EVALUATION OF THE REFERENCE FUEL CONSUMPTION AND CO_2 EMISSION OF VEHICLE WITH USING OF THE MAP OF OPERATING CONDITIONS FOR SELECTED AGGLOMERATION

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Abstract

Vehicle operating fuel consumption estimation has a measurable significance for both individual users as well as transport and communications companies. Complex analysis of the results may cause reduction of power (fuel) consumption, CO_2 and toxic compounds emissions in exhaust gases. Operating fuel consumption estimation carried out by drivers' encounters basic difficulties connected with the lack of reliable reference standard for comparison of measured fuel consumption during car usage. Therefore it is necessary to identify vehicle operating conditions and ascribe them reference fuel consumption according to the accepted reference standard. A method of description of real vehicle operating conditions has been presented in this paper. Presented examples show that vehicle operating conditions may be unambiguously described with the use of proposed indicators. They can be also used to forecast the fuel consumption with high accuracy. Exclusive use of certification tests as model of operating conditions for this purpose does not allow keeping high conformity of assumptions with usage practice. Creation of an individual map of operating conditions for a chosen agglomeration would enable to optimize choice of vehicle or fleet for an intended place of operation. Utilization of such operating conditions map may be: to determine reference fuel consumption for assumed operation area or optimal route of drive from the point of view of minimizing fuel consumption, energy or CO_2 emission to the atmosphere. Selected examples of utilization of such operating conditions map have been presented.

Keywords: *road transport, simulation, vehicle operating conditions, fuel consumption, CO_2 emission*

1. Introduction

High intensity urban development and the increase in transport of goods and people [22] causes the intensification of work to identify the actual traffic conditions in these areas [1-3, 6, 9, 16, 18, 19, 23, 24], the level of toxic emissions into the atmosphere from road transport [4, 8, 17, 20, 21], and ultimately reduce these emissions. The major purpose of identifying the actual vehicle operating conditions are: the evaluation of the reference fuel consumption for the identified or assumed operating conditions to determine the impact of road engineering solutions for structural energy consumption and emissions of harmful substances into the atmosphere (for the particular structure of our vehicles), selecting the optimal route with respect to minimize fuel consumption, energy or CO_2 emissions into the atmosphere. The present work is focused on using proprietary methods to evaluate the operating conditions of vehicles using the unit energy consumption [13-15]. Using this method was dictated by the possibility of extremely precise correlating parameter describing the operating conditions of vehicle with fuel consumption and CO_2 emissions and this is demonstrated later in this work. Below is presented an example of the preparation and use of map of operating conditions for the several streets of the city of Gdansk.

2. Identification of the real operating conditions

The operating conditions will be identified by a numerical index called specific energy consumption Φ, which includes both the influence of external conditions as well as driving style

[13, 15, 23]. The value of the parameter Φ [J/(mkg)] for the assumed cycle time t_c, can be calculated using the following equation [15]:

$$\Phi = \frac{E}{L_n \cdot m}, \tag{1}$$

where:
E - mechanical energy supplied by the transmission system to the wheels,
L_n - distance covered by the car during propulsion phase,
m - vehicle's mass.

Place of operation (traffic intensity) and the driving style can be in the proposed method [15] clearly described by the density function of parameter Φ:

$$f_\Phi = f(\Phi). \tag{2}$$

For assumed changes of the parameter Φ the following condition must be met:

$$\int_{\Phi_{min}}^{\Phi_{max}} f_\Phi d\Phi = 1. \tag{3}$$

Function (2) can be used both as continuous and discrete (histogram).

3. Relationship between fuel consumption and specific energy consumption

Figure 1 shows the influence of specific energy consumption (Φ) for complete drives on fuel consumption in propulsion phase (Q_n). Data were collected during the road tests of a passenger vehicle in real urban traffic in Gdansk [12].

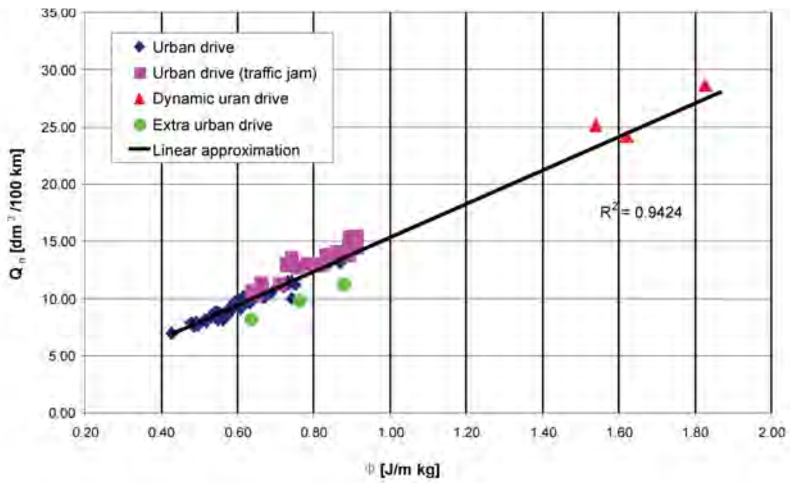

Fig. 1. Influence of specific energy consumption (Φ) on fuel consumption in propulsion phase (Q_n)

Results presented in Fig. 1 allow to state that there is a strong correlation between fuel consumption in propulsion phase (Q_n) and specific energy consumption (Φ). The above relation may be approximated by linear function in the following form [12-14]:

$$Q_n = k_1 \cdot \Phi + k_0, \tag{4}$$

where:
Q_n [dm^3/100 km] - fuel consumption in propulsion phase (excluding fuel consumed by the engine at idle speed),
k_1, k_0 - approximating function coefficients.

The relation obtained by linear approximation may be used with good accuracy (for data shown in Fig. 1 R^2=0.942) for forecasting fuel consumption during vehicle operation in urban conditions. In extra-urban conditions, on account of extremely favourable conditions of engine running, the results may be burdened with certain systematic error (small variable load and favourable, from the point of view of engine efficiency, position of engine operating point [5, 10, 24]).

4. Reference fuel consumption

With the use of equation (4), identified by an experimental method, it is possible to calculate reference fuel consumption for identified operating conditions (for the same probability density function of parameter Φ – in discrete form it will be a histogram) [12]:

$$\overline{Q} = \frac{1}{L}\left\{ L_n \int_{\Phi_{\min}}^{\Phi_{\max}} \left[f_\Phi (k_1 \cdot \Phi + k_0) \right] d\Phi + \vartheta_{b.j.} + \vartheta_h \right\}, \tag{5}$$

where:
$\Phi_{\min}$, $\Phi_{\max}$ - parameter Φ change limit,
$\vartheta_{b.j.}$ [dm^3] - fuel consumed during engine work at idle speed,
ϑ_h [dm^3] - fuel consumed during braking (during engine braking: $\vartheta_h \to 0$),
L [m] - total distance covered by the vehicle.

Fuel consumed during engine work at idle may be calculated on the basis of the following relation:

$$\vartheta_{b.j.} = \frac{t_{b.j.}}{t_c} \cdot t_c \cdot G_{b.j.}, \tag{6}$$

where:
$G_{b.j.}$ - fuel consumption during engine work at idle,
t_c - total drive time,
$t_{b.j.}$ - duration of engine work at idle speed.

5. Relationship between fuel consumption and CO_2 emission

The formation of CO_2 comes directly from the combustion of hydrocarbons, which constitute fuels used in cars. For the full and complete combustion close relationship between the mass of fuel burned in the engine and the mass of CO_2 emitted take place. In the real operating conditions the hydrocarbon burning is accompanied additionally by the formation of CO and hydrocarbons (HC). Between the quantity of compounds emitted in the exhaust gas containing carbon and the quantity of the used fuel (gasoline) can be arranged the following relation [7, 9, 18]:

$$Q = \frac{0.866(HC) + 0.429(CO) + 0.273(CO_2)}{\frac{\rho_{pal}}{0.1154}}, \tag{7}$$

where:
Q - fuel consumption [dm^3/ 100 km],
HC, CO, CO_2 - emission in the exhaust gases [g/km],
ρ_{pal} - density of fuel (for petrol adopted 0.739 kg/dm^3).

Typically, the relation (7) is used during the certification test of vehicles to determine fuel consumption in the method called „carbon balance”. Neglecting the impact of CO and HC on the fuel consumption a simplified relationship can be stayed, in which the proportionality factor will be depended on how is going the engine operation [8]:

$$CO_2 = k_{CO2} \cdot Q \cdot \left(10 \cdot \rho_{pal}\right), \tag{8}$$

where:
k_{CO2} = 3.15 - proportionality factor for the total and complete combustion [8].

6. The map of operating conditions for selected agglomeration

Proposed in this paper map of operating conditions allows the prediction of selected operating parameters and their comparison for alternative travel routes and different means of propulsion. The main parameters of the map for the selected configuration the vehicle-road are: the total energy spent to drive the selected vehicle, fuel consumption, travel time, average speed of travel, CO_2 emissions. According to equations (1), (5), (6) and (8) evaluation of the above parameters is possible using the following parameters vector:

$$\boldsymbol{Y_M} = \left[\overline{\Phi}, \overline{V}, \frac{L_n}{L}, \frac{t_{b.j.}}{t_c}\right], \tag{9}$$

where:
$\overline{\Phi}$ - average specific energy consumption for the analyzed road section,
$\overline{V}$ - average vehicle speed for the analyzed road section,
$\frac{L_n}{L}$ - share of the propulsion phase in comparison to the total distance,
$\frac{t_{b.j.}}{t_c}$ - share of the engine working at idle in comparison to the total time.

For the selected road section between the points indicated by “0” and “k” the map of operating conditions should take the form of multi-dimensional characteristics:

$$\boldsymbol{Y_M}\Big|_0^k = \boldsymbol{f_M}\left(\{\varphi_0, \lambda_0\}, \{\varphi_k, \lambda_k\}, T, D\right), \tag{10}$$

where:
φ_0, λ_0 - latitude and longitude of a starting point for the analyzed road section,
φ_k, λ_k - latitude and longitude of a ending point for the analyzed road section,
T - day of the week. The set with 2 elements has been proposed: (weekday, weekend};
D - time of day. The set with 6 elements has been proposed: {6^{01}-9^{00}, 9^{01}-12^{00}, 12^{01}-15^{00}, 15^{01}-18^{00}, 18^{01}-21^{00}, 21^{01}-6^{00}}.

From a practical point of view, the proposed map of the operating conditions should take the discrete form, not continuous. Analyzing the operational performance of vehicles (e.g. fuel consumption) can only be performed for existing and tested roads, not for unlimited geographical coordinates. Choice of route depend on selecting the next available in the database points, which constitute the beginning or end of sections of road surveyed. Examined road will be divided into sections of fixed length of 100 m. The only exception is the last section, the length of which is apparent from the difference in length of the entire route, and accumulated in earlier episodes. Therefore, most convenient form of maps will be the tabular record.

This paper will present the results of research carried out on the road in the city of Gdansk in regular city traffic with passenger vehicles equipped with GPS location system and system for communicating with on-board CAN network to record the selected vehicle operating parameters. Height measurement using the GPS system subjects to the phenomenological correction [11].

Driving style was subordinated to follow a randomly selected vehicle [16]. The selected vehicle has been „tracked” by the test vehicle in order to reduce the outflow of individual driving style. As a part of the work 5 routes in the city center (including the 3-lane main arteries of

Gdansk) have been tested. Studies, because of the need to reduce costs, have been made in the 9^{01}-12^{00} hours (short travel time) on weekdays, but each test was repeated 6 times. Results presented below relate to data averaged for the 7 trials for each segment explored. Graphical representation of multidimensional characteristics (10) will be the geographical map of the area with marked tested road sections, to which vector values of $\mathbf{Y_M}$ (9) were assigned after the road test. The present work contains an example of such a graphical representation of one parameter of vector $\mathbf{Y_M}$ (9) performed with the use of original software that uses the geographical maps available in the application "Google Earth" (Fig. 2). The scale of values and corresponding colours were added to the graph in the form of colours bar.

Fig. 2. Map of operating conditions - the specific energy consumption ($\overline{\Phi}$)

7. An example of the map use for selected operating routes

Presented below example concerns the evaluation of projected operating parameters of the selected vehicle (CO_2 emissions, fuel consumption, travel time, etc.) for the two alternative routes from the point with indication "START" to the point with indication "END| (in both directions). The first route marked by „1" goes 3-lane main street of Gdansk, and then two-lane road with large capacity. The second route marked by „2" runs one-lane road with low capacity, and then two-lane road with a small number of crossings. The routes in north direction (sign: „N") and south direction (sign: „S") have been analyzed separately. Considered in this example are a popular communication route in the city center, which connects the seaside residential areas (Zaspa, Przymorze, Zabianka) with commercial and industrial districts. Because of the potential capacity benefits of the route No. 1, it is very likely to be chosen by the drivers of Gdansk, despite the clearly greater length. In the case of heavy traffic in rush hours, Route No. 1 has a better ability to maintain acceptable traffic flow. The studies relate to the journey in the working day (weekday) 9^{01}-12^{00} and should allow to consider the appropriateness of the longer routes advantages or disadvantages, when traffic flow is mainly attributable to the traffic light settings, and to a lesser extent, the volume of traffic. Tab. 1 shows the parameters of the vehicle used in the calculations.

Tab. 1. The parameters of the vehicle used in the calculations

Parameter		Value	Used relation
Vehicle's mass	m [kg]	1343	(1)
Coefficient of the approximating function	k_1	1.6449	(4)
Coefficient of the approximating function	k_2	13.5849	(4)
Fuel consumption when the engine is idling	$G_{b.j.}$ [dm^3/h]	0.92	(6)

Using the data collected in the map (10) and equations (1), (5), (6), (8), for the given projected routes and selected vehicle the following operating parameters have been determined (Tab. 2).

Tab. 2. General characteristics of the projected route and the predicted operational performance of the selected vehicle

Route	Distance [m]	Time [s]	Consumed fuel [dm^3]	Q [dm^3/100 km]	CO_2 [g/km]	$\bar{V}$ [km/h]
1N	5470	608	0.421	7.70	181	32.4
1S	5425	545	0.395	7.29	171	35.8
2N	4106	437	0.306	7.45	175	33.9
2S	4049	480	0.310	7.66	180	30.3

A more detailed analysis of the results enables its graphic form, which was reproduced in Fig. 3.

Fig. 3. CO2 emissions on the routes: 1N i 2N

Analyzing the results shown in Tab. 2 can be concluded that for both directions the fastest route is the route No. 2. This route also gives lower fuel consumption and CO_2 emissions. Basing on Fig. 3 a more detailed analysis of the results in the assessment of road engineering solutions applied can be performed. In this assessment, it was decided to use as a criterion the CO_2

emissions. For example, on the route No. 1, 1.5 km from the starting point (Fig. 3) it can be seen in the appropriate section high level of CO_2 emissions (orange color - about 500 g/km). Designated section of the road corresponds to the junction of Al. Grunwaldzka (towards route No. 1) with Slowackiego Street, which is another important communication route of Gdansk. The extension of the green light phase for the direction of Al. Grunwaldzka is impractical solution, because it would create congestion on the perpendicular road. The ultimate solution to this problem seems to be building non-collision intersection, which a solution is already implemented. Another example of segment with high level of CO_2 emissions is a crossroads Kolobrzeska Street with Szczecinska Street (4.6 km from the starting point). In this place main stream is stopped for a long time for one-way street with relatively small traffic. Some settings correction for the traffic lights control would be appropriate.

8. Conclusions

The proposed method of creating of operating conditions map may be carried out using cheap and simple to operate equipment. The basic equipment is a vehicle equipped with a GPS system for measuring and registration the position. The method uses „tracking" procedure of the randomly selected vehicle in motion to limit the outflow of the individual driving style on the results. It also gives unexpected results. The average speed, in certain sections, is higher than permitted by the regulations. Prediction of operating parameters such as fuel consumption, CO_2 emissions can be made using a simple for calibration model (4). Made study [12] shows that for the selected vehicle the journey in a city traffic with a total length of more than 8 km must be performed. Work out the example of the map of operating conditions using shows the simplicity of comparing alternative routes for the selected vehicle, due to criteria such as travel time, fuel consumed or CO_2 emissions. This example also shows the possibility of assessment of road engineering solutions, which can be fully conclusive, if the map will be available for the operating conditions for all streets in the area under consideration, and not just for the major transportation routes.

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