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The influence of multi-speed transmissions on electric vehicles energy consumption

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Abstract. The electric vehicle (EV) represents an important option in the process of road transport decarbonization. The limited driving range and high speed performances are obstacles for EV customer acceptance. While until now the emphasis for the improvement was on battery, power electronics and motor technologies, it becomes obvious that the transmission must be also addressed. The extensively used single-ratio transmission can satisfy the demands of city use, but do not attain other important functional needs that are ensured by conventional and hybrid electric vehicles. The aim of this paper is to analyse the energy consumption of an EV with multi-speed transmission in five test cycles among which Worldwide Harmonized Light duty Test Cycle (WLTC) is considered. This study is done by means of simulation using a model specifically developed in a simulation environment. In the interest of analysing the performances in several test cycles, one needs to compare global parameters such as: vehicle speed fluctuation (VSF), overall transmission efficiency, energy consumption ratio (ECR). A comparison between test cycles is made taking into consideration a relative parameter (ECR). The correlation between ECR and VSF is investigated as well. The results are also compared with those produced for a vehicle with diesel engine.

1. Introduction

In order to improve the powertrain efficiency and extend the driving range for a given battery capacity and motor size of an EV, one can adopt a reasonable approach that refers to the use of multi-speed transmission instead of single-ratio reduction transmission. The multi-speed transmission has the capability to improve acceleration time 0-100 km/h, maximum speed and energy consumption. At the same time, it increases the transmission's gross weight, reduces the transmission efficiency and the manufacturing costs are higher [1, 2].

The transmission efficiency is dependent on the gear ratio and the number of gears, so when the number of gears increases the overall transmission efficiency decreases [1], but the motor is operated at higher efficiency, reducing in this way the energy consumption.

The paper analyzes the influence of two gears transmission on energy consumption comparing with single gear transmission. The energy consumption is determined for a B-class passenger car at constant speeds and for five test cycles: US 06, Japanese 10-15 Mode Cycle (10-15), Highway Fuel Economy Test Cycle (HWFET), New European Driving Cycle (NEDC) and WLTC test 3B class [3].



2. Model development

The model for the purpose of this study (figure 1) was developed in LMS Imagine.Lab AMESim, a programme which has a specialised library of components (IFP Drive) for the study of energy consumption in test cycles using different powertrains types [4]. The important sub models used for the model development are: a driver sub model (DRVDRVA00A) necessary to follow the cycle given by the mission profile and ambient data sub model (DRVMP2A), electric motor (DRVELMT0A), battery (DRVBAT04), power electronic converter (DRVPE0B), control unit for an electric vehicle (DRVCUE0A), dual clutch transmission (DRVDC01), transmission control unit for automatic gearbox (DRVAGTCU01), which allows the shifting gears according to a proposed shifting schedule and 1-D vehicle (DRVVEH4A).

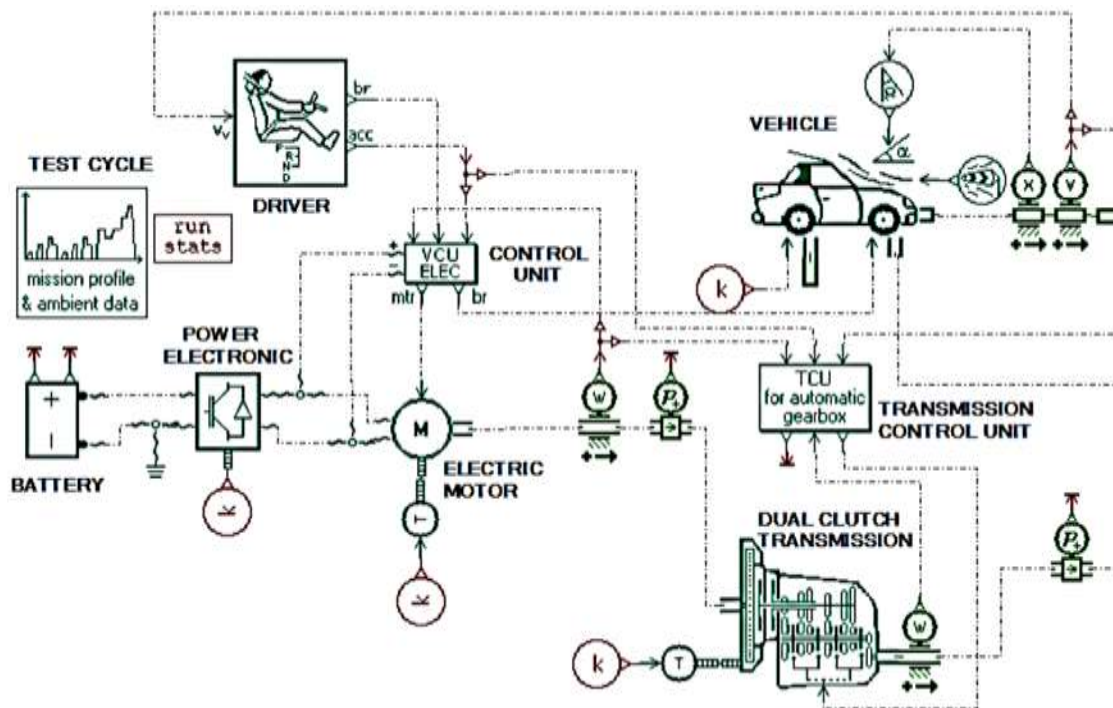


Figure 1. Model design for energy consumption study.

3. Gear ratio

In case of a two gears transmission, the first gear is used for high accelerations at low speeds and climbing and the second gear is utilized for driving conditions with high speed [1].

For this study, the first and second gear ratios are determined using the equation (1) respectively equation (2) [5].

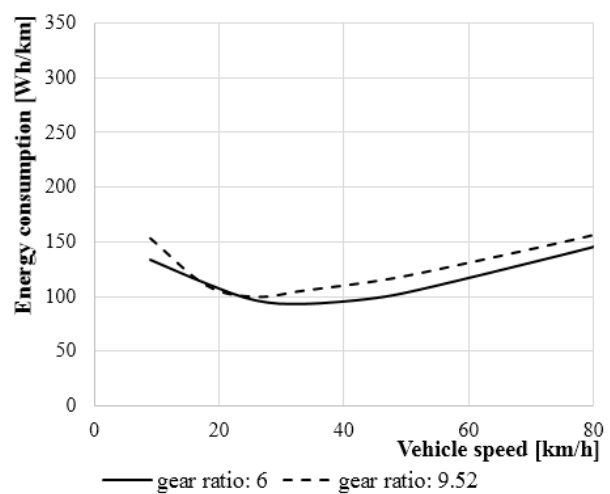
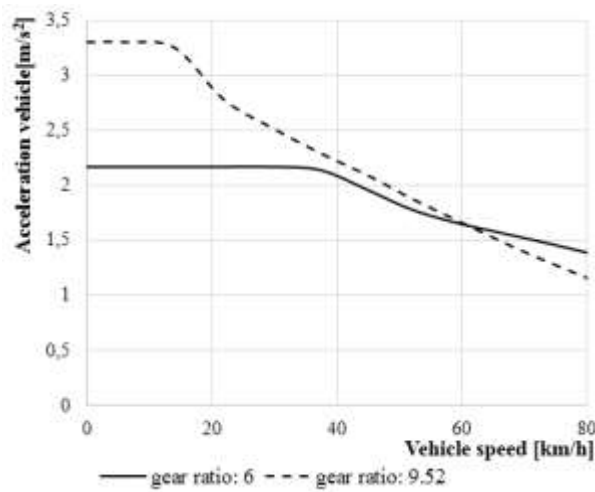
$$i_{t \max} = \frac{r_r \cdot m \cdot g \cdot (f_r \cdot \cos \alpha + \sin \alpha)}{T_m \cdot \eta_{pt}} \quad (1)$$

where r_r – rolling radius (0.289 m), m – vehicle mass (1966 kg), g – gravity, f_r – rolling resistance coefficient (0.014), α – road incline angle (16.7°), T_m – maximum torque (220 Nm), η_{pt} – powertrain efficiency (0.8).

$$i_{\min \text{ speed}} = \frac{3.6 \cdot \pi \cdot n_m \cdot r_r}{30 \cdot v_{\max}} \quad (2)$$

where n_m – maximum motor speed (7500 rev/min), v_{\max} – maximum vehicle speed (135 km/h).

The obtained values for gear ratio are $i_{t\ max} = 9.52$ and $i_{\min\ speed} = 6$, the variation of vehicle



acceleration being represented for these two values in figure 2.

Figure 2. Vehicle acceleration.

Figure 3. Energy consumption at constant speeds.

Taking into account the energy consumption at constant speeds for the two gears (figure 3) and the variation of vehicle acceleration (in the domain of interest), figure 4 reflects the shifting schedule used for this study.

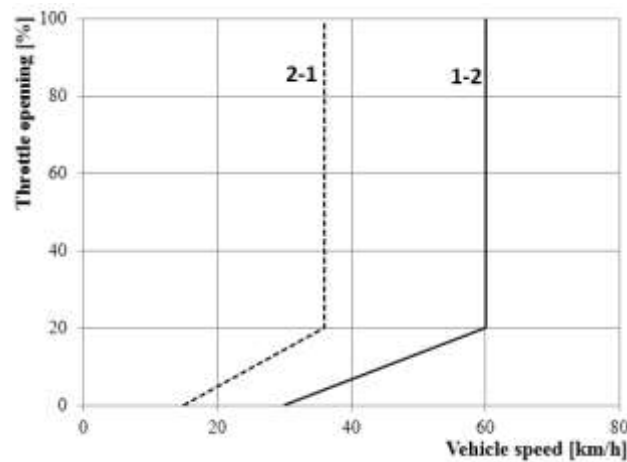


Figure 4. Shifting schedule for two speed transmission.

The electric vehicle performances resulted within simulations with the chosen gear ratios, are presented in table 1.

4. Vehicle Speed Fluctuation

VSF is a global parameter that quantifies the fluctuation of vehicle speed in a test cycle and is defined by relation (3) [6]. The values of this parameter for several test cycles computed in [7] are shown in table 2 in ascending order.

$$VSF = \frac{\sigma}{m} \cdot 100 \quad [\%] \quad (3)$$

where: σ – standard deviation of vehicle speed; m – average vehicle speed.

Table 1. Electric vehicle performances

No.	Parameter	One gear 9.52	One gear 6	Two gears 9.52/6
1	Maximum speed [km/h]	134	171	171
2	Acceleration time 0-100 km/h [s]	13.9	16.5	14
3	Acceleration time 0-50 km/h [s]	4.9	6.8	4.93
4	Maximum grade [%]	30	18	30
5	Energy consumption in NEDC [Wh/km]	169.1	153.3	152.5
6	Energy consumption in WLTC [Wh/km]	185.1	158.6	158.3
7	Energy consumption at 50 km/h [Wh/km]	199.2	103.5	103.5
8	Energy consumption at 100 km/h [Wh/km]	199.6	181	180.5

Table 2. Values of VSF parameter for studied test cycles.

No.	Cycle	m (km/h)	σ (km/h)	VSF (%)
1	HWFET	78.2	15	19.2
2	US 06	83.4	34.2	41
3	10-15	33.6	18.2	54.1
4	WLTC	53.3	33.5	62.8
5	NEDC	44.6	28.1	63

5. Results

5.1. Overall transmission efficiency

Given that the transmission efficiency depends on the number of gears, in this paper, the transmission efficiency is considered to be 0.95 for single ratio and 0.92 for two gears [8, 9].

The overall transmission efficiency (η_{t_cycle}) is a global parameter that quantifies the losses over the entire cycle and is defined by relation (4) [6].

$$\eta_{t_cycle} = \frac{\int P_o dt}{\int P_i dt} \cdot 100 [\%] \quad (4)$$

where P_o is the transmission output power and P_i is the transmission input power.

Taking into consideration only positive power, the resulted values are summarized in table 3.

Table 3. Overall transmission efficiency.

No.	Cycle	$\eta_{t_cycle} [\%]$		
		One gear 9.52	One gear 6	Two gears 9.52/6
1	HWFET	93.4	94.1	91.4
2	US 06	91.7	93.6	90.7
3	10-15	88.7	91.7	89.7
4	WLTC	91.6	93.7	90.6
5	NEDC	90.9	92.9	90.4

5.2. Energy Consumption

In figure 5, the energy consumption obtained at constant speeds is compared with the energy consumption obtained in the studied test cycles. Also the energy consumption is compared for two types of middle class vehicle, an electric vehicle and a vehicle equipped with a turbocharged diesel engine.

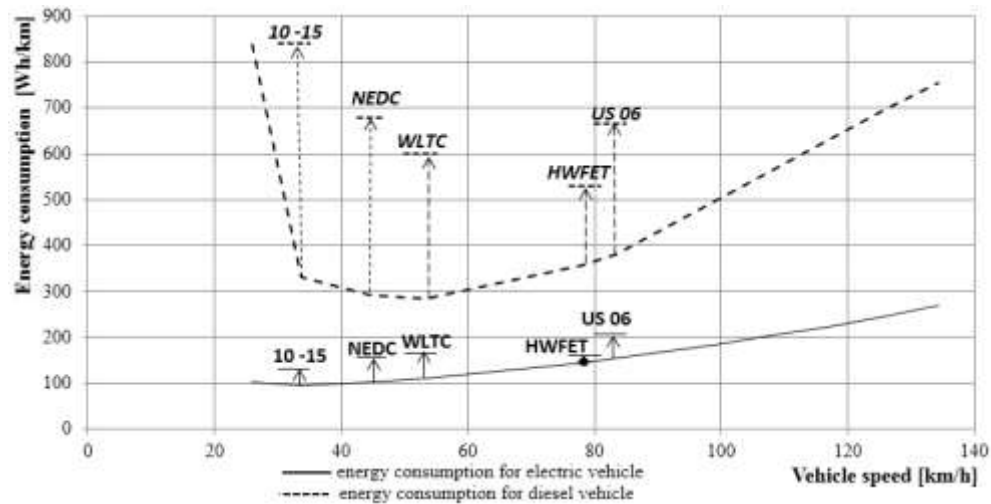


Figure 5. Comparison of energy consumption.

From figure 5 one can observe the highest difference on the level of NEDC cycle, between energy consumption obtained at constant speed and energy consumption resulted in test cycle in case of an electric vehicle. Also, it can be observed that the ratio between the energy consumption at constant speeds for the electric vehicle and the energy consumption for diesel vehicle is between 2.5 and 8.5, this ratio being higher at low speeds.

ECR (Energy Consumption Ratio) is a relative parameter that allows the comparative study of energy consumption in different test cycles and is defined here in a similar way with fuel consumption ratio from [6]:

$$ECR = \frac{EC_{cycle}}{EC_{ct.speed}} \cdot 100 [\%] \quad (5)$$

where: EC_{cycle} – energy consumption obtained in the test cycle; $EC_{ct.speed}$ – energy consumption obtained at constant speed movement equal to the average speed of cycle.

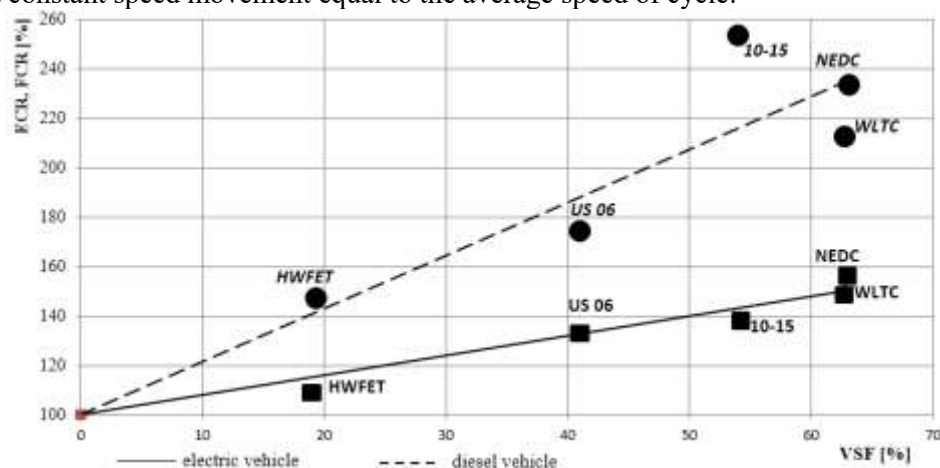


Figure 6. Correlation between ECR and VSF.

In figure 6 two regression lines are represented, having set as intercept (imposed point) the corresponding point of the constant speed movement (0, 100). They have a coefficient of determination $R^2 = 0.968$ (current application), respectively $R^2 = 0.871$ (diesel vehicle) [10]. Regarding the above regression line for an electric vehicle, a better linear correlation between ECR and VSF can be observed.

6. Conclusions

An improvement in energy consumption is resulted, by using two gears, when compared with a single speed transmission with the high ratio: 9.8% in NEDC cycle respectively 14.5% in WLTC cycle. Also, the maximum speed is increased with 37 km/h (27.6%).

If a low ratio is used for the single speed transmission, at the same improvements in energy consumption and maximum speed, the vehicle is penalised in term of dynamic performances as follows: 37.9 % increase of the acceleration time from 0 to 50 km/h, 17.9% increase of the acceleration time from 0 to 100 km/h and 40% reduction of the maximum grade (from 30% to 18%).

Taking into consideration the values obtained for ECR parameter, it resulted the fact that the cycles with the highest values for VSF parameter (NEDC and WLTC) are also the most disadvantageous ones.

When referring to a single ratio, the value's influence is emphasized when the global efficiency is compared for the studied test cycles. A difference from 0.7% to 3% is calculated between the values of overall transmission efficiency. For gear ratio 9.52 and gear ratio 6, it resulted an absolute difference of 4.7% respectively 2.4% between maximum and minimum overall transmission efficiency.

Comparing the coefficient of determination values obtained in the papers [7, 10] for constant and variable thermal powertrain regime, $R^2 = 0.976$ respectively $R^2 = 0.871$, with the resulted value within present study, $R^2 = 0.968$, one could remark further in the current application the linear correlation between ECR and VSF.

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