Ivan Blagojević
Gradimir Ivanović
Slobodan Janković
Vladimir Popović

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A MODEL FOR GEAR SHIFTING OPTIMIZATION IN MOTOR VEHICLES

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Summary

This paper presents an implemented idea for gear shifting optimization with the aim of fuel consumption minimization. A new combined theoretical and experimental approach has been developed using the On-Board Diagnostic (OBD) technology which so far has not been used for this purpose. A matrix of driving modes according to which tests were performed is obtained and a special data acquisition system and analysis process have been developed. Functional relations between experimental test modes and adequate OBD parameters have been obtained and all necessary operations have been conducted to enable their use as inputs for the designed algorithm. The created model has been tested in real exploitation conditions on a passenger car.

Key words: *fuel saving, gear selection, optimization*

1. Introduction

Results of more studies [4, 8] with arguments point out that manual gear shifting may be considered to be an automatic process performed routinely but only for experienced drivers. However, for drivers who have just been granted a driving licence this process requires a mental effort. Automation is therefore acquired through experience, which is mostly independently acquired by a driver, without any subsequent suggestions based on facts.

In addition, detailed analyses of the relation between driver's behaviour and fuel consumption [1, 5, 10] proved that the elements of driver's behaviour that are related to gear selection, driving speed and acceleration and/or deceleration have the largest influence on fuel consumption. Fuel consumption at the same average driving speed can be increased up to 20% only due to a difference in the manner of gear shifting [6].

The effect of gear selection on fuel consumption at some driving speeds is presented in Figure 1; the results are obtained by investigations carried out by Volkswagen on a passenger car [7]. The increase in fuel consumption in percentages when driving in third and fourth gear is shown relative to the fuel consumption when driving in fifth gear at the speeds of 50 km/h and 90 km/h (fuel consumption in fifth gear at the speed of 50 km/h was accepted as the reference value – 100%). When the differences in fuel consumption in different gears in the same conditions are perceived, it can be concluded that significant savings in fuel consumption can be achieved by adequate selection, which has both great economic and environmental significance.

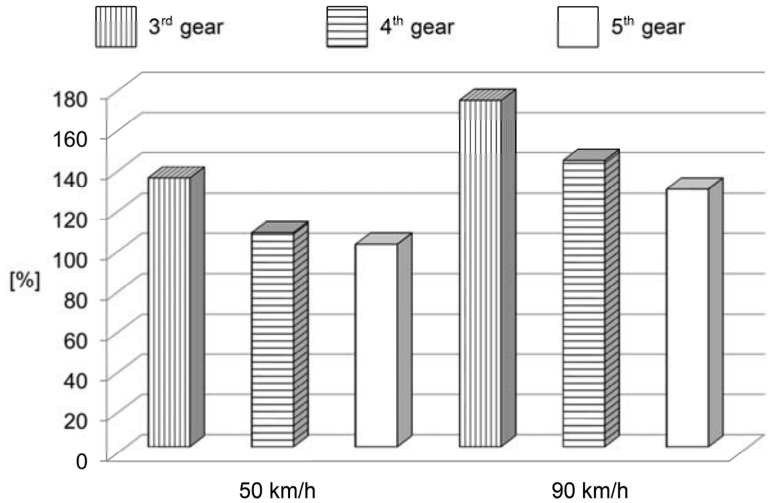

Fig. 1 Fuel consumption related to 50 km/h in 5th gear

Devices in the vehicle (e.g. Gear Shift Indicator – GSI) would to a large extent contribute to resolving the issue of timely gear shifting because they would clearly indicate to drivers, both inexperienced and experienced, which gear to use and in which moment [2, 9, 11].

A group of experts from Germany [3] submitted to the Economic Commission for Europe, namely to its Working Party on Pollution and Energy (GRPE) a proposal of amendments to the Regulation No. R83 with 05 series of amendments, in which they proposed changes in the testing procedure by using the so called special gear shifting strategy which defines gear shift points. They start their proposals of amendments by introducing a new paragraph proposing the definition: "Technical gear shift instrument means an information device or display, clearly perceptible (visible or acoustic) to the driver, which indicates proposed gear shifts in the case of special gear shifting strategy according to the manufacturer's instructions". In this way, the experts from Germany as proposers try to introduce the concept of a gear shift indicator in some regulations relating to motor vehicles for the first time.

Taking into account everything laid down previously in the text, the subject of investigation i.e. the study on timely and optimal gear shifting from the aspect of decreasing fuel consumption offered itself to the authors of this paper. At the same time, the functional dependence of some operating parameters of the internal combustion (IC) engine on output vehicle performances in some gears of the transmission in real service conditions as well as the possibility of the optimization of the operating parameters were included. Objective of the investigation was to create a model of gear shifting optimization of a motor vehicle with manual transmission aiming at achieving the minimum fuel consumption for the required performances while using an On-Board Diagnostic (OBD) system in the vehicle.

2. Experimental monitoring of and investigation into characteristic parameters in different driving modes

2.1. Selection of characteristic parameters

Selection of characteristic parameters was performed based on the assumption that some conclusions with respect to the selection of gear and fuel consumption for an actual vehicle which represent the data source can be reached by analyzing their values obtainable in real time for different driving modes. The basic criterion set in the selection of characteristic parameters is that their values can be obtained in real time through the vehicle OBD system, whose application in passenger vehicles has been mandatory for a longer period of time (USA since 1996, EU since 2001 for Otto engines). In this way, the subsequent fitting of new data acquisition systems into vehicles is avoided. Also, it was taken into account that characteristic parameters belong to the group of the so called standard parameters of the OBD system to which the access is enabled in all vehicles if the application is mandatory. The investigations are limited to a passenger vehicle with a fitted Otto engine and an electronic fuel injection system. The group of the selected characteristic parameters includes:

a) calculated load value – L [%]; Represents the ratio of the current intake air flow to the maximum possible intake air flow at an appropriate engine speed. This means that for a readout value of e.g. 33 % at certain engine speed it can be said that the engine at such engine speed was loaded only one third of the maximum possible load;

b) mass air flow – MAF [g/s]; Represents the intake air mass flow. The required fuel quantity is determined according to the value of MAF in order to provide stoichiometric combustion. This indicates the fact that apart from the modes at which additional mixture enrichment is performed, the current fuel consumption can be perceived through the value of mass air flow. In this respect, the monitoring of this parameter is of particular significance because it enables observing the differences in fuel consumption at different modes, and its values can be used for comparison and were not used for the calculation of absolute values of the current consumption, as these values were not of importance in the investigation;

c) throttle position – $\O$ [%]; Defines the degree of the throttle opening and can be approximated by the position of the accelerator pedal;

d) O_2 sensor voltage – O_2 [V]; The purpose of the classification of this parameter in the so called characteristic parameters is to observe the modes which require additionally enriched mixtures (where the mixture composition is not stoichiometric).

e) engine speed – n [rpm];

f) vehicle speed – v [km/h];

In the group of characteristic parameters, although only as a control parameter as it cannot be considered to be sufficiently precise, the parameter of the average fuel consumption – l_{mean} [litres per 100 km], which can be monitored by the vehicle on-board computer, is also included.

2.2. Obtaining data in real time at different driving modes

The basic condition to obtain a database of selected parameters of the vehicle operation and its engine is the implementation of experimental testing of the vehicle concerned in modes that correspond to real life occurrences and needs of drivers in daily traffic. In accordance with this and taking the significant differences which such modes may have in gear shifting into account, the classification of driving modes was performed by varying three basic variables, i.e.: vehicle speed, acceleration and current gear. In this way, a matrix of modes according to which tests were performed is obtained, i.e. the modes of vehicle motion at a constant speed (Table 1) and the vehicle motion with acceleration (Table 2) which, from the aspect of investigation, were considerably more complex.

Table 1 Modes of vehicle motion at constant speed

		constant vehicle speed [km/h]					
		40	50	60	70	90	60
Gear	2nd	✓	✓	-	-	-	-
	3rd	✓	✓	✓	-	-	-
	4th	-	✓	✓	✓	✓	✓
	5th	-	✓	✓	✓	✓	✓
Road gradient [%]		0					7

Table 2 Modes of vehicle motion with acceleration

	acceleration											
	0 to 60 km/h			40 to 60 km/h			50 to 70 km/h			60 to 90 km/h		
degree of acceleration / gear	full	med.	low	full	med.	low	full	med.	low	full	med.	low
2nd	-	-	-	✓	✓	✓	-	-	-	-	-	-
3rd	-	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
4th	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓
5th	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓
gear change at 2000 rpm	✓	✓	✓	-	-	-	-	-	-	-	-	-
gear change at 2500 rpm	✓	✓	✓	-	-	-	-	-	-	-	-	-
gear change at 3000 rpm	✓	✓	✓	-	-	-	-	-	-	-	-	-
gear change at 4500 rpm	✓	✓	✓	-	-	-	-	-	-	-	-	-
from 2nd to 3rd at 3000 rpm	-	-	-	✓	✓	✓	-	-	-	-	-	-
from 3rd to 4th at 2500 rpm	-	-	-	✓	✓	✓	-	-	-	-	-	-
from 3rd to 4th at 3000 rpm	-	-	-	-	-	-	✓	✓	✓	-	-	-
from 4th to 5th at 3000 rpm	-	-	-	-	-	-	-	-	-	✓	✓	✓

The intensity and the degree of acceleration by which a driver's need with respect to time needed for reaching the desired speed is defined have gained special significance in modes with acceleration. In this respect, three degrees or levels of acceleration were established, which were expressed through the position of the accelerator pedal and gave more precise information about the range of throttle position changes in the engine intake manifold expressed in percentage, and which can be monitored as a datum (throttle position - $Ø$ [%]):

- "full throttle" – degree of acceleration defined by the maximum position of the accelerator pedal, and/or degree of the throttle opening which changes within the limits of over 70 %. This level of acceleration corresponds to the driver's need for maximum acceleration performances and/or minimum time required in situations of critical vehicle overtaking;

- "medium throttle" – degree of acceleration defined by the mid position of the accelerator pedal, and/or the throttle position varying within the limits from 30% to 70%. This level of acceleration corresponds to average driver's needs during overtaking or reaching higher speed of motion;
- "low throttle" – degree of acceleration defined by the throttle position varying within the limits up to 30 %. This level of acceleration corresponds to the increase in the vehicle speed due to a change in the traffic flow speed or reaching higher constant permissible speed.

The vehicle in which the investigation was carried out was Toyota Yaris 1.0, production year 2001 (engine type 1SZ-FE, 998 cm^3, 50 kW). It is important to mention that tests in all modes were carried out under the same weather conditions.

With the software-hardware aided support and the existing OBDII system the reading of characteristic parameters in real time and their storage in the database for the purpose of further investigation was enabled (Fig. 2).

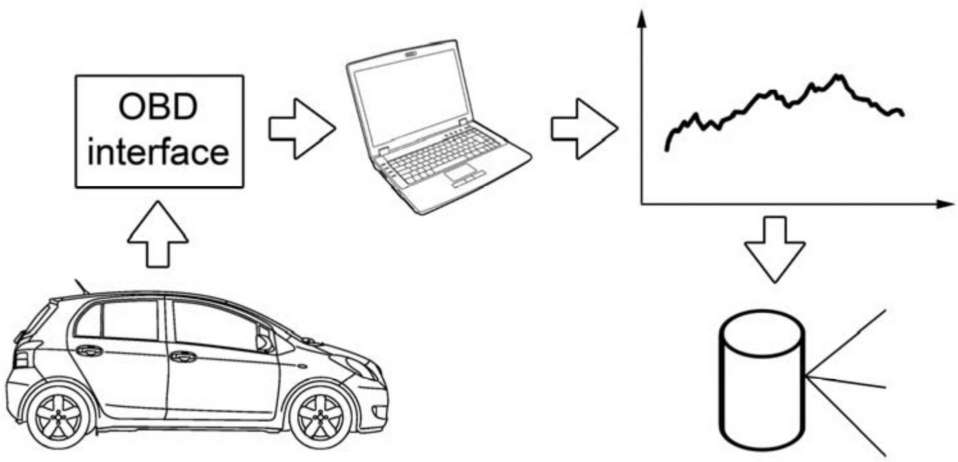

Fig. 2 Data flow

During testing, the time of commencement and completion of each of the mentioned modes was recorded in order to locate it in the time database in the later analysis as soon as possible. The so formed, unique database enabled the obtaining of new, derived databases containing additional data required for the investigation into e.g. minimum, maximum and average parameter values for each mode, the speed of parameter change, the mode duration, as well as mutual ratios of individual parameters and their numerical values as additional indicators. In this way, the value $L/Ø$ representing the ratio of the engine calculated load value L (in percentage) to the throttle opening $Ø$ (in percentage) was formed, which seemed particularly interesting during the testing.

As an example of the obtained data processing the case of acceleration from 50 to 70 km/h is presented in the paper, considered through twelve modes: four gears (3^{rd} gear, 4^{th} gear, 5^{th} gear and shifting from 3^{rd} to 4^{th} gear at 3000 rpm) multiplied by three degrees of acceleration ("full throttle", "medium throttle" and "low throttle"). The overview of the obtained characteristic parameters and their minimum, maximum and mean values during this acceleration (where applicable) for all modes is given in Table 3.

The first group of modes which was analyzed was the one with the maximum degree of acceleration designated as "full throttle". The calculated loads in all gears were close to maximum and exceeded 90 %, although it should be mentioned that in third gear the entire acceleration process took place at the maximum load of 100 % and the maximum torque, which resulted in maximum acceleration performances and considerably less time consumption in comparison with other modes. The average values of the mass air flow decreased with the shift to a higher gear, while the total consumption and the sum of mass air flows were increasing with the shift to a higher gear, which could be explained by effects of the acceleration duration (shorter acceleration time with larger average consumption in the final calculation may give lower total consumption). Real proof is the mode in third gear which at the largest average mass air flow reaches the most favourable total consumption in the shortest time period. Consequently, this can be considered to be the best solution for the given conditions, which describes the highest value of the parameter $(L/Ø)_{mean}$=1.33 relative to other modes. In fifth gear, the maximum engine load could not be utilized at "full throttle" and the maximum throttle opening, which eliminates such mode due to the highest consumption, and due to the less torque reserve which can be used for acceleration needs. The mode with gear shifting at an engine speed of 3000 rpm is in this respect considerably more favourable, but to realize the given acceleration 3 seconds more are needed relative to the "fastest" third gear.

Table 3 Overview of obtained characteristic parameters during acceleration from 50 to 70 km/h for all modes

gear / degree of acceleration	*L* min/max/mean [%]	MAF min/max/mean [g/s]	Σ MAF [g/s]	*Ø* min/max/mean [%]	n_{mean} [rpm]	O_{2mean} [V]	*t* [s]	l_{mean} [l/100km]	$(L/Ø)_{mean}$ [-]
3rd / full	99/100/100	25/33/28	84	74/76/75	3121	0.77	4	-	1.33
4th / full	91/100/94	17/24/21	85	80/80/80	2443	0.73	7	10.8	1.20
5th / full	89/91/90	15/20/17	90	79/80/79	2001	0.70	9	10.2	1.13
from 3rd to 4th at 3000 rpm / full	71/100/91	20/25/23	72	72/79/75	2661	0.65	7	9.8	1.15
3rd / medium	59/68/61	17/19/18	82	32/39/37	3152	0.47	9	10.3	2.28
4th / medium	63/80/73	14/19/17	76	32/42/38	2394	0.70	9	9.0	2.37
5th / medium	57/87/80	13/19/16	84	33/44/40	1980	0.46	10	9.6	2.08
from 3rd to 4th at 3000 rpm / medium	76/82/78	17/22/20	79	19/36/28	2713	0.80	8	9.3	2.23
3rd / low	41/75/57	14/17/15	90	24/29/27	3142	0.56	10	9.4	2.17
4th / low	49/64/60	13/15/14	84	25/26/26	2485	0.43	12	8.4	2.39
5th / low	67/71/69	11/13/12	76	22/26/25	2025	0.72	12	7.5	2.72
from 3rd to 4th at 3000 rpm / low	51/61/56	13/15/14	106	25/26/26	2697	0.61	14	7.8	2.25

Increased values of the O_2 parameter are noticeable which indicate a richer mixture (over 0.7 V) in all "full throttle" modes and they do not refute the drawn conclusions. On the contrary, if some modes were characterised very rich mixture and other were not, more essential differences could occur when comparing mass air flows and fuel consumption.

The modes associated with the "half throttle" degree of acceleration were characterized by calculated load values which increase with a shift to a higher gear and the average values vary from 61% for third gear to 80% for fifth gear, which is characterized by the largest throttle opening (in average 40%). While the average values of the mass air flow increase with a shift to a lower gear, the minimum cumulative flow is achieved in fourth gear. Parameter $(L/Ø)_{mean}$ again confirmed the optimum selection of gear as it reached the maximum value (2.37) for the mode in fourth gear relative to modes in other gears at the same acceleration level. Fifth gear also represents a favourable selection, although the measured acceleration duration is by a whole second longer (which is not a critical criterion for the degree of acceleration not being the maximum – “full throttle”).

Modes characterized by a small degree of acceleration – “low throttle” – are most similar to the modes of constant motion speed, and in this respect the optimum selection tends to gears with a minimum possible engine speed, which was confirmed by the analysis of the acceleration modes at “low throttle” of 50 to 70 km/h. In support of this, numerical data are also shown: the minimum value of both the average and the total mass air flow, the acceleration time of 12 seconds which is satisfactory relative to other modes, but also the ratio $(L/Ø)_{mean}$ which reached the highest value (2.72) in this mode relative to other modes with the same degree of acceleration, by which the role of the mentioned parameter as one of the criteria when selecting the optimum gear was proved.

The acceleration mode with the shift from third to fourth gear at 3000 rpm which proved to be unfavourable at low acceleration should also be pointed out, as well as the use of third gear. The basic reason lies in the fact that without the need for higher torque the areas of higher engine speeds are used in a longer time interval characteristic of this type of acceleration. Therefore, in the case of a gear shift, due to the mode nature, 3000 rpm was reached, and in third gear even the maximum of 3140 rpm was reached.

The obtained databases, processing and analysis of the obtained values represent the base for the preparatory phase of the created model based on which the executive phase thereof and the algorithm itself can be implemented.

3. Optimization model

3.1. Model criteria

The concept of gear shifting optimization of motor vehicle transmission means timely continuous determination of a gear which satisfies the set criteria. The basic criterion which the authors of the paper opted for was the criterion of minimum fuel consumption for current conditions imposed by the driver-vehicle-environment system.

An additional criterion is associated with the maximum acceleration modes at which minimum acceleration time should be provided as well as conditions for this. This criterion was imposed by the needs of drivers that may affect the traffic safety (mostly related to the overtaking process) and as such it becomes primary in the specified cases.

3.2. Impacts of driver-vehicle-environment system to the model

Relevant factors for gear shifting in different modes imposed by the driver-vehicle-environment system may be quantitatively expressed by the values of one or more characteristic parameters or data which at the same time represent input data required for the process of optimization.

It is important to mention that the model has the task to respond to the input parameters and the data reported by the driver-vehicle-environment system with the recommended gear and to potentially correct driver’s behaviour only in this segment. Although the conclusions on the economy of individual modes irrespectively of gear (e.g. motion at a slower speed reduces fuel consumption or gradual acceleration is more economic than very intensive acceleration), the model does not provide such information. Hence, the model does not comment on the imposed conditions, but can mitigate their consequences by giving recommendation.

Driver: Conditions imposed by the driver can be observed as his/her desires transmitted to the vehicle through appropriate controls. Basic measurable data directly affected by the driver are vehicle speed and degree of acceleration. In addition, current position of the clutch and the transmission control, i.e. gear selection are also factors determined by the driver.

Vehicle: A vehicle determines a group of data expressed by its technical characteristics, primarily referring to engine and transmission. Such data include: number of gears, gear ratios, final drive ratio, dynamic rolling radius, characteristic parameters that can be read by the vehicle OBD system, but also engine characteristics (such as principle of operation, manner of engine operation control and providing mixture – carburettor or fuel injection, torque curves and diagrams of specific fuel consumption) which have effect on the manner of changing characteristic parameters and their minimum, maximum and mean values, depending on the mode being implemented. These data can be considered as invariable only in case of the same vehicle brand and type with the same type of engine and transmission.

Environment: Environmental factors having effect on the optimization of gear shifting are expressed by motion resistance. Gradient resistance and air resistance which increase with square of velocity are expressed by their effects. In both cases, changes in their values have a direct impact on the engine load value as well as on the values of other characteristic parameters if some of them are not maintained constant (vehicle speed, engine speed, throttle opening).

3.3. Model structure – preparatory and executive phases

Having observed the different effects of the “vehicle” factor on the one hand and the “driver” and “environment” factors on the other hand, the development of the model meant its division into the preparatory phase and the executive phase (Fig. 3), which was conditioned by the previous division of data and parameters used by the model into:

a) a group of parameters which are read out in real time by the OBD system, whose values are changing and depend on the driver’s requirements and road resistance. These parameters fall into a group of characteristic parameters that were used during the implemented investigation and they are (a1):

- calculated load value L;
- throttle opening $Ø$;
- engine speed n;
- vehicle speed v.

The obtained values of the mentioned parameters, describing the current mode of motion, are used directly by the model algorithm in order to recommend an optimum gear.

b) a group of data and criterion parameters that are determined by the technical characteristics of the vehicle, its engine, transmission and the OBD system, and which affect, directly or indirectly, the values of the criteria which are an integral part of the algorithm structure. The data refer to the values declared by the manufacturer and are considered as constants not derived and they are (b1):

- gear ratios i_i;
- final drive ratio i_o;
- dynamic rolling radius r_d;
- a list of characteristic parameters provided by the OBD system of significance for the model.

Criterion parameters are, on the other hand, the values which are not declared (except $n_{i\min}$, $n_{Me\max}$) but derived on the basis of investigations that should be implemented (section 2) in order to reach the numerical values of these parameters used by the model algorithm. Such criterion parameters include (b2):

- minimum engine speed for each gear $n_{i\min}$;

- engine speed at which the maximum torque is reached $n_{Me\max}$;
- initial throttle position (corresponding to the initial position of the accelerator pedal) $Ø_0$;
- maximum calculated load value $L_{i\mathrm{const}}$ at the maximum value of the throttle opening $Ø_{i\mathrm{const}}$ indicating the constant speed driving mode in each gear;
- minimum calculated load value $L_{a\max}$ at the minimum throttle opening value $Ø_{a\max}$ indicating the maximum acceleration driving mode;
- limit values of the derived value $L/Ø$ for each gear for acceleration modes which exclude top gear $(L/Ø)_{i\min}$;
- engine speed-vehicle speed ratio relative to the transmission ratio i_c;
- transmission ratios intervals for determining current gear $[i_{i\min}, i_{i\max}]$.

Based on the above mentioned it can be concluded that the second group requires some data acquisition (b1) and analysis for the purpose of obtaining the mentioned parameters (b2), which represents the adjustment of the model to the specific vehicle. This is a task of the model preparatory phase (Fig. 3). The investigation is implemented as partially shown in section 2 on the basis of the data (b1) and the database formed on the basis of experimental tests, according to the specified modes. Therefore, the mentioned data (b1) and the database obtained by the experimental investigations make the preparatory phase input, while parameters (b2) are the preparatory phase output.

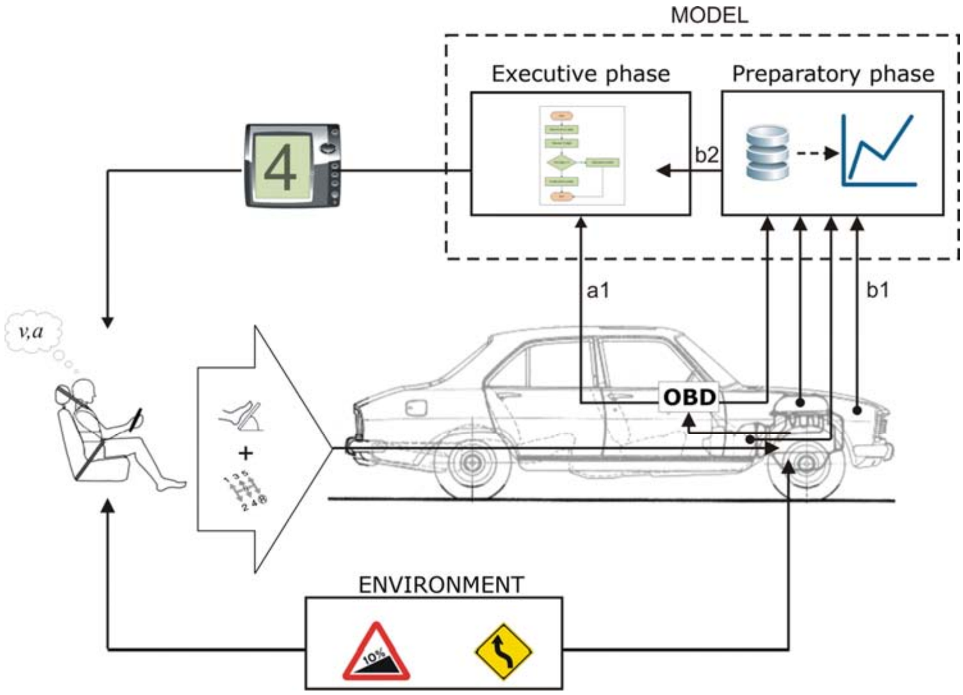

Fig. 3 Model scheme

The model executive phase uses only parameters as inputs, i.e. two groups; the first group of parameters (a1) comes from the vehicle OBD system, while the second group of the so called criterion parameters (b2) is obtained directly from the preparatory phase (Fig. 3). The group of criterion parameters (b2) is required prior to the beginning of downloading the parameters (a1), in order to be integrated into the algorithm and its criteria. The integration of parameters (b2) is performed by the software, whereby the user should enter the required values into appropriate fields (Fig. 5). Downloading the group of data (a1) from the vehicle OBD system is automatically performed in real time, for which a specific software part is foreseen, whose task is to process the obtained data and adjust them to the algorithm input.

The core of the executive phase is the optimization algorithm which provides the result of the entire model in the form of a recommended gear (Fig. 3).

3.4. Model algorithm

The core of the optimization model is the algorithm which should result in the recommendation of a gear. The input parameters of the vehicle operation in real time, expressed by characteristic parameters, flow through the algorithm structure comparing themselves with the set criteria which direct them toward a recommended gear. The mentioned algorithm criteria will be explained in detail in the description of its structure which follows.

The algorithm structure is shown in Fig. 4a and Fig. 4b. Its elements are marked by letters, i.e. I – input, D – if-then statement, P – assignation or computation procedure, O – output.

The algorithm begins with the input I which collects and enters the required parameters. As already explained, there are two groups of input parameters in the algorithm: the group of parameters (a1) which are downloaded from the vehicle OBD system and represent the vehicle operation parameters in real time ($L, Ø, n, v$) and the group of criterion parameters (b2) representing the result of the model preparatory phase and used for the criteria and the required computations ($L_{i\mathrm{const}}$, $Ø_{i\mathrm{const}}$, $L_{a\max}$, $Ø_{a\max}$, $(L/Ø)_{i\min}$, i_c, $[i_{i\min}, i_{i\max}]$).

The if-then statement P0 determines whether the vehicle is in the stationary position ($v = 0$) or in motion ($v \neq 0$). If the vehicle is not in motion, the procedure returns to the beginning, because in the case of a stationary vehicle it is not necessary to determine the gear. If the vehicle is in motion, the procedure P0 follows by which the transmission ratio is computed based on engine speed, vehicle speed and parameter i_c, as follows:

$$i = i_c \cdot \frac{n}{v} \tag{1}$$

where n is represented in rpm, v is represented in km/h, and i_c is obtained in the preparatory phase by the following equation:

$$i_c = \frac{3600}{1000} \cdot \frac{\pi}{30} \cdot \frac{r_d}{i_o} \tag{2}$$

where r_d [m] is the dynamic rolling radius and i_o [-] is the final drive ratio.

Upon the computation of the gear ratio, a series of if-then statements (D1, D2, D3, D4, D5) follow, in which it is determined which gear is engaged. Due to the dynamism of the process of reading the parameters of engine speed and vehicle speed, the obtained gear is not compared with the discrete values of gear defined by the manufacturer, but some deviations defined by the interval $[i_{i\min}, i_{i\max}]$ obtained in the preparatory phase are permissible. If the obtained transmission ratio belongs to the interval for certain gear, in the next procedure (P2 to P5) the values used in the further process are assigned, i.e. to the parameter CG the current gear is assigned, and to the parameters L_{const}, $Ø_{\mathrm{const}}$ and $n_{\min}$ the appropriate values of these parameters for this gear $L_{i\mathrm{const}}$, $Ø_{i\mathrm{const}}$ and $n_{i\min}$ are assigned. The parameters L_{const}, $Ø_{\mathrm{const}}$ and $n_{\min}$ determine one by one the maximum calculated engine load value for the constant speed driving mode, the maximum throttle opening value for the same mode and the minimum recommended engine speed at which the engine can provide the torque. If first gear is engaged (P1: CG = 1) then the if-then statement D6 on exceeding the engine speed in first gear follows (the adopted 3500 rpm, taking into account that first gear is exclusively intended for starting and overcoming large gradients). If the engine speed is exceeded, second gear is recommended by the output O1.

If it is determined by the if-then statements D1 to D5 that no gear is currently engaged, it shall be determined by the if-then statement D7 whether this is a case of higher motion speed (higher than 40 km/h) or less at the minimum throttle opening (which excludes short-time gear shift). If the speed is less than 40 km/h, no gear is recommended (RG = 0) by the output O2, otherwise, it is the operating mode in which fuel is unnecessarily spent and so the recommendation O3 follows with the highest possible gear computed by the procedure P6.

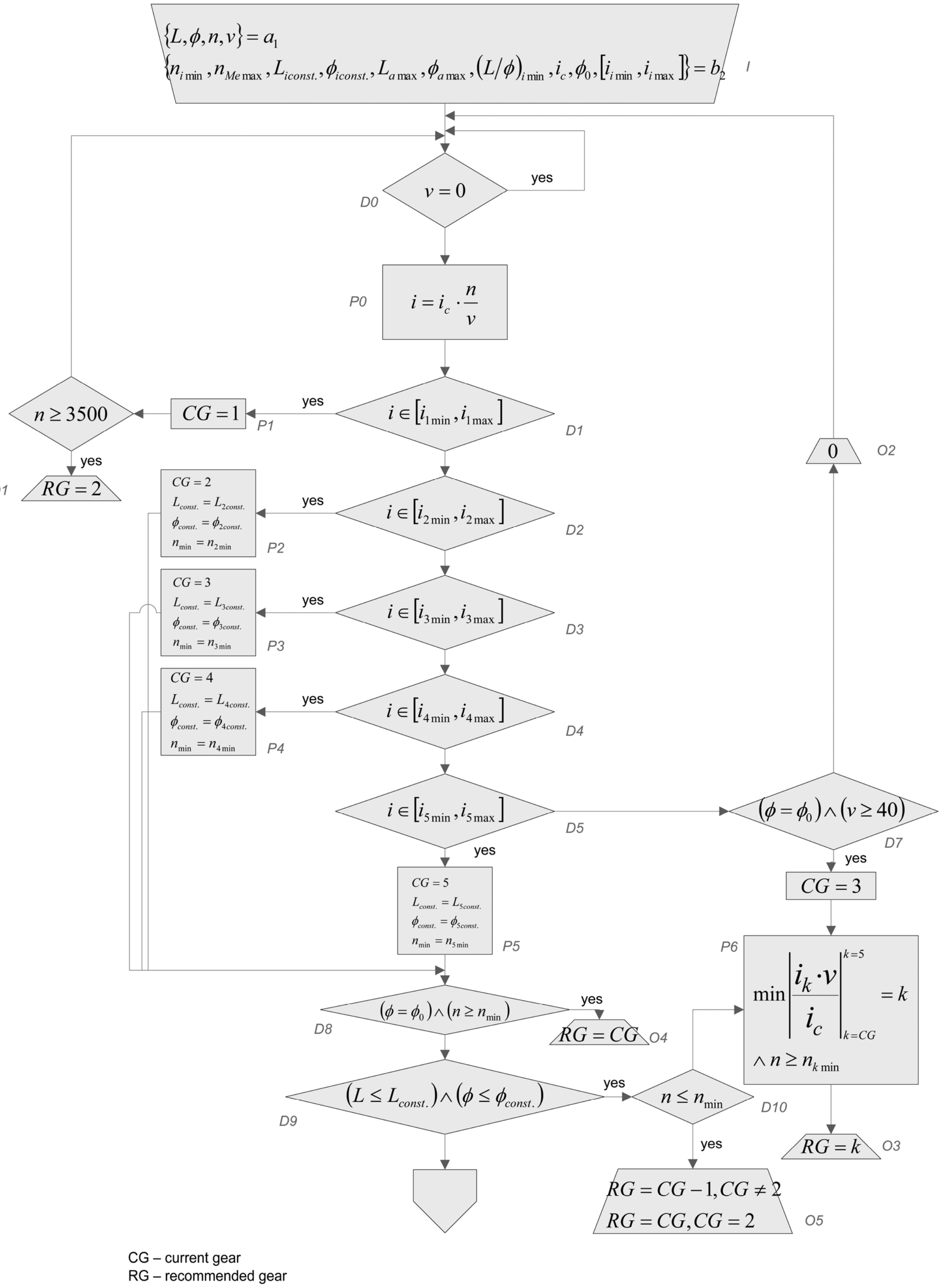

Fig. 4a Model algorithm (part I)

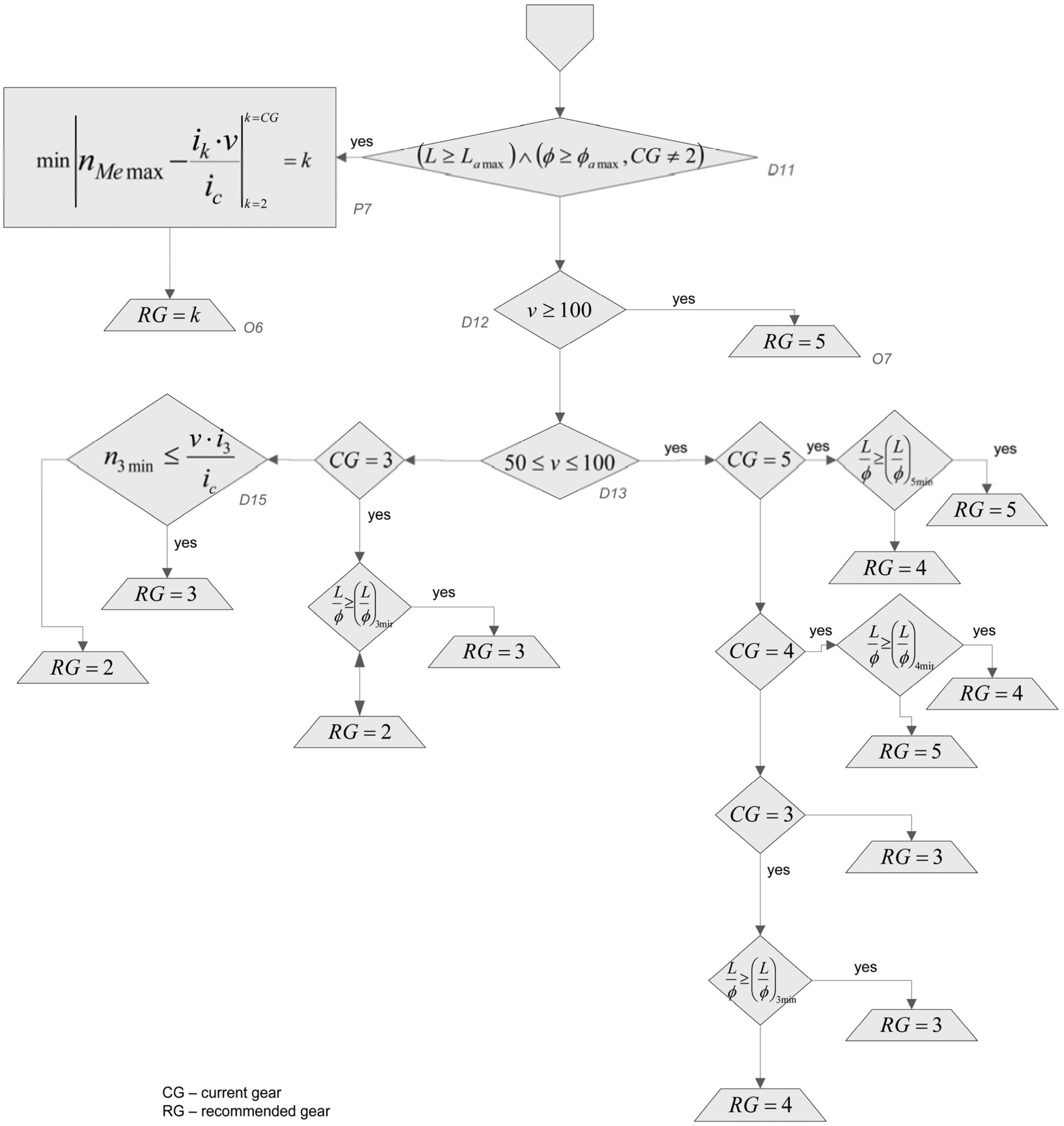

Fig. 4b Model algorithm (part II)

If one of the gears is engaged (2nd, 3rd, 4th or 5th) then the if-then statement D8 follows, which checks whether the throttle is in idle position and whether the accelerator pedal is pressed by comparing the throttle opening $Ø$ with its initial position $Ø_0$. For a positive answer, the output O4 follows according to which current gear is retained. Otherwise, the if-then statement D9 follows, by which it is checked whether the mode of motion is at an (approximately) constant speed, in comparison with both appropriate limit values L_{const}, $Ø_{const}$ obtained by the analysis in the preparatory phase. In case that the mode of uniform motion is recognized, first, D10 is performed to check whether the engine speed is less than the minimum for this particular gear ($n < n_{i\min}$). For a positive answer, the output O5 follows, which gives an instruction to shift to a lower gear (except for second gear which remains the same), and for a negative answer, the gear is obtained at the output O3 in the procedure for computing the highest possible gear P6.

If it is not the mode of (approximately) uniform motion speed, it is checked whether this is the mode of maximum acceleration D11, by comparing current parameters of the calculated load value and the throttle opening with limit values for such mode $L_{a\max}$ i $Ø_{a\max}$. For second gear, the comparison of $Ø$ with $Ø_{a\max}$ is not foreseen, because the analysis in the preparatory phase proved that at the maximum acceleration in this gear high values are often not reachable due to a short duration of acceleration. For the detected maximum acceleration mode a recommendation of gear follows which is by the engine speed most close to the one corresponding to the maximum engine torque $n_{Me\max}$, which is computed by the procedure P7 and displayed as the output O6.

If it is not the mode of maximum acceleration, the driving mode with mid and low degrees of acceleration remains. If it is established by the if-then statement D12 that the current vehicle speed is higher than or equal to 100 km/h, the highest gear (RG = 5) is recommended directly by the output O7 as it is the case of high speeds without any requests regarding acceleration time. If motion speeds are between 50 and 100 km/h, which is determined by the if-then statement D13, third, fourth or fifth gear are available, depending on the current ratio of the calculated load value and the throttle opening value ($L/Ø$) and satisfying the criterion that this ratio is higher than its minimum value for this gear $(L/Ø)_{i\min}$, which is the condition that gear needs not be shifted.

For vehicle speeds less than 50 km/h, second or third gear are available for recommendation whereby third gear is preferential if it is according to D14 $(L/Ø) > (L/Ø)_{3\min}$, and if the engine speed in third gear is greater than the minimum one according to D15. Otherwise, second gear is recommended.

3.5. Verification of developed model

The developed model was tested in real service conditions and by driving the experimental vehicle Toyota Yaris, as the investigation for different driving modes was carried out, representing the mandatory part of the preparatory phase of the model.

The model implementation can be presented as the following sequence:

1. collecting the group (b1) parameters and data;
2. application of the presented method of the combined theoretical and experimental investigations by which the values of characteristic parameters are collected and their statistical processing and analysis are carried out (section 2);
3. based on the implemented method, appropriate conclusions are drawn with regard to the values of the group (b2) parameters and these values are entered using the appropriate software user interface (Fig. 5).
4. Upon entering the group (b2) data and parameters, they are automatically positioned in the algorithm, which can be started by using the software aid. Previously, a computer, i.e. hardware is connected with the appropriate vehicle OBD system interface, by which the reading of characteristic parameters in real time of the vehicle service is enabled.

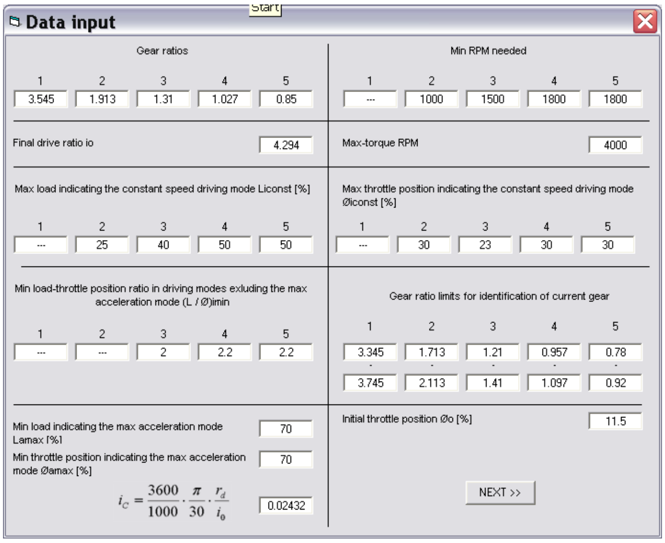

Fig. 5 Software user interface

Fig. 6 shows a software output window which, for the needs of this experimental investigation, in addition to recommended gear in the form of the most noticeable number, displays also all relevant parameters in order to perform the control of the algorithm operation in real conditions.

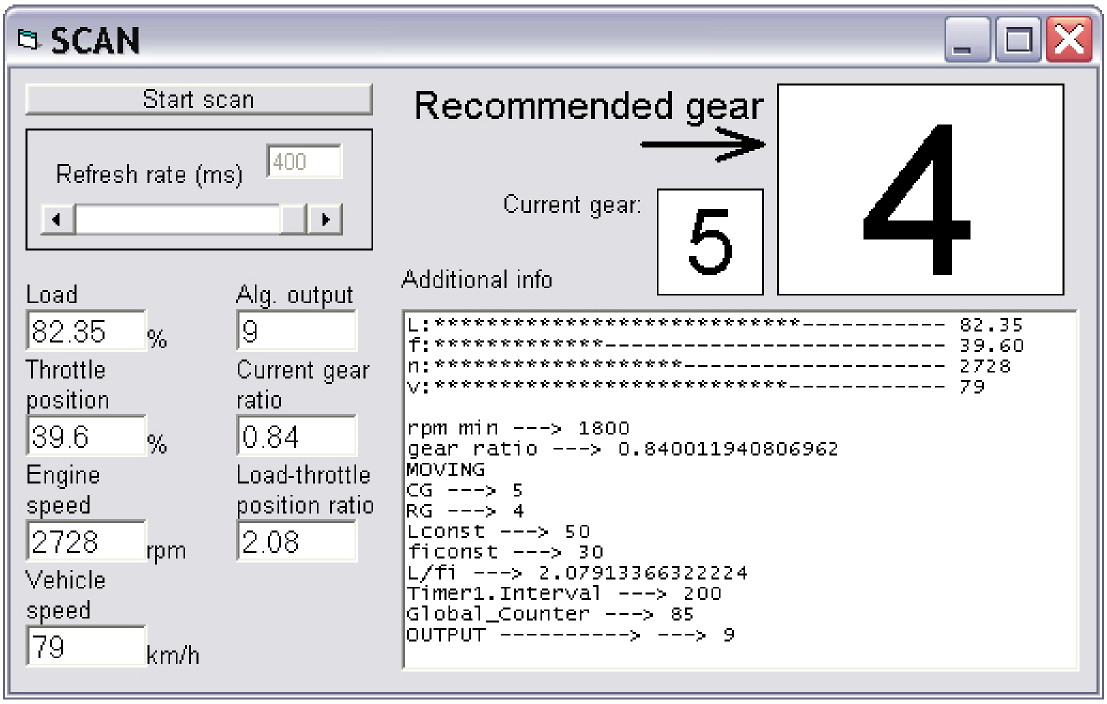

Fig. 6 Software output window of the model executive phase (algorithm) with recommended gear

The developed model was tested in real exploitation conditions and by driving the experimental vehicle Toyota Yaris. More than noticeable fuel consumption reductions were recorded, but they are not particularly pointed out, taking into account their relative significance with respect to the value and composition of a statistical sample.

4. Conclusion

The issue of gear shifting optimization still represents a real challenge to scientists and experts in the field of motor vehicles. This paper presents an implemented idea on how it is possible to perform gear shifting optimization for the purpose of reducing fuel consumption. Originality can be observed in the approach of solving the issue, whereby the study has not been done to improve existing models and the manner how they can be reached, but a new combined theoretical and experimental approach to investigation has been developed, with the use of the OBD technology which so far has not been used for this purpose, and which, for the needs of the developed model, can be used in vehicle daily service without any changes in it. The verification of the model has been realized through its implementation into an experimental vehicle. The final verification of results, based on the objective analysis of the test results in a representative sample of drivers, shows a decrease in fuel consumption. Also, driver training schools should not be forgotten, where the application of the model would also have educational character.

There is considerable room for further investigations in the area. This primarily refers to the implementation of the presented theoretical and experimental investigations and to a potential modification of the model for different categories of motor vehicles, both passenger and freight vehicles and buses. In addition, it is necessary to investigate the behaviour of vehicles with fitted Diesel engines and to establish possible differences in the given modes. Also, further investigation is possible in the domain of transmission with a larger number of gears (in passenger vehicles there are transmissions with six gears, while in freight vehicles and buses this number is even larger).

Also, investigations should be carried out into the verification of the model efficiency in fuel saving and preparation costs. The verification of the model with respect to fuel saving requires complex tests which would include very precise modes of motion and a statistically valid number of different drivers to be selected according to various criteria (professionals/amateurs, young/old, inexperienced/experienced, etc.). Also, investigations referring to the effects that the model has on exhaust emissions also should not be neglected.

REFERENCES

[1] I. de Vlieger, D. de Keukeleere, J.G. Kretzschmar: *Environmental effects of driving behaviour and congestion related to passenger cars.* Atmospheric Environment, 34(27), 4649-4655 (2000).

[2] J. Decicco, M. Ross: *Recent advances in automotive technology and the cost-effectiveness of fuel economy improvement*. Transportation Research Part C, 1(2), 79-96 (1996).

[3] Experts from Germany: *Proposal for draft amendment to the 05 series of amendments to Regulation No. 83 (Emissions of M1 and N1 categories of vehicles).* to: Economic Commission for Europe, Inland Transport Committee, World Forum for Harmonization of Vehicle Regulation (WP.29), Working Party on Pollution and Energy (49th GRPE), 4 November 2004.

[4] J.A. Groeger, B.A. Clegg: *Automaticity and driving: Time to change gear conceptually*. In V.E. Carbonell, T. Rothengatter (eds.): Traffic and transport psychology: Theory and application, Pergamon Press, Oxford 1997.

[5] J.N. Hooker: *Optimal driving for single-vehicle fuel economy.* Transportation Research Part A, 22(3), 183-201 (1988).

[6] National Research Council: *Automobile fuel economy – How far should we go*? National Academy Press, Washington D.C. 1992.

[7] K.P. Schindler: *Fuel savings by car*. Presented at the Strategies for promoting fuel saving on-board technologies – OPET workshop, Brussels, Belgium 2003.

[8] D. Shinar, M. Meir, I. Ben-Shoham: *How automatic is manual gear shifting*? Human Factors, 40(4), 647-654 (1999).

[9] M. van der Voort, S. M. Dougherty, M. A. Van Maarseveen: *Prototype fuel-efficiency support t*ool. Transportation Research Part D, 9(4), 279-296 (2001).

[10] J. van Mierlo, G. Maggetto, E. van de Burgwal, R. Gense: *Driving style and traffic measures – influence on vehicle emissions and fuel consumption.* Proc. IMechE, Part D: Journal of Automobile Engineering, 218(N1), 43-50 (2004).

[11] J. Vanke: *Techniques for influencing driving - The driver's view*. Presented at the ECMT Expert Workshop on In-Car Technology, Delft, Netherlands 1996

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Dr Ivan Blagojević
Prof. dr Gradimir Ivanović
Doc. dr Vladimir Popović
University of Belgrade - Faculty of Mechanical Engineering
Kraljice Marije 16
11125 Belgrade, Serbia
Prof. dr Slobodan Janković
University of Novi Sad – Faculty of Technical Science "Mihajlo Pupin"
Đure Đakovića bb
23000 Zrenjanin, Serbia