Unplugged Series Hybrid Bike Study: Cost versus Performance Analysis

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UNPLUGGED SERIES HYBRID BIKE STUDY: COST VERSUS PERFORMANCE ANALYSIS

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Short abstract

Series Hybrid Bike (SHB) offers a complete decoupling between the bike motion and the power given to the system by the cyclist. The main advantage for the cyclist is to pedal with a minimum of torque and power peaks, and therefore manage its own physiological energy. Nevertheless, one major drawback of the SHB is the system efficiency. This paper focuses on determining the optimal component sizing for improving the performances while controlling the financial costs.

Keywords – Electric bike, Series Hybrid Bike, Efficiency and financial costs optimization, Powertrain modelling

Introduction

Series Hybrid Bikes (SHBs) are chainless bicycles. The mechanical energy from the cyclist is first converted into electrical energy thanks to an electrical generator located around the crankshaft. At the same time the motion is created by a motor assembled in the wheel which is using the energy produced by the user and/or the one stored in the Energy Storage System (ESS) [1], [2]. The powertrain architecture of SHB is described in the *figure 1*.

The cyclist provides energy to the system and the power that he produces is considered to be constant during the trip. Indeed, the SHB architecture makes it possible for the cyclist to pedal in a fixed manner regardless of the road conditions thanks to the motion decoupling between wheel and crankshaft.

In order to cope with the power demand from the rear wheel motor and to keep the cyclist effort constant during all the driving phases, an ESS is needed. This project foresees using supercapacitors to store energy. Indeed, the ESS interest in SHB is not comparable to a classical e-bike battery that needs to be recharged by the power grid. On a SHB, the cyclist will manage his own energy, never recharge the ESS on the grid and will therefore need a lower storage capacity. Supercapacitors also offers a high-efficiency device, extended lifetime and a friendlier environment solution alternative to batteries that make them suitable for the application [3]–[5].

The SHB most critical aspect is the efficiency. A previous study analysed the minimum energy efficiency criteria (η_{SHB}) and found that η_{SHB} could drop down to 60% and still travel as fast as a classical chain bicycle thanks to energy recovery and the energy management features [6].

This paper focuses on determining design rules for SHBs. Indeed, financial cost shall stay as low as possible, performances shall be good enough to guaranty a new pedaling feeling where the power pedaling is smoother. This paper aims to propose optimal sizing solutions trying to minimize the costs and maximize the system's efficiency.

Therefore, this paper will first focus on describing the model used for the simulation, then describe the methodology used for finding optimal solutions and finally describe the various results improvements and conclusions extracted through the optimization.

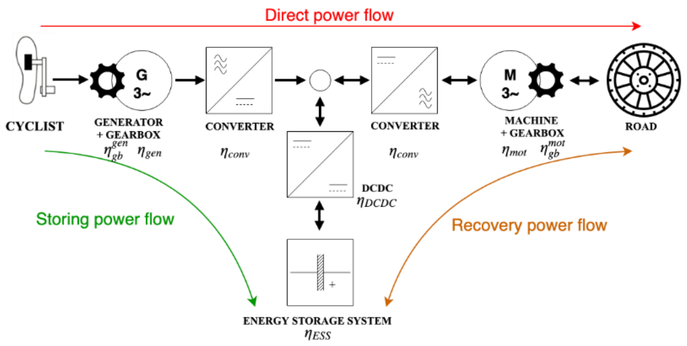

Figure 1: Series Hybrid Bike architecture and associated efficiencies

I. Model description

The following sections will describe the model and the assumptions made to simulate the system. The global model is run using the VEHLIB environment which is a Simulink based tool using energy transfers principles [7], [8].

A. Modelling guidelines

The system modelling aims to provide performances estimation of subparts for maximizing the global efficiency and reducing the costs. Therefore, the user, both machines and their associated gearboxes, the DC-DC converter and the ESS will be described using quasistatic models. Costs will also be evaluated.

Costs are often the addition of several expenses as raw material, subsystems and manufacturing costs in addition to the commercial margin. This study expresses financial costs in a simple but realistic manner thanks to market prices analysis.

B. Energy and movement equations of bicycle

In order to track the position of the bike, the speed (V_k) is updated at every time step (Δt) using variations of the kinetic energy (E_k):

$$E_{k+1} = E_k + P_k \Delta t \quad (1)$$

$$P_k = \frac{T_{mot} V_k}{R_{wheel}} - \sum F_{ext} V_k \quad (2)$$

Those variations are due to a change of power (P_k) created by the bicycle (motor torque: T_{mot}, radius: R_{wheel}), and external forces (F_{ext}).

External forces are mainly due to the rolling resistance (C_r), the drag area (SC_x) and the current slope (α_k) (*equation (3))* [9]. The bicycle and the cyclist are modelized as a unique mass (M_{tot}) with g the standard gravity and ρ the standard air mass.

$$F_{ext} = M_{tot} g(\mathrm{C_r} + \sin(\alpha_k)) + \frac{\rho}{2} SC_x V_k^2 \quad (3)$$

$$V_{k+1} = \sqrt{V_k^2 + \frac{2P_k}{M_{tot}} \Delta t} \quad (4)$$

Once the speed has been found, it is possible to extract both the bicycle position (X_k) and the current slope (α_k) by integrating the speed and updating the parameter from the ride profile (*see section I.F*).

$$X_{k+1} = X_k + V_k \Delta t \quad (5)$$

$$\alpha_k = SlopeLookUp(X_k) \quad (6)$$

C. Cyclist

The cyclist is more easily simulated on a SHB than on a regular bicycle. Indeed, the chainless power transmission allows the user to pedal in a regular way independent from the road profile. The user was modeled as a varying sinusoidal torque generator (T_{user}) depending on pedals position (θ_{user}) (this is a fair approximation according to [10]). The pedaling speed was considered to be constant thanks to the torque control algorithm of the generator that simulates the inertia of a classic chain bicycle.

$$T_{user} = T_{mean} cos\left(2\theta_{user} - \frac{\pi}{2}\right) + T_{mean} \quad (7)$$

The torque constant T_{mean} represents the mean torque value as well as the amplitude of the cosinus. Indeed, the user is assumed to produce no torque at both crank vertical dead positions ($\theta_{user} = 0 \wedge \pi$) [10].

D. Electrical machines and gearboxes

The system has two gearboxes. One of them is in charge to increase the pedaling speed before the generator and the second multiply the motor torque (input torque is called T_{in} and output torque T_{out}). Gearboxes may have several stages which have to fit the bicycle geometry requirement, it was considered a one stage maximum ratio of 3 ($k_{stage} \leq 3$). The number of stages (Nb_{stage}) has an influence on the overall gearbox ratio (k_{gb}) but also on the costs (Ct_{gb}) and on the overall gearbox efficiency (overall gearbox efficiency η_{gb}; one stage efficiency η_{stage}). The efficiency of a single stage is considered to be constant over speed and load. Moreover this efficiency doesn't take into account the manufacturing quality. [11], [12].

$$\eta_{stage} = 0.97 \quad (8)$$

$$T_{out} = k_{gb} T_{in} \eta_{gb} \quad (9)$$

$$\eta_{gb} = \eta_{stage}^{Nb_{stage}} \quad (10)$$

$$Nb_{stage} = ceil \frac{log(k_{gb})}{log(k_{stage})} \quad (11)$$

The gearbox costs (Ct_{gb}) is modeled only based on the number of stages required to achieve the desired multiplication ratio. The complexity of modeling the cost was introduced in *section II.A*. In this case, Ct_{gb} shall include gears, bearings, manufacturing and assembly costs. In order to simplify the model, a several stages gearbox is assumed to have the same cost at each stage (β_{gb}: €/$stage$). Cost per stage is determined from typical supplier's price offers ($\beta_{gb} \approx 30$ €/$stage$). Minimizing the cost is therefore equivalent as minimizing the number of stages.

$$Ct_{gb} = \beta_{gb} Nb_{stage} \quad (12)$$

The machines (Brushless DC motors only) and their associated converters are modeled in a simple manner thanks to a loss table (P_{loss}^m) differentiating the input power from the output power (P_{in}^m, P_{out}^m). Losses were assumed to fit a model including conduction losses (resistor R_m), dry friction losses (f_d) and viscous losses (f_v). The classical torque constant was also introduced (K_T: $Nm.A^{-1}$).

$$P_{out}^m = P_{in}^m - P_{loss}^m \quad (13)$$

$$P_{loss}^m = R_m \frac{T}{K_T^2}^2 + f_d \omega + f_v \omega^2 \quad (14)$$

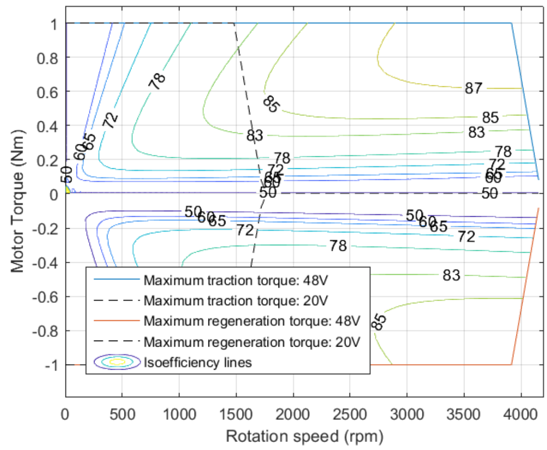

Figure 2 : Maxon Motor EC flat 160W typical efficiency map

This paper deals only with commercially available machines. The losses are then fitted (*thanks to equation 14*) from the available data in the datasheet. Moreover, the maximum motor torque (T_{max}) is also an important parameter influencing the weight, and the gearbox design. [13].

	EC Flat 160	*EC Flat 220*	*Special design*
Torque (Nm)	0.457	0.729	3
Efficiency (%)	85	85	93
Cost (€)	121	128	700

Table 1: Generator set

The generator will be chosen among the Maxon motors EC-FLAT series and a specific machine design realized by a manufacturer [14] (*figure 2* and *table 1*) (α_{gen} is the choice variable: $\alpha_{gen} = 1$ for the first generator…). Moreover, a set of motor representative of the market machines diversity (direct drive ($\alpha_{mot} = 1$), geared motor ($\alpha_{gen} = 2$), the same special high quality motor design ($\alpha_{mot} = 3$)) has been selected (*see table 2*).

	Direct drive	*Geared motor*	*Special design*
Torque (Nm)	50	3	3
Efficiency (%)	81	86	93
Cost (€)	180	50	700

Table 1: Motor Set

E. Storage System and related DC-DC converter

The storage system is at the heart of the SHB, this system absorbs the cyclist's power variations and represents a major part of the costs.

ESS's performances vary along the solicitation frequencies. However, the discharge occurs within minutes and transient behaviors were then not considered. This work then focuses only on power losses (P_{loss}^{ESS}) mainly due to the pack internal resistance (R_s) and the current flowing through the storage system (I_s):

$$P_{loss}^{ESS} = R_s I_s^2 \tag{16}$$

Finally, the state of energy (SOE) of an E_{tot} energy rated ESS, is an important control parameter [6]. It can then be directly derived from the pack open circuit voltage (U_{pack}) assuming a constant capacity over SOE and a maximum voltage of $2.7V$ for each cell:

$$SOE = \frac{U_{pack}^2}{max(U_{pack})^2} \tag{17}$$

The supercapacitor pack costs (Ct_{ESS}) are depending on the number of cells (N_{cell}), on the supercapacitor capacitance (C_{SC}) and on a price coefficient (β_{ESS}) expressed in €/F:

$$Ct_{ESS} = \beta_{ESS} N_{cell} C_{SC} \tag{18}$$

$$E_{tot} = \frac{C_{SC} max(U_{pack})^2}{2N_{cell}} = 3.65 N_{cell} C_{SC} \tag{19}$$

Low energy storage quantity lead to high variations of SOE and therefore to large voltage variations. Cut off voltages are implemented to ensure the system is running safely. However, situation where the voltage is low leads to high currents in the system thus increasing the losses (*see figure 7*). In order to improve the system, an option ($\alpha_{DCDC} = 1$ if DCDC activated, 0 otherwise) is to implement a DCDC converter between the ESS and machines terminals (bus) that will keep the bus voltage constant. Moreover, a low bus voltage will lead to reduced machines performing areas and therefore to deteriorated efficiency and traveling time. Yet, implementing a DCDC converter adds costs to the system and losses which is not necessary if the SOE is high, the voltage being high enough to ensure correct performances.

The converter modelling is based on the LT8708 converter from Texas Instrument, it is a 4 switches buck boost converter capable of controlling the current in both directions (charging or discharging). Converter losses calculations are based on MOSFET losses (P_{loss}^{mos}) modelling through the internal resistance (R_{dson}), the switching times ($t_{fall}$and t_{rise}), the MOSFETs current (I_{mos}) and open state voltage (U_{mos}). The losses (P_{loss}^{DCDC}) are calculated according to the operating point (ESS current I_s, bus voltage V_{dc}) and modes (Buck, Boost, direct or reverse current) each leading to different losses calculations. Finally, the DCDC cost (Ct_{DCDC}) is considered to be fixed.

$$P_{loss}^{mos} = R_{ds} I_{mos}^2 + \frac{(t_{rise}+t_{fall}) U_{mos} I_{mos}}{2} \tag{20}$$

$$P_{loss}^{DCDC} = f(P_{loss}^{mos}, I_s, V_{dc}, V_{ESS}) \tag{21}$$

$$Ct_{DCDC} = 100€ \tag{22}$$

F. The trip: hilly profile and flat profile

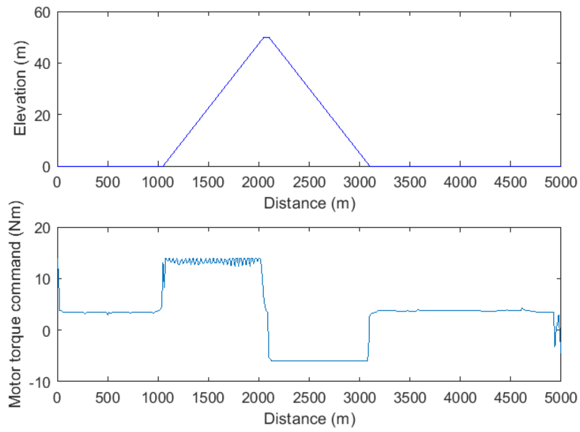

Figure 3: (a) Trip profile and (b) motor torque command

SHBs main advantage is to smooth the developed cyclist power against ride discontinuities (hills, stops). The chosen ride used for the simulation is a virtually created trip as shown *figure 3(a).*

A standard 50m hill crossing was chosen as it represents the average hill crossing in town, based on the analysis of 30 French cities elevation maps (figure 4) with Standard Elevation defined as: $SE = CityCenter\ mean\ elevation - \min elevation$.

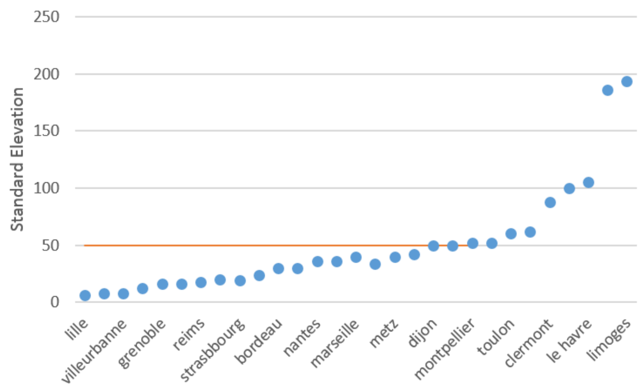

Figure 4: Nominal elevation values

A second profile is also considered in this paper as a comparison case. The second trip is a one-kilometer flat profile.

G. Control system

The motor control is based on torque control. An optimal motor control law has previously been found by using Dynamic Programming (DP) (*see figure 3b*) [6]. The discrete torque control solution is then interpolated and implemented in the simulation.

DP's parameters have an influence on the optimal control law. All the parameters described in *section II.B* shall therefore remain the same in both simulations. The following parameters can be adjusted and have influence on the control law:

- The system energy efficiency (η_{SHB})
- Power produced by the cyclist (P_{user})

❖ The ESS energy (E_{tot})

The derived control law (and its associated travel time t_{ride}) presented in *figure 3.(b)* is the optimal SHB control law associated with a global efficiency of 0.7, a $8Wh$ energy storage pack and a 100W constant human power generation.

H. Performance indicators

SHB performances shall be analyzed. Therefore, the overall energy efficiency (η_{SHB}^{e}) will be computed as well as the losses for each subsystem (*see figure 4*) presented above (*section II*). The energy efficiency is the ratio between the input energy from the user ($E_{user} = P_{user}t_{ride}$) and the effective power given to the wheel (E_{motor}). It also takes into account for the energy difference between the initial and the final $SOE(\Delta SOE)$.

$$\eta_{SHB}^{e} = \frac{E_{motor} - E_{tot}\Delta SOE}{E_{user}} \quad (23)$$

This energy efficiency gives a direct indication about the average performance of the bicycle.

II Methodology

A. Optimization Goal

The main purpose is to increase the system efficiency and therefore aims to reduce system's losses. On the other hand, it is necessary to reduce the costs to achieve an affordable bicycle.

The optimization problem will also be constrained to reduce the possible solutions and keep results within boundaries.

B. Optimization Method

Optimization problems have been widely addressed in the literature. Achieving the best compromises between global system costs and performances requires to solve a multiobjective problem [15]–[17].

The optimization process will find optimal trade-off between two cost functions. Indeed, objectives are contradictory to each other. As an example, increasing the performance will also increase the costs.

Let f_1 *and* f_2 be the functions to optimize:

$$f_1 = min(\sum Ct) \quad (24)$$

$$f_2 = max(\eta_{SHB}) \quad (25)$$

The following variables will be optimized:

	Description	Interval	Unit
$k_{gb}^{gen}, k_{gb}^{mot}$	Gearbox ratio	[1; 50]	
N_{ESS}	Cells number	[1; 22]	
C_{SC}	Cells capacity	[60; 3500]	F
α_{DCDC}	DC-DC activated	[0; 1]	
α_{gen}	Generator choice	[1; 2; 3]	
α_{mot}	Motor choice	[1; 2; 3]	

Table 2: Parameter limits

Moreover, some constrains have been added to the system:

$$400 < Ct_{SHB} \leq 2000€ \quad (26)$$

$$k_{gb}^{gen} T_{max}^{gen} \geq 2T_{mean} \quad (27)$$

$$k_{gb}^{mot} T_{max}^{mot} \geq max(T_{cmd}) \quad (28)$$

The simulation also has to be constrained. Indeed, faults may occur during the trip. For example, the motor power demand can empty the ESS as a result of a to small embedded capacitance. Therefore, it is also necessary to ensure the trip as been complete at the end of the simulation.

$$X_{end} \geq max(Distance) \quad (29)$$

The NSGA II (Non dominated Sorting Genetic Algorithm) is a multiobjective optimization tool that as already be widely covered in the literature and will be used here to solve the problem described above. [18]

III Results

A. Reference result

The reference simulation, not yet optimized, is based on the topology used on an existing SHB prototype (generator nominal power $800W$, generator rated speed $1000rpm$, $T_{max} = 7Nm$, 3 stages gearbox, 8 supercapacitors of 1200F in series). Every subsystem was designed separately from each other according to the state of the art (torque considerations, embedded energy needed...). This design will be challenged thanks to the optimization.

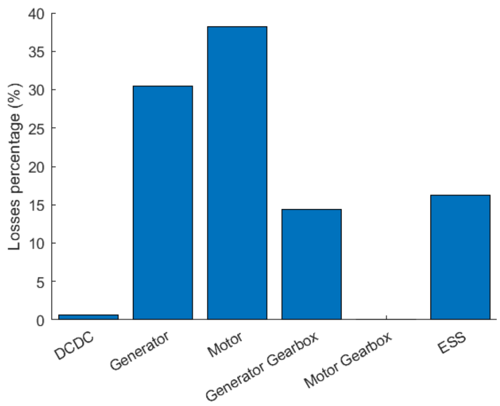

Figure 5: Losses percentage overview of the reference design (non-optimized)

Finally, the motor used here is a direct drive meaning there is no gearbox between the motor and the wheel (and therefore no gearbox losses).

Figure 5 shows a typical losses distribution for the standard ride defined in *section I.F* for the reference design bicycle configuration. The global associated bicycle energy efficiency is $\eta_{SHB}^{e} = 0.36$. This level of performances would cause a bad user experience. Improving the efficiency up to 0.6 is then mandatory to achieve a successful bicycle [6].

Most losses (*see figure 5*) occur in the machines, indeed close to 70 % of the energy is lost in the generator and the motor. Machines are then key components to optimize. Losses in the ESS represents around 15% of the losses. However, ESS's losses are strongly varying depending on its solicitation and SOE. (*see figure 7*).

For the hilly trip, the supercapacitors are delivering the needed power in addition to the generated power in order to follow the demand power as it is shown in *figure 6*. The trip profile lasts 1287 seconds. The power is oscillating due to sinusoidal user power production and represents an important losses increase (up to 13% more losses).

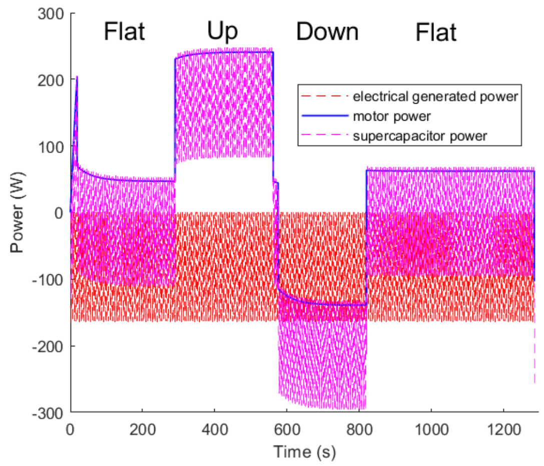

Figure 6: power exchanges in the system for the hilly trip

Finally, SOE as well as the ESS losses are plotted in the *figure 7*.

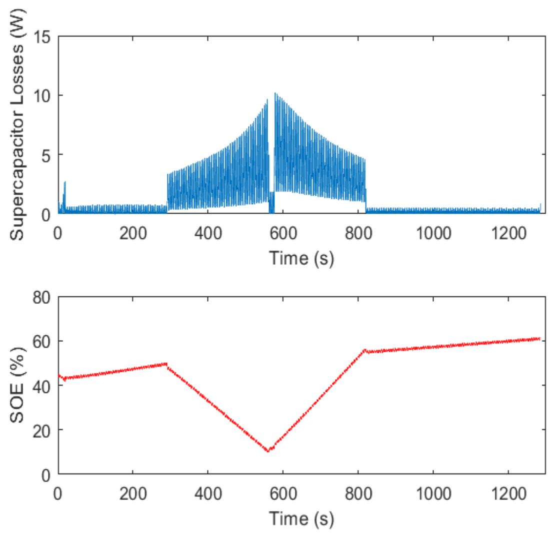

Figure 7: SOE and ESS'losses for the hilly trip

B. Optimization results: the hill case

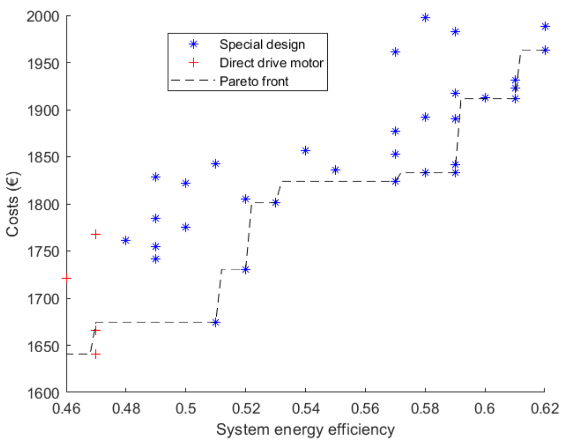

Figure 8: optimization result

The optimization was launched based on the NSGA II algorithm. The optimization process was involving all the parameters defined in *table 3*.

Figure 8 shows the results. As expected, the costs are kept between boundaries and it is possible to observe cost/efficiency variations. The transmission system's total costs (€) is plotted against the best energy efficiency achievable.

First, one motor out of the 3 versions came out of the simulation (the special design), both other don't performs well enough to reach the required performances and therefore aren't part of the optimal solution. This also point the major importance of motors for achieving a performing system. Moreover, cost are quite high especially due to the high quantity of embedded energy needed. Finally, the optimized design has better performances than the reference design as energy efficiency progressed from 0.36 up to 0.62.

The results are meeting the efficiency requirement defined in the study even if only reached by a few percents [6] and therefore validate the possibility and the structure to build in order to create an unplugged SHB.

Nevertheless, costs are quite high for this trip and the efficiency only shortly reach the requirement. The next section will investigate the better efficiency one might reach with the best-case scenario.

C. Optimization results: the flat case

Another case was studied in order to compare the result presented in *section III.B*. The alternative case is a standard one-kilometer flat drive including no stops and no hill. The system run on steady state point on this type of trip which enables to find an optimal maximum efficiency operating point. This configuration shows the highest efficiency level the system can reach with the available components.

The typical results are shown in *figure 9.* The results for this optimization goes beyond the objective. However, it is necessary to recall this efficiency is an optimum and could not be reached on a non-steady state drive cycle (on the hilly trip with those components for example).

The results confirm the major importance of the motors in the performance evaluation. A better motor automatically provides a better solution (for this drive) independent from the generator choice, supercapacitors…

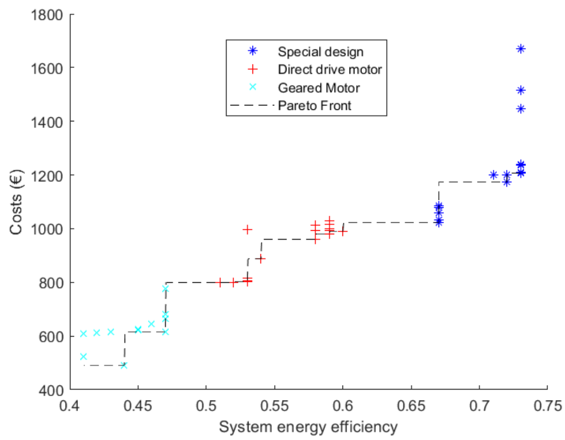

Figure 9: optimization result for a flat land drive

D. Comparison

Both cases described in previous *sections B and C* are complementary. Indeed, the efficiency close to 75% confirm the possibility to create an efficient enough system in order to reach more than 60% energy efficiency. This is even possible while maintaining reasonable costs as the needed embedded energy is quite low on a flat land.

However, the steep hill crossing presented in this paper is showing some limits to those results. Indeed, the need for a bigger energy storage quantity as well as the higher power flowing through the motor combined with an eventually limited speed and therefore a limited efficiency is causing the system to have worse performances and higher cost than on the flat drive.

One challenge to be faced is to propose cost effective motors that can achieve high level performances for the application.

Conclusion

This works is a major step to the unplugged SHB technical validation. Furthermore, it has shown the limit and potential of the system pointing out it is possible to reach an efficient level system that will propose an interesting performance to cost ratio but that this achievement is strongly dependent on the drive cycle.

This study has not only validated the possibility to build a SHB reaching the energy efficiency basic conditions but it also proposes an entire range of architecture possibilities depending on the costs and performances requirement. The comparison between several cases also gives us more information about the robustness of the design choice and the capability of the system to outstand various solicitations (hills, start/stop…).

The optimization shows it is possible to reach more than 60% energy efficiency on a specific non continuous ride (the hilly ride) but it has also shown the bicycle structure could achieve up to 75% percent efficiency with optimal drive situations (flat profile). Finally, the study has also increased the previous prototype efficiency by 26% and pointed out the advantages of a global system optimization over separate standalone design. However, efficiency requirements were reached using special high-quality designs.

This study also only focuses on the structural bicycle, one major step will be to integrate the user and its physiological efficiency into the calculations. The optimization goal wouldn't be to maximize efficiency but to control user's effort and minimize user's fatigue that will be reduced thanks to steady state pedaling rate.

Moreover, DP and NSGA II algorithms are run independently and could be run together in order to get more precise and accurate results. In addition, the dynamic programming as a command can also be conflicting with the reality as it is an optimal which will never occur on real conditions drives. One further improvement could be to implement real time energy management system based on MPC (Model Predictive Control) or ECMS (Equivalent Consumption Minimization Strategy) for example.

Finally, the model and performances shall be tested on real prototype for modeling and result validations.

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