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Design and use of a modular measurement module for speed pedelecs

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Executive Summary

The speed pedelec is rapidly rising in popularity within Europe as a short and medium range transportation method. This fast electric bicycle is fitted with a motor of up to 4 kW and has a maximum motor assisted speed of 45 km/h. The influence of several environmental factors on the usage pattern, power consumption and consequently on the travel range is still unclear. To address these uncertainties, a modular stand-alone measurement module has been developed. This module monitors the power consumption, location and environmental factors during test rides, enabling the opportunity to unravel the key factors that characterise speed pedelec use.

Keywords: bicycle, data acquisition, electronic, environment, user behaviour.

1 Introduction

Speed pedelecs are electrical pedal-assisted bicycles (EPACs), with a maximum motor power of up to 4 kW and maximum motor-assisted speed of 45 km/h. These light electrical vehicles (LEVs) form an interesting alternative for short to medium range transportation methods. Speed pedelecs are not only beneficial for bypassing traffic jams [1], but also have a fraction of the CO_2 footprint of cars (both electrical vehicles and internal combustion vehicles) per km travelled [2], [3].

Due to these advantages, speed pedelecs have experienced a rapid growth in popularity. In Belgium, the annual new vehicle registrations for speed pedelecs evolved from 5800 in 2017, to more than 16,000 in 2021 [4], [5]. Despite this popularity, there is hardly any data available how these vehicles behave on the Belgian roads [6]. However, having insights in that behavior is crucial for the users, manufacturers and policymakers. Capturing data of speed pedelecs can serve to identify important power-consuming factors in the interest of the travel range, and can be used to validate the corresponding manufacturer claims. Furthermore, the captured data can serve policymakers in answering fundamental questions regarding the use and potential risks of speed pedelecs on the road.

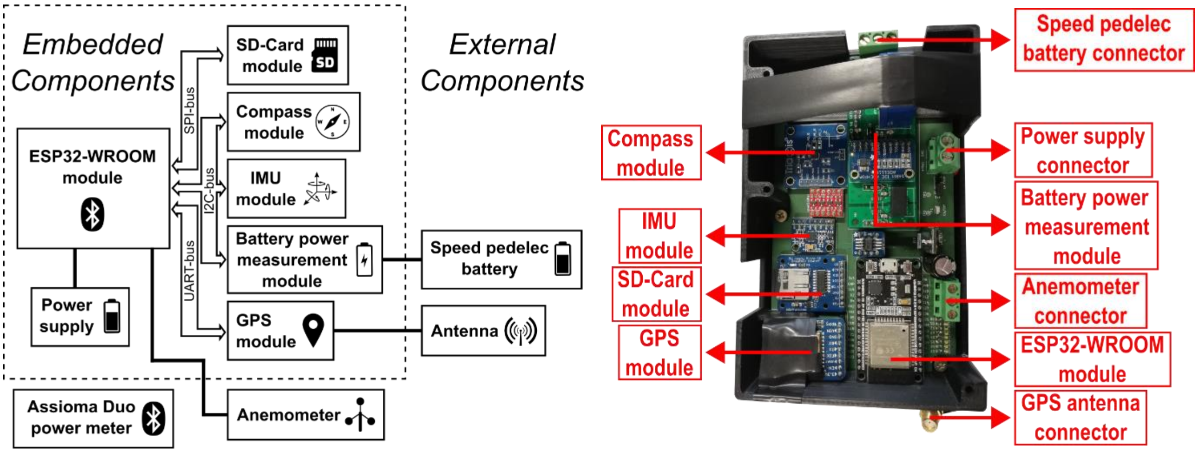
A previous paper [6] discussed the development of a measurement module to capture the energy consumption of speed pedelecs. This paper represents an elaboration on this work: the speed pedelec measurement module is improved and upgraded, allowing both output power and rider input power to be linked to various environmental factors, including GPS and road vibrations.

2 Methodology

To obtain insight into the power consumption and overall road behaviour of speed pedelec committers, data needs to be collected. To log the required data properly, a proof of concept modular measurement module for speed pedelecs is proposed in this work. The development of the measurement module starts from a power balance, presented in equation 1, which identifies the various environmental factors that influence the energy consumption of the speed pedelec [7]–[9]. In this equation the power-generating terms on the left-hand side are P_c and P_m, which are the power contribution from the cyclist and the motor of the vehicle respectively. On the right-hand side of the equation, the power terms linked to the aerodynamic drag P_a and the rolling resistance P_r can be found, as well as the P_{ke} and P_{pe}, representing the loss or gain of power due to the increase or decrease in kinetic and potential energy.

$$P_C + P_m = P_a + P_r + P_{ke} + P_{pe} \tag{1}$$

Derived from this power balance, various environmental factors can be determined and the appropriate sensors are selected. The proposed speed pedelec measurement module is build around an ESP32 [10] microcontroller with Bluetooth Low Energy (BLE) communication capabilities. This BLE communication enables communication with various external sensors, such as power pedals which monitor P_c. Hence, the motor or battery power can be linked with the input power from the cyclist. An inertial measurement unit (IMU) [11], a compass [12] and the battery power measurement module [13] can be read out using I^2C [14]. These sensors capture data such as vehicle vibrations, acceleration and angles taken while cycling, which are useful to obtain a more complete picture of the use of the speed pedelec or EPAC in question, as well as the condition of the roads it travels on. An Adafruit ultimate GPS v.3 breakout board [15] is used to capture GPS signals, with data stored on a microSD card. Finally, an anemometer [16] can be connected to the ESP32 to measure the relative wind speed at the front of the handlebar. This connection gives an indication of the impact of the effective wind speed on the aerodynamic power Pa. A schematic overview and the working prototype of the measurement module are shown in Figure 1.



(a) (b)

Figure 1: (a) A schematic overview and (b) proof of concept measurement module

The ESP32 captures data at a maximum rate of 5 Hz. Two lithium-ion (LFP) rechargeable batteries with an energy content of 3350 mAh are used to power the measurement module, thus allowing up to 33.5 hours of autonomy. The PCB is placed within a custom 3D-printed housing, enabling robust stand-alone operation.

The measurement module has been designed to capture data with embedded sensors (e.g. IMU and GPS data) but can be extended with multiple external sensors, such as an anemometer or an EPAC battery power measurement unit. Depending on the data to be collected, certain sensors can be omitted or added without affecting the overall functionality of the system. The module provides the means to map and compare the behaviour of different vehicles, for example standard bicycles, pedelecs and speed pedelecs.

To validate the operation of the measurement module, a Moustache speed pedelec with a Bosch performance line motor [17] has been modified. To increase the accuracy of the GPS module, a GPS antenna [18] is mounted on the driver's helmet. The cyclist power is captured using Assioma duo power pedals [19] with BLE communication capability. The electric connection between the motor and speed pedelec battery connector is extended and allows the voltage and current to be measured. The measurement module is placed in the bicycle bag near the rear end of the speed pedelec. An anemometer is placed on the handlebars to monitor the relative wind speed. The resulting speed pedelec with corresponding indications is presented in Figure 2.

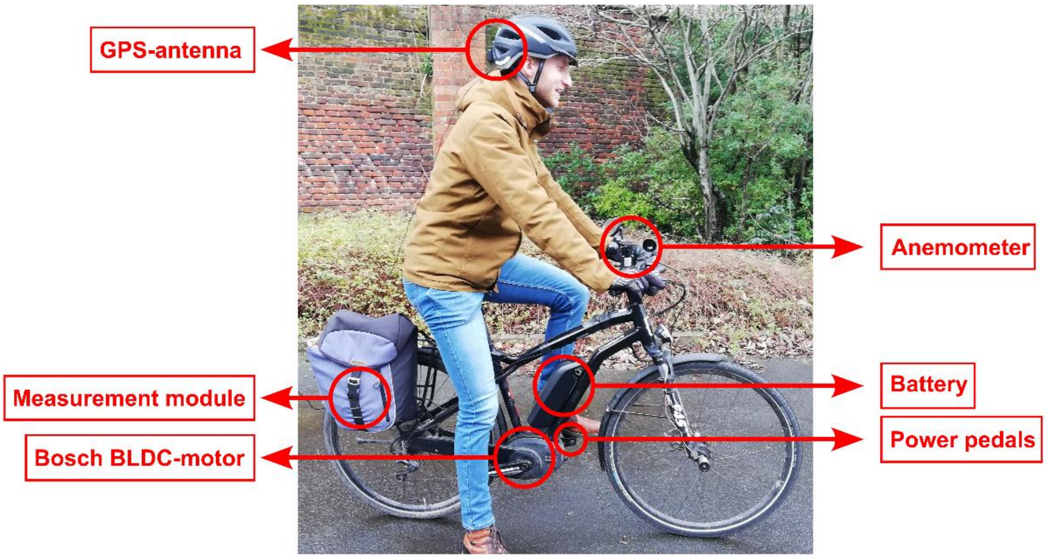


Figure 2: Visualization of the modified Moustache speed pedelec with peripherals

3 Measurements

To demonstrate the performance of the proposed measurement module, a Moustache speed pedelec, equipped with the measurement module, was tested over a trajectory of approximately 7 km, Figure 3.

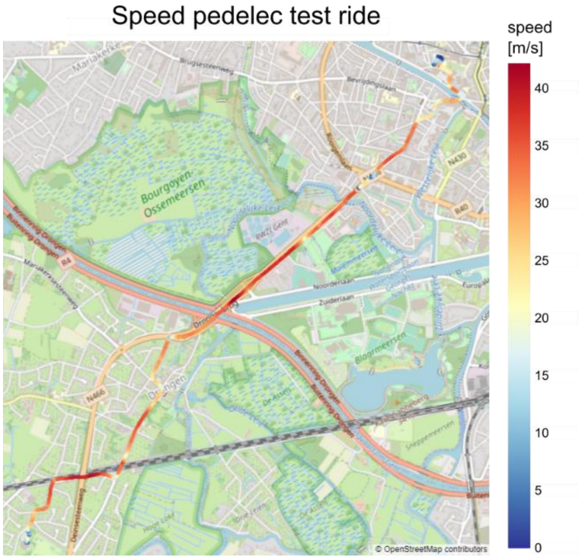


Figure 3: Travelled trajectory of the test ride

Various sensor data can be visualized post trip, correlated to the travelled trajectory or time. Figure 3 shows the speed and route taken. Figure 4 visualizes the relative wind speed, cycling speed, X-acceleration (forward acceleration), experienced vibrations in the vertical (Z-axis: acceleration), pedal power and utilized battery power.

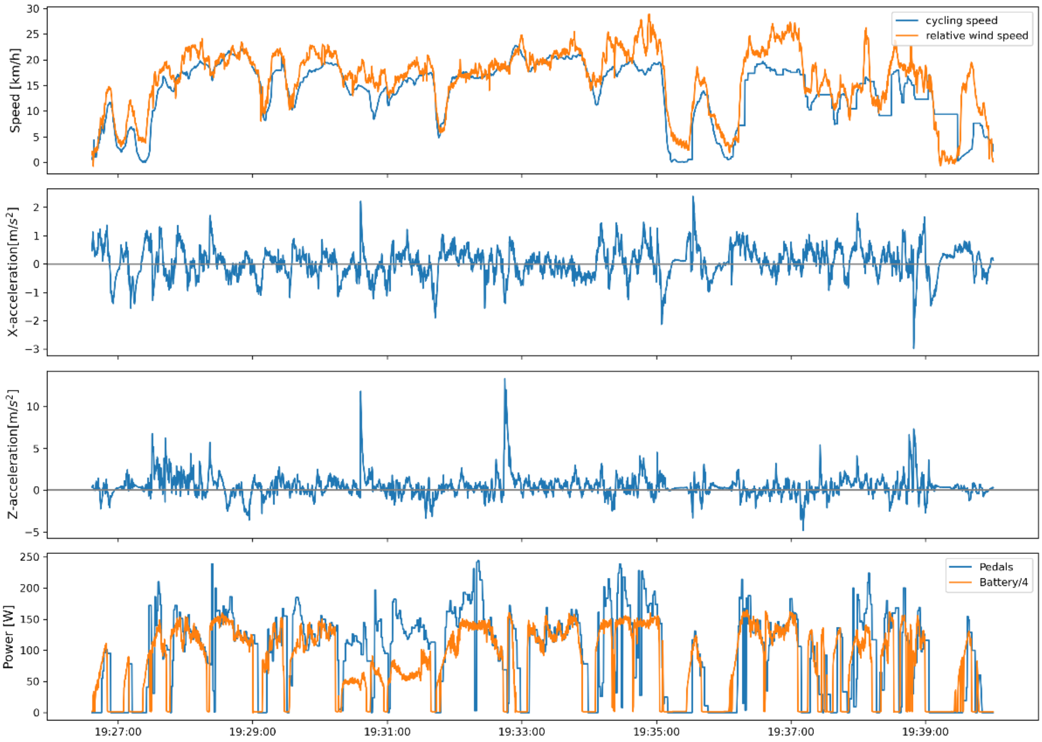


Figure 4: Relative wind speed, cycling speed, X-acceleration (forward direction), vertical (Z-axis) acceleration, battery power and pedal power measurements of the test ride, using the measurement module

Figure 4 shows how the different sensor data can be used to contextualise and understand achieved speeds and cyclist performance. For example, the two spikes in vertical acceleration (at around 19:31 and 19:33) are indicative of bumps on the road. Such bumps can be a challenge for speed pedelecs, as over time these may result in metal fatigue and the need to replace or repair wheel spokes or even bike frames. Similarly, these bumps may also indicate risks to riders, as they can affect the controlabillity of the vehicle. It can be noted from the pedal and battery power that the rider ceased to pedal at these instances, indicating that the rider was aware of this risk factor. Similarly, the acceleration and deceleration instances (as seen with both the speed and the X-acceleration) between 19:35 and 19:37 show how the cyclist had to halt, re-started cycling, to slow down again, and subsequently cycled again at the chosen speed. The anemometer data is useful in quantifying the impact of wind speed and direction for the cyclist: where the wind speed measured at the handlebar is (much) higher than the cycling speed, this indicates a headwind. This data can then serve to quantify the impact of wind speed and direction on fuel efficiency and available range for the cyclist, as well as estimate the impact on the trip duration.

The measured data can be used for various research objectives: the measured relative wind speed, for instance, can be related to the aerodynamic drag [20]. In turn, the IMU-data can be used to assess the quality of the road surface [21], [22], identify the slope of a hill [23], or even record the travelled trajectory itself [24]. With a sufficient number of trips monitored, the relationship between the environmental factors and energy consumption can be investigated. Although investigation of these correlations is beyond the scope of this work, the power balance from equation 1 can be verified along with identification of the key factors associated with the power consumption of the speed pedelec. The proposed measurement module can be used with other speed pedelecs, allowing the comparison of the power consumption and the influence of environmental factors between different speed pedelec designs.

Besides logging of the environmental factors, the proposed measurement module can monitor the battery power and pedal power. It can be of interest to correlate these parameters for multiple assistance modes, these correlations can determine the implemented assistance factors. Figure 4 illustrates the monitored battery power and pedal power measured during the test ride of Figure 3.

The use of the measurement module is not limited to identify the environmental factors affecting power consumption nor to compare and verify the implemented assistance factors. Both the user's behaviour and dangerous road situations can be determined post trip with the proposed speed pedelec measurement module.

When mapping the pattern of speed pedelec riders, data about the driven speed, experienced vibration and cycling power are relevant. Capturing this data on a large scale can benefit (e)-cyclists, and policy makers and road authorities, e.g. by providing data about route choice and the need for road repairs or improvements (e.g. "Why do people avoid that road? Too many bumps on the road"). Similarly, obtaining data about where €-cyclists travel fastest on certain road sections allows policy-makers and urban mobility planners to make informed decisions. To identify unsafe road situations, the speed pedelec measurement module can be used to recognize unusual rider behavior. Post trip, the captured IMU data can be used for fall detection, or abrupt braking behavior, see Figure 5. The occurence of abrupt braking events is indicated by sharp declines in the direction of movement acceleration data. Similary, fall detection can be correlated with a rapid upsurge in gyroscope data along the direction of motion axis.

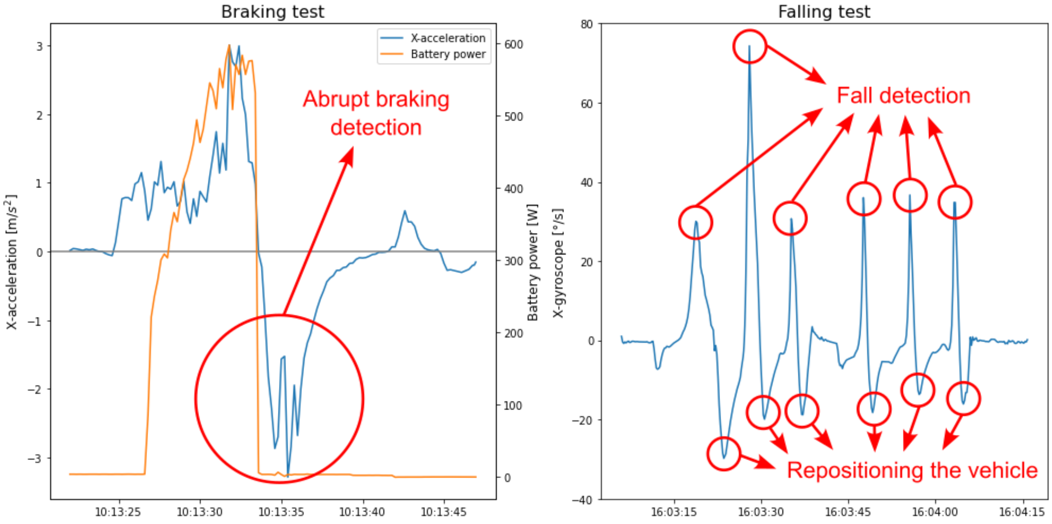


Figure 5: Identification of abrupt breaking events and fall detection using the proposed module

In particular with abrupt braking detection and direction changes, the measurement module will facilitate obtaining statistics on near-misses and near-falls. Linking these events to the ridden trajectory enables the captivation of dangereous encounters, providing the stakeholders with valuable information about road conditions and cyclist behaviour. Consequently, research and policy making can be based on measured data over full trajectories in naturalistic settings, over extrapolations based on limited observations.

4 Conclusion

A modular measurement module for speed pedelecs and EPACs in general is presented in this work. With this measurement module, data is measured at 5 Hz, combining speed pedelec power consumption with several environmental factors (speed, location, acceleration and direction of travel, wind speed and ambient temperature). The measurement module allows detailed insights in the power consumption of speed pedelecs (and EPACs), combined with information on the influencing factors, from road quality via IMU measured vibrations to the actual power input by the cyclist. The measurement module captures high quality data which enables the evaluation and correlation between the power consumption and multiple key factors. This will be of great interest for LEV stakeholders, from policymakers, to end-users and manufacturers.

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Presenter Biography

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.