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A full hybrid electric bike: how to increase human efficiency

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***Abstract*—Energy and environmental considerations, new paradigms for urban mobility and transportation increased in the past few years the interest on Light Electric Vehicle (LEV).**

In that context, Electrically Power Assisted Cycles (EPACs) received a great attention: several efforts have been made in order to improve their performance in terms of autonomy, weight, esthetic and feeling with the driver.

In this work, project and realization of a full hybrid electric bike (HEB) are presented. The main idea, borrowed from the more explored 4-wheel world, is to use the possible energy fluxes between cyclist and motor in order to improve the efficiency of the primary engine (the human body) being completely self-sustaining and grid-independent (differently to all the other EPACs). Collected biometric data that lead to the algorithm design are presented in detail focusing particularly on human metabolic efficiency measurement. Finally, an experiment performed in cycling track compares the mechanical and metabolic results between traditional and hybrid electric bike.

I. INTRODUCTION

THE increased sensibility for environmental problems and the growth of oil price brought scientist and companies to invest significant resources on exploiting different energy sources and means of transport with more than one source of power. Particularly automotive field dragged an increasing interest in vehicle electrification. Moreover in urban area environmental and traffic issues lead to enforce strict normative and to create new paradigm for urban mobility (e.g. car and bike sharing), in order to decrease pollutant emissions [1], [2].

In this urban context, Light Electric Vehicles (LEVs) are receiving great attention, particularly Electrically Power Assisted Cycles (EPACs). Several studies have been made in order to explain the growth of EPACs in the market, to analyze the state of the art and to try to predict their technical possible evolution based on users evaluation [3], [4]. These studies pointed out that main issues of EPACs are:

- ✓ Autonomy – the number of kilometers with electric assistance
- ✓ Weight – basically related to the motor and battery pack
- ✓ Duration and problem of recharging the battery pack

On the other hand, the main positive characteristic of EPACs for users is the reduction of physical effort.

In this work the realization of a full hybrid electric bike (HEB) is proposed. The concept here described in detail has been patented [5] and presented to the press. The main idea is borrowed from the automotive field: HEB is configured as a parallel hybrid vehicle. The main characteristic of the HEB are:

- ✓ Charge sustaining mode (bike does not need to be recharged from electric grid differently from EPACs)
- ✓ One power source (the cyclist)
- ✓ Small added weight (HEV and HEB need smaller battery pack, exploiting differently energy fluxes)
- ✓ HEB improves human efficiency (as a HEV, HEB uses the main power source converter at its best operative point). To achieve this objective a deep metabolic analysis of experiments performed in a cycling track has been carried out. From the result of this analysis a control algorithm has been designed and then experimentally validated.

In Section II the vehicle description is provided. Particularly the focus is on the added electronic components, their dimension and weight and the system integration. Section III shows all the possible energy fluxes that involves cyclist, battery pack, motor and finally regenerative brakes. Description of metabolic pathways and instrumentation used for biometric experiments is detailed in Section IV. In the same Section a deep analysis of metabolic experimental data is carried out. Metabolic results gave the guidelines for the design of the new algorithm presented in Section V. In Section VI the algorithm that improves human efficiency is experimentally validated: a comparison of the same test carried out with the bike (without electrical assistance) and with HEB is provided.

II. VEHICLE DESCRIPTION

A. *Mechanical frame*

The hybrid bike is based on Bianchi Camaleonte carbon light frame. It is provided by a Shimano Alfine 11v group and two hydraulic disk brakes. Rims and steer are standard city bikes light components.

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B. *Electrical components*

Brushless motor

Brushless motor chosen is the most off-the-shelf compact bike hub motor (250W nominal power and 36V nominal voltage).

ECU and motor driver

ECU and motor driver are specifically developed for this project. The main components are:

- ✓ Two microcontrollers (Motor and Vehicle Control)
- ✓ Continuous output power more than 250W
- ✓ Tri-axial accelerometer for slope estimation
- ✓ CAN Bus communication
- ✓ Bluetooth module for communicating with smartphone
- ✓ High efficiency (>94%)
- ✓ Small dimensions: 8cm x 5cm

Battery Pack and Battery Management System (BMS)

Battery pack (ten batteries in series of A123System Nano-phosphate, 990W nominal power, 36.3Wh nominal capacity) and its "custom" Battery Management System (BMS) guarantee instantaneous power capabilities during boosts (start-up of pedaling).

Pedaling speed sensor is completely integrated into the bottom bracket.

Smartphone

The smartphone used for the application features Android OS; the application lets the cyclist monitor energy flows, cyclist and motor power and state of charge (SOC) of the battery. It includes also an odometer and the possibility to set via Bluetooth the most important parameters of the vehicle controller implemented in the ECU.

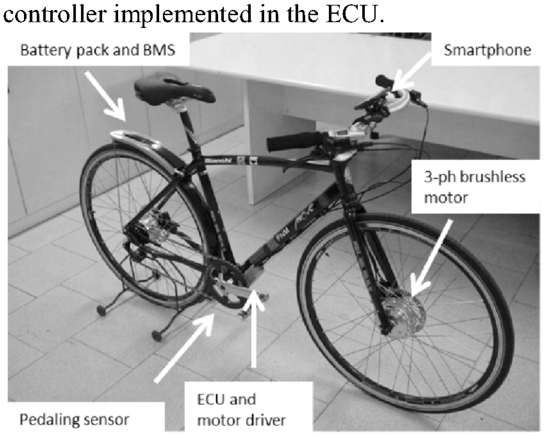

Fig. 1 – The integrated hybrid electric bike

In Fig. 1 the integrated system is shown. The arrows indicate the added electronics. The additional weight is about 2.5kg.

III. Energy Management in an Hybrid Electric Bike

The analysis of the energy and power flux in a hybrid vehicle is the basis of its correct energy management. Considering the more developed analysis in 4-wheel field (cars, trucks, etc.) [6] we can divide hybrid electric vehicles (HEVs) into series and parallel HEVs depending on vehicle configurations:

- ✓ In a series HEV, the engine drives the generator that charges the batteries. The electric motor receives the energy from the battery pack. Essentially the vehicle has only electric traction.
- ✓ In a parallel HEV, the engine and the motor are coupled to drive the vehicles. Engine and motor/generator can propel the vehicle together or separately: when only one of the two sources is being used, the other must either also rotate in an idling manner or be connected by a one-way clutch or freewheel.

The hybrid bike can be considered a parallel HEV.

A. *Power involved during assisted cycling*

During a bicycling trip the instantaneous power developed by the cyclist and electric assistance is:

$$\begin{aligned} &P_{cyclist} + P_{mot} = P_{inertia} + P_{slope} + P_{fric} + P_{braking} \\ &P_{cyclist} \geq 0 \\ &P_{braking} \geq 0 \\ &P_{fric} \geq 0 \end{aligned} \qquad (1)$$

$P_{cyclist}$ is the power developed by pedaling [W];

P_{mot} is the power developed (>0) or regenerated (<0) by motor/generator [W];

$P_{braking}$ is the power dissipated thermally by brakes [W];

P_{fric} is the power that has to be overcome to win bicycle friction forces [W];

$P_{inertia}$ is the total inertia power [W];

P_{slope} is the power (positive or negative) due to slope [W];

From equation (1) it is possible to describe different energy fluxes for parallel hybrid bike described in the next paragraph.

B. *Energy fluxes during traction*

Different power fluxes can be exploited in order to guarantee the charge sustaining behavior of HEB. Possible fluxes for an EPAC are presented in the followings.

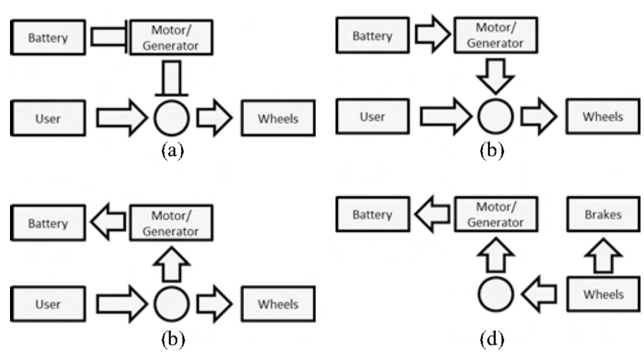

Fig. 2 – Operation modes: (a) no assistance (b) electric assistance during traction (c) cycling regeneration during traction (d) regenerative braking

✓ No assistance during traction

The power to overcome inertia and frictions is given by user. Motor is in idle and rotates at the same speed of front wheel Fig. 2a.

✓ Electric assistance during traction

User and motor cooperate in order to overcome inertia, frictions and slopes Fig. 2b.

✓ Cycling regeneration during traction

Cyclist provides mechanical power to the bike and at the same time to the generator in order to recharge the battery pack as shown in Fig. 2c.

✓ Regenerative braking

During braking (or downgrade) power is partially regenerated and partially dissipated by brakes Fig. 2d.

C. Full hybrid electric bike: requirement

The requirement for a full hybrid electric bike is its complete independence from the electric grid: as a matter of fact, the only external source of energy is the cyclist. In this sense the developed hybrid bike is a "charge-sustaining hybrid vehicle".

Thus considering the power depleted and stored into the battery during a long run (few kilometers):

$$\int_{t_0}^{t_{end}} (V_{dis}(t)I_{dis}(t) + V_{ch}(t)I_{ch}(t)\eta_{ch})\, dt = 0 \qquad (2)$$

where:

t_0 is the time at the beginning of the ride [s];

t_{end} is the time at the end of the ride [s];

$V_{dis}(t)$ and $I_{dis}(t)$ are the voltage at the poles and the current depleted from the battery during discharge [V];

$V_{ch}(t)$ and $I_{ch}(t)$ are the voltage at the poles and the current stored into the battery during charge [V];

$\eta_{ch}(t)$ is the charge efficiency of the battery [adim];

The energy management strategy takes into account this requirement.

IV. Metabolic Human Cycling Efficiency

The development of an algorithm that increases the human energetic efficiency requires the study of the efficiency of the "human engine" during pedaling. In the next paragraphs literature, equipment, tests and results are presented.

A. Oxygen Uptake Measurements

In order to evaluate the efficiency of a cyclist, a special portable device was used: the VmaxST system (Sensormedics, Bilthoven, The Netherlands).

The VmaxST system is a fully portable cardiopulmonary gas-exchange measurement system, based on breath-by-breath technology. It is composed of a close fitting facemask over the mouth and nose, a volume turbine measuring respiratory flow, a gas sample line measuring both oxygen and carbon dioxide concentrations in the expired air, and a battery-operated unit which is worn on the shoulders. The system has been validated in several medical studies (for instance [7]).

B. Metabolic mechanisms

Sport medicine and physiology literature describes the metabolic pathways during exercises [8]. Nutrients (carbohydrate, fat, and protein) contribute to the fuel supply needed by the body to perform exercise. These nutrients get converted to energy in the form of adenosine triphosphate (ATP). The energy released by the breakdown of ATP allows the muscles cells to contract.

However the human body cannot easily store ATP (and its consumption lasts in few seconds); thus it is necessary to continually create ATP during exercise. The two major ways the body has to convert nutrients to energy are:

- ✓ Aerobic metabolism (with oxygen)
- ✓ Anaerobic metabolism (CP and lactic system without oxygen consumption)

The combination of energy systems supplies the "fuel" needed for exercise: the intensity and duration of the exercise determines which metabolic pathway is followed.

During a ride cyclist moves through these metabolic pathways. At the beginning, ATP is produced via anaerobic metabolism, while breathing and heart rate increase. This leads to increase the availability of the O_2 that fuels the aerobic metabolism (simplified scheme is depicted in Fig. 3).

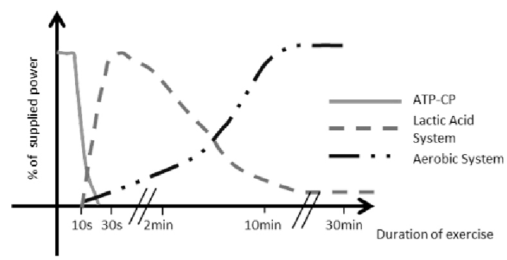

Fig. 3 – Metabolic pathways occurring during exercise

C. Metabolic measurement

There are several works in literature about metabolic measurements carried out during steady-state exercises. In fact during steady-state it is easier to find the equilibrium point between the anaerobic and aerobic pathway and to combine the results taking into account:

- ✓ Oxygen consumption for aerobic metabolism
- ✓ Lactate production (by a simple blood analysis) for anaerobic lactic system

In the case considered in this work there are two main differences:

- ✓ The interest is for "urban cycles" (frequent start-stops, no steady-state)
- ✓ It is necessary to find an easier way to calculate human efficiency without considering lactate production

In some physiological literature, scientists make efforts to model the relationship between oxygen uptake and energy expenditure [9]. The subsequent models are very complex, but show some results that can be exploited:

- ✓ It is possible to consider oxygen to calculate the efficiency of human body
- ✓ Results are valid only to compare consumption for the

same cyclist using the hybrid bike with and without assistance algorithm (thus using it as a "traditional" bike), performing the same test protocol

- ✓ It is necessary to take into account the excess post exercise oxygen consumption until the rest level consumption of oxygen (consumption before the exercise) is reached again.

Excess post exercise oxygen consumption (EPOC) refers to the "inertia" of the body to decrease the oxygen consumption to the level at rest after an intense activity. After an exercise oxygen must oxide lactic acid and build-up again creatine phosphate, thus the athlete has to pay back the oxygen debt

D. *Human efficiency analysis*

Given the consideration in the previous paragraph a definition of "equivalent human efficiency" η_{met} has been developed:

$$\begin{aligned} \eta_{met} &= \frac{E_{mech}}{\Delta V_{O_2}} \\ \Delta V_{O_2} &= \int_{t_{start}}^{t_{stop}} (\dot{V}_{O_2} - \dot{V}_{O_{2,idle}}) dt \\ E_{mech} &= \int_{t_{start}}^{t_{stop}} P_{mech}\, dt \\ P_{mech} &= P_{inertia} + P_{fric} \geq 0 \ \text{(cyclist power)} \end{aligned} \tag{3}$$

η_{met} is the equivalent metabolic efficiency [kJ/l];
ΔVO_2 is the total oxygen consumption [l];
$\dot{V}_{O_2}$ is the oxygen consumption per minute [l/min];
$\dot{V}_{O_{2,idle}}$ is the oxygen consumption per minute at rest [l/min];
t_{start} is the time at the beginning of the test [s];
t_{stop} is the time at the end of the test [s];
E_{mech} is the mechanical energy produced by cyclist [kJ];

Friction power is calculated following the methodology described in [10]. The greater the value of η_{met} in (3) the greater the mechanical energy that can be produced given the same amount of oxygen.

In the next subparagraphs metabolic results are presented.

1) *Tests*

Tests were performed riding the hybrid bike with electric motor at idle (no electric assistance) around a professional cycling track: this condition is perfect because it has a great repeatability. Moreover no wind was present during tests. Cyclist was not a professional athlete.

Two different tests were performed:

- ✓ Constant speed test
- ✓ Acceleration (transient) test

Constant speed test

Three different speeds were tested:

- ✓ 10km/h
- ✓ 20km/h
- ✓ 25km/h

Cyclist performed - using the same gear - a slow acceleration until actual and reference speed were the same. After $\dot{V}_{O_2}$ reached steady state (oxygen debt) cyclist had to maintain for other 350s the same speed. Then cyclist stopped and sat down for resting (EPOC evaluation). Test was considered finished after reaching $\dot{V}_{O_{2,idle}}$ for at least 200s.

This protocol was repeated three times for each speed.

$\dot{V}_{O_{2,idle}}$ was evaluated at the beginning of the session (cyclist completely relaxed sat down for ten minutes consumed 0.37l/min of oxygen).

Due to the long gear used for the experiment, the first test was accomplished at 12km/h instead of 10km/h: in fact cyclist had some difficulty to maintain a constant pedaling rate at lower speed. Table 1 underlines no great differences between constant speeds although η_{met} is lower for very low constant speed.

TABLE 1
CONSTANT SPEED TEST RESULTS

Speed [km/h]	η_{met} [kJ/l]
12	3.87
20	4.39
25	4.37

Acceleration (transient) test

The aim of these experiments is to evaluate human body efficiency during "impulsive muscle efforts". The term "impulsive" in this case means an intensive step of mechanical power without dependency on its duration (cycling on a slope can be considered an extended impulsive muscle effort).

Cyclist had to perform acceleration from 0km/h to 33km/h with 3 different behaviors:

- ✓ Slow acceleration
- ✓ Medium acceleration
- ✓ High acceleration

After reaching the desired speed, cyclist stopped immediately and sat down in order to evaluate EPOC. Test was considered finished once $\dot{V}_{O_2}$ goes back to the rest level.

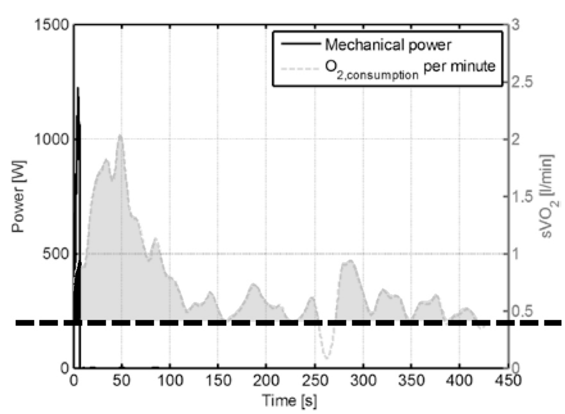

Fig. 4 – Mechanical power and $\dot{V}_{O_2}$ in 0.28g acceleration

An example of mechanical power and $\dot{V}_{O_2}$ time history for high acceleration is shown in Fig. 4 where oxygen debt and its compensation are evident. The black solid line shows the developed mechanical power: the acceleration lasts less than 7 seconds. O_2 consumption during acceleration is the small black area. However, only 45 seconds after the exercise, cyclist had the peak of $\dot{V}_{O_2}$: oxygen debt contracted during the acceleration is paid back after several seconds. The overall V_{O_2} is the sum of the black and gray area. Dashed black line is $\dot{V}_{O_{2,idle}}$.

The average results of several experiments are presented in Table 2.

TABLE 2
ACCELERATION (TRANSIENT) TEST RESULTS

Max acceleration during test [g]	η_{met} [kJ/l]
0.1	2.35
0.2	2.25
0.28	1.92

The greater the acceleration the lower the efficiency.

Moreover, the comparison between Table 1 and Table 2 underlines the effects of "impulsive muscle effort": metabolic efficiency during transient is substantially smaller than during constant loads (constant speed test).

This result helps the design of control strategy to increase human efficiency.

V. THE PROPOSED CONTROL ALGORITHM

On the basis of the above considerations, and considering a city-bike common usage (frequent start-stops and cruise speed lower than 25km/h) the guidelines for the control algorithm design are the followings:

- ✓ Electric assistance has to be predominant during impulsive muscle effort: starts and slopes. For the first version of the algorithm sprints are not considered
- ✓ Electric assistance progressively decreases until a cruise speed is reached
- ✓ Electric recovery has to be as greater as possible during braking
- ✓ Electric recovery can be activated during constant cruise speed where metabolic efficiency is greater

Moreover, the most important requirement is that:

- ✓ Hybrid-bike has to be energetically self-sustaining

A synthetic description of the first version of control is in Fig. 5 and Fig. 6.

From standstill condition, once a pedal motion is detected, system enters in *boost (start)* state. During that state the current setpoint sent to motor microcontroller increases linearly from 0 to its maximum value $I_{boost,max}$ [A] with the pedal covered angle (from 0 to $\vartheta_{boost.max}$ [rad]) and then saturate at the maximum value for the first pedal revolution ($\theta_{ped\_start} > 2\pi$). After one revolution, the control goes in *pedaling* state if the estimated gear ratio τ [m/rev] (ratio between bicycle speed and pedaling speed) is equal to the actual (k [m/rev]). In this state the current increases linearly from 0 to $I_{ped,max}$ with bike speed v_{bike} [km/h] (0 to $v_{torque,max}$ [km/h]). From $v_{torque,max}$ to v_{ped} [km/h] current setpoint has a linear decrease staying positive. For speed higher then v_{ped} [km/h], current setpoint continues to decrease linearly, becoming negative (recovery during pedaling), until it reaches the saturation value $I_{ped,min}$.

From *pedaling* state, *boost* is reached once v_{bike} is lower than v_{min} (the minimum speed in order to stop any electric assistance) and cyclist is not pedaling (ω_{ped} is the pedaling speed [rev/min]). Otherwise if cyclist is in "idle" (thus he is not pedaling, or he is pedaling slower than the needed to keep the measured v_{bike}) or a braking is detected (by means of bike acceleration signal), control enters in *braking* state. Current setpoint in braking state is always negative and decreases linearly from 0 to the saturation value $I_{rec,min}$ [A] with v_{bike} (from $v_{no\,rec}$ [km/h] to $v_{rec,max}$ [km/h]). If estimated and actual gear ratio are the same and v_{bike} is greater than v_{min}, control enters again in *pedaling* state The remaining two transitions between *braking* and *boost* states are self-explaining (and same as other already described transitions). For the first version of the control in order to prove the concept of human efficiency improvement, self-sustaining requirement is obtained by a correct selection of the parameters depending on the average urban speed profile.

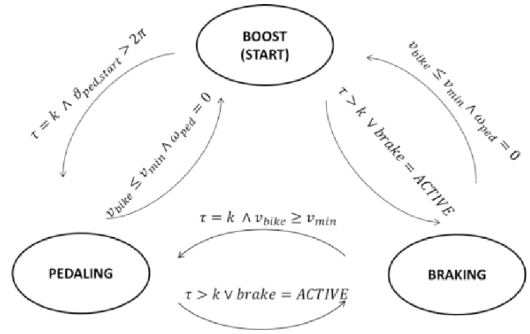

Fig. 5 – Control algorithm layout

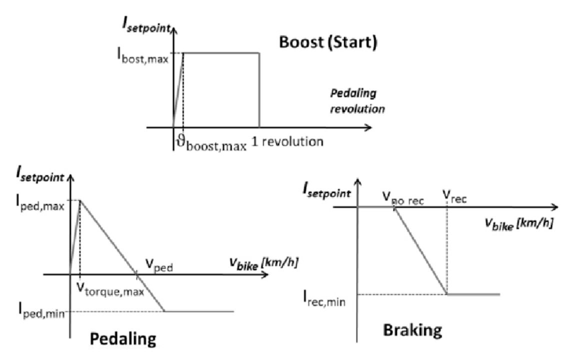

Fig. 6 – Current setpoint generating function for different states

VI. RESULTS

In order to evaluate if the strategy can improve human efficiency a test protocol has been designed taking into account a possible urban cycle:

- ✓ Frequent starts-stops (steady-state never reached);
- ✓ Cruise speed: 20km/h;

The test has been performed dividing a cycle track in four sectors: in Table 3 all the characteristics of the test protocol are reported.

The test has been performed into two different conditions:

- ✓ Bicycle with electric motor at "idle" (no assistance: bike behaves as a "traditional" bike)
- ✓ Control algorithm described in Section V is active.

The analyzed mechanical data in Table 4 shows that tests are comparable: this is a precondition for comparing metabolic efficiency.

TABLE 3
CHARACTERISTICS OF TEST PROTOCOL

Track length	400m
Sectors	4
Number of start-stops	11
Total covered distance	1100m
Length of single sector	100m
Cruise speed	22km/h
Distance for reaching cruise speed	20m
Distance for stopping bicycle	20m
Average acceleration	0.1g
Average deceleration	0.1g
Seconds between stop and re-start	10s

TABLE 4
MECHANICAL COMPARISON BETWEEN TESTS

	No assistance	Electric Assistance
Duration	357s	372s
Average speed (with start/stop and rests)	10.47km/h	10.11km/h
Average mechanical power at wheel (cyclist + motor)	103.8W	100W
Total mechanical energy developed at wheel	37kJ	37.5kJ

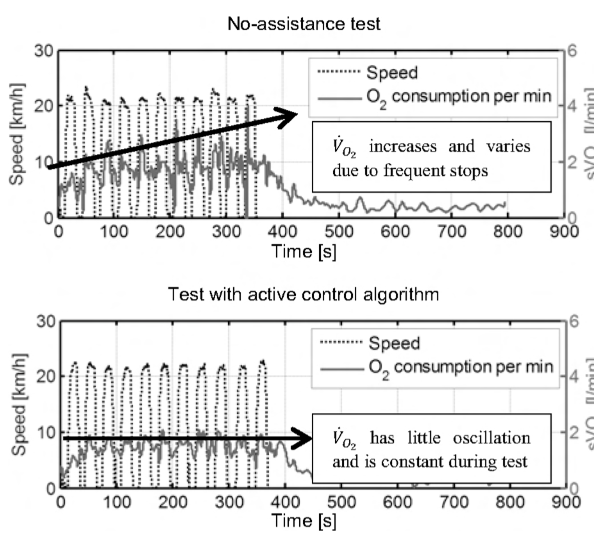

Fig. 7 – Comparison between speed and V_{O_2}

TABLE 5
METABOLIC RESULTS

	No assistance	Assistance
Duration (with cool down for evaluating EPOC)	800 s	800 s
Difference between maximum and minimum $\dot{V}_{O_2}$ during test	3.67 l/min	1.71 l/min
Total V_{O_2}	9.31 l	7.19 l
η_{met}	3.98kJ/l	5.21kJ/l

Time histories of speed and oxygen consumption for the two tests are shown in Fig. 7.

SOC of the battery during test with assistance has increased from 70% at the beginning of the test to 71% at the end (thus, self-sustaining requirement has been fulfilled).

Metabolic comparisons are reported in Table 5: from collected data it can be assessed that the hybrid electric bike for the protocol proposed has increased human efficiency of 30.9%.

VII. CONCLUSION

This paper presents the design of a self-sustaining hybrid electric bike for improving human efficiency: system integration, energy fluxes, physiological consideration and an algorithm to prove the possibility of decreasing oxygen consumption are presented. Results show that a correct strategy can improve human efficiency for a specific protocol over than 30%.

Algorithm can be improved in order to guarantee a self-sustaining behavior in every condition. Sprints are not considered in the actual version of algorithm and should be included. Moreover the effects of changing covered distance between starts and stops need to be further investigated.

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