Article citation info:
Hemlecki P, Fabiś P, Kubica G. Analysis of design changes and operating parameters in the case of using an electric engine in a city motorcycle. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-203884

Piotr HEMLECKI
Paweł FABIŚ
Grzegorz KUBICA

Combustion Engines
Polish Scientific Society of Combustion Engines

Analysis of design changes and operating parameters in the case of using an electric engine in a city motorcycle

ARTICLE INFO

Received: 4 December 2024
Revised: 27 March 2025
Accepted: 9 April 2025
Available online: 19 May 2025

The study presents the methodology and technical aspects of converting a city motorcycle from a combustion to an electric drive. As an example, a prototype motorcycle vehicle built at the Faculty of Transport and Aviation Engineering of the Silesian University of Technology was used. The traction characteristics of the vehicle before and after the drive conversion were compared. Laboratory tests were conducted on a chassis dynamometer under various test conditions. The performance of both drive configurations, the effect of temperature, and speed on energy consumption were evaluated. The changes in vehicle dynamics indicators for both types of propulsion systems were determined, and the advantages of the propulsion conversion process were presented.

Key words: *electric vehicle, conversion, engine performance, flexibility, BEV exploitation*

1. Introduction

In recent years, there has been a significant increase in the number of electric vehicles. The changes are particularly visible in the groups of passenger cars and buses, but also apply to two-wheeled vehicles. That trend has seen the emergence of a new group of personal transport means, namely electric scooters. The high popularity of the latter results from the relatively low costs of both purchase and use. Although they are characterized by a small range of up to several dozen kilometres, their small size allows for agile movement around the city. Two-wheeled vehicles generally provide much better mobility conditions than public transport. Using electric drive, they fit into the vision of modern and ecological cities.

The growing importance of electromobility can also be seen in motorsport. In addition to the more well-known racing series, such as the eTouring Car World Cup (eTCR) or Formula E, there are also smaller ones, such as Formula Student, which also contributes to the development of BEV vehicles [1, 6].

One of the most frequently cited disadvantages of electric vehicles is their range. In the case of electric scooters, the speed is limited by law to small values, such as 20 km/h in Poland. Climatic conditions also play a significant role. The frequency of precipitation, strong winds, and low temperatures significantly reduces the comfort of using this type of vehicle. For this reason, many people still travel by passenger car. Although the number of passenger cars powered by electricity is still growing, changing the type of power supply does not contribute to improving traffic organization in cities, where traffic jams are still a common phenomenon. In addition, many drivers draw attention to the shortage of parking spaces.

One possible solution is to increase the share of motorcycles in urban traffic. Due to their size, they take up much less space in urban space, both when moving and parking. This results in the possibility of reducing traffic jams and solving the parking problem because the same area can accommodate more motorcycles than cars.

The power source of a motorcycle that fits into the vision of ecological cities of the future is electricity. Analysing the market, it can be seen that the offer of electric motorcycles is very small, and their share in the sales of new motorcycles is marginal. Although there are several electric models in every motorcycle class, their offer is much smaller than that of combustion engine (ICE) vehicles. Despite the rather modest offer of electric motorcycles, more and more such vehicles are appearing, as the dynamics of the growth of interest in such vehicles is significant. In the period from January to October 2024, 34,914 new motorcycles were registered in Poland, of which only 407 were electric, which is less than 1.2% of the total [20]. The reason for this state of affairs may be the range of these vehicles, which is significantly smaller than in the case of cars, and the relatively long time for energy replenishment. The solution presented in the paper does not solve the problem of a small range, but it contributes to a significant reduction of the time of energy replenishment in the vehicle.

Currently, there are many scientific works on the conversion of a conventional vehicle into an electric vehicle, including doctoral and master's theses [2, 5, 17, 22]. They contain a design of a drive system with structural elements for mounting the drive system and control systems for the electric drive.

In the literature, there are also studies describing the operational aspects of the vehicle [7, 9, 13, 21]. They contain bench tests of electric motorcycles. The goals adopted by the authors were to reduce the noise emitted by the vehicle and to reduce the operating costs.

The development of motorcycle control elements was presented in the works [4, 8, 10–12, 19]. Publications [4, 16, 19] were devoted to the design of a prototype vehicle and the selection of drive system components using simulation models. The authors of the works [8, 10–12] presented test studies of the manufactured prototypes.

2. Construction changes

No changes were made to the vehicle's load-bearing elements. The changes were limited to removing the combustion engine and replacing it with an electric system. The place of the combustion engine and gearbox was used to mount the battery. The fuel tank was removed from the vehicle, and an inverter and BMS were installed in its place. The electric engine was mounted directly in the rear wheel hub, which involved removing the chain transmission (Fig. 1). As a result of the conversion, the vehicle's weight was reduced from 125 kg to 116 kg.

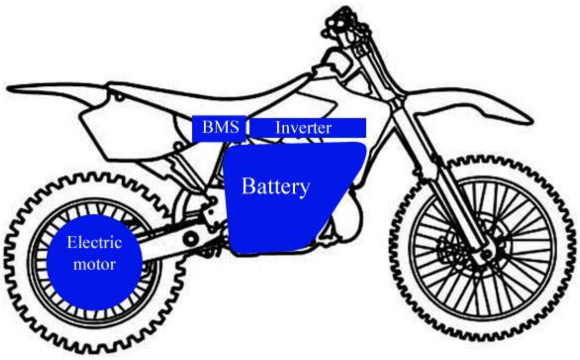

Fig. 1. Location of electric drive components relative to the combustion drive

Knowing the traction parameters of the conventionally powered vehicle, which are presented later in the paper (Fig. 7), the electrical system was selected. The basic parameters of the modified motorcycle vehicle are presented in Table 1.

Table 1. Main data of the electric drive

No	System	Parameters
1	Electric motor	Power: 8 kW Torque: 191 Nm Maximum current: 130 A Maximum instantaneous current: 190 A Rated speed: 110 km/h
2	Battery	Cells: Li-Ion Sony 2600 mAh Number of cells: 440 Maximum current: 400 A Voltage: 72 V
3	Battery Management System (BMS)	Maximum current: 300 A Possibility of the cell balancer Thermal protection of the battery

Fig. 2. Vehicle after modification

The electric drive unit is based on a BLDC electric motor located in the rear wheel hub of the vehicle. The electric motor is controlled by a programmable, sine wave inverter that can operate with devices with a current consumption of up to 300 A. The traction battery consists of 18650 VTC5A cells. The architecture of the energy storage was selected for the engine operating voltage (72 V) and the highest possible energy capacity. As a result, a traction battery with a configuration of 20 cells connected in series and 22 cells connected in parallel was created (20s22p).

The traction battery must be equipped with a system supervising the process of charging and discharging Li-ion cells. For this purpose, the so-called BMS (Battery Management System), which, in addition to monitoring the charging and discharging current, can measure the cell temperature (at 4 points). In addition, the BMS has the ability to equalize voltages in individual battery modules, the so-called balancer, which increases the efficiency of using the energy stored in the battery.

The modified motorcycle vehicle is shown in Fig. 2. The vehicle's electric drive system was tested on a chassis dynamometer (Fig. 3).

Fig. 3. View of an electric motorcycle during the dynamometer test

3. Analysis of the drive train

3.1. Power and torque

The selection of an electric drive unit must be preceded by a traction analysis of an internal combustion engine (ICE) vehicle. The combustion drive unit of the adapted motorcycle was subjected to a traction analysis, determining, on the basis of available data, the external characteristics of the engine (Fig. 4). Table 2 shows the most important parameters of the engine of a combustion vehicle.

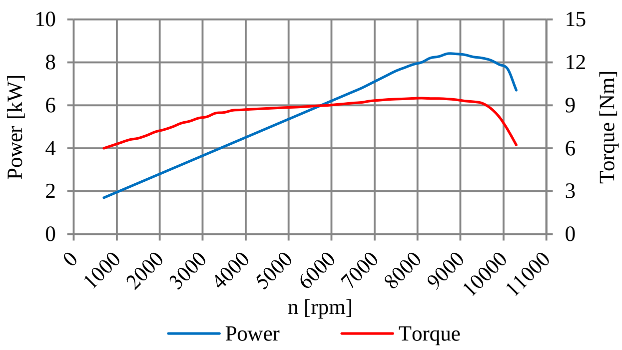

Fig. 4. Power and torque characteristic of ICE [23]

Table 2. Data of the IC engine [23]

Number of cylinders	1
Power at rpm	8.4 kW/8650 min^{-1}
Torque at rpm	9.5 Nm/8000 min^{-1}
Capacity	124 cm^3
Bore	57.0 mm

Taking into account the data of a vehicle with a conventional drive, the traction characteristics were developed and the movement resistance of a two-wheeled vehicle was determined. These characteristics are the starting point for the modification and electrification of a motorcycle vehicle.

The development of traction characteristics requires determining the vehicle's movement resistance and data from the vehicle's external characteristics. An essential part of determining traction characteristics is determining the vehicle's aerodynamic drag force. The force of aerodynamic drag was determined based on the following relationship [3, 15, 18]:

$$F_A = 0.047 \cdot C_D \cdot \rho \cdot A_f \cdot v^2 \text{ [N]} \quad (1)$$

where: C_D – frontal resistance factor, ρ – air density, A_f – fill factor, v – velocity of the vehicle [km/h].

The literature [3, 18] provides values of the filling factor for a motorcycle vehicle equal to 0.7–0.9 b × a. However, for this study, calculations of the frontal surface of the tested vehicle were carried out (Fig. 5).

According to literature data, the value of the frontal resistance coefficient C_D is within the range of 0.5–0.7, assuming that the measurement was made with the driver.

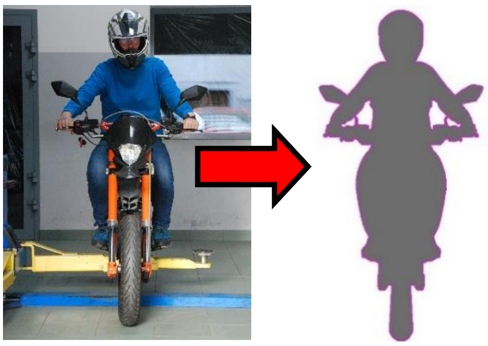

Fig. 5. Determining the frontal surface area of the vehicle

Value of the rolling resistance and driving forces described by the following relationship [3, 15, 18]:

$$F_T = f_T \cdot m \cdot g \text{ [N]} \quad (2)$$

where: F_T – rolling resistance, f_T – resistance rolling factor, m – vehicle mass [kg], g – acceleration [m/s^2].

$$F_N = M \cdot i \cdot \varepsilon \text{ [N]} \quad (3)$$

where: F_N – driving force, M – torque [Nm], i – gear ratio, ε – efficiency.

The driving forces for each gear (F_{N1}–F_{N5}) and movement resistance of a motorcycle with an internal combustion engine is shown in Fig. 7.

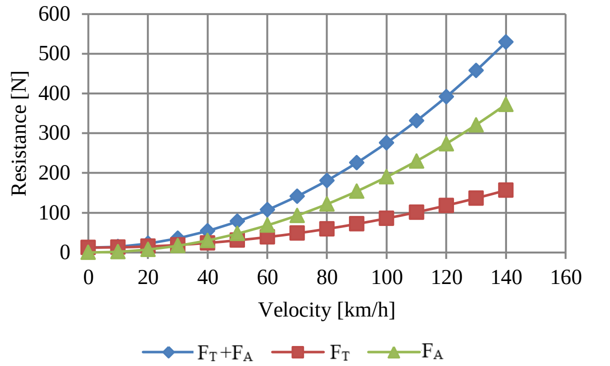

Fig. 6. Vehicle movement resistance

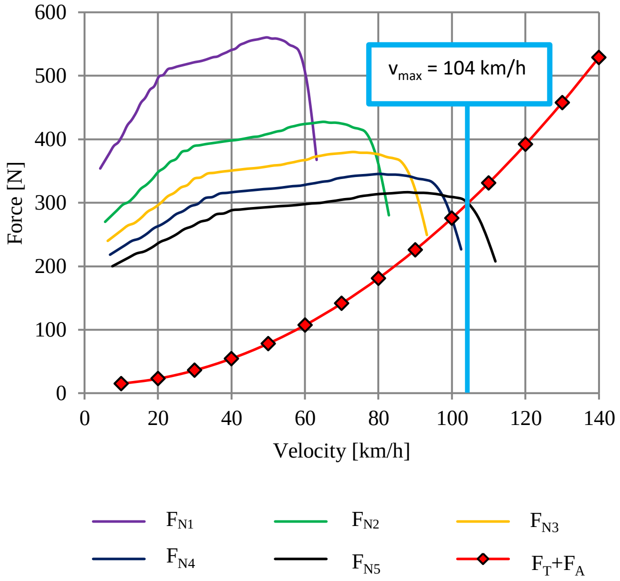

Fig. 7. Vehicle movement chart with the resistance

Based on the characteristics and data of the drive system, traction characteristics were developed and the maximum speed of the motorcycle was determined to be 104 km/h (Fig. 7).

As part of these tests, the external characteristics of the electric motor were obtained and traction characteristics were calculated (Fig. 8 and 9).

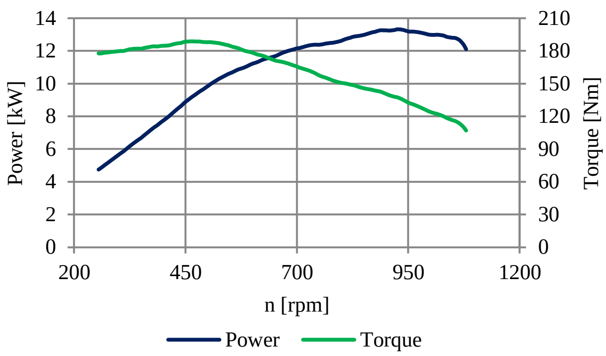

Fig. 8. Electric motorcycle engine charts

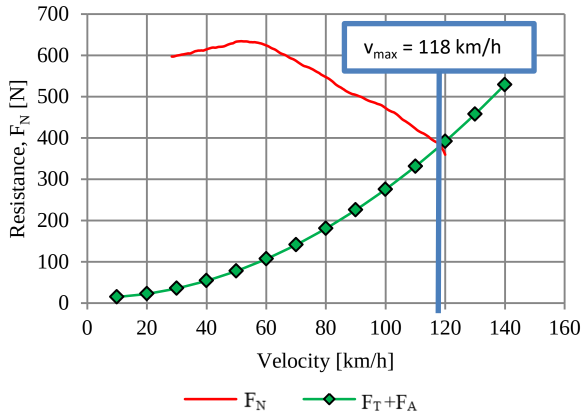

Fig. 9. Electric vehicle movement chart with the resistance

Comparing the traction characteristics of a conventional (combustion engine) and an electric vehicle reveals a higher value of the driving force of the electrified vehicle. This value is approximately 20% higher at the point of maximum vehicle speed.

3.2. Vehicle flexibility

The value and shape of the torque curve significantly influence the dynamics of vehicle movement. Design work related to combustion engines has long been focused on obtaining a torque curve in which the maximum value is constant over a wide or, most preferably, the entire engine speed range, i.e., from idle speed to maximum rotation speed. This torque pattern will guarantee constant dynamics of vehicle movement in every rotational speed range. Current designs of drive systems allow for obtaining a constant value of maximum torque in certain rotational speed ranges. Vehicles equipped with such engines are characterized by high acceleration, but only in the range of maximum torque. The undoubted advantage of using electric motors to drive vehicles is the high value of torque and the availability of this value at low engine speeds (and therefore driving speed).

The assessment of the dynamics of movement, referred to as flexibility, can be made by using simple relationships between the values of maximum torque, the torque value at maximum power, and their rotational speeds [3, 15, 18].

The shape of the torque curve and the speed range between the rotational speed corresponding to the maximum torque and the speed corresponding to the rotational speed of maximum power determine the engine's ability to automatically adapt to the current driving conditions of the vehicle (load). The adjustment of the engine is more pronounced the greater the slope of the torque characteristic, and specifically, it comes down to obtaining the largest possible spread between the maximum torque T_{max} and the torque corresponding to the maximum power T_{Pmax}. Engines characterized by a large range of T_{max} and T_{Pmax}, and a large range of rotational speeds (n_T and n_P), are considered flexible. The torque range e_M relationship is presented below:

$$e_M = \frac{T_{max}}{T_{Pmax}} \tag{4}$$

The range of RPM's is described by the following relationship:

$$e_n = \frac{n_P}{n_T} \tag{5}$$

The flexibility of the engine is defined as the product of the coefficients presented in the above relationships and is called the flexibility coefficient E:

$$E = e_M \cdot e_n \tag{6}$$

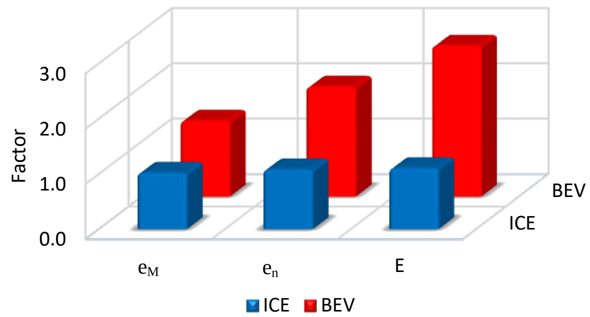

Fig. 10. Drive system comparison of the vehicle flexibility

The calculated values of the flexibility coefficient, torque range, and rotational speed range are presented in Fig. 10.

4. Exploitation analysis

The constructed electric vehicle has been approved for use on public roads. Use in real conditions made it possible to assess the vehicle's operational parameters.

The analysis was carried out in the period from April to October, i.e. in the spring-summer-autumn period. The vehicle was not used in winter conditions. A total of 21 test drives were performed in various traffic conditions to determine the specific energy consumption (SEC). Selected results are presented in Fig. 11. The vehicle's route included urban areas. Based on the measurement results, an attempt was made to present the impact of the main parameters on SEC.

However, the assessment as a function of the average driving speed did not reveal any clear trends (Fig. 11). The reason is the driving style, which was not sufficiently illustrated by the parameters measured during the tests.

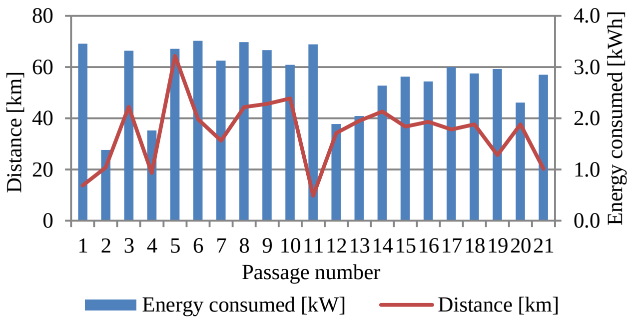

Fig. 11. Dependence of energy consumption on distance travelled

The impact of the ambient temperature on a SEC is illustrated in Fig. 12 and 13. The calculated SEC reaches the highest values at low temperatures. Nevertheless, with the increase in the ambient temperature, SEC decreases. Even so, in this case it is also necessary to extend the range of measured parameters, e.g. by information on the engine load level, in order to determine this effect more precisely.

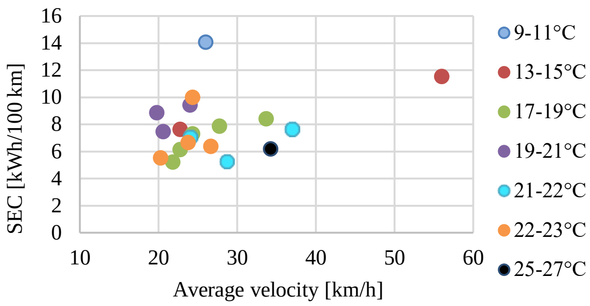

Fig. 12. Dependence of SEC on average speed in different temperature ranges

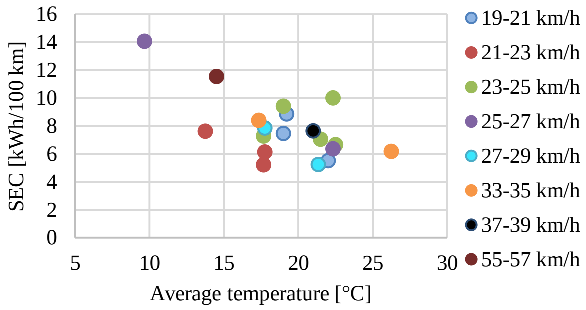

Fig. 13. Dependence of SEC on temperature in different average speed ranges

The conclusions from studies published in this field indicate that the influence of driving style on the range achieved by electric vehicles is clearly more noticeable than in the case of combustion vehicles [14].

Based on the research, the average energy consumption was 8.1 kWh/100 km. Considering the reference price of electricity in Poland, the cost of driving 100 km is about PLN 10. This corresponds to the price of less than 2 liters of petrol. Considering that combustion motorcycles with comparable parameters consume about 4 liters of petrol, the cost of driving 1 km in the case of an electric motorcycle is about half as much.

5. Conclusions

The article presents calculations of traction properties after converting a conventional vehicle to an electric drive. The change in the type of drive system resulted in a significant increase in vehicle movement dynamics (acceleration) and a decrease in vehicle operating costs. The presented traction characteristics allow for a direct comparison of the dynamics of a conventional vehicle and a vehicle converted to electric drive. Taking into account the above, the work and research carried out lead to the following conclusions:

– converting a conventional drive system to an electric one is possible. However, this requires significant modifications to the motorcycle vehicle's systems, and the vehicle's approval for operation requires meeting additional requirements
– as a result of the conversion, the motorcycle's weight decreased by 9 kg and top speed increased from 104 to 118 km/h
– the unit energy consumption, determined on the basis of measurements taken during rides in spring and summer (motorcycle season) is 8.1 kWh/100 km, which, taking into account the reference price of electricity, results in approximately half the cost of using the motorcycle than before the conversion
– the results of the conducted measurements showed that a drop in ambient temperature causes an increase in energy consumption. However, it is also strongly dependent on the driving style (intense acceleration and use of regenerative braking)
– the increase in average travel speed does not have a significant impact on the increase in energy consumption
– using an electric motorcycle reduces operating costs not only related to energy supply, but also to fewer necessary vehicle maintenance activities. Considering also ecological considerations, this solution is an attractive alternative and complement to the range of individual means of urban transport.

Nomenclature

BEV	battery electric vehicle
BLDC	brushless direct current
BMS	battery management system
eTCR	eTouring Car World Cup
ICE	internal combustion engine
SEC	specific energy consumption

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Piotr Hemlecki, MEng. – Faculty of Transport and Aviation Engineering, Silesian University of Technology, Poland.
e-mail: *piotr.hemlecki@polsl.pl*

Paweł Fabiś, DSc., DEng. – Faculty of Transport and Aviation Engineering, Silesian University of Technology, Poland.
e-mail: *pawel.fabis@polsl.pl*

Grzegorz Kubica, DSc., DEng. – Faculty of Transport and Aviation Engineering, Silesian University of Technology, Poland.
e-mail: *grzegorz.kubica@polsl.pl*