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To cite this article: C Renea *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1037** 012050

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The influence of the hybridization factor on vehicle energetic consumption for different e-gearbox configurations

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Abstract To reduce the CO₂ emission level for the new CAFE regulations, it is mandatory that automobile producers should choose the hybridization approach.

Relevant published literature show that for a mild hybrid passenger car, increased values of the hybridization factor (HF) have marginal influence over the fuel economy for high speed values if a fixed ratio e-gearbox is used. This paper analyzes the energetic consumption for a Through the Road Hybrid Vehicle (TTR-HEV) when using a two-gear ratio transmission for the electric axle.

To investigate the energetic performances, a complex model developed in a performant simulation environment is used. The energetic consumption is determined for five different test cycles in terms of speed and duration by analyzing the fuel consumption ratio (FCR) for different values of the HF.

In order to compare the test cycles, the FCR parameter is used, after which the correlation with vehicle speed fluctuation (VSF) is explored.

The simulation results obtained for the current application are compared with a hybrid vehicle equipped with a single gear in the rear axle. The results are also expressed in terms of CO₂ emission.

1. Introduction

Compared to the vehicles solely equipped with internal combustion engines, hybrid vehicles improve the fuel consumption as well as the CO₂, given the fact that these two requirements are strongly related to one-another.

According to the traction component types of the powertrain, these vehicles are categorized in three different types: parallel, serial and mixed respectively.

Another classification based on the hybridization factor [1], defined as the ratio between the power of the electric motor and the total power for both thermal and electric sources of the vehicle (equation 1) is presented in table 1.

$$HF = \frac{P_{em}}{P_{em} + P_{ICE}} \quad (1)$$

where P_{em} is the power of the electric motor and P_{ICE} represents the power of the internal combustion engine.

A particular parallel structure is approached for this study, known in the published literature as the Through the Road Hybrid Vehicle (TTR-HEV).

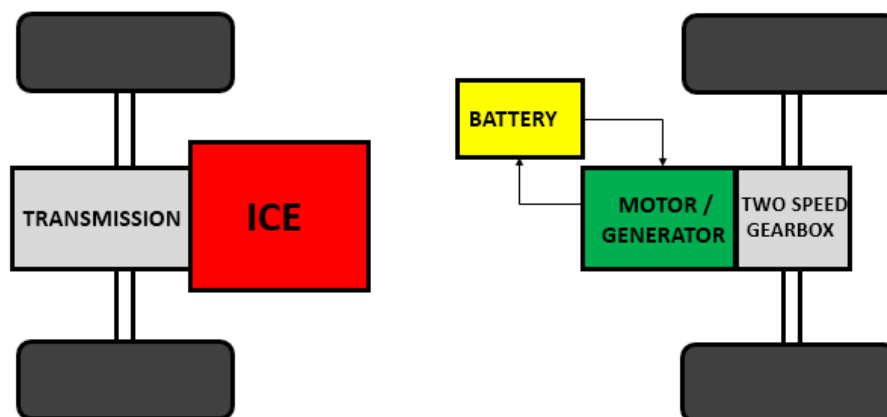


Table 1. Vehicle classifications based on HF values

HF	Hybrid type	Characteristics
0 ... 0.1	Minimal Hybrid	No pure electric mode
0.25 ... 0.5	Mild Hybrid	The energy provided by the purely electric mode cannot support a full standard driving cycle completion
0.5 ... 0.7	Full Hybrid	The electric system fully supports the vehicle to follow a standard cycle

The specific powertrain components for this structure are an internal combustion engine, which is placed on the front axle, and an electric motor that provides power to the rear axle.

The electric motor also functions as a generator, in order to allow the regenerative braking, [2].

**Figure 1.** Through the road parallel hybrid vehicle structure

As for the pure electric mode of the TTR-HEV but requiring improvements in terms of vehicle performances such as: driving on steep roads or driving at high speed on a horizontal road, an increased number of gears for the electric axle represents a good solution.

Furthermore, increasing the number of gears results in the cut back of the energetic consumption, therefore imposing the electric motor to function at high efficiency.

On the other hand, this implies more weight for the electric axle, a reduced transmission efficiency, and also an additional gear shifting mechanism needs to be installed, thus making the manufacturing cost high.

Consequently, the optimum number of gear ratios must be chosen such that the adopted solution should reduce the energetic consumption, but in the same time the vehicle's overall cost to be maintained as low as possible.

The purpose of this paper is to analyse the energetic consumption for a middle class vehicle when two gear ratios are used for the electric axle of a TTR-HEV, considering three different values of the hybridization factor from the mild hybrid range. For all HF values, the battery capacity was kept constant at 5 Ah in the hybrid model simulation.

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

2. Model development

The hybrid vehicle model, figure 2, has been developed based on specialized libraries from the simulation environment LMS Imagine.lab AMESim, [3, 4].

There are 10 main submodels used for the HEV model, all of which have the parameters modified in order to correlate the vehicle speed with the cycle profile and also to simulate all the topologies aforementioned.

The main submodels used for the HEV model are: a driver submodel (DRVDRVA00A-1) necessary to follow the cycle given by the mission profile and ambient data submodel (DRVMP2A-1), electric motor (DRVELMT0A), battery (DRVBAT03), internal combustion engine (DRVICE01E), control unit for a parallel hybrid vehicle (DRVCUPH1A), gearbox (DRVMGC01), e-Gearbox (DRVDC01), Transmission Control Unit for Automatic Gearbox (DRVAGTCU01), which allows the shifting gears according to a proposed shifting schedule and 1-D vehicle (DRVVEH4A).

For the power electronic converter that includes the standard DRVPET0B submodel, two special supercomponents were added, one having the role of completely interrupting the electric machine circuit when the torque command is null and the other which removes the discontinuities caused by portions of the test cycle when the vehicle is stationary.

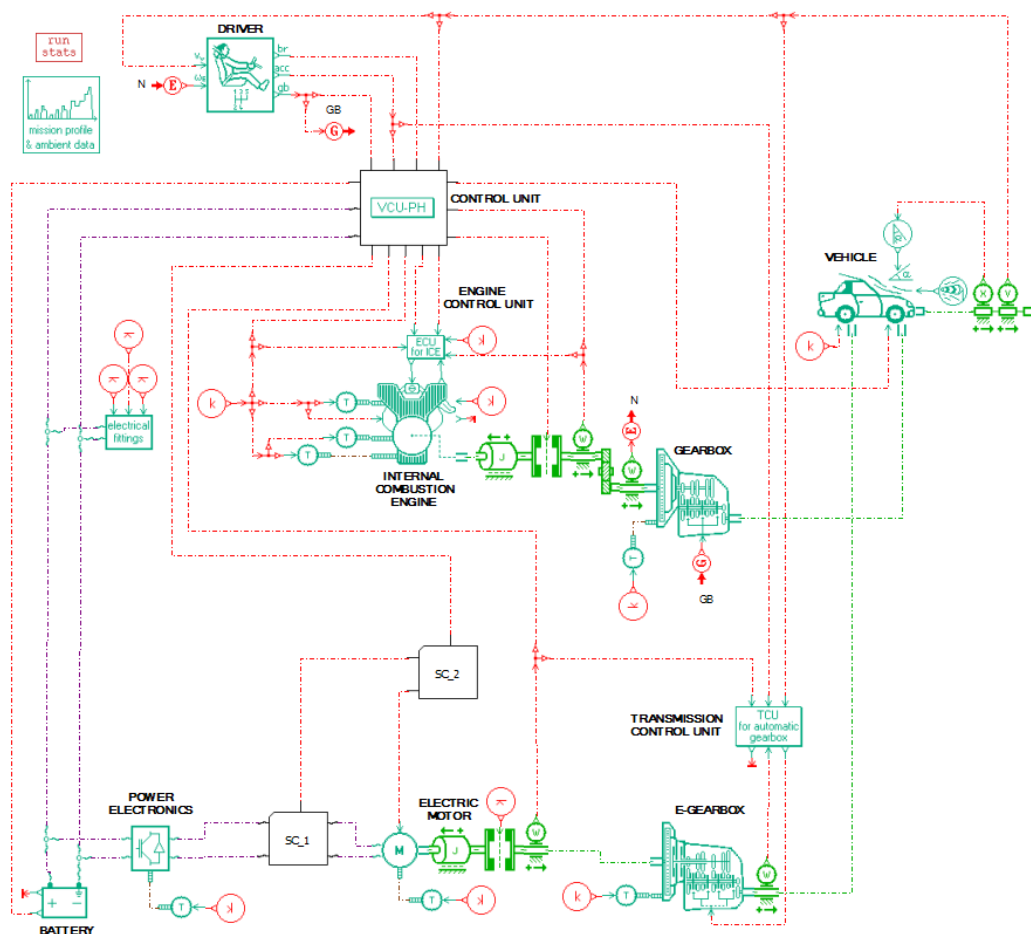


Figure 2. TTR-HEV model for the energetic consumption study

For the front axle driver command, the gearbox ratio control is the signal input, whereas three more signal inputs are used for the mechanical components such as wheel rotary velocity, engine torque and gearbox temperature.

For the rear axle, an automatic gearbox linked to another control unit is preferred when shifting two gears, whereas for the single gear model the latter component is no longer needed.

The most important submodel for a hybrid vehicle is the electronic control unit. It gets information from the driver, the engine, the electric machine, the battery and it receives vehicle speed data.

3. Gear ratios and shifting schedule

For a TTR-HEV that has a two speed gearbox on the electric axle, the first gear is used to gain acceleration at low speeds and to climb inclines, whereas for high speeds the second gear is necessary [5].

For this study, the first and second gear ratios are determined using the equation (2) and equation (3) respectively, [6].

$$i_{t\max} = \frac{r_r \cdot m \cdot g \cdot (f_r \cdot \cos \alpha + \sin \alpha)}{T_m \cdot \eta_{pt}} \quad (2)$$

where r_r – rolling radius (0.3 m), m – vehicle mass (1600 kg), g – gravity, f_r – rolling resistance coefficient (0.01), α – road incline angle (20°), T_m – maximum torque (208 Nm), η_{pt} – e-gearbox efficiency (0.95).

$$i_{\min\text{speed}} = \frac{3.6 \cdot \pi \cdot n_m \cdot r_r}{30 \cdot V_{\max}} \quad (3)$$

where n_m – maximum motor speed (6800 rev/min), $V_{\max}$ – maximum vehicle speed in pure electric mode (128 km/h).

The obtained values for gear ratio are $i_{t\max} = 8.4$ and $i_{\min\text{speed}} = 6$, the variation of vehicle acceleration being represented for these two values in figure 3.

The pure electric mode was obtained based on the TTR-HEV model, where the internal combustion engine was set unfunctional, thus making the front axle non-driven. The vehicle acceleration and energy consumption in this mode are presented in figure 3 and figure 4.

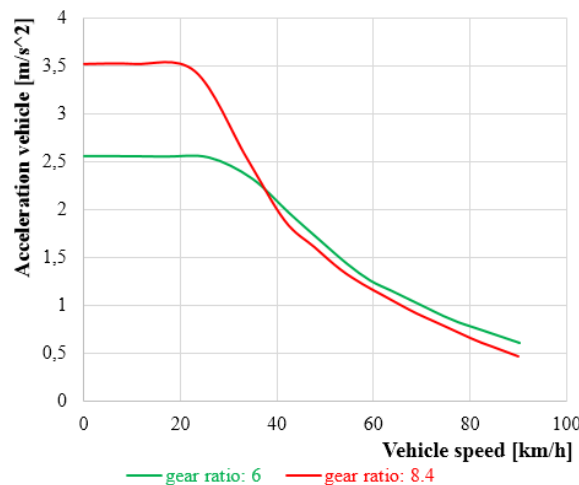


Figure 3. Vehicle acceleration

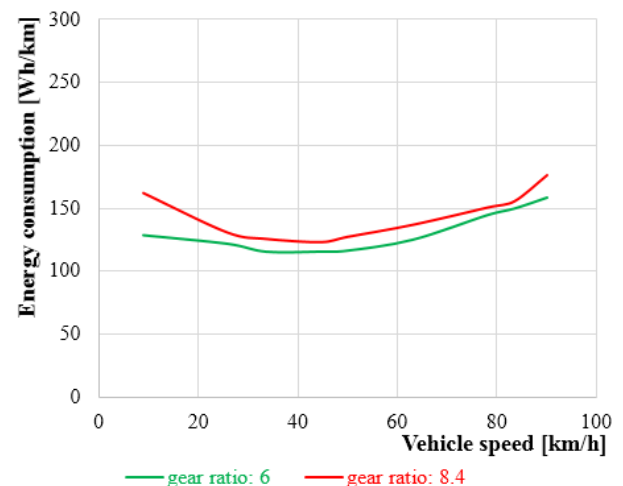


Figure 4. Energy consumption at constant speeds

As the transmission efficiency depends on the gear, the values for the e-gearbox efficiency are 0.95 for an 8.4 ratio and 0.97 for a 6 ratio, respectively.

Figure 5 reflects the shifting schedule used for this study [7], by considering the energy consumption at constant speeds for the two gears (figure 4) and the variation of vehicle acceleration (in the domain of interest).

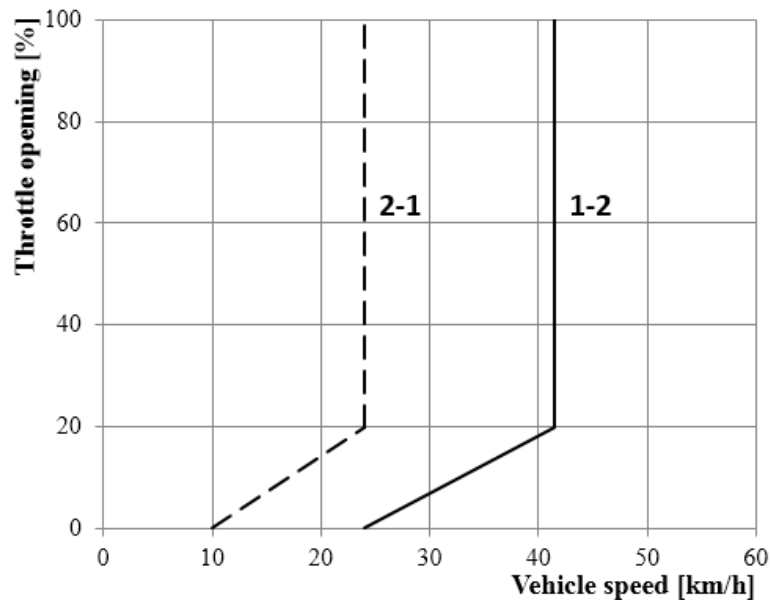


Figure 5. Shifting schedule for two speed transmission

The vehicle performances in pure electric mode resulted within simulations with the chosen gear ratios, are presented in table 2.

Table 2. Vehicle performances in pure electric mode

No.	Parameter	One gear 8.4	One gear 6	Two gears 8.4/6
1	Maximum speed [km/h]	110	128	128
2	Maximum acceleration [m/s]	3.52	2.07	3.48
3	Acceleration time 0-50 km/h [s]	5.4	6.18	5.42
4	Maximum grade [°]	20	14	20
7	Energy consumption at 50 km/h [Wh/km]	127.3	115.8	116.4

4. Results

In the hybrid mode, the fuel consumption for different powertrain solutions is being determined, considering three values for the hybridization factor.

Table 3 shows the fuel consumption classified in two categories, based on the hybridization factor and also considering different e-gearbox configurations (one that has two gear ratios and a single ratio gearbox).

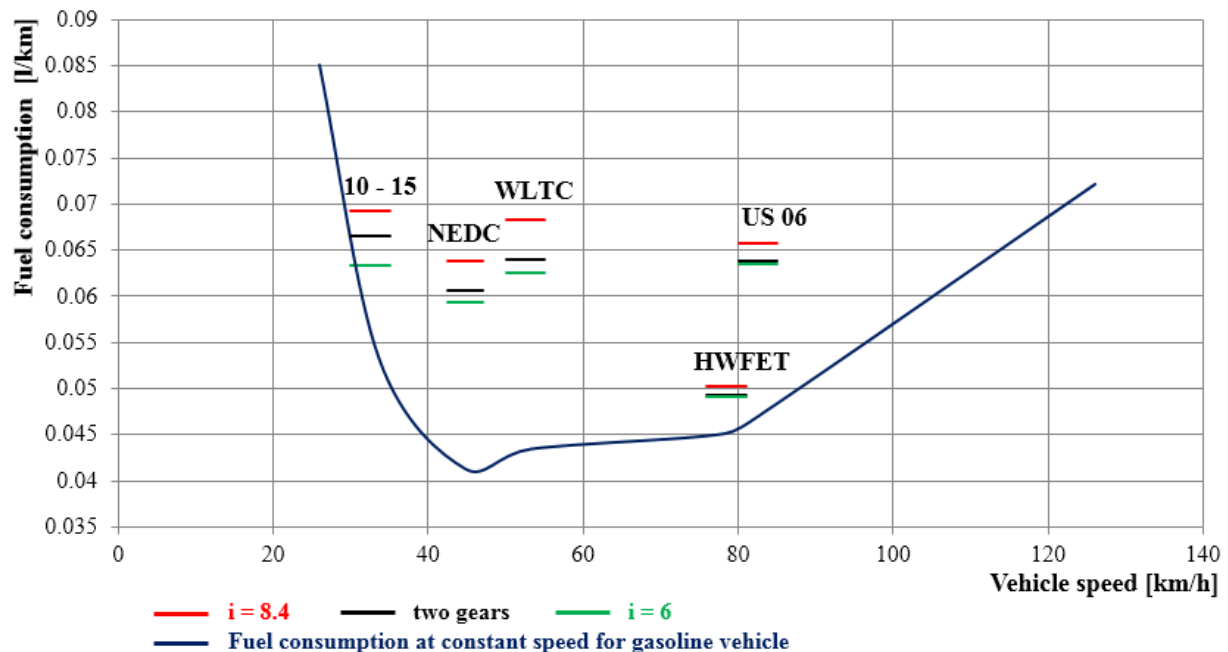
Table 3. TTR-HEV fuel consumption for different HF

No.	Cycle	HF=0.22			HF=0.32			HF=0.42		
		6	Two gears	8.4	6	Two gears	8.4	6	Two gears	8.4
1	NEDC	5.366	5.355	5.3	5.5482	5.535	5.664	5.934	6.062	6.39
2	WLTP	5.786	5.840	5.818	5.902	6.034	6.14	6.257	6.406	6.833
3	10-15	4.797	5.076	5.032	5.458	5.702	5.944	6.338	6.654	6.93
4	US-06	6.28	6.354	6.44	6.342	6.397	6.569	6.343	6.39	6.57
5	HWFET	4.99	5.015	4.896	4.91	4.929	4.908	4.91	4.93	5.03

From table 3, one can observe that as the hybridization factor increases, the difference between the fuel consumption obtained for using a single speed e-gearbox with $i=6$ and $i=8.4$ increases for each cycle driven, thus utilizing a 2-speed e-gearbox clearly becomes advantageous. It can be stated that the fuel consumption for using a 2-speed e-gearbox is close to the one for a single gear with $i=6$ ratio, but with a far superior dynamic performance, as shown in table 2.

It can be noticed that for average speed higher than 80 km/h cycles, US-06 and HWFET, when the hybridization factor is 0.32 and 0.42, the fuel consumption for a 2-speed e-gearbox configuration is similar. Also, from table 3 it can be observed that when driving on HWFET cycle, the three configurations studied have the least influence on fuel consumption.

In figure 6, the fuel consumption obtained from 5 driving cycles considering 3 transmission configurations for HF=0.42 is shown. The data obtained from the gasoline vehicle model at a constant speed equal to the average speed value for each cycle is considered as the reference curve.

**Figure 6.** Fuel consumption for different gear ratios at HF=0.42

After completing the simulations, it is observed that using a 2-speed e-gearbox becomes increasingly advantageous as the average speed of the driven cycle is higher.

In figure 7, the correlation between FCR and VSF is shown, [8]. Four regression lines are represented, one for each degree of hybridization for a 2-speed e-gearbox configuration and a regression line for the gasoline vehicle with a point of intercept set at (0,100).

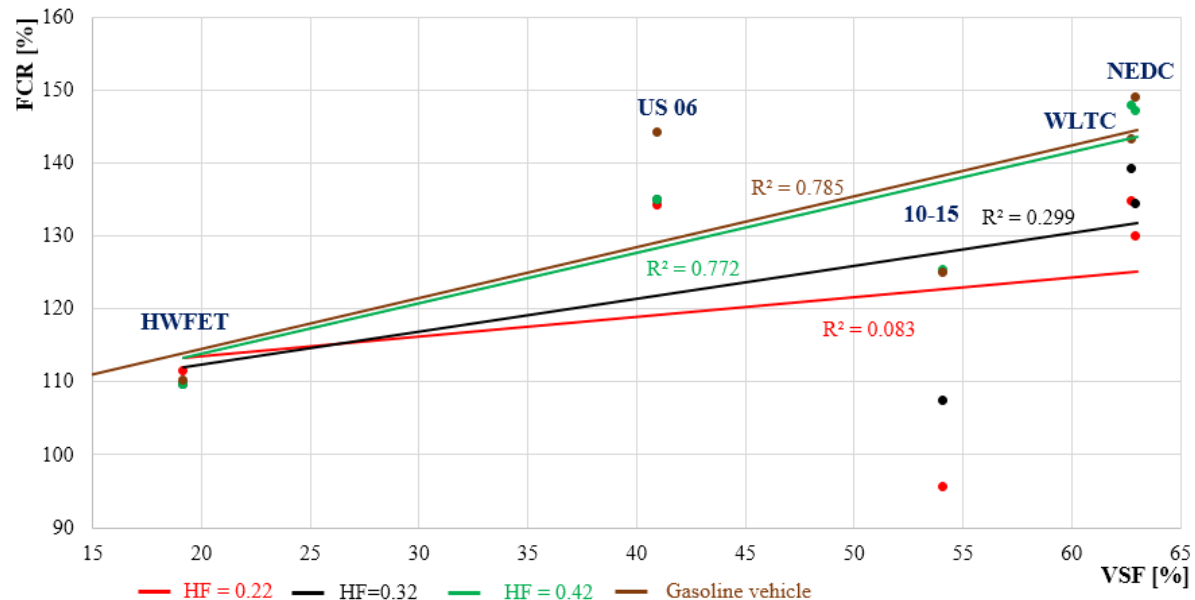


Figure 7. Correlation between FCR and VSF for three degrees of hybridization

Based on the low value of the coefficient of determination R^2 , it can be noted that there is no linear correlation between FCR and VSF for the TTR-HEV equipped with a two-speed e-gearbox.

5. Conclusions

As the hybridization factor increases, implementing a 2-speed e-gearbox solution clearly becomes advantageous because the difference between the fuel consumption obtained when using a single speed e-gearbox for two different ratios increases for each test cycle.

The fuel consumption for using a 2-speed e-gearbox is close to the one for a single gear with a ratio of 6, but with a much better dynamic performance.

One can observe that the linear dependency between FCR and VSF, defined by the coefficient of determination, is being reduced as the hybridization factor decreases.

In terms of CO₂ emissions of the two-speed e-gearbox vehicle model, the relative difference from a maximum value, obtained for the Japanese 10-15 cycle, and a minimum value, achieved for HWFET mode, is of 25%. Also, it can be acclaimed that the hybridization degree has a minor influence (less than 3.5%) for cycles with high average speed (US-06 and HWFET cycles).

For the current application, no notable improvement in terms of fuel consumption has been observed, but for the pure electric mode, the dynamic performance and the energetic consumption are far superior. Thus, a two-speed e-gearbox can be very useful to be implemented on a plug-in hybrid vehicle.

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Acknowledgement: This work has been funded by the European Social Fund from the Sectoral Operational Programme Human Capital 2014-2020, through the Financial Agreement with the title "Scholarships for entrepreneurial education among doctoral students and postdoctoral researchers (Be Antreprenor!)", Contract no. 51680/09.07.2019 - SMIS code: 124539.