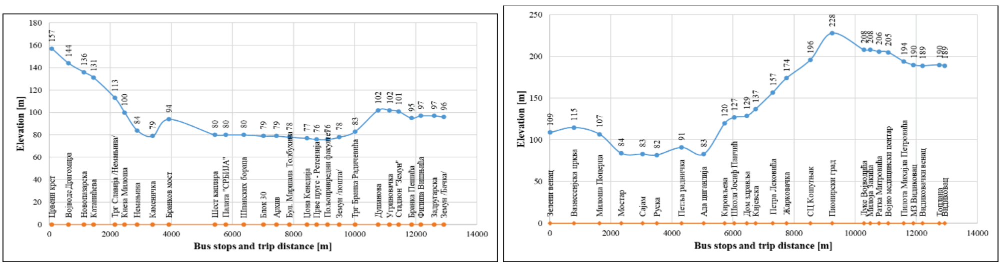

Figure 5. Recorded road slope on line 83 (left) and line 53 (right) in direction A

Urban driving conditions can be observed through speed profile recorded in real-world operating conditions for each bus line. From Figure 6 it can be seen that the speed profile is characteristic for urban driving conditions due to lower speeds (below 50 km/h), frequent speed oscillations (acceleration and deceleration) and stops.

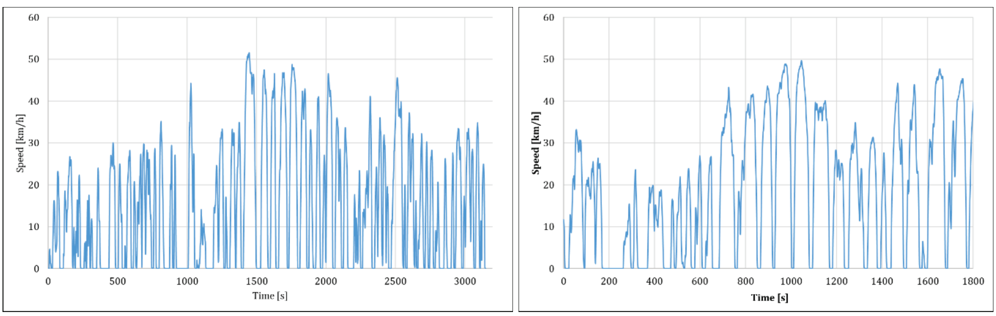

Figure 6. Recorded speed profile on line 83 (left) and line 53 (right) in direction A

After the average values of vehicle capacity utilization, trip distance and fuel consumptions are determined in real-world operating conditions, the developed model estimates output values and validate them. In Table 1 are given the values of all mentioned parameters which are used in model. Furthermore, in the same table, the recorded values of fuel consumption in real operating conditions, as well as estimated fuel consumption values are presented. It can be seen that estimated fuel consumption by the model is approximately 5% lower than fuel consumption in real operating conditions. The biggest deviation (-7.81%) is obtained on line 83 in direction A, while the smallest deviation is on line 53 in direction from Zeleni Venac to Vidikovac (-3.23%). Based on the obtained deviations, the model is validated and it can be used for determination of fuel consumption and GHG emissions.

It is important to emphasize that reference data used are not obtained for the observed vehicle and same operating conditions. Additionally, the data recording was conducted in winter conditions, with heating turned on, leading to increased fuel consumption.

Table 1. Values of the observed parameters used for model validation

Bus line	Direction [A/B]	Average speed [km/h]	Average load [%]	Average slope [%]	Line length [m]	Recorded fuel cons. [l]	Model FC [l]	Difference between FC in model and recorded FC [%]
53	A	18.59	9.2	0.62	12,925	5.56	5.38	-3.23
53	B	18.65	30.3	-0.62	12,927	4.86	4.61	-5.14
83	A	14.75	14.9	-0.47	12,914	5.53	5.08	-7.81
83	B	14.43	19.3	0.53	13,624	6.59	6.34	-3.79

After successful validation of the model in terms of fuel consumption, the emissions of GHG such as carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and particulate matter (PM) are determined. The emitted quantities of these gases on the observed lines are presented in Table 2.

Table 2. The emitted values of CO, NOx, HC and PM on line 53 and 83 in both directions

Bus line	Direction [A/B]	CO [g]	NOx [g]	HC [g]	PM [g]	Bus line	Direction [A/B]	CO [g]	NOx [g]	HC [g]	PM [g]
53	A	20.77	11.75	0.51	0.08	83	A	23.04	20.79	0.55	0.07
	B	18.79	15.02	0.46	0.07		B	26.78	17.74	0.63	0.09

5. CONCLUSION

This paper presents a developed model for estimating fuel consumption and exhaust emissions in road transport. The model is based on the EMEP/EEA air pollutant emission reference database on fuel consumption and emission factors for different types and categories of commercial vehicles' speeds, load/capacity utilizations and road slopes. The contribution of this paper is reflected in the developed model for bilinear interpolation to estimate more precisely fuel consumption and exhaust emissions than those given in the observed database. Additionally, the contribution of the paper is the successful validation of the model on urban bus lines in Belgrade. The average deviation of the obtained fuel consumption in the model and the actual fuel consumption in real operating conditions is about 5%.

The modeled fuel consumptions and exhaust emissions in real operating conditions are important to logistics and transport operators in view of their carbon footprint, economic and environmental sustainability. Further benefits can be achieved by model application in selecting the most efficient vehicle category on actual transport routes. The model can also support decision making in heavy duty vehicle procurement by estimating the fuel consumption of new vehicle types and categories for existing transport demands and operating conditions.

Directions of future research is in the application of the model on other vehicle categories. Also, the model can be used for commercial vehicle fleet carbon footprint estimation in different areas of operation.

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