Design and Construction of a Solar Hybrid Car (Electric motor and human propulsion)

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Abstract. This work presents the design and the construction of a solar hybrid vehicle whose principal driving force is a photovoltaic system, assisted by human propulsion. The solar race of Atacama Desert (Chile) was the first challenge that the solar vehicle faced, with a maximum catchment area of 4 m^2, storage 1500 Wh and a maximum cost of 7000 USD. Built vehicle was tested, reaching speeds on flat terrain of 40 km/h with engine and 50 km/h with human-powered contribution. Proposed design could be projected as a vehicle for transporting person average Latin American roads. The important contribution is the interaction between two different energetic sources to support power demands at different load solicitations.

Key words

Renewable energy, sustainable transportation, solar vehicle, embedded electrical motor.

1. Introduction

Transportation at global level remains a major contributor to greenhouse gas emissions, recently developed technologies have tried to diversify the types of energy sources in vehicles: hydrogen fuel cells, electric motors, hybrid generation, natural gas, etc. Colombia is experiencing a transition into the renewable energy sources, where the sustainable transportation becomes one of potential lines of development. The electric vehicles and in particular solar cars are an interesting alternative in terms of sustainable transport. However, the great challenge comes in high load demands (torque and power) due to high slopes, acceleration and starts.

Human-powered vehicles have attracted interest for many years; the association World Human Powered Vehicle Association (WHPVA), an international federation that promotes the development of "human-powered vehicles" and organizes sporting events mainly in Europe. Although most of their work is related to the development of the "bicycle" (particularly the recumbent, being the fastest), also promotes research on vessels and aircraft or "blimps" human-powered. Similarly different competitions around the world as the World Solar Challenge in Australia or Chile's Atacama Desert have motivated scientists and academics to innovate with solar and hybrid vehicles becoming more efficient, promoting a culture for sustainable transport. Electric bikes have become a pole of development. Motors embedded in the drive wheel give high flexibility to deploy other alternatives traction. A photovoltaic panel as a power source for the motor and human power from the pilot may be perfectly complementary power sources. The human propulsion can be used in load solicitations (torque, speed) of the electric motor during inefficient operations.

2. Design

The design involves several systems, namely: chassis, suspension, steering, fairing, traction and electrical system. This publication is intended to emphasize the power and traction systems and the way they interact.

A. Determination of the required power

Power demand ($\dot{W}$) in a moving vehicle is defined by the product of overall strength and reached speed. The total force F_T is defined by the sum of all the resistive forces [1], [2]: force due to the slope F_θ, tire rolling resistance Fr, and force by aerodynamic effects Fa. Figure 1 presents these loads, W represents the total weight of the vehicle and θ the slope.

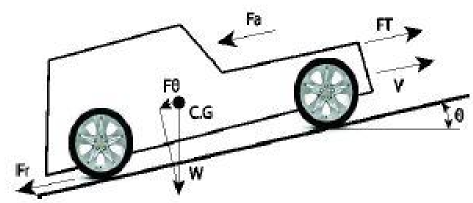


Fig 1. Forces in moving vehicle

With direction of motion and using Newton's second law, the total traction force required by the load is obtained [1]

$$F_T = W\sin\theta + C_r W\cos\theta + \frac{1}{2}\rho S K_a V^2 + ma \quad (1)$$

Where: Cr is rolling coefficient which depends on the friction between road-tire and the pressure of tire, K_a is coefficient of aerodynamic restriction which depends on airfoil and the relative wind speed against the vehicle, S is transversal section of vehicle perpendicular to the direction of movement, ρ (wind density), m (mass) and a (acceleration). Acceleration as the inertial effects (acceleration causes the inertial force by the principle of Da Lambert [2]) significantly influence on the total force required by the drive wheel. Power will be determined by:

$$\dot{W} = \left(W \sin\theta + C_r W \cos\theta + \frac{1}{2}\rho S K_a V^2 + m\ a\right) \times V (2)$$

With this expression can be analyzed the influence of each component on the total power demand.

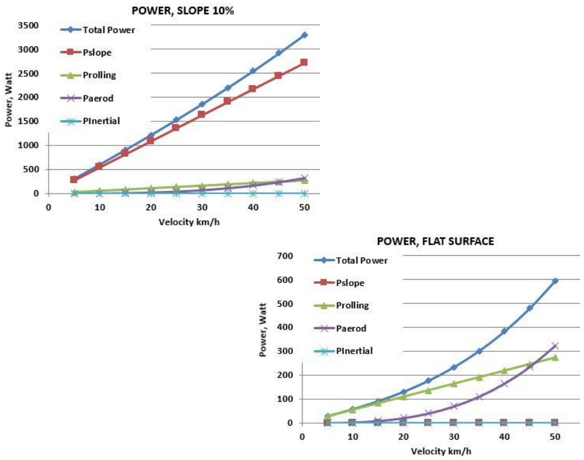


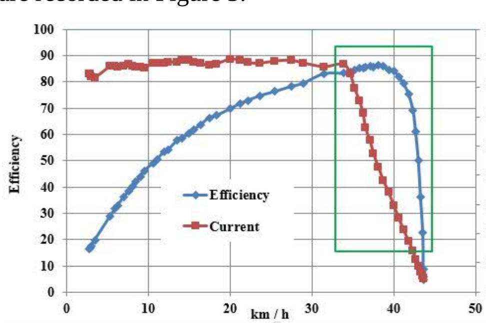
Fig. 2. Power components, inclined and flat surfaces.

Assumed parameters: Cr=0,01, S=1 m^2, K_a=0,2, m=200 kg. It can be seen that the vehicle (moving to 30 km/h) will require 1800W on slopes of 10%, but only 220 W on flat ground. With steep slopes, the component $W \sin\Theta$ is the most influential, but on flat surface the rolling and aerodynamic effects (at high speeds) are predominant. Mass is the most influential to accelerate and overcome inertia. A driving torque from the power unit is required to put the vehicle in motion. This torque will depend on the total force (equation 1) and the driving wheel R_T (equation 3) [3].

$$T_T = \left(W \sin\theta + C_r W \cos\theta + \frac{1}{2}\rho S K_a V^2 + ma\right) R_T \ (3)$$

B. Electrical Motor

A 2 kW engine was selected for the vehicle and embedded to the driving wheel. The performance curves are recorded in Figure 3.



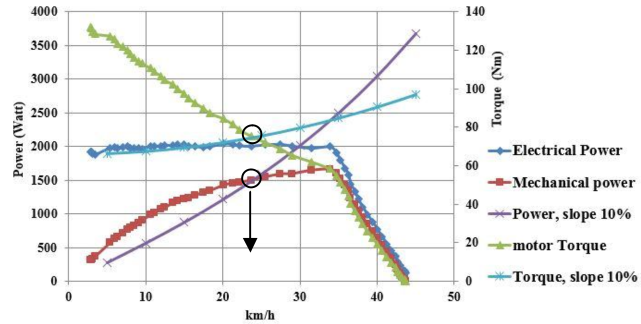


Fig. 3. Development Curves of motor

Figure 3 also includes Torque and Power curves (equations 2 and 3) on 10% slope. Traction wheel diameter is 26 inches (R_T=13 in). The circles show the motor operating point. In the aforementioned load demands, the vehicle reaches 24 km/h with efficiency of 75%, however on flat roads it will able to reach 42 km/h with maximum efficiency.

C. Human Propulsion

Pilot of vehicle can give extra power when required. According to transmission relation, driver would deliver high torque at low velocity or vice versa. Figure 4 presents a scheme with the gears employed in transmission.

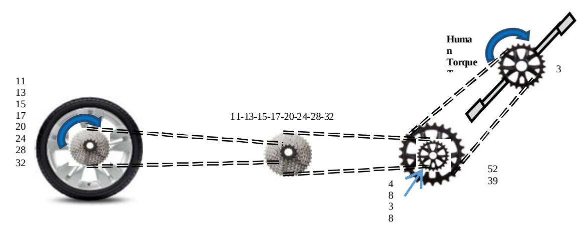


Fig. 4. Transmission relation in vehicle

There are 384 possible combination of transmission relation with a maximum gain of 4,54. Studies [4] have shown that a normal person is able to deliver a force of 300N over pedal in a bicycle with a connecting rod of 17 cm length, keeping a velocity of 1,2 rpm. This represents a torque of 51 Nm and approximately 390 Watt. Figure 5 shows forces measured of tests pedaling in bicycle employing load cells adapted at pedal.

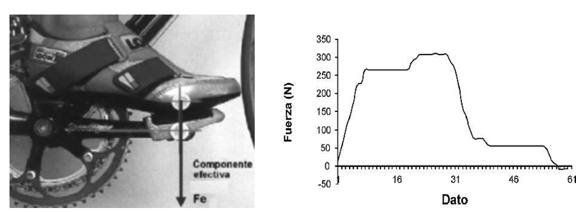


Fig. 5 Force over bicycle pedal [4]

Human propulsion plays a paper very important in the satisfaction of high power demands principally in starts and high slopes. With a transmission relation of high torque pilot can delivers until 231,5 Nm at traction tire. This results of 51 Nm x 4,54.

D. Electrical System

Electrical System is configured with 2 photovoltaic panels of 345 W each one, 2 lithium batteries of 15 Ah each one, 1 controller of 40 A and 1 electrical motor of 2 kW. Figure 6 presents the scheme of system.

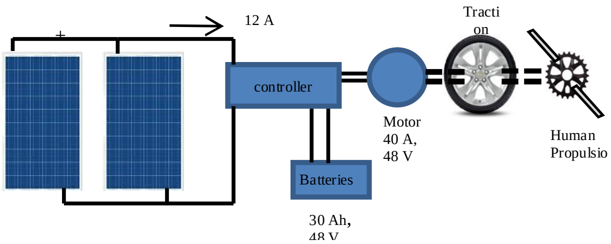


Fig. 6. Electrical system

Photovoltaic systems work normally with a load regulator to keep voltage adequate levels. In the Beginning the solar vehicle electrical system was assembled with a regulator MPPT (maximum point power track). This system allow find the maximum power of photovoltaic system. However, this appliance imply additional weight and a loss of voltage system.
It has been decided by the designers that system would work without voltage regulation if panels configuration delivers voltage near to 48V. This implies that pilot has all responsibility to on or not the panels connection and to keep adequate load demands. Batteries can help to regulate the voltage but is important to avoid power sources (panels) when batteries are full.

1) Photovoltaic panels

To guaranty major efficiency (relation power/weight) used panels were of monocrystalline type (Each module is made from a single silicon crystal). Each module delivers 345 Wp and allow to work a 48 Vdc system, adequate voltage to used motor. Each panel has next characteristics:
Efficiency: 21,5%, Vmpp = 57,3V, Voc = 68,2V, Impp = 6,02A, Isc = 6,39A.

With the panels in parallel the system can deliver a current of 12,04 A and Voltage of 57,3 V in maximum power point.

2) Storage System (Batteries)

There have been 2 Batteries of Lithium Iron Phosphate (LiFePO4), are rated at 1500 to 2000 recharge cycles by the cell manufacturer and come installed with a Smart high current battery management system (BMS). The BMS ensures that the battery remains within manufacturer limits for maximum recharge cycle life, and protects the battery from overcharge and over-discharge. The BMS is also responsible for balancing each row of cells during the charge cycle. Fully charged voltage is 58,4V. This voltage is major than Vmpp of panels, allowing work without regulation, but is necessary ensure not panels connection when there isn't radiation to avoid voltage near to Voc (although current is very low in this range).

To electrical traction of vehicle it has been selected an embedded motor in tire of vehicle, some features are:

- Brushless motor has no internal wear parts.
- 440 Watts at 36V, **1920 Watts at 48V (used in system)**, 2880 Watts at 72V.
- Speeds up to 30 MPH without pedaling.
- Can be laced to 20, 24, **26 inch** (used) or 29/700C rim.

3) Load Controller

To accelerate the motor depending of load demands It has been used a controller with features like:

- Controls speed and torque of brushless sensorless motors
- Also works on brushless motors with AND without hall effect sensors.
- Can be used for Wilderness Energy, and other brushless direct drive motors.

4) Monitoring Display

This controller allow the use of active power management display (APM), is an all in one speedometer, odometer and distance gauge. Use to configure controller parameters for voltage, max current, top speed, low voltage. Some features:

- Speedometer, tripmeter, power meter
- Can limit speed and current for novice riders and/or range conservation.
- Display options include speed, RPM, Watts, Amps and more!
- Blue backlit screen with large numbers.

3. Analysis of traction

Last curves (Fig 2 and 3) were analyzed in load demands without consider acceleration (or inertial effects). In starts or suddenly acceleration appears an important component force which increase the power. In starts (speeds almost cero) increasing of torque is more notable. Figure 7 shows power and torque curves in slope 10%, considering an acceleration of 2 m/s^2. (suppose a start with change of velocity from 0 to 10 m/s in 5 s).

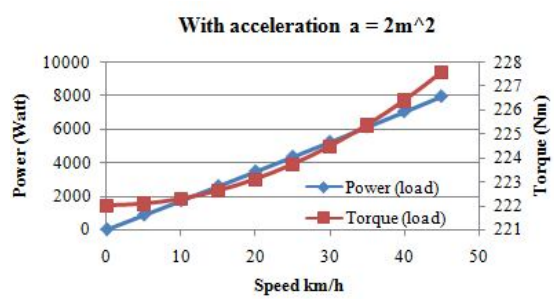


Fig. 7. Torque and power demands with acceleration

Comparing curves (fig. 7) with curves (fig 2) is notable that power increases considerably with application of accelerations. For this reasons changes of velocity have to do very slowly.

In starts the limitation of electrical motor is major. Now, comparing Torque Curves (Fig 7 vs Fig 3) can be seen that motor delivers approximately 130 Nm at low velocities. This torque doesn't satisfy the load demand which overpass the 220 Nm. This torque could be satisfied by pilot (human traction) by means of high torque transmission relation (231,5 Nm, ref 2.C).

4. Conception of vehicle

Other system of vehicle have been developed analyzing design factors like resistance of material, low weight, ergonomics, low aerodynamic restriction, reliability in direction and suspension and others.

For instance, to design the structure it has been used simulation to ensure that satisfy the requirements of Real Spanish Federation of automotive. Figure 8 presents results of simulation of chassis with loads equal to 8 times the weight of vehicle on top to verify the resistance of roll cage.

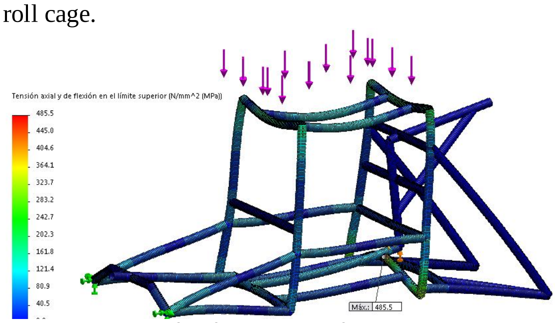


Fig 9. Simulation of deformations of chassis with vertical loads over roll cage

Figure 10 presents design of different developed systems: Double wishbone suspension

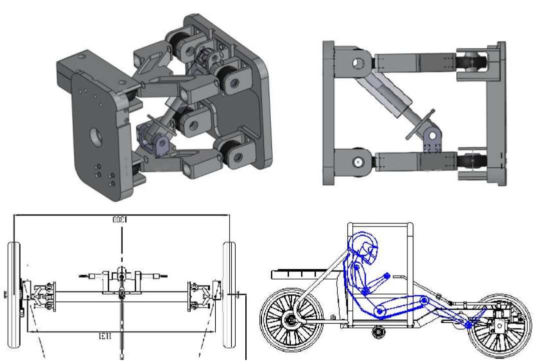


Fig 10. Suspension, direction and cabin systems

Figure 11 presents the 3D design and the actual vehicle during Solar Atacama Rally.

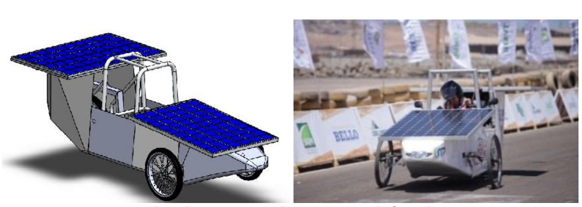


Fig. 11. Vehicle XUE, design and final prototype.

5. Conclusions

A hybrid vehicle was designed and built with a combined power system consisting of electrical motor embedded in the rear driving wheel and mechanical transmission. Electrical Power Sources are composed by 2 photovoltaic panels of 350 Wp each one and 2 lithium batteries of 48 Vdc and 15 Ah each one. Pilot is able to deliver additional power of 400 W, and torque of 230 Nm (51 Nm x Gain) at low velocities. This is very useful in starts and sudden acceleration. Tests over vehicle showed a maximum speed reached of 40 km/h on flat roads and it increased until 50 km/h with high velocity relation.

Participation in competence in Atacama desert was successful. Monitoring of power showed behavior very near to projected theoretical curves. Optimal efficiency was reached with vehicle on flat land at 40 km/h keeping constant velocity, such as it was showed in figures 3 and 4. In this operating point, motor consumes 13 A approximately with an efficiency of 84%. Keeping this rate of consumption, the storage bank (30Ah) worked during almost 2 hours (without panel). However with plenty radiation (1000 W/m^2), batteries kept practically loaded (fed by Impp).

This vehicle can be used like means of transport over any land (until steep slopes roads), becoming a model of sustainable and economical transport to many places in Latin-American and the world. Other versions of hybrid vehicles have been developed reducing weight and simplifying mechanical and electronic components (Fig 12).

Fig. 12. Other simple version of hybrid vehicle

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