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Estimation of required power and energy for bicycle electrification using global positioning system

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Abstract. When designing an electric motor drive for a conversion of bicycle to an electric vehicle it is obligatory to determine the required power of the electric motor and the energy of a battery pack. By using a classical method, drive requirements can be established with speed and torque measurement on the drive wheel of the vehicle using a torque meter. The given traction profile is used for the design of the drive. This paper describes the method for estimation of power and required energy of vehicle only by means of global positioning system (GPS). When selecting a GPS device, it is necessary to take the resolution of the device and accuracy of vehicle speed and altitude into account. Using the measured track (speed and altitude profile) and the drag model of the vehicle it is possible to calculate both power that the vehicle develops, and energy consumed for a certain distance. The GPS device measurements, selection of electric drive, bicycle electrification and analysis of processed KTM Knoxville electric bicycle is presented.

Keywords: GPS device, longitudinal speed, vehicle drag, estimation, bicycle electrification

1. INTRODUCTION

Last few years' vehicle electrification is one of top themes in the world with the big boom happened in 2017 and still running [1]. The main electrification question is how much power, and energy is needed to travel from one point to another. Second one is how to get that data fast and accurately. Can GPS measurement replace classical method and give results which can be good base for electrification?

When designing an electric motor for electric bicycle, it is necessary to know the traction characteristics and multiple factors connected to different forces which act on vehicle during driving [2]. A classic method for determining the traction characteristics of a vehicle is using rotation speed and torque measurement by means of a torque meter mounted on the drive wheels of a vehicle. Such a method requires dismounting and then assembly of drive wheels and a set of gauging equipment. For that reason, the novel GPS method is proposed. In less time but with demanded accuracy it is possible, according to the specific track that user often drives, to design and adapt the drive to user requirements.

2. BICYCLE DRAG FORCES MODEL

To drive the vehicle at constant or changing speed, it is necessary to overcome the forces acting on that vehicle [3]. In the case of a bicycle it is possible to use pedals or in the case of an electric version using a motor. Forces that acts are acceleration F_a, rolling resistance F_{rr}, aerodynamic drag F_D and gravitational force F_{gx} shown on Figure 1.

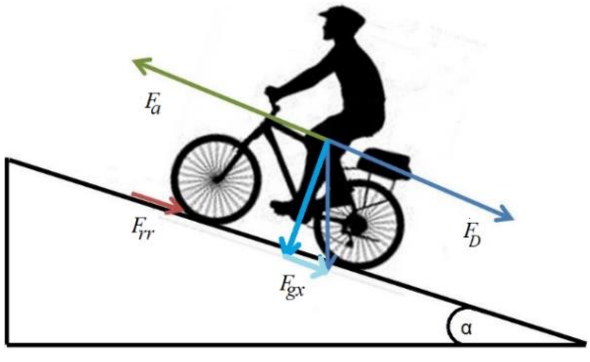

Figure 1. Vehicle forces

Forces equations are as follows:

$$F_a = ma \quad (1)$$

$$F_{rr} = mgc_{rr}\cos(\alpha) \quad (2)$$

$$F_D = c_d \frac{1}{2}\rho A v^2 \quad (3)$$

$$F_{gx} = mg\sin(\alpha) \quad (4)$$

where m is the vehicle mass, a acceleration, g gravitational acceleration constant, c_{rr} rolling resistance coefficient, α road incline, c_d aerodynamic drag coefficient, ρ air density, A frontal area and v vehicle speed.

In order for a bicycle to achieve a certain speed, it must develop a power sufficient to overcome its forces on its propulsion shaft. Expression for vehicle power using (1) to (4) is given (5):

$$P(v) = (F_a + F_{rr} + F_W + F_{gx})v \qquad (5)$$

Figure 2 shows the dependency of the power and bicycle speed. It has to be taken into account that the average coefficient of air resistance, rolling resistance, bicycle and driver surface are related to particular system so the values shown are not and cannot be valid for any system due to different vehicle configurations and are shown only as guidelines for researches.

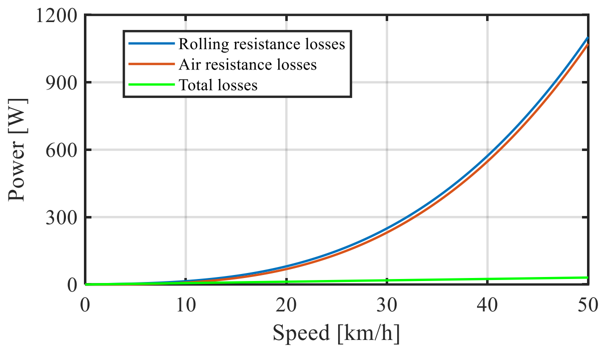

Figure 2. Total vehicle losses

3. USED SYSTEM

Bicycle used in this paper is KTM, model Knoxville, year 2009 weighing 15 kg and with 26 Inch wheels. For the purpose of this research commercial 1 Hz GPS device was not satisfactory [4] so for measuring was chosen model PhidgetGPS with sampling frequency of 10 Hz which was mounted on the top of helmet for the best possible signal receiving. Measuring system was upgraded with inertial measurement unit (IMU) device model PhidgetSpatial Precision with sampling frequency 250 Hz mounted on bicycle frame top tube to enable precise measurement of angular speed and acceleration (Figure 3) for data comparison.

To achieve a full 250 Hz reading speed for PhidgetSpatial Precision it was decided that the data will be collected in the LabVIEW programming environment.

At the beginning of each measurement, a LabVIEW program and GPS device have been started. Because of stabilization and retrieval of the position, 5-minute pause was placed before moving.

When running the program, the data was stored in the .csv file. Excel was used as a tool for manipulating data and Matlab for graphical representation.

Figure 3. Mounted GPS and IMU device

4. GPS AND IMU MEASUREMENTS, DATA PROCESSING AND PARAMETAR ESTIMATION RESULTS

The start and the end of the track was Zrinjevac, park in Zagreb. The track was chosen to be the one with the least traffic and traffic lights. The highest point of the track was park Cmrok. At the end of the ride the entire track was entered (geographic latitude and longitude from GPS) in Google Earth and marked with yellow line as shown in Figure 4.

Figure 4. Google Earth track

Recorded data was imported in Matlab where graphical representation of recorded values in time dependency and data were processed with moving average filter which is commonly used for digital signal processing. Results were acceleration from IMU device, speed and altitude from GPS device (Figure 5).

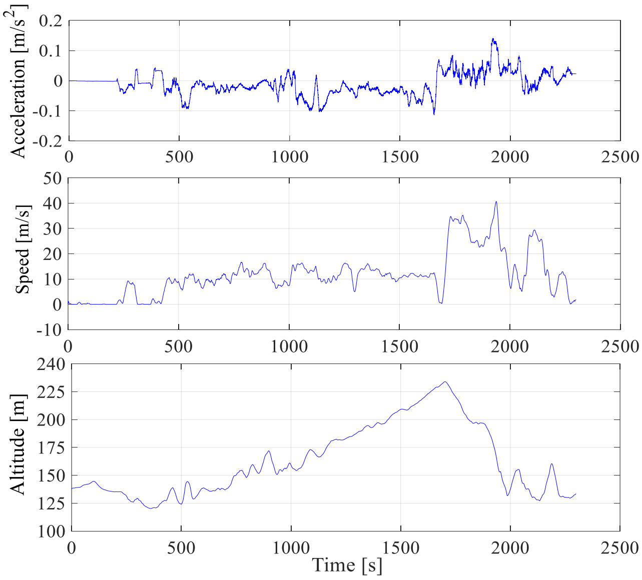

Figure 5. IMU acceleration, GPS speed and altitude measurement

After processing the first set of measurements, it was necessary to carry out measurement associated with forces opposing the motion of the bike and resistance coefficients. This connects measurements of the speed and altitude of the vehicle with the required power that the vehicle should produce on the axle.

In the case of the bicycle to which these measurements are carried out, it is known that the mass of the driver and the bike together is equal to 115 kg and that their frontal area is

approximately 0.46 m^2 [5]. Furthermore, the air density according to the International Standard Atmosphere at 15 °C is about 1.225 kg/m^3 and the weighing force is 9.81 m/s.
All the above mentioned data are given in Table 1.

Table 1. Data used in coast down test

Mass [kg]	115
Height [cm]	115
Width [cm]	40
Frontal surface [m^2]	0.46
Air density [kg/m^3]	1.225
Gravity [m/s^2]	9.81
Incline angle of the road [rad]	0

The coast down test is performed by accelerating to a certain speed, stabilizing the vehicle at a given speed for a few seconds, and by allowing the vehicle to stop only by the action of air and rolling resistance. Such a test is required to be performed on a perfectly flat road and assume that the angle of incline α during the whole measurement is equal to 0 [6]. In that case when the vehicle is decelerating, the force acting on the vehicle is described as follows:

$$ma = F_{rr} + F_D \qquad (6)$$

For this research coast down test was performed from 45 km/h to 0 km/h. The force is calculated by obtaining the vehicle acceleration from the speed measurement and knowing the vehicle mass. To avoid high noise caused by discrete derivation the speed data is fitted as a polynomial $v = p_1 t^3 + p_2 t^2 + p_3 t + p_4$. Matlab curve polyfit function was used and next coefficients were obtained $p_1 = -4.50e^{-5}$, $p_2 = 0.0069$, $p_3 = -0.4432$ and $p_4 = 12.4084$.

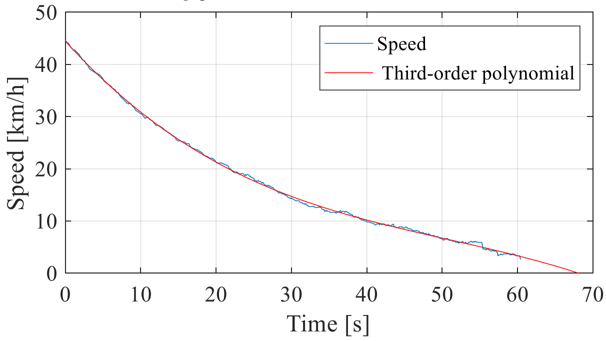

Figure 6. Speed polynomial fit

Then a simple polynomial derivative is given:

$$a = 3p_1 t^2 + 2p_2 t + p_3 \qquad (7)$$

Using the above equation and measured mass the vehicle drag power is calculated:

$$P_{drag} = mav \qquad (8)$$

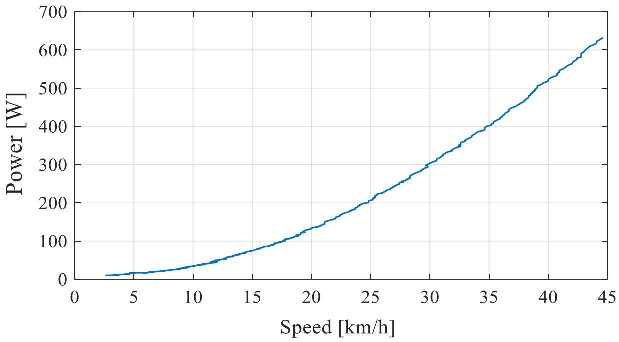

Figure 7. Vehicle estimated power

In order for resistance coefficients to be obtained, it was necessary to construct a third-order polynomial with the power-speed dependency data. In this case the formula for power is:

$$P = c_d \frac{1}{2} \rho A v^3 + c_{rr} mg \cos\alpha \, v \qquad (9)$$

By obtaining the coefficients c_d and c_{rr} [7], it would be possible to determine the required power for any speed. Therefore, the curve adjustment tool (Figure 7) gave the following coefficients $p_1 = 0.2531$, $p_3 = 15.5$.
A further calculation obtains parameters:

$$c_d = \frac{2p_1}{\rho A} = 0.9294 \qquad (10)$$

$$c_{rr} = \frac{p_3}{mg} = 0.0137 \qquad (11)$$

To calculate the specified force, it is necessary to know the road incline, α [8]. The road incline was obtained with two methods using GPS data $\alpha = \tan^{-1}\left(\frac{dh}{ds}\right)$ and accelerometer data $\alpha = \tan^{-1}\left(\frac{-G_y}{G_z}\right)$.

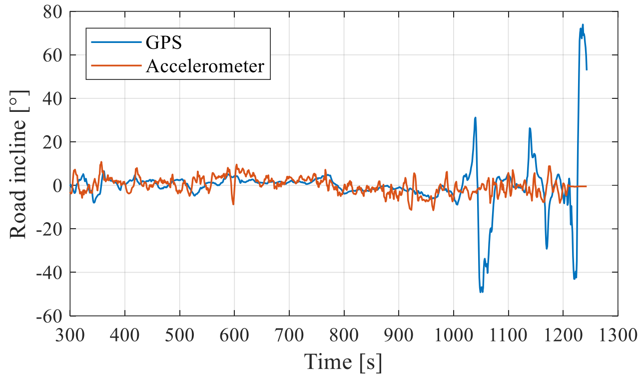

Figure 8. Comparison of inclines obtained by accelerometer and GPS

By finalizing the incline of the road, it is possible to calculate the total power required for the traversed path. The following formula will be required:

$$P_{izr} = c_d \frac{1}{2} \rho A v^3 + (mgc_{rr} \cos(\alpha) + mg sin(\alpha))v \qquad (12)$$

Incorporating the displayed profiles and other values previously obtained in this paper will ultimately get the power profile needed to maintain the speed shown on Figure 9.

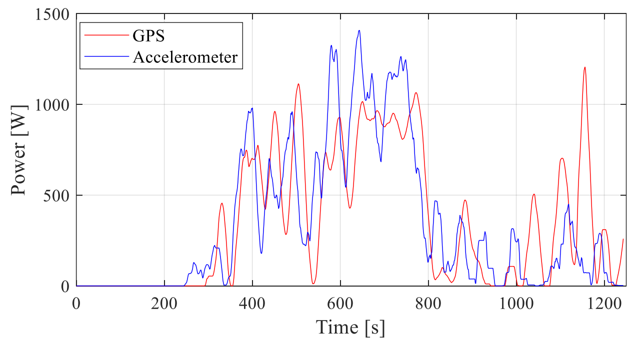

Figure 9. The estimated power profile on the given track

When analysing the recorded data, the GPS device's inaccuracy is clearly visible vis-à-vis the accelerometer that does not depend on external influences. Although the GPS power profile may in some cases be able to track the accelerometer, where the signal is excellent and there is a view of the open sky, in other situations there are quite a few rough errors in the calculation. This is best seen at the end of the measurement when the track goes back to the city and to tall buildings and narrow streets. But in order to quantitatively compare how accurate that kind of profile is, the energy required for the same path was calculated, with the following formula:

$$E = P(n) * (t(n) - t(n-1)) \qquad (13)$$

In this way, the total energy needed to run the track with the calculated power in two ways will be obtained. With the power calculation method using the accelerometer, the energy was equal to 117.17 Wh, while with the power calculation method using the GPS device, energy was equal to 119.15 Wh. By comparing the amount of energy, it is apparent that the difference between the measurements is negligible and in case the accelerometer is not available, it is possible to measure power and energy by GPS. Such a measurement method requires only GPS, which simplifies measurement and makes it cheaper and more accessible.

5. ELECTRIFICATION

For this and some expanded research verification it was decided to electrify bicycle with 1,7kW BLCD motor and a three-phase inverter rated 2000 W [9]. The inverter uses 12 IRFB3077 MOSFETs, manufactured by Infineon Technologies. Four MOSFETs are used for each phase, maximum current of 120 A, with its limit of 31 A for the protection of equipment. The battery pack consists of 6 lithium-polymer batteries each consisting of 4 cells. The rated voltage of each cell is 3.7 V, while their capacity is 8 Ah. With configuration 12s2p, the rated voltage of the system is 44.4 V and the total system power of 710.4 Wh. Monitoring the voltage and temperature of each cell is essential for the long service life and safe use of the battery pack which task is performed by a battery management system (BMS).

In order to know power value which is entering the electric bicycle system, it is necessary to measure the current and voltage. Allegro Microsystems sensor model ACS758LCB-050B-PFF-T and analogue digital converter (ADC), manufactured by Texas Instruments, model ADS1115 were used for measurement.

The ATmega 328p, Atmel, which is on the development board of Arduino Nano [10] was selected for processing and storing data. Programming was performed in the Arduino IDE development environment and is used as a programming language by Java. Electrification result is shown in Figure 10.

Figure 10. Bicycle with electric drive system

6. RESULTS COMPARISON

To compare the obtained calculated power and energy with the really needed power and energy, the same track was driven on the bicycle using an electric drive. During such a challenging task a speed profiles had to be as similar as possible to compare power. The speed profiles of the two measurements are shown in Figure 11.

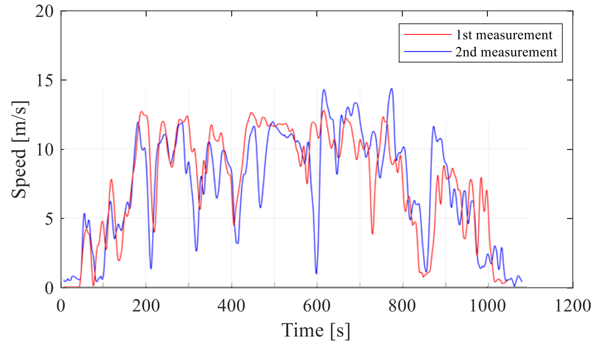

Figure 11. Two speed measurements comparison

One should be aware that two signals are obtained during two different voyages, and for that reason they cannot have completely the same speed profiles, which means they cannot even get the same power over time. The calculated power throughout the ride is quantitatively lower than measured (Figure 12), as a result of losses in the real system, and the loss of driving.

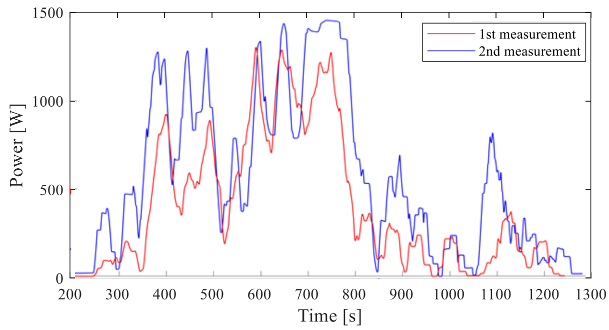

Figure 12. Two power measurements comparison

It was obtained that the energy needed is equal to 169.95 Wh. It is useful to calculate energy ratio which for this case is 68.9 %. If we do not neglect the power below 0 W calculation gives the total energy of 161.39 Wh, while the power returned is 8.54 Wh, which represents only 5.3% of the used energy. Such a gain is considered too small to be used solely for the purpose of energy return but is advantageous when it comes to preserving the battery system during major downhills.

7. METHOD VERIFICATION

To verify this method and calculation, it was proposed to run the track up to the top of Medvednica, mountain near Zagreb. To check in advance if there is enough energy in the battery pack, a power and energy calculation was required. Formula 12 and 13 were used again. All calculated and measured coefficients remained the same, while a speed was constant, and its determined value was 25 km/h or 6.95 m/s. The path was split into two parts with similar inclinations across parts. Their length, initial and final altitudes were measured in Google Earth. The length of the first part was 6700 m with a climb of 143 m, while the length of the second part was 14000 m with a climb of 811 m. In the first part it was assumed that the inclination is constant and equal to $\alpha_1 = 1.223°$, while of the second part is $\alpha_2 = 3.315°$. After incorporating both coefficients in equation 12, the theoretical mean power required for driving was obtained. Then using the equation 13 theoretical energy, which sums up two parts, was 457.46 Wh. If this theoretical amount is multiplied by the previously calculated efficiency of 0.689, the total energy needed to drive to the top of Medvednica is 663.95 Wh.

During this measurement, only the GPS device and the Arduino data were included, which include speed, voltage and current. The following figure 13 shows the calculated power obtained from GPS device measurements of speed and altitude and processed in Matlab.

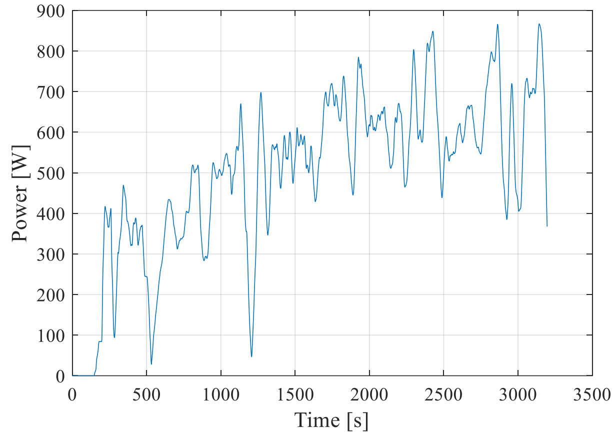

Figure 13. GPS data - power calculation

After calculating the power, it was finally possible to calculate the total energy needed to reach the peak. It was 440.72 Wh.
In order to compare this result, the previously described power generation procedure with the current sensor and voltages measured using Arduino was repeated.
Knowing the voltage and current, it was possible with the ease to calculate the power as described above. The calculated power is shown in Figure 14.

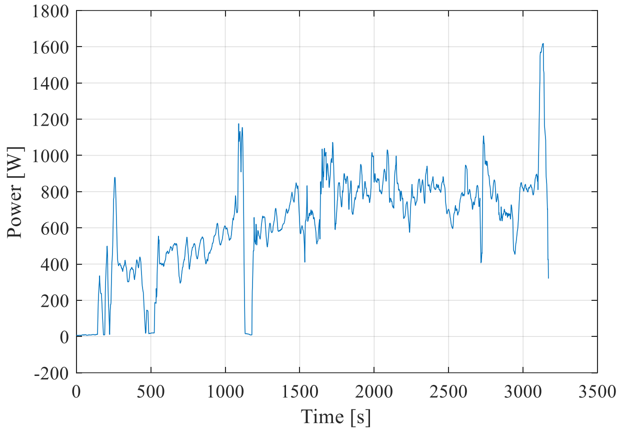

Figure 14. Arduino data – power calculation

After calculating the power, it is possible to calculate the required energy. By using the above-described account, the energy was 548.97 Wh. The efficiency in this case was 80.28 %.
Getting such difference efficiencies can be explained by the fact that the vehicle has stopped and used the brakes only once. So, there were no major changes in speed, while in measuring up to Cmrok there were multiple braking, making most of the mechanical energy turned into heat dissipation on disc brakes. During downhill ride, the energy returned to the battery pack by regenerative braking. From the top of Medvednica to the bottom, a total of 74.92 Wh was returned to the battery pack, which corresponds to 13.65% of the total used energy. The reason for such a high rate of return of energy is clear: the downhill ride took place from a relatively steep mountain and was constant, enough to return the energy to the battery pack. This energy gain is relatively large and cannot be neglected in the calculations.

It should be taken into account that this track is very specific and very demanding by itself, and it is unlikely that this will be the track for which the electric drive will be designed.

8. CONCLUSION

The electric drive is becoming more and more present today due to its numerous advantages over internal combustion engines. Such a trend is seen not only in the automotive but also in bicycle world. This paper describes a method by which it is possible to calculate the parameters of the electric drive and on the basis of which they finally convert bicycle into the electric one.
With this paper, the method of estimating the traction characteristics of a vehicle is proposed solely by measuring the speed of the vehicle with the specified GPS device. This allows an estimation of power that a vehicle develops, and the energy required for each track. What makes this method universal is the fact that the method can be applied on all vehicles because no mechanical modifications are required on the vehicle. Namely, only a GPS device is required to carry out the measurements, which makes this method applicable and easy to use.
To improve the method, it is necessary to use the GPS device with greater precision due to limitations, most of all in the precision of displaying the altitude of the objects. Also, if possible, using an accelerometer improves the precision of calculating the road incline, especially in the track sections where there is a dense layout of high buildings.
The above-mentioned power and energy calculation can be used when dimensioning an electric bicycle drive and is a base for further research and development of the measuring system.

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