Assessment of the interest of series hybridisation for a human-powered vehicle

Electric pedal generator pre-sizing

Judicaël Aubry, Bertrand Barbedette

ESTACA'LAB, S2ET Energy and Embedded Systems for Transportation
ESTACA Campus Ouest, Rue George Charpak, 53061 Laval Cedex 9, France
judicael.aubry@estaca.fr

ABSTRACT. *Only physical training allows to improve the effort management on a bike. Electric bikes (e-bike, pedelec category) add a torque when travelling difficulties appear. But this facility does not manage the energy developed by the cyclist. A series hybrid type drivetrain for bikes, well known in the automotive field, is presented in this paper which improves the management of human efforts. The first results show the advantage of this solution compared to conventional self-management on the basis of a simple model of untrained cyclist behaviour. The paper argues that an energy storage device associated to series hybrid drivetrain will ensure an improved balance of the human effort management. However, the efficiency of this conversion chain must be high to maintain its benefits. In this context, a first sizing of an electric generator is introduced.*

RÉSUMÉ. *Pour bien gérer son effort sur un vélo, seul l'entraînement physique permet de s'améliorer. Les vélos à assistance électrique (VAE) donnent un regain de couple lors de difficultés de parcours mais ne gère pas l'énergie développée par le cycliste. Une chaîne de traction de type hybride série pour vélo, connue dans le domaine automobile, est présentée dans cette article et permet la gestion de l'effort humain. Les premiers résultats montrent l'intérêt de cette solution comparée à la gestion classique sur la base d'un modèle simple de comportement de cycliste non entraîné. L'article démontre qu'un stockage d'énergie garantira un meilleur bilan de la gestion de l'effort humain. Toutefois, le rendement de cette chaîne de conversion devra être suffisamment élevé pour garder ses bénéfices. Dans ce cadre, un premier dimensionnement spécifique d'une génératrice est présenté.*

KEYWORDS: *human powered vehicle, series hybrid, human energy management, human fatigue model.*

MOTS-CLÉS : *véhicule à propulsion humaine, hybride série, gestion de l'énergie humaine, modèle de fatigue.*

DOI:10.3166/EJEE.17.419-438 © Lavoisier 2014

1. Introduction

Private vehicles used for our daily trips have a generally oversized motorization in regard to our traditional transportation needs. Statistical indicators such as the average number of persons on board[1], the distance travelled[2] or the urban average speed[3], show well that the car is under-used in relation to its energetic capacity. This under-use leads to an energy cost, expressed in kilojoule per kilometre per person, which is relatively high compared to collective transportation in rush hours (cf. Table 1).

Table 1. Energetic cost on life cycle of several transportation means per person and per kilometre (Source (Dave, 2010)), the uncertainty ranges are not indicated in the original paper but the GHG emission rates are presented.)

Vehicle type	Energetic cost in kJ.km^{-1}.person^{-1}	Energetic cost in Wh.km^{-1}.person^{-1}
Walking	63	17
Bike	198	53
Pedelec	221	60
Passenger car	2 917	788
Bus (rush hours)	688	186
Bus (average)	2 647	715
Metro	1 846	498
Boeing 737	1 862	503

The energetic performance of human-powered transportation means such as walking or cycling are significantly higher. These transportation means are more appropriate with regard to our real needs for urban use. But some difficulties, even irrational, stop a majority of people from using it.The French national plan for cycling, written in January 2012, lists some difficulties and failures:

– travel distance
– bicycle theft
– climate
– landscape

Despite these difficulties, some benefits can be shown:

– health
– reduction of polluting gases and greenhouse gas emissions

1. According to the World Bank, there are in France 482 private vehicles per 1000 persons, which suggests a low rate of use. For the Commissioner-General for Sustainable Development, the average number of persons per vehicle was estimated in 2010, between 1.07 and 1.92.

2. In France, 80% of the trips realized in motorized vehicles are shorter than 5km.

3. The Urban Community of Bordeaux (UCB) in 2009 estimated the car average velocity at 22km/h in UCB trips, against 13km/h for bikes

- noise reduction
- household budget
- Less dependence on public transportation means

The safety aspect is discussed separately, but it must be considered with caution. Statistics show that by increasing the number of cyclists, the number of injured cyclists rises, but the number of accidents by cyclist goes down. This phenomenon is known as “safety by numbers”. Mass behaviour can reduce the accident risks due to transgressive driving of some cyclists.

Given both interesting benefits and the low daily utilization rate of human-powered transportation means, it seems appropriate to think about solutions to increase and facilitate this use.

The electrical assistance is one of the means to facilitate the use of bicycles which manufacturers of the cycling world have greatly developed over the past two decades, although the idea is much older. Currently, the assistance facilitates the use of bicycles by providing an additional torque either on one of the wheels or directly on the crank set. On recent e-bike models, the assistance motor torque is controlled proportionally from the pedalling torque measure. Thus, the cyclist still has a feeling of pedalling without using the full assistance. It should be underlined that the current solutions of e-bikes can all be classified as parallel hybrid powertrain, named "plug-in hybrid" which uses rechargeable batteries. So, compared to a conventional bicycle, the embedded energy is not exclusively human. This characteristic is the legal distinction between a cycle and an e-bike or pedelec (a low-powered e-bike). A non-rechargeable e-bike would not be categorized as an e-bike according to the present European legislation. Also, the new design of e-bikes would not be subject to speed restrictions (25 km/h) and power (250W).

In automotive and railway areas, other hybrid vehicle powertrain configurations have been designed and developed: Parallel hybrid or series/parallel hybrid also called "full hybrid". These other types of hybridization have a number of advantages compared to parallel hybrid configurations. For example in cars, it allows the complete decoupling of the internal combustion engine speed against the vehicle speed. Thus, the engine speed can be adapted to minimize specific consumption and a good compromise between consumption and the emission of pollutants can be found.

Although these three types of hybridization are developed in the automotive field, the parallel hybrid is mainly used in the e-cycle industrial area. In the research area or the e-cycle niche market, some attempts exist:

1.1. Kinzel, 1975

Augustus B. Kinzel patented in 1975, *"A power operated cycle including a manually powered generator which supplies energy to drive a motor associated with one of the wheels of the cycle for thereby imparting motion to the cycle".* This patent

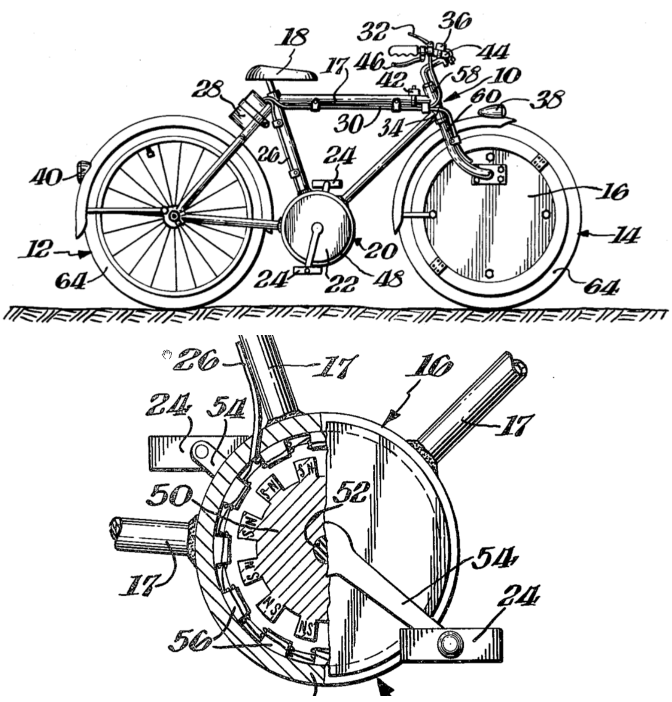

Figure 1. "Electrically powered cycle" (Kinzel, 1975) : global representation of the bike on the above image , and below, zoom on the electrical generator crank set.

presents the idea of serial hybridization without using an energy storage system between pedalling production and the consumption in the in-wheel motor. Functionally, this system is known in mechanical technology as a Continuously Variable Transmission (CVT). Here, it is an electrical CVT where one of the objects *"is to provide a power operated cycle capable of continuously variable speed operation"*.

1.2. Andreas Fuchs & Jürg Blatter

In 1988, Andreas Fuchs and Jürg Blatter made a prototype of a human-powered vehicle with a series hybrid power drive and a storage system. Their work consisted of developing this architecture adapted to a tricycle. A prototype was made. This study focused on the torque control law applied to the crank set and this control strategy was patented (Fuchs, 2007). The torque control is functionally important but the energy efficiency is a very important dimension. For instance, the work did not cover the optimization of the system components such as electrical and electromechanical conversion elements, or the energy management strategy of the electrical storage system.

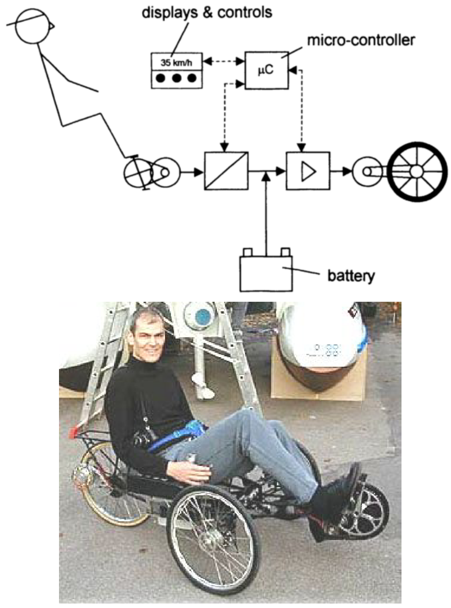

Figure 2. Prototype of a tricycle with series hybrid drivetrain made in 1998 at the University of Berne b Andreas Fuchs and Jürg Blatter (Fuchs, 2008; Wilson, 2004)

1.3. Watterson

The Watterson's paper made a state-of-art of the series-parallel hybrid architectures. More particularly, it focused on the Moeller's patent and the Toyota Prius hybridisation architecture. Different combinations between electrical machines and planetary gear trains were presented. A solution where two motor generators are placed in each of the two wheels is shown in Figure 3. This article deals with concepts and architectures, but it does not address the sizing of these architectures.

1.4. Mando Footloose

Mando Footloose (Korean company Mando Corp.), was introduced in August 2012 at the Eurobike exhibition. The main objective of this bike is to be foldable and easily transportable. To achieve this objective, the mechanical chain transmission is replaced by an electrical generator in the crank set and a rear in-wheel motor. The solution is an e-bike with a series hybrid architecture. The power of the rear in-wheel motor is 250W. It is also equipped with a 36V/8.2Ah Lithium battery. This e-bike can reach up to 45 km autonomy, in a 100% electric mode. Unfortunately, this e-bike has not been designed to operate in a 100% human mode like a classical bike. The crank

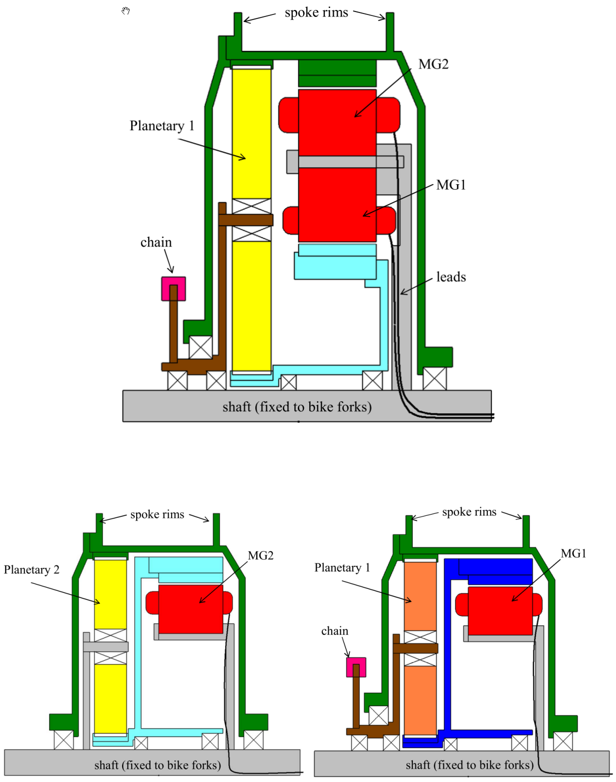

Figure 3. Series/parallel hybrid architectures integrated in the wheel hub. Above, architecture integrated in one hub. Below, an architecture separated in the rear and front hubs. (Watterson, 2008)

set generator allows extending the autonomy when the battery state of charge is low, but no intelligent system manages the human energy.

1.5. Zehus : the WIZE Hub with Bike+ technology

ZEHUS (Zero Emission HUman Synergy) is a spin-off of the Polytechnic university of Milano. Based on Spagnol et al. research works (Spagnol, 2012), a commercial product was developed: the WIZE Hub. This concept takes over the idea of the Copenhagen Wheel developed at MIT. This hub incorporates the electrical motor, the power electronic converter, an electronic control unit and a battery pack. The Bike+ technology is associated to the WIZE Hub for managing the electrical energy. The heart of this technology is based on an optimized algorithm whose objective is to provide

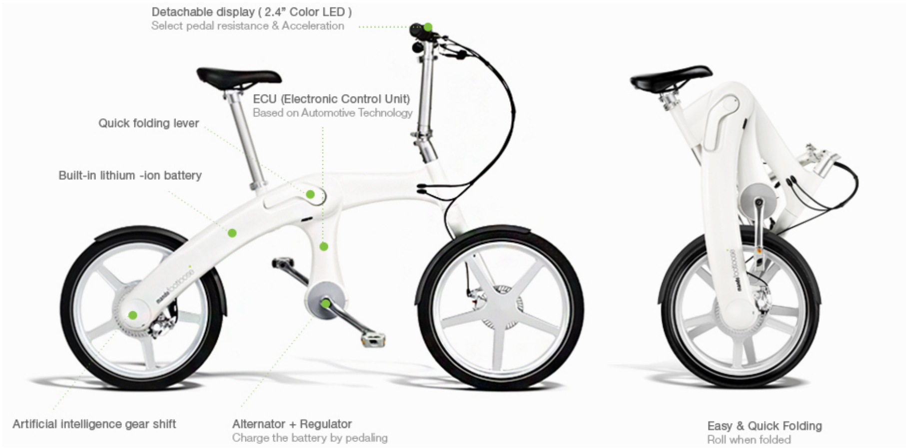

Figure 4. Mando Footloose (commercial photography) (Mando, 2014)

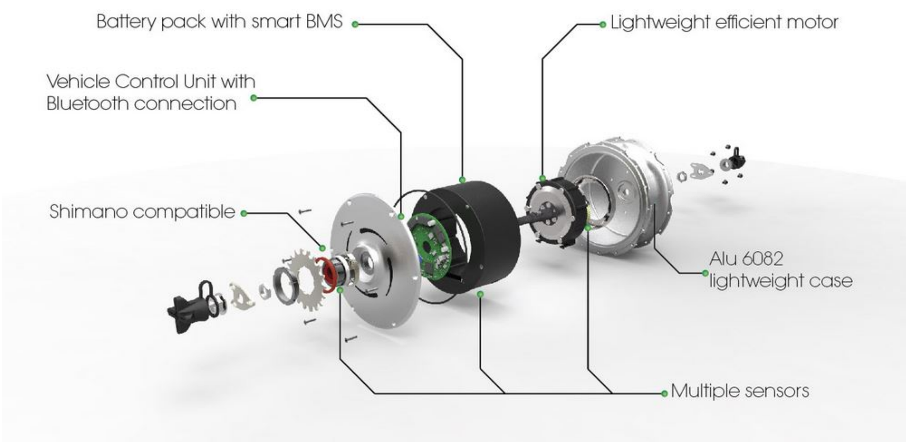

Figure 5. Split view of the WIZE Hub (commercial image) (Zehus, 2014)

an assistance without external energy: the battery must be recharged only with human energy.

The results indicate that for an identical itinerary, the assistance did not allow improving or deteriorating significantly the average speed or the average power supplied by the cyclist. However, the consumption of dioxygen VO_2 decreased from 9.31L to 7.19L (the measurement uncertainties are not specified in the original article) and at constant mechanical energy (37kJ), the metabolic efficiency increased from $3.98\text{kJ}\,\text{L}^{-1}$ to $5.21\text{kJ}\,\text{L}^{-1}$.

The technology developed by ZEHUS does not use series hybrid architecture, but parallel hybrid architecture. However, physiological indicators are taken into account in the energy management integrated to the electrical assistance. This update appears consistent to the potential for the serial hybrid architecture. The ZEHUS technology won in 2014 the first prize for innovation at the "China Cycle" and the price of the most innovative company in the "Innovators under 35" MIT Technology Review.

2. Preliminary analysis of the interest of series hybrid drivetrain for a bike.

The state of the art shows us that a couple of studies or attempts on this subject did not go into depth, especially those of sizing optimization of the electrical conversion system and the energy management. These studies have not permitted to evaluate quantitatively the interest of a new hybridisation for a cycle. In the following, we will focus on series hybridisation. The series-parallel hybridisation is also an interesting solution but which will not be addressed in this article.

On a cycle, a series hybridisation is comprised firstly of a pedal generator. Then, the cyclist plays a role analogous to that of the ICE (internal combustion engine) in the automotive solution. He can pedal at a regulated rate and provide a power that can be monitored (eg. visual display of the produced power and bio-feedback self regulation). The electrical generator converts the mechanical human power into electrical power that is transmitted via the DC-bus, in order to be used directly by a motor mechanically linked to the wheels or to be partially stored in an electrical energy storage system for a deferred use. The electrical motor linked to the wheels could also work in generator mode during regenerative braking phases.

If no storage system is considered, this hybridisation type has the same function as a continuously variable transmission (CVT), as mentioned in the section 1.1 above.

If a storage system is considered between the pedal generator and the wheel-motor, an external charge possibility is not mandatory. Therefore, in this case, the energy required to move would be **only human** in the same way as a classical bicycle but unlike an ordinary electric-assisted bicycle (parallel hybridisation type) where a part of the energy comes from the electrical grid. As mentioned above, such a hybridisation, even though providing an electrical assistance, can be classified, in the French legislation, in the cycle category and not necessarily in the electric-assisted cycle category.

It is obvious that the efficiency, **from the pedal to the wheel**, of such an electrical transmission will be lower than that from a mechanical chain or timing belt transmission. However, from our point of view, the question of efficiency must be extended to the cyclist. If a series hybrid transmission reduces the energy consumption and/or fatigue feeling for the cyclist, this reduction must be compared to the additional losses created by the electrical transmission. The objective is to improve the efficiency from the cyclist to the wheel. Two levers allow this improvement. Firstly, the sizing opti-

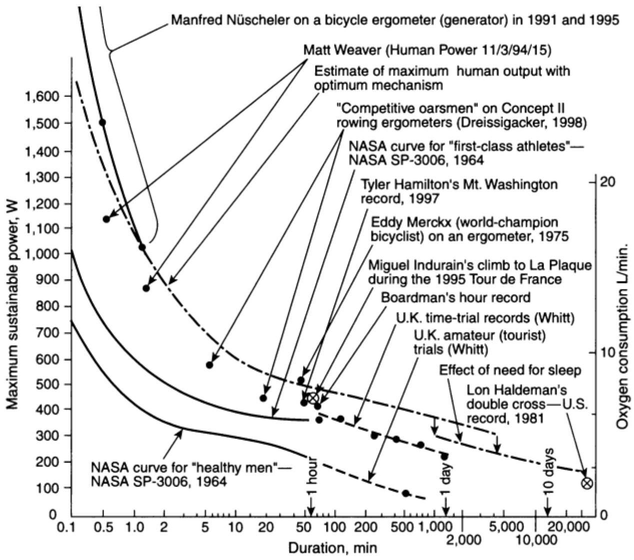

Figure 6. Exhausting curves or Critical power curves (Wilson, 2004)

misation of electrical parts (eg motor) is always a multi-objective problem and a particular trade-off must be chosen. At these levels of power (around 100W), the chosen trade-offs often favour the minimisation of the mass to the detriment of the efficiency. For this application, the choice of the best trade-off could be different while favouring the efficiency to the detriment of the mass. A second lever can be found on the energy management. Indeed, an energy storage system enables buffering power fluctuations. Then, it becomes possible to pedal at a nearly-constant rate and power, which is less tiring, but also to ride at a nearly-constant velocity, which permits to reduce aerodynamic drag losses but needs to provide fluctuating electrical power to the wheel-motor due to road slope fluctuations.

2.1. Definition of a fatigue criterion depending on a mechanical human power time-series.

The above curves come from (Wilson, 2004) and represent exhausting limits in the pedalling power vs Duration plane. By focusing on the "healthy men" curve, physiological tests have shown that it was possible to maintain a power level of 200W during 1h before being totally exhausted. A power level of 100W is tenable during 6h while a power level of 750W can only be maintained for 6s for an average "healthy men". Therefore, the relationship between human power and the resulting fatigue level is highly non-linear. Then, for a given trip, it appears preferable, in terms of induced fatigue, to keep a nearly constant human power rather than enduring power fluctuations.

Based on this curve, also called *"critical power curve"*, we elaborate a formula to calculate a fatigue indicator for a given human pedalling power time-series denoted $P_{human}(t)$. The exhausting curve can be formulated as a function of the effort duration. We will use rather the inverse function denoted $f_{exhaust}$:

$$d_{exhausting} = f_{exhaust}(P_{critical}) \tag{1}$$

Then, we introduce a cumulated fatigue indicator, related to the human pedalling power time-series, as follows :

$$i_{fatigue}(t) = \int_0^t \frac{1}{f_{exhaust}(P_{human}(t))} \mathrm{d}t \tag{2}$$

This criterion is proposed in a way to quantify the fatigue via a percentage of total exhaustion, considering that, for a given constant power level, the fatigue sensation increases linearly as a function of time. Thus, pedalling during 30min at 200W corresponds to a fatigue indicator of 50%. Obviously, the main idea is to apply this formula on realistic power time-series. But, more than the value itself, the interest is to compare, in terms of fatigue, various pedalling power profiles.

2.2. Problem modelling

A simple mechanical modelling based on the Newton's second law gives :

$$(m_{human} + m_{cycle}) \frac{dv}{dt} = \frac{P_{human}(v,t)}{v} - \frac{1}{2}\rho S C_x v^2 - (m_{human} + m_{cycle})\, g \left(C_{rr} + \frac{dz}{dx} \right) \tag{3}$$

where

m_{human} the mass of the cyclist ($=$ 80kg)

m_{cycle} the mass of the cycle or human powered vehicle ($=$ 20kg)

ρ air volumetric mass density $\left(= 1200\mathrm{g\,m^{-3}}\right)$

SC_x is the equivalent drag area $\left(= 0.4\mathrm{m^2}\right)$

v is the velocity of the cycle in $\mathrm{m\,s^{-1}}$

$P_{human}(v,t)$ is the power produced by the cyclist in W. (No losses are considered in this preliminary study along the conversion chain)

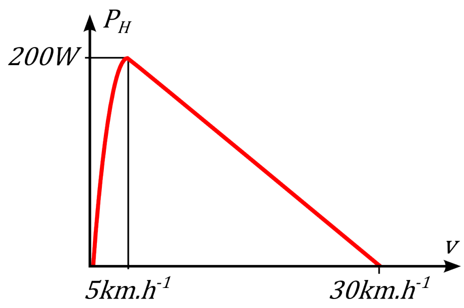

Figure 7. Human power behaviour modelling as a function of cycle velocity.

C_{rr} is the rolling coefficient $(= 0.01)$

$z(x)$ is the elevation profile of the considered trip in m

In the scope of this preliminary analysis, dynamical effects are neglected, thus the relation 3 can be reformulated as a power balance :

$$P_{human}(v,t) = \frac{1}{2}\rho S C_x v(t)^3 - (m_{human} + m_{cycle})\, g \left(C_{rr} + \frac{dz}{dx}\right) v(t) \qquad (4)$$

The instantaneous velocity $v(t)$ results from the instantaneous power provided by the cyclist $P_{human}(t)$. Therefore, we need to establish a model for the behavior of the cyclist in order to evaluate that power $P_{human}(t)$. This is the subject of the following.

2.3. *Power behaviour modelling of a cyclist on a classical bicycle*

We suppose that the instantaneous power provided by the cyclist is related to its velocity according to a function $P_{human}(v)$. Our starting point is that above a certain velocity (here 30km h^{-1}), a cyclist stops pedalling and provides no power. Besides, when his velocity becomes low, he provides more power in order to keep a sufficient velocity to maintain its equilibrium on a hill, for example. Obviously, at lower velocity, the power can not be maintained and decreases because the torque can not tend to infinity. The considered $P_{human}(v)$ curve is shown in Figure 7.

2.4. *First preliminary results for three types of transmission : classical with chain, series hybrid without storage, series hybrid with storage*

The first plot of the Figure 8 presents an example of road elevation on a specific round-trip. The second plot shows, in blue, the cycle velocity, and in green, the power

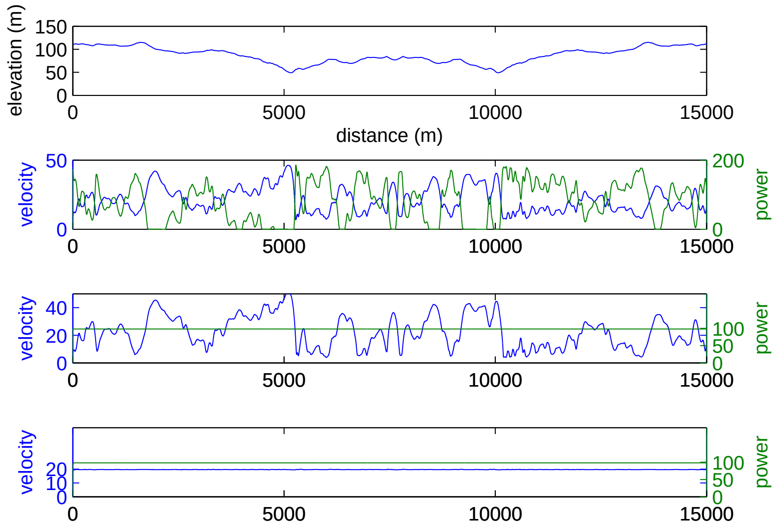

Figure 8. Examples of simulation results, from the top to the bottom : 1 - elevation profile, 2 - velocity profile (in $\mathrm{m\,s^{-1}}$*) and power (in W) for a classical cycle, 3 - for a cycle with a series hybrid drivetrain without storage, 4 - for a cycle with a series hybrid drivetrain with storage*

developed by a cyclist on a bicycle with a classical chain transmission and calculated with the above cyclist modelling.

The third plot depicts velocity and power time-series that would be obtained on a cycle that would be equipped with a series hybrid transmission without energy storage system. The pedalling power is being considered as a constant equal to the average value that was obtained in the previous case (classical transmission). As mentioned above, such a hybrid transmission plays a role similar to that of a CVT. We can note that, for a constant developed power, velocity fluctuations are greater than previously.

Finally, the last plot presents velocity and power time-series that would be obtained on a cycle that would be equipped with a series hybrid transmission with energy storage system. The storage capacity is considered sufficiently high to ensure that the charge limits are not reached. In the later case, the pedalling power level can be maintained nearly constant just as well as the cycle velocity. The value of the velocity is determined here in such a way that the average power provided by the energy storage system is zero. The calculation of that value requires the knowledge of the journey and its slope, what is generally the case for daily trips. Thus, the required energy from the beginning to the end of the trip is only human.

To conclude, a hybrid series transmission without storage enables to maintain a nearly constant rate and power level of pedalling, regardless of slope variations on the route. A hybrid series transmission with storage enables in addition to maintain a constant velocity if the route is known in advance.

2.5. Performance analysis of the three types of transmission

In this paragraph, the performances of that three transmission types with regard to the previously defined fatigue indicator (cf equation 2) are analysed. The Figure 9 shows performances in the (Travel time,$i_{fatigue}$) plane. The considered round-trip travel is the same as the one previously presented. The blue circle refers to the results obtained with a classical transmission (with chain). Red triangles are those obtained with a series hybrid transmission without storage for different human power levels. It can be noted that this transmission offers no better trade-offs than the classical transmission.

Another conclusion can be made with series hybrid transmissions with storage (purple squares) which offers better trade-offs. For example, it is possible to reduce travel time for the same cumulated fatigue level or to reduce fatigue level for the same travel time. We insist on the fact that the value of the fatigue indicator must not be considered as a precise value. It provides especially a comparison tool between different cases. Here, the gap is sufficiently important to believe in a positive interest of such a transmission.

The Figure 10 presents the same results but with an assumption of efficiency of 80% from pedal to wheel for the two series-hybrid cases. This simplistic assumption gives a first idea of the influence of the efficiency parameter. Thus, the series hybridisation with storage remains interesting. A particular attention must be brought on the sizing of the electrical parts of the transmission in order to have sufficient efficiency despite low levels of converted power. A first step of this work is presented in the following and focuses only on the pedal generator which is the first element of the whole conversion chain.

3. Pre-sizing of a particular component of the series hybrid drivetrain : the pedal generator

So that the series hybrid will be relevant, and this even if we said previously that the question of efficiency must not be limited to conversion components but also extended to the cyclist, we have shown the need of having efficient electrical components. Let consider the case of the pedal generator which has to convert a power comprised between 100 and $200W$ in average. At these power levels, off-the-shelf products are generally designed in order to minimize a mass and/or cost criterion rather than losses.

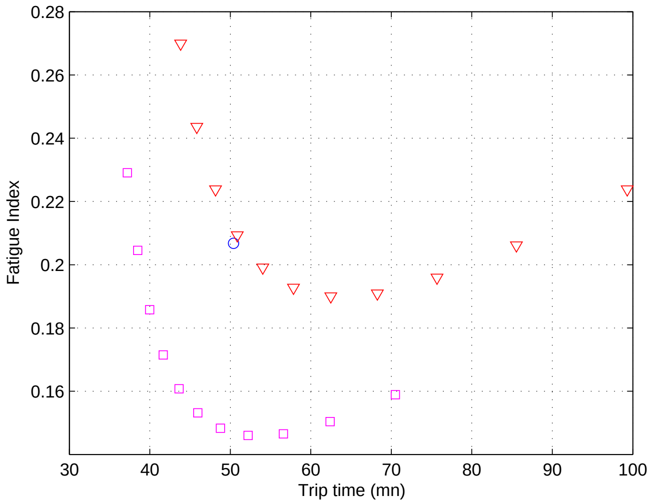

Figure 9. Performance comparison of three different transmissions : classical (blue circle), series hybrid without storage (red triangle) and series hybrid with storage (magenta square). The transmission efficiency is considered equal to 100% and the additional mass of the hybrid transmission is considered as $10kg$ for the both last two cases.

We want to show here that it is possible to design a low power generator exhibiting a high efficiency level. Obviously, this choice is made to the detriment of the mass.

The Figure 11 presents the result of a bi-objective optimization mass versus efficiency for a surface permanent magnet synchronous machine. The considered modelling is the same as the one presented in (Aubry, 2012). We invite the reader to refer to this work for more details. The main difference to this previous work is that we do not consider the power electronic converter here. The optimization algorithm that has been used is based on Particle Swarm adapted to a bi-objective problem (MOPSO : Multi-objective Particle Swarm Optimization). We present here the main parameters of the problem.

The considered constraints are the following :

- $e > 0.2 + 3\sqrt{r_s l_s}$ (mm)
- $r_s - e - h_{mag} \geq h_{rot}$
- $r_s + h_{slot} + h_{stat} \leq r_{max} = 150$(mm)
- $w_{dent} \geq 3$ (mm)
- $w_{encoche} \geq 3$ (mm)

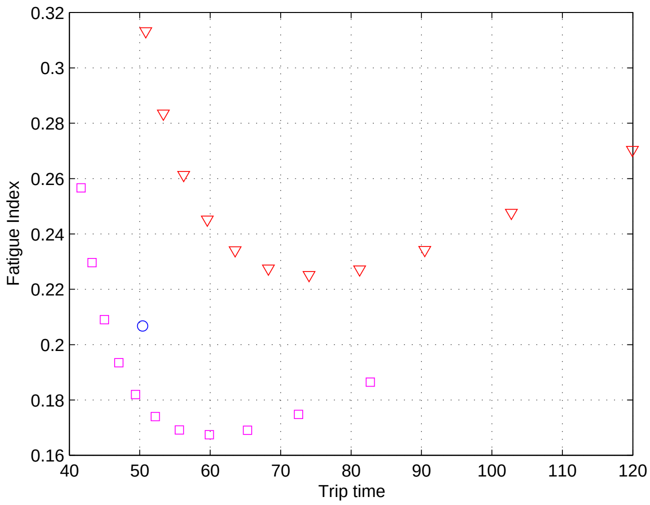

Figure 10. Performance comparison of three different transmissions : classical (blue circle), series hybrid without storage (red triangle) and series hybrid with storage (magenta square). The transmission efficiency is considered equal to 80% for series hybrid cases and the additional mass of the hybrid transmission is considered as $10kg$ for the both last two cases

Table 2. Optimisation parameters

	Description	**Range**	**Unity**
l_u	Active length of the stator	$[0.01; 0.5]$	m
r_s	Bore radius	$[0.05; 1]$	m
p	Pole pair number	$[1; 200]$	$-$
e	Airgap length	$[0.2; 100]$	mm
h_{mag}	Magnet height	$[2; 100]$	mm
h_{rot}	Rotor yoke height	$[0.1; 20]$	cm
h_{slot}	Slot height	$[0.1; 20]$	cm
h_{stat}	Stator yoke height	$[0.1; 20]$	cm
k_{slot}	Slot to tooth pitch width ratio	$[0.3; 0.7]$	$-$

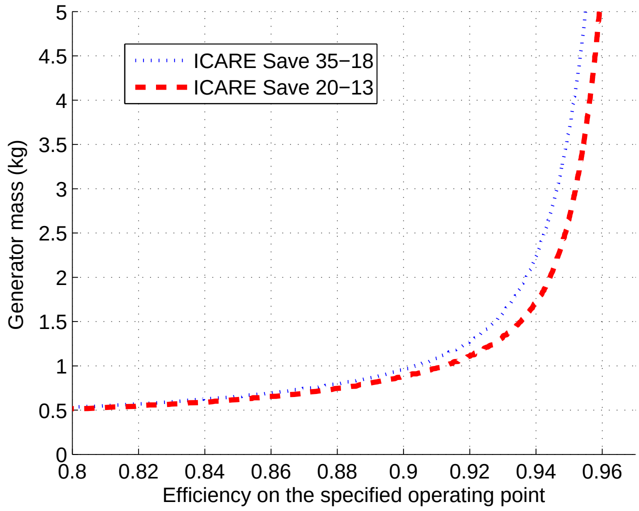

Figure 11. Mass-Efficiency Bi-objective optimisation result for the sizing of a surface permanent magnet synchronous machine dedicated for the pedal generator. Two material options for the iron laminations are considered. The specifications for the sizing are : 80rev/min, 100W at the crank set, with a speed reduction ratio of 10, it gives a velocity of 800rpm and a torque of 1,2N.m

Table 3. Constant parameters

	Description	**Valeur**
B_r	Remanent induction of permanent magnet	$1\,T$
k_{fill}	Slot-filling factor	0.4
k_H	Hysteresis loss coefficient (ICARE Save 20-13)	$39\,A.m.V^{-1}.s^{-1}$
α_p	Eddy current loss coefficient (ICARE Save 20-13)	$0.011\,A.m.V^{-1}$
k_H	Hysteresis loss coefficient (ICARE Save 35-18)	$40\,A.m.V^{-1}.s^{-1}$
α_p	Eddy current loss coefficient (ICARE Save 35-18)	$0.022\,A.m.V^{-1}$
ρ_{Cu}	Copper resistivity @$130°C$	$2.5.10^{-8}\,\Omega.m^{-1}$
λ_{Cu}	Equivalent thermal conductivity of winding	$0.5\,W.m^{-1}.K^{-1}$
λ_{Fe}	Radial thermal conductivity of laminations	$30\,W.m^{-1}.K^{-1}$
h	Convective heat transfer coefficient	$20\,W.m^{-2}.K^{-1}$

– $\Delta\Theta \leq 110°C$

The particular value of the convective heat transfer coefficient has been considered as a constant located between natural convection and forced convection. A more accurate model should properly take into account the speed of the cycle but is not considered in this work.

The sizing specification is summarized to a sole operating point :

– $P = 100$W
– $N = 800$tr/min
– $T = 1,2$N.m

This specifications corresponds to a generator that would follow a speed reducer with a reduction ratio of 10. Actually, rotation velocities at the crank set are generally considered as human efficient around 80tr/min.

The optimisation has been conducted for two types of iron laminated sheets which present different loss characteristics. For higher efficiency solutions, the mass saving between the two iron options reach 1kg. It is equal to 300g for the solutions at 93% efficiency.

The Figures 12 and 13 shows the efficiency map and the geometry of the generator obtained for an efficiency of 93% and the iron sheet ICARE Save 20-13. While this solution is chosen among the highest efficient solutions, the temperature constraint is not reached as it can be seen in Figure 12.

At this point, we want to note that the question of mass is less important on a series hybrid cycle than on a classical bicycle. As it can be seen on the Figure 14, around the mass of reference (100kg for classcial bike and 110kg for series hybrid cycle), the impact of mass on the fatigue is around three times more important for a classical bike than for a series hybrid cycle. In addition, for series hybrid, increasing the mass could improve efficiency as shown in the part about the sizing of the generator while the efficiency is considered the same on this figure (80% for the series hybrid transmission).

The energy storage system will store actually potential energy and the effect of mass on the fatigue of the cyclist is strongly reduced. In the case of classical transmission by chain, every additional mass will increase the power required to climbing a hill. This mass will also have an effect at every stop and start of riding, which are not considered in this work. The fatigue depends on power with a highly non linear relation. On a classical cycle, the mass must be minimised in order to reduce the fatigue. Besides, for a series hybrid cycle, the mass is not so penalizing especially as it could allow to increase human efficiency.

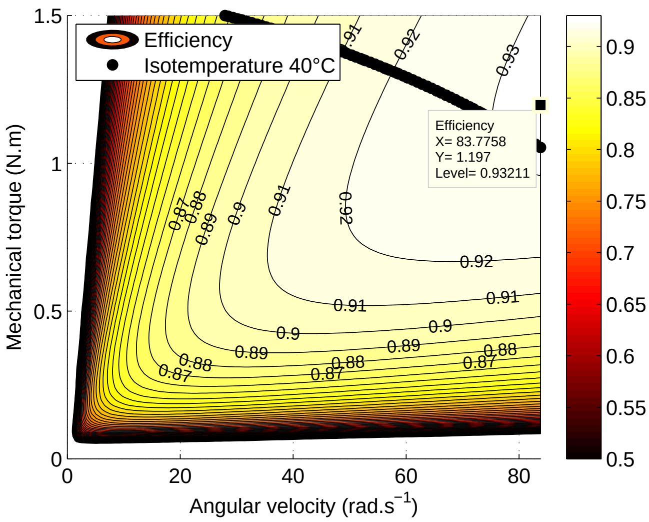

Figure 12. efficiency map of one of the front Pareto solutions and iso-temperature curve of $40°C$

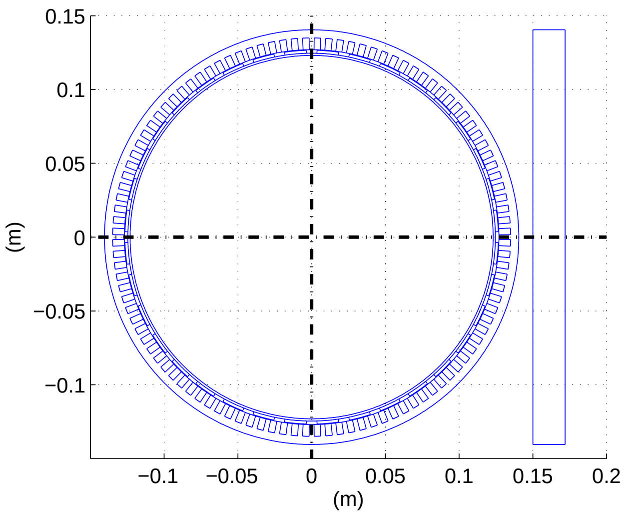

Figure 13. Geometry of the considered solution

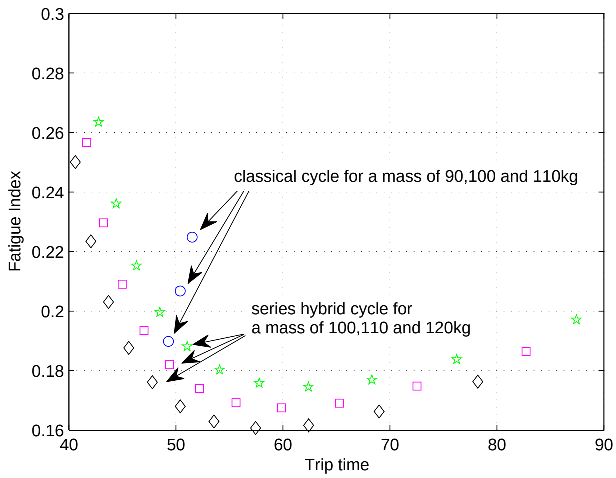

Figure 14. Performance comparison of two different transmissions : classical (blue circle) series hybrid with storage (black diamonds, magenta squares and green stars) for different mass. The transmission efficiency is considered equal to 80% *for the series hybrid case*

4. Conclusions and further works

In this paper, we have set up a state of the art on existing hybridization cycle types. The parallel hybridization is the most common solution in this area, but in these days, new solutions of hybridization like Mando Footlose appear.

Our aim was to assess the relevance of series hybridization on the fatigue experienced by the cyclist. For this, we suggest a fatigue index allowing a means of comparison which we have tested on a special travel. The series hybrid transmission type seems to be particularly interesting for the fatigue management. This solution offers, for a given travel, an interesting compromise with a twofold objective: travel time is minimized as well as the fatigue index. According to the user, a different compromise can be chosen. Our study is based on a simple model of cyclist behavior which should be improved and more formalized in further studies. The same applies for road events like stops or slowdowns which can have an important impact on results.

In a second step, we wanted to show that it is possible to design components for a weak nominal energy conversion having enough efficiency for this application. However, this design choice implies a bigger mass. This issue should be subject to further studies on dimensioning of other machine types or on winding, which is more suitable for this application. Fractional slotting and concentric winding are more adapted technologies which are used for most of the current in-wheel motors for e-bikes.

Studies are currently ongoing on other aspects not mentioned in this paper as the optimisation of energy management. In order to maintain a most constant speed (which is important for energy management), it is relevant to take a known travel into account as it is the case for daily trips. The use of algorithms based on dynamic programming allows to solve this optimisation problem under constraints.

It is planned to build a prototype to confirm the preliminary computed results. First, it will be static in order to finalise physiological models as well as the cyclist behaviour. One of the objectives of this step will be to draw an efficiency map of the cyclist (like for internal combustion engines) and to assess his fatigue. Thereafter, we will make it rolling in order to test in real time energy management strategies. The impact of changes in the relationship and the activity, we used to have on our bikes will also be evaluated.

References

Dave S. (2010). *Life Cycle Assessment of Transportation Options for Commuters*. Master Thesis. MIT.

Kinzel A. B. (1975). *ELECTRICALLY POWERED CYCLE*. US Pat. 3,884,317.

Fuchs A. (2008). *Series Hybrid Drive-System: Advantages for Velomobiles*. Hum. Power eJournal. no. April, pp. 1–13.

Fuchs A., Blatter J. (2007). *Drive system operated by muscle-power*. US Patent 7,156,780.

Watterson P. (2008). *An electric assist bicycle drive with automatic continuously variable transmission*. ICEMS. pp. 2992–2997.

Moeller F., Weber M. (2007). *BICYCLE TRANSMISSION SYSTEM*. US Pat. 2012/0012412.

Mando. *Mando Footloose*. Available: http://www.mandofootloose.com/

Wilson D. G. (2004). *Bicycling science*. 3rd ed. Cambridge, MA. MIT Press.

Spagnol P., Alii G., Spelta C., Lisanti P., Todeschini F., Savaresi S. M., Morelli A. (2012). *A full hybrid electric bike: How to increase human efficiency*. American Control Conference pp. 2761–2766.

Zehus. *Zehus|Wize Hub*. Available: http://www.zehus.it/

Aubry J., Ben Ahmed H., & Multon B. (2012). *Sizing Optimization Methodology of a Surface Permanent Magnet Machine-Converter System Over a Torque-Speed Operating Profile: Application to a Wave Energy Converter*. IEEE Transactions on Industrial Electronics. 59(5), 2116–2125. doi:10.1109/TIE.2011.2163287.

Received : 28 February 2015
Accepted : 1 September 2015