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Assessing Lightweight Layouts for a Parallel Hybrid Electric Vehicle Driveline

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***Abstract*— The presence of multiple power sources and the several possible architectures that can be designed when referring to hybrid electric vehicle (HEV) powertrains complicate the identification of an optimal HEV configuration. Among the diverse parameters that can be chosen in design and sizing processes of a parallel full HEV, the number of gears and the gear ratios in the transmission are considered as fulcra of this case study. For this scope, five different transmissions have been sized while assessing drivability and acceleration performance along with the fuel economy capability. A dynamic programming-based approach algorithm has been utilized for controlling the HEV, thus providing reliable outcomes and enhancing the consistency of the study. The results obtained in the sizing process suggest that the presence of an electric machine may mitigate the effect of the lower number of gears and enhance the fuel consumption efficiency even when reducing the number of gears in the transmission to 2 or 3. More precisely, even though they might be associated to slightly higher fuel consumption and, in turn, operative costs compared with the other considered configurations, these drawbacks can be overcome by the higher savings in production costs, thus suggesting parallel full HEVs with a reduced number of gears as an appealing design option.**

Keywords*— *driveline, economic consideration, fuel economy, hybrid electric vehicles (HEVs), sizing

I. Introduction

Worldwide, the CO_2 emission regulations for vehicles are becoming stricter in a strong effort of diminishing the overall amount of this pollutant. For this scope, the European Union (EU) is proposing a reduction of the CO_2 emissions of about 15% and 37.5% for road vehicle fleets manufactured in 2025 and 2030 respectively, taking as benchmark the emissions of the 2021 [1]. At the same time, stringent regulations will also be held in USA for which it is forecasted that, in order to meet the 2025 CO_2 target and addressing it totally to a reduction in fuel economy, its average value of the fleets will be of about 4.32 L/100 km (or 54.5 mpg) [2]. In this scenario, hybrid electric vehicles (HEVs) are gaining importance due to their capabilities of fuel saving and good performance in driveability. Not only because of this trade-off, but also HEVs could be the connection between Conventional Vehicles (CVs) and Battery Electric Vehicles (BEVs), by diminishing the so-called "charge-anxiety" felt by most of the drivers when riding the latter [3][4].

The actual era has been referred to as "Competition era" by Tammy et al. as regards HEV development [5]. In this period, the technology is permitting huge improvements in the HEV field, both when considering sizing and controlling of these systems. Nonetheless, the complexity, stemming from the presence of two different power sources and the several possible configurations, currently does not allow to easily and exhaustively address the optimal HEV design problem, which still represents an important challenge in this field [6]. The full parallel P2 has been chosen as the HEV architecture in the simulations of this case study, due to its high benefits in fuel economy and its relatively low differences in comparison with a CV powertrain layout. Moreover, the choice of using a full hybrid (and not a plug-in) is related to its trade-off between the efficiency in energy consumption and the production simplicity of the vehicle [7]. Considering the driveline of this type of vehicles, the optimal number of gears in the transmission has not been determined yet. Indeed, when the size of the electric machine (EM) is sufficient for propelling the vehicle alone, some opportunities are offered in modifying the number of gears embedded in the transmission gearbox compared with CV layouts. Particularly, the capability of EMs of delivering high values of torque at low values of angular speed could be exploited to reduce the number of gears required in a parallel HEV to maximize fuel savings and achieve smooth driving. A lightweighting of the overall HEV driveline could be possible in this way, thus achieving benefits in terms both of tailpipe emissions and of overall cost. Referring to P2 HEV architectures, in the past decade car manufacturers have indeed selected different transmission layouts. When it comes to market applications: the BMW X5 has a 8-speed gearbox [8], the Nissan Infiniti Q50 features a 7-speed transmission [9] and a 6-speed transmission is embedded in the Hyundai Sonata [10]. Instead, the Honda Accord is designed with no multi-speed gearbox [11]. In this paper, a comparison is performed for a P2 HEV equipped with different gearboxes having 2, 3, 4, 5 and 6 speeds, respectively. The analysis has been carried out in MATLAB® software by sizing the different driveline configurations according to driveability, 0-100 km/h time and fuel economy criteria, evaluated by means of numerical tests. Once the optimal solution for all the transmissions has been found, the economic comparison has been done to show potential benefit of reducing the number of gears and exploiting the co-operation of both EM and internal combustion engine (ICE). Results show that the fuel economy is slightly better when considering the 6-Speed transmission HEV, nonetheless due to the lower complexity in production and reduced costs of the other transmissions, these could represent a suitable choice when considering the different parameters used for designing the P2 HEV.

II. HEV MODEL CONFIGURATION

In this section, the HEV architecture as well as the related modelling equations are introduced. Then, the Dynamic Programming (DP) algorithm used and the HEV sizing parameters can be found.

A. HEV architecture

For the purpose of this study, a parallel P2 configuration of the HEV has been chosen. In this configuration, the power can be delivered to the input shaft of the transmission in three different ways: pure electric, i.e. supplying the power using only the battery; pure thermal, i.e. providing the power needed only by means of the ICE; torque split, i.e. a mix of the two just mentioned. The last operational mode represents the hardest to control, since the amount of power provided by the two sources has to be chosen so to enable the ICE to work at its high efficiency points without letting the battery discharge considerably. As it can be seen in Fig. 1, a clutch is embedded between the EM and the ICE that enables to detach the latter when a pure electric mode is chosen. Moreover, the presence of a gear between the output shaft of the ICE and the EM allows the former to spin at a different angular speed than the latter and to provide the torque accordingly to the gear ratio.

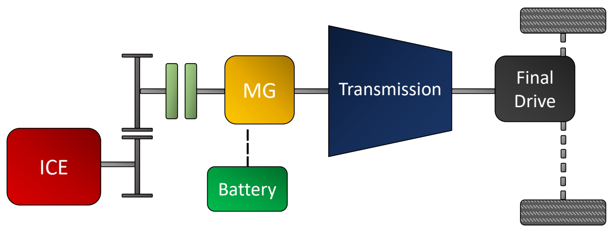

Fig.1. P2 HEV architecture

B. HEV model

The a priori knowledge of the drive cycle, together with the coastdown coefficients of the vehicle, allow to compute the torque required at the wheel to follow the target velocity. Then, in order to calculate the torque to be delivered by the ICE and EM, a term needs to be added which depends on the acceleration and the ratios of the differential and the selected gear are considered as well. The last term relates to the slope of the drive cycle. The equations solved at each timestep (1 second in this case study) in a quasi-static approach are therefore the following ones:

$$T_{wheel} = (A + Bv + Cv^2 + ma + mgsin(\alpha)) \cdot r_{dyn} \quad (1)$$

$$T_{in} = \frac{T_{wheel}}{(\tau_{diff} \cdot \tau_{gear}) \cdot \eta_{gear}{}^{sign(T_{wheel})}} \quad (2)$$

in which T_{wheel} and T_{in} are the torques required at the wheel and at the input shaft of the transmission respectively. A, B and C are the coastdown coefficients, r_{dyn} is the wheel effective radius. m , a and g are the vehicle mass, the requested acceleration and the gravity acceleration. α is the road slope, τ_{diff} and τ_{gear} represent the gear ratios of the differential and the gearbox respectively, while η_{gear} is the gear efficiency. Once T_{in} is known, it is crucial to split this requested torque between the ICE and the EM in such a way to minimize the fuel consumption. This split, together with the gear selection, can be considered the two degrees of freedom adopted when controlling the HEV since the angular velocities of both EM and ICE are constrained by the vehicle speed. Therefore, the delivered torque at each timestep is computed as follows:

$$T_{del} = T_{ICE} \cdot \tau_{ICE} \cdot \gamma + T_{EM} \cdot (1 - \gamma) \quad (3)$$

in which τ_{ICE} represents the gear ratio between the ICE and the EM, γ is the split term between the two power sources which can be even greater than one in case the battery is charged by means of the ICE. Instead, the power output demanded to the battery is computed using the following equation:

$$P_{batt} = (\omega_{EM} \cdot T_{EM}) + \mathcal{L}_{EM}(\omega_{EM} \cdot T_{EM}) + P_{aux} \quad (4)$$

where $\mathcal{L}_{EM}$ represents the losses of the EM, which depend on the torque (T_{EM}) and spinning velocity (ω_{EM}) of the electric machine and can be derived using an empirical table. P_{aux} embeds all the powers requested by the auxiliaries. In equation (5) the rate of state of charge (SOC) of the battery is computed following an equivalent open circuit approach:

$$S\dot{O}C = \frac{V_{oc} - \sqrt{V_{oc}{}^2 - 4R_{in}{}^2 P_{batt}{}^2}}{2R_{in}Q_{batt}} \quad (5)$$

in which R_{in}, V_{oc} and Q_{batt} are the internal resistance, the open circuit voltage and the battery capacity in amp-seconds, respectively.

C. HEV control

In order to compute the ideal fuel consumption of the different sizing candidates according to an optimal energy management strategy, a DP-based approach has been implemented here. This optimizer runs backwardly the drive cycle and computes at each time step the cost function for each discretized control value at each discretized state value. Then, the control strategy is chosen in order to minimize the overall value of cost function [12]. Therefore, when running DP, it is needed to specify the control variable space U, the state variable space X and the cost function J as in equation (6). X includes the binary engine state ICE_{state} (i.e. on/off), the SOC value and the gear engaged n_{gear}. While the number of elements for ICE_{state} are fixed to be 2 and n_{gear} depends on the type of simulated transmission, besides the discretization for the SOC is a parameter to be chosen. On the other hand, in the control variable space, the gear selection and the power split parameter are found. Regarding the last term, the cost function J is composed of three parameters: the fuel consumption (FC) and two penalty terms aimed to account for the number of gear shifting and ICE activation. Particularly, $\mu_{gearshift}$ and $\mu_{ICE,on/off}$ represent two flags respectively detecting gear shifting and ICE activation, while α_1 and α_2 are constant weighting factors. These two have been embedded in this case study to diminish the number of gear shifts and ICE activations, thus ensuring higher standards on drivability [13]:

$$X = \begin{Bmatrix} ICE_{state} \\ SOC \\ n_{gear} \end{Bmatrix}, \quad U = \begin{Bmatrix} n_{gear} \\ \gamma \end{Bmatrix},$$

$$J = FC + \alpha_1 \cdot \mu_{gearshift} + \alpha_2 \cdot \mu_{ICE,on/off} \quad (6)$$

Few additional constraints were added to this algorithm. The first regards the battery SOC, so that to have the final value of this parameter equal to the starting one (with a tolerance of +1%). Another constraint was on the vehicle velocity to be equal to the one given by the driving mission. Finally, speeds, torques and powers of components of the electrified powertrain are constrained to operate within the correspondingly allowed limits.

D. HEV sizing parameters

In the sizing procedure, the first step involves choosing the parameters to be swept in order to create a design space with all the possible configurations. Considering the architecture shown in Fig. 1, for this case study the first and the last gear ratios of the transmission were selected as parameters to be swept. More precisely, the first gear ratio varies from 1.0 to 5.0 using a search step of 0.25, whereas the last gear ratio varies from 0.2 to 3.0. In this case though, two search steps were used: the first of 0.1 (in the interval from 0.2 to 1.0) and the second of 0.25 in the remaining span. Besides, for what concerns the 3-6 gears transmissions, the intermediate gear ratios were computed following progressive gear steps. The related equations are [14]:

$$\varphi_1 = \sqrt[z-1]{\frac{1}{{\varphi_2}^{0,5(z-1)(z-2)}}\tau_{G,tot}} \;,\; \tau_{G,tot} = {}^{\tau_1}/_{\tau_z} \;,$$

$$\tau_n = \tau_z {\varphi_1}^{(z-n)} {\varphi_2}^{0,5(z-n)(z-n-1)} \qquad (7)$$

where z is the number of gears, φ_2 is the progression factor (equal to 1.1 in this case study) , and τ_n is the gear ratio of the n-gear.

III. SIZING TESTS

In this section, the two preliminary sizing tests are described, namely the driveability test and the 0-100 km/h time test. The two have been implemented to find the suitable designs whose fuel consumption was later evaluated. At the end, the description of the driving missions for evaluating the fuel economy can be found, together with the method used for evaluating the average fuel economy for each sizing candidate.

A. Driveability test

The driveability of the several candidates was tested by checking the satisfaction of four different driving requirements. These tests are listed in Table I [15] and consider different slopes and tasks. As it can be seen, test #1 includes the simulation of a vehicle standing start considering a 30% road slope. Moreover, tests #2 and #3 are each other similar requiring a constant velocity of 150 km/h and 80 km/h respectively, however the third test includes also a road slope of 14%. The fourth test considers the capability of the ICE to charge-sustain the battery at a vehicle speed of 130 km/h and a 7.2% of road inclination.

TABLE I. DRIVEABILITY TESTS

Test #	***Road Slope [%]***	***Task***
1	30	*Perform a standing start*
2	0	*Keep a constant vehicle speed of 150 km/h*
3	14	*Keep a constant vehicle speed of 80 km/h*
4	7.2	*Charge-sustain the battery at 130 km/h*

Then, all the candidates demonstrating successful in the four different tasks were tested for the 0-100 km/h time.

B. 0-100 km/h time test

To assess the acceleration performance of the various candidates, the 0-100 km/h test was carried out by modeling the HEV architecture of Fig. 1 in SIMULINK®. This test was performed at Wide Open Throttle (WOT) and the gear shift schedule has been implemented accordingly. More precisely, for each gear of the tested configuration, the maximum torque deliverable at the wheel was computed as a function of the vehicle speed. The gear shift has been performed each time the maximum torque deliverable using the next gear was higher than the previous one. An example of the gear shift velocities computed for the 5-Speed transmission configuration is shown in Fig. 2.

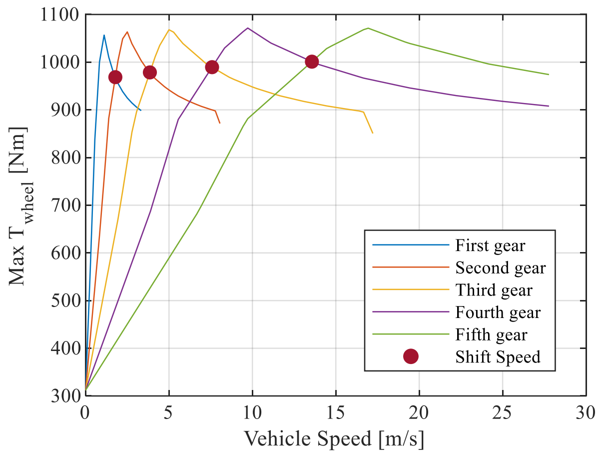

Fig. 2. Gear shift schedule for a 5-Speed transmission HEV while performing the 0-100 km/h test.

After simulating all the suitable candidates, the ones whose 0-100 km/h time was below 15 s were kept and their fuel economy was evaluated.

C. Fuel economy assessment

In order to simulate a sufficient number of different scenarios, six different drive missions have been used in this case study for assessing the fuel economy. Four of them are standard drive cycles, namely the worldwide-harmonized light vehicle test procedure (WLTP), the urban dynamometer driving schedule (UDDS), the supplemental US federal test procedure (US06) and the highway fuel economy test (HWFET). The last two cycles are user defined cycles that have been collected using a Global Positioning System (GPS) and consider different scenarios: the first real-world cycle (RWC1) includes uphill driving conditions and extra-urban/highway paths, whereas the second (RWC2) is a drive mission through the city of Turin and involves an urban drive profile. The main properties of these real-world drive cycles can be found in [15].

Moreover, each candidate has been tested for fuel consumption both running at curb weight and in loaded condition. For the latter scenario, 4 passengers (each of 80 kg) have been added inside therefore including also the ability of carrying loads when searching for the optimal design. In order to express the fuel consumption of each sizing candidate, an average value has been included. This depends on the results obtained simulating the six different driving missions retaining the DP algorithm as off-line HEV control algorithm. $FE_{avg,stand}$ is firstly evaluated as the average between the WLTP fuel economy and the Environmental Protection

Agency (EPA) one (retaining UDDS and HWFET) [16]. $FE_{avg,RWC}$ is then computed separately, averaging the fuel economy values for RWC1, RWC2 and US06 respectively. The final estimated fuel economy result for the HEV powertrain layout is the average between $FE_{avg,stand}$ and $FE_{avg,RWC}$. The related formulas are:

$$FE_{avg,stand} = 0.50 \cdot FE_{WLTP} + \cdots$$
$$0.50 \cdot (0.55 \cdot FE_{FTP} + 0.45 \cdot FE_{HWFET}) \quad (8)$$
$$FE_{avg,RWC} = 0.33 \cdot FE_{US06} + \cdots$$
$$0.33 \cdot FE_{RWC1} + 0.33 \cdot FE_{RWC2} \quad (9)$$
$$FE_{avg} = 0.50 \cdot FE_{avg,RWC} + 0.50 \cdot FE_{avg,stand} \quad (10)$$

IV. RESULTS

In this section, results obtained in terms of the 0-100 km/h test and the estimated fuel economy, are presented for the different HEV configurations.

The different parameters for the HEV are firstly enlisted in TABLE II. A variation in the transmission weight depending on the number of gears has been particularly considered in order to reduce the overall vehicle weight accordingly (11):

$$\Delta M = (5 - z) \cdot 0.12 \cdot P_{max,ICE} \quad (11)$$

where ΔM is the mass to be subtracted or added from the vehicle curb weight (initially related to the mass of the 5-Speed HEV), z is the number of gears and $P_{max,ICE}$ is the maximum power deliverable by the ICE in kW, namely 90 kW for this case study. The coefficient 0.12 has been derived by interpolating the formulas found in [17].

In order to provide a glimpse of the control actions selected by the DP algorithm, in Fig. 3-5 the behavior of the HEVs embedding a different number of gears in their transmissions is found. More precisely, in these figures the information on SOC, fuel rate and gear number are shown for a time window of 400 s of the WLTP cycle (going from 600 s to 1000 s).

TABLE II. HEV DATA

Curb weight mass [kg]	$1162 \pm \Delta\boldsymbol{M}(\boldsymbol{z})$
ICE displacement [L]	1
ICE max power [kW]	90
EM max power [kW]	94
Battery energy [kWh]	2.1
Final drive ratio [/]	3.75
ICE to EM ratio [/]	4

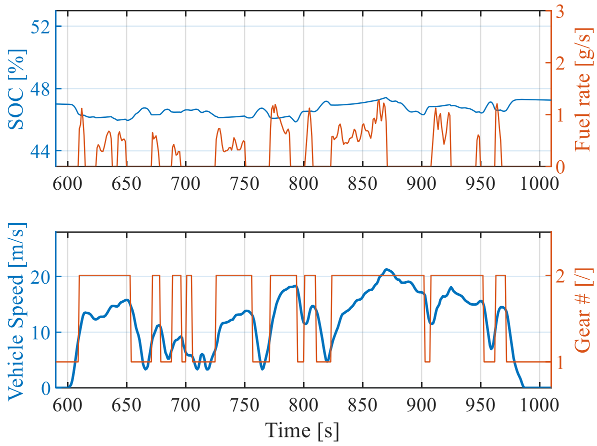

Fig. 3. DP-based control strategy of the 2-Speed HEV in the WLTP for a time-window of 400s

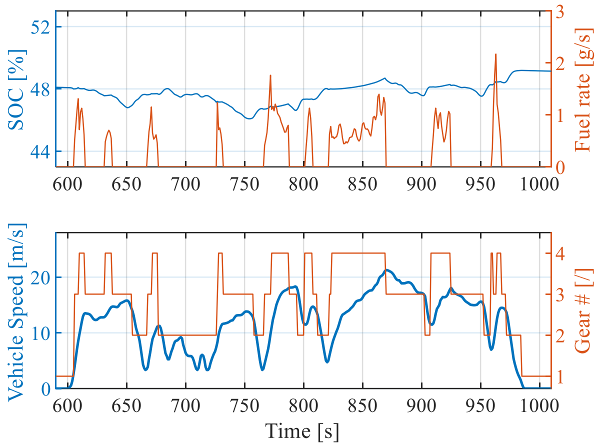

Fig. 4. DP-based control strategy of the 4-Speed HEV in the WLTP for a time-window of 400s

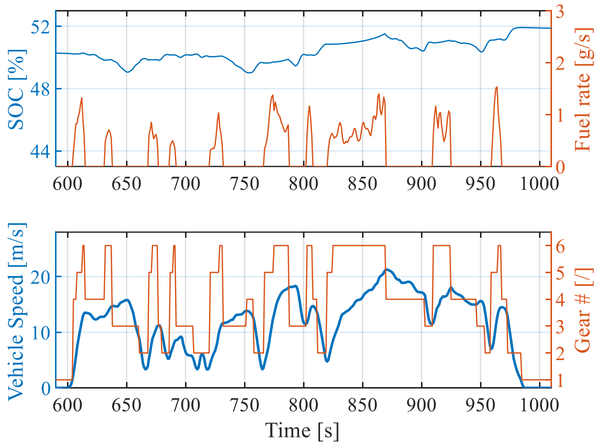

Fig. 5. DP-based control strategy of the 6-Speed HEV in the WLTP for a time-window of 400s

Moreover, in Fig. 6 a comparison is presented regarding the ICE operating points of the 2, 4 and 6 gears transmissions obtained from the simulations of the US06 at curb weight conditions. As it can be seen, the 2-Speed HEV is found working at higher Brake Specific Fuel Consumption (BSFC) points than the other two configurations due to the decreased number of gears, thus leading to overall slightly less efficient fuel consumption.

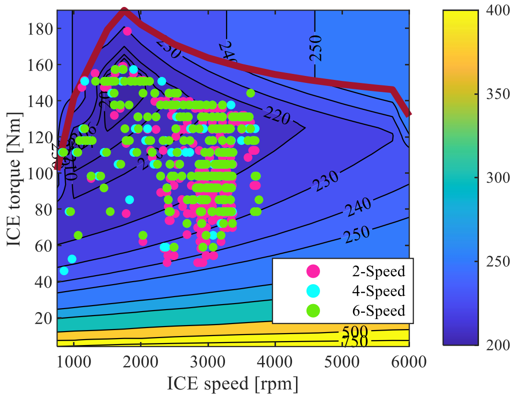

Fig. 6. BSFC map comparison of the US06 for three different transmission configurations at curb weight conditions. In dark red, the Wide Open Throttle (WOT) line is found.

Sizing results obtained in this case study are found in Fig. 7, where the Pareto frontier is shown reporting the 0-100 km/h time on the x-axis and FE_{avg} on the y-axis, respectively. For each HEV configuration one optimal design is identified and highlighted with a large diamond marker. It comes out that the optimal design of the 5-Speed transmission, is the globally optimal one (i.e. the optimal for both performance metrics considered), whereas for the remaining configurations a trade-off has been chosen among the sub-optimal designs. Besides, in TABLE III - IV more specific data regarding the optimal layouts are reported, namely the gear ratios and the mean fuel consumption values considering curb weight and full load scenarios for each drive mission.

As shown in Fig. 7, when considering the optimal designs only, the 6-Speed HEV has the lowest average fuel economy, whereas the 5-Speed performances are the best when referring to the 0-100 km/h time. However, the differences between the 3, 4, 5 and 6 gears transmission performance are little for both the parameters analyzed in this case study. Namely, the 0-100 km/h time of the 3-Speed and 4-Speed HEVs are 0.45 s and 0.16 s higher than the 5-Speed one (i.e. 11.74 s), respectively. Whereas for what concerns the average fuel economy, the values for these two different configurations are 3.824 L/100 km and 3.804 L/100 km respectively, against the 3.796 L/100 km of the 6-Speed HEV. Besides, for the case of the optimal 2-Speed HEV layout, its 0-100 km/h time is 13.8 s (i.e. 2 s higher than the 5-Speed HEV) and the evaluated average fuel economy is approximately 3.901 L/100 km (i.e. 0.105 L/100 km higher than the 6-Speed HEV).

TABLE III. OPTIMAL LAYOUTS GEAR RATIOS

	Gear Ratios [/]					
2-Speed	1.75	0.20	-	-	-	-
3-Speed	1.75	0.56	0.20	-	-	-
4-Speed	2.00	0.84	0.39	0.20	-	-
5-Speed	2.00	0.98	0.52	0.31	0.20	-
6-Speed	2.00	1.04	0.60	0.38	0.26	0.20

TABLE IV. OPTIMAL LAYOUTS RESULTS, EXPRESSED IN L/100 KM

#-gear	*WLTP*	*US06*	*UDDS*	*HWFET*	*RWD1*	*RWD2*
2	3.904	4.588	2.666	3.829	5.298	2.882
3	3.841	4.465	2.565	3.841	5.251	2.815
4	3.815	4.437	2.526	3.815	5.247	2.790
5	3.797	4.439	2.511	3.797	5.248	2.797
6	3.793	4.423	2.506	3.793	5.250	2.801

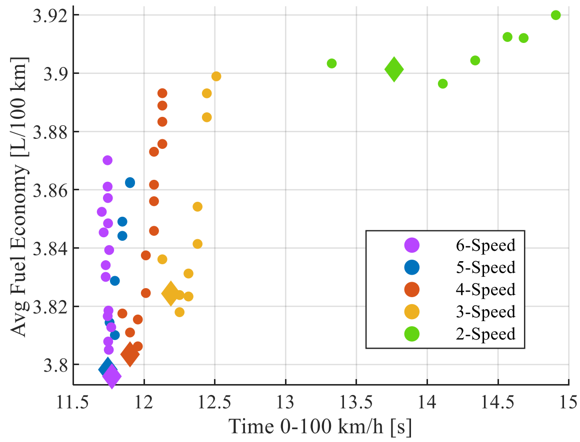

Fig. 7. Pareto frontier of the different HEV configurations in which the large diamond markers indicate the optimal design for each transmission.

In order to make further analyses, it has been considered a life (D_{life}) of 200'000 km for each HEV optimal configuration and a simple economic comparison has been carried out by considering the total cost for riding the HEVs in their life (while steadily repeating the retained driving missions) and the production costs of the different transmissions. Moreover, the 5-Speed HEV has been considered as the benchmark for this analysis and a difference in costs among this HEV and the others is presented. TABLE V collects the results of this analysis. The total cost of gasoline ($C_{gasol,n}$) of the n-Speed, the production cost ($C_{prod,n}$) of the n-Speed HEV (deducted from [17] by means of interpolation) and the variation in costs ΔC considering as benchmark the 5-Speed HEV are reported. Besides, in brackets it is found the difference between each value and the corresponding 5-Speed one. The used formulas are as follows:

$$C_{gasol,n} = FE_{avg,n} \cdot Price_{gasol} \cdot D_{life} \qquad (12)$$

$$C_{prod,n} = \alpha_1 \cdot \alpha_2 \cdot P_{max,ICE} \qquad (13)$$

In which $FE_{avg,n}$ is the average fuel economy of the optimal design for the n-Speed transmission expressed in L/km, $Price_{gasol}$ is the gasoline price in Italy equal to 1.47 \$/L [18]. Coefficient α_1 is related to the size of the vehicle and is equal to 1 for compact cars. Coefficient α_2 is measured in kg/kW, depends on the number of gears and is equal to 4.35, 5.59, 6.83, 8.07 and 9.32 for the 2-6 gears transmissions, respectively. $P_{max,ICE}$ is the maximum power of the ICE. Moreover, all prices were lately converted in euro by means of the May 2020 exchange rate, that is 0.9 €/\$ [19].

From the obtained results, it is worth of note that, even though the 6-Speed HEV has the most efficient fuel consumption among the analyzed configurations, the production costs overtake the benefits leading to the worst results when considering fuel cost and production costs. Moreover, with an economical saving of around 130€, the 3-Speed HEV seems to be an optimal trade-off considering the drivability performances, the 0-100 km/h time, the fuel economy and the costs related to it.

TABLE V. ECONOMIC ANALYSIS RESULTS

# gear	C_{gasol} [€]	C_{prod} [€]	ΔC [€]
2	10343 (+274)	352.4 (-301.3)	-27.3
3	10138 (+69)	452.8 (-200.9)	-131.9
4	10086 (+17)	553.2 (-100.5)	-83.5
5	10069	653.7	/
6	10065 (-4)	754.9 (+101.2)	+97.2

V. CONCLUSIONS

In this paper, different transmission configurations, on the basis of from 2 to 6 gear ratios into the gearbox, for a Parallel P2 HEV have been sized by comparatively evaluating the performance related to drivability tests, 0-100 km/h time and fuel economy. Drivability requirements ask for satisfaction of some riding performance and put limitation to the number of gear shifts and of the ICE activation. For the fuel economy evaluation a properly conceived mix of 6 different driving cycles has been considered. Further two conditions, namely curb weight and full load, have been considered for the vehicle mass. After the sizing procedure, the optimal layout has been appointed for each transmission and a comparison among them has been carried out. In general, this analysis suggests that:

- the interaction between EM and ICE could balance the lower number of gears and makes the latter work at high efficiency points, if carefully controlled;
- the 5-Speed HEV has the best performances when considering the 0-100 km/h time, whereas the 6-Speed obtained the minimum fuel consumption, yet their differences are narrow;
- the 4-Speed and 3-Speed HEVs show similar behaviors to the 5-Speed and 6-Speed ones, however their performances are slightly lower;
- the 2-Speed HEV has the worst performance considering both the 0-100 km/h time and the fuel consumption
- the negative judgment for the highest fuel consumption attained by the 3-Speed and 2-Speed HEVs can be mitigated when considering also the production costs. Economical production savings particularly overcome the increased operative costs, thus making these HEVs a suitable trade-off between the different performances analyzed in this case study.

For what concerns the related future works, more detailed economic analyses could be carried out considering also maintenance costs. Moreover, real-time control and a higher fidelity model could be considered to simulate the HEV more precisely (e.g. using a dynamic modeling approach).

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