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Design and use of an energy measurement module for speed pedelecs

Kiran Peirens[1], Nikolaas Van den Steen[1], Bert Herteleer[1], Jan Cappelle[1]

[1]*KU Leuven Technologycampus Ghent, Gebroeders De Smetstraat1, 9000 Ghent, Belgium, kiran.peirens@kuleuven.be*

Summary

The speed pedelec is an electric pedal assisted cycle (EPAC) that forms an interesting alternative for short range transportation methods. In contrast to pedelecs whose motor power is limited to 250 W, the speed pedelec comes with the advantage of higher speed limit (45 km/h) and motor power (up to 4 kW). However, the power consumption of speed pedelecs (and most EPACs) is often unknown, and with it, the potential travel range. To address these uncertainties, a standalone, accurate power monitoring device for speed pedelecs is designed and tested. The measurement module permits data to be captured enabling the investigation of research questions, such as the ratio of human input power versus motor assistance, or total power consumption by the (speed) pedelec motor.

Keywords: bicycle*,* HEV (hybrid electric vehicle), data acquisition, energy consumption, vehicle performance

1 Introduction

Electrically Pedal Assisted Cycles (EPACs), in particular speed pedelecs (i.e. 4 kW maximum motor power and 45 km/h speed limit), are growing in popularity, and have a fraction of the CO_2 footprint of cars (electrical vehicles or internal combustion vehicles) per km travelled [1]. Speed pedelecs have increased in popularity in Belgium, with annual new vehicle registrations changing from 5800 in 2017, to more than 14000 in 2019 and 2020 [2]. Despite this increased popularity, the energy consumption of speed pedelecs is poorly known.

By contrast, the energy consumption of ordinary pedelecs (max. 250 W and 25 km/h) has been studied [3]–[8]. Capturing the power consumption of speed pedelecs can serve to answer questions by policymakers regarding the use of speed pedelecs on the road, and can be used to validate manufacturer claims regarding travel range. This paper presents the development of a stand-alone measurement module, as well as its practical implementation on a speed pedelec, with the end result being dynamic measurements of energy output linked to rider input during realistic trips. This then permits the accurate estimation of the power-assisted cycling range as a function of the vehicle type, level of motor assistance, or route selection.

2 Methodology

Since the purpose of the stand-alone measurement module is to determine the realistic power consumption of a speed pedelec, there are a number of key factors that need to be measured. These key factors are derived from the intended functionalities of the measurement module by means of a block diagram presented in Figure 1.

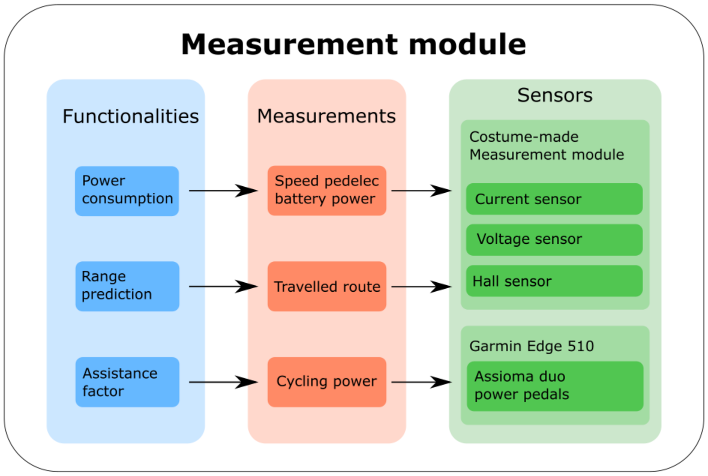


Figure 1: block diagram showing the intended functionalities of the measurement module and the quantities to be measured

As illustrated in Figure 1, there are several functionalities of the measurement module that need to be taken into account. First, there is the power consumption for which the battery power needs to be monitored. Second, there are other functionalities such as the assistance factor and the range prediction, that need monitoring. For both, battery power, speed, cycling power and the travelled route need to be registered. To measure these variables, two strategies are used. At the start, a custom-made measurement module is designed for recording the battery power as well as the rotations per minute of the wheel using a hall sensor. By contrast, GPS and pedal power measurements are done using a Garmin Edge 510 [9] and Assioma Duo pedal meters [10], which share data via Garmin Connect. A schematic of the measurements captured with a speed pedelec (Moustache with Bosch 2nd generation speed pedelec motor, $P_{continuous}$ 250 W [11]) is given in Figure 2.

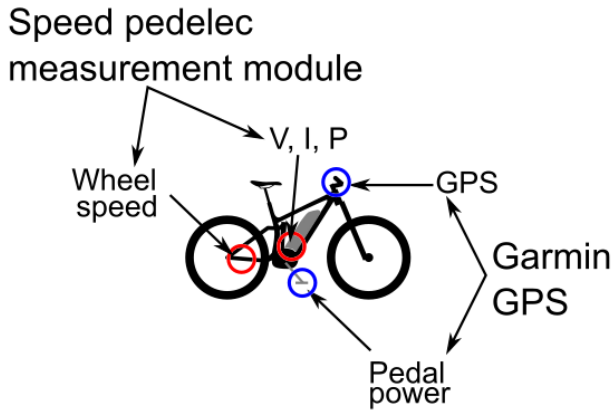
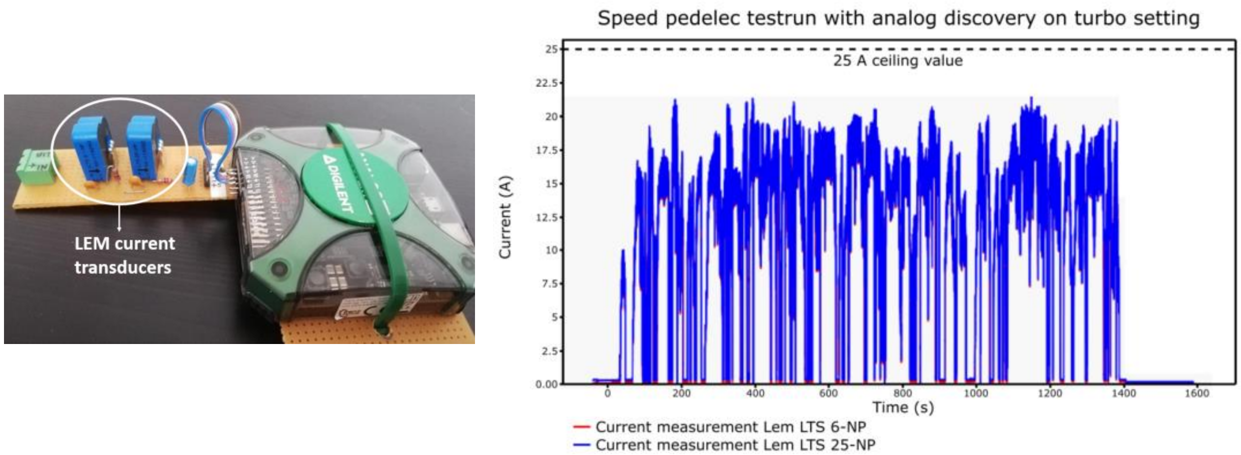


Figure 2: Schematic of the speed pedelec measurement module and auxiliary measurements using a Garmin Edge 510 and the Assioma duo power meter.

As a result all the necessary variables can be measured during realistic rides to provide the intended functionalities.

2.1 Development of the power measurement module

The developed speed pedelec power measurement module is built around an Arduino Uno [12] which measures the battery voltage and current with a customized voltage and current sensor. While the battery voltage level was known in advance (36 V nominal) for the 500 Wh battery of the selected speed pedelec, the motor current was unknown. As such, before developing the measurement module, the current range had to be defined. To determine the current range, 2 LEM current transducers [13], [14] connected to an Analog discovery 2 [15] were used. With this measurement unit several trips in a variety of conditions were undertaken and examined. As a result of these measurements, a ceiling value of 25 A for the current range was defined, as illustrated in Figure 3.



(a) (b)

Figure 3: (a) the LEM current transducers connected with the analog discovery 2, (b) illustration of the 25 A ceiling value on a current measurement with the analog discovery.

Once the current measurement range is known, the stand alone speed pedelec measurement module can be developed which is shown in Figure 4. As discussed earlier, this measurement module must register the battery voltage, battery current and cycling speed in function of the time. Measuring the voltage is done with a voltage divider coupled to an external 16-bit analog-to-digital converter (ADC), the ADS1115 [16]. This ADC is also coupled to 2 LEM current transducers with different ranges, being 0-6 A and 0-25 A nominal, both with 320% over-range capabilities. Although the previous measurement allowed the use of a specific current sensor for this measurement unit, the use of the 2 current transducers with a different nominal value benefits the overall accuracy of the developed measurement module.

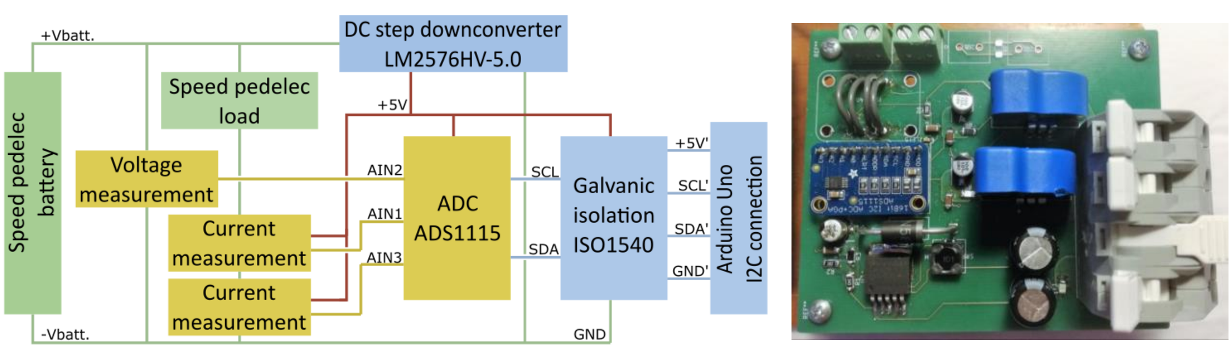


Figure 4: schematic and printed circuit board of the used speed pedelec power consumption measurement

The speed pedelec measurement module further captures the cycling speed using the SSE49 linear hall effect sensor [17]. Finally, an Adafruit SD card data logging shield [18] and Adafruit Powerboost 500 rechargeable battery shield [19] with the 103456A-1S-3M li-ion battery [20] are added to allow stand-alone operation. The system is capable of measuring approximately 10 hours of trip data between charges, capturing all data at 1 Hz.

3 Measurements

The power consumption of speed pedelecs is difficult to assess without specifying boundary conditions. Using the average battery power or the difference in battery state of charge is logical, but that depends, among others, on the used assistance mode, the cyclist as well as the environment. To identify, and potentially compare the power consumption of speed pedelecs, an objective measurement strategy must be used. The measurement strategy is based on [21] in which the assistance speed between different speed pedelecs was compared. Thus, an assistance battery power P_{bn} (with n the assistance level) for each assistance level was defined as follows: the power delivered by the speed pedelec battery while the cyclist delivers 100 W ± 10% at a cadence of 80 rpm ± 5%. Note the difference in the power margin from [21]. This study uses a 10% margin is instead of a 5%. This is done as a practical testing showed that the 5% margin was difficult to maintain. In the following section two test rides will be discussed. The first test ride examines the assistance battery power using the discussed power margin. A second test ride is performed without any constraints. This is done to investigate the natural power consumption of the examined speed pedelec.

The first test was performed on a straight cycle path between two stoplights at the maximum motor support setting, on a flat road without obstacles, as shown in Figure 5. The onward trip (direction SW) had tailwind, whereas the return trip (direction NE) had headwind: in both cases, wind was ~7 km/h from NE (60°). The data from the Garmin Edge 510 (TCX file obtained from Garmin Connect) and the speed pedelec measurement module (CSV) were read and synchronised in python, by aligning data according to the speed profiles (ramp up and ramp down).

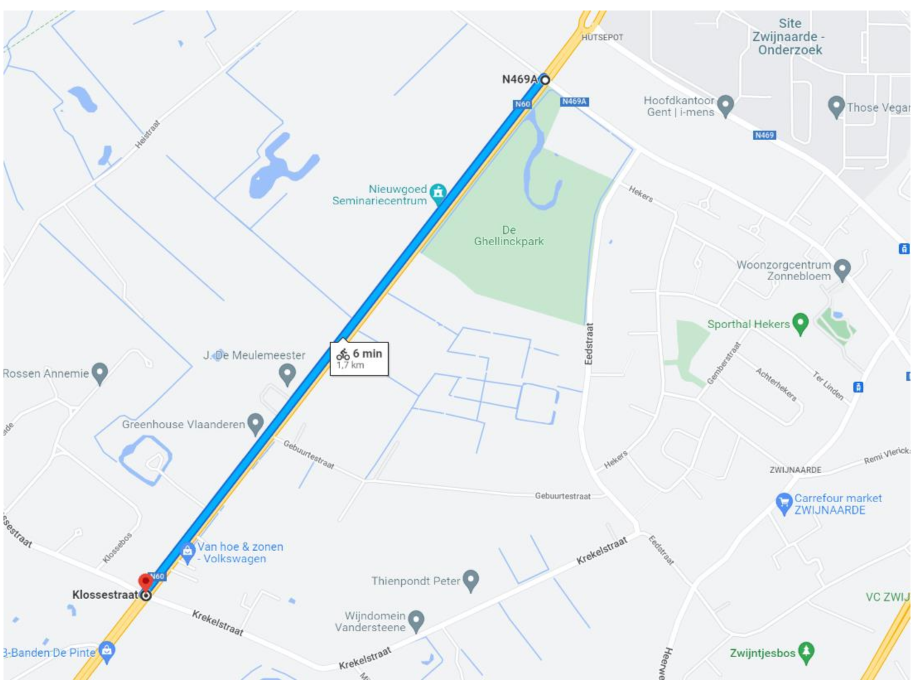


Figure 5: Start and end points for onward and return trips for pedal-motor power testing

Figure 6 shows the filtered speed, cyclist power, and battery power during a ride using the previously discussed power margin of 100 W (±10%) and 80 RPM (±5%) with the speed pedelec at its maximum motor support setting. As can be seen in Figure 6, an average speed difference of 4.4 km/h (38 km/h with tailwind, 33.6 km/h with headwind) resulted, when the cyclist aims for 100 W (±10%) and 80 RPM (±5%) on the pedals, excluding the nonconforming data points. The return trip saw more data points excluded, primarily because the headwind made it more challenging to remain in the 100 W ± 10% tolerance band. For speed pedelec characterisation in the field, this suggests that either the power tolerance band has to be widened, or that longer or more tests need to be performed.

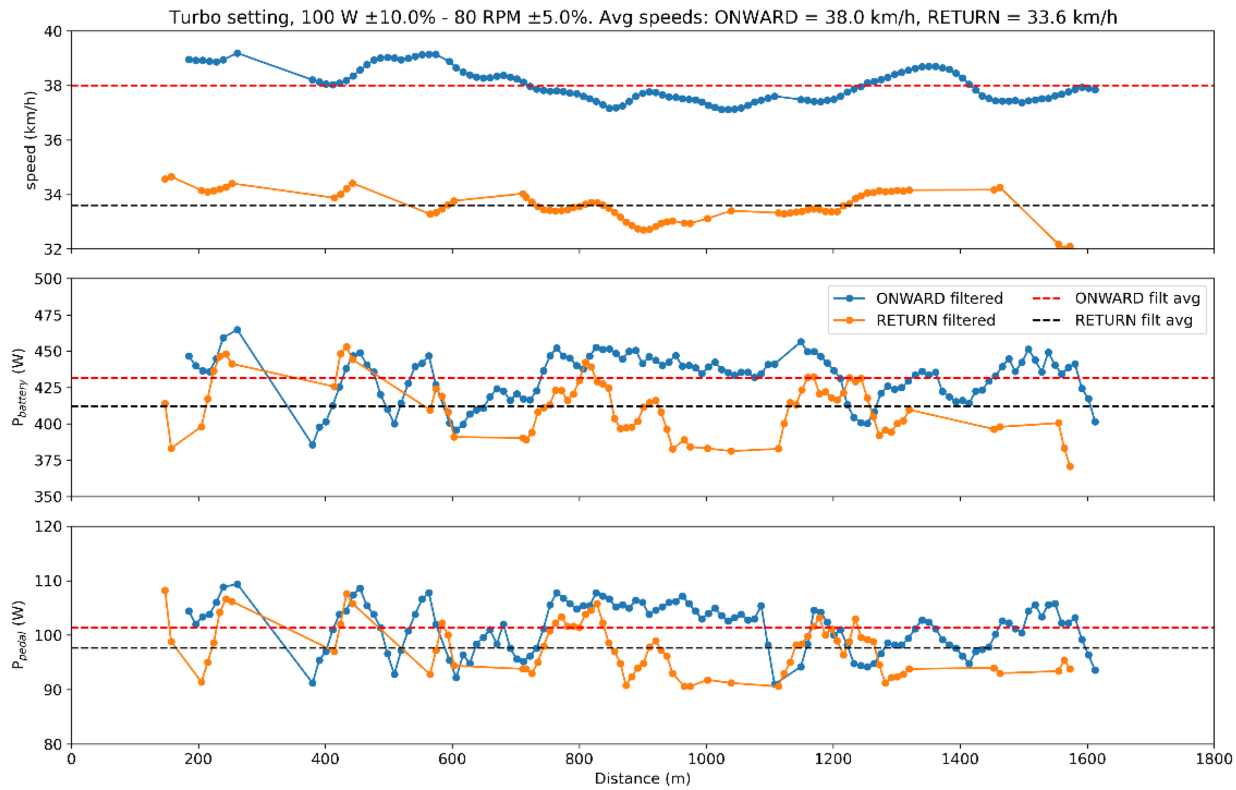


Figure 6: Filtered datapoints for a return testing trip. Note the large impact of the wind speed and direction on the achieved cyclist speed, while power (pedal and motor) values are similar.

Figure 7 shows the speed and power profiles for a trip between Ghent and Dendermonde, again with the speed pedelec at its maximum motor support setting. During this test ride, the speed pedelec user was unable to reach the maximum speed for the first 15-20 minutes, as the route encounters traffic and red lights. Once the cyclist leaves the city centre, the frequency of stops declines and the achieved cruising and average speeds increase. As such, the largest time gains for speed pedelec users for commuting can be obtained when longer, obstacle-free road segments are encountered, which are typically outside of city centres. As can be observed, the rider provided 159 Wh of mechanical energy, with the battery providing 393 Wh of energy to the motor. While the motor power-efficiency characteristic of this speed pedelec is unknown by the researchers, an average electric-to-mechanical efficiency value of 82% is assumed for speed pedelec BLDC motors. As such, the motor provides 322 Wh of mechanical energy, or 202% of the cyclist input energy. Contrasting Figure 6 with Figure 7, it is evident that the cyclist must push significantly above the "comfortable" 100 W expectation to reach speeds above 40 km/h with this speed pedelec, and that this vehicle shows a strong susceptibility to wind.

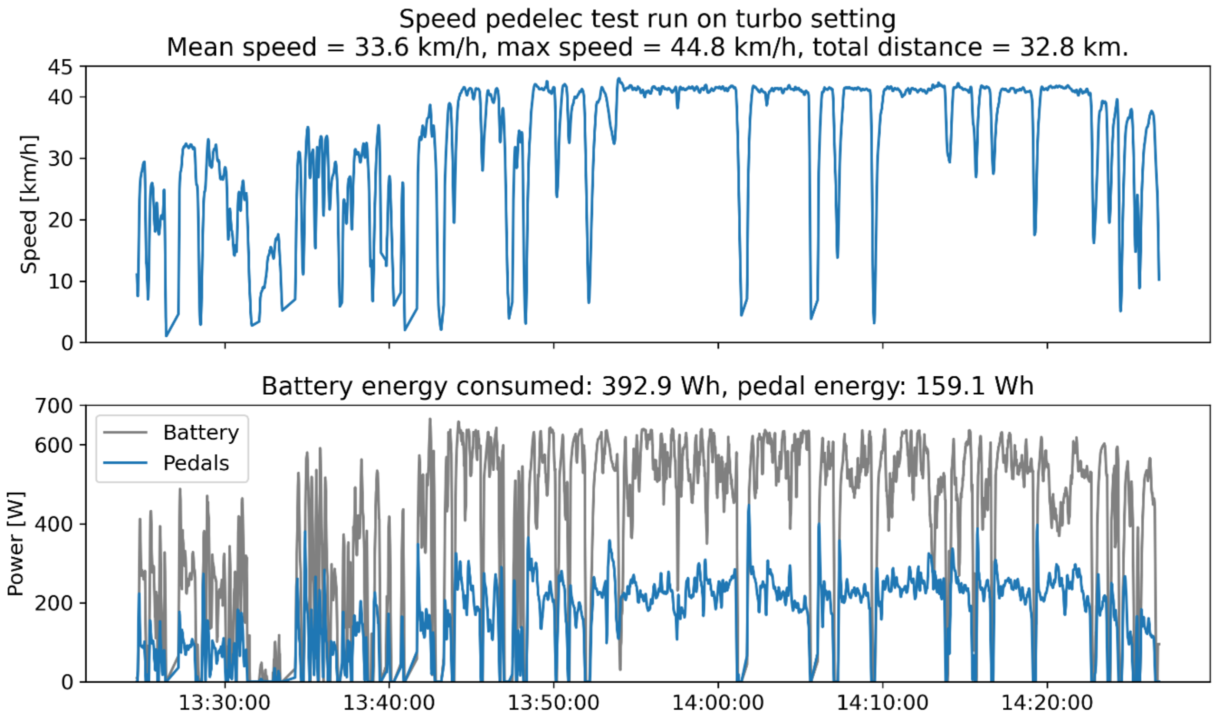


Figure 7: Speed and battery power measurement of the second test ride, using the Garmin Edge 510 and the developed measurement module

4 Conclusions

The measurement module for speed pedelecs and EPACs presented in this work is built around an Arduino Uno and permits data to be measured to evaluate the power consumption of speed pedelecs, as well as determining effective motor assistance levels. As illustrated in this paper, the dynamic energy consumption by the motor and pedals can be captured, allowing research into motor controller behaviour and speed-assistance profiles. With the designs measurement module, who captures data at a frequency of 1 Hz, tests were undertaken and analysed. As a result a dependency between the tested speed pedelec speed and the wind speed at a cycling speed of 100 W ± 10% and a cadence of 80 rpm ± 5% was found. Further, it was determined that although the test speed pedelec can reach speeds above 40 km/h, this cannot be done without pedalling above the 100 W.

The developed measurement module can additionally be optimized. For instance, a GPS and BLE module can be added to the module to allow all data to be captured with one measurement module. This offers the advantage that the data is measured in a more synchronized manner and thus does not need to be synchronized further down the line based on the measured speed.

Towards the future, several tests will be undertaken and several speed pedelecs tested. In this way, the power consumption of speed pedelecs from various manufacturers will be determined. This, among others, will aid policymakers in better understanding and regulating the use of speed pedelecs.

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Authors

Kiran Peirens graduated in 2021 of a Master of Energy Engineering Technology Master of Science (MSc) Specialization Electrical Engineering at the KU Leuven Technologycampus Ghent and is since 2021 a joint researcher associate (KU Leuven & Odisee) under the supervision of Jan Cappelle (KUL) and Ben Minnaert (Odisee). His field of expertise are speed pedelecs and resonant inductive wireless power transfer.