Comparison of Energy Consumption in Electric Vehicle Equipped with Single- or Multi-Speed System of Power Transmission

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Abstract
Still growing popularity of electric vehicles and various mass-production solutions offered by big OEMs, coexisting in the market with small-series production solutions offered by a smaller manufacturers, encourage to analysis of an advantages and disadvantages of offered solutions. The paper presents results of comparative tests in range of energy consumption, concerning Full Electric Vehicles (FEV) with single- and multi-speed system of power transmission. The comparison was performed on the base of energy consumption measurements of a selected research vehicle in powertrain configurations with mechanical five-speed gearbox and in configuration with the gearbox blocked in the 3rd gear, i.e. in the configuration corresponding to a vehicle with single-speed system of the power transmission.

Keywords: electric vehicle, energy consumption, single speed system, multi speed system, power transmission

Introduction
During the last 20 years of automobile development we have been observing growing interest in vehicles using electric motors as a driving units. These motors are battery-supplied and Li-Ion batteries of different types are commonly used. Hybrid drive vehicles have been present in the market for a long time and are quite well settled in by now. In these vehicles the drive system consists of IC engine (basic component) and electric motor (auxiliary component). Classic examples of hybrid cars are popular Toyota Prius or Honda Insight. The market offer of renowned manufacturers such as GM, Nissam, Renault or BMW is steadily being extended by including all-electric vehicles, the so-called FEV (Full Electric Vehicles), which are constructed from scratch as fully electric vehicles, e.g. GM EV1, Nissan Leaf, Renault Zoe, BMW i3 [3] [4]. High-speed three-phase synchronous PM motors are used for the drives; they are characterized by high rotational torque, which ensures possibility of using transmission system specially dedicated to electric motor (front wheel drive usually), reduced to one-speed gear integrated with the differential mechanism.
A separate group of electric vehicles consists of vehicles built on the basis of ICE cars and using a transmission system adapted from the original vehicle (e.g. np. Karabag 500 E, Zilent Courant, Detroit Electric SP:01). This solution makes it...
possible to use simpler and cheaper motors, with lower rotational speeds, lower torque and maximum power in relation to motors used in vehicles built from scratch as electric vehicles with one-speed gearbox coupled with differential mechanism. Depending on adopted strategy, these vehicles either use all possible speeds of the gearbox (Zilent Courant, Detroit Electric SP:01) or utilize one gear only, in spite of the limited torque and maximum power (the gearbox may be locked in one position - e.g. in third gear as in cited Karabag 500E car [1], where it is accepted that maximum speed is limited). The authors have compared the energy consumption in the car using all possible gears of the transmission and the car using gearbox locked in the third gear. The tested car belonged to the FEV category and was built using original ICE vehicle with five-speed standard mechanical gearbox.

1 Vehicle And Selected Testing (Comparison) Procedures

In order to compare energy consumption we have used vehicle prepared by KOMEL. It is based on IC engine version of popular Fiat Panda car with five-speed manual gearbox. General view of the vehicle is shown in Photo 1.

![Photo 1: General view of the test car](image)

This vehicle uses three-phase PMSM electric motor in place of IC engine. Drive transmission elements, i.e. serially-manufactured gearbox and clutch have been left intact [5].

The basic vehicle parameters are given below:
vehicle category M1
complete vehicle kerb weight– 1180 kg
maximum power (*) – 37 kW at 4700 rpm (47 kW at 2700 rpm)
maximum torque (*) – 168 Nm at 1500 rpm (171 Nm at 2200 rpm)
tyres R14 175/65 , r = 0,285 m
air drag coefficient Cx = 0,32
front face – 2,039 m².
Li-Ion supply battery with 15 kWh capacity / charging time < 6 h from AC 230 V socket or < 2,5 h from 400V socket
maximum speed (*)– 145 km/h (160km/h)

Gear data is given in Table 1.

On the basis of previously conducted analysis of driving force and torque at wheels (Figure 1) (test data of Karabag 500 E vehicle had been used), we decided to compare energy consumption of Fiat Panda vehicle reconstructed by Komel in two configurations A and B:

A) making it possible to drive using all gears of five-speed mechanical gearbox
B) making it possible to drive using only the third gear of five-speed mechanical gearbox installed in the car.

Configuration A, i.e. the one using five-gear gearbox is a standard configuration used by KOMEL. It ensures good traction properties (overcoming increasing resistance to motion and obtaining appropriately high maximum speed equal to 140 km/h).

It is possible to operate the car with gearbox locked permanently in the third gear (configuration B) thanks to the concept of the motor stopped when the car is at a standstill with released acceleration pedal. The driving force available in this gear is sufficiently sufficient to move car over a flat terrain and at small grades (grade up to 13% without full vehicle load) occurring in typical urban environment. Using the third gear with gear ratio equal to ic = 5,088 brings about certain limitations related to diminished ability of overcoming increased resistance to motion, i.e. in case of grades exceeding 13% or to maximum car speed equal to 118 km/h (limitation imposed on account of maximum rotational speed of the motor equal to 5600 rpm). In spite of the described limitations of traction properties of a car with the gearbox locked in the third gear, it is possible to conduct measurements of energy consumption both in case of the test set in accordance with Annex 7 to Regulation No. 101 (exception - maximum speed decreased by 2 km/h for tests combined of /urban/ UDC and /extra-urban/ EUDC) and in case of the test conducted under typical urban driving conditions.

(*) measurement with active energy recuperation function., measurements in brackets without energy recuperation function.
Table 1: Gear ratios of the test vehicle

<table>
<thead>
<tr>
<th>Gear ratio</th>
<th>1st gear</th>
<th>2nd gear</th>
<th>3rd gear</th>
<th>4th gear</th>
<th>5th gear</th>
<th>Reverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st gear</td>
<td>1:4,100</td>
<td>1:2,158</td>
<td>1:1,480</td>
<td>1:121</td>
<td>1:0897</td>
<td>1:3,818</td>
</tr>
<tr>
<td>Total gear ratio</td>
<td>1:14,096</td>
<td>1:7,419</td>
<td>1:5,088</td>
<td>1:3,854</td>
<td>1:3,084</td>
<td>1:13,126</td>
</tr>
</tbody>
</table>

In order to compare energy consumption in vehicle for two selected configurations, a test drive has been conducted over a test route chosen in accordance with Annex 7 to Regulation No. 101 (a simplified method of configuring the engine test bench has been used - for the tested vehicle we have adapted catalogue parameters the same as in case of original IC engine vehicle) and Urban Driving Cycle test, 38.76 km long (route is shown in Fig.2). This choice was imposed by repeatability of conditions - in case of tests conducted in accordance with Annex 7 to Regulation No. 101 and reference to real vehicle energy consumption in case of typical urban driving– in case of the tests conducted in accordance with selected test route.

2 Energy consumption measurements

All energy consumption measurements described below refer for vehicle with active energy recuperation function.

2.1. Measurements with chassis dynamometer in accordance with procedure described by Annex 7 to Regulation No. 101

The measurement of energy consumption was run in accordance with procedure described in Annex 7 to Regulation No. 101, within the framework of two NEDC tests consisting of 4 elementary cycles = UDC and EUDC. Total driving time was 2360 s. The obtained energy consumption results:
- for car with configuration A 3.54 kWh (165 Wh/km),
- for car with configuration B 3.36 kWh (156 Wh/km).
Figure 2: Route map of energy consumption in real urban driving
Figs. 3 to 6 shown below present battery current waveforms [A], car speed [km/h] and motor's rotational speed [RPM] vs. time [s] for 1 elementary cycle of UDC test and EUDC test for vehicle configured as A and B.

Figs. 7 and 8 shown below present the instantaneous power absorbed from the battery [kW] and car speed [km/h] for double NEDC test for vehicle configured as A and B, respectively.

Figure 3: Course of battery current waveforms, car speed and motor's rotational speed vs. time - vehicle configured as A - single elementary urban cycle (195 s)

Figure 4: Course of battery current waveforms, car speed and motor's rotational speed vs. time - vehicle configured as B - single elementary urban cycle (195 s)
Figure 5: Course of battery current waveforms, car speed and motor's rotational speed vs. time - vehicle configured as A - EUDC test

Figure 6: Course of battery current waveforms, car speed and motor's rotational speed vs. time - vehicle configured as B - EUDC test
Figure 7: Course of electric instantaneous power absorbed from the battery and car speed vs. time - vehicle configured as A - double NEDC test

Figure 8: Course of instantaneous electric power absorber from the battery and car speed vs. time - vehicle configured as B - double NEDC test
The Figure 9 shows measurement circuit used to record the quantities mentioned above.

Figure 9: Measurement circuit

2.2. Measurement of energy consumption in road test - urban driving, real-life conditions

The energy consumption was measured after driving over a distance of 38.76 km as set by procedure described in Annex 7 to Regulation No. 101, i.e. by charging the battery after completion of the test and reading the quantity of energy used to charge batteries to 100% level in 12 hours. On account of local traffic regulations, the daytime running lamps were used; other on-board devices supplied with electrical energy were not used and vehicle load was equal to c. 150 kg (driver + passenger). During the tests of both car configurations similar road conditions were kept - no rain or snow, moderate sun operation, temperature about 20-22°C, dry road surface.

On account of varying road conditions different driving times and different average speeds were attained - for car configuration A it was 4986 s and for configuration B it was 4686 s. Total energy consumption during the test was equal to, respectively: configuration A 9,612 kWh (248 Wh/km), configuration B 8,701 kWh (224 W/km). Exemplary courses of motor's supply current/vehicle speed and motor's rotational speed, recorded over measurement route are shown in Figs. 10 and 11. The presented section of route corresponds to vehicle acceleration (total recording time 44 s for test vehicle configured as in B and 64 s test vehicle configured as in A.

Figure 10: Course of battery current waveforms, car speed and motor's rotational speed vs. time – vehicle configured as A – the interval of 64 s illustrating acceleration of car during measurement of energy consumption in road test in real conditions of urban driving
Figure 11: Present battery current waveforms, car speed and motor's rotational speed vs. time – vehicle configured as B – the interval of 44s illustrating acceleration of car during measurement of energy consumption in road test in real conditions of urban driving.

Energy measurements were conducted using ORNO OR-WAT-408 wattmeter (measurement error 2%).

3 Conclusions

Measurement results cited in the section 2 of this paper show that use of multi-gear transmission system in electric vehicle does not significantly affect energy consumption. The negligible differences in PMSM efficiency in different operation ranges, which may be utilized by vehicle equipped with multi-gear transmission system (exemplary chart is shown in Fig.12) are not sufficient to compensate losses generated by, among other factors, frequent engagement and disengagement of the clutch.

In real-life urban traffic the vehicle with configuration A did not attain lower energy consumption either; however, in this case the end result was affected by longer test drive time caused by different traffic conditions (intensity of traffic).

Nevertheless, it must be pointed out that vehicle with configuration B did not provide satisfactory attributes such as maximum speed or properties such as in particular its ability to overcome increased resistance to motion occurring in case of high curb (14 cm high) or starting against the grade of 26%. Such obstructions required the use of first or second gear, the third gear could not ensure adequate driving force. Therefore, in case of using medium-speed electric motor with limited rotational torque (c.160-180 Nm), it is fully justified to adapt multi-gear transmission system; however, using two or three gears seems to be adequate. This opinion is supported by numerous references, e.g. [6]. The use of such design will guarantee proper traction properties of the vehicle, comparable or even better than those exhibited by present-day ICE vehicles using five-speed, six-speed or even more complex gearboxes.
Figure 12: Electric motor’s efficiency map as a function of rotational torque and rotational speed

References


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