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Estimation of Energy Consumption in Battery-electric Motorcycles Using a Virtual Vehicle Model and the Development of a Customized Measurement System

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Abstract
The paper addresses the development of a virtual vehicle model for an electric motorcycle and the design and implementation of a universal measurement system. By integrating the measurement system with the virtual model, accurate estimation of energy consumption data can be achieved in the future. Currently, in Europe, emission standards and other regulations are predominantly focused on passenger cars due to their higher numbers. However, on a global scale, the energy consumption of motorcycles, along with their range and usability, must also be addressed, as they serve as primary means of transportation in many regions. Furthermore, in Europe and other developed countries, replacing traditional internal combustion engine motorcycles with efficient electric motorcycles could significantly reduce harmful emissions in urban areas.
The research began with the design of the virtual vehicle model and the measurement system and concluded with the validation of the measurement system. It was established that a universally applicable, low-cost measurement system can be developed, requiring minimal modifications for installation, which allows for the measurement of real-world energy consumption and the necessary drivetrain data. Additionally, it is important to highlight that a virtual vehicle model requiring low computational power can be developed, providing sufficiently accurate predictions of energy consumption.

Keywords
electric motorcycle, range estimation, measurement system

1 Introduction

Measuring the real-world consumption of electric vehicles (EVs) has become increasingly important, as these vehicles play a growing role in the development of sustainable transportation systems (Kocsis et al., 2024). The efficiency and energy consumption of vehicles, particularly EVs, can vary significantly between laboratory conditions and real-world usage (Fontaras et al., 2017). Consequently, accurate measurements based on actual driving conditions are necessary to provide users with realistic information about vehicle consumption and range, as well as to assist manufacturers in further developing the technology.

Furthermore, real-world consumption data is a cornerstone in achieving environmental goals in the transportation sector. Accurate data on consumption is essential for assessing the ecological footprint of vehicles and planning the development of charging infrastructure (Peng et al., 2024). Vehicles with range tailored to user needs are also critical to increasing market share (Alatawneh and Torok, 2024), while the deployment of adequate charging infrastructure—simpler for motorcycles–could increase their share in urban transportation (Gan, 2023).

There is, however, a significantly lower volume of research and data available regarding the energy consumption of motorcycles compared to cars, as research and regulations are more focused on passenger cars, which constitute a larger share of the transportation sector. The environmental impact of cars, including emissions and fuel consumption, has been studied more extensively (Komnos, et al., 2022). Moreover, due to the different usage patterns and technological features

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of motorcycles, they have received less attention. Yet, measuring the energy consumption of motorcycles is particularly important in regions where they serve as a significant mode of transportation, such as in Southeast Asia and Africa, where motorcycles are widely used for daily travel (Gu et al., 2021). Electric versions of motorcycles could provide a mass solution to reducing emissions (Sannoh et al., 2024) if they can offer a viable alternative to their internal combustion engine counterparts (Nguyen et al., 2023).

A holistic approach has been taken to develop a digital twin for motorcycles that accounts for numerous factors, including the analysis of real-world trips. However, there are several limitations (e.g., tools designed for much higher-powered vehicles than electric motorcycles) that make its application to electric motorcycles more challenging (Smeets et al., 2024).

Thus, it is necessary to develop a simplified estimation methodology that, considering the initial parameters, can estimate the energy consumption of an electric motorcycle with low error, without requiring detailed knowledge of the actual road segment. This requires the development of an affordable, reliable measurement tool and a virtual vehicle model that can be integrated. Once these are in place, the energy consumption can be predicted with low error for specific usage conditions and vehicle types, which translates into a realistic range for users (Lech and Nikończuk, 2022).

The data derived from estimations using the virtual vehicle model can be integrated into the vehicle's onboard system, enabling the dynamic display of real-time range calculations based on driving style. For fleets, it is also possible to determine the actual energy demand over any desired time period.

2 Methods

The work carried out can be divided into two main sections. The first section involves the creation of the virtual vehicle model, which varies according to the basic parameters of each vehicle type. The second section focuses on the development and calibration of the measurement system. The goal is to ensure that the measurement system can be used universally after reprogramming.

2.1 Vehicle parameters

The virtual vehicle model was developed based on the parameters of a specific type of vehicle, and the measurement system was installed on this vehicle for testing.

2.2 Virtual vehicle model

For the virtual vehicle and drivetrain model used to estimate the energy consumption, it is essential to define a drivetrain model applicable to the motorcycle and the fundamental derived parameters, as shown in Table 1.

The vehicle is influenced by various resistance forces, which must be counteracted by the forces generated by the drivetrain, as summarized in Table 2. The relationship between these two resultant forces–the resistance force and the traction force–determines the dynamics of the vehicle. (Eq. (1))

The resistance forces depend on the characteristics of the vehicle and the rider, the speed of travel, weather conditions, and road conditions.

$$F_{\text{resultant}} = F_{\text{traction}} - F_{\text{resistance}} \tag{1}$$

Rolling resistance is derived from the deformation of the road surface and the vehicle's tires, as well as from bearing friction. It logically follows that the quality of the road surface significantly influences this value; however, the tire pressure and design also play a crucial role in determining the magnitude of the resistance factor. In this case, a coefficient of 0.007 was calculated for asphalt roads.

Aerodynamic drag is dependent on the vehicle's speed, the size of its frontal area, the density of the medium, and the drag coefficient. To achieve a more accurate representation of reality, the frontal area was divided into five sections for calculations. The greatest uncertainty in the calculation of aerodynamic drag arises from the squared behavior of the drag coefficient, which leads to error propagation affecting the resultant resistance force and consumption data.

Table 1 Initial data

Parameter	Value
Vehicle weight	164 kg
Driver weight	105 kg
Frontal area size	0,8048 m^2
Nominal power	7 kW
Maximum power	9 kW

Table 2 Resistance forces

Designation	Formula
Rolling resistance	$F_{\text{rolling}} = m \times g \times f$
Drag	$F_{\text{drag}} = \frac{\vartheta \times A \times c_w \times v^2}{2}$
Grade resistance	$F_{\text{grade}} = m \times g \times \text{tg}\alpha$
Acceleration resistance	$F_{\text{acceleration}} = 1 + \vartheta \times m \times a$

For motorcycles, the drag coefficient is estimated to range between 0.5 and 1. In this study, a value of 0.6 was assumed.

Grade resistance is encountered when ascending a slope, indicating the extent to which gravity acts against the direction of the vehicle's motion.

The moment of inertia factor can be expressed using the work equation applied to a rotating body. For the motorcycle under consideration, the moment of inertia factor is determined to be 0.0153.

Given that the motorcycle features a hub motor, it is noted that the drivetrain does not incur any mechanical losses beyond the rolling resistances that have already been considered.

2.3 Measurement system model

In order to perform accurate measurements, it is necessary to first define the parameters that must be measured to determine energy consumption as precisely as possible, depending on the vehicle's motion. The vehicle is affected by resistance forces; to establish these, the following parameters need to be measured:

- Speed;
- Exact time;
- Change in altitude.

These tasks were implemented in the measurement system as follows:

- Wheel rotation measurement – seven signals per wheel rotation;
- GPS module – for measuring altitude above sea level, from which the change in altitude can be determined.

Given the knowledge of the vehicle's drivetrain parameters, instantaneous energy consumption can be determined. The following parameters need to be measured for this purpose:

- Battery terminal voltage;
- Battery current;
- Current direction;
- Power consumed by the motor.

The manifestation of these parameters in the system is as follows:

- Measurement of battery voltage;
- Measurement of battery current;
- Measurement of current direction;
- Measurement of dissipated power magnitude at the inverter (measured voltage at the inverter).

In the measurement system, analog signal processing occurs on measurement cards, followed by converting to digital format, after which the data is stored.

2.3.1 Measurement of wheel rotation speed

The measurement of wheel rotation speed was conducted using a reed relay, which was activated by seven neodymium magnets mounted at equal distances on the front wheel hub. The switching of the reed relay was performed by the magnets. Due to noise filtering, an optocoupler was utilized for interfacing with the microcontroller. The phenomenon of preloading was filtered through software by limiting the sampling time.

2.3.2 Measurement of height

The measurement of height is a straightforward task, as ready-made modules are available for this purpose. The module itself performs both the measurement and the conversion.

2.3.4 Measurement of temperature

The measurement of temperature is essential for several reasons. Firstly, measuring the ambient temperature is fundamental; secondly, the temperatures of the motorcycle battery and the measuring shunt are necessary for accurate calculations.

The measurement is carried out by commercially available sensors, which report the temperature as 273 K/100, meaning that zero degrees Celsius appears 2.73 V. To simplify data processing and reduce susceptibility to noise in operations with analog signals, a value of 2 V is subtracted from the signal emitted by the sensor, and the remainder is multiplied by four, allowing for more accurate processing of the signal. The measurement range is thus established at −18 to +102 degrees Celsius.

2.3.5 Measurement of battery voltage

The battery voltage measurement is conducted using a simple voltage divider, which reduces the battery voltage by a factor of seven. The microcontroller can quickly process the resulting analog signal.

2.3.6 Measurement of battery current

The current measurement is performed on a measuring shunt, which serves as a component for conducting the motorcycle's current. The voltage drop is minimal; therefore, the A/D conversion is carried out after amplification. Due to the change in the current direction, an absolute value is calculated prior to amplification. Varying temperatures diminish the accuracy of the measurement, so the measured values are compensated based on the temperature of the component during data processing.

2.3.7 Measurement of current direction

The motorcycle is capable of regenerative braking; therefore, it is essential to know whether energy has been drawn from the battery or has been regenerated for the recorded values. The measurement of the current direction is conducted using a zero comparator (on the measuring shunt), where the transmitted value varies between logical 0 and 1, depending on the polarity of the shunt.

2.3.8 Measurement of theoretical engine power

The measurement is considered theoretical because it assumes the engine operates at 100% efficiency. The connection to reality is established through dynamometer measurements, during which the efficiency characteristics of the engine were recorded. The electrical power supplied to the motor can be determined as the difference between the power drawn from the battery and the power dissipated in the inverter.

During the measurement, one phase of the motor is evaluated. It is assumed that there is no star-point displacement and that the three phases are entirely symmetrical.

The measurement procedure is as follows:

- Voltage division–similar to battery voltage measurement;
- Rectification of phase signal;
- Peak value formation;
- Difference calculation with the battery voltage;
- Doubling the obtained voltage value due to the involvement of another FET in the bridge configuration;
- Multiplication by battery current (as permitted and correct according to Kirchhoff's law)—thus, the power is correctly generated, since the losses dissipated in the inverter depend on the voltage across the currently open FETs and the magnitude of the switched current.

3 Results

3.1 Virtual vehicle model

Based on the previously described data and relationships, a model has been developed that is capable of processing speed, altitude, and time data received from the measurement system. The model operates on a time basis with a second-level granularity.

This approach facilitates the programming of the measurement system and simplifies the implementation of official measurement cycles (e.g., WLTP). The model expects the data at its input, as listed in Table 3 and detailed in Table 4.

3.2 Model output

The model produces the following values from the input dataset over time, utilizing the relationships and calibration functions discussed previously:

- Estimated energy consumption from the battery (W/s);
- Estimated energy fed back into the battery (W/s);
- Estimated energy consumption for vehicle propulsion from the drivetrain (W/s);
- Estimated energy fed back into the drivetrain from vehicle propulsion (W/s);
- Actual energy consumption from the battery (W/s);
- Actual energy fed back into the battery (W/s);
- Actual energy consumption for vehicle propulsion from the drivetrain (W/s);
- Actual energy fed back into the drivetrain from vehicle propulsion (W/s).

In addition to the time-series data, the model determines the following values for a given route:

- Estimated total energy consumed (Wh);
- Actual total energy consumed (Wh);
- Estimated specific consumption (Wh/km);
- Actual specific consumption (Wh/km).

Table 3 Input data

Designation	Formula	Substituted based on the initial parameters	Variable – data received from the measurement system
Rolling resistance	$F_{\text{rolling}} = m \times g \times f$	21.11 N	–
Drag	$F_{\text{drag}} = \frac{\vartheta \times A \times c_w \times v^2}{2}$	$F_{\text{drag}} = 0.2908 \times v^2$	v – speed
Grade resistance	$F_{\text{grade}} = m \times g \times \text{tg}\alpha$	$F_{\text{grade}} = 2638.89 \times \text{tg}\alpha$	ds – altitude change
Acceleration resistance	$F_{\text{acceleration}} = 1 + \vartheta \times m \times a$	$F_{\text{acceleration}} = 273.1157 \times a$	v_1 – speed v_2 – speed (previous and current instantaneous velocity)

Table 4 Input data types

Designation	Data type	Unit
Battery voltage	number	V
Battery current	number	A
Current direction	bin	–
Temperature	number	K

3.3 Construction, placement, and activation of the measurement system

The measurement system was mounted on a panel for practicality, facilitating easy placement on the motorcycle. The system operated effectively outside the motorcycle and met the expected requirements. Following this, installation was carried out. A suitable storage box was affixed to the motorcycle, and wiring and the securing of other components were accomplished.

Initial field tests occurred post-installation. No wiring or other faults were observed. The input analog signals were measurable on the measurement panel, while simultaneous writing to the SD card was functional, and the system recorded data corresponding to the measured incoming signals.

3.4 Calibration of the measurement system

The calibration of the completed measurement system was essential for accurate final results.

3.4.1 Calibration of speed measurement

During the speed measurement, the signals from the magnets divide one complete rotation into seven segments. The recorded and stored data represent speed. Known distances were traversed for calibration, and these distances were compared to those extracted from the recorded data. The system provided accurate results after software parameterization using the constant thus determined.

3.4.2 Calibration of height measurement

The height measurement is crucial for calculating tangent values; thus, only the relative value is significant rather than the absolute height. By elevating the sensor to a known height relative to its starting position, accuracy can be established. The sensor met the expected accuracy and responded rapidly to changes in position.

3.4.3 Calibration of current measurement

Due to imperfections in circuit elements, an offset error occurred. This offset error is constant, necessitating a subtraction for each data series. The calibration involved applying various current values (three loading currents, with five measurements per value) and comparing the results from an independent current measuring device to those measured by the system. After software adaptation of the calibration function thus derived, a maximum error of 2% was achieved in the range above 150 A. For values below 150 A, the error was less than 1%.

3.4.4 Calibration of voltage measurement

In this case, the recorded values were compared to a data series measured with a simple multimeter. The measurement system showed no significant deviations. (The measurement system is also equipped with a display, allowing for the reading of instantaneous values.)

3.4.5 Calibration of power measurements

Due to the design of the measurement system, the losses of the motor controller and the motor are recorded as a single data point. The system cannot measure the mechanical power used for vehicle propulsion at the wheel contact point. The relationship between the values recorded concerning the drivetrain's state and the actual wheel power was established through dynamometer measurements, as illustrated in Fig. 1.

The dynamometer measurement commenced with installation, software setup, and testing, during which the motor was braked at stationary rotational speeds and the corresponding torque values were recorded, while the system registered the current and voltage. Afterward, the power and efficiency field of the motor and controller were established by assigning the current and voltage values corresponding to each point, as presented in Fig. 2. From the averages of the efficiencies, a function was created that demonstrates the relationship between the measured electrical power values during the traveled distances and the actual mechanical (vehicle propulsion) power, as summarized in Fig. 3.

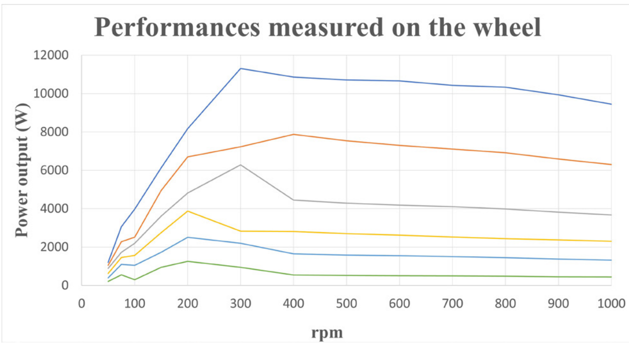

Fig. 1 Performances measured at the wheel

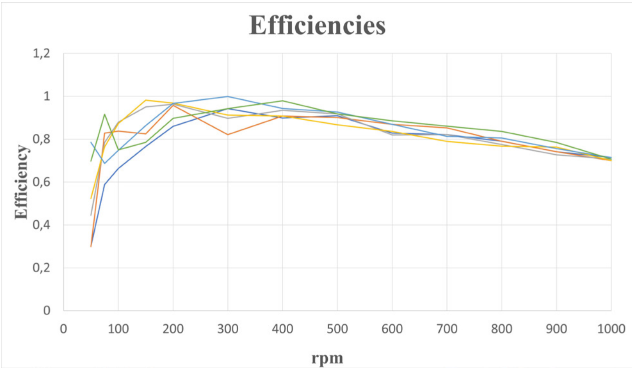

Fig. 2 Efficiencies

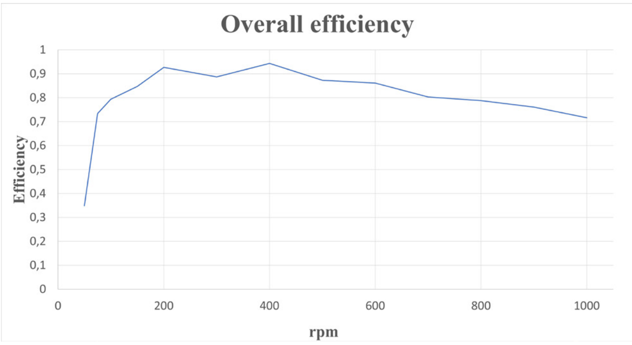

Fig. 3 Overall efficiency

4 Discussion

The previously presented virtual vehicle model and measurement system facilitates the comparison of measured consumption based on real data with consumption values derived from the virtual model (Ma et al., 2024). Through the calibration procedures demonstrated in the measurement system, the system can measure and record actual energy consumption with minimal error, while also capturing the internal states of the powertrain. This allows for the vehicle's motion state and the powertrain's condition to be compared and analyzed at any given moment. In addition to accurately determining energy consumption, this capability enables the further development and optimization of the powertrain (Xiong et al., 2024).

The material cost of the device (excluding the hardware required for programming and labor hours) does not exceed 100 Euros. Since the device measures directly, it can be considered universal to a limited extent; with modifications to the program code, it can be adapted to other vehicles while still providing reliable data at a low cost. Due to the principles of measurement, a slight alteration of the powertrain is necessary (placement of a shunt, installation of terminals); however, this duration is short, taking less than one hour. Notably, there is no interference with the vehicle's communication system or code decryption, which further reduces the time and costs associated with measurements and does not compromise the manufacturer's warranty. From the perspective of the automotive industry, the development and application of similar tools for recording real consumption data should be considered (Yuan et al., 2024).

The broader application of the measurement system and the virtual model could enhance and complement various data-driven traffic models (Maghrour Zefreh et al., 2023), wherein energy consumption and operational costs may also be incorporated in the future. By associating a battery model with the virtual model, environmental impacts can also be represented, as ambient temperature can significantly influence the achievable range (Szilassy and Földes 2024).

5 Conclusion

The accurate estimation of energy consumption based on actual usage data plays a crucial role in optimizing the efficient use of energy in vehicle fleets and developing sustainable transportation systems. The presented system offers a solution that enables precise energy consumption forecasting, directly contributing to increased cost-effectiveness. The virtual vehicle model, which forms the basis of the system, has a broader range of applications, as after appropriate validation measurements, energy consumption can be accurately determined merely by measuring the kinematic parameters. This has significant economic advantages, as the tools required for measuring these parameters are often already available in vehicles, particularly motorcycles. Thus, energy consumption monitoring and optimization can be achieved at the fleet level with minimal financial investment.

However, the method and tool presented have several limitations. For example, the virtual model does not include a battery model that accounts for the effects of ambient temperature, which could be particularly important for fleets operating under various climatic conditions. Furthermore, the measurements and estimates have so far been conducted only for a specific vehicle and have not been extended to more extensive samples of fleets. Nevertheless, by parametrizing the device, the possibility of applying it to other types of vehicles arises, indicating further research and development directions for the future.

Overall, due to the device's cost-effectiveness, universality, and versatile applicability, its wider adoption would be justified, especially in light of the increasingly urgent global climate goals regarding the decarbonization of the transportation sector. The next steps will include conducting measurements under real conditions and applications on larger fleets, allowing for broader validation and refinement of the system.

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