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The influence of number and values of ratios in stepped gearbox on mileage fuel consumption in NEDC test and real traffic

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Abstract. The article presents the influence of number and values of ratios in stepped gearbox on mileage fuel consumption in a city passenger car. The simulations were conducted for a particular vehicle characterized by its mass, body shape, size of tires and equipped with a combustion engine for which the characteristic of fuel consumption in dynamic states was already designated on the basis of engine test bed measurements. Several designs of transmission with different number of gears and their ratios were used in virtual simulations of road traffic, particularly in the NEDC test, to calculate mileage fuel consumption. This allows for a quantitative assessment of transmission parameters in terms of both vehicle economy and dynamic properties. Also, based on obtained results, recommendations for the selection of a particular vehicle for a specific type of exploitation have been formulated.

1. Introduction

Fuel consumption of the car is for many customers one of the most important criteria for the selection of the particular model. Car manufacturers, which sell cars in Europe, shall provide in catalogues fuel consumption obtained in three homologation tests: urban (UDC), extra-urban (EUDC) and combined (NEDC). These tests are performed on a chassis dynamometer in a standardized test. The vehicle motion is described by an appropriate driving schedule, and gear-change points are strictly determined. The homologation test is the same for all passenger cars, which allows to compare their properties in the same traffic and environmental conditions. The NEDC (New European Driving Cycle) test is currently in force in Europe [1]. Unfortunately, this test significantly differs from the real traffic conditions [2]. This is one of the factors that often leads to significant discrepancies between the homologation and the real traffic fuel consumption [3]. Another reason are the gearbox ratios. They influence both car driveability and real fuel economy.

Gearbox ratios must ensure both required tractive force to put the vehicle in motion as well as reaching high top speed. To provide the best dynamic properties engine must work between the speed of the nominal torque and nominal power, which affects the theoretical number of gears. In practice, city cars usually are equipped with 5 gears regardless of the engine characteristic [4, 5]. It turns out, however, that even for vehicles with very similar technical characteristics, the gear ratios may vary significantly. This affects both vehicle dynamics and the mileage fuel consumption. The objective of the present work is to quantitative asses impact of the different gearbox ratios (in one car) on fuel consumption in NEDC test and in a few selected situations of the real traffic.

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2. The use of fuel consumption characteristic in dynamic states of the engine in simulations

2.1. Measurements on engine test bed

Simulations of mileage fuel consumption for a particular vehicle are possible, only when it is equipped with an internal combustion engine, for which the fuel consumption characteristic in dynamic operating states has already been designated. Such a characteristic is created based on data collected during measurements performed on the engine test bed (Figure 1). Three basic parameters of the engine were measured: engine speed *n*, engine torque *M* and fuel mass flow *G*. Sample graph is given in figure 2.

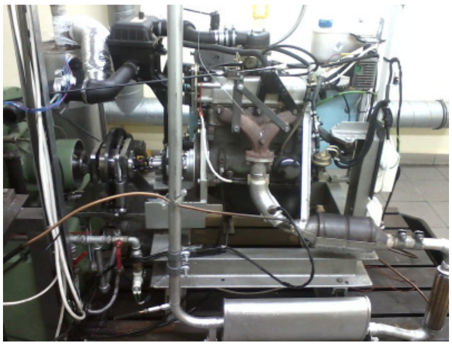

Figure 1. 899ccm SI engine for which characteristic of fuel consumption was designated.

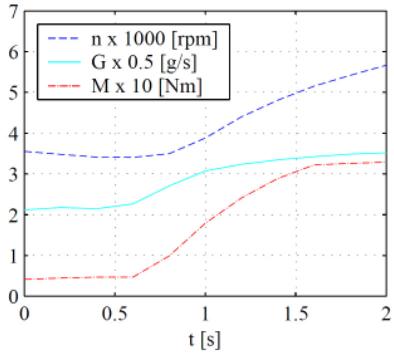

Figure 2. Engine working parameters in a single measurement.

The development of such a characteristic requires the use of artificial neural network (ANN) trained in supervised mode. The method is described in details in the works of the author [6, 7]. Architecture of ANN used to develop such a characteristics is shown in figure 3.

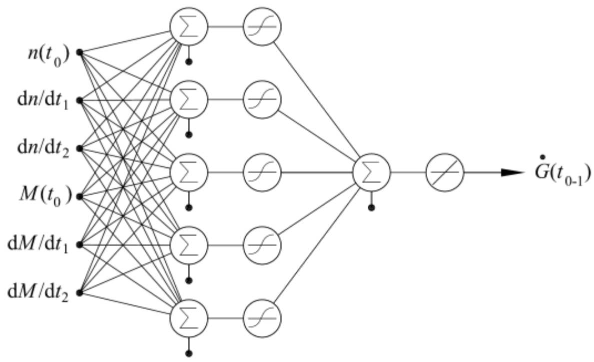

Figure 3. Artificial neural network used for calculation fuel mass flow in dynamic states.

The specificity of this method is based on analysing engine rotational speed and torque in a time window of a given length. Such an action takes into account series of phenomena occurring in the engine in dynamic operating states, e.g. changes in kinetic energy of parts in motion, changes of air-fuel mixture composition and delay in engine response to the control signal. The use of this method allows to calculate the current value of fuel mass flow *G*, both in static and dynamic working states. In comparison to other methods [8, 9] of calculation fuel consumption in dynamic states, this one is possibly the most general. In works [7, 10] it is demonstrated that in dynamic states only the use of such a characteristic allows to obtain reliable results of fuel consumption simulations. Universal characteristic can be only used in static or quasi-static operating states. The validity of the approach proposed by the author is confirmed by the regression graph shown in figure 4. The fit of ANN model to measurement data presented to the network in specific way is very good. It shows that there is a strong relationship between fuel mass flow G and three consecutive values of engine rotational speed n and torque M.

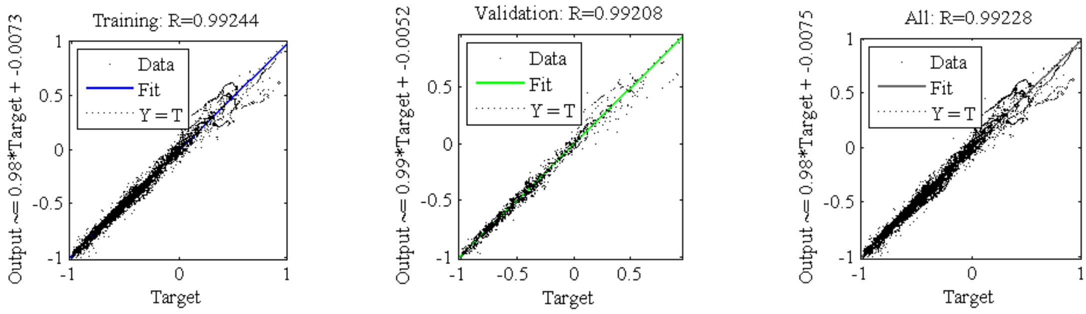

Figure 4. Regression plots received after ANN training.

Characteristic used in this article is based on measurements performed on a spark ignition engine with a nominal power 29 kW/5500 rpm and nominal torque 65 Nm/3000 rpm. Therefore it will be fitted in a small city passenger car. All further considerations will be targeted at this group of vehicles.

2.2. Application of fuel consumption characteristic for simulations of mileage fuel consumption in car

Fuel consumption characteristic in dynamic states, described in the above paragraph, can be used in simulations of mileage fuel consumption for a specific vehicle. Certainly, all vehicle key technical prameters must be known: vehicle mass m_p, wheel diameter D_k (and dynamic radius r_d), tyre rolling-resistance coefficient f, aerodynamic drag coefficient C_x, frontal area A, the total transmission efficiency η_c, coefficient of rotating masses in transmission δ, nominal engine torque and power. Based on these data, overall ratios of the transmission i_{c1}, i_{c2}, i_{c3}, i_{c4}, i_{c5} are calculated. Then with all these technical data it is possible to determine the engine rotational speed n and torque M on the basis of vehicle speed v and acceleration a. The dependence between the above parameters are described by the following relationships:

$$n = \frac{v \cdot 60 \cdot i_c}{2 \cdot 3.6 \cdot \pi \cdot r_d} \tag{1}$$

$$M = \frac{\left(m_p \cdot a \cdot \delta + F_p + F_t\right) \cdot r_d}{i_c \cdot \eta_c} \tag{2}$$

These two engine parameters are then directly used to simulate the ANN at every moment of the test. On the inputs of the network three successive values of engine rotational speed and torque are presented in time intervals 0.1 s. They are forthwith computed on the output – the value of fuel mass flow– with accordance to properly trained weights and biases.

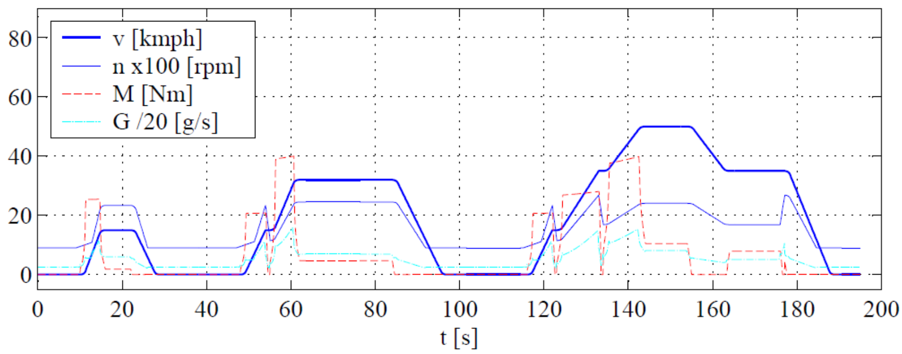

Figure 5. Vehicle A parameters in UDC test.

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After completion of the test the whole amount of fuel is known, as well as the total distance of the vehicle. This allows to easily calculate mileage fuel consumption expressed in $dm^3/100$ km.

3. Construction parameter of city passenger cars used in further simulations

As it has been mentioned before, fuel consumption characteristic in dynamic states was designated for a small SI engine wherefore it will be used as a propulsion of a small city passenger car.
To the class of small city cars the following ones can be included: Volkswagen Up 1.0 44 kW move up! 2011 [4] Mitsubishi Space Star 1.0 Instyle 2015 [5], Mitsubishi Space Star 1.2 Intense + 2013 [5] Kia Picanto 1.0 EcoDynamics Spirit 5-d in 2015 [5] Toyota Aygo 1.0 VVT-i and x-wave Style 2015 [4], Suzuki Celerio 1.0 Comfort 2015 [4], the Hyundai i10 1.0 i-Motion Premium 2013 [5] and Fiat Panda 1.2 Pop Fire 2012 [5].
For a group of the above-mentioned cars the value of dynamic coefficient in first gear equals $D = 0.32 \div 0.39$. This means that the total value of the first gear ratio can be included within: $i_{c1śr} \pm 9\%$. It also turns out, that the theoretical vehicle speed at fifth gear, at nominal engine speed, is always higher than the vehicle top speed of 10% to 50%. This shows that designers have a wide range of possibilities when choosing a final construction solution, that will affect both vehicle dynamics and economy. Hereinafter the extreme values of the above ranges will be applied in two cars that are designed for virtual fuel consumption simulations. The technical data of both vehicles are shown in table 1.

Table 1. Basic technical parameters of vehicles A and B used in simulations of mileage fuel consumption.

Parameter	Vehicle A	Vehicle B
Vehicle mass m_p [kg]	730	
Total vehicle weight [kg]	1130	
Vehicle frontal area A [m^2]	2.0	
Aerodynamic drag coefficient C_x	0.32	
Tires size	R14 165/70	
Tyre rolling-resistance coefficient f [-]	0.01 – 0.015	
Nominal engine power [kW] / [rpm]	29 / 5500	
Nominal engine torque [N·m] / [rpm]	65 / 3000	
Top speed [kmph]	138	
1^{st} gear overall ratio	16.709	19.919
2^{nd} gear overall ratio	8.214	10.242
3^{rd} gear overall ratio	5.116	6.574
4^{th} gear overall ratio	3.732	4.891
5^{th} gear overall ratio	3.024	4.016

Vehicle A has a long geared transmission whereas Vehicle B has a short geared transmission. Data from table 1 can be written in a different way: dynamic coeffcient in first gear for Vehicle A equals $D = 0.32$ and the top speed exceeds the theoretical maximum of 50%, however, the Vehicle B has dynamic coefficient of $D = 0.39$ and theoretical speed exceeding the top speed by 10%. Finally, the Vehicle B may be equipped with 6 gears (point 8). Figure 6 shows speed graphs for all gear ratios in each gearbox.

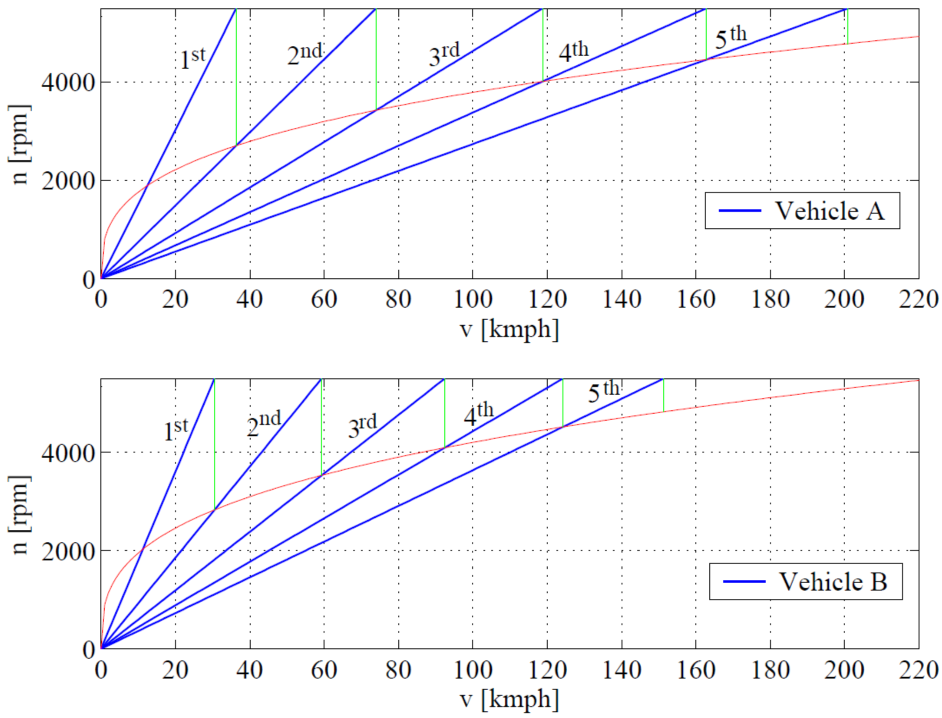

Figure 6. Engine rotational speed vs vehicle speed on each gear.

Gearbox ratios directly influence tractive force in all gears, which is shown in figure 7.

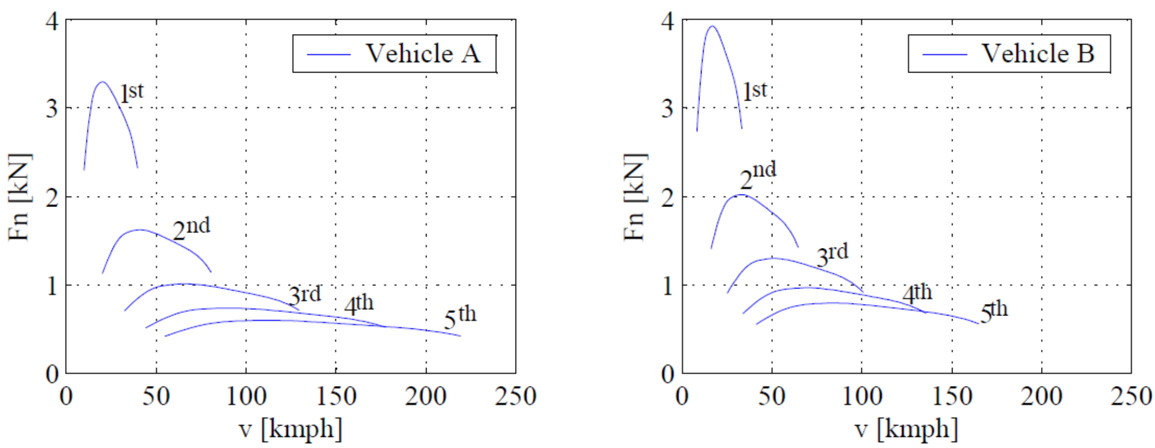

Figure 7. Tractive force on each gear for Vehicle A and B.

From the analysis of the figure 7 it results that Vehicle B has a greater tractive force on every gear than Vehicle A. The consequence of this is better dynamic, allowing the achievement of better acceleration in every gear.

4. Fuel consumption in the NEDC test

In the NEDC test vehicle speed is described by an appropriate driving schedule and the gear-changes occur at predetermined speeds. For a particular vehicle it directly determines the engine rotational speed and torque thus affecting fuel consumption in the test. Figure 8 shows the course of the vehicle speed in this test.

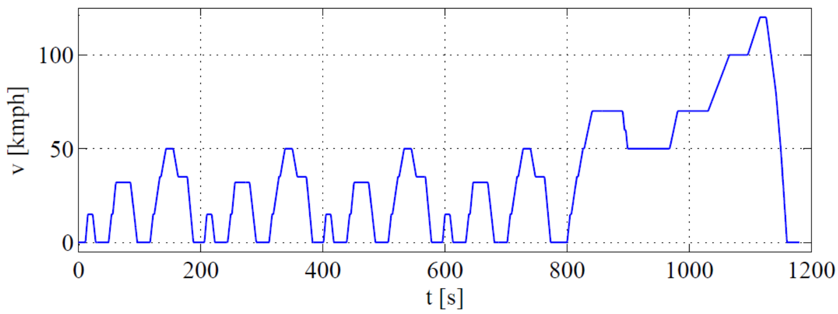

Figure 8. Vehicle speed vs time in NEDC test.

With use of the formulas described in section 2.1, engine rotational speed and torque can be easily calculated. Then these parameters are presented to network inputs, and current fuel mass flow is forthwith claculated. The above parameters for vehicles A and B are shown in figure 9.

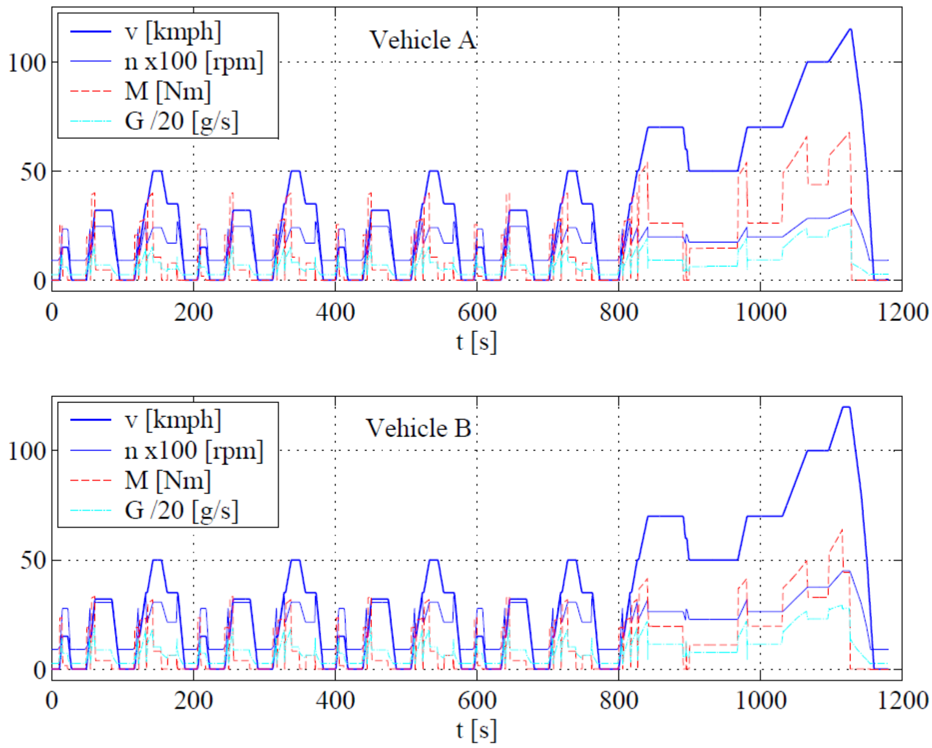

Figure 9. Vehicles speed and engine working parameters in NEDC test.

From obtained plots in figure 9 it results that in case of Vehicle A, the engine works under greater load and lower rotational speed. In such working conditions engine efficiency is possibly the highest so the fuel consumption is low, which is presented in table 2.

Table 2. Fuel consumption of Vehicle A and Vehicle B in homologation tests

Fuel consumption [dm^3/100 km]	Car A	Car B
UDC test (city)	6.8	8.0
EUDC test (highway)	4.0	4.8
NEDC test (combined)	5.2	6.1

From the performed simulations we can observe, that in case of the NEDC, long gear transmission is a significantly better solution than short gear transmission. Vehicle A has considerably lower fuel consumption than Vehicle B in all tests: UDC, EUDC and NEDC, respectively 15%, 17% and 15%. Certainly, dynamics of both vehicles, determined by the speed course in the test, is the same.

5. Fuel consumption in a real city traffic

5.1. Specificity of real city traffic

The real traffic puts greater demand on vehicle dynamics than NEDC test. Acceleration to 50 kmph takes about 14-20 s, while the 70 kmph is reached within about 20-25 s. These values are lower about 30% than in the test. Besides in the real traffic conditions driver must adjust the speed of the vehicle so that move smoothly in the stream of cars and with accordance to road traffic regulations. Moreover, gears can be shifted at any speed in contrary to NEDC test. According to the e.g. Ecodriving rules the engine should work under high load and in range of small rotational speed due to the highest efficiency in this area of work field. However, in order to ensure proper durability of the engine minimum rotation speed at which it can operate with a maximum load is 1500 rpms. The following simulations will be conducted with accordance to this rules.

5.2. Acceleration to 50 kmph

In most cases, the vehicles speed in the city is restricted to 50 kmph, similarly to UDC test. However, the acceleration time is shorter. The following simulation, shown in figure 10, will be performed for acceleration from 0 to 50kmph. Gearshift moments are different for each vehicle.

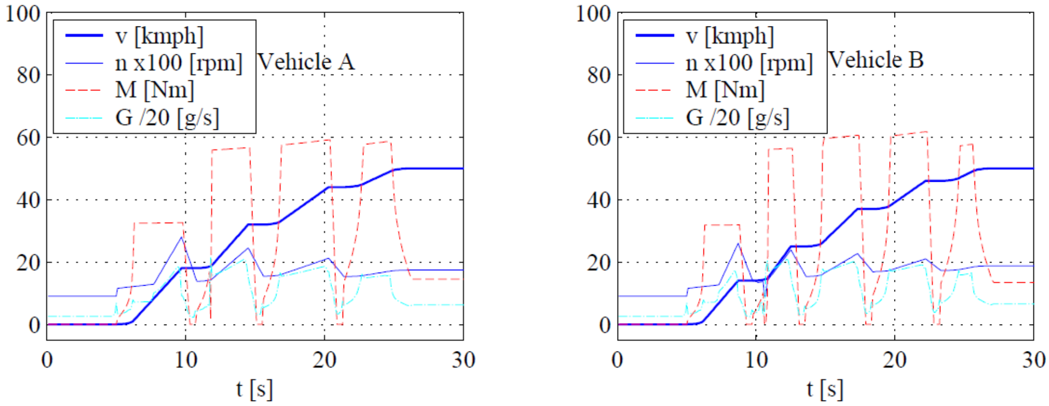

Figure 10. Acceleration to 50 kmph.

From the performed simulations it results that average fuel consumption of two vehicles is almost the same – Vehicle A – 7.2 dm^3/100, whereas Vehicle B – 7.3 dm^3/100km. It was possible due to the fact that in Vehice B gearshifts were quicker. Moreover, after reaching a speed of 50 kmph the Vehicle B can shift to 5th gear while the Vehicle A can shift only to 4th gear.

5.3. Acceleration to 70 kmph

The maximum speed which usually can be reached in a city is 70 kmph. In the next simulation, shown in figure 11, both cars will accelerate from 0 to 70 kmph in the same time. As in the previous case, both engines will work in area of maximum efficiency field, and both cars will cover the same distance.

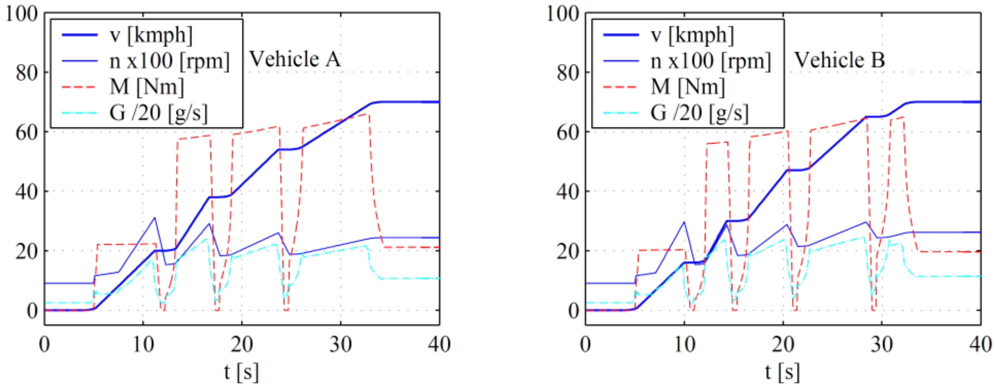

Figure 11. Acceleration to 70 kmph.

In this case average fuel consumption of Vehicle A is 7.6 dm^3/100km, and Vehicle B 7.8 dm^3/100km. This means that also in this instance, fuel consumption is similar, but requires a different gearbox shifting. Another difference is that in Vehicle B all five gears are used whereas in Vehicle A fifth gear can be shifted only after reaching final speed. Otherwise acceleration would take much more time in comparison to Vehicle B.

6. Acceleration to 100kmph with full throttle opening

Acceleration time from 0 to 100 km/h is one of the basic dynamic parameters of the vehicle. Figure 12 shows how different gearbox ratios affect acceleration process. Acceleration to 100 kmph is done so that upshifts take place after reaching nominal engine speed 5500 rpms, and the throttle is fully opened. In this case shift time is shorter than in previous simulations and lasts 1 s.

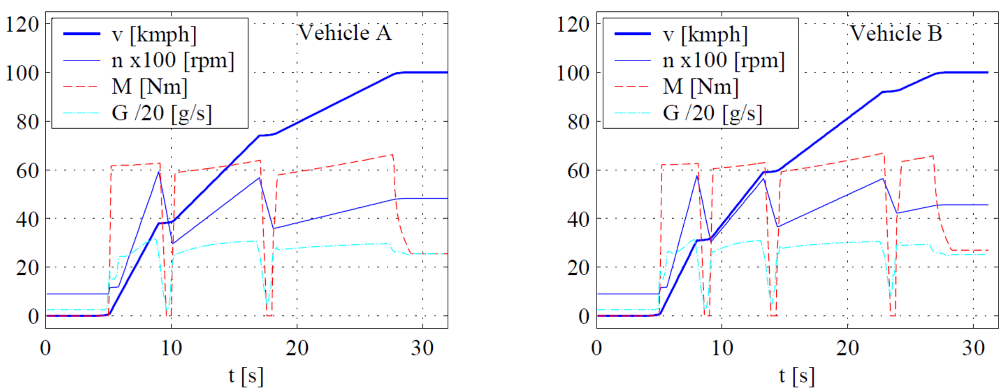

Figure 12. Vehicle parameters while accelerating to 100kmph.

The obtained results show that the acceleration time of Vehicle B is 1 s shorter than Vehicle A and the average fuel consumption equals respectively 9.3 dm^3/100km and 9.2 dm^3/100km.

7. Extra-urban / Motorway driving

At a constant highway speed of 120 kmph Vehicle A with longer gear ratios achieves a fuel consumption of 5.2 dm^3/100km while vehicle B 5.6 dm^3/100km. This means that the Vehicle A has 7.7% better fuel economy than Vehicle B. It's a noticeable difference, but it should be noted that in overcoming any major hill or while overtaking downshift will be needed what entails an increase in fuel consumption.

8. Increase in number of gears to 6

It is possible to increase the number of gears to six in Vehicle B. Using the method of gear graduation shown in figure 13, 6th gear in Vehicle B would have overall ratio of i_{c6} = 3.522.

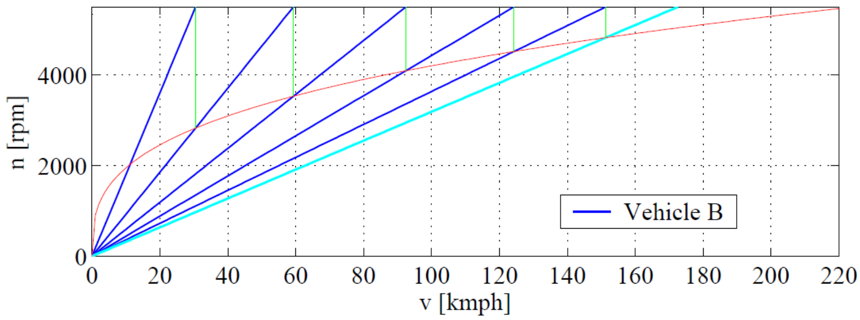

Figure 13. Vehicle B speeds on each gear including 6th.

At a constant speed of 120 kmph it would allow to decrease engine speed of 520 rpms thus reducing fuel consumption by 0.2 dm^3/100km in comparison to the five-speed version. The benefits of using 6 speed gearbox are rather negligible and are achievable only in specific conditions.

9. Conclusions

The paper describes quantitative differences in mileage fuel consumption of a small city car, depending on gearbox ratios. Both solutions of vehicles A and B were within the limits applied in the construction arisen over the past five years. It turns out that the fuel consumption given by an car manufacturer and obtained in homologation test should not clearly determine the selection of a particular vehicle. Indeed - a vehicle with long gear ratios is always more economical in NEDC test (in described case it was 15% in the UDC test, 17% in extra urban and 15% in combined), however, in a real city traffic vehicle with short gearbox ratios is better. First of all it allows for full use of all five gears within speed range to 70 kmph. Secondly it provides better vehicle dynamics if needed, and finally, with proper gear handling, allows to achieve the same mileage fuel consumption as the vehicle fitted with a gearbox with long gears. The potential benefits of long geared transmission can be obtained only in extra-urban driving on the flat roads and when frequent overtaking is not required.
The use of sixth gear in the Vehicle B can reduce fuel consumption when driving at constant motorway speed of 120 kmph by 4%. In a strictly urban vehicle it is an expendable solution. The potential of the six speed transmissions can be fully used rather in vehicles with turbocharged engines, which have a high torque allowing for smooth acceleration even in sixth gear with the lowest ratio, than in small city cars.

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