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doi:10.15199/48.2024.11.12

Enhanced Performance of Solar-Powered Dockless E-Scooters on Inclined Roads with Cruise Control Systems

***Abstract**. Solar electric scooters (Solar E-Scooters) are an environmentally friendly mode of future transportation. Adding additional features to the vehicle technology can increase safety and comfort. This study investigates how the addition of cruise control feature and the influence of road slope factors on the performance of Solar E-Scooters. A monitoring device was used to measure battery consumption at different slopes. The battery power required at 5° and 20° slope is 205.2 W and 285.6 W, respectively. The results show that the greater the road slope, the more battery power is required.*

***Streszczenie.** Hulajnogi elektryczne napędzane energią słoneczną (Solar E-Scooters) są przyjaznym dla środowiska środkiem transportu przyszłości. Dodanie dodatkowych funkcji do technologii pojazdu może zwiększyć bezpieczeństwo i komfort. W niniejszym badaniu zbadano, w jaki sposób dodanie funkcji tempomatu i wpływ czynników nachylenia drogi na osiągi hulajnogi Solar E-Scooters. Urządzenie monitorujące zostało użyte do pomiaru zużycia baterii przy różnych nachyleniach. Moc baterii wymagana przy nachyleniu 5° i 20° wynosi odpowiednio 205,2 W i 285,6 W. Wyniki pokazują, że im większe nachylenie drogi, tym większe zapotrzebowanie na moc baterii. (**Zwiększona wydajność zasilanego energią słoneczną skutera elektrycznego bez dokującej na pochyłych drogach z tempomatem**)*

Keywords: Solar Electric Scooter, Cruise Mode, Road Slope, Power Consumption
Słowa kluczowe: Skuter elektryczny solarny, tryb rejsu, nachylenie drogi, zużycie energii

Introduction

Dependence on finite fossil fuels has created an energy crisis due to their unsustainable use. Transitioning to renewable energy sources is critical to achieving sustainable energy practices [1, 2]. Solar energy is a promising alternative because it can convert sunlight into electricity [3,4]. A promising alternative lies in harnessing renewable energy, particularly solar PV technology. Solar PV utilizes solar cells, composed of semiconductors, to convert the sun's electromagnetic energy into electrical energy [5-7]. This energy can then be used to recharge electric vehicle batteries, reducing reliance on fossil fuels. Its applicability extends to powering electric vehicles, demonstrating its potential to contribute significantly to the transportation sector [8-11].

Currently, technological advancements in solar panel technology are also accelerating, with improvements in materials, shapes (models), sizes, and efficiency levels. The solar panels play a critical role in solar power plants, generating electricity whenever sunlight is available. This generated electricity can be stored in batteries for use during the night or during periods of low sunlight. Due to the reliance on sunlight for energy generation, careful planning is essential. One key aspect is determining the charging power output of the solar panels, which may influence the choice of solar panel shape or model for installation on electric vehicles [12].

Electric vehicles (EVs) offer a significant reduction in exhaust emissions, making them a compelling alternative to conventional gasoline-powered vehicles. Driven by growing environmental concerns and dwindling fossil fuel reserves, a global transition to EVs is underway. Governments around the world, including Indonesia, are investing significantly in the development of EV technology. Over the past five years, Indonesia has implemented policies and incentives to foster a strong domestic EV ecosystem [13].

Electric vehicle technology extends beyond cars, transforming various modes of transportation into more sustainable options. Dockless Electric scooters (DES), in particular, have gained significant popularity for short-distance travel, offering a compelling alternative to traditional vehicles. This literature review analyzes previous research on enhancing electric scooter performance through hybrid power sources, added features, and design aspects. Studies since the 2000s have investigated micro-mobility modes, emphasizing design and performance. Feasibility and safety considerations related to production have also been explored [14,15].

Satworo et al. [16] developed a functional and strong e-scooter prototype for eco-friendly transportation on campus. The e-scooter prioritizes strength, comfort, and functionality, with a 350-watt BLDC motor powered by 39 lithium-ion units. This prototype has potential for use in various public spaces beyond the campus, such as offices, shopping malls, and parks. The feasibility of solar-powered electric scooters has gained significant research interest due to their potential to reduce air pollution and extend range.

Sri Vidhya et al. [17] addressed this by developing a solar-powered scooter with an in-wheel motor design. The motor draws power from a rechargeable battery, which is continuously charged by a solar panel mounted on the scooter's body. An Arduino microcontroller constantly monitors the scooter's performance, making it ideal for short-distance commutes while contributing to a reduced environmental footprint. On the other hand, a study conducted by Alfian et al. [18] examined the battery consumption of a solar-powered electric scooter prototype on a flat road. The study found that the average power consumption increased with the increase in speed. The results indicated that the average power consumption was 64.69 W, 87.71 W, and 116.51 W, respectively, at speeds of 10 km/h, 15 km/h, and 20 km/h.

Begam et al. [19] proposed the use of Adaptive Neuro-Fuzzy Sliding Mode Control (ANF-SMC) to overcome the problems of electric vehicles, in terms of achieving precise speed control due to high torque requirements and the uncertainty of load dynamics on permanent magnet brushless DC (PMBLDC). Experimental results show the achievement of dynamic performance, increased driving distance and validation of the regenerative braking system for improving the performance of electric vehicles. In addition, an innovative cruise control design by Németh [20] introduces a novel control strategy with three components: predictive optimal control, robust LPV control, and an optimization-based supervisor. This approach prioritizes primary performance metrics (safety and speed limits) for autonomous vehicles while considering secondary objectives like fuel efficiency and travel time optimization.

This research investigates the battery power consumption of a solar-powered e-scooter prototype on a sloped road. The e-scooter is equipped with a cruise control function to maintain a steady speed. The aim is to improve the performance of the designed solar dockles e-scooter.

Material and method

The conceptual framework, illustrated in Fig. 1, outlines the relationships between key variables in this study. Measurement sensors for voltage, current, and inclination angle are installed on the prototype solar scooter to collect data. The cruise mode feature, designed to maintain speed on inclined roads within the specified slope range (as defined by the research variables), is also included. Battery power consumption will be determined based on voltage and current sensor data, observed and recorded at various road inclination angles.

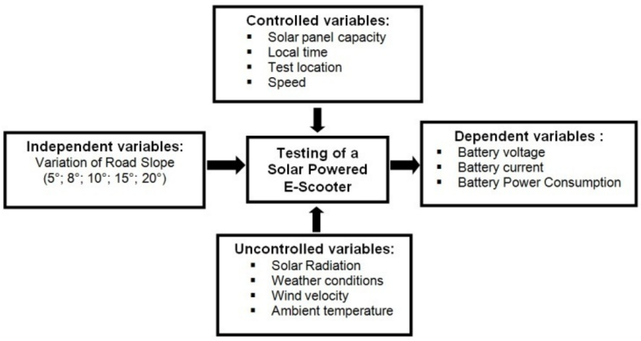

Fig.1. The conceptual framework for DES performance

The study used a quantitative research method. An electric scooter with a monitoring system was driven on an inclined road, recording its speed, set point time, and power consumption. The experiment was conducted five times at different slope angles; 5°, 8°, 10°, 15°, and 20°, and the data were recorded and stored in the monitor's memory for further analysis. One-way ANOVA was used to analyze the effect of road slope angle on the battery power consumption of the electric scooter. Meanwhile, the prototype solar-powered dockless electric scooter (DES) used in this study is shown in Fig. 2.

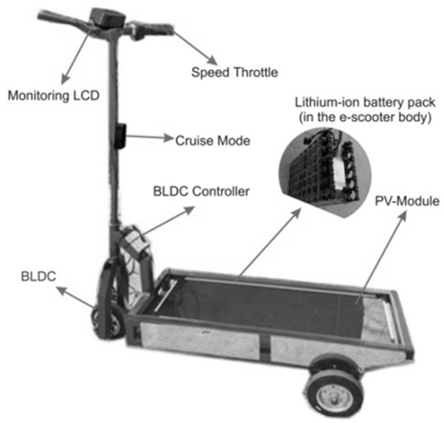

Fig.2. The prototype of solar powered dockles e-scooter (DES)

The dimensions of the electric scooter in length, width and thickness are 1060 mm, 380 mm and 1500 mm, respectively, and it has a ground clearance of 70mm. The main components of DES consist of a 15 Wp Amorphous PV module, 29.4V/12 Ah Lithium-Ion battery, BLDC Controller, and 24V/250W BLDC Motor-hub.

The monitoring tool on the DES uses Arduino UNO. This microcontroller processes data from sensors and components installed on the DES, including a voltage sensor, ACS712 current sensor, RTC module, LCD, MPU6050 sensor for measuring inclination angle, and an SD card data logger module for storing data recorded during testing. The software used to create the programming code for the monitoring tools is Arduino IDE. Meanwhile, the additional cruise mode feature is used to lock the speed of the electric scooter so that it remains constant at that speed. The electronic diagram of the cruise mode feature is shown in Fig.3.

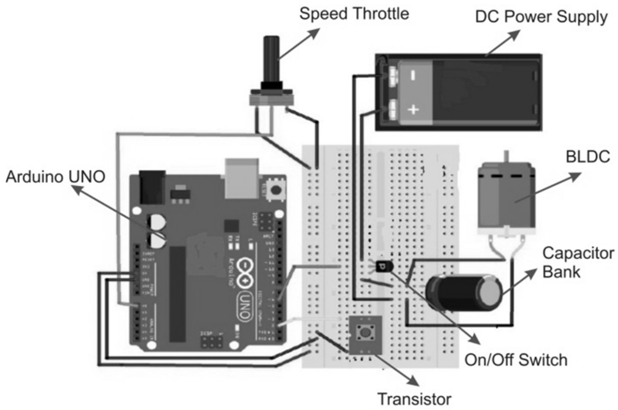

Fig.3. The circuit diagram of cruise mode feature on DES

Most vehicle models use ordinary differential equations or state space representations, focusing on basic parameters like mass and drag. Real-time torque adjustments are needed for electric vehicles using cruise control on inclines due to changing pitch and speed. The Cruise Control System must adapt driving and braking torque to maintain the desired speed under these conditions. A free-body diagram illustrating the longitudinal dynamics of a dockless electric scooter is shown in Fig. 4. The main factors influencing vehicle performance are rolling resistance force, aerodynamic drag force, slope resistance force, and acceleration resistance force [21-23].

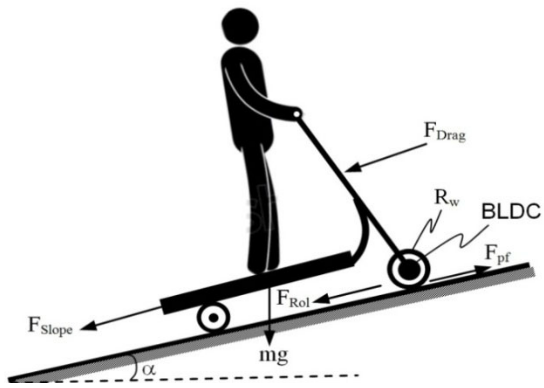

Fig.4. Longitudinal Dynamics of Dockless E-Scooter

Considering Newton's second law, the total resistance force acting on a moving electric scooter inclined at an angle α can be defined by [24, 25],

$$F_{pf} - F_{Rol} - F_{Drag} - F_{Slope} = ma = m\frac{d^2x}{dt^2} \tag{1}$$

where: F_{pf} – the driving force, F_{Rol} – The rolling resistance/friction, F_{Drag} – The aerodynamic drag, F_{Slope} – the slope/inclination/grade resistance.

The rolling resistance (F_{Rol}) depends on the road condition and total vehicle mass, which can be expressed by Eq. (2) [23],

$$F_{Rol} = mg\mu \cos\alpha \quad (2)$$

where: m – the mass of DES and rider, g – the earth's gravity, μ – the rolling resistance coefficient.

The aerodynamic drag (F_{drag}), a resistance force acting on objects in motion, arises from their interaction with air. The object's shape, velocity, and air density all play a role in the magnitude of this force, as described by Eq. (3),

$$F_{Drag} = \frac{1}{2} A_a C_d \rho \left(v_w + v_{DES}\right)^2 \quad (3)$$

where: A_a – the frontal area of the vehicle and the driver, C_d – The coefficient of aerodynamic drag, ρ – the density of air, v_w – the wind velocity, v_{DES} – the speed of velocity Dockless E-Scooter.

The resistance force due to slope (F_{slope}), also known as grade resistance, is influenced by both the vehicle's total mass and the angle of inclination. This relationship is formulated in Eq. (4),

$$F_{Slope} = mg \sin\alpha \quad (4)$$

Furthermore, the driving torque (T_{pf}) can be represented by Eq. (5),

$$T_{pf} = F_{pf} R_w \quad (5)$$

where: F_{pf} – the driving force, R_w – the wheel's radius.

The BLDC (hub-motor) is installed on the front wheel of the DES as shown in Fig. 4. Therefore, the driving torque (T_m) can be calculated by Eq. (6).

$$T_{pf} = \left(F_{Rol} + F_{Drag} + F_{Slope} + m\frac{d^2x}{dt^2} \right) R_w = T_m \quad (6)$$

Based on Eq. (5), the torque generated by the BLDC motor can be expressed by Eq. (7).

$$T_m = F_{pf} R_w \quad (7)$$

Then, the mechanical output power (P_m) is determined by using the Eq.(8).

$$P_m = T_m \omega = T_m n \frac{2\pi}{60} \quad (8)$$

where: ω – angular speed, n – rotations per minute.

Meanwhile, the BLDC electric input power refers to the power drawn by the electric motor from the battery. The electrical input power (P_E) can be calculated using Eq. (9).

$$P_E = V.I \quad (9)$$

where: V – Voltage applied to the BLDC, I – Current drawn by the BLDC.

Based on Eq. (8) and (9), the BLDC efficiency (η), can be written with Eq. (10) as follows,

$$\eta = \frac{P_m}{P_E} = 0.033 \frac{T_m \pi n}{VI} \quad (10)$$

Results and discussion

The Dockless E-Scooter (DES) was operated in cruise mode on inclined roads at a preset speed of 10 km/h. A monitoring tool recorded and analyzed the DES's battery power consumption data. The independent variable in this experiment was the road incline angle, which varied across five settings: 5°, 8°, 10°, 15°, and 20°. Table 1 presents the results of five test runs conducted at each incline in the DES data test.

Table 1. Results of inclination tests on the electric scooter

Road Inclination (°)	Voltage (V)	Current (A)	Baterry Power Comsuption (W)
5	23.74	8.73	207.25
	23.40	8.79	205.69
	23.05	8.95	206.30
	23.64	8.52	201.41
	23.94	8.65	207.08
		Average	**205.55**
8	22.81	9.88	225.36
	22.81	9.91	226.05
	22.71	9.94	225.74
	22.81	9.88	225.36
	23.64	10.04	237.35
		Average	**227.97**
10	22.17	10.92	242.10
	22.32	10.81	241.28
	22.46	10.73	241.00
	25.41	9.75	247.75
	21.82	11.15	243.29
		Average	**243.08**
15	23.15	11.36	262.98
	22.17	11.98	265.60
	22.81	11.47	261.63
	22.32	11.86	264.72
	22.12	12.19	269.64
		Average	**264.91**
20	23.15	12.58	291.23
	22.17	12.84	284.66
	22.12	12.89	285.13
	22.27	12.77	284.39
	23.40	12.15	284.31
		Average	**285.94**

One-way ANOVA, a statistical technique suited for data with one categorical independent variable and multiple groups, was employed to assess the impact of road inclination on DES current, voltage, and power. In this study, road inclination (categorized into different levels) served as the independent variable. We compared the means of DES measurements across these inclination categories using one-way ANOVA with a significance level of 5% (0.05). Table 2 provides a summary of the average test data for voltage, current, and power for each of the inclination groups.

Table 2. Summary of the average test data

Groups	Count	Sum	Average	Variance
Inclination	5	58	11.6	35.3
Voltage (Volt)	25	572.41	22.8964	0.630974
Current (Amp)	25	268.74	10.7496	2.048479
Power (Watt)	25	6137.279	245.4912	826.9226

Table 3 shows the results of a one-way ANOVA, a statistical test used to compare the means of multiple groups.

Table 3. Result of one-way ANOVA

SoV	SS	df	MS	F	P_{value}	F_{crit}
Btwn Grps	9.04×10^5	3	3.01×10^5	1142.7	4.17E-63	2.73
Within Grps	2.00×10^4	76	263.84			
Total	9.2×10^5	79				

The data analyzed here examines the effect of inclination on voltage, current, and power. The F-statistic reflects the degree to which the means of the groups differ relative to the variation within the groups. The p-value indicates the probability of observing a test statistic as extreme as the one obtained, assuming there's no real difference between the groups (the null hypothesis). In this case, the large F-statistic (1142.7) and the small p-value (4.17E-63) allow us to reject the null hypothesis. This means that there is a statistically significant difference between the means of the voltage, current, and power groups.

In addition, the influence of the road inclination on the current and voltage of the battery in DES can be explained by the graph in Fig. 5.

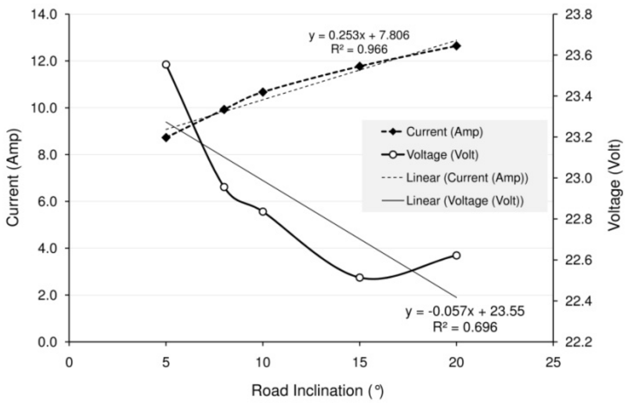

Fig. 5. Influence of road inclination on battery current and voltage of Dockless E-Scooter (DES)

Fig. 5 shows a direct relationship between the incline of the road and the current drawn by the electric scooter's battery. Conversely, a negative correlation is observed between road inclination and the battery's output voltage. The equations for the plotted lines are: Current (A) = 0.253x + 7.806 (R^2 = 0.966) and Voltage (Volts) = -0.057x + 23.55 (R^2 = 0.696). R^2, the coefficient of determination, indicates how well the regression lines fit the data. Here, the higher R^2 value (0.966) for current suggests a stronger correlation with road slope compared to voltage (R^2 = 0.696).

Figure 5 shows a decrease in battery voltage as the electric scooter is discharged. Initially, with a 5° incline and a full battery (100% SOC), the average voltage was 23.55 V. However, during a subsequent test with a 20° incline, the average voltage dropped to 22.62 V. This illustrates the effect of battery usage on voltage. State of Charge (SOC) is a more reliable indicator of remaining battery power, expressed as a percentage (0% = empty, 100% = full). Voltage gives a basic idea of the battery's state of charge. However, it is not always reliable because it can fluctuate during use [23].

The impact of cruise control on current characteristics is evident in Figure 5 and Table 1. Fig.5 shows a clear correlation between increasing road angle and rising current. This aligns with the expected rise in BLDC torque (T_m) due to the increasing $\sin \alpha$ (Eq. 4), which influences the magnitude of F_{slope}. Additionally, the current increase reflects the motor's effort to maintain constant speed under cruise control, a feature confirmed by the constant speed values across five tests at each incline (Table 1). The current range for a 5° incline (8.52-8.95 Amp) rises to (12.15-12.89 Amp) at a 20° incline. As the slope increases, the motor automatically boosts power to maintain the set speed, consequently raising the battery current [26].

Battery power consumption in electric vehicles can be impacted by several factors, including ambient temperature, wind speed, load, distance, driving style, and road conditions such as uphill and downhill inclinations. A literature review conducted by [27] suggests that the factors mentioned above can have an impact on battery power consumption in electric vehicles. However, this research study focuses specifically on the effect of road inclination on battery consumption. The study analyzed power consumption at different road inclinations while using a cruise control mode set at a speed of 10 km/h. Fig. 6 shows the effect of the road inclination on the battery power consumption of the electric scooter.

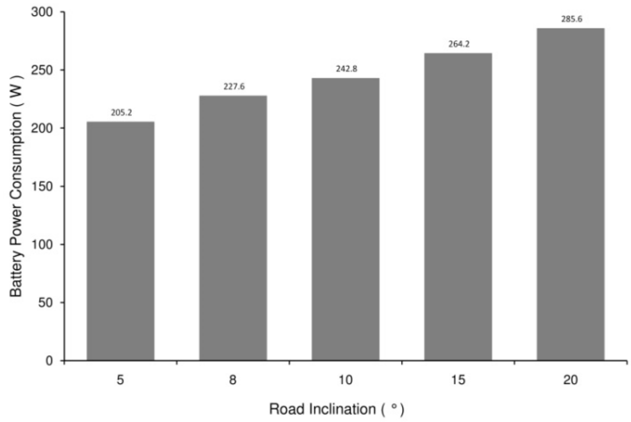

Fig. 6. Influence of road inclination on DES battery power consumption

The DES test results in Fig. 6 show a strong correlation between power output and variations in road inclination. Power output increased steadily from 205.55 W at a 5° incline to 285.94 W at a 20° incline. This trend underscores the significant impact of uphill and downhill inclines on electric vehicle battery consumption. Similar results were reported in [28], where a 3° incline resulted in a more than 50% increase in energy consumption. Furthermore, this study complements the results of [18], which focused on flat road conditions. Comparing these results, there is a significant increase (300%-400%) in energy consumption on inclined roads compared to flat roads.

Therefore, adding cruise mode to the dockless electric scooter (DES) significantly reduces battery drain on inclines. Test results show that increasing the road inclination from 5° to 20° only increases the battery consumption by 39%. It is concluded that the cruise mode effectively conserves battery power, resulting in improved performance of the electric scooter.

Conclusions

This e-scooter prototype runs on solar power and doesn't require a dock. It has a 250W BLDC hub motor, a 15W amorphous solar panel, and a 29.4V/12Ah lithium-ion battery. The scooter has a cruise control function that helps maintain a speed of 10 km/h on different inclines (5°, 8°, 10°, 15°, and 20°). During tests, it was observed that the battery consumption increased significantly on inclines (300-400%) as compared to flat roads. However, when the cruise control function was turned on, the battery consumption increased by only 39% on inclines ranging from 5° to 20°. This indicates that the inclination of the road affects the battery consumption of the electric scooter. The steeper the incline, the more energy the battery will consume. But, using the cruise mode significantly reduces the battery power consumption, which increases the efficiency of the electric scooter.

Acknowledgements

This research was financially supported by Politeknik Negeri Malang through grant DIPA-023.18.2.677606/2023.

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