DEVELOPMENT OF ALGORITHM FOR REDUCTION OF FUEL CONSUMPTION AT LIGHT DUTY MOTOR VEHICLES

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INTRODUCTION

The development of modern motor vehicles is based on increasing the power and the torque of IC engine providing improvement of the vehicle dynamic properties what can be carried out only by introduction of the new technical and technological solutions in the power train. Thereby, special attention is dedicated to reduce the fuel consumption and the pollutants emissions. Considering light cargo delivery vehicles, insisting to increase the mass of the empty vehicle and its load capacity is the priority. The solution of those complex demands mentioned above is generally the compromise for a car manufacturer, which is confirmed through the certification testing of the vehicle. But, how does it look in the reality? Does the exploitation of some light cargo delivery vehicle truly confirm the results of the certification testing? How much each driver can participate in the realization of such heavy task? Finally, the most important, is it possible to manipulate by costs during exploitation of the vehicle regarding the fuel consumption? Having in mind these questions, a realization of the following objectives will be presented in the paper:

1. Make the calculation of the fuel consumption during vehicle driving by different driving cycles.
2. Perform the analysis with a view to define optimal drive regarding to fuel consumption.
3. Define parameters in order to obtain optimal drive conditions considering the fuel consumption.
4. Recommend the algorithm to obtain an optimal drive that leads to reduce of fuel consumption.

DEFINITION OF FUEL CONUMPTION FOR TEST VEHICLE

For this purpose, a one light duty motor vehicle is chosen. Having in mind the limited number of pages for this paper, the technical data of the light duty motor vehicle can be easily found in [5]. In order to perform further fuel consumption analysis of the light duty cargo delivery vehicle it is necessary to obtain the diagram of the constant specific fuel consumption (g_e) as a function of engine speed and engine load i.e. mean effective pressure (p_e). This diagram, with the constant specific fuel consumptions from 240 to 800 g/kWh, is shown in the Figure 1.

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Starting from the motor vehicle, general equation of the vehicle movement can be written in the following form:

$$\sum R = R_f \pm R_u + R_z \pm R_j = m\,g\,f\cos\alpha \pm m\,g\sin\alpha + \frac{1}{2}c_x\,A\rho v \pm m\lambda_{mj}\,\frac{dv}{dt} \qquad (1)$$

where are m - vehicle mass, g - ground acceleration, α - road grade, c_x – air drag coefficient, A - vehicle frontal area, v – velocity, ρ - air density, λ_{mj} - rotating component mass coefficient. Inserting known rolling radius of the tire r_d , total propulsion moment at the ground M_T can be written as:

$$M_T = F_T r_d = \sum R\, r_d = \left[m\,g\left(f\cos\alpha \pm \sin\alpha\right) + \frac{1}{2}c_x\,A\rho v \pm m\lambda_{mj}\,\frac{dv}{dt}\right] r_d \qquad (2)$$

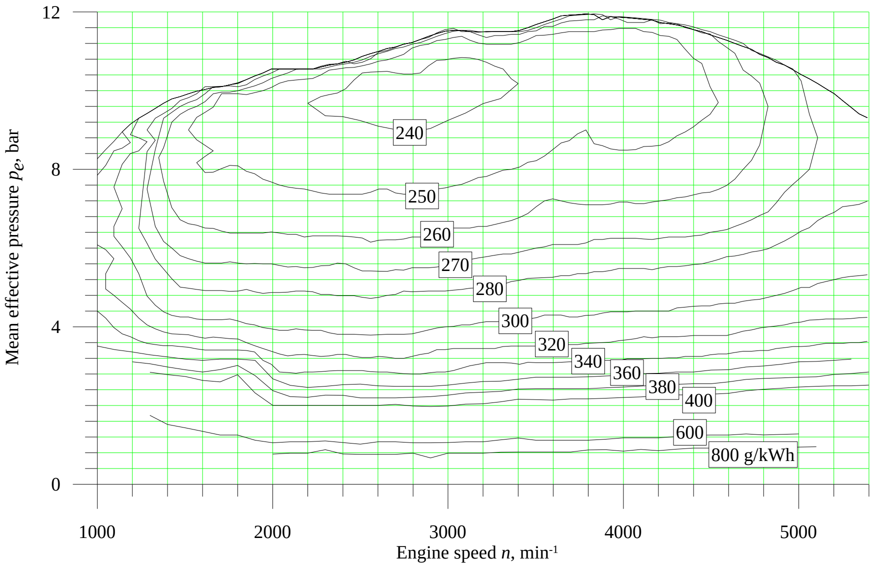

Figure 1: *Original fuel consumption diagram*

Considering the correlation between effective engine torque and the propulsion moment at the ground always persists, knowing total transmission ratio i_T and efficiency of the transmission η_T, the following equation can be given by:

$$M_e = \frac{M_T}{i_T\eta_T} = \frac{\left[m\,g\left(f\cos\alpha \pm \sin\alpha\right) + \frac{1}{2}c_x\,A\rho v \pm m\lambda_{mj}\,\frac{dv}{dt}\right] r_d}{i_T\eta_T} \qquad (3)$$

From the expression above the direct correlation between road resistances incorporated in the engine torque value M_e that is used for the motor vehicle movement is obvious. On the other hand, using kinetic correlations, engine *rpm* by which it generates the engine torque needed to overcome total road resistances can be defined by:

$$\omega = \frac{i_T\, v}{r_d} \quad \Rightarrow \quad n = \frac{\omega}{2\pi} \tag{4}$$

When the values of the engine torque needed to prevail road resistances are clearly defined as well as the corresponding engine *rpm* as a function of total transmission ratio i_T, applying the interpolation method and digitalized form of the fuel consumption diagram given in the Figure 1, the current values of the specific consumption g_e for the related case of the vehicle movement can be calculated.

Thus, with a known density fuel value, the hourly fuel consumption in the volumetric units can be defined as:

$$Q = \frac{G_h}{\rho} = \frac{g_e Pe}{\rho} \quad \left[\frac{l}{h}\right] \tag{5}$$

Finally it is possible to determine the road travel fuel consumption closer to everyday motor vehicle driver, i.e. fuel consumption by travel made in *l/100 km* by following expression:

$$Q_{l/100\mathrm{km}} = Q\frac{100}{v} \quad \left[\frac{l}{100km}\right] \tag{6}$$

DEFINITION OF FUEL CONSUMPTION IN ONE URBAN CYCLE

Unified conditions of the engine parameters and the driving parameters of the vehicle are always present problem, not only to determine the fuel consumption but to determine emission of pollutants too. So, these conditions are defined by the corresponding cycles since the early 50s of the last century. The cycles defined by ECE R15 regulations, modified and agreed with the real driving conditions of the vehicle have special importance during the last 2 decades in the Western Europe.

Considering that the fuel consumption, determined during non-stationary driving conditions by given cycle, presents one of the numerous certification tests, by this the fuel consumption values are clearly defined. On the other hand, different road configurations aren`t and cannot be included within this cycle, as well as the different driving methods (cases) that the optimal fuel consumption is defined. Therefore, the driving cycles recording along the same test track in the urban area has done by the different driving methods (cases) i.e. the gear shift for different engine speeds. Besides this test track, driving cycles are recorded, based on CAN BUS and GPS data, for case of driving by various speeds on the open road and along the highway.

Calculation of the fuel consumption was carried out for all of the driving cycles recorded like: driving uphill, horizontal road drive and „open“ drive – intercity drive. In order to determine the fuel consumption, the biggest road grade of 4.29 % was chosen along the test track in the urban area and presented in this paper.

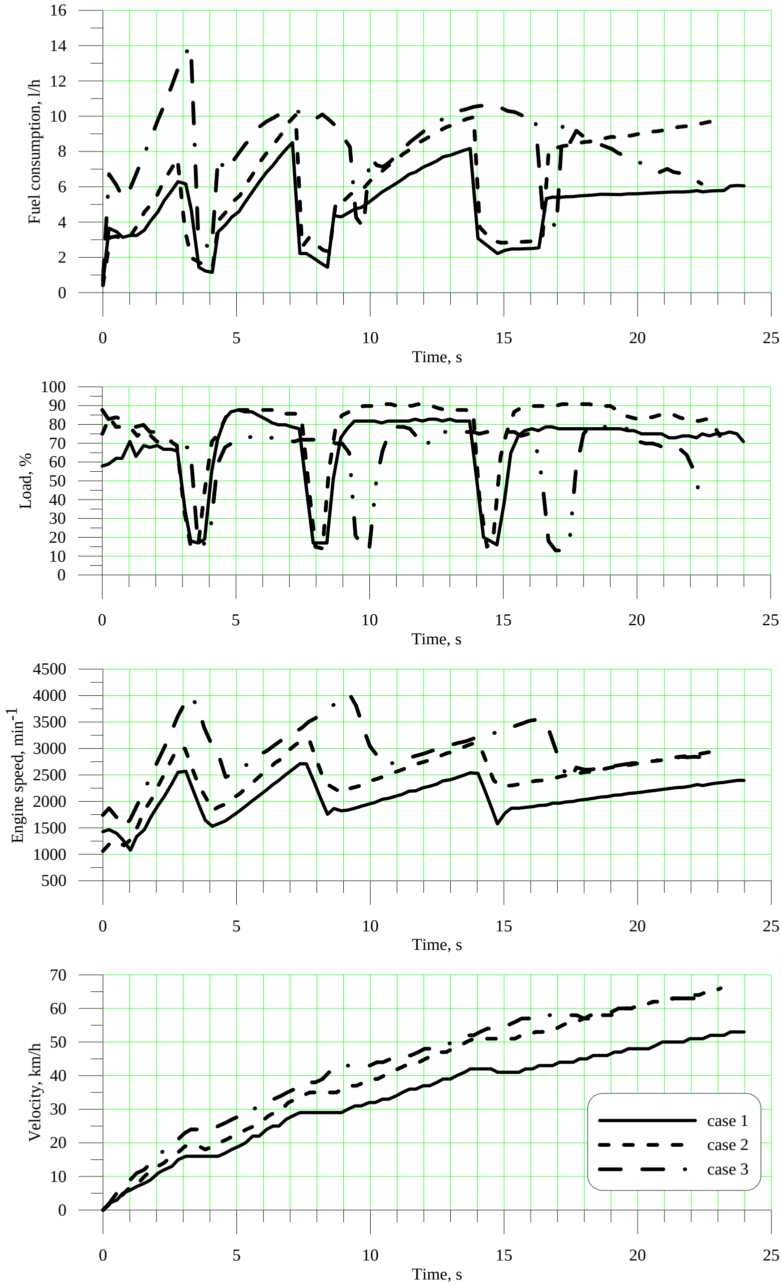

***Figure 2:** Comparison display of the specific parameters by different driving cases driving uphill along the road grade of 4.29 %*

The Figure 2 shows the realized driving cycles on the same test track and by different ways of driving and obtained results through the both of the cases. Simulation of the various driving cases is imagined to be through the different cases of the gear shifting during the acceleration of the vehicle. The first driving case tend to be by shifting gear around 2500 min^{-1} engine rpm during acceleration, the second driving case is to shifting gear by engine rpm of 3000 min^{-1} during the acceleration of the vehicle, although the third driving case is to shifting gear by engine rpm of 4000 min^{-1} in the first and second gear, until it depends on traffic conditions regarding the other gears shifting, and it is carried out in the range of 3000-3500 min^{-1}.

The clearer picture about the impact of different driving cases over the same test section comparing the results offers the Figure 2. It can be seen in the Figure 2 that if the gear shift is carried out later, i.e. achieved by higher engine speed in each of the respective gears, the vehicle performs better dynamic properties in terms of the resulting acceleration of the vehicle. This is the best illustrated in the vehicle speed diagrams as a function of the engine speed. It has to be noted that the driver pushed down the gas pedal evenly through the all driving modes and it is clearly visible on the load diagram.

However, the first diagram in the Figure 2, referring to the values of the current fuel consumption, shows certainly the most interesting part of this analysis. Apparently the price of better dynamic properties of the vehicle, achieved by the gears shift at higher engine speed, is pay by the vehicle customer through the higher current fuel consumption but through the total fuel consumption as well driving by given section.

Keeping in mind the total fuel consumption consumed during the acceleration with different driving cases along the test track the average fuel consumption along the travel made can be defined. The overview of the average fuel consumptions values is shown in the table 1.

Table 1: *The fuel consumption refers to different driving cases*

Driving cycles	Travel during acceleration, *km*	Fuel consumption, *l/100 km*
Case 1	0.248	20.42
Case 2	0.248	22.42
Case 3	0.240	25.06

Although the road traveling fuel consumption values expressed in *l/100km*, on the first sight, seems to be significant, higher than normal road travel fuel consumptions given by the catalogs and displayed by onboard computers but here is important to note that it is about values relevant in the case of the vehicle acceleration driving uphill along the road grade of 4.29%.

The relative fuel consumption, defined in order to implement the analysis of fuel consumption by various driving cases, is shown in the table 2.

Table 2: *Relative fuel consumption by various driving cases*

Driving cycles	Relative fuel consumption, %	Increase of the consumption, %
Case 1	100.00	0.00
Case 2	109.79	9.79
Case 3	122.72	22.76

Based on presented results, it can be concluded that if the gear shift is carried out earlier during acceleration of the vehicle, significant effect to the fuel consumption can be realized, but to the dynamic characteristics of the vehicle as well. It is well known that the gear shift at lower engine speed, especially driving uphill, depends on the experience of the driver and his skills to do it fast enough on that way to vehicle achieves stable drive in the next gear. For this reason, it is necessary to ensure the optimal engine speed to the gear shift what will be analyzed through the further specific driving cases. As an example, if the driving case number 2 is optimal, it would increase the fuel consumption by 11.78% between driving case number 3 and driving case number 2.

The same conclusions were obtained in analysis of fuel consumption during acceleration on the horizontal road. The special attention is dedicated to „open drive" – intercity drive. Based on the conducted analysis, the determination of the influenced parameters had done, as well as definition of optimal drive regarding fuel consumption.

DETERMINING OF THE INFLUENCED PARAMETERS

Based on the calculation results of the fuel consumption during the cargo delivery vehicle movement by the recorded driving cycles in the urban area, with characteristic of non-stationary ride conditions with a frequent accelerations and decelerations along the strait road, but along the road with the grade angle also, driving cycles of the vehicle in the intercity routes and by the highway as well, corresponding parameters affecting fuel consumption can be defined:

1. *Acceleration of the vehicle* is the most important influenced parameter during non-stationary ride in the urban area. Extreme acceleration is very common followed by extreme deceleration in urban area what suppose to be a consequent influenced parameter by many explorers. Due to that, from big importance is:

    a) In order to avoid extreme acceleration of the vehicle it is necessary to push down gas pedal rationally as possible to have a control by *engine load* values, i.e. by *gas pedal position*

    b) Besides engine load, avoiding of extreme vehicle acceleration is possible to achieve by shifting gears earlier, i.e. shifting gears on lower *engine RPM*.

2. The most important parameter during non-stationary ride in urban area and the intercity routes and by the highway is *driving speed* and *the information about which of the gears is running*. Therefore, the fact known well is that by driving

speed of 90 km/h, the vehicle running in the 5th gear accomplishes lower fuel consumption then the vehicle running in 4th gear, etc.

3. *Road configuration* can have a significant influence to the fuel consumption. Thereby it is necessary to make a difference between the uniform strait linear and curvilinear vehicle movement with possibilities to rich lower vehicle speed. Apart from vehicle movement path, very important influenced parameter is the *road grade*, and it is difficult to determine it. Information about road grade is available by modern and very accurate GPS devices, but installation is doubtful because of its high price. However, information about axle loads can be useful to determine the road grades, but considering change of loads over the acceleration, i.e. over deceleration of the vehicle, its accuracy can be under question. Finally, due to determined vehicle acceleration and engine load, required information about road grade can be obtained, but it takes a lot of data that must be processed by computer with some presumptions, thus it will not be used in the further analysis.

DEFINING OF THE OPTIMAL DRIVE

The best illustrated view of defined optimal drive is algorithm shown in the Figure 3. The presented algorithm can serve to assemble the computer program that will enable to achieve optimal drive and fuel consumption of the light duty motor vehicle.

Considering influenced parameters mentioned in the last chapter, the following method to accomplish optimal drive can be proposed:

- Analyzing the shape of the fuel consumption diagram, it can be noted that the constant specific fuel consumption curves reach minimal values in the range of 2500 – 3000 min^{-1}. Although, analyzing the results affecting the fuel consumption during different drive cases, i.e. different engine speed shifting gears, it can be concluded that minimal values has reached throughout the first driving case, i.e. by shifting gear at 2500 min^{-1}. Since shifting gears by this engine speed enables stable ride in the next gear, even traveling uphill, shifting gears from 1st gear to 2nd, from 2nd to 3rd, from 3rd to 4th and finally from 4th to the 5th gear has to be done exactly by this rpm. In this case, this provides to driver get the information about necessity to shift gear, because of „total inertia" the shifting gear could be by something higher engine speed, let`s say about 2800 min^{-1} where the engine runs still with minimal specific fuel consumption.

- The minimal engine speed necessary to obtain the gears shift from 5th to 4th, from 4th to 3rd, and finally from 3rd to 2nd gear amounts 1200 min^{-1}.

- In order to make registration sudden vehicle decelerations, due to extreme accelerations, driver reaction coming out late and beginning to brake, etc., because that can lead to intensive wear of the friction surfaces on the break surfaces, continuous acceleration i.e. deceleration is recommended. According to data in [8], common deceleration values amounts about 2.0-2.5 m/s^2. According to latest experiments, common ordinary deceleration values today amounts about 2.5-3.0 m/s^2. Considering eventual error of the calculated deceleration because of rounded values of velocity of the movement and short interval of time (less than 1s), and because of the inertia of system as well, registration of all vehicle deceleration values over 4 m/s^2 is recommended.

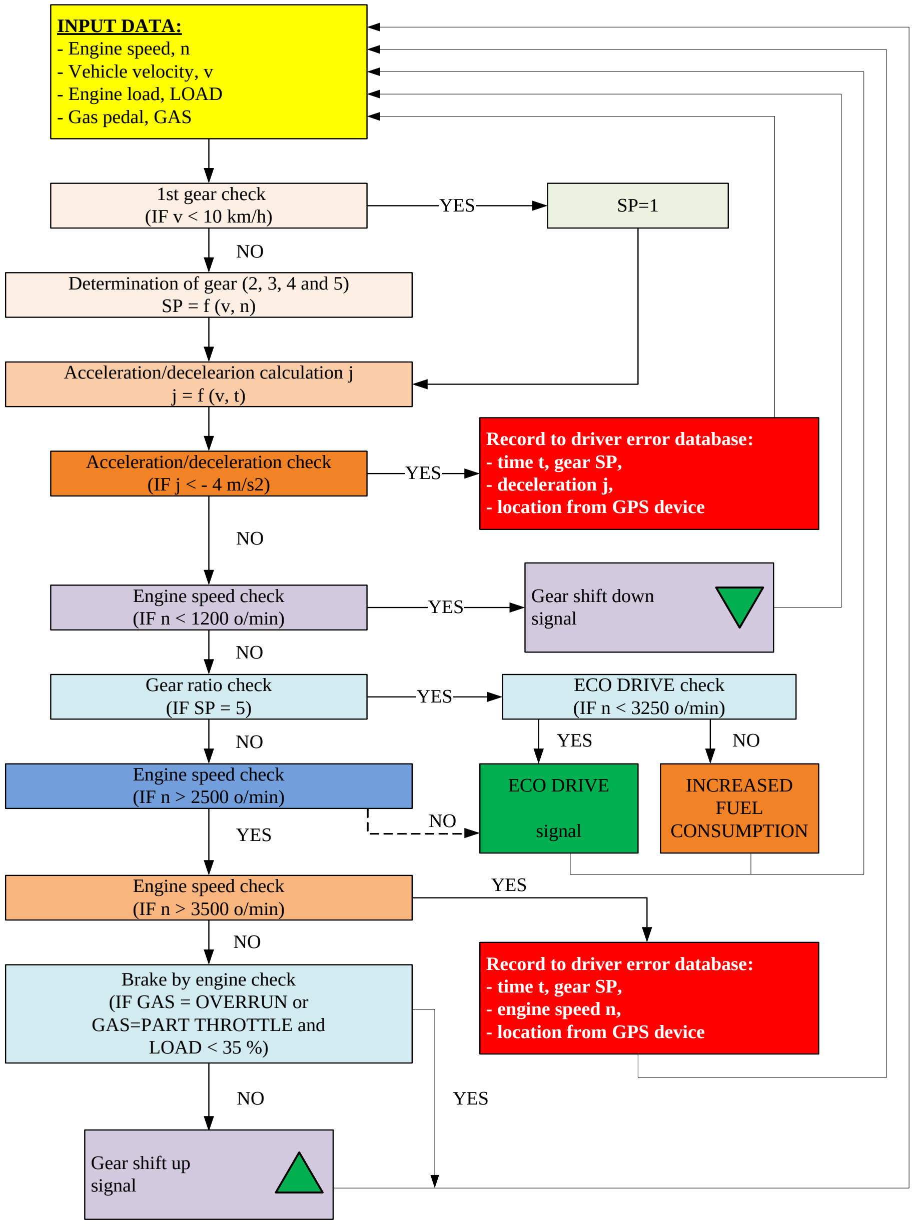

***Figure 3:** Algorithm to achieve the optimal drive and optimal fuel consumption*

- Having in mind a fact that during vehicle motion downhill could happen the ride with the engine speed that corresponds to recommended engine speed to shift to the next gear, for ex. from 2nd to 3rd, from 3rd to 4th, from 4th to 5th, this situation can lead to the additional acceleration of the vehicle reducing-in the break-by-engine effect. That is the reason why the engine load information are so important as well as the information about gas pedal position. Assuming the values OVERRUN or PART THROTTLE are registered by the gas pedal position or below the engine load of 35%, it is not necessary to signalize shifting gears.

- If the engine runs above 3250 min^{-1} during the ride of the vehicle by constant velocity in the 5th gear, warning about the increased fuel consumption is obtained, i.e. uneconomic ride.

CONCLUSIONS

In order to provide more realistic image about exploitation of the light duty motor vehicle, recording of driving cycles with different cases of the ride in the downtown along various road configuration (strait road, uphill, downhill), but also in the intercity ride and by the highway has done. Recorded cycles have been used into the purpose for calculation of the fuel consumption pointed-out on the influenced parameters by the aspects of fuel consumption.

Considering obtained parameters, fuel consumption diagram of the engine using the petrol like driving fuel, results of the calculation and analysis carried out by the aspects of fuel consumption, algorithm is made for making of the computer program of the optimal ride for the light duty motor vehicle.

In the realization of the optimal ride, the problems in the case of the complex road configurations may appear such as: extreme uphills, narrow traffic lanes along the road with a significant number of the curves, etc. Considering the problems to determine road grade described before, complex calculation of the optimal ride and demands for the computer capacities, different capabilities of the driver regarding fast changeover the gears driving upwards, advice to the drivers in the situations mentioned is the next: the ride, engine load and engine speed and the gear is running adjust to obtain the stable and the safe ride.

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