Comparative study of different electric vehicle configurations in terms of energy consumption

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Abstract. In order to respect the new fleet-wide average emission regulations, recent studies show that car manufacturers produce an increased number of electric vehicles. For improving the dynamic performances of an electric vehicle while maintaining a low energy consumption, different solutions are used, such as the multi-speed transmission, or the continuously variable transmission (CVT). Another solution more advantageous than other EV typologies consists of a dual motor two speed direct drive, that implies each motor being connected with the final drive through a separate gear. The aim of this paper is to analyse the energy consumption and the overall transmission performance in different test cycles for a middle class with different configurations. The study was carried out by developing a model in a performant simulation environment. The obtained simulation results from the chosen configuration are compared in different test cycles in terms of energy consumption ratio (ECR) and vehicle speed fluctuation (VSF) with the ones from a direct drive EV and a two-gear transmission EV.

1. Introduction

The electric powertrain solution that consists of one motor and a two-speed transmission is considered a better alternative to the electric vehicles that have a single motor and one gear ratio, with respect to the dynamic performance and the energy efficiency.

Adjusting the operating point of the motor in a high efficiency region can be achieved by using a two-speed transmission and an optimized gear shifting schedule [1].

In addition, by making use of the high and low gear ratios corresponding to the speed regime imposed by the vehicle it is possible to obtain a much better dynamic performance in terms of acceleration and maximum speed.

However, a multi-speed transmission has a disadvantage in terms of drivability because the problem of torque interruption during the gear shifting process persists.

Several studies conducted for electric vehicles on multi-motor and multi-speed transmissions show that these topologies achieve higher efficiency than a single motor and multi-speed transmission solutions [2].

Some papers investigate the powertrain solution which consists of two motors working together but being limited in terms of rotational speed [2, 3], while other sources are not focused on applying a specific limitation for the electric machines.

In this paper, one of the electric machines is being decoupled by a clutch at a certain rotational speed through a functioning strategy that was implemented.

To eliminate the torque interruption inconvenience, each motor needs to be connected to a gear set, thus making the use of a separate shifting device unnecessary. Therefore, for a non-shifting EV powertrain, it is essential that the number of motors to be equal to the number of gears [4].
Figure 1 illustrates the structure of a dual motor and a two-speed direct drive EV powertrain.

![Diagram of dual motor and two-speed direct drive EV powertrain]

GM – gear set of the motor

**Figure 1.** Structure of the dual motor two speed direct drive EV powertrain

Each motor is connected to a gear and these gears share a single output shaft. The torque of the output shaft is finally transferred to the driving wheels [1].

The aim of this paper is to analyse the energy consumption and dynamic performance of a middle class vehicle for one motor with one speed, one motor with two-speed transmission and dual-motor with two-speed direct drive.

All the parameters will be determined for five driving cycles: US06, Japanese 10-15, HWFET, NEDC and WLTC.

2. **Model development**

The simulation model was created with the aid of LMS Imagine Lab AMESim, a specialized software that contains several components organized in libraries [5].

The main submodels were extracted from the IFP Drive library and some of them are listed as follows: a driver submodel (DRVDRVA00A) necessary to follow the cycle given by the mission profile and ambient data submodel (DRVMP2A), two electric motors (DRVELMT0A), two control units (DRVCUE0A), a battery (DRVBAT04), a power electronic converter (DRVPET0B) and 1D vehicle (DRVVEH4A).

Aside from these components, four more blocks were composed as supercomponents, two of which having the role of interrupting the electric machine circuit when the torque command is null, and the other two being used for coupling and decoupling the two motors based of the functioning strategy.

The clutch corresponding to motor 2 is added only based on causality considerations of the simulation model, having no functional role.
Figure 2. Model design of the dual motor two speed direct drive EV for the energy consumption study

3. Gear ratio determination
Because the first gear ratio is always higher than the second gear ratio ($r_2 \leq r_1$), when the vehicle is driving at the maximum speed only the second motor generates the driving power, as the first motor is decoupled (it does not exceed the allowable maximum motor speed).

Since the power gets split between the two motors, thus reaching the maximum reference speed being difficult to achieve, the power of motor 2 is calculated such that the maximum vehicle speed is reduced with 10% compared with the one motor and two speed reference powertrain.

The two motors were rescaled such that the sum of their maximum powers is equal to the power obtained from the reference motor [6] and motor 2 should have the required power to reach the maximum speed.

The power required for obtaining the maximum imposed speed is calculated with equation (1)

$$ P = \frac{1}{\eta_t} \left( f_r \cdot m \cdot g \cdot \cos \alpha + \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot V_{\text{max}}^2 \right) \cdot \frac{V_{\text{max}}}{3600} \quad (1) $$

where: $\eta_t$ - overall efficiency of the powertrain (0.95), $f_r$ - rolling resistance coefficient (0.01), 
$m$ - vehicle mass (1966 kg), $\alpha$ - road incline angle ($0^\circ$), $\rho$ - air density (1.225 kg/m$^3$), 
$C_d$ - air drag coefficient (0.3), $V$ - maximum vehicle speed (152 km/h), $A$ - frontal area of the vehicle (2.5 m$^2$)
The obtained value for the required power is 45 kW.

Based on the required maximum vehicle speed, the gear ratio for motor 2 \( (r_2) \) can be expressed as follows:

\[
    r_2 = \frac{3.6 \pi n_p r_r}{30 V_{\text{max}}}
\]

where \( n_p \) – motor speed for maximum power (6500 rev/min), \( r_r \) – rolling radius (0.31 m), \( V_{\text{max}} \) – maximum vehicle speed (152 km/h).

The value for \( r_2 \) has therefore been set to 5.

The gear ratio for motor 1 \( (r_1) \) is calculated such that the same traction force from the reference motor with the maximum torque of 220 Nm and a gear ratio of 9.52 is obtained \[6\]. This will ensure the same maximum slope that the vehicle can drive on.

\[
    F_{t \text{ ref}} = F_{t1} + F_{t2}
\]

Expressing the traction force as a function of each motor’s torque, the below expression is obtained,

\[
    \frac{T_{\text{ref} \cdot \eta_{\text{ref}}}}{r_r} = \frac{T_1 \cdot r_1 \cdot \eta_{t1}}{r_r} + \frac{T_2 \cdot r_2 \cdot \eta_{t2}}{r_r}
\]

From eq. 4 results

\[
    r_1 = \frac{T_{\text{ref} \cdot \eta_{\text{ref}} \cdot GM_2 \cdot \eta_{t2}}}{T_1 \cdot \eta_{t1}}
\]

Thus, it resulted a value of 22 for the gear ratio of motor 1.

The variation of the vehicle acceleration for different powertrain configurations is represented in figure 3.

![Vehicle acceleration](image)

**Figure 3.** Vehicle acceleration

Therefore, it resulted a smaller maximum acceleration than the reference vehicle acceleration due to the high ratio of GM\(_1\) that amplifies Motor 1 inertia.

The efficiency map of the two motors was obtained by rescaling the power losses and the torque maps of the reference electric machine.

Figure 4 shows the energetic consumption at constant speed values, including the medium speed values of each driving cycle, for different powertrain solutions for every gear.
Table 1. Electric vehicle performances

| No. | Parameter                        | Motor 1 | Motor 2 | Combined motors | Reference motor Two gears |
|-----|----------------------------------|---------|---------|-----------------|---------------------------|
| 1   | Maximum speed [km/h]             | 54.9    | 152.6   | 152.6           | 171                       |
| 2   | Maximum acceleration [m/s]       | 1.87    | 1.33    | 3.1             | 3.3                       |
| 3   | Acceleration time 0-50 km/h [s]  | 19.5    | 10.8    | 6.5             | 4.93                      |
| 4   | Acceleration time 0-100 km/h [s] | –       | 29.1    | 24.8            | 14                        |
| 5   | Maximum grade [%]                | 21.2    | 13.5    | 30              | 30                        |
| 6   | Energy consumption at 50 km/h [Wh/km] | 131.4  | 98.3    | 98.3            | 103.5                     |

4. Results

In principle, due to the low values of torque developed by motor 1, the electric vehicle cannot undergo the driving cycles without motor 2, therefore one must establish strategies that can satisfy this condition.

For the vehicle to go through the test cycles, an efficient control based on load and rotational speed has been developed, thus three different strategies have been implemented, as follows.

- **S1** – the electric vehicle has only motor 2 set working,
- **S2** – both motors act simultaneously, motor 1 being decoupled at 30 km/h. After improving the motor load and rotary velocity control, the minimum consumption for which motor 1 is decoupled has been obtained for the vehicle speed of 30 km/h.
- **S3** - The two motors work alternatively. Motor 1 functions with the load appropriate to the minimum energetic consumption, therefore, when the vehicle reaches 30 km/h, it gets decoupled. For vehicle speed values higher than 30 km/h, motor 2 is set functional.

Table 2 shows the energetic consumption for the presented strategies.
Table 2. The energetic consumption for different motor functioning strategies

| No. | Cycle   | Energy consumption [Wh/km] |
|-----|---------|---------------------------|
|     |         | S1 | S2 | S3   | Reference vehicle |
| 1   | NEDC    | 150.4 | 133 | 131.3 | 152.5 |
| 2   | WLTC    | 170.9 | 154.7 | 151.7 | 158.3 |
| 3   | 10-15   | 135 | 113.7 | 106.3 | 132.5 |
| 4   | US-06   | 200.1 | 192.3 | 190   | 206.1 |
| 5   | HWFET   | 152.1 | 146.5 | 146.3 | 158.9 |

The energetic consumption obtained at constant speed values is compared with the energetic consumption for five different driving cycles when the functioning strategy is S2, as shown in figure 5.

![Figure 5. Energy consumption comparison](image)

In figure 6, the correlation between ECR and VSF is presented. Also, two regression lines are illustrated, having set as an imposed point of the constant speed movement with coordinates (0,100).

![Figure 6. Correlation between ECR and VSF for different powertrain configurations](image)
For these lines, the coefficient of determination is also indicated. Regarding the above regression lines for the electric vehicle, when strategy S2 is implemented, a less linear correlation between ECR and VSF can be observed.

5. Conclusions

In the current application, when compared with the two gear transmission reference vehicle, the dynamic performances at high velocity are drastically reduced. Consequently, the acceleration time from 0 to 100 km/h is increased with 77.1%.

When applying a functioning strategy that uses an alternative coupling of the two motors (S3), the drivability of the vehicle is less convenient because of the shock induced when the motors are coupled/decoupled, compared with other strategies that allow a smoother torque shift (S2).

The energetic consumption obtained for an alternative motor coupling strategy (S3) is lower than for when the two motors work simultaneously.

When compared with the reference vehicle, a clear improvement of energy consumption was achieved: 14.2% for 10-15 Japanese cycle, 12.8% for NEDC, with the smallest benefit for WLTC of 2.3%.

For the present study, as opposed to the reference vehicle [6], a less linear correlation between ECR and VSF is highlighted.

References

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