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Modeling, Simulation, and Validation of An Electric Scooter Energy Consumption Model: A Case Study of Indonesian Electric Scooter

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ABSTRACT Indonesia has the third-largest motorcycle population in the world. These motorcycles have been known as a source of air pollution. Therefore, shifting the motorcycle to electric-driven based technology is inevitable. However, it is quite challenging as the residents prefer higher performance (in terms of power and speed) of the electric model which is unavailable in the market. Unfortunately, the demand for higher performance models creates other problems, such as the requirement for a bigger battery. This is because there is a range of anxiety phenomena in-vehicle usage. However, the capability to accurately estimate the electric motorcycle's range does not exist. Therefore, this paper focuses on how to develop an electric scooter model to simulate its performances, especially its range estimation. The modeling approach was the use of an electric scooter longitudinal model developed in MATLAB/Simulink environment. Based on the dimensions and targeted performance, the developed model was simulated to determine its power and energy requirements. It is then validated using an experimental test on a dynamometer and on-road conditions. Based on the experimental data analysis, it can be concluded the developed model is valid and can be used as a basis for the next development of any electric motorcycle.

INDEX TERMS Electric scooter, range anxiety, electric scooter energy consumption model, MATLAB/Simulink, simulation.

I. INTRODUCTION

Indonesia is a country with a high population of motorcycles that currently utilize internal combustion engines as its main traction units. However, due to unclean combustion which occurs in the internal engine, these machines are one of the major sources of air pollution in Indonesia [1]. In fact, there is already health hazard due to the pollution in some of the big cities. The type of motorcycles is similar to those frequently found in developing countries. It has a smaller engine size (average of 125 cm^3) with an average power of approximately 8 horsepower. Its population was estimated at around 133 million units [1] and steadily increased as the sales of new motorcycles reach 7 million units per year, with an estimated growth of 7% in successive years [2].

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These increasing figures are somewhat worrying in terms of the Indonesian sustainable developments. As previously stated, internal combustion engine (ICE) motorcycles are the principal source of air pollution. Moreover, they all require fossil fuels (gasoline) as a source of energy. The country has no privilege in the fossil fuel source as of 2006, hence, it has been a net oil importer. The increasing requirement for this fuel means it must be imported from other countries at an expensive cost. However, the economy can no longer depend on imported fossil fuels.

To create a better and more sustainable development, a shift from the current ICE technology to electric-driven motorcycles is favorable [3]. However, electric motorcycles have received little attention. Most countries put electric car initiatives ahead of electric motorcycles since they can only be found in developing nations like Indonesia and its neighboring countries in Southeast Asia. According to several works reported in references, electric-driven vehicles (including motorcycles in this case) offers various benefits compared to their internal combustion-powered counterpart [4]–[11]. Moreover, they have greater powertrain efficiency, minimal maintenance requirements, and zero tailpipe emissions [12]. Indonesia's government recognizes that it must shift its transportation sectors (passenger cars and motorcycles) to electrically driven to make the country better and more sustainable in the future. Furthermore, the government issued Presidential Decree No. 55/2019 concerning the acceleration of the battery electric vehicle program in the transportation sector [13]. The Presidential Decree specifically states that the electric motorcycle is the priority to be shifted. This directive is in line with the trend in India [14], Philippine [15], UAE [16], China [17], [18], and Germany [19]. They generally agreed that the adoption of these vehicles (passenger cars) faces several problems and barriers, such as performance, range, the total cost of ownership, shortage of charging infrastructure, and consumer unawareness about EV technology which critically influences its adoption. With similar conditions occurring in Indonesia, especially a lack of charging infrastructure, it is logical to choose the electrification of motorcycles over passenger cars [20]. This model does not need the infrastructure as it can be charged everywhere using residential electric power sockets. It is expected that at least 20% of the motorcycle will be powered by an electric drivetrain in 2025.

To support the government initiative, two strategies can be implemented Firstly, import the electric motorcycle from other countries, especially China, or secondly, self-design and self-develop them. However, several companies have already implemented the former strategy, but they struggle with sales. This is because the Chinese model is different from what Indonesian need. Most of them are low on power and speed. While Indonesians much prefer higher speed and cheaper motorcycles. Even though electric driven are expensive in terms of purchase cost compared to conventional motorcycles, they still have lower performance. Therefore, the logical choice would be to self-design and develop electric motorcycles based on customers' preferences. To implement this, the type of electric motorcycle to be designed or developed should be based on the ICE motorcycle type which dominates the market. Based on a market survey conducted, this type is a scooter. Therefore, the work reported in this paper focused on the designing, developing, and validating process of electric scooters.

To begin with this process, an engineering analysis and modeling is required. Unfortunately, only a few numbers of literature were obtained in this area, this includes [3], [21], [22]. None of them discussed high-level modeling. To facilitate the designing, developing, validating, and ultimately producing the machine, high-level modeling, which is the focus of this study is required. With this, the basic specifications and performances of an electric scooter can be predicted [23]. However, the problem with the simple model is its accuracy, hence, model validation is required. It was carried out to evaluate whether the model simulation behavior is similar to its actual performance. Once the validity is confirmed, the model can be used for other design and development activities.

Those are the work reported in this paper. Besides, the validation process of the developed model (in MATLAB/Simulink environment) was also discussed. This process utilized an electric scooter prototype and was tested on a dynamometer using ISO Standard drive cycles. The point of interest to be validated is energy consumption. This is because it is the final output of electric motorcycle engineering design and analysis. Therefore, its confirmation means that all previous engineering designs, calculations, and production of the machine are correct.

Moreover, energy consumption is the most important parameter, therefore, it needs to be predicted at the beginning of the design process. This is because one of the major drawbacks concerning motorcycles is the question of their range. This creates what is known as ''range anxiety'' among the potential users. Also, it is the most frequent question asked concerning electric vehicles (including scooters).

However, as identified by [24], the available range estimates in EV were not accurate. In the case of the nearly matured technology, such range estimates are inaccurate, it can be ensured that this is also applied in the electric motorcycle field. Therefore, the development of an accurate estimation is mandatory. It will be presented and validated in the work reported in this paper.

This paper is organized as follows, the electric scooter model development in MATLAB/Simulink along with its mathematical model is presented in Section 2. The validation process and scenarios are elaborated in Section 3. Furthermore, the comparison analysis between the model and the electric scooter prototype performance is discussed in Section 4. Finally, in Section 5, the conclusion of the work process and scenarios are elaborated Section 3. Furthermore, the comparison analysis between the model and the electric scooter prototype performance is discussed in Section 4. Finally, in Section 5, the conclusion of the work reported in this paper and its future studies or work direction is set up and presented.

II. THE ELECTRIC SCOOTER MODELING

The energy consumed by the electric scooter was modeled according to the block diagram depicted in Fig. 1. This was defined by how much is required to drive the electric scooter or provide energy for its load accessories. Meanwhile, the energy required was determined by its dynamic characteristics. Therefore, the longitudinal modeling of the scooter was required to be carried out. The model was simulated to determine its dynamic characteristics by using a drive cycle. While accessories load was assumed as constant load.

The source of electric energy was drawn from the traction battery. Therefore, the energy flow equations according

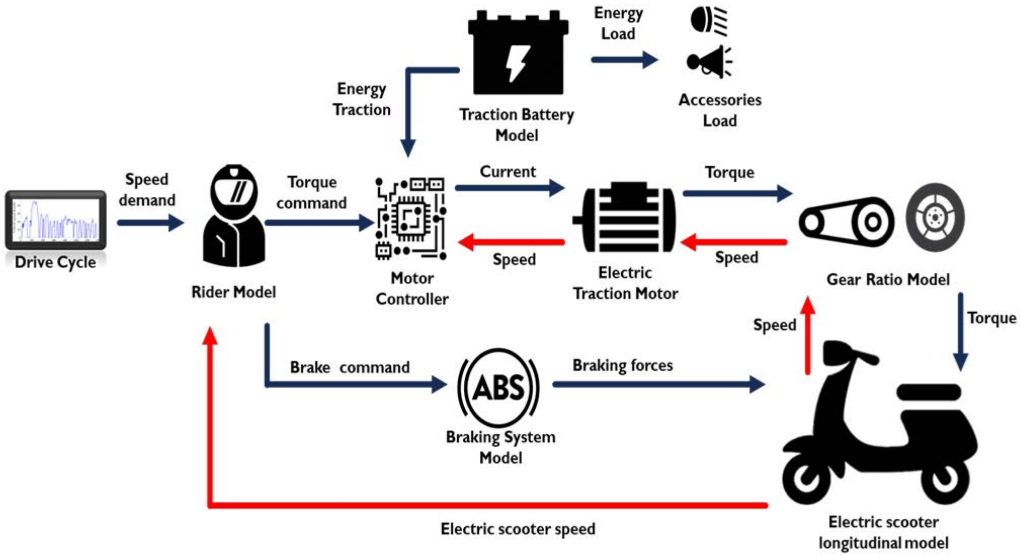


FIGURE 1. Electric scooter energy flows model architecture.

to [24] are as follows:

$$E_{Cons} = \frac{E_{Batt}}{d} \tag{1}$$

where, E_{Cons} is the estimated energy consumption per unit distance (kWh/km), E_{Batt} is the total energy output from the battery (kWh), and d is the total distance covered by the electric scooter (km).

According to the conservation energy laws, the total energy input is equal to the total energy output and energy loss, hence:

$$E_{Batt} = E_{Traction} + E_{Load} + E_{Loss} - E_{Regen} \tag{2}$$

where, $E_{Traction}$ is the total energy required for moving the vehicle; E_{Load} is the total energy to power up any accessories found in the vehicle; E_{Loss} is the total energy loss due to inefficiency in the vehicle energy conversion and E_{Regen} is defined as the total energy generated during vehicle regenerative braking events, respectively.

According to [24], it is defined that $E_{Traction}+E_{Load}+E_{Loss}$ is equivalent to the total energy drawn from the battery and it is denoted as E_{Batt_out}. Therefore, (2) can be rewritten as:

$$E_{Batt} = E_{Batt\_out} - E_{Regen} \tag{3}$$

Or in terms of the power required, it can be expressed as:

$$E_{Batt} = \left(\int_{Traction} P_{Batt\_out}(t)\, dt - \int_{Regen} P_{Batt\_in}(t)\, dt \right) \times \frac{1}{3600} \tag{4}$$

$$P_{Batt\_out} = \frac{R_{Total} \cdot V_{ElectricScooter}}{\eta_{PowerTrain}} \tag{5}$$

$$P_{Batt\_in} = \beta \times P_{Regen} \tag{6}$$

where, P_{Batt_out} is the total power (including loss) to propel the electric scooter. The traction battery should be able to supply all the power required to drive the machine (overcome all of the resistive forces (R_{Total}) and losses in its power transmission ($\eta_{PowerTrain}$) system) at a specified velocity ($V_{ElectricScooter}$). P_{Batt_in} is the total energy. recovered by the traction battery during regenerative braking. It is specified by β and P_{Regen} is the percentage of the braking energy recovery ($0 < \beta < 1$) while P_{Regen} is the regenerative power from the electric scooter during braking, respectively.

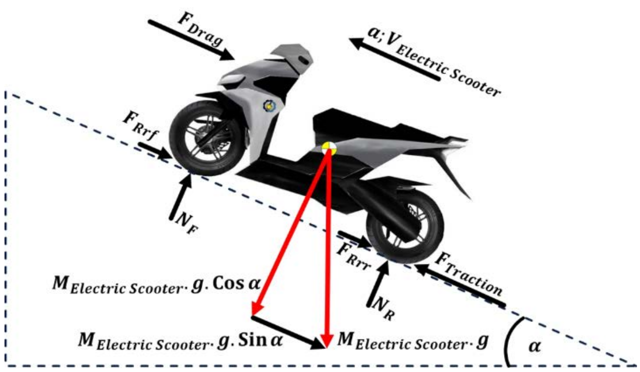


FIGURE 2. Electric scooter dynamics longitudinal free body diagram.

The total resistive force of the scooter when moving can be derived from its dynamic equation of motion. This was determined using the longitudinal model shown in Fig. 2.

In Fig. 2, the total resistive forces for a moving electric scooter in an inclination road angle of α (using the longitudinal model) can be derived as follows.

$$R_{Total} = F_{Traction} \tag{7}$$

$$P_{Wheel} = F_{Traction} \cdot V_{ElectricScooter} \tag{8}$$

$$F_{Traction} = F_{Drag} + F_{RollingResistance} + F_{Grade} + F_{Inertia} \tag{9}$$

where,

$$F_{Drag} = \frac{1}{2}\rho \cdot C_d \cdot A_f \cdot V_{ElectricScooter}2 \quad (10)$$

$$F_{RollingResistance} = FrontTire\left(F_{Rrf}\right) + RearTire\left(F_{Rrr}\right)$$
$$= C_{RR} \cdot M_{ElectricScooter} \cdot g \cdot cos\,\alpha \quad (11)$$

$$F_{Grade} = M_{ElectricScooter} \cdot g \cdot sin\,\alpha \quad (12)$$

$$F_{Inertia} = M_{Inertia} \cdot a \quad (13)$$

$$M_{Inertia} = 1.15 \times M_{ElectricScooter} \quad (14)$$

Based on (1) to (14), a MATLAB/Simulink model was developed. This model aims to investigate and evaluate the scooter's performance characteristics. Total energy consumption can be easily predicted using a certain drive cycle input. The model is based on the work reported in the reference [23]. However, some modifications are required to match it with the requirements of the work reported in this paper.

A. ENERGY CONSUMPTION EQUATION MODEL

To calculate the energy consumption, the battery was also modeled as it was assumed to be a single pack with a total capacity and open voltage terminal of 3 kWh and 115 volt respectively. A simple high voltage model of the battery pack is shown in Fig. 3. The battery pack was modeled as a high voltage model due to rules set by UN/ECE Regulation [25]. According to the regulation, an operating voltage of more than 60V is categorized as a high voltage system. Hence, the battery pack was modeled as a high voltage battery pack. The equation to calculate energy consumption based on a model in Fig. 3 can be derived as:

$$P_{Batt.Ideal} = P_{Batt.Actual} + P_{Batt.Loss} \quad (15)$$

$P_{Batt.Loss}$ is the battery power losses due to internal resistance, therefore, the equation becomes:

$$P_{Batt.Ideal} = I \cdot V_{OC} \quad (16)$$

$$P_{Batt.Actual} = I \cdot V_{OC} - I^2 R_{Internal} \quad (17)$$

$$I = V_{OC} - \sqrt{\frac{V_{OC}^2 - 4 \cdot R_{Internal} \cdot P_{Batt.Actual}}{2 \cdot R_{Internal}}} \quad (18)$$

$$V_{Terminal} = V_{OC} - I \cdot R_{Internal} \quad (19)$$

According to (15) to (19), the total available energy in the battery pack can be expressed as:

$$W_{Batt.Actual}(t) = V_{Terminal}(t) \cdot I_t(t) \quad (20)$$

$I_t(t)$ is the nominal energy-specific contained in the battery (ampere-hour) which is assumed to be constant when the battery is still at its nominal voltage. Therefore, to calculate the energy used, it will be simply expressed as:

$$Total_{EnergyBatt.Used} = W_{Batt.Acatual}(0) - W_{Batt.Acatual}(t) \quad (21)$$

Assuming $I_t(t)$ is constant, (21) can be rewritten as follows:

$$Total_{EnergyBatt.Used} = I\left(V_{Terminal}(0) - V_{Terminal}(t)\right) \quad (22)$$

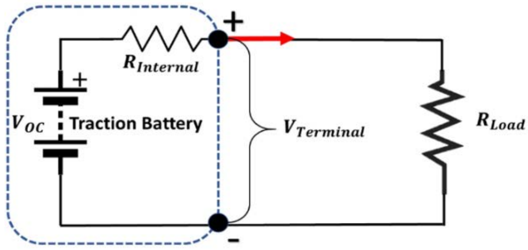


FIGURE 3. Traction battery model.

The total battery energy used can be expressed through other methods by defining its State of Charge (SoC) value. This can be calculated by integrating the current drawn from the battery. This method is known as "coulomb counting" and can be used in the developed simulation model through the following equation:

$$SoC_{current} = SoC_{t=0} - \left(\int_0^t \frac{V_{OC} \cdot I(\tau)}{E_{Capacity}} d\tau\right) \quad (23)$$

For modeling and simulation, the electric scooter parameters are tabulated in Table 1. The scooter's power and torque were calculated using the equations above at the maximum load value of 250 kg, road inclination angle of 20-degree, acceleration between 0 – 60 kph in 5 sec, and a max speed of 110 kph.

With all the electric scooter specifications and parameters (Table 1), a MATLAB/Simulink model was created. As previously stated, the model was adapted from the battery electric vehicle technique developed by [23]. Furthermore, it was originally developed for an electric vehicle, therefore, to suit the scooter's requirements, some modifications were performed on the motor and driveline model, battery capacity, as well as vehicle specification as listed in Table 1. It has been also reported in the authors' recent publication in IEEE Electrification Magazine [26]. However, this development cannot be covered in this paper, but interested readers are suggested to consult [23], [27], [28]. The complete MATLAB/Simulink model is presented in Fig. 4. Meanwhile, its drive cycle was set according to ISO 13064-1:2012 and presented in Fig. 5. Subsequently, a simulation was conducted, and the results are presented in the next section along with the analysis and validation process to determine its validity. The ISO 13064-1:2012 drive cycle was selected firstly because of how it is in the validation process, subsequently, the experimental test setup utilized the ISO standard. Therefore, it will be easier to validate the modeling and simulation results as similar standards will be used.

Secondly, the electric scooter was designed for urban conditions. The drive cycle as per ISO 13064-1:2012 was used (Fig. 5) and it can be explained as follows. The speed was accelerated from zero kph (stand still) to 60 kph (37.5 mph) in 20 seconds and was maintained for 30 seconds before decelerating to 20 kph in 10 seconds. Subsequently, the speed was maintained at 20 kph for 30 seconds as well. The final cycle was from 20 kph, where the speed decelerated to zero in

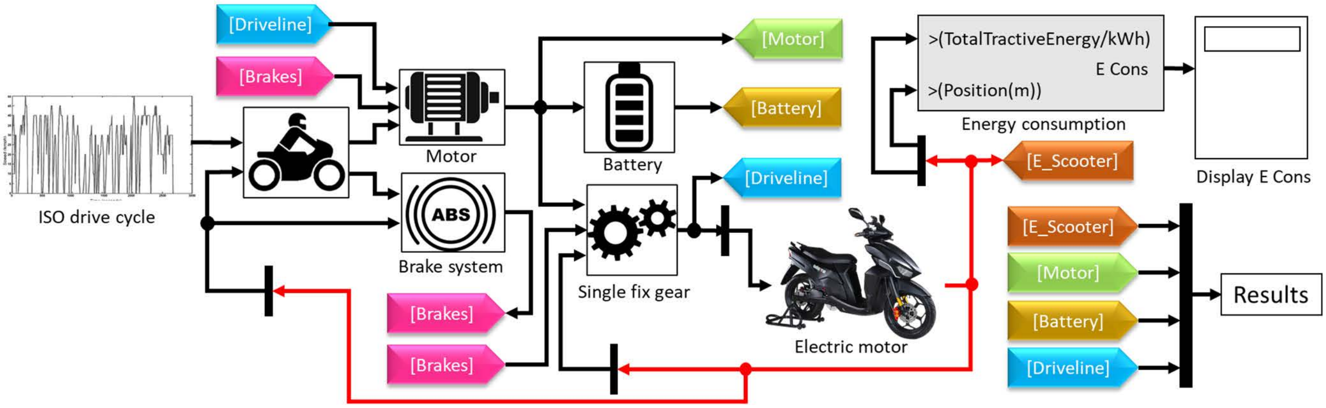


FIGURE 4. MATLAB/Simulink model of the electric scooter.

TABLE 1. The electric scooter parameters for modeling and simulation purposes.

Parameter	Notes	Values
$M_{Electric\ Scooter}$	Total electric scooter mass including its rider	190 kg
C_d	Coefficient of drag	0.6
A_f	Electric scooter frontal area	0.8
C_{rr}	Coefficient of tire rolling resistance (on-road)	0.013
$V_{Electric\ Scooter}$	The velocity of the electric scooter	110 kph (max)
H_p	Powertrain efficiency	90%
Wheel diameter	-	440 mm
Accessories load	Power to supply accessories load	100 watt (constant)
Transmission ratio	Single fixed ratio	1:5; 1:6, 1:7
Wheel radius	Rear tire radius	0.260 M
Drive cycle	-	Urban cycle as per ISO 13064-1:2012 Standard

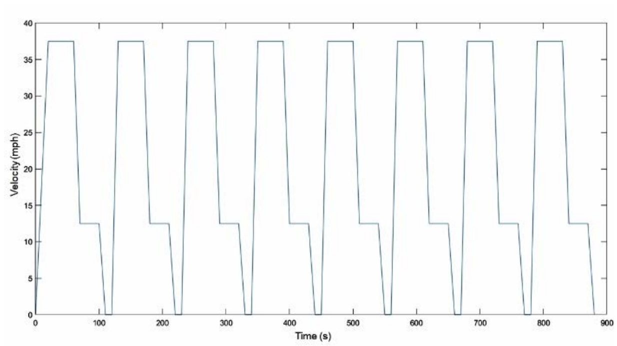


FIGURE 5. ISO 13064-1:2012 drive cycle as modeling and simulation input of the electric scooter model.

10 seconds and was maintained for another 10 seconds before repeating the cycle using a similar velocity profile. The cycle was continuously repeated until the SoC reached 5%.

The simulation results are shown in Fig. 6 – 9. Figure 6 showed the MATLAB/Simulink scooter's model capability to perform the driving cycle according to the standard.

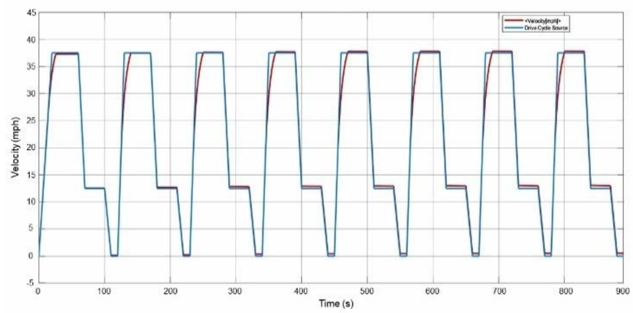


FIGURE 6. Velocity profile of the electric scooter simulation using ISO 13064-1:2012 drive cycle.

Furthermore, the model can track the velocity profiles for the whole simulation time, accelerate, maintain speed, and decelerate very well. According to Fig. 6, the velocity line (blue line) coincides with the drive cycle velocity line (red line) except in the time spent to reach maximum speed.

The electric scooter model's performance responses to the drive cycles (ISO 13064-1:2012) were also confirmed with the required power and torque. The power required to perform the specified drive cycles was 3.0 kW (Fig. 7). In Fig. 7(a), the electric motor was operated from 0 to 3.0 kW, with a maximum rotational speed of 4000 rpm. Meanwhile, the scooter requires 3.0 kW to reach the specified speed of 60 kph (37.5 mph). It is depicted in Fig. 7(b).

Similar to the power required analysis, the required torque plot against motor rotational and the electric scooter speed are shown in Fig. 8. It indicated that the required torques to perform the ISO 13064-1:2012 drive cycle standard were all below the available torque where the maximum required value was 17.7 N.m at the rotational speed of 1598 rpm (Fig. 8(a)). While in terms of speed, the maximum torque occurred when the electric scooter was at the speed of 28 kph (17.2 mph). This phenomenon can be observed in Fig. 8(b).

Based on the simulated performance, it can be concluded that the model can perform the specified drive cycle. Subsequently, its energy consumption was calculated from the total

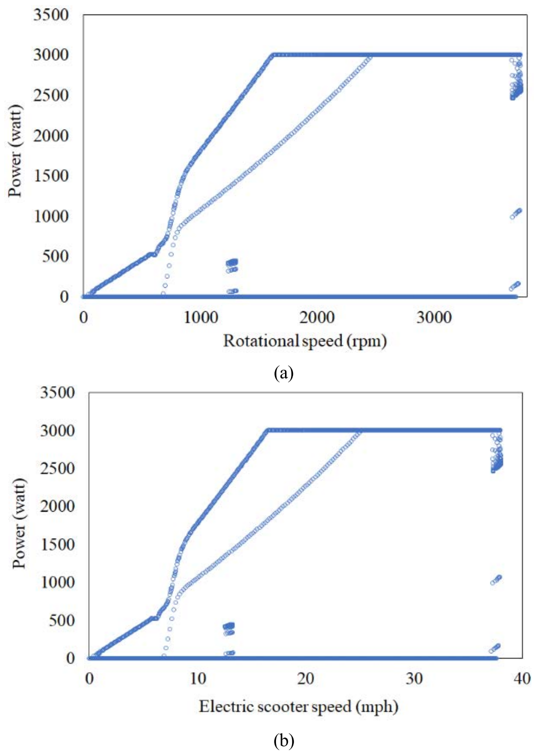


FIGURE 7. The required electric motor power (watt) versus (a) rotational speed (rpm) and (b) the electric scooter speed (mph), according to ISO 13064-1:2012 drive cycle.

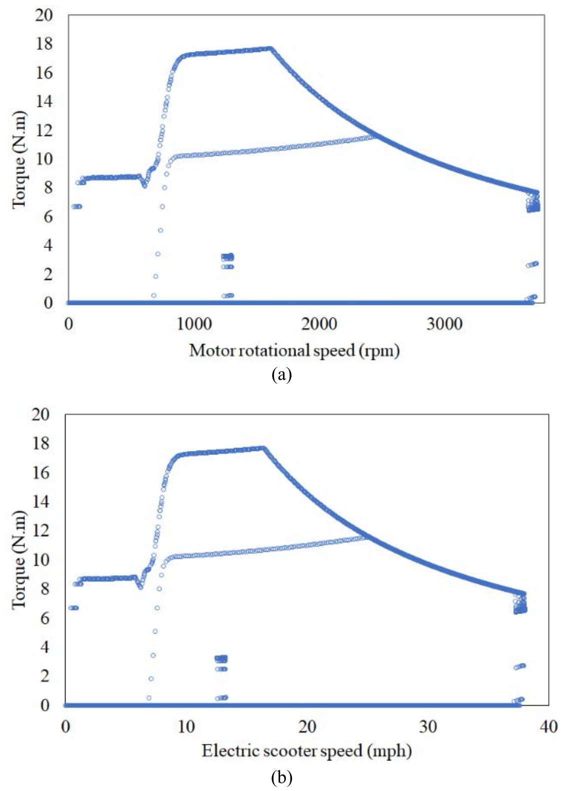


FIGURE 8. The required electric motor torque (Nm) versus (a) rotational speed (rpm) and (b) the electric scooter speed (mph), according to ISO 13064-1:2012 drive cycle.

energy spent in the simulation until the battery SoC was 5% (Fig. 9(c)). According to Fig. 9(a), the total energy required in the simulation was 3272 watthours which were used to cover a simulated distance of 63470 meters (Fig. 9(b)). Based on (1), the simulated/predicted energy consumption was 0.052 watthours/meter or 19.4 km/kWh.

The result of electric motor torque and power required versus its rotational speed is of paramount importance. It is subsequently used as a basis for designing and developing the tractive electric motor. The complete parameters and specifications of the required traction motor are tabulated in Table 2.

Based on the traction motor performance requirement, a Brushless Direct Current (BLDC) motor was designed and developed. Based on Table 2, subsequent, the developed motor will be coupled with fixed gear transmission by employing a chain belt drive with a ratio of 1:6 as per the simulation modeling suggested. To be able to drive the motor as per rider torque and power requirements, a controller is required. In this case, a 3-phase 100V motor controller is implemented. The complete specification of the electric motor drivetrain can be seen in Table 3.

However, this process will not be covered in this paper but will be presented in other publications. Readers are suggested to consult [26]. The developed traction motor is presented in Fig. 10, while its characteristics performance is shown in Fig. 11. The developed motor was installed in the electric scooter prototype which was subsequently used to justify the validity of the simulation model. The validation process was conducted by testing the real electric scooter using the standard. This will be elaborated in Section 3 of this paper.

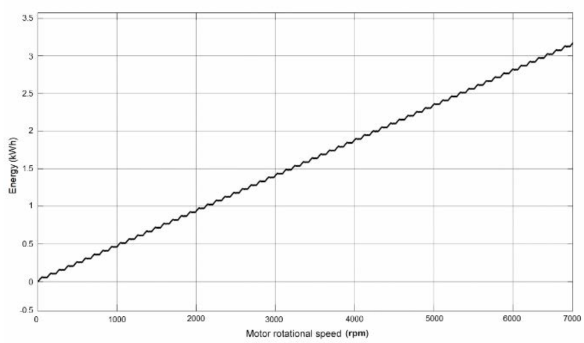
TABLE 2. Traction motor performance characteristics.

Parameters	Value
Motor power (Rated/Max)	3000 watts / 5000 watts
Motor torque (Rated/Max)	20 Nm / 25 Nm
Motor revolution speed (Base)	1600 rpm
Motor revolution speed (Max)	4000 rpm (field weakening)

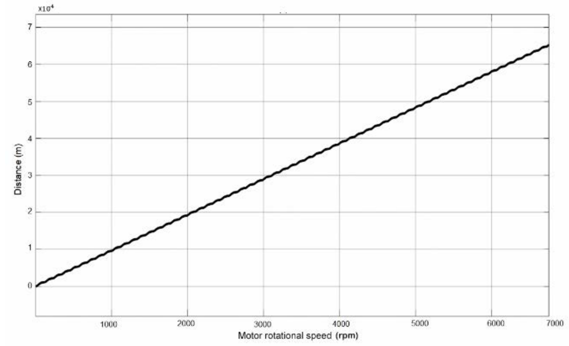
III. THE ELECTRIC SCOOTER MODELING AND SIMULATION VALIDATION USING STANDARD DYNAMOMETER AND ON-ROAD TESTING

In this section, a detailed explanation of the scooter testing using the ISO 13064-1:2012 standard is presented. The tested motorcycle was a prototype version of the Indonesian designed electric scooter known as GESITS. This is presented in Fig. 12. The prototype version specifications are shown in Table 3.

As it has been previously explained. Initially based on the vehicle dynamic model parameter tabulated in Table 1, the MATLAB/Simulink model is created. Then using the urban drive cycle (ISO 13064-1:2012). Based on the driving cycles and Simulink simulation, the power and torque required can then be defined.



(a)



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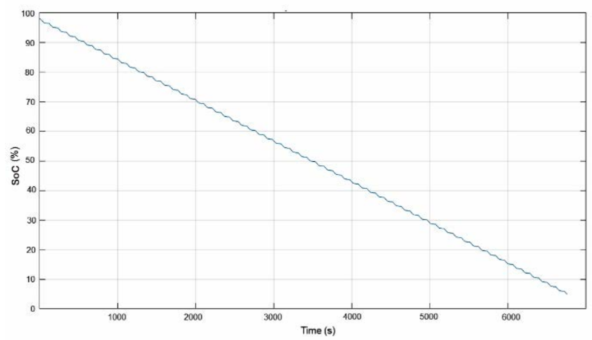

(c)

FIGURE 9. The electric scooter simulation results in (a) Total energy required, (b) Total distance of the electric scooter, and (c) Electric scooter % battery SoC.

TABLE 3. GESITS prototype specifications.

Specification	
Type	Electric scooter
Range per charge	70 – 100 km/charge
Top speed	110 kph
Electric motor / power / torque / max rpm	BLDC / 3.5 kW / 25 N.m / 3000 rpm
Battery / capacity	Li Ion (NCMA) / 3 kWh
Payload	± 80 kg
E-Drive train	Mid drive (belt/chain) / fixed ratio
Transmission ratio	1:6
L × W × H (mm)	1950 × 700 × 1100
Weight	125 kg

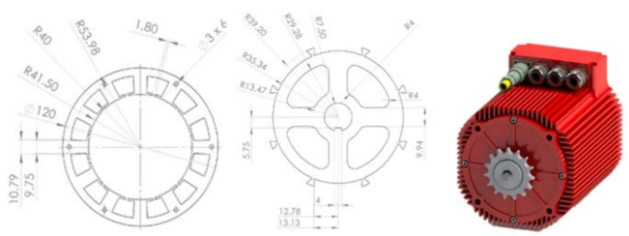

FIGURE 10. CAD drawing of the motor and snapshot of the developed traction motor.

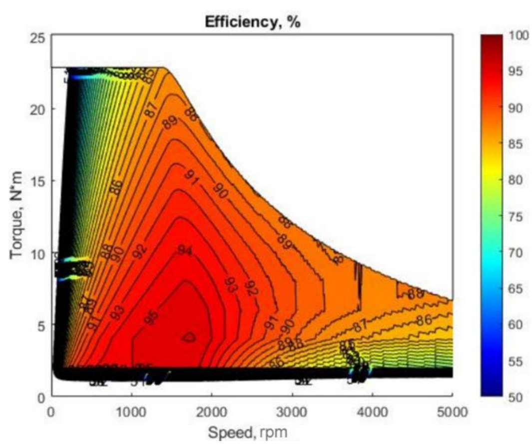

FIGURE 11. Simulated traction motor expected performance.

Based on those simulations and modeling data output, then real full-scale electric motorcycle prototype (GESITS) is then developed. Then the real electric motorcycle is using dynamometer tests and on-road condition tests. To get a specific parameter to be compared, i.e., energy consumption, the dynamometer must be set up to reflect the real-life GESITS performance. It is performed as ISO 28981:2009 standard requirements, such as GESITS running resistance due to real-life ambient environments such as temperature, wind velocity, relative humidity, ambient air temperature, ambient air pressure, and ambient air density.

Following the ISO 28981:2009 standard, some data values for correcting the output from dynamometer tests are then implemented. To validate the model, two activities were carried out. Firstly, testing the electric scooter using an inertial dynamometer, and secondly, a normal test on the

FIGURE 12. The prototype version of GESITS.

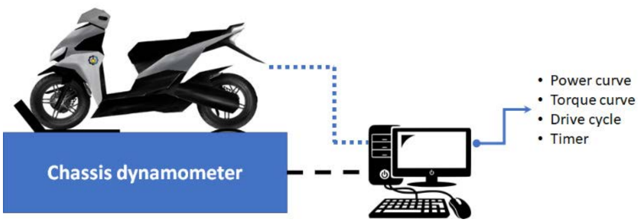

FIGURE 13. The dynamometer experimental setup.

public road. This device used the standard drive cycle specified in Fig. 5. Both tests were conducted according to ISO standard-setting and requirements, such as correction due to ambient conditions, standardized rider weight or height, and others.

A. DYNAMOMETER TESTING SET UP

An inertial chassis dynamometer is used to validate the electric motorcycle prototype energy consumption model. The dynamometer experimental setup is shown in Fig. 13 as follows. Before being used in the experimental testing, the dynamometer parameters must be set up.

The set-up is carried out as per ISO 28981:2009 standard. The ISO 28981 standard is used to define the dynamometer running resistance. It is particularly of importance as this value will be employed to compensate for the energy consumption of the electric motorcycle. Once the dynamometer running resistance is defined, subsequently the electric motorcycle energy consumption test was performed using the standard drive cycle of ISO 13064-1:2012. The drive cycle regime to be performed in the dynamometer is tabulated in Table 4.

While if it is plotted on the time and speed axis, it can be depicted in Fig. 14.

B. DYNAMOMETER TESTING RESULTS

The dynamometer test was initiated when the battery pack capacity was approximately at 100% SoC and ended at 0%. It is defined by measuring its terminal voltage. Therefore, at 100%, the battery's terminal voltage should read about 99 volt and 67.5 volt at 5%. The total energy was measured using a Joulemeter by charging the battery from 5% to 100%. At 100% the energy contained was 3.396 kilowatthours (average).

TABLE 4. Urban drive cycle regime performed in the dynamometer experimental testing as per ISO 130641-2012.

Phase	Operation	Acceleration (m/s^2)	Speed (kph)	Duration (sec)	Cumulative time (sec)
1	Idling	-	0	8	8
2	Acceleration	Full throttle	0 to max	57	-
3	Steady speed	Full throttle	max	57	-
4	Deceleration	–0.56 max	Max to 20	57	65
5	Steady speed	-	20	36	101
6	Deceleration	–0.93	20 to 0	6	107
7	Idling	-	0	5	112

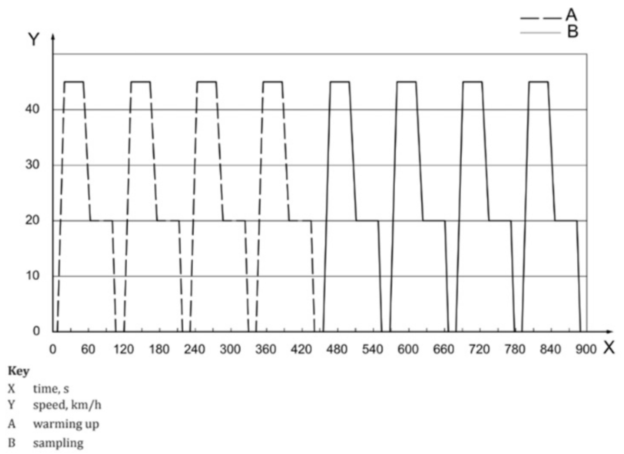

FIGURE 14. Urban drive cycle performed in the dynamometer experimental testing as per ISO 130641-2012.

Using the velocity profile in Table 4 and Fig. 14, the electric cycle was driven on the dynamometer, while the battery voltage, time, and the total distance for each testing were recorded. The dynamometer test results which were obtained from 15 experiments with 22 cycles of the ISO driving cycle standard are presented in Fig. 15.

Fig. 15(a) presented the scooter's energy requirement during each test run. According to observation, the energy required during the simulation run was almost similar, except in test numbers #6 and #14. This indicated the good performance of the battery pack during the dynamometer test runs. Based on the 15 data tests, the average value of the energy required graph was calculated and drawn as presented in Fig. 15 with a black dotted line. The average initial value of the battery pack capacity was 3396 watthours. The value was equivalent to the total average energy of 5% SoC (67.5 volt) at the end of the test. Also, it was subsequently used to calculate the total energy consumption. Fig. 15(b) showed the scooter's battery SoC evolution during the dynamometer test run. Its value was recorded at the end of each cycle using a data logger in its battery management system. Based on the observation in the figure, the battery SoC behaved similarly to the energy required graph presented in Fig. 15(a). The test run

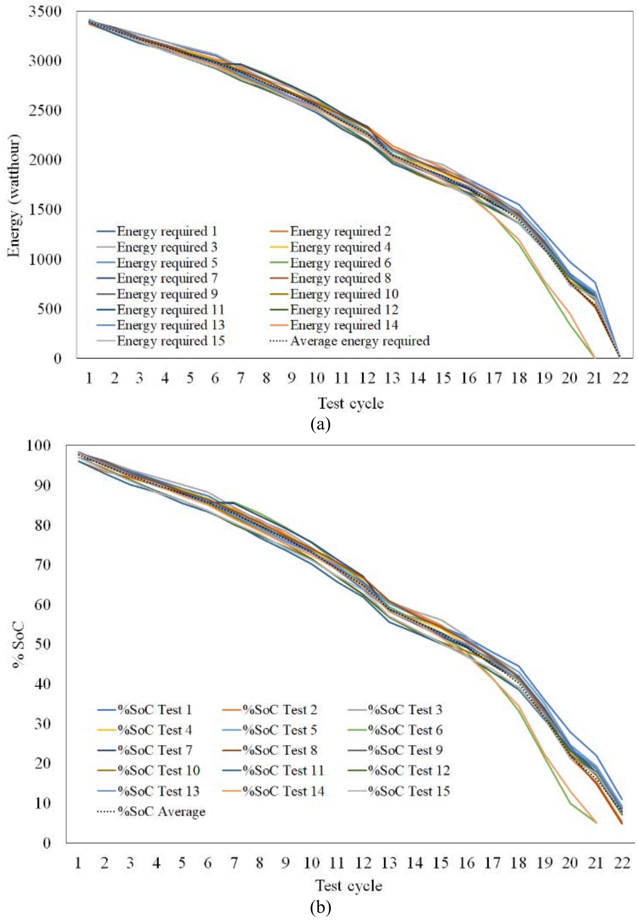

FIGURE 15. Dynamometer test result: (a) Energy required, and (b) Battery SoC.

was initiated when the SoC was 97.5% (average) and ended at 7.74% (average).

At this point, the battery was unable to power the electric scooter, and it is unsafe to force the battery pack until the energy completely drained out.

To calculate the energy consumption according to (1) during the dynamometer simulation runs, the equivalent distance traveled by the electric scooter was also measured and recorded. Table 5 showed the distance reached during each test. According to Table 5, the average test duration was 3 hours 42 minutes 30 seconds, while the average range of the scooter on the experimental test was 60.46 kilometers. Based on the average total energy required and the range in (1), the average energy consumption (E_{Cons}) for the total 15 test runs is as follows;

$$E_{Cons} = \frac{E_{Batt}}{d}$$
$$E_{Cons} = \frac{3396\,\text{Wh}}{60463\,\text{m}} = 0.056\,\text{Wh/m or } 17.80\,\text{km/kWh}$$

C. ON-ROAD TESTING

Similarly, the on-road testing was conducted using the battery SoC related to the dynamometer test runs. The experiment was carried out on a public road with normal traffic and condition in Indonesia. It was performed in three testing cycles. The test aimed to investigate the scooter's energy consumption in real-life conditions. The results are presented in Fig. 16.

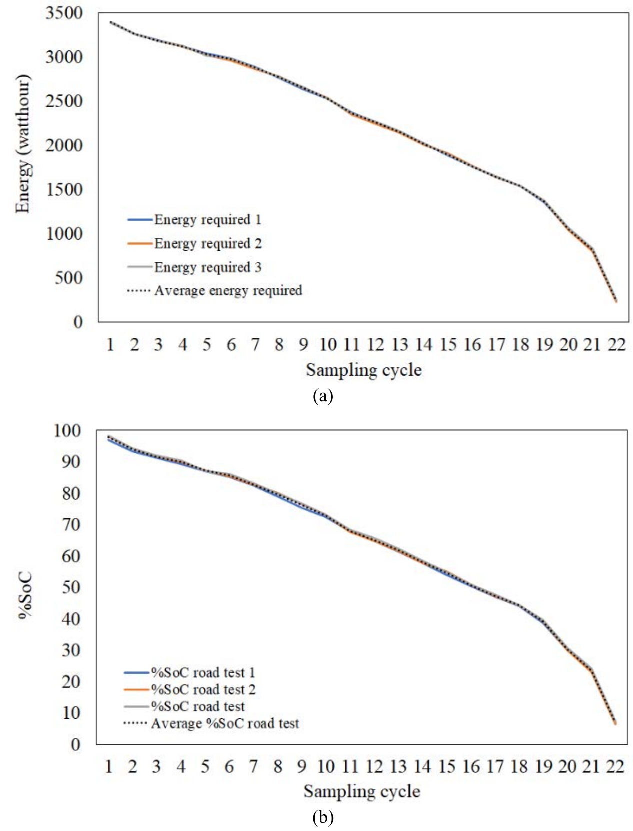

FIGURE 16. On-road test result: (a) Energy required, and (b) Battery SoC.

Figure 16(a) showed the energy required during the on-road testing. The test was initiated when the battery pack had average energy of 3396 watthours. Using an onboard data logger connected to the battery management system, the energy consumptions were logged. Meanwhile, the test ended when the battery pack SoC was equal to or slightly larger than 5% (in this case the average SoC is 7.1%). It is equal to 242 watthours. The energy required graph had a similar trend with SoC as shown in Fig. 16(b). According to observation, the on-road test was initiated and ended when the average battery SoC was 97.8% and 7.1% respectively. The results of total distance and testing duration are presented in Table 6.

Based on the values in Fig. 16 and Table 6, the average energy consumption of the electric scooter in road testing can be calculated as follows

$$E_{Cons} = \frac{E_{Batt}}{d}$$
$$E_{Cons} = \frac{3396\,\text{Wh}}{62833\,\text{m}} = 0.054\,\text{Wh m or } 18.50\,\text{km/kWh}$$

IV. RESULTS ANALYSIS

As it has been previously explained, this study discussed the modeling and simulation of electric scooters. Moreover,

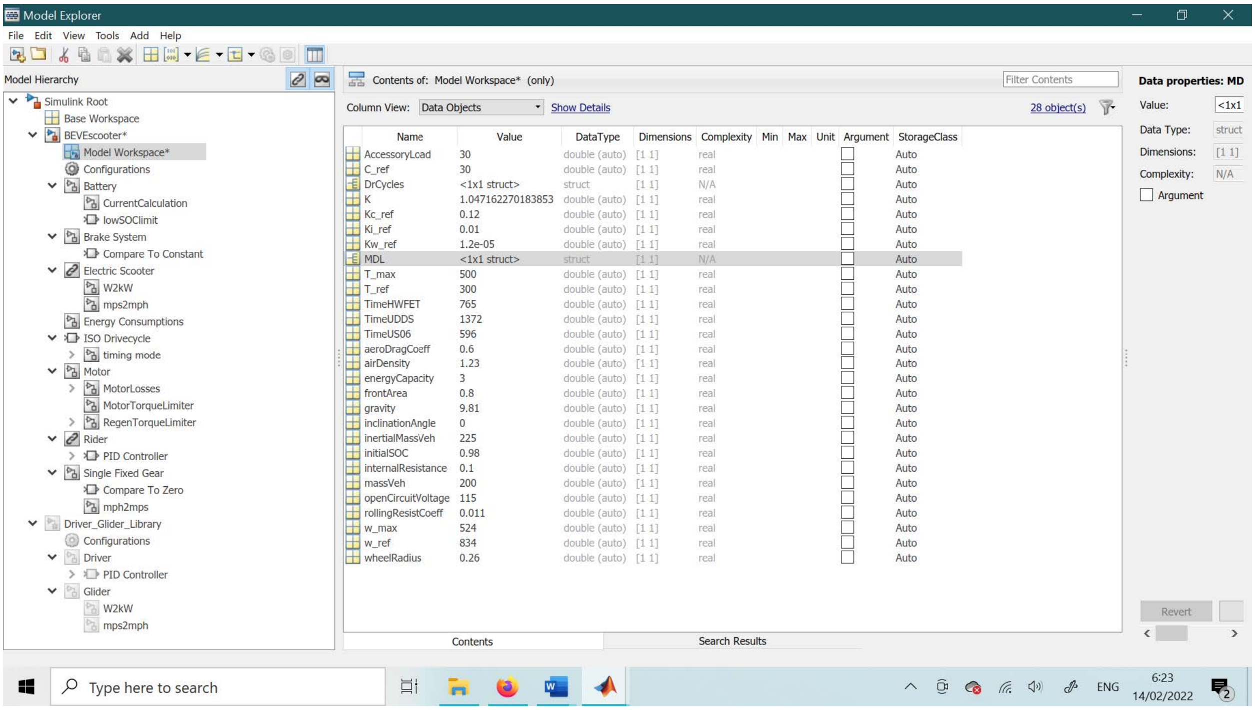

FIGURE 17. Snapshot of the MATLAB/Simulink electric vehicle model explorer.

TABLE 5. Dynamometer test runs: duration and distance.

Test	Duration	Distance (m)
1	03:43:19	60.610
2	03:44:49	61.313
3	03:43:16	60.608
4	03:36:40	60.995
5	03:43:05	61.283
6	03:36:40	59.190
7	03:43:27	60.615
8	03:41:51	59.904
9	03:43:33	60.621
10	03:45:16	61.324
11	03:43:40	60.645
12	03:42:07	59.918
13	03:41:38	59.920
14	03:36:44	59.087
15	03:45:42	61.313
Average	03:42:30	60.463

TABLE 6. On-road testing results: range, test duration, and average speed.

	Test 1	Test 2	Test 3	Average
Distance (m)	62.430	63.496	62573	62.833
Duration of test	03:05	03:12	03)14	03:14
Average speed (kph)	20	19.8	19.4	19.7

the model used in the simulation was validated through a dynamometer. ISO standard (ISO 13064-1:2012) was implemented in modeling and dynamometer experimental testing. To prove its performance in real life, on-road testing using normal traffic and environmental conditions was also conducted. The tests were performed during the day and its regenerative braking was switched off. Therefore, pure energy consumption from the battery can be defined. Based on this set up, the energy consumed was mainly used to propel the electric scooter and to power up its internal energy, which includes powering up the controller and battery management system. According to the simulation, dynamometer, and on-road testing results data, a comparison table was set up as presented in Table 7.

TABLE 7. Simulations, dynamometer tests, and on-road test results comparison.

	Simulation	Standard dynamometer test	Road test
Total energy required (Wh)	3272	3396	3396
Error (%)		**-3,79%**	**-3,79%**
Range (m)	63470	60460	62830
Error (%)		**4,74%**	**1,01%**
Energy consumptions (Wh/m)	0,052	0,056	0,054
Error (%)		**-8,63%**	**-4,75%**

This comparison was used to justify the model. According to the previous explanation, the drive cycle used in the simulation was ISO 13064-1:2012 (Fig. 5). The simulation results were used as a basis for comparison with the standard dynamometer and on-road test. The three parameters observed in the comparisons include energy required, range and energy consumption. The errors in the comparison are shown in Table 7. Firstly, the model simulation output of the total energy required was 3,272 watthours. Meanwhile, in the dynamometer test, the total energy required for 22 cycles of the run was 3,396 watthours on average. This is similar to the

TABLE 8. Performance comparisons of the electric scooter against internal combustion engine scooter in ride-hailing applications [29].

No	Parameter	Baseline (Internal combustion engine)	Scenario 1		Scenario 2	
			Value	Diff. to baseline	Value	Diff. to baseline
1	Average daily trip (km)	87.00	48.00	-45%	121.00	39%
2	Total energy cost per kilometer (IDR/km)	284.00	30.80	−89%	31.00	-89%
3	Average daily maintenance cost (IDR)	1,000.00	0.00	−100%	0.00	−100%
4	Average daily income (IDR)	162,487.00	92,235.00	−43%	227,624.00	40%
5	Average daily net income (IDR)	132,872.00	90,778.00	−32%	223,888.00	68%
6	TTW $CO2_e$ emission (metric tons of CO_e)	0.48	0.00	−100%	0.00	−100%

energy output required by the on-road test, which was also 3,272 watthours. However, the error was –3.79% compared to the simulation model energy required. In terms of range (distance covered), the simulation model can reach 63470 meters. Meanwhile, in the dynamometer tests, the electric scooter can reach an average range of 60,460 meters or 62,830 meters on normal on-road testing. Based on these results, the comparison errors are as follows, the standard dynamometer and on-road tests had 4.74% and 1.01% errors respectively. In terms of energy consumption, the simulation model had 0.052 watthours per meter. Meanwhile, the value was 0.056 watthours and 0.054 watthours per meter for dynamometer and on-road tests respectively. These data indicated −8.63% and −4.75% of error in the dynamometer and normal on-road tests respectively.

The errors in the comparisons can be evaluated as model development limitations in handling non-linear phenomena which occurred in the real-life application of the electric scooter. One of the non-linearity sources was friction. According to the comparison observation, the dynamometer test error was higher compared to the on-road. This is because its friction was both internal and from the device. While the friction was only internal in the on-road test. In terms of the energy model, the friction was energy absorbent. Therefore, the higher the friction, the more energy absorbed. As friction is non-linear, it was very difficult to model its phenomenon in the developed model. This is because the developed model was linear (kindly see Fig. 9, all simulation results were linear).

However, due to the magnitude of the errors which were quite small (−8.63% and −4.75% in the energy consumption comparison) as well as the reasons for such errors, the developed MATLAB/Simulink model was valid. Overall, the simulation results can demonstrate a satisfactory level of accuracy according to the ISO 13064-1:2012 standard for predicting the energy consumption of an electric scooter. Therefore, it can be used as a basis for further studies to estimate or predict other characteristics or behavior in the future. It can be used as a basis for developing and prototyping its traction motor. This topic will be reported in the subsequent paper.

Another paper has been prepared to report the electric motorcycle performance comparisons in terms of their economic impact on ride-hailing riders. Readers interested in this area are suggested to consult [29]. Its performance was compared against internal combustion engine motorcycle counterparts in the same class. Based on the work, it is concluded that the electric motorcycle's performance is outperformed the internal combustion engine motorcycle. The result can be shown in Table 8.

V. CONCLUSION

This study aims to obtain a model that can be used as a base for studying or predicting the characteristics and behavior of an electric scooter. This is of importance as the availability of such a model does not exist. To do this, the model must be validated. In this paper, a drive cycle based on ISO standards was used as an input for the model. Subsequently, a prototype version was also tested using the standard requirements. To determine its accuracy and robustness, further comparison with real-life application of an electric scooter was conducted.

As previously defined, this study aims to compare the energy consumed by this machine for a certain range of travel. Based on the comparison analysis, the model was concluded to be valid and had a satisfactory level of accuracy in predicting energy consumption with errors of only −8.63% and −4.7% during experimental dynamometer and normal on-road testing. Therefore, it can be used as a base for the further development of other electric scooters or motorcycles. As it is a high-level model, further improvements can be proposed to improve its accuracy, especially in terms of the battery pack energy measurements and chemical characteristics. In this paper, the two parameters were approached using simple energy consumption calculation formula. In terms of battery chemistry characteristics, a linear approach was used. Moreover, a detailed energy absorbent by friction in the scooter should be elaborately modeled. These are the further studies and experiments that can be performed shortly.

The real-life performance application of the electric scooter has been reported [29]. It is compared to its ICE scooter counterparts. The electric scooter outperforms the ICE scooter in several criteria. It can be concluded that the development of the energy consumption model of the electric scooter is valid and can be used to predict the real-life performance of energy consumption. In a real-life application in the ride-hailing application, the electric scooter is better by 89% in total energy cost (its energy consumption is far less than its ICE counterpart).

APPENDIX

MATLAB/SIMULINK MODEL OF THE ELECTRIC SCOOTER DEVELOPMENT

As it has been previously stated the electric scooter MATLAB/Simulink model is developed based on the electric vehicle energy consumption model. Some modifications are performed to suit the model into the electric scooter model. The electric vehicle model is based on a single mass dynamic mathematical model (high-level abstraction model). To suit the electric scooter, it only needs to define the parameter as listed in Table 1 such as electric scooter mass, its drag coefficient, scooter frontal area, tire dimensions, tire rolling resistance, battery capacity, electric motor characteristics, and driveline (transmission gear ratio and expected efficiency).

As it is a single mass dynamic model, inputting those scooter parameter values into the model will define the model as the electric scooter model, not the electric vehicle. The following figure is the parameter to be inputted into the model and it is specifying the electric scooter model. As can be seen in the figure, the model and its input parameter have been modified to facilitate the electric scooter predicted performance (based on Table 1 – 4). The model developed by [26] is very versatile and adaptive to many specific applications in electric vehicle prediction performance, hence utilized in this paper. One only needs to input the parameter that suits their requirements.

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