# Characterization and Performance Analysis of a Pedal Electric-Assisted Bicycle

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**Abstract**

In the last decade, large urban environments have attempted to combat air pollution, using legislation to prohibit the circulation of internal combustion vehicles. Recently, the electric bicycle has become a new alternative in the market. This alternative consists of equipping a traditional bicycle with an electric propulsion system, so that it promotes work, and assists the driver in his trips. This work aims to estimate the efficiency of the electric system of an electric bicycle, by comparing the electric power consumed and the mechanical power required for the vehicle to move, within a test circuit. The results show that the efficiency of the electric system studied is very low, less than 10 %, making it infeasible to use these bicycles as an alternative to cars, motorcycles and public transport vehicles.

**Keywords:** Electric drive system, bicycle, power, efficiency.

## 1. Introduction

Despite being a topic that is not new, electric vehicles continue to be a relevant area. With the growing environmental concern at European level and with the measures announced in recent years, both at the level of taxes and at the legislative level, there are efforts to make electric powered vehicles an integral part of society and to reduce the number of traditional vehicles driven by oil fuel [1, 2].

This work concerns another type of vehicle, namely an electric bicycle, which appears not to be as well publicized as electric cars, although efforts are already being made to implement it for city wide mobility. This type of vehicle can be appealing to the task at hand, mobility in the city, due to the low cost of acquisition when compared to a car or a motorcycle, as well as the cost of supplying the battery, and the ease in finding a parking spot. However, when compared to a classic bicycle, the electric bicycle may not be offer a better option, due to higher prices, more complex and expensive maintenance, lack of efficiency and fear of theft.

## 2. Background

A social survey [3] was performed in Europe in 2015-2016 to understand what made people buy an e-bike and what was the perception of the bicycle owners social environment's opinions towards e-bikes. 24 people were interviewed, with age ranging from the early forties to the sixties. Half of the population was from the Netherlands, an European country know for having a strong cycling culture, with roughly 27% of all trips being done by bicycle [3], while the other half of the population was from the United Kingdom, a country with a much lower percentage of trips done by bicycle, roughly 1% [3].

The main reason for acquiring an e-bike are health issues or declining physical abilities. The purchase of e-bikes increased the users' overall physical activity, and in some cases replaced car rides with bicycle rides, providing a sense of well-being to the user.

Concerns of e-bike users consist in the higher speed achieved when compared to the classic bicycle, technical reasons associated with purchase price and battery performance, associated with fear of not having enough charge to fulfil a trip, social stigma and potential theft.

### 2.1. E-Bike Work Process

The electric bicycle work process differs due to the existence of an electric drive system, aiding the movement. The electric drive system does not work isolated, the rider must provide the initial propulsive force for the system to move, hence the characterization of this type of vehicle as an electrical assisted vehicle. The electric bicycle work process is described in Figure 1.

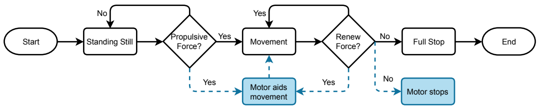



Figure 1: Electric bicycle work process.

## 2.2. Overall Characteristics

The study in hand is conducted using a typical cruiser bicycle provided with an electrical traction system composed by a lead-acid battery, a brushless direct current motor (BLDC motor) installed on the back wheel axis, a display installed on top of the handle bar, and a controller designed to decide whether or not to start the motor, deciding as well the power provided to the motor based on the level of assistance selected in the display. A photograph of the bicycle can be seen in Figure 2.

Figure 2: Bicycle used in this thesis, Wayscral 300.

The bicycle used is a Wayscral 300. The model itself is outdated and is not available to purchase any more. This model is equipped with a brushess DC motor and a lead-acid battery. Table 1 presents the characteristics of the bicycle utilized.

Table 1: Electric bicycle characteristics provided by the manufacturer.

| E-Bike Characteristics | |
|---|---|
| Top Speed [km/h] | 25 |
| Range [km] | 25-30 |
| Motor | Brushless DC |
| Rated Power [W] | 250 |
| Battery | Lead-acid |
| Rated Voltage [V] | 24 |
| Rated Capacity [Ah] | 10 |
| Total Mass [kg] | 30 |

## 2.3. Battery Characteristics

The lead-acid battery is one of the most common type of batteries available, with a wide range of designs suited for a large range of operations. The lead-acid technology has good overall characteristics [4, 5] suited for the use in an e-bike as stated in [6, 7, 8], such as this one whose model dates back to the late 2000s. These characteristics are displayed in Table 2.

Table 2: General lead-acid battery characteristics [4, 5] .

| Lead-Acid Battery | |
|---|---|
| Price | Affordable |
| Depth of Discharge | High |
| Discharge Current | Low |
| Self-Discharge | Low |
| Energy Density (Wh/kg) | Low |
| Environment | Unfriendly |

The capacity of a batter is given as [9, 10]

$$C_p = T_{dis} \cdot I_{dis}^K, \tag{1}$$

where $C_p$ represents a constant battery's capacity in ampere hour $[Ah]$, being discharged at a constant current $I_{dis}$, for a period of time $T_{dis}$ in hours. The variable $K$ represents the Peukert constant specific to the battery in use. The Peukert constant varies its value between 1 and 2, representing how well a battery performs under situations of discharge situations. Values close to 1 indicate low losses and good overall performance of the battery for a wide range of values for $I_{dis}$. Higher values for $K$ indicate that the battery is not suited for situations where $I_{dis}$ has a high value, due to high losses. For lead-acid batteries, $K$ has a a value ranging between 1.10 and 1.30 [9].

For smaller periods of constant discharge, the discharged capacity ($C_D$) is the integral of the discharged current:

$$C_{dis} = \int I_{Dis}^K(t)dt \tag{2}$$

With the remaining capacity ($C_R$) being given as the difference between the battery's capacity ($C_B$) and the discharged capacity.

$$C_R = C_B - C_{dis} \tag{3}$$

## 3. Implementation

The purpose of this study is to analyse the viability of the electric drive system originally installed in the bicycle through its power consumption, and understand what factors impact the performance of the system.

The forces equation for an electric bicycle is given as

$$m.a = F_{PH} + F_{PM} - \left(\frac{1}{2}\rho C_D A(v_B + v_W)^2 + C_r W\cos(\alpha) + W\sin(\alpha)\right) \tag{4}$$

For the left side terms, the total mass ($m$) varies as different riders tested the bicycle, while the acceleration is obtained with the aid of the GPS tracker. For the right side terms of the equation, with the exceptions of the rolling resistance coefficient ($C_r$), and the propulsive forces provided by both the motor ($F_{PM}$) and the rider ($F_{PH}$), all the other quantities are known [11] and listed on Table 3.

Table 3: Values for air density, drag coefficient, aerodynamic frontal area and bicycle mass considered in the tests.

| $\rho$ [kg/m] | $C_D$ | $A$ [m$^2$] | $v_W$ [m/s] |
|---|---|---|---|
| 1.20 | 1 | 0.45 | 0 |

For a system in linear movement, the power ($P_k$) associated to the work done by a force ($F_k$) is given as the multiplication of the force with the speed ($v_s$) at which the system is traversing.

$$P_k = F_k \cdot v_s \tag{5}$$

3.1. Signal Acquisition Hardware and Acquired Signals

The hardware can be decomposed in two parts: the Arduino board, which reads the electric current and voltage, and the GPS board, used to acquire data regarding position, time and speed.

The analogue pins are limited to 5 V of input. Because of this, an external electric circuit was needed to convert the 24 V provided by the battery to a lower voltage level. The circuit is also designed to provide data about the current drawn. The designed circuit is presented in Figure 3.

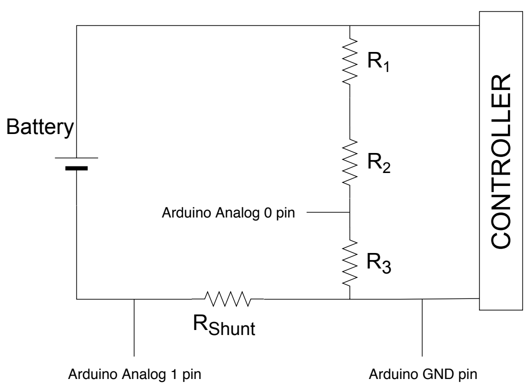



Figure 3: Electric circuit used to convert the voltage of the battery to a lower level.

In the circuit presented, pin analog 0 reads the voltage, pin analog 1 reads the current, and GND pin serves as both the ground and reference for the board. The voltage is acquired through the use of a voltage divider, with $R_1$, $R_2$ and $R_3$ having their values at 62, 27 and 18 k$\Omega$ , respectively. The current is read with the help of a shunt resistor ($R_{Shunt}$), valued at 0.1 $\Omega$. The fourth part are the digital pins which were not used in this thesis.

For both safety and simplicity, the sensors were installed between the battery and controller, as the connection between battery and controller represent a simpler circuit with a single phase, while the circuit between the controller and the motor is a three phase one. Therefore, the sensors were installed in the DC part of the system, reading the current and the voltage provided by the battery to the controller, allowing to compute the total electric power consumed. Figure 4 displays the connections between battery, sensors, controller and motor.

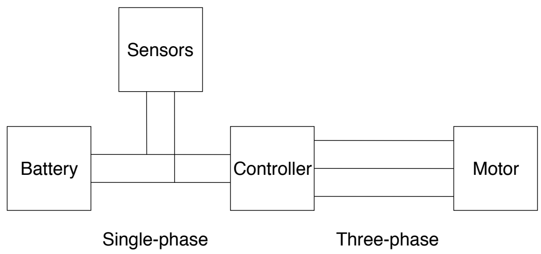



Figure 4: Connection schematic.

The GPS extension is directly installed on top of the Arduino board. The GPS board is the Adafruit Ultimate GPS equipped with a FGPMMOPA6H GPS module manufactured by GlobalTop Technology Inc.. The manufacturer specifies the module has a gain of -165dBm, and updates the GPS data at the frequency of 1 hertz. The board is equipped with a SD card slot, which is used to log the data. The GPS board acquires data for position, in the form of latitude, longitude and altitude, speed, and time.

3.2. Acquired Signals

The signals acquired are used for different purposes. The Arduino logs electric current and voltage, used to compute the electric power provided by the battery. The GPS signals are used for a wide range of purposes. The data regarding position (latitude, longitude and altitude) is used to track the position along the the test track, which is further used to map the test track, compute distances between points, estimate rolling resistance coefficient ($C_r$) and the road slope ($\alpha$). Speed and time are used calculate acceleration, which is further used to calculate forces and the moving power, and are also used to estimate $C_r$.

### 3.3. Estimation of Rolling Friction Coefficient

To estimate the bicycle needs to be on free movement, with no forces being applied. Since no propulsive force is applied, the sum of resistive forces in those segments is given as

$$m.a = -\left(\frac{1}{2}\rho C_D A(v_B)^2 + C_r W\cos(\alpha) + W\sin(\alpha)\right) \tag{6}$$

Manipulating equation (6), it is possible to estimate $C_r$ as

$$C_r = -\frac{m.a + \frac{1}{2}\rho C_D A(v_B)^2 + W\sin(\alpha)}{W\cos(\alpha)} \tag{7}$$

with the aid of the values acquired from the GPS to compute the acceleration.

Since the estimations are done over a significant period of time, the final estimations are done by calculating the mean values for the parameter.

Table 4 shows the final values estimated for the coefficient and the pressure values used for the tests.

Table 4: Estimated values for the rolling friction coefficient for the four given tyre pressure values.

| Pressure [bar] | 3 | 3.5 | 4 | 4.5 |
|---|---|---|---|---|
| $C_r \times 10^{-3}$ | 42 | 37 | 27 | 16 |

## 4. Results

The focus of this work is to compare the efficiency and energetic performance of the electric bicycle.

### 4.1. Electric Power Analysis

The first set consists in three laps around the test track, marked in Figure 5 and Table . One rider went around the track, while using different levels of assistance for each lap.

As shown, the first period of usage corresponds to the traverse of the uphill segment, and the first half of the no slope segment. This period of electric power consumption happens between the 3 seconds mark and the 84 seconds mark, as displayed in Figure 6b. Power does not exceed 200 W, and maintains itself between 110 W and 170 W for the greater part of this period.

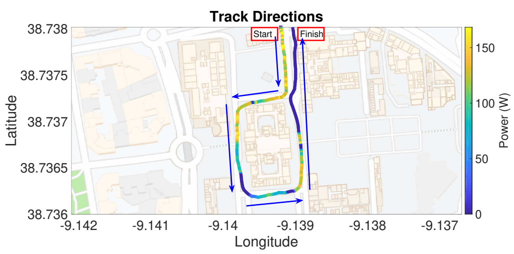
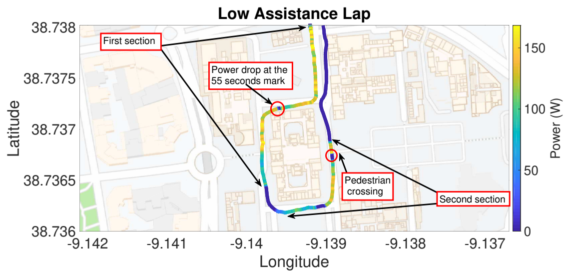
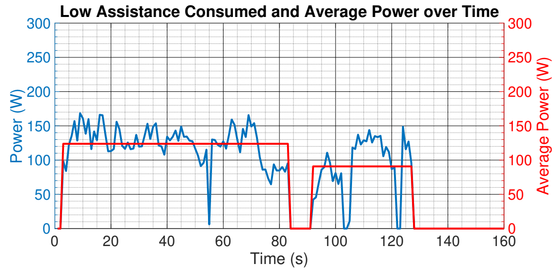



Figure 5: Example of a map indicating the direction and how the track is traversed.

The results for the low assistance are displayed in Figure 6.




(a) Power consumption throughout the track and points of interest.




(b) Electric power consumption over time.

Figure 6: Low assist lap results.

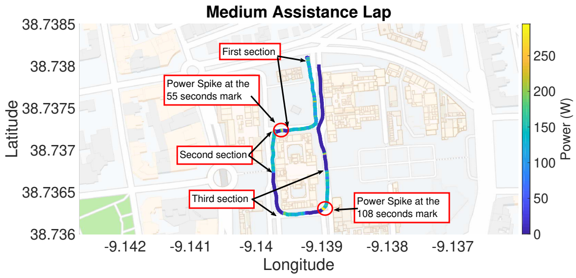
The second period is associated with the traverse of the second half of the track. The main segment happens between the 105 seconds and the 125 seconds marks, at the beginning of the last straight line of the track, with values between 90 W and 140 W. The main part is separated from two other minor sub periods, one before and one after, by two small moments of no consumption. The latter period has consumption values ranging between 90 W and 150 W, while the first one has values ranging between 80 W and 110 W.

Table 5 presents the mean value for consumed electric power for both periods of usage. The second part has a smaller mean value, due to the first subperiod having lower values when compared to the rest of the power levels expressed in Figure 6b.

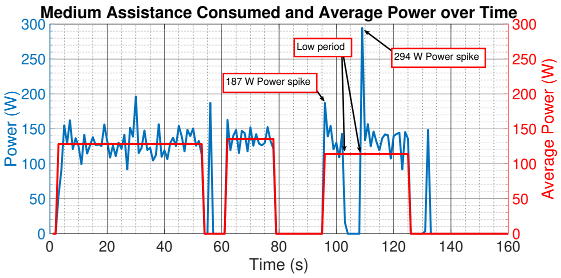
Table 5: Mean power level consumption for each section during the test with low assistance.

| Section | First | Second |
|---|---|---|
| Energy Spent [kJ] | 10.03 | 3.27 |
| Mean Power [W] | 124 | 91 |

The results acquired from the medium assistance test are displayed on Figure 7 and listed on Table 6. In this second lap, the consumption of power is more even throughout the entire lap, not having regions of continuous consumption at a lower or higher value than the mean value between 100 W and 150 W. However, it does have moments were it shows power spikes exceeding 150 W, specially in the later part of the track, when the electric drive system is turned on.




(a) Power consumption throughout the track and points of interest.




(b) Electric power consumption over time.

Figure 7: Medium assist lap results.

As verified in Figure 7b, the electric drive system has a first period of usage, which lasts for 55 seconds and coincides with the traverse through the uphill and the east to west straight line sections of the track. In between the first and second sections of electric power consumption, the rider stopped pedalling and began pedalling for a very brief moment, originating the time period between the 55 and 60 second marks with a power spike in it, as evidenced in 7b.

The electric drive system is triggered once again in the north to south straight line of the no slope part of the track. Here, it is verified that the system was turned on during the first half of the straight line (light blue section of Figure 7a) and the electric power consumption was even throughout its use, corresponding to the time period between the 60 and 80 seconds marks shown in Figure 7b.

The last section is composed by two sub-periods. Most of the values acquired are similar to the ones occurred in the first and second track sections. Despite this, one can also observe a power spike happening at the beginning of this section. This power spike happens at the 95 seconds mark and its value is measured at 187 W.

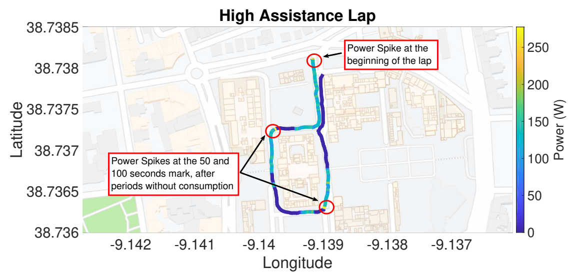
For the second sub-period, the acquired power is also similar to previous periods. However, as in the first sub-period, there is also a power spike at the start of this second sub-period, around the 108 seconds mark. This power spike is the biggest in this test having been measured at 294 W.

Between these two sub-periods exists a period of low to none consumption, due to the rider not pedalling as he approach to the final corner of the track.

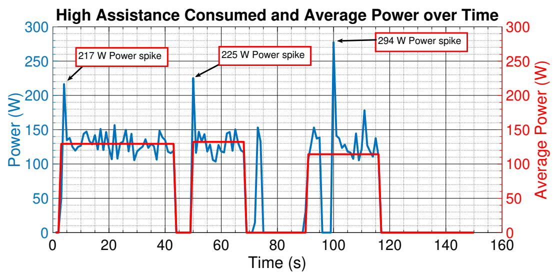
Table 6: Mean power level consumption for each section during the test with the medium level.

| Section | First | Second | Third |
|---|---|---|---|
| Energy Spent [kJ] | 6.54 | 2.31 | 3.43 |
| Mean Power [W] | 128 | 136 | 115 |

Lastly, Figure 8 and Table 7 show the results obtained for the high assistance test. The evolution for electric power consumption is similar to the one observed in the test with the medium level of assistance, having most of the values obtained within the range of 100 W and 150 W. This test does however differ from the previous one in the fact that more power spikes were recorded and appear to happen when the electric drive system is turned on.




(a) Power consumption throughout the track and points of interest.




(b) Electric power consumption over time.

Figure 8: High assist lap: a) electric power consumption throughout the track, b) electric power consumption over time (blue) and the mean power over the consumption time periods (red).

Like the test with medium assistance, the first section starts in the uphill part, and stops at the end of the first straight line, in the no slope segment. In this period, the electric power values are within 100 W and 150 W, with the exception of the power spike at the beginning with a value of 217 W, and a value acquired at the 22 seconds mark with its value being just slightly higher than 150 W, being read as 157 W.

The second section goes from the 50 to the 68 seconds mark. This section is similar to the first one by the fact that all the electric power values range within 100 W and 150 W, with the exception of the power spike as it was stated before. Within this section it is also observed a power spike at the beginning with its value being much higher than the mean value, measured at 225 W.

The final section of interest happens in a similar way as observed before in the other tests, having two sub-periods where the system is turned on, separated by a small period where it is once again turned off. In this section. The computed values for electric power float between the same values observed as in the first and second periods, with the exceptions of the power spike. The power spike in this period happens at the 100 seconds mark, being measured at 278 W.

Table 7: Mean power level consumption for each section during the test with high assistance level.

| Section | First | Second | Third |
|---|---|---|---|
| Energy Spent [kJ] | 5.31 | 2.51 | 3.00 |
| Mean Power [W] | 129 | 132 | 114 |

When comparing all three tests, it is verified that the medium and high assistance levels show similar results, having their electric power divided in three distinct periods with similar mean values values. The lowest assistance seems to work in a more reserved manner. In the later part of the circuit, the lowest assistance presents the lowest average, while also not having power spikes. For the uphill part of the track, all three assistance levels perform similarly in that specific situation.

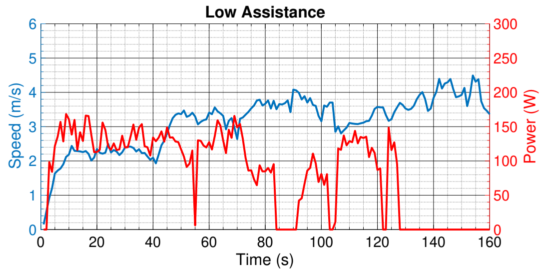
Despite the medium and high levels having similar behaviour and values, it is also observed that the high level assistance test finishes around 10 seconds earlier than the medium level test. A few reasons can be consider for this to happen, the first one is related to the existence of power spikes and how they could apply a stronger acceleration. This situation does not seem plausible as in the medium test there are also power spikes but the duration of this test and the low level test have the same duration of 160 seconds. For this reason, the most plausible motives for the high level test having a smaller duration of 150 seconds are associated with favourable track conditions, and a more familiarity of the system and track by the rider.

Table 8 lists the elapsed time on each lap, the total energy spent, and the mean power, for the data acquired and for the mean value approach. The last row presents the difference between the acquired data and the mean values.

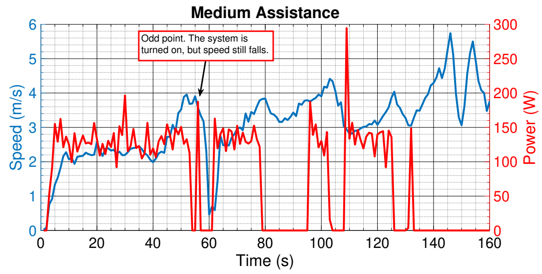
4.2. Speed and Electric Power Correlation

It is important to understand what kind of impact the electric drive system has on the system. In order to do so, it is intended to see what kind of effect and correlation exist between the electric power consumption and the bicycle's speed.

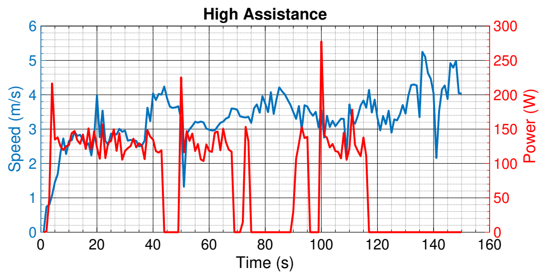
Figure 9 displays both electric power and speed acquired during the three tests.




(a) Low assistance values for speed and electric power.




(b) Medium assistance values for speed and electric power.




(c) High assistance values for speed and electric power.

Figure 9: Speed (blue) and consumed power (red) throughout the three laps.

In all three graphics presented, similar actions occur in the first part of the track. Speed rises steadily in the first seconds, stabilizing its value for the rest of the uphill part. The differences between the three levels come in the mean values computed for the mean acceleration, which seem to increase with the increase of assistance level. Since the mean acceleration gets higher for each assistance, it also means the energy and power spent in this section are higher.

After the first period, once the bicycle reaches the end of the hill it is observed that speed once again increases in all three tests. However, as discussed in section 4.1, the low level test presents a consump-

Table 8: Electric energy spent on each lap, in kilojoules, and the absolute difference between the raw acquired data and the mean value approach.

| Assistance Level | Low | Medium | High |
|---|---|---|---|
| Elapsed Time [s] | 160 | 160 | 150 |
| Energy Spent - Acquired Data [kJ] | 13.3 | 12.6 | 11.1 |
| Mean Power - Acquired Data [W] | 83.1 | 78.9 | 74.1 |
| Energy Spent - Computed Values [kJ] | 13.3 | 12.3 | 10.8 |
| Mean Power - Computed Values [W] | 83.1 | 76.8 | 71.9 |
| Difference [%] | - | 2.7 | 3 |

tion profile that differs significantly from the other two levels, which will impact speed. This helps understanding why speed also behaves similarly in the medium and high levels, but behaves differently in the lower level.

In the medium and higher levels, after the acceleration, one verifies speed stabilizes its value once again. However, as soon power stops being consumed its value drops abruptly in both cases, only to rise up steadily again when the electric drive system is turned on for a second time.

In contrast, the low level does not present an instant where speed drops, stabilizing its value for a longer period of time. It is also worth mentioning that power never stops being consumed, which means the rider does not stop pedalling, aiding in maintaining the bicycle's speed.

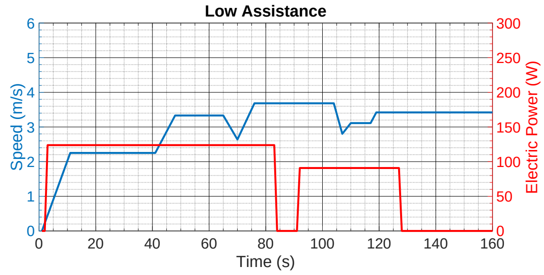
Lastly, in the later part of the track, speed and power behave homogeneously in all three levels, since whenever the electric system is turned on, speed either maintains or raises its value.

As shown, throughout all the moments were the electric drive system is turned on, speed maintains or raises its value, which means there is no deceleration.

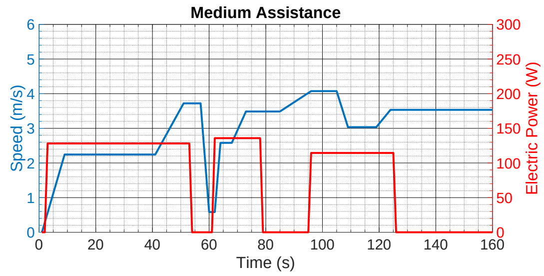
In Figure 10 is shown the mean value for both speed and power throughout the track for the three laps. This approach is the one considered for the rest of the test and simulations ahead. Naturally, there are differences in value for speed around the track. Table 10 lists the mean absolute error between the acquired data and the mean values approach. The mean absolute error is less than 10 %.

Table 10: Mean absolute error for the mean value approach of speed, for each assistance level.

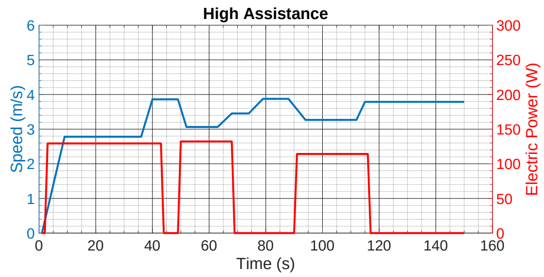
| Assistance Level | Low | Medium | High |
|---|---|---|---|
| Absolute Error [%] | 6.7 | 8.4 | 8.5 |




(a) Low assistance mean values for speed and electric power.




(b) Medium assistance mean values for speed and electric power.




(c) High assistance mean values for speed and electric power.

Figure 10: Mean values for speed (blue) and consumed electric power (red) throughout the three laps.

4.3. Battery Capacity, Output and Useful Power

In every battery, the output is dependant of the remaining capacity, and the lesser the capacity, the lesser is the output. Two batteries were used for this part. The first battery was discharged to less than 50 % of its capacity, while the second one was fully charged. Three parts of the track were used to compare the results. The uphill part, the first part of the upper part of the track with no slope (zone

A), and the final part of the track with no slope (zone B). Figure 11 shows the three zones considered.

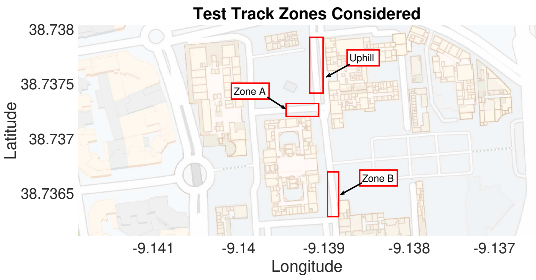



Figure 11: Zones of the track considered.

The mean power discharged for these situations is presented in Table 11.

For both charged and below 50 % tests, the uphill part of the track is the one where higher discharged power values are presented, and the last part is where discharged power presents the lower values. The difference between each test comes in the discrepancy between these two situations, where a lower charge level leads to a lesser discrepancy. For the middle test with charge below 75 %, the region where a higher discharge happens is not on the uphill part, but after it, during the first part of the no slope region of the track(zone A). Despite this, in all assists both regions show very similar values, even having the same value for the lowest assist. The last part of the track remains the one with the lowest values for the discharged power. Lastly, as the capacity of the battery fades, the discharged power between assist levels tends to equalize, which in turn makes the usage of difference assist levels becomes meaningless at lower capacity levels.

The difference in output could provide a higher speed achieved by the bicycle under similar track situations. In Table 12 is listed the mean speed achieved, and the needed mechanical power to move at said speed.

In a preliminary analysis, a higher discharged electric power does not necessarily imply a higher speed achieved, as the speed achieved in the test with the least power discharge by the battery presents values for speed greater than the ones obtained with the discharge power at a charge below 75 %. It is also shown that the charged battery provided enough output to impact the speed achieve, having this test achieved the greater values of all three.

When also taking into consideration the results obtained for power, from all three scenarios, the worst one is the middle one with the charge below 75 %, as it displays the lowest values for speeds with considerable values for discharged electric power. In contrast, the best scenario is the charged scenario, as power seems to influence the greater speeds achieved. In order to estimate what portion of the electric power is useful, a comparison was made between the best and worst scenario, in both the no slope parts of the track. The lower charge test was disregarded, mainly due to speed being similar, and sometimes higher, than the one achieved in the 75 % test. Additionally, the power discharged in the lower charge test is close in value to the needed mechanical power.

The uphill results display similar speed achieved throughout all the charge levels and assists. This fact can imply that the overall output provided by the electric system is fairly low, leading to low efficiency. The results also lead to considering the functioning of this kind of vehicles does not provide an equally distributed work load between the motor and person. Table 13 displays the results for all the tests conducted in this section, regarding the percentage of the needed mechanical power that is provided by the electric system, and what percentage of the discharged electric power is used. Considering that most power is provided by the person, the results selected for the simulation are the ones corresponding to a workload distribution of 60-40 %, 70-30 %, 80-20 % and 90-10 % between human and motor. The results show that less than 10 % or the original power drawn by the battery is used to aid the rider.

## 4.4. Battery Evaluation and Number of Trips

The evaluation of the battery is done under the simulation of four hypothetical situations. The first three emphasise on the use of a singular assist level throughout the entire use of the battery. The forth test combines the use of different assist levels, taking into consideration the remaining capacity of the battery. The high assistance is used if the battery is above 75 %, the medium assistance is used if the battery is below 75 %, and the low assistance is used if the battery is below 50 %.

For these tests, the remaining capacity is calculated in a recursive way:

$$C_K = C_{K-1} - C_{dis}, \tag{8}$$

where $C_K$ is the battery's capacity at iteration K, $C_{K-1}$ is the battery's capacity in the previous iteration, and $C_{dis}$ is the discharged capacity, calculated as seen in (2).

It is considered the battery is fully charged at the beginning of each simulation, the battery is fully discharged at the end, and a lap corresponds to an iteration. The results for the simulations are listed in Table 14.

The results show that increasing the Peukert constant (K) leads to less available trips. For every value of K, the results show the low level assistance

Table 11: Discharged power by the battery in three situations on the track. In each charge situation, each row represents an assist level, with the first one being the lowest setting, the second one being the medium setting and the third one being the highest setting. All the values are measured in watt.

| Battery | Assistance | Output Power [W] | | |
|---|---|---|---|---|
| | | Uphill | No Slope (Zone A) | No Slope (Zone B) |
| Charged | Low | 257 | 110 | 74 |
| | Medium | 308 | 198 | 255 |
| | High | 309 | 300 | 257 |
| Below 75 % | Low | 124 | 124 | 91 |
| | Medium | 128 | 136 | 115 |
| | High | 129 | 132 | 114 |
| Below 50 % | Low | 78 | 22 | 76 |
| | Medium | 70 | 70 | 62 |
| | High | 62 | 62 | 56 |

Table 12: Speed and needed mechanical power, for each track part, charge level and assistance. For each battery, the first row represents the lowest assist level, the second row represents the medium assist level, and the third row represents the high assist level.

| Battery | Uphill | | Zone A | | Zone B | |
|---|---|---|---|---|---|---|
| | Speed [m/s] | Power [W] | Speed [m/s] | Power [W] | Speed [m/s] | Power [W] |
| Charged | 2.73 | 199.64 | 3.64 | 22.65 | 4.16 | 30.49 |
| | 3.31 | 244.73 | 4.87 | 44.08 | 4.96 | 46.00 |
| | 3.16 | 233.40 | 4.67 | 39.85 | 5.50 | 59.46 |
| Below 75 % | 2.25 | 162.99 | 3.33 | 18.79 | 3.11 | 16.36 |
| | 2.24 | 162.23 | 3.72 | 23.75 | 3.02 | 15.43 |
| | 2.78 | 203.38 | 3.86 | 25.75 | 3.27 | 18.10 |
| Below 50 % | 2.76 | 201.77 | 3.75 | 24.18 | 3.33 | 18.74 |
| | 3.00 | 220.34 | 4.06 | 28.85 | 3.67 | 23.27 |
| | 2.86 | 209.64 | 3.75 | 24.11 | 2.87 | 13.95 |

Table 13: Percentage of electric power aiding the bicycle's movement, taking into consideration the motor workload, the battery charge, the assistance level and the track zones considered.

| Battery Capacity | Motor Workload [%] | Low | | Medium | | High | |
|---|---|---|---|---|---|---|---|
| | | Zone A | Zone B | Zone A | Zone B | Zone A | Zone B |
| Charged | 40 | 8.24 % | 16.48 % | 8.91 % | 7.22 % | 5.31 % | 9.25 % |
| | 30 | 6.18 % | 12.36 % | 6.68 % | 5.41 % | 3.98 % | 6.94 % |
| | 20 | 4.12 % | 8.24 % | 4.45 % | 3.61 % | 2.66 % | 4.63 % |
| | 10 | 2.06 % | 4.12 % | 2.22 % | 1.80 % | 1.33 % | 2.33 % |
| Below 75 % | 40 | 6.06 % | 7.19 % | 6.99 % | 5.37 % | 7.80 % | 6.35 % |
| | 30 | 4.55 % | 5.39 % | 5.24 % | 4.03 % | 5.85 % | 4.76 % |
| | 20 | 3.03 % | 3.60 % | 3.49 % | 2.68 % | 3.90 % | 3.18 % |
| | 10 | 1.52 % | 1.80 % | 1.75 % | 1.34 % | 1.95 % | 1.59 % |

leads to more trips, the medium and high assistance have similar values, lower than the low assistance level, and the combination test has its number of trips between the low assistance and the other two levels. Incrementing the assistance level lessens the number of trips at the charged and below 50 % capacity. However, the number of trips for each assistance levels seems to increase when the capacity is below 75 %.

The results show this behaviour due to the amount of time where the electric drive system is used decreases, with the increase of assistance. If the amount of time was similar for all assistance, then the number of trips would not increase.

Considering a person uses this kind of bicycle for 2 daily trips, a month has 20 working days, leading to 40 monthly trips, and also considering said person uses the medium or high level, the average

Table 14: Test results assuming constant DC current discharge from the battery.

| Peukert Constant | Test | Charged | Below 75 % | Below 50% | Number of Trips |
|---|---|---|---|---|---|
| 1.1 | High Level | 8 | 16 | 43 | 67 |
| | Medium Level | 9 | 14 | 44 | 67 |
| | Low Level | 14 | 13 | 65 | 92 |
| | Combination | 8 | 13 | 66 | 87 |
| 1.2 | High Level | 6 | 14 | 39 | 59 |
| | Medium Level | 8 | 11 | 38 | 57 |
| | Low Level | 12 | 11 | 57 | 80 |
| | Combination | 6 | 12 | 57 | 75 |
| 1.3 | High Level | 5 | 11 | 34 | 50 |
| | Medium Level | 6 | 10 | 33 | 49 |
| | Low Level | 10 | 9 | 50 | 69 |
| | Combination | 5 | 9 | 51 | 65 |

Table 15: Number of total trips and yearly cost of using the battery in a single assistance level, and combining the three.

| Simulation | High | Medium | Low | Combination |
|---|---|---|---|---|
| Number of trips | 58 | 58 | 80 | 75 |
| Yearly Charges | 8 | 8 | 6 | 6.4 |
| Battery Energy [kWh] | 0.24 | | | |
| Energy Price [€ /kWh] | 0.16 | | | |
| Yearly Cost [€] | 0.31 | 0.31 | 0.23 | 0.25 |

Table 16: Number of total trips and yearly cost of using the battery, assuming the battery is charged once it dips below 50 % of remaining capacity.

| Simulation | High | Medium | Low | Combination |
|---|---|---|---|---|
| Number of trips | 10 | 10 | 12 | 9 |
| Yearly Charges | 48 | 48 | 40 | 53 |
| Battery Energy [kWh] | 0.24 | | | |
| Energy Price [€ /kWh] | 0.16 | | | |
| Yearly Cost [€] | 1.84 | 1.84 | 1.54 | 2.04 |

number of trips is 58 trips. This means the battery needs to be recharged every month and a half, which leads to 8 charges throughout an entire year. Using the same conditions to the low assistance level, the average number of trips is 80 trips, resulting in a charge every 2 months, leading to 6 charges in an entire year. Lastly, the combination of all three assistance levels leads to an average number of trips of 75 trips, very similar to the low level, which leads to a total number of 6.4 charges per year. No battery ageing effect is considered.

The nominal energy available in the battery is given as

$$E_{Bat} = V_N \cdot C_N = 240 \text{ Wh}, \tag{9}$$

where $V_N$ is the nominal voltage of battery, and $C_N$ is the nominal capacity of the battery. The nominal values of the battery are listed in Table 1. Considering the price of energy at 0.16 € per kWh, the total cost of charging the battery throughout an entire year for the four simulation is listed in Table 15.

The results show the yearly price for charging the battery is less than 35 cents per year, for a person who uses the bicycle 40 times per month, draining the entire battery.

As seen in Chapter 4.3, less than 10 % of the output power is used to aid the bicycle's movement. Considering this, it is fair to assume once the battery is going to be charged once the battery's capacity dips below 50 %. With this assumptions, the average number of lessens to 10 trips for the high/medium level, 12 for the low level, and 9 for the combination of two levels based on the remaining capacity. Consequently, this leads to 4 charges per month, resulting in 48 charges per year, at the high and medium level, 40 yearly charges for the low level, and 53 charges for the combination. The cost of charging the batteries in these conditions is listed in Table 16.

The price increase is significant, increasing 4.9 times for the high and medium assistance, 5.7 times for the low assistance, and 7.16 times for a combination of both high and medium assistances, based on the remaining capacity.

## 5. Conclusions

The purpose of this work is to study the electric drive system's components, and their influence and impact on the motion of the bicycle, and deliberate if the system is viable for city wide mobility.

As seen in (5), the higher the speed at which the bicycle moves, the higher the necessary mechanical power to move. However, the percentage of consumed electrical power that can be used in aiding the motion is less than 10 %, and lower capacity levels lead to a lesser percentage of usable electric power, which ultimately leads to a meaningless assistance at high speed, and low battery capacities.

Electric components are known for having high power efficiency, therefore, the loss in power comes in the transmission of power between the electric motor and the back wheel axis.

For city wide mobility, this model of electric assisted bicycles is not a suitable alternative to conventional transportation methods, such as public transportations (bus, subway, among others), for cities were the terrain has several uphill zones. It does however provide an alternative to the regular bicycle, as the price of charging the batteries over a year is meaningless, and the price ranges between 500 € to 1200 € for an after market bicycle, and it can be as low as 1000 € for a brand new one in official retailers. There are also services who provide electric bicycles at the cost of a subscription that could be more beneficial for the consumer.

This study focused on the overall system as a whole. As such, it would be interesting to study each component of the electric system individually, in order to develop an equivalent model for each part, consolidating them together in a complete model of the electric drive system of the bicycle. The battery could be the first component to be studied in a deeper way, estimating its charge through the use of dedicated sensors, allowing for estimations regarding the state of charge of the battery, based on the voltage and current drawn from it. Since no information is given regarding the controller, the development of a new controller should also be considered.

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