

Research Paper

Modeling, Simulation, and Assessment of Electric Motorcycle and Battery Characteristics under the Driving Cycle Test

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Abstract

Global warming, increasing temperatures, and air pollution have become significant challenges in the past decade due to traditional emissions. Therefore, using green energy, especially electric vehicles and electric motorcycles, is the key solution to protecting the environment. Electric motorcycles are widely used in many countries due to their convenience, ease of use, and flexibility. Thus, modeling and simulating electric motorcycles are crucial for accurately calculating and designing the battery pack energy requirements. In this study, electric motorcycles were modeled and simulated to investigate energy characteristics under driving cycle test using Matlab/Simulink software. The results show the electric motorcycle dynamics and energy consumption, the influence of electric motorcycle mass, aerodynamic drag, the quality of the road, road slope angle on the electric motor power, and operating ambient temperature on the battery behavior in the heat generation. In addition, the characteristics of batteries and suitability for selecting of battery required power were compared under various batteries and proposed the best battery for the electric motorcycle. The battery trademark of the A123 (pouch) model was selected as the most suitable for the required battery pack owing to superior characteristics compared to other batteries, with the insight characteristics of high capacity of 19.5 Ah, continuous current of 19.5 A, mass of battery pack of 9.45 kg, and number of cells of 19, with total average energy consumption of 28.23 Wh km⁻¹. This study is significant for the design and precise calculation of the battery's required power for new electric motorcycles.

Keywords: Electric motorcycle; Driving cycle test; Modeling and simulation; Energy consumption; Battery characteristic; Battery pack

1. Introduction

Recently, numerous studies on internal combustion engines (ICEs) have focused on enhancing engine performance [1], [2], [3] and developing systems [4] to improve efficiency. However, traditional energy sources still pose significant challenges due to emissions, especially with internal combustion engines. In contrast, green transportation technology has become increasingly popular worldwide, leading to rapid growth in the fields of electric vehicles (EVs) and

electric motorcycles (EMs) [5]. The use of electric motorcycles has rapidly increased in many countries due to their convenience, ease of use, and flexibility [6]. Indeed, EMs offer numerous benefits over traditional ICEs. They generate no emissions, promoting cleaner air and lowering greenhouse gas levels. Additionally, EMs typically offer higher cost-effectiveness due to lower maintenance and operating costs. Their quiet operation also helps reduce noise pollution in urban areas.



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Nomenclature	
A_f : Frontal area of EM (m^2)	WLTC : Worldwide harmonized Light-duty Vehicle Test Cycles
$A(p)$: A123 (pouch)	E_{bs} : Battery energy content of one string (Wh)
$A(c)$: A123 (cylindrical)	E_{aux} : Average energy consumption of auxiliary loads (Wh km^{-1})
c_j : Concentration of the species of j ($mol\ m^{-3}$)	E_s : Total energy consumption (Wh)
C_{bp} : Capacity of a battery pack (Ah)	E_{cb} : Energy of the cell battery (Wh)
C_{cb} : Battery cell capacity (Ah)	E_g : Energy density by weight (Wh kg^{-3})
C_{rate} : Charge-discharge ratio (h^{-1})	F_R : Force of rolling resistance (N)
C_d : Aerodynamic drag coefficient	F_G : Gravitational force (N)
C_R : Rolling resistance coefficient	F_{Ad} : Force of aerodynamic drag (N)
C_{cb} : Capacity of the cell battery (Ah)	F_T : Total required traction force (N)
C_{max} : Maximum charge-discharge ratio (h^{-1})	F_A : Force of acceleration (N)
D_{cb} : Diameter of the cell battery (cm)	g : Gravity acceleration ($g = 9.81\ m\ s^{-2}$)
EM : Electric motorcycle	H_{cb} : Height of the cell battery (cm)
E_p : Average energy consumption (Wh km^{-1})	$\overline{H}_j$: Partial molar enthalpy (J mol^{-1})
E_{aec} : Total average energy consumption (Wh km^{-1})	I_{bpc} : Continuous current of the battery pack (A)
E_v : Energy density by volume (Wh m^{-3})	I_{bmc} : Battery pack maximum current (A)
I_{bpc} : Continuous current of the battery pack (A)	I_{smc} : String max current (A)
I_{bmc} : Battery pack's maximum current (A)	$\dot{Q}$: Battery pack's heat generation rate (W)
I_m : Operating current of the battery pack (A)	Q_{joule} : Ohmic (Joule) heating (W)
I_{scc} : String continuous current (A)	$Q_{entropic}$: Entropic (reversible) heat (W)
$K(p)$: Kamco (pouch)	R_b : Internal resistance of the battery (Ω)
L_{cb} : Length of the cell battery (cm)	R_w : Wheel radius (m)
L : Total length of the driving cycle (km)	t : Time (s)
M_{sp} : Total number of strings of batteries connected in series that are connected in parallel	T : Operating ambient temperature (K)
M_{EM} : Electric motorcycle mass	T_{EM} : Torque of electric motorcycle (Nm)
$M(c)$: Molice (cylindrical)	T_{cb} : Thickness of the cell battery (cm)
M_{EM} : Mass of electric motorcycle (kg)	$T(p)$: Toshiba (pouch)
m_{cb} : Cell battery mass (kg)	U : Open circuit voltage (V)
m_{bp} : Mass of the battery pack (kg)	U_{bp} : Voltage of the battery pack (V)
N_{cp} : Total number of cell batteries in the battery pack	U_{cb} : Cell battery voltage (V)
N_{cs} : Number of cells connected in series for each string	U_{bp} : Rated voltage of the battery pack (V)
PMR : Power-to-mass ratio	U^{avg} : Voltage of the property evaluated at the volume-averaged concentration (V)
P(c) : Panasonic (cylindrical)	$V_{cv(c)}$: Volume of the cell (cylindrical (L))
$P_{EM(max)}$: Maximum rated power (W)	$V_{cv(p)}$: Volume of the cell battery (pouch (L))
P_{bmp} : Maximum battery pack power (W)	V : Velocity of electric motorcycle ($km\ h^{-1}$)
P_{bpc} : Battery packs continuous power (W)	V_{bp} : Volume of battery pack (m^3)
P_{EM} : Power of electric motorcycle (W)	v : Volume of the battery (m^3)
P_{aux} : Power of auxiliary loads (W)	W_{cb} : Width of the cell battery (cm)
Greek letter	
ρ_{air} : Air density ($\rho_{air} = 1.25\ kg\ m^{-3}$)	$\frac{\partial U}{\partial T}$: Coefficient of voltage temperature (mV K^{-1})
α : Slope angle of the road	ΔH_i^{avg} : Chemical reaction enthalpy variation of i (J mol^{-1})
Δt : Duration of electric motorcycle operation (h)	η_p : Efficiency of the powertrain

During EM operation, various factors influence its performance, including tractional forces, road quality, load mass, external forces, geometry design, and operating conditions. Therefore, the dynamics of EM were considered and investigated during operation. Hanifah *et al.* [7] carried out a simulation of the kinematics and dynamics of EM and concluded that the model was suitable for estimating the range traveled. Koenen *et al.* [8] investigated the vibration of the motorcycle in curves using a mathematical model

with eight degrees of freedom, demonstrating that the model effectively implemented rider behavior and the impact of road surface quality on vibration. Cossalter *et al.* [9] modeled and simulated the steady turning of motorcycles using nonlinear equations that considered the longitudinal and lateral slip of the wheels. They discussed the effects of tire characteristics, geometry, and inertial properties on steering torque in detail. Lin *et al.* [10] proposed a dynamic system for EM using feedback linearization

techniques to track EM velocity, revealing that the model was suitable for designing and controlling longitudinal velocity. Del Rosso *et al.* [11] constructed a mathematical model to investigate and validate motorcycle dynamics at low speeds, indicating the model's suitability for model-based control design. Sharp *et al.* [12] advanced the modeling of motorcycle dynamics, considering various factors. Their results indicated that the model was reasonable and observed various factors. Chen *et al.* [13] simulated the dynamics of a parallel hybrid electric motorcycle (HEM) using Matlab/Simulink software, showing an 11.6% improvement in fuel consumption compared to traditional motorcycles. Similarly, Shao *et al.* [14] conducted simulations and experiments on the parallel HEM dynamics, revealing the superiority of HEM over traditional motorcycles. Zhu *et al.* [15] performed a study on motorcycle dynamics under nonslip and slip conditions during turning, showing that the steering torque matched the model after verification. Hima *et al.* [16] developed a motorcycle dynamic model with six linked bodies using the algorithmic Lagrange equation, revealing that the model considered numerous external forces and performed well on a straight-line profile. Bonci *et al.* [17] simulated motorcycle dynamics, considering tire slip and rear traction. Their results demonstrated various behaviors exhibited by a real motorcycle navigating a curve or when the supplied torque was high enough to cause longitudinal slip. Moreno Giner *et al.* [18] developed a model to analyze motorcycle dynamics using Maple mathematical software, concluding that the model provided a basis for developing a virtual rider. Ringdorfer *et al.* [19] proposed a control strategy to investigate the stability of EVs by monitoring sensor signals. Their results showed that the EV motion controller could adapt to preserve driving safety during signal faults. Xian *et al.* [20] simulated the dynamics of EVs under various driving cycles in Matlab's ADVISOR environment, concluding that energy consumption per distance was higher for larger vehicles. Armenta-Déu *et al.* [21] developed a new method to estimate EV range under different driving conditions, including descent, ascent, constant speed, deceleration, and acceleration. Their results provided insights into EV dynamics under various conditions, such as changes in shape, size, and mass. Pardhi *et al.* [22]

modeled and simulated vehicle dynamics to assess the effect of the electric motor on the regenerative braking system using Matlab Simulink. Their results showed that the regenerative braking system significantly impacted vehicle dynamics. Yap *et al.* [23] proposed a multi-model approach to simulate hybrid electric scooter performance and evaluate economic effectiveness. They demonstrated significant reductions in fuel consumption and energy costs for electric scooters. Naik *et al.* [24] evaluated and analyzed in detail the effects of energy consumption, power, torque requirements, and the dynamic performance of EV-based motorcycles compared to conventional motorcycles.

The battery's dynamic energy and characteristics play a crucial role during EM operation, as they determine the EM's operational distance. Numerous studies have focused on battery energy. Indeed, LeBel *et al.* [25] presented a method for battery pack sizing in EMs, showing how to calculate the number of cells in parallel and series under various battery pack dimensions. Chan *et al.* [26] examined several models of battery use in EVs and battery energy storage, proposing a method to mitigate high-frequency charging and discharging currents. Vermeer *et al.* [27] reviewed battery characteristic models, highlighting the effect of operational stress factors on battery aging. Dubarry *et al.* [28] introduced a new method to evaluate battery performance and characteristics, demonstrating its superiority over traditional methods. Additionally, Dubarry *et al.* [29] modeled battery energy storage to investigate battery characteristics and performance under various operating conditions, concluding that the model achieved high accuracy in monitoring the battery.

Ménard *et al.* [30] developed and experimentally validated a lithium-ion battery model, providing insights and proposing the Bond Graph model. Benabdelaziz *et al.* [31] created a simulation model of battery dynamic energy for electric vehicles using Matlab/Simulink software, proposing a dynamic model that considers temperature changes for EVs. Chen *et al.* [32] studied the battery dynamic energy model using SimPlorer software to evaluate battery dynamics under various operating conditions, revealing an overview of battery dynamic energy

under different conditions. Tremblay *et al.* [33] conducted modeling and experiments to evaluate the battery dynamic characteristics for EVs, showing that the battery dynamic model closely matched experimental data. Han *et al.* [34] developed a thermal battery dynamic model for EV applications. They concluded that the model is significant for managing battery thermal performance. Zhang *et al.* [35] modeled battery dynamics for HEV applications under various operating conditions, providing insights for optimizing battery performance using multi-objective approaches. Hu *et al.* [36] developed a dynamic battery model using linear varying parameters for automotive applications, revealing that the model can be applied to both lithium-ion and nickel-metal hydride (NiMH) batteries. Paganelli *et al.* [37] conducted simulations of a battery dynamic model and estimated the state of charge for hybrid EV batteries, offering insights into energy management strategies for hybrid EVs. Mesbahi *et al.* [38] developed a battery dynamic model and proposed an optimization algorithm for optimal EV parameters, indicating a modeling error of only 0.5% under various operating conditions. Cao *et al.* [39] developed a battery dynamic model considering multiple factors, showing that the simulation results closely matched the measurement data.

In summary, numerous studies have modeled and simulated EM dynamics and battery energy models for EMs and EVs, but these studies remain limited. Recently, most studies have focused on EM dynamic models and battery energy models separately and independently. In this study, the modeling, simulation, and assessment of EM and battery characteristics under driving cycle tests were conducted and discussed in detail. In other words, the EM dynamics and battery characteristics were combined and considered in the driving cycle test. In our previously published [40], the techno-economic factor was considered under varying driving cycle tests, while the EM and battery pack characteristics were considered under various operating conditions, including the effect of external factors, and the behavior of heat generation of the battery pack was discussed and analyzed in detail in this study. The results reveal the dynamics and energy consumption of electric motorcycles, the influence of electric motorcycle mass, aerodynamic drag, road slope, and the

quality of the road on the electric motor power. Additionally, the batteries' characteristics and suitability for selecting the required battery power were compared under various conditions, proposing the best battery for the electric motorcycle. This study is significant for the design and precise calculation of the battery's required power for new electric motorcycles.

2. Methods

Figure 1 illustrates the flowchart for modeling, simulation, and assessment of the EM in this study. The modeling and simulation were conducted in the Matlab/Simulink software. Firstly, the specifications of the EM were investi-

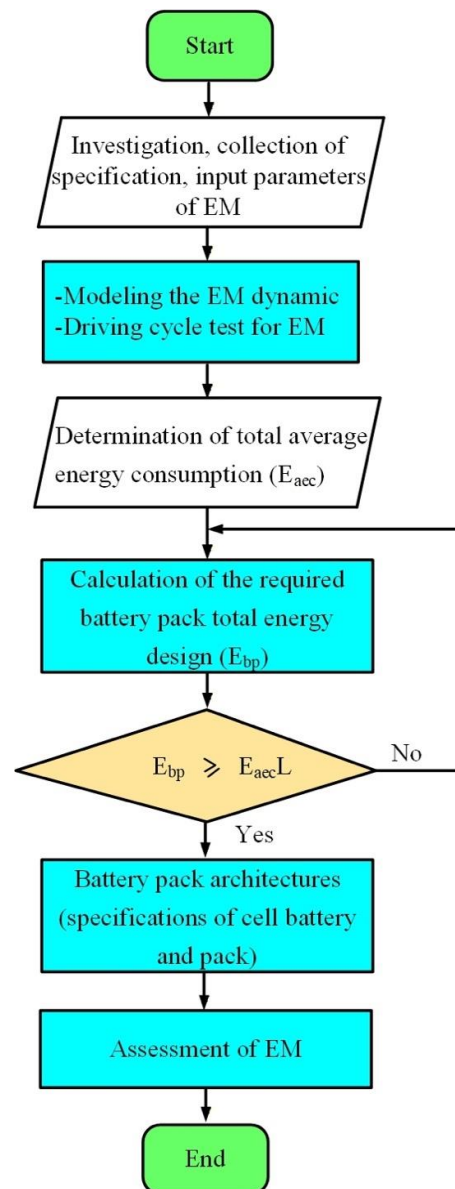


Figure 1. Flowchart of modeling, simulation, and assessment of EM in this study

gated and collected. Secondly, the modeling and simulation of EM dynamics were performed under a driving cycle test to calculate the total average energy consumption. Next, the required battery pack total energy design was determined and compared with the average energy consumption using the driving cycle test. It is noteworthy that the required battery pack should be higher than the average energy consumption. If the average energy consumption is higher than the required battery pack total energy design, the calculation of the required battery pack total energy must be repeated, as the supplied power should exceed the auxiliaries' power. Ultimately, the battery pack architecture and the assessment of the EM dynamics were discussed and evaluated in this study.

2.1. Driving Cycle Test for Electric Motorcycle

The cell battery was linked in parallel and series to produce the battery pack with high voltage and capacity in the EM. The high voltage of the battery is the key parameter and plays an important role in EM. Because it represents the dynamic performance, charging time, and range operation of EM. Additionally, the average energy consumption and range operation of EM are the key metrics to calculate the battery-required power. Therefore, the driving cycle test should be used to determine average energy consumption and the range operation of EM following international standardization. In this study, the EM characteristics were carried out under a driving cycle test. The average energy consumption was determined on a homologation cycle. On the other hand, the EM in this study

belongs to the light vehicle type. Thus, the Worldwide harmonized Light-duty Vehicle Test Cycles (WLTC) was utilized reasonably in this study. Recently, the WLTC was classified into 3 classes depending on the rated power ($P_{EM(max)}$) and kerb mass of EM (M_{EM}) and represented by the power-to-mass ratio (PMR), as summarized in [Table 1](#). The PMR can be calculated as follows:

$$PMR = \frac{P_{EM(max)}}{M_{EM}} \quad (1)$$

The rated power of the EM was 1800 W, and the mass of the EM without a load was 112 kg in this study. Therefore, the PMR was determined to be 16.07, which is lower than 22. Consequently, the WLTC class 1 was used to conduct the simulation. The EM was operated with two phases: Phase 1 represents low-speed operation in urban regions, while Phase 2 corresponds to medium-speed operation in suburban regions. The characteristics of WLTC class 1 were described in detail and summarized in [Table 2](#).

The velocity profile of WLTC class 1 is shown in [Figure 2](#) and includes two phases: low and medium speed. Phase 1 represents the EM operation in the urban region with low velocity and a duration of 589 s. Phase 2 denotes the EM operation in the rural area with medium velocity and a duration of 433 s. Additionally, the driving cycle test in this study was embedded and modeled, as illustrated in [Figure 3](#). The output parameters, including distance, velocity, and acceleration of the EM, were utilized for calculating the properties of the propulsion system and auxiliary system of the EM in the next section.

Table 1. The characteristics of classes of WLTC [41]

Class	PMR	Speed phase	Description
1	$PMR \leq 22$	Low, and medium	The driving cycle test was used for low-power vehicles. The cycle performed a low-medium-low velocity sequence. The medium-velocity region was substituted with a low-velocity region when the maximum velocity of EM was less than 70 km h ⁻¹ .
2	$34 \geq PMR > 22$	Low, medium, and high	The driving cycle test was used for medium-power vehicles. The cycle performed a low-medium-high velocity sequence. The high-velocity region was substituted with a low-velocity region when the maximum velocity of EM was less than 90 km h ⁻¹ .
3	$PMR > 34$	Low, medium, high, and very high	The driving cycle test was used for high-power vehicles. The cycle performed low-medium-high-very high-velocity segments, with non- and urban parts accounting for 48% and 52% of the cycle, respectively. The low, medium, high, and very high velocities reached up to 56.5, 76.6, 97.4, and 131.3 km h ⁻¹ , respectively.

Table 2. The WLTC with class 1 characteristics in this study [41], [42]

Description	Low	Medium	Total
Duration (s)	589	433	1022
Distance (m)	3324	4767	8091
Stop time (s)	155	48	203
% of stop	26.3%	11.1%	19.90%
Highest acceleration / m s ⁻²	0.76	0.63	–
Minimum acceleration / m s ⁻²	-1.00	-0.57	–
Mean velocity without stops / km h ⁻¹	27.6	44.6	35.6
Highest velocity / km h ⁻¹	49.1	64.4	–
Mean velocity with stops / km h ⁻¹	20.3	39.6	28.5

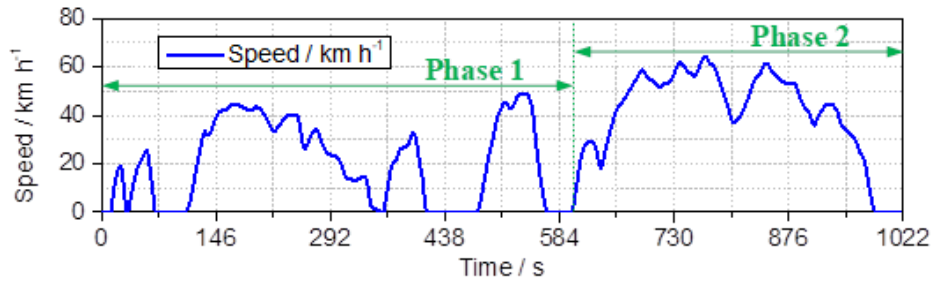


Figure 2. Velocity profile of WLTC with class 1 in this study

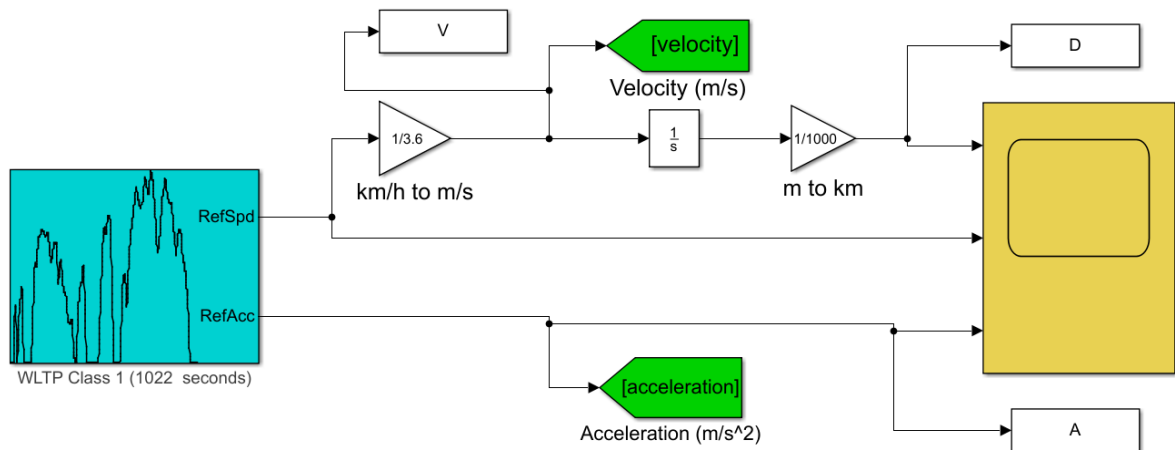


Figure 3. WLTC with class 1, including distance, velocity, and acceleration of EM in Matlab/ Simulink

2.2. Modeling the Electric Motorcycle Dynamics

The parameters of the commercial EM Klara S model were utilized for modeling and simulation under a driving cycle test in this study. The specifications of the EM Klara S are tabulated in Table 3.

As we all know, the propulsion system and auxiliary system affect the required battery power during EM operation in WLTC. Therefore, the input parameters are listed in Table 4 to update the model. Obviously, when evaluating battery characteristics, certain parameter inputs should remain constant, assuming that driver behavior is normal during the driving cycle test. Additionally, the electric motorcycle was

operated in a straight line, without any cornering, throughout the entire driving cycle test.

During EM operation, the dynamics of the EM are influenced by various forces, as illustrated in Figure 4. Specifically, the EM is affected by the acceleration force, the force of the rolling resistance, the force of the gravitational, and the force of aerodynamic drag. All these forces are measured in Newtons (N). The total required traction force at the wheel can be determined using the following governing equation:

$$F_T = F_A + F_{Ad} + F_R + F_G \quad (2)$$

where: F_T , F_A , F_{Ad} , F_R , and F_G represent the total force, the force of acceleration, the force of

aerodynamic drag, the force of rolling resistance, and gravitational force, respectively.

The force of acceleration depends on the mass of EM and acceleration and can be calculated using Eq. (3):

$$F_A = M_{EM} \frac{dV}{dt} \quad (3)$$

where M_{EM} is the EM mass, in kg, and V is the velocity of EM, in km h⁻¹.

Table 3. Specifications of EM Klara S model [43] in this study

Parameter	Value	Unit
Electric motorcycle weight	112	kg
Rated power	1800	W
Maximum power	3000	W
Max velocity	78	km h ⁻¹
Wheelbase	1313	mm
Clearance ground	125	mm
Length x Width x Height	1895 x 678 x 1130	mm
Max carry-on luggage	130	kg
Charging time	5.5	h
Electric motor type	Bosch/In-hub	Dimensionless
Battery type	Lithium-ion	Dimensionless

Table 4. Input parameters to simulate characteristics of EM in the Matlab/Simulink environment

Description	Symbol	Value	Unit
Mass of EM and driver	M_{EM}	177	kg
Frontal area of EM	A_f	0.9	m ²
Wheel radius	R_w	0.24	m
Density of air	ρ_{air}	1.25	Ns ² m ⁻⁴
Gravitational acceleration	g	9.81	m s ⁻²
Propulsion system efficiency	η_p	90	%
Rolling resistance coefficient	C_R	0.011: urban (phase 1) 0.023: suburban (phase 2)	dimensionless
Transmission ratio	–	1.0	dimensionless
Aerodynamic coefficient	C_d	0.6	dimensionless

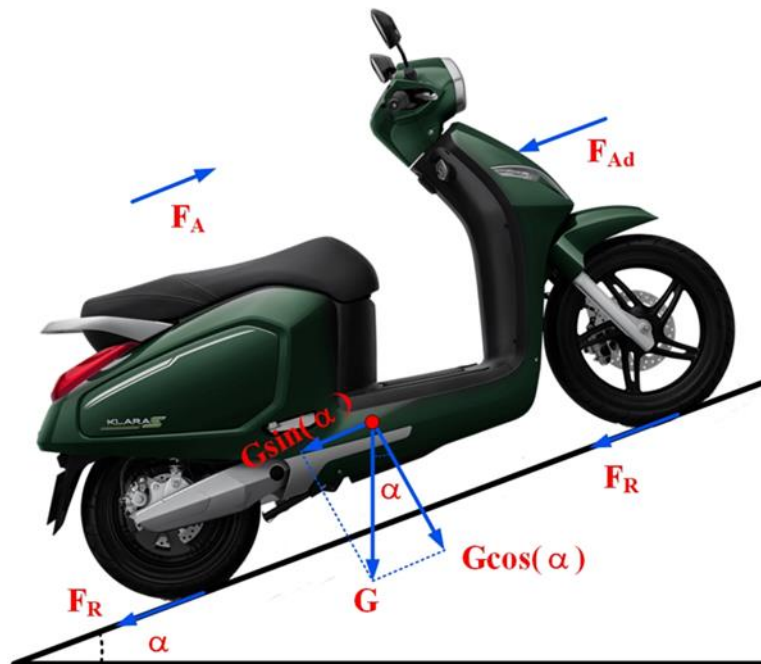


Figure 4. Dynamic of EM in this study

The force of aerodynamic drag is a function of the frontal area and velocity of the EM, determined as follows:

$$F_{Ad} = \frac{1}{2} \rho_{air} C_d A_f V^2 \quad (4)$$

where ρ_{air} , C_d , and A_f denote the air density ($\rho_{air} = 1.25 \text{ kg m}^{-3}$), aerodynamic drag coefficient, and frontal area of EM, in m^2 , respectively.

During EM operation, the rolling resistance force affects the wheel. It depends on the mass of the EM and the quality of the road surface, which is determined by the rolling resistance coefficient. In this study, the EM was operated under the driving cycle test of WLTC class 1. Thus, the rolling resistance coefficient varied during the low and medium speed phases, corresponding to urban and suburban regions. For the urban and suburban regions, the EM was operated on good asphalt or concrete pavement and gravel roads, resulting in rolling resistance coefficients of 0.011 and 0.023, respectively [44]. The rolling resistance force is calculated by Eq. (5):

$$F_R = g C_R M_{EM} \cos(\alpha) \quad (5)$$

where g denotes the gravity acceleration ($g = 9.81 \text{ m s}^{-2}$), C_R represents the rolling resistance coefficient, and α is the slope angle of the road.

The gravitational force was determined by Eq. (6). The gravitational force affected the EM, it depends on the mass of the EM and the slope angle. When the EM operates on a flat road, the slope angle is zero. Thus, the gravitational force will be ignored during the flat road.

$$F_G = g M_{EM} \sin(\alpha) \quad (6)$$

Because the EM Klara S model uses an Inhub-type electric motor, which is placed at the wheel hub, power is transmitted directly from the motor to the wheel. The required electric motor power and torque of the propulsion system can be determined as follows:

$$P_{EM} = F_T V \quad (7)$$

$$T_{EM} = F_T R_w \quad (8)$$

where R_w is the wheel radius, in m.

Ultimately, the total energy consumption during EM operation, in Wh, is determined by Eq. (9):

$$E_s = \int_0^{t_e} P_{EM} dt \quad (9)$$

where: t_e represents the end time in the driving cycle test, in seconds.

Therefore, the average energy consumption, in Wh per km, for the propulsion of EM during the driving cycle test can be calculated as follows:

$$E_p = \frac{E_s}{L} \quad (10)$$

where L is the total length of the driving cycle, in km.

Figure 5 illustrates the modeling and calculation of average energy consumption for the propulsion of EM during the driving cycle test. The average energy consumption depends on the distance of EM operation and the power of the electric motor.

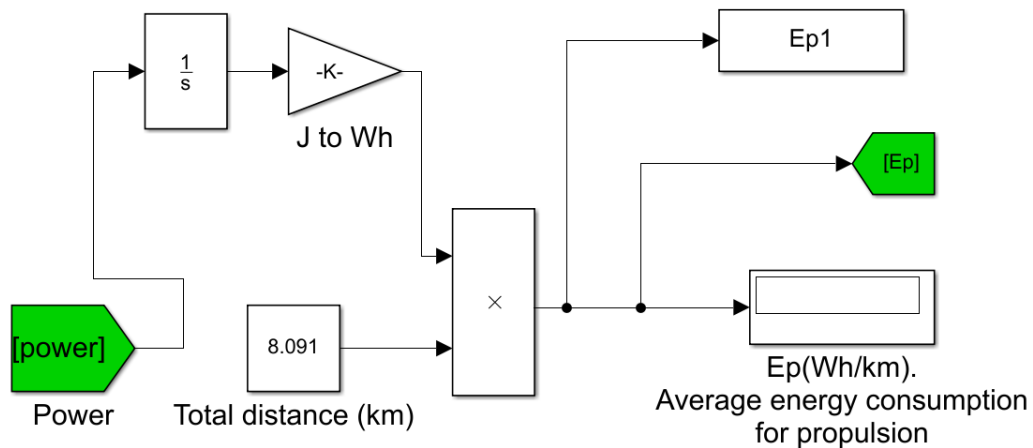


Figure 5. Modeling and calculation of average energy consumption for the propulsion system of EM during the driving cycle test

From Eq. (2) to Eq. (8), the key dynamics metrics of EM, including total forces, power, and torque, were modeled during the EM operation in the driving cycle test. **Figure 6** indeed illustrates the EM propulsion system modeling under the impact of forces. The subsystem block includes partial forces such as gravitational force, rolling resistance force, aerodynamic force, and acceleration force.

During the operation of the EM, auxiliary power consumption was considered as it affects the power required from the battery. The auxiliary power consumption is summarized in **Table 5**. The auxiliary power was of the EM Klar S model, similar to the EM Evo200 Vinfast model due to the same manufacturer and model. Auxiliary power in the EM consists of permanent and intermittent loads. Permanent auxiliary loads include the battery management system (BMS), headlight system, and information display system. Intermittent auxiliary loads include the signal light system, brake light system, and horn system. The auxiliary power in EM was depicted in detail

in the **Figure 7**. The average energy consumption of auxiliary loads, in Wh km⁻¹, in the EM can be estimated as follows:

$$E_{aux} = \frac{P_{aux}\Delta t}{L} = \frac{(P_{ap} + P_{ai})\Delta t}{L} \quad (11)$$

where: P_{aux} , and Δt represent the power of the auxiliary, in W, and the total time during the driving test cycle, in h, respectively. In addition, P_{ap} and P_{ai} denote the permanent auxiliary loads, in W, and intermittent auxiliary loads, in W, respectively.

The permanent auxiliary load in EM, in W, consisted of the power of the battery management system, screen information light system, and headlight (high beam) system. It was determined by Eq. (12):

$$P_{ap} = P_{ab} + P_{as} + P_{ah} \quad (12)$$

where: P_{ab} , P_{as} , and P_{ah} refer to the auxiliary power of the battery management system, the screen information light system, and the highlight (head beam) system, respectively.

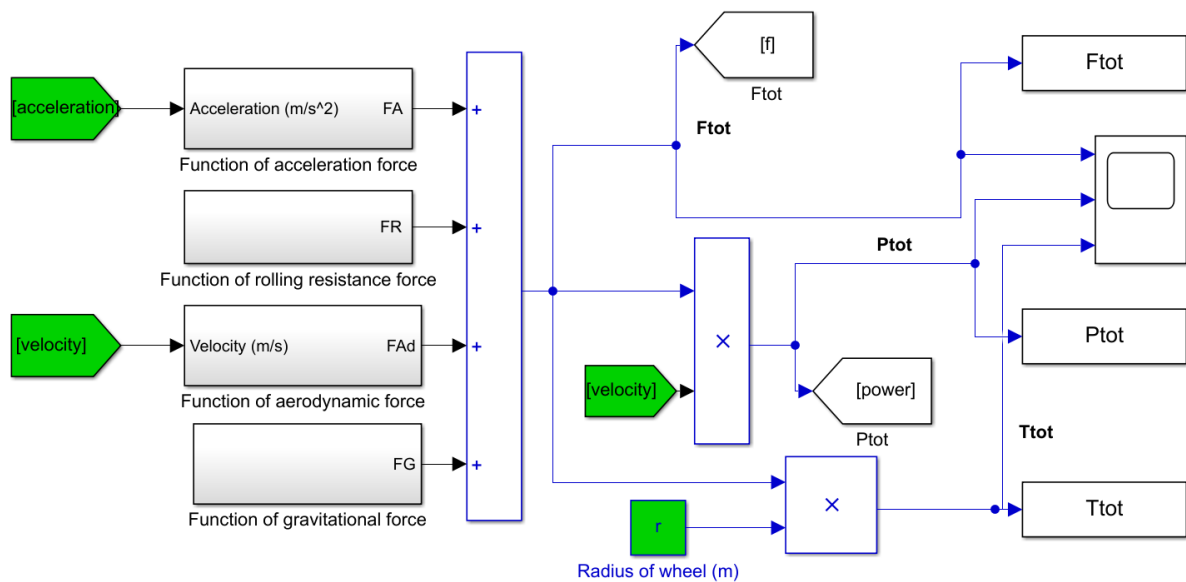


Figure 6. Modeling the propulsion of the EM system, including total forces, power, and torque

Table 5. The auxiliary power in the EM Klara S model [43]

Auxiliary power type	Description	Symbol	Value (W)	Total (W)
Permanent auxiliary loads	Battery management system	P_{ab}	18	59
	Screen information light system	P_{as}	6.0	
	Headlight (high beam) system	P_{ah}	35	
Intermittent auxiliary loads (account for 10%)	Signal light system	P_{ais}	10.24	3.48
	Braking light system	P_{aib}	9.6	
	Horn system	P_{aih}	15	

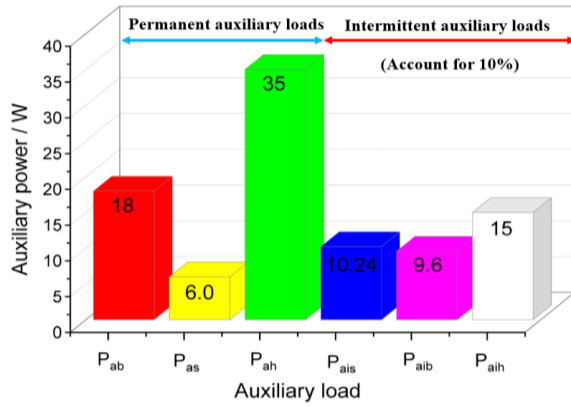


Figure 7. Permanent auxiliary loads, intermittent auxiliary loads in EM

The intermittent auxiliary loads encompassed the signal light system, brake light system, and horn system. Generally, intermittent auxiliary loads account for 10% of the total auxiliary load and were calculated by Eq. (13):

$$P_{ai} = P_{ais} + P_{aib} + P_{aih} \quad (13)$$

where: P_{ais} , P_{aib} , and P_{aih} represent the intermittent auxiliary loads of the signal light system, braking light system, and horn system, in W, respectively.

Ultimately, the total average energy consumption (E_{aec}), in Wh km⁻¹, was determined and the proposed in this study, which was described in Eq. (14):

$$E_{aec} = (E_p + E_{aux}) * (2 - \eta_p) \quad (14)$$

where: η_p is the efficiency of the powertrain, which changes the electric energy to mechanical energy. The second term, $(2 - \eta_p)$, serves as a

safety coefficient in designing the required battery pack power for the EM. In other words, the required battery pack power should be higher than the total average energy consumption of the EM to compensate for voltage losses during operation. In this study, the powertrain efficiency was 0.9; therefore, the resulting safety coefficient was 1.1.

It is noteworthy that the total average energy consumption is a crucial metric in designing and calculating the energy requirements for electric motorcycles (EM). The total energy capacity of the battery pack should meet or exceed the minimum total average energy consumption to optimize the battery pack. If the designed total energy of the battery pack is lower than the total average energy consumption, the EM may not operate due to insufficient energy to supply both the electric motor and auxiliary loads.

The modeling of the average auxiliary load's energy consumption during EM operation in WLTC was carried out and is shown in Figure 8. The average energy consumption of auxiliary loads, including both permanent and intermittent loads, depends largely on the duration and distance of the test cycle.

The total average energy consumption is crucial in designing and calculating the power requirements for EM. It serves as a key metric for determining the necessary battery capacity in this study. Figure 9 illustrates the modeling and calculation of total average energy consumption during EM operation in the driving test cycle. This includes the average energy consumption of auxiliary loads and propulsion systems.

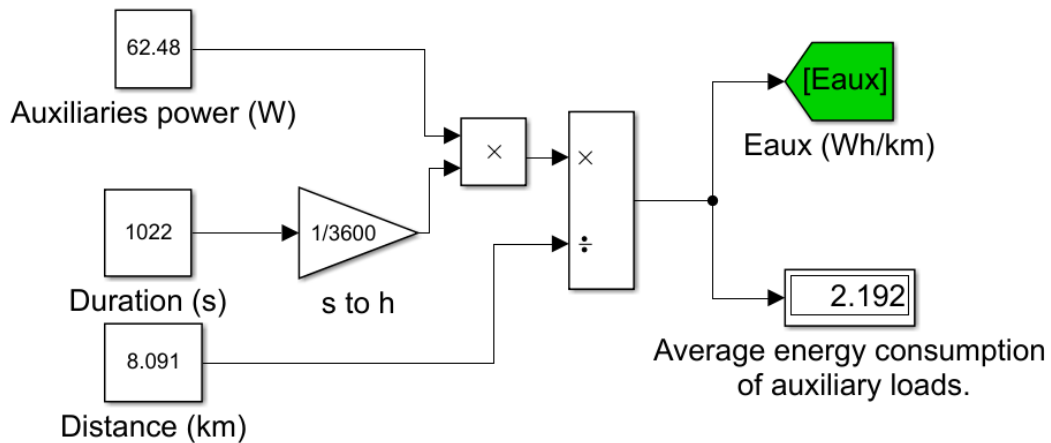


Figure 8. Modeling and calculation of the average auxiliary loads energy consumption during EM operation in WLTC

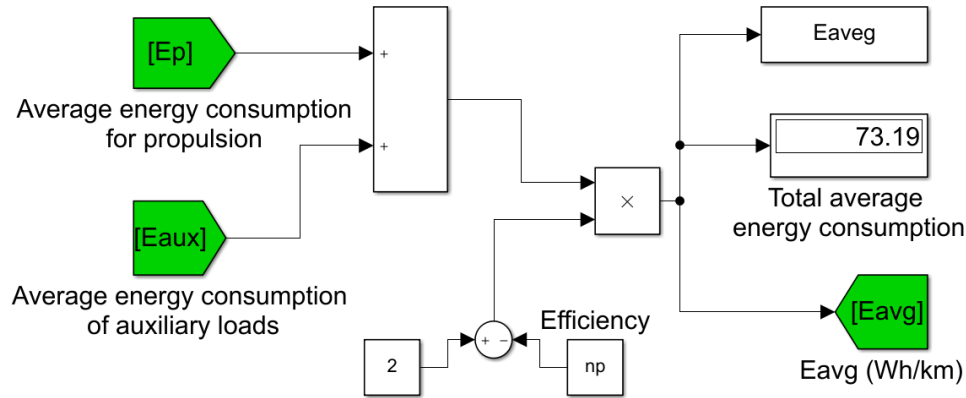


Figure 9. Modeling and calculation of total average energy consumption during WLTC

2.3. Modeling the Required Battery Energy for an Electric Motorcycle

2.3.1. Modeling the specifications of batteries

To generate a high voltage power source and current capacity for EM propulsion, the cell batteries are linked in groups arranged in parallel or in series to create a battery pack, as depicted in [Figure 10](#). The individual cells in these groups, whether linked in series or parallel, are called modules or packs. The total voltage of the battery pack was determined by summing the voltages of the individual cells when Ncs cells are linked in series. The dimensions of the battery pack rely on the characteristic dimensions of the cell battery and the required battery energy. To enhance current capacity in the EM, the battery cells are arranged in parallel by connecting Msp strings of series-connected cells.

In this study, battery characteristics were investigated across various battery trademarks

with the aim of recommending the best battery for EM, considering multiple factors. The specifications of battery cells available commercially, including basic dimensions, mass, capacity, voltage, and C-rate, are listed in [Table 6](#) based on manufacturer data. The batteries are divided into two categories based on the geometry type of the cell battery: Category 1 consists of batteries with a "pouch" geometry type, and Category 2 includes batteries with a "cylindrical" geometry type.

The battery dimensions, which relate to battery volume and mass, were considered primarily because they have a profound influence on the propulsion system. In addition, the volume of the cell battery depends on its geometry. Recently, cylindrical and pouch types have become popular in EM. The dimensions of cell batteries corresponding to cylindrical and pouch types are depicted in detail in [Figure 11a](#) and [Figure 11b](#).

Table 6. The specifications of cell batteries under various battery trademarks

Manufacturer	Category 1			Category 2		
	Kokam [45]	A123 (P) [46]	Toshiba [47]	A123 (C) [48]	Panasonic [49]	Molicel [50]
Model	SLPB7570270	20Ah	20Ah	ANR26650m1-B	NCR18650B	ICR-18650K
Symbol	K(p)	A(p)	T(p)	A(c)	P(c)	M(c)
Geometry type	Pouch	Pouch	Pouch	Cylindrical	Cylindrical	Cylindrical
L _{cb} (cm)	0	0	0	6.50	6.53	6.52
H _{cb} (cm)	27.20	22.70	10.30	0	0	0
D _{cb} (cm)	0	0	0	2.6	1.85	1.86
W _{cb} (cm)	8.20	16.0	11.50	0	0	0
T _{cb} (cm)	0.77	0.725	2.2	0	0	0
M _{cb} (kg)	0.317	0.496	0.51	0.076	0.0485	0.05
U _{cb} (V)	3.6	3.3	2.3	3.3	3.6	3.7
C _{cb} (Ah)	15.6	19.5	20	2.5	3.2	2.6
C _{rate} (h ⁻¹)	2	1	1	10	1	1
C _{max} (h ⁻¹)	3	10	1	24	1	2

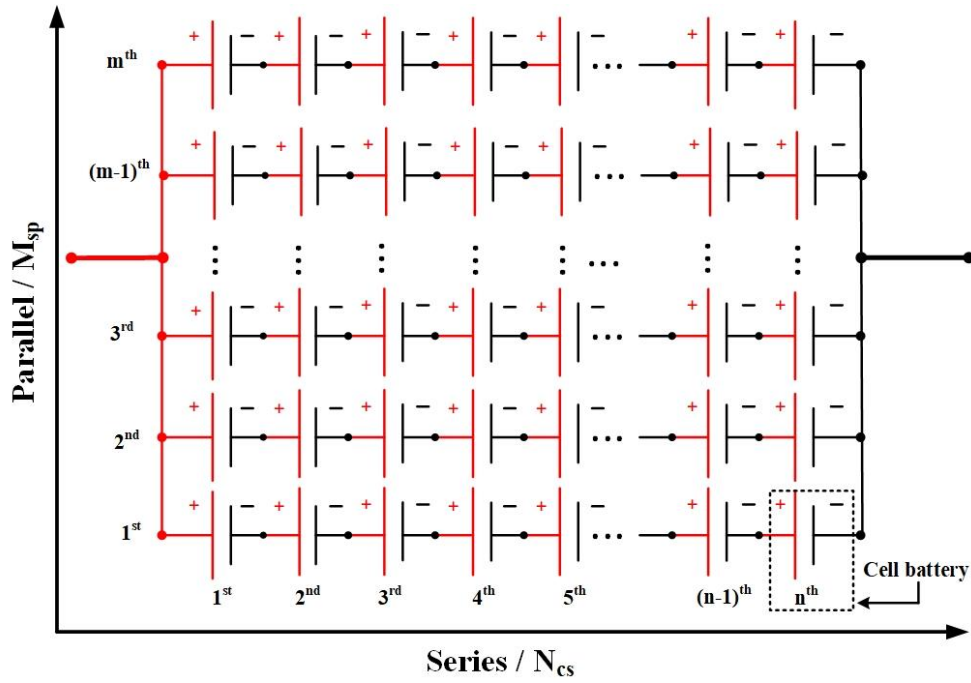


Figure 10. The architecture of cell battery in series and parallel in battery pack

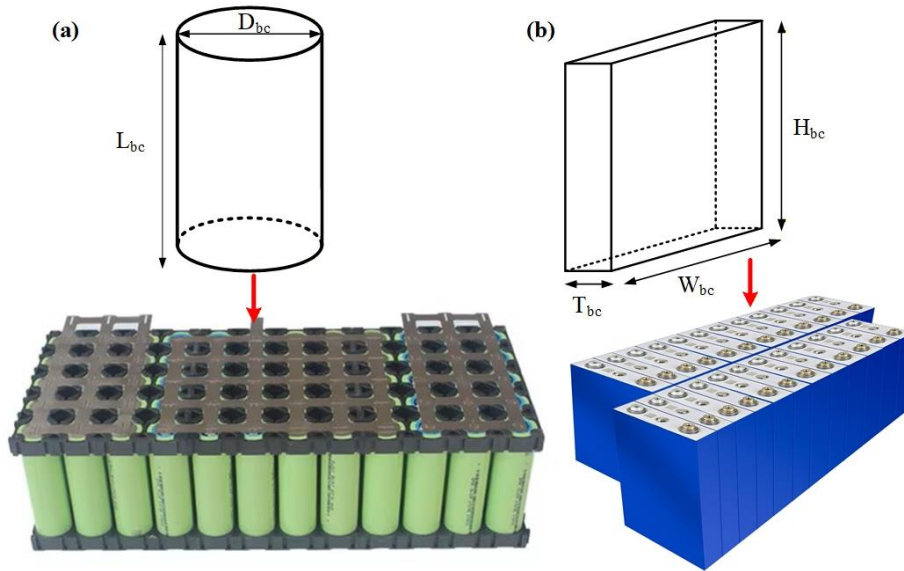


Figure 11. Illustration of the geometries and dimensions of a cell battery (a) Cylindrical; (b) Pouch

It was modeled as shown in [Figure 12](#). The cell battery volume for the cylindrical type ($V_{cv(c)}$) and pouch type ($V_{cv(p)}$) can be determined by Eq. (15) and Eq. (16), respectively.

$$V_{cv(c)} = \frac{\pi D_{cb}^2}{4} L_{cb} \quad (15)$$

$$V_{cv(p)} = T_{cb} W_{cb} H_{cb} \quad (16)$$

where: D_{cb} , L_{cb} , T_{cb} , W_{cb} , and H_{cb} denote the diameter of the cell battery, length of the cell battery, thickness of the cell battery, width of the cell battery, and height of the cell battery.

The energy of the cell battery (E_{cb}), in Wh, was calculated by Eq. (17):

$$E_{cb} = U_{cb} C_{cb} \quad (17)$$

where: U_{cb} and C_{cb} represent the cell battery voltage, in V, and the capacity of the cell battery, in Ah, respectively.

The cell battery energy density is a key parameter that determines the efficiency of cell energy relative to the size of the battery. Higher values indicate higher energy content for a given size of battery. The cell battery energy density includes energy density by weight (E_g), in Wh kg⁻¹

and energy density by volume (E_v), in Wh m^{-3} , were determined by Eq. (18) and Eq. (19), respectively.

$$E_g = \frac{E_{cb}}{m_{cb}} \quad (18)$$

$$E_v = \frac{E_{cb}}{V_{cv(c),(p)}} \quad (19)$$

where: m_{cb} is the cell battery mass, in kg.

Ultimately, based on the specifications of cell batteries provided by manufacturers in Table 6, the energy densities of different cell batteries were calculated and summarized in detail in Table 7. These calculations were also modeled as depicted in Figure 13.

To significantly of the cost of the cell battery, the cost per Wh of the cell battery, in $\$ \text{Wh}^{-1}$, can be calculated by Eq. (20):

$$\text{Cost per kWh} = \frac{\text{Cost}_{cb}}{U_{cb} \times C_{cb}} \quad (20)$$

where: Cost_{cb} represents the cost of the cell battery, in \$.

After modeling the dynamics of the EM and testing it in the WLTC driving cycle, the average energy consumption was calculated. To match the electric power supply for the EM, battery pack architectures were considered based on the total average energy consumption. Indeed, the minimum electric power required for the battery pack to supply the EM was determined as follow Eq. (21).

$$E_{bp} \geq E_{aec}L \quad (21)$$

The total required battery pack energy for the EM depends on the length of the WLTC driving cycle test. It was determined by Eq. (22):

$$E_{bp} = E_{aec}L \quad (22)$$

The battery architects were considered during the design of the battery pack for EM. The number of cells connected in series for each string (N_{cs}) was determined by Eq. (23) and modeling as depicted in Figure 14. Additionally, since the number must be an integer, the number of cells connected in series for each string was rounded up to the nearest integer:

$$N_{cs} = \frac{U_{bp}}{U_{cb}} \quad (23)$$

where: U_{bp} represents the rated voltage of the battery pack of EM, in V.

In addition, the battery energy content of one string (E_{bs}), in Wh, depends on the cell battery energy and the number of cells connected in series. It was determined by Eq. (24) and modeled as shown in Figure 15.

$$E_{bs} = N_{cs}E_{cb} \quad (24)$$

To increase the current capacity, the strings of cell batteries connected in series are combined in parallel to form the battery pack. The total number of strings of batteries connected in series that are connected in parallel (M_{sp}) can be determined by Eq. (25). It should be rounded up to the nearest integer:

$$M_{sp} = \frac{E_{bp}}{E_{bs}} \quad (25)$$

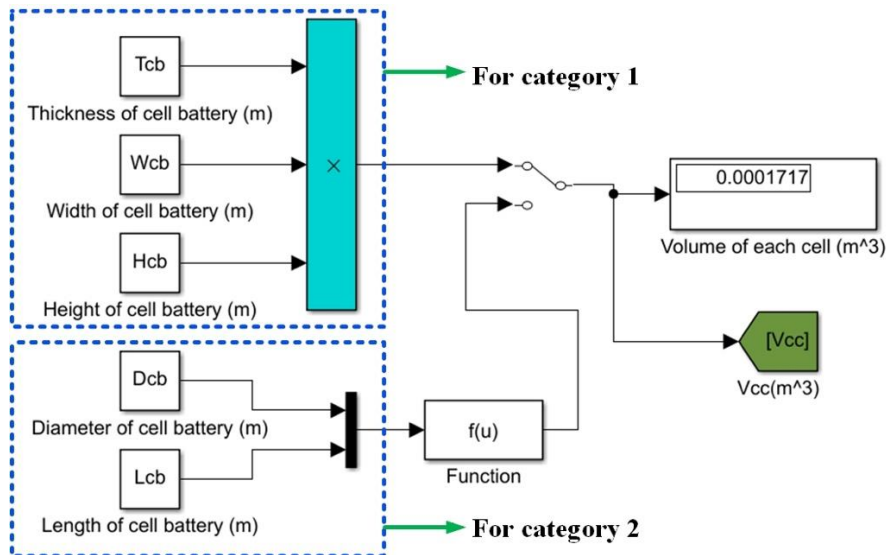


Figure 12. Modeling the volume of the cell battery based on the dimensions

Table 7. The energy density of a cell battery under various cell battery trademarks

Manufacturer	Category 1			Category 2		
	Kokam	A123 (P)	Toshiba	A123 (C)	Panasonic	MoliceI
Model	SLPB7570270	20Ah	20Ah	ANR26650m1-B	NCR18650B	ICR-18650K
Geometry type	Pouch	Pouch	Pouch	Cylindrical	Cylindrical	Cylindrical
Symbol	K(p)	A(p)	T(p)	A(c)	P(c)	M(c)
$V_{cv(c), (p)} \times 10^6$ (L)	171741	263320	260590	0.34510	0.17553	0.17716
E_{cb} (Wh)	56.16	64.35	46	8.25	11.52	9.62
E_g (Wh kg ⁻³)	177.16	129.74	90.20	108.55	237.53	192.40
E_v (Wh m ⁻³)	327	244.38	176.52	239.06	656.31	543.01
Cycle life (times)	4000	3000	2000	1000	400	1000
Cost (\$)	15	8.2	11	5.6	2.2	1.0
Cost per Wh	0.267	0.127	0.239	0.679	0.191	0.104

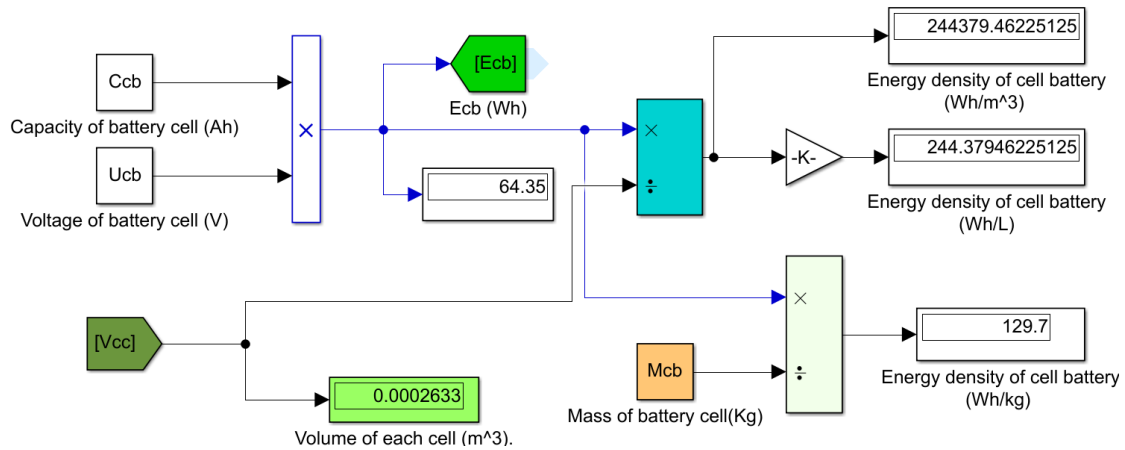


Figure 13. Modeling the energy density of a cell battery

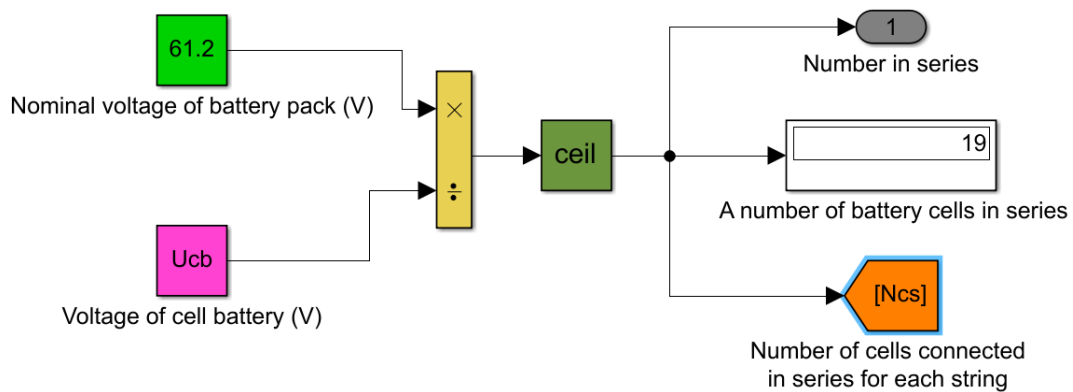


Figure 14. Modeling the number of cells of the battery in series for each string

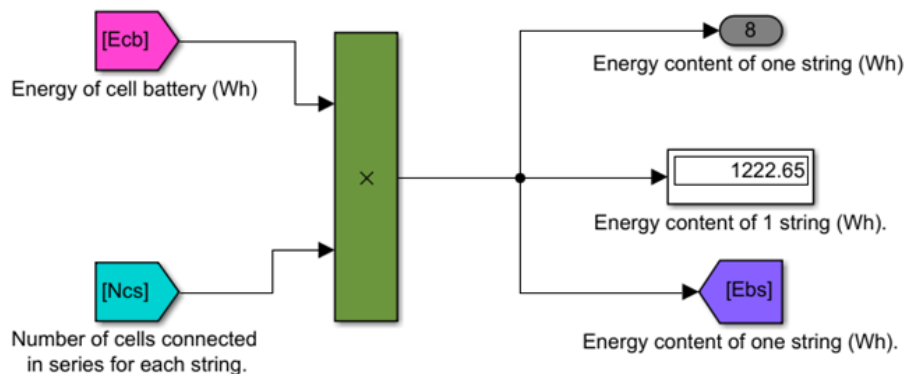


Figure 15. Modeling the energy content of one string

The capacity of a battery pack (C_{bp}), in Ah, can be estimated by the total number of strings battery pack of connected series was connected in parallel (M_{sp}) and cell battery capacity (C_{cb}):

$$C_{bp} = M_{sp} C_{cb} \quad (26)$$

The total number of cell batteries in the battery pack (N_{cp}) was determined through a total number of strings battery pack connected in series for each string (N_{cs}) and the total number of strings of batteries connected in series that are connected in parallel (M_{sp}). It was determined as follows:

$$N_{cp} = N_{cs} M_{sp} \quad (27)$$

Because the volume and mass of the battery pack affect the dimensions of EM, they were considered during the battery pack design process with the aim of reducing dimensions. The mass of the battery pack (m_{bp}), in kg, and volume of battery pack (V_{bp}), in m^3 , can be calculated using Eq. (28) and Eq. (29), respectively.

$$m_{bp} = N_{cp} m_{cb} \quad (28)$$

$$V_{bp} = N_{cp} V_{cv(c),(p)} \quad (29)$$

Figure 16 illustrates the modeling of key metrics such as the volume and mass of the battery pack, which are related to the number of cell batteries used.

2.3.2. Modeling the specifications of batteries

To ensure sufficient power supply for both propulsion and auxiliary systems, the cell batteries were connected in parallel and series to achieve high capacity and high voltage. Therefore,

the parameters of a high-voltage battery were considered and modeled in this study. Specifically, the string max current (I_{smc}), in A, is determined by the relationship between the battery cell capacity (C_{cb}), in Ah, and the maximum charge-discharge ratio (C_{max}) of the battery, in h^{-1} . It is calculated as follows:

$$I_{smc} = C_{cb} C_{max} \quad (30)$$

The battery pack's maximum current (I_{bmc}), in A, depends on the overall number of strings of the battery pack connected in parallel (M_{sp}) and the string max current (I_{smc}), in A. The highest current of the battery pack is the multiply of these values and is determined by Eq. (31):

$$I_{bmc} = M_{sp} I_{smc} \quad (31)$$

In addition, the maximum battery pack power (P_{bmp}), in W, was calculated using the battery pack voltage (U_{bp}), in V, and the battery pack maximum current (I_{bmc}), in A, as follows.

$$P_{bmp} = U_{bp} I_{bmc} \quad (32)$$

The string continuous current (I_{scc}), in A, was determined between the cell battery the capacity (C_{cb}), in Ah, and the charge-discharge ratio (C_{rate}) of the battery, in h^{-1} .

$$I_{scc} = C_{rate} C_{cb} \quad (33)$$

The continuous current of the battery pack (I_{bpc}), in A, can be defined by the relationship between the overall number of strings of the battery pack connected in parallel (M_{sp}) and the string continuous current (I_{scc}), in A. It is calculated using Eq. (34):

$$I_{bpc} = I_{scc} M_{sp} \quad (34)$$

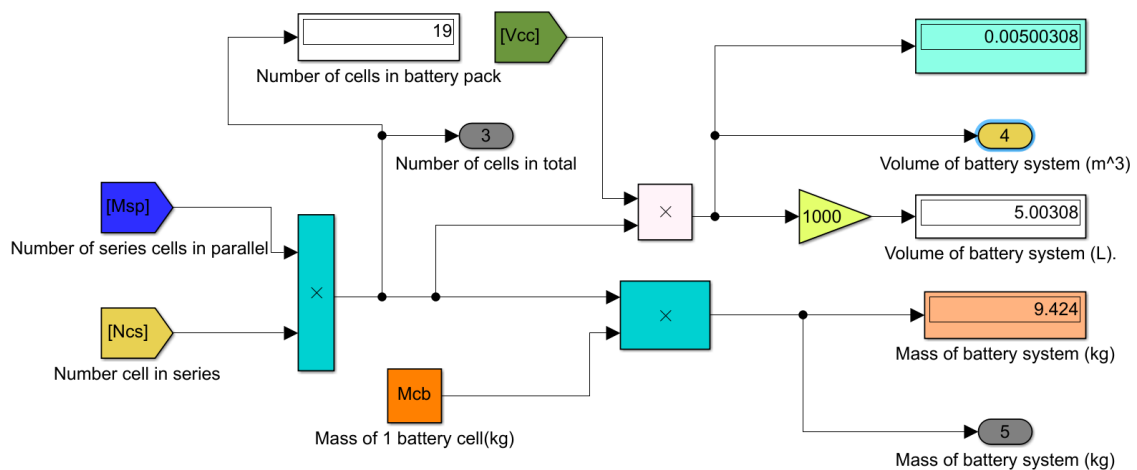


Figure 16. Modeling the battery pack volume and mass

Ultimately, the battery packs continuous power (P_{bpc}), in W, depends on the voltage of the battery pack (U_{bp}), in V, and the continuous current of the battery pack (I_{bpc}), in A. The continuous power of the battery pack is identified as follows:

$$P_{bpc} = U_{bp} I_{bpc} \quad (35)$$

From Eq. (30) to Eq. (35), the modeling was constructed as described in Figure 17. Additionally, the modeling of the battery pack requirements is illustrated in Figure 18. The primary input parameters included the battery pack nominal voltage and the overall average energy consumption. The expected output parameters consisted of the characteristics of the required battery pack, including the number of series connected in parallel, the number of cells in series, the total number of cells, the power of the battery pack, the volume and mass of the battery system, the string continuous current, the string maximum current, the battery pack capacity, and the energy content of one string.

2.3.3. Behavior of heat generation of the battery pack

During the EM operation in the driving cycle test, the operating ambient temperature affected the battery heat generation. Therefore, it was considered in this study. Indeed, the battery pack's heat generation rate, in W, occurred when the stored chemical energy turned to electric energy during EM operation, encompassed four terms, and was expressed in Eq. (36), which was derived from the Thomas and Newman equation [51].

As following Eq. (36), I_m represents the operating current of the battery, in A; U_{cb} denotes the operating voltage of the battery, in V; U refers to the open circuit voltage, in V; T was the operating ambient temperature, in K; $\frac{\partial U}{\partial T}$ is the coefficient of voltage temperature, in mV K⁻¹; ΔH_i^{avg} denotes chemical reaction enthalpy variation of i , in J mol⁻¹; r_i is the reaction rate of i ; $\bar{H}_j$ represents the partial molar enthalpy of species of j ; $\bar{H}_j^{avg}$ represents the property evaluated at the volume-averaged concentration partial molar

$$\dot{Q} = N_{cs} M_{sp} \left[I_m (U_{cb} - U) + I_m T \frac{\partial U}{\partial T} - \sum \Delta H_i^{avg} r_i - \int \sum_j (\bar{H}_j - \bar{H}_j^{avg}) \frac{\partial c_j}{\partial t} dv \right] \quad (36)$$

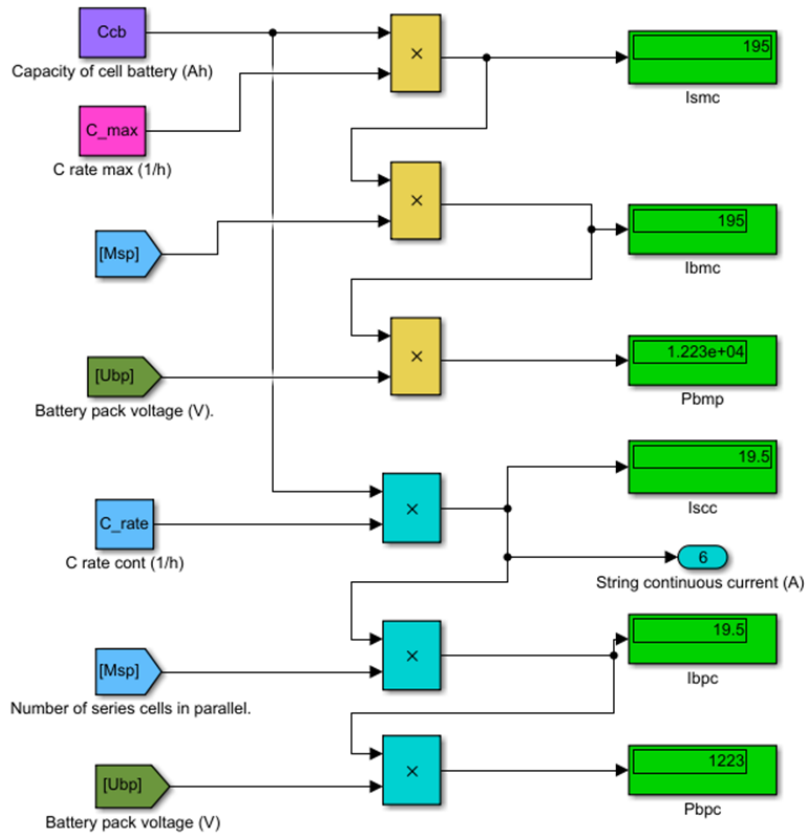


Figure 17. Modeling the parameters of high-voltage batteries

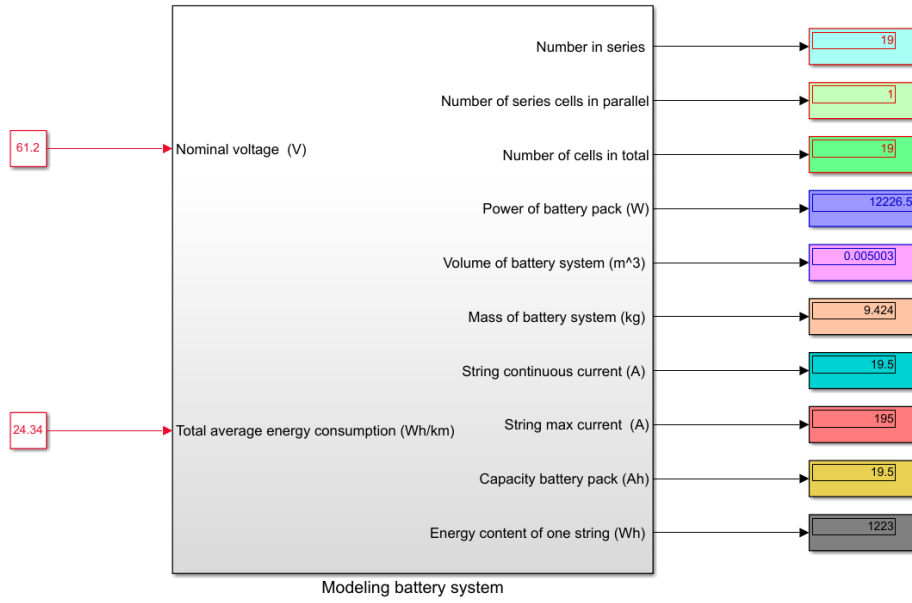


Figure 18. Modeling the characteristics of the battery required energy

enthalpy of species of j , in J mol^{-1} ; c_j is the concentration of the species of j , in mol m^{-3} ; t denotes the time, in s ; and v refers to the volume of the battery, in m^3 .

On the right-hand side of the equation, the first term represents the irreversible heat generated by resistive dissipation, which is always positive. The second term denotes the reversible heat, represented by the entropy-related heat process endothermic during charging and exothermic during discharging. The third term refers to the heat produced by electrochemical reactions, and the last term represents the mixing heat process [51]. In general, the third and fourth terms have very small magnitudes and can be neglected when the battery pack operates under normal conditions. Consequently, the equation can be simplified as follows:

$$\dot{Q} = N_{cs}M_{sp} \left[I_m(U_{cb} - U) + I_mT \frac{\partial U}{\partial T} \right] \quad (37)$$

The voltage of the battery was determined by Eq. (38)

$$V_b = I_m R_b + U^{avg} \quad (38)$$

where: R_b is the internal resistance of the battery, in Ω . The internal resistance is the total battery resistance, consisting of contact resistance, joule resistance, and polarizable resistance. U^{avg} indicates the voltage of the property evaluated at the volume-averaged concentration, in V .

Eq. (39) presented the simplified form of the required battery pack's heat generation rate. It

consisted of the ohmic (Joule) heating and entropic heating.

$$\begin{aligned} \dot{Q} &= N_{cs}M_{sp} \left[I_m^2 R_b - I_mT \frac{\partial U}{\partial T} \right] \\ &= N_{cs}M_{sp} [Q_{joule} + Q_{entropic}] \end{aligned} \quad (39)$$

where: Q_{joule} is the ohmic (Joule) heating, in W , which is caused by the internal resistance of cells, busbars, and connectors. Additionally, it is dominated by a dominant at high current, such as acceleration, fast discharge, and heavy load. $Q_{entropic}$ represents the entropic (reversible) heat due to heat generation or heat absorption, in W .

The operating current behavior of the battery is primarily determined by the current drawn by the auxiliary loads, especially the current consumed by the propulsion system in the EM.

$$I_m = \frac{P_{EM}}{\eta_p U_{cb} N_{cs} M_{sp}} \quad (40)$$

The battery pack's heat generation rate depends on the operating current, internal resistance, and ambient operating temperature, as modeled in Figure 19. The voltage–temperature coefficient represents the reversible heat generation. Doris *et al.* [52] reported that an increase in temperature raises the cell potential for LFP chemistry but lowers it for LiCoO_2 (LCO). Forgez *et al.* [53] showed that this coefficient is negative up to a state of charge (SOC) of 35% and becomes positive at higher SOC values for LiFePO_4 (LFP) cells. In this study, a constant

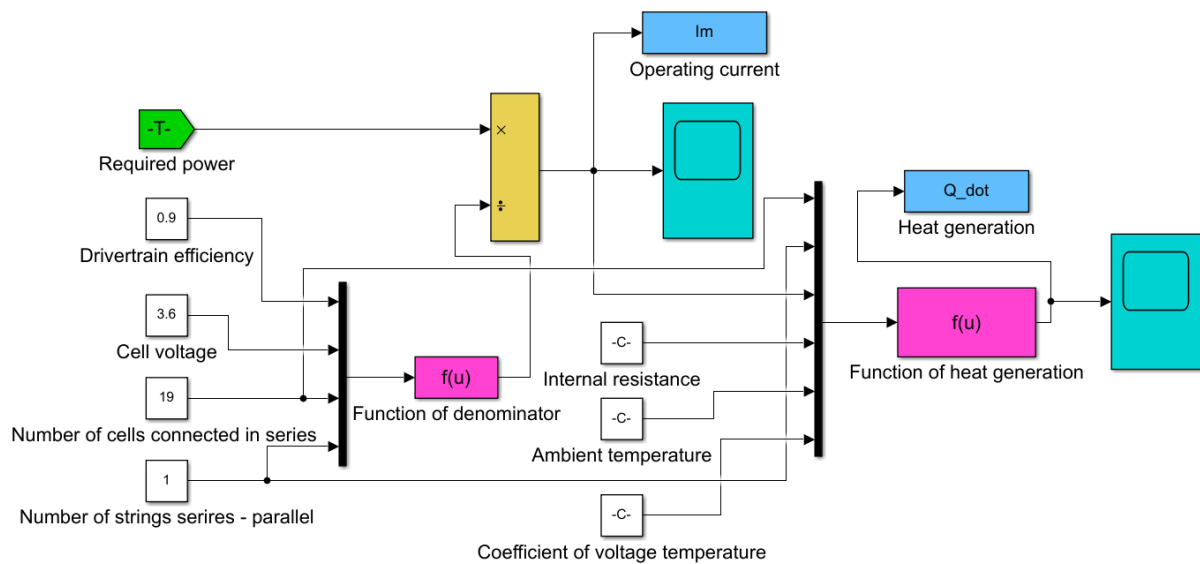


Figure 19. Modeling of the heat generation of the required battery pack in EM

voltage–temperature coefficient of 0.005 mV K^{-1} [53] was used. Additionally, the internal resistance of the battery, which depends on the cell materials used in manufacturing, was obtained from the manufacturer, as shown in Table 8.

3. Results and Discussion

3.1. Electric Motorcycle Dynamics and Energy Consumption during Driving Cycle Test

Figure 20 shows the distance, velocity, and acceleration of the electric motorcycle during EM operation in the WLTC. The distance gradually increased, achieving a total of 8.091 km in 1022 s, as shown in Figure 20a. The velocity fluctuated, sometimes increasing and sometimes decreasing, following the driving cycle test. The maximum velocity reached 13.64 and 17.89 m s^{-1} , corresponding to the low phase and medium phase, as described in Figure 20b. Additionally, the acceleration of the EM varied, with a minimum of -1 and -0.57 m s^{-2} for the low phase and medium phase. The maximum acceleration was 0.76 and 0.63 m s^{-2} for the low phase and medium phase, as shown in Figure 20c.

Figure 21 depicts the dynamics of the electric motorcycle during the driving cycle test. In the initial stage of the driving cycle test, as the EM begins to start, there is a sudden increase in acceleration, resulting in the total force peaking at 154.56 N at 13 s after accelerating, as shown in Figure 21a. During the low-speed phase of EM operation, the total force varies and primarily

depends on the acceleration force, which is related to the acceleration of the EM during the driving cycle test. It is noteworthy that the total force increased and averaged around 117.22 N between 700 and 876 s during the medium-speed phase due to the high acceleration of the EM. Generally, as the EM's velocity increases, the total force also increases to appropriately match the traction force of the EM.

In this study, the electric motor was placed using an in-hub type. Consequently, the electric motor power was transferred directly to the wheel. The variation in the electric motor's power is depicted in Figure 21b. The electric motor power fluctuated depending on the velocity of the EM and the total force. During the medium-speed phase, the electric motor power increased suddenly and reached high levels, averaging 1822.57 W between 700 and 850 s. Notably, the maximum electric motor power reached 3152.99 W at 766.5 s, quite close to the maximum power of the EM listed in Table 1. This key value is critical for designing the required battery power in this study.

The variation in the torque of the electric motor is depicted in Figure 21c. To provide more propulsion, the torque of the electric motor reached a high magnitude of 37.09 N m at the initial stage of the driving cycle test. A similar phenomenon is observed during the medium-speed phase. The maximum torque of the electric motor was achieved at 43.24 Nm at 766.5 s.

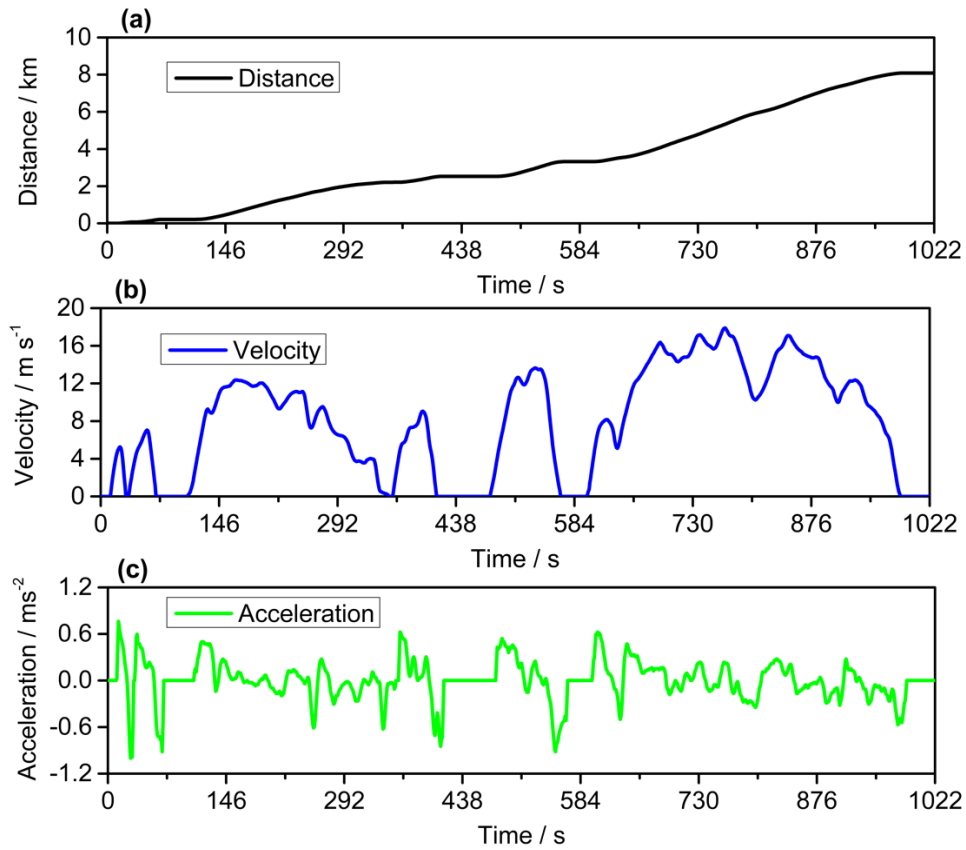


Figure 20. (a) Distance; (b) Velocity; and (c) Acceleration during the EM operation

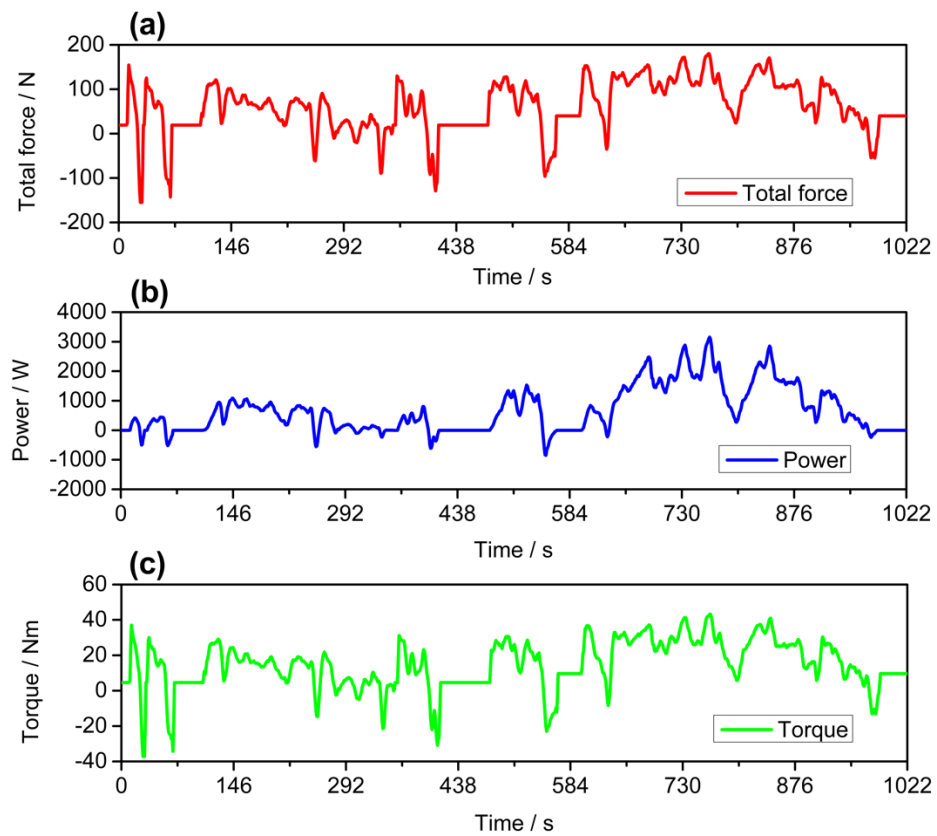


Figure 21. The variation of total force, electric power, and electric torque during WLTC

Table 8. The internal resistance of the battery under various batteries

Manufacturer	Category	Geometry	Model	Internal resistance (R_b / m Ω)	Reference
Kokam	1	Pouch	SLPB7570270	0.32	[45]
A123 (P)		Pouch	20Ah	0.5	[48]
Toshiba		Pouch	20Ah	0.5	[54]
A123 (C)	2	Cylindrical	ANR26650m1-B	6.0	[48]
Panasonic		Cylindrical	NCR18650B	100	[49]
Molicel		Cylindrical	ICR-18650K	80	[50]

During the design of the required battery power, energy consumption was a key parameter affecting the power source. Indeed, the average energy consumption in this study was determined under the driving cycle test, as described in [Figure 22](#). Determining the average energy consumption propulsion system gradually increased, reaching a maximum value of 23.517 Wh km⁻¹ during EM operation in the driving cycle test. Additionally, the total average energy consumption, which includes both the propulsion system and auxiliary loads, gradually increased and reached around 28.23 Wh km⁻¹ in this study.

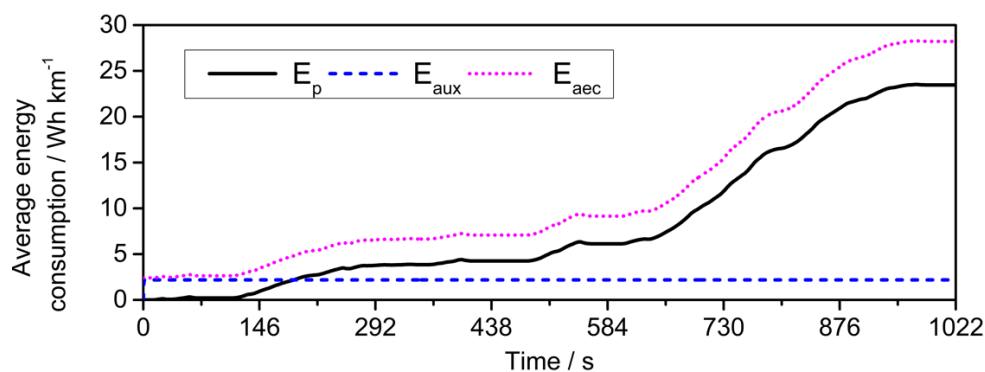
3.2. Effect of EM Mass and Aerodynamic Drag on the EM Power

During EM operation, the traction force is impacted by varying factors, such as the mass of the load and aerodynamic drag. Therefore, designing the required battery power should account for these external factors. The power variation under different loads during the WLTC class 1 is depicted in [Figure 23](#). It was seen that as the mass of the load increases, the power of the EM also increases. This is because the electric motor's power needs to increase to adapt to the changing operational conditions of the EM. Specifically, the highest power of the electric motor was achieved at 3646.62 W at 766.5 s during the medium-speed phase when the load mass

increased to 242 kg. For load masses of 177 kg and 112 kg, the highest electric motor power reached 3152.99 W and 2659.357 W, respectively.

Similarly, as the aerodynamic drag coefficient increased from 0.5 to 0.9 in steps of 0.2, the electric motor power also increased during the WLTC class 1, as shown in [Figure 24](#). The highest electric motor power was achieved at 4057.385 W with an aerodynamic drag coefficient of 0.9. For drag coefficients of 0.7 and 0.5, the power of the electric motor reached 3454.455 W and 2851.526 W, respectively. This increase in power can be elaborated by the need for the electric motor to overcome the greater aerodynamic drag force and other external factors affecting the EM operation.

The frontal area was also considered during the design of the required battery power due to its impact on electric motor power. In this study, the power of the electric motor was investigated under various frontal areas. [Figure 25](#) depicts how the power of the electric motor was affected by frontal areas of 0.7, 0.9, and 1.1 m². It can be observed that as the frontal area increases, the power of the EM also increases. This is similar to the impact of the aerodynamic drag coefficient on motor power. The maximum power of the EM was achieved at 2751.037 W, 3152.99 W, and 3554.944 W, corresponding to frontal areas of 0.7, 0.9, and 1.1 m², respectively. Notably, the percentage

**Figure 22.** The variation of average energy consumption for the propulsion system, auxiliary system, and total

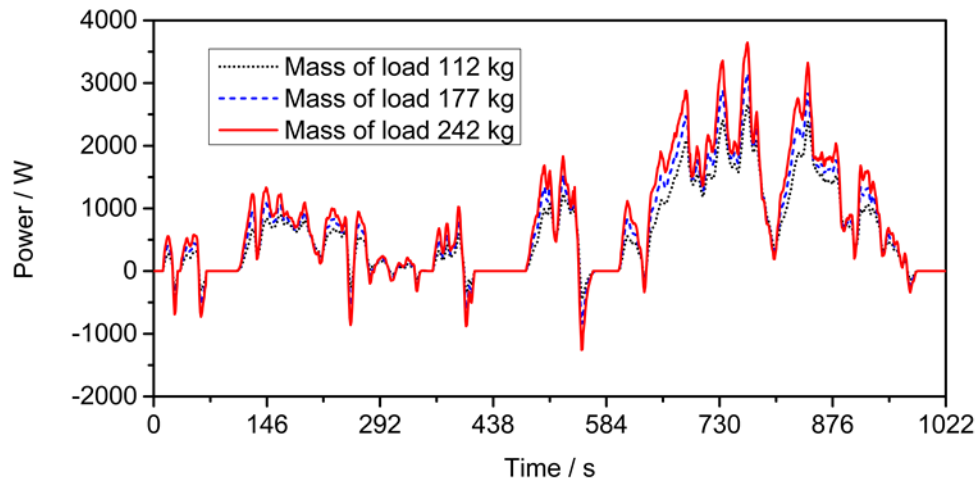


Figure 23. EM power variation under various mass of load levels

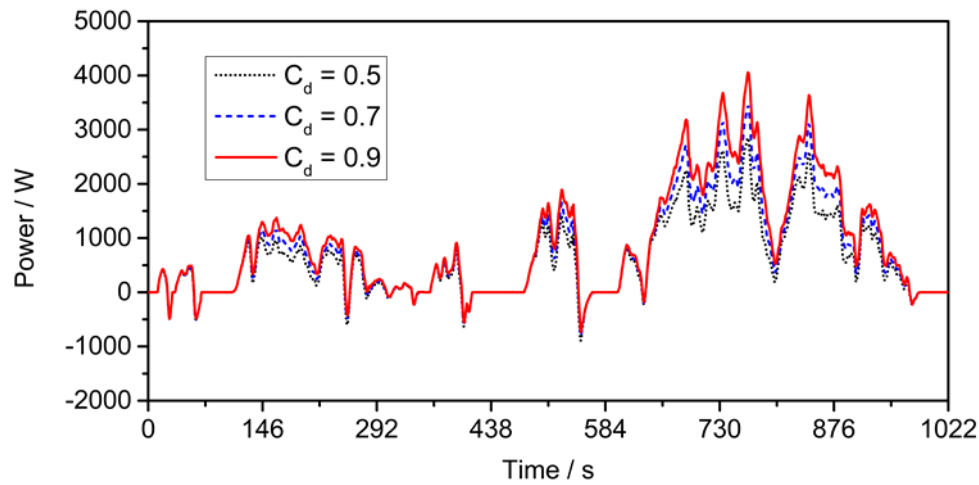


Figure 24. EM power variation under various aerodynamic drag coefficients

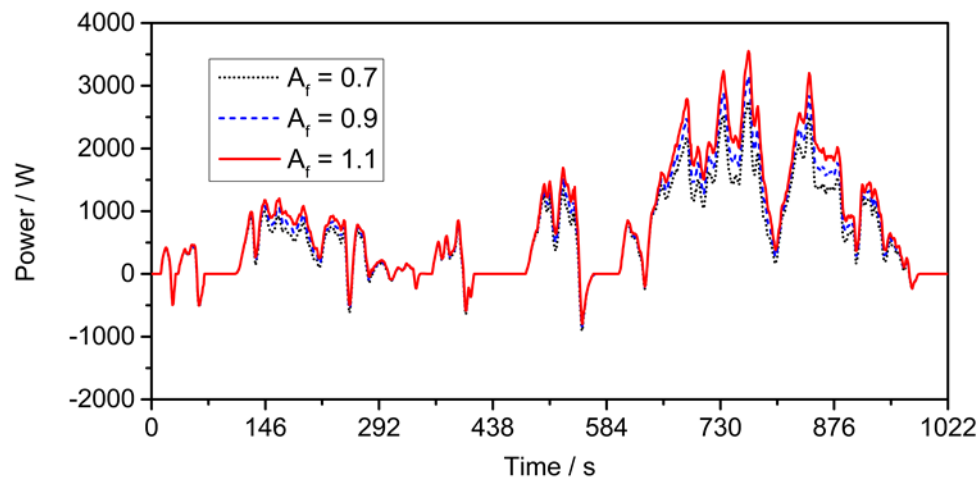


Figure 25. EM power variation under various frontal areas

increase in power between the maximum and minimum frontal areas was 1.29%. In other words, as the frontal area increased, the power of the electric motor had to increase to adapt to the external force conditions.

3.3. Effect of Road Quality on the EM Power

Actually, the rolling resistance force was affected by the EM power when the EM was operated under various road conditions in different regions. Therefore, the effect of road

quality on the EM power characteristic should be considered carefully in this study. Indeed, the coefficient of rolling resistance depended on the quality of the road. The relationship between the road types and the coefficients of rolling resistance was summarized in [Table 9](#) during EM operation. It was noteworthy that a lower coefficient of rolling resistance is better.

[Figure 26](#) shows the variation in EM power under different road types. It can be observed that when the EM operated on poor road surfaces, the EM power required was higher due to increased rolling resistance. In simpler terms, the higher energy is needed to overcome the increased rolling resistance. The EM power reached a maximum of 7771.74 W on muddy, dirty roads. In contrast, as the road quality improved, the EM power tended to decrease due to the reduction in the rolling resistance coefficient. The best case occurred when the EM operated on good asphalt or concrete surfaces.

In summary, the quality of the road directly influences the power requirements of an EM. Poor road surfaces increase rolling resistance, leading to higher power consumption, while good quality surfaces reduce resistance, improving efficiency and reducing power demand.

3.4. Effect of Road Slope Angle on the Electric Motorcycle Dynamics Performance

The road slope affects the dynamic performance of the EM during operation. Because the EM was evaluated using a driving cycle test, the slope angle varied across city, urban, hill, and rural conditions. To accurately assess the required battery pack power and EM dynamics, these varying road slopes were incorporated into the analysis. [Figure 27](#) illustrates the EM power at

different road slope angles. As shown, an increase in road slope results in a higher required battery pack power. In other words, as the slope becomes steeper, the EM must deliver more power to overcome the gravitational component of the slope force.

The EM power variation was achieved at the lowest without the road slope angle when the EM operated on the flat road. As the road slope angle increased from 1° to 7°, the required battery pack power also increased. The maximum EM power reached 6489.041 W at 766.5 s.

3.5. Effect of Operating Ambient Temperature on Required Battery Pack Dynamics

The operating current of the battery has a significant impact on its heat generation. During EM operation in the driving cycle test, the EM load varied with changing operating conditions, causing the battery pack's operating current to fluctuate in response to the auxiliary load. [Figure 28](#) illustrates the battery pack's operating current during the driving cycle under different battery configurations. As shown, the operating current changed in accordance with the auxiliary load. In other words, when the auxiliary load increased, the battery pack's operating current also increased.

During the driving cycle test, the battery pack's operating current in the EM reached 57.244 A for the required Kokam (cylindrical) battery pack. Because the EM operated in the driving cycle, where different operating ambient temperatures, consisting of the city, urban, and rural. Thus, the heat generation response dynamics of the battery pack were considered under varying operating ambient temperatures. From the previous analysis, when the operating current of the battery

Table 9. The coefficient of rolling resistance under various road types [44]

Road types	Mark	Coefficient of rolling resistance (%)	Selected in this study to simulate
Snow	I	3.0 – 5.0	4.00%
Iced	II	1.5 – 3.0	2.25%
Wet sand	III	6.0 – 15	10.5%
Muddy dirty	IV	10 – 25	17.5%
Pressed dirty (during rain)	V	5.0 – 15	10.0%
Pressed dirty (with dry)	VI	2.5 – 3.5	3.00%
Pebble with having potholes	VII	3.5 – 5.0	4.25%
Gravel	VIII	2.0 – 2.5	2.23%
General asphalt or concrete	IX	1.8 – 2.0	1.90%
Good asphalt or concrete	X	1.0 – 1.8	1.40%

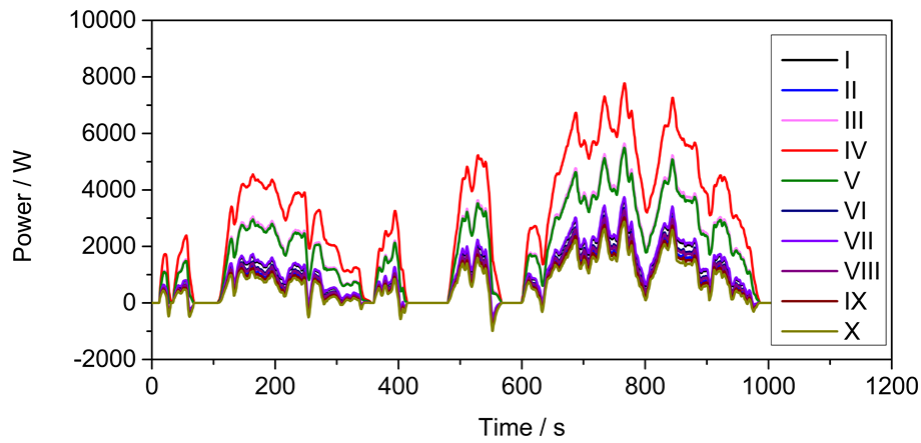


Figure 26. EM power variation under various road types

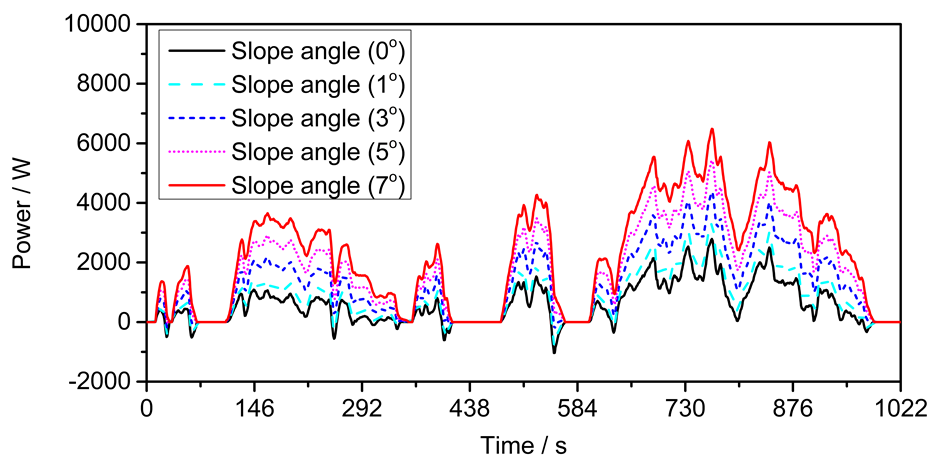


Figure 27. EM power variation under various road slope angles

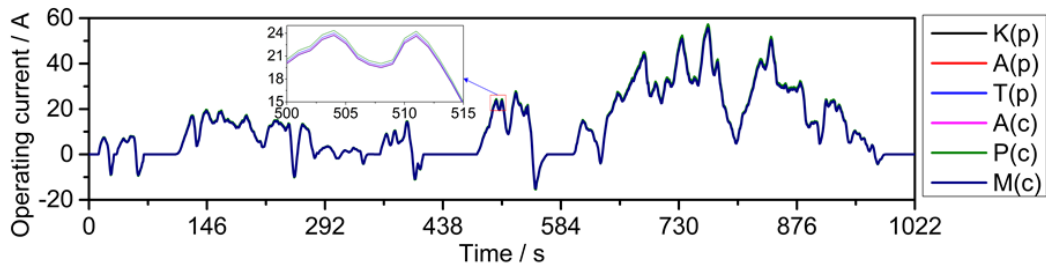


Figure 28. The operating current of the battery pack in EM during the driving cycle test

pack increases, the heat generation increases owing to a strong electrochemical reaction in the battery. In this section, the A123 (pouch) was selected to investigate the effect of operating ambient temperature on the heat generation rate response dynamic of the battery pack in EM. Figure 29 depicts the battery pack heat generation response dynamics during the EM operation in the driving cycle under various required battery packs. The operating ambient temperatures were changed, ranging from 25 to 40 °C, with an increment of 5 °C. It can be observed that the rate

of heat generation of the battery pack in EM was fluctuating, following the operating current of the battery pack. When the operating ambient temperature increased, the behavior of the heat generation rate of the battery pack decreased. This trend is in accordance with a previous study [55]. This can be explained that at higher temperatures, the electrolyte and electrodes inside the battery conduct ions and electrons more easily [56]. That reduces the battery's internal resistance, both ohmic resistance and kinetic concentration, which are related to resistances, which in turn reduces

Joule heating. Additionally, when the operating ambient temperature increases, the ion mobility and reaction rates inside the battery improve. That means the electrochemical processes charge and discharge were more efficient, so less energy is “wasted” as heat.

3.6. Characteristics of Batteries and Suitability for Selecting of Battery Required Power

The characteristics of the battery are a key metric and play a crucial important in evaluating the dynamics of the EM. In this study, various batteries were used to investigate their characteristics and to suggest the suitability for selecting the required battery power for the EM, considering a trade-off of multiple characteristics. According to Section 2.2, the total average energy consumption (E_{aec}) of 28.23 Wh km^{-1} was determined during EM operation in the WLTC class 1. This is a key parameter for determining the characteristics of the cell battery and battery pack. The battery characteristics were calculated and summarized in Table 10.

Selecting a suitable battery for the required power is a non-trivial task owing to the consideration of many factors. Figure 30 illustrates

the battery characteristics under various trademarks, including the voltage of the cell battery, capacity, and energy density (volumetric and gravimetric) for different battery trademarks. It can be observed that the voltage of cell batteries from trademarks such as Kokam (pouch), Panasonic (cylindrical), and Molicel (cylindrical) is relatively high, with values of 3.6 V, 3.6 V, and 3.7 V, respectively, as depicted in Figure 30a. In addition, the cell battery capacity is a crucial factor because it affects energy storage, charging requirements, and the operational range of the EM. The highest capacities were found in Category 1, with cell batteries from Kokam (pouch), A123 (pouch), and Toshiba (pouch) having capacities of 15.6 Ah, 19.5 Ah, and 20 Ah, respectively, as illustrated in Figure 30b. The energy density, both volumetric and gravimetric, for Category 2 is higher than that for Category 1, as depicted in Figure 30c and Figure 30d. This can be explained by the lighter mass of cell batteries in Category 2 compared to those in Category 1.

Figure 31 depicts the battery pack characteristics for different battery trademarks. The battery pack power is shown in Figure 31a. It is evident that for Category 2, the battery pack

Table 10. Summarization of battery characteristics under various battery trademarks

Manufacturer	Category 1			Category 2		
	Kokam	A123 (P)	Toshiba	A123 (C)	Panasonic	Molicel
Model	SLPB7570270	20Ah	20Ah	ANR26650m1-B	NCR18650B	ICR-18650K
Geometry type	Pouch	Pouch	Pouch	Cylindrical	Cylindrical	Cylindrical
Symbol	K(p)	A(p)	T(p)	A(c)	P(c)	M(c)
N_{cs}	17	19	27	19	17	17
M_{sp}	1	1	1	1	1	1
N_{cp}	17	19	27	19	17	17
E_{bs} (Wh)	954.7	1223	1242	156.8	195.8	163.5
P_{bmp} (W)	2864	12226.5	1242	3762	195.84	327.08
V_{bp} (m ³)	0.00293	0.005	0.007	0.00066	0.0003	0.0003
M_{bp} (kg)	5.389	9.424	13.77	1.444	0.8245	0.85
C_{bp} (Ah)	15.6	19.5	20	2.5	3.2	2.6
I_{sc} (A)	31.2	19.5	20	25	3.2	2.6
I_{smc} (A)	46.8	195	20	60	3.2	5.6

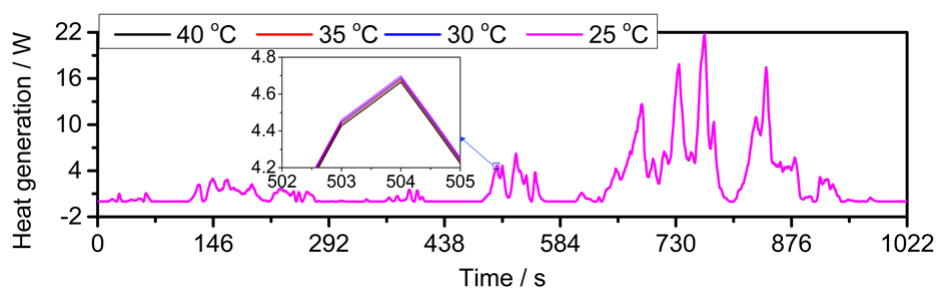


Figure 29. Behavior of the heat generation of the battery pack under various operating ambient temperatures

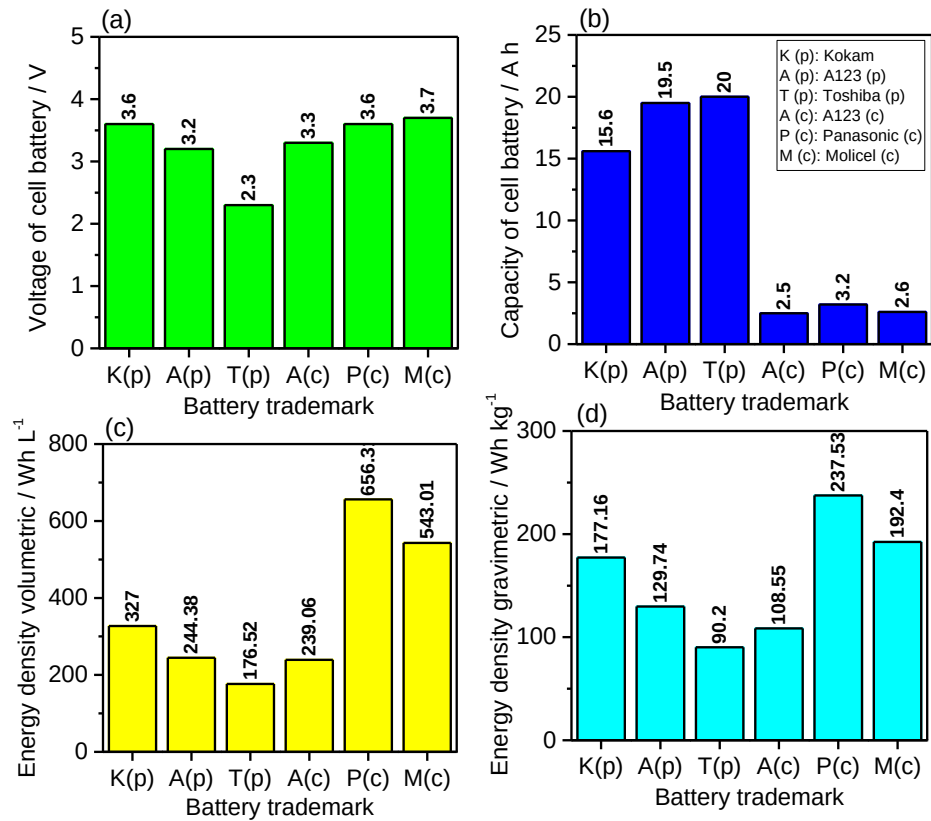


Figure 30. Battery characteristics under various battery trademarks (a) Voltage of cell battery; (b) Capacity of cell battery; (c) Energy density volume; and (d) Energy density gravimetric

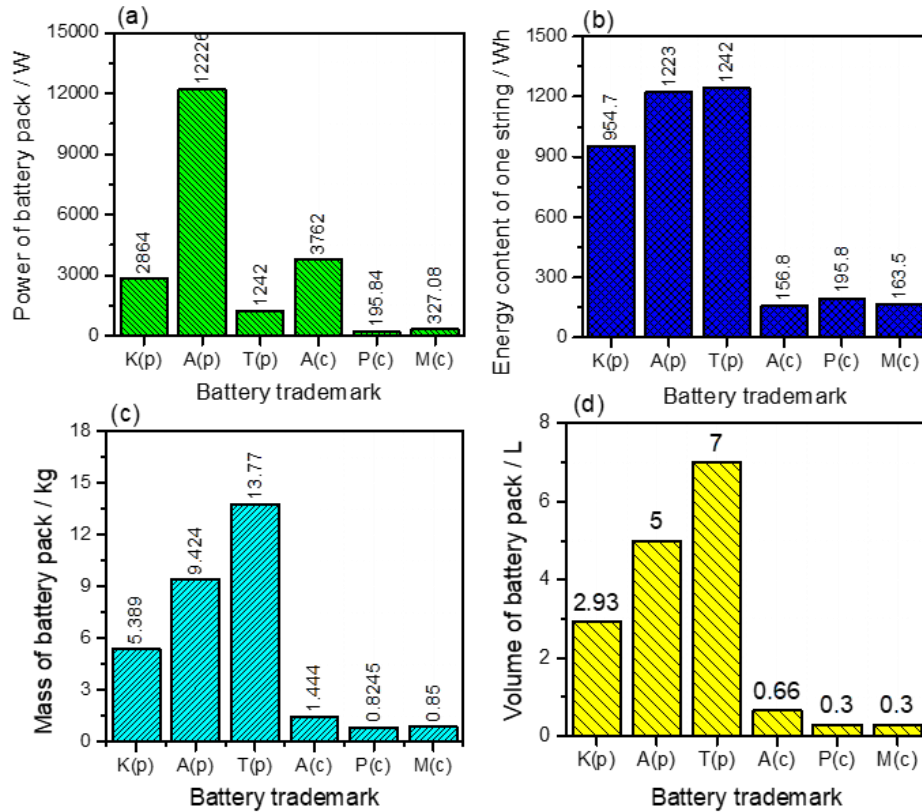


Figure 31. Battery pack characteristics under various battery trademarks (a) Power of battery pack; (b) Energy content of one string; (c) Mass of battery pack; and (d) Volume of battery pack

power is lower due to the lower cell battery capacity. Consequently, the battery pack's power is less than the power required by the motor, resulting in insufficient energy for the electric motor. Additionally, the energy content of one string in Category 2 is lower than that in Category 1, as shown in [Figure 31b](#). Therefore, Category 2 is not suitable for the required battery power.

The dimensions of the battery pack were also considered, as they affect the size and arrangement within the EM. The battery pack mass and volume are described in [Figure 31c](#) and [Figure 31d](#), respectively. The mass and volume in Category 1 are higher than those in Category 2 due to the higher number of cell batteries in the pack. However, the mass and volume in Category 1 are still reasonable.

[Figure 32](#) illustrates the characteristics of the battery pack, including the battery pack capacity, number of cell batteries, and string maximum current for different battery trademarks. It can be

observed that the Toshiba trademark (pouch) has the highest capacity of 20 Ah and 28 cells in the battery pack. In contrast, battery packs in Category 2 have lower capacity, fewer cells, and lower string max current compared to those in Category 1.

After evaluating multiple characteristics, the A123 (pouch) battery from Category 1 was selected as the most suitable for the required battery pack in this research. The A123 (pouch) offers superior characteristics compared to other batteries, such as high capacity, higher string max current, better power of the battery pack, and reasonable dimensions.

4. Conclusion

The modeling, simulation, and assessment of the electric motorcycle and battery characteristics under the driving cycle test were carried out and discussed in detail. Several conclusions were drawn from this study. Indeed, the electric motorcycle dynamics were modeled and

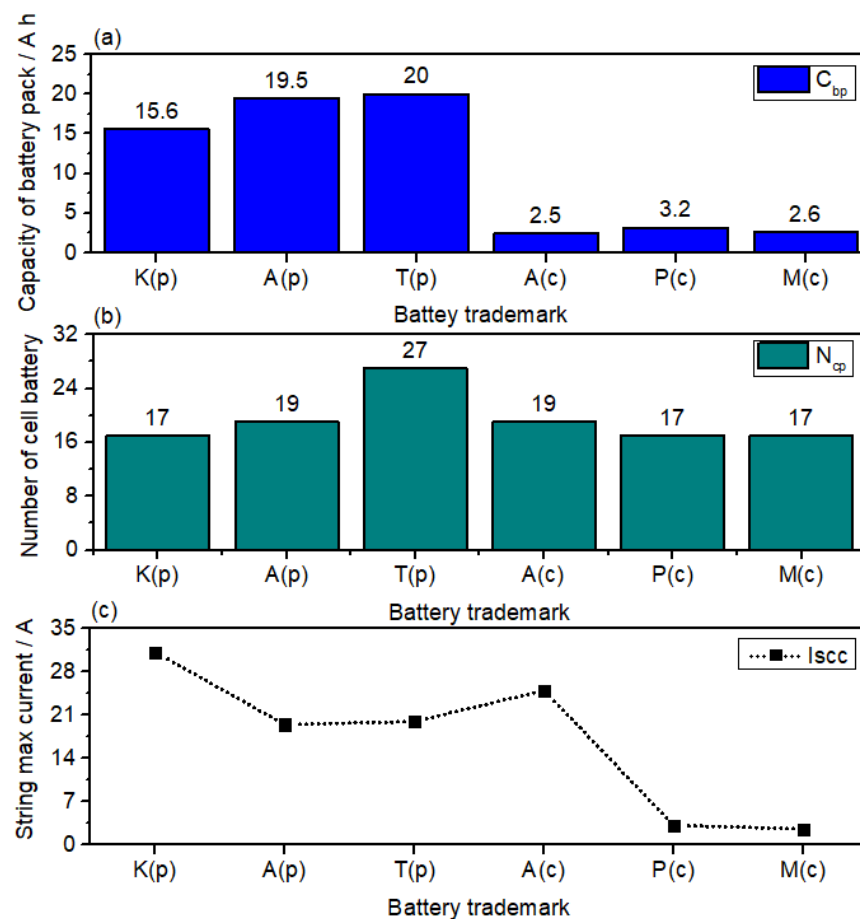


Figure 32. Battery pack characteristics under various battery trademarks: (a) The battery pack capacity; (b) Number of cell batteries; and (c) String maximum current

simulated under the WLTC class 1 driving cycle test. Additionally, external factors such as mass load, aerodynamic drag, road quality, road slope angle, and operating ambient temperature on heat generation of the battery pack were considered and analyzed in detail. When the mass load, aerodynamic drag, and road slope angle increased, the power and torque of the electric motor increased to adapt to the external force conditions. In contrast, when road quality improved, the electric motor required less power due to reduced resistance and lower overall power demand. Additionally, the behavior heat generation of the required battery pack was considered under various operating ambient temperatures. The battery characteristics were investigated and compared across various parameters and battery trademarks. The A123 (pouch) battery model was found to be the best option for designing the required battery pack in this study. On the other hand, this study is significant for the design and precise calculation of the battery's required power for new electric motorcycles.

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Author's Declaration

Authors' contributions and responsibilities

Tan-Thich Do (Conceptualisation; Methodology; Validation; Investigation; Formal analysis; Data curation; Software; Writing - original draft). Tan-Ngoc Dinh (Investigation; Resources; Software; Visualisation; Writing - review & editing). Vinh-Dat Ly (Conceptualisation; Writing - review & editing; Funding acquisition; Project administration; Supervision).

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Competing interests

The authors declare no competing interest.

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