

Assessing the Energy Demand of an Electric Two-Wheeler under Different Standard Driving Cycles on a Motorcycle Chassis Dynamometer

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Abstracts

The study presents an experimental results for evaluating the power demand and energy consumption of an L3e-category electric motorcycle in accordance with United Nations Economic Commission for Europe (UNECE) standards, using a motorcycle chassis dynamometer. The test was conducted under two driving cycles, including the ECE R40 driving cycle, and the Worldwide Harmonized Motorcycle Test Cycle (WMTC). Energy metrics including traction energy consumption, regenerative braking recovery, net energy consumption, and specific energy consumption per distance traveled were calculated from measured voltage, current, and vehicle speed data. Results indicate that the WMTC cycle exhibited the higher total energy consumption of 35.9 Wh/km compared to 31.8 Wh/km for the ECE R40 cycle. Moreover, the WMTC cycle showed the higher average specific energy consumption owing to higher demanding of energy in transient conditions. Regenerative events occur more frequently on WMTC because the cycle features sharper decelerations and stronger transients (more frequent and larger-magnitude negative acceleration) than ECE R40. In the signals, WMTC shows numerous short negative current bursts immediately after throttle lift/brake application, whereas R40 mostly exhibits smoother decels with shorter, lower amplitude regen. Although the total recovered energy remains small, the higher event density on WMTC is consistent with its more transient kinematic profile.

Keywords: Dynamometer, electric motorcycle, energy consumption.

1. Introduction

Many nations are implementing large initiatives to conserve energy and cut greenhouse-gas emissions in transport, motivated by climate change and the depletion of fossil fuels. Since transport draws substantial energy, it has become a focal point for policymakers, manufacturers, and consumers. In Vietnam and many Asian cities, the two-wheeler (2W) fleet has expanded rapidly, making two-wheel electric vehicles (2W-EVs) increasingly important for energy planning and operations at scale [1-3]. The International Energy Agency (IEA) provides a system wide view of transport within the energy system, highlighting electrification trends and their implications for national demand and energy security [1]. The World Bank & German Agency for International Cooperation (GIZ) outline a low carbon transport roadmap policy instruments, investment levers, and priority measures underscoring why standardized evidence on energy use is valuable for planning [2].

International Council on Clean Transportation (ICCT) documents the rapid growth of Vietnam's

2W-EV market, key drivers and barriers, and product trends, motivating rigorous benchmarking across models and manufacturers [3]. Consequently, quantifying 2W-EV energy consumption (EC) under well defined test conditions is practically important for technology comparison, product design, and operations management [1-5]. Yuwono *et al.* (2024) compare EC, CO₂, and cost between hybrid and battery electric motorcycles, demonstrating the usefulness of distance normalized metrics for policy and technology assessment [4]. Kammuang-lue *et al.* (2020) discuss draft Minimum Energy Performance Standards (MEPS) and High Energy Performance Standards (HEPS) for 2W-EVs in Thailand, signalling a regional shift toward explicit energy efficiency standards that contextualizes laboratory benchmarks [5].

For testing and type approval of L-category vehicles, the Worldwide Harmonized Motorcycle Test Cycle (WMTC) and Economic Commission for Europe Regulation No. 40 (ECE R40) cycles are widely used as canonical representations of typical operating scenarios [6, 7]. United Nations, Global technical

regulation (UN GTR) No. 2 defines WMTC phase structure, speed time patterns, and test conditions as the global reference for L-category approval, providing the legal technical basis for dynamometer testing [6]. United Nations Economic Commission for Europe (UNECE) Regulation No. 40 specifies the R40 cycle and associated measurement procedures for motorcycles, enabling cross cycle comparison in laboratory settings [7]. The European Commission - Joint Research Centre (EC-JRC) preparatory work for the Euro 5 step synthesizes technical evidence and environmental impacts for L-category vehicles, clarifying the role of standardized cycles in regulatory progression [8]. Nevertheless, standard cycles may not fully capture regional driving behavior or traffic conditions; hence many studies have developed localized motorcycle cycles and examined their impacts on energy/fuel use and emissions, emphasizing potential deviations versus standard cycles and the need for systematic verification before transferring standard cycle results to real world use [9-13]. Tzeng and Chen (1998) [9] develop a Taipei-specific motorcycle cycle from on road data to measure emissions and fuel economy, illustrating a data driven methodology and why localization matters.

Tsai *et al.* (2005) [10] construct a real-world motorcycle cycle for emission factor measurement, detailing collection, processing, and validation steps that materially affect test outcomes. Le *et al.* (2012) [11] measure emission factors and fuel consumption on a chassis dynamometer using a localized cycle methodologically relevant here even though the subject vehicles are internal combustion engine. Duarte *et al.* (2016) [12] show that cycle selection (regulated vs. alternative) can materially change fuel consumption and emissions, reinforcing the case for verification when generalizing from standard cycles. Barlow *et al.* (2009) [13] compile representative driving cycles and provide practical guidance on their application in emissions and energy testing, making their Transport Research Laboratory (TRL) reference book a key source for selecting appropriate cycles. Even so, standardized cycle assessments remain essential to benchmark across models/vehicles and to decompose by phase (acceleration steady cruise-deceleration/idle) to identify sources of energy differences among speed profiles [4, 5].

In this study experiments are conducted in a laboratory on a chassis dynamometer to faithfully reproduce WMTC and ECE R40 speed time traces, control test conditions, and improve repeatability. Vehicle speed $v(t)$ is taken from the dynamometer roller (encoder/speed channel), while pack voltage $U(t)$ and current $I(t)$ are measured directly using an oscilloscope with appropriate probes and simultaneous sampling for time alignment [14, 15]. Energy consumption is computed directly from the measured signals via $\int U(t)I(t) dt$ normalized by distance

(Wh/km), without inferring mechanical power or assuming drivetrain load [5, 14, 15]. AVL's technical material on electric dynos describes drive principles, measurement channels (including encoder speed), and trace reproduction capability, supporting our equipment description and channel selection [14]. Nguyen *et al.* (2021) [15] propose a robust pipeline for instantaneous motorcycle data (synchronization, cleaning, and integration) in on road studies; the same steps inform our in-lab processing to ensure signal consistency before energy integration. Standard signal processing techniques, such as least-squares fitting and denoising, improve the stability of numerical integration performed on discretely sampled data [15, 16].

Selesnick's (2013) [16] note on least squares provides practical recipes for multi channel alignment and noise reduction, limiting accumulation error in $\int UI dt$. This laboratory configuration also avoids common on road data limitations Global Positioning System (GPS) accuracy degradation in urban canyons/tunnels and the lack of On-Board Diagnostics (OBD) or Controller Area Network (CAN) on most 2Ws by relying on laboratory grade sensing and control [17-19]. Niemeier *et al.* (1999) [17] evaluate data collection protocols for driving cycle development, highlighting risks and variance when acquisition is not well controlled. Tong & Hung (2010) [18] offer a structured framework for building cycles from on road data (sampling, clustering, and synthesis), underscoring that localization requires standardized procedures to be representative. Duran & Earleywine present a GPS filtering method for drive cycle analysis (drift/step handling, and urban canyon effects), further qualifying raw on road signals [19].

The energy demand of 2W-EVs was assessed under standard WMTC and ECE R40 cycles on a chassis dynamometer, focusing on the three measured quantities $v(t)$, $U(t)$ and $I(t)$, and computing energy via $\int U(t)I(t) dt$ per distance. Results are discussed for benchmarking applicability and in relation to regional policy and standardization efforts relevant to 2W-EVs [4-7, 20].

2. Research Methodology

The experiments were conducted in a controlled laboratory using a chassis dynamometer to quantify the electric motorcycle's EC under different standardized driving cycles in Fig. 1. The vehicle was configured with an equivalent inertial mass, while voltage $U(t)$, current $I(t)$, and speed $v(t)$ were recorded and time aligned. Tests covered two cycles ECE R40 and WMTC from which traction,

regenerative, net energy metrics, and specific energy per kilometer were computed.

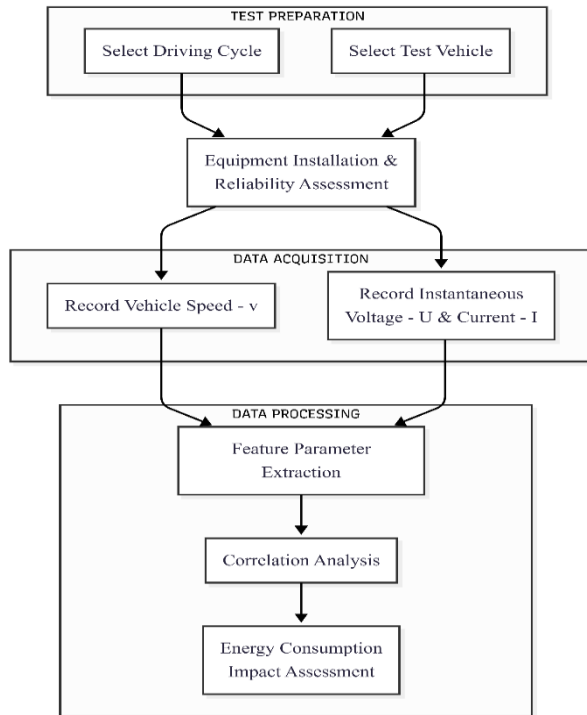


Fig. 1. Procedure for evaluating the impact of driving cycles on the energy consumption of 2W-EV

2.1. Test Vehicle and Data Acquisition System

For this study, the Selex Camel 2 (2W-EV) features a scooter style design with a high load capacity frame. Its electric motor delivers a maximum power of 4000 W and a peak torque of 140 Nm, with a top speed of

80 km/h. The vehicle uses three swappable lithium-ion battery packs (total capacity is 3.48 kWh), enabling a maximum range of about 150 km when all three packs are installed. The motorcycle supports a payload of up to 150 kg. The key technical specifications of the 2W-EV are summarized in Table 1.

The procedure for collecting instantaneous voltage and current at a 4 Hz sampling rate was extracted from a Rigol DS1052E oscilloscope, as illustrated in Fig. 2. A Hantek CC65 clamp-type current sensor was used for DC measurements with a sensitivity of 1 mV per 100 mA featuring an accuracy of $\pm 2\%$ over the 0.1–40 A range and $\pm 4\%$ over 40–65 A. For voltage, a Fnrirs P6100 probe operated in the X1 setting was used for DC voltages below 200 V. Vehicle speed was measured directly from the chassis dynamometer roller.

Table 1. Specifications of the test 2W-EV

Item	Parameters	Unit
Brand and model	Selex Camel 2	-
Motor type	Rear wheel	-
Maximum motor power	4000	W
Maximum motor torque	140	Nm
Maximum vehicle speed	80	km/h
Battery units	3 packs	-
Movement range	150	km
Max. payload	150	kg

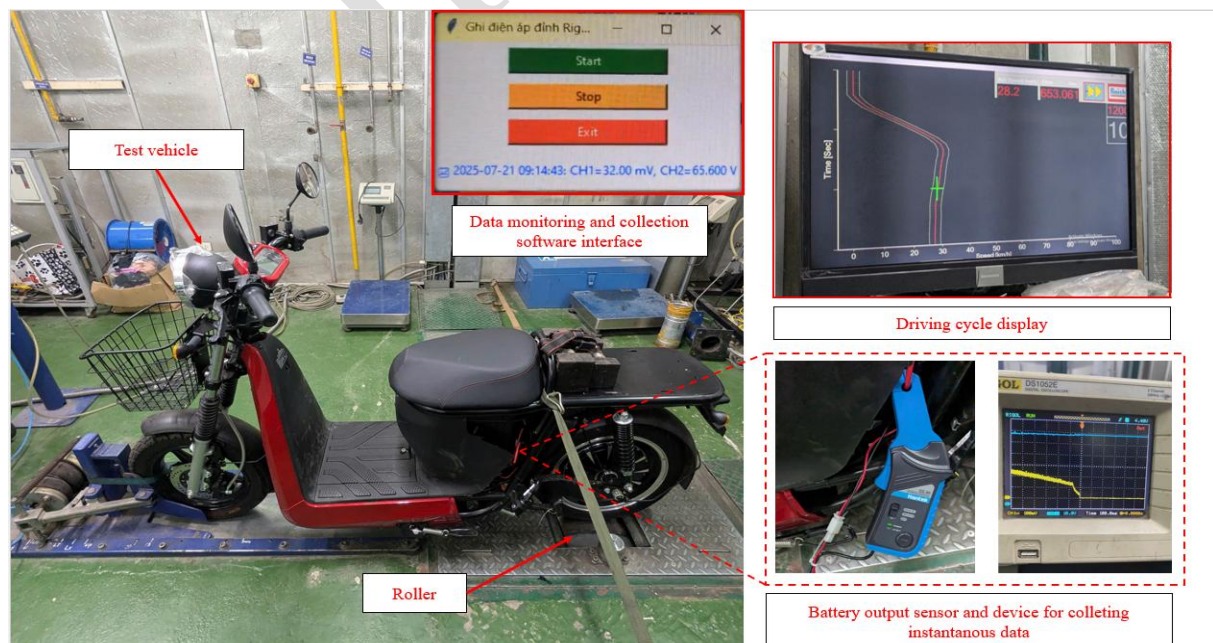


Fig. 2. Installation diagram of the data acquisition system on the 2W-EV during chassis dynamometer testing

2.2. Selecting Driving Cycles for Chassis-Dynamometer Simulation

The test bench used is an AVL List GmbH (AVL) chassis dynamometer [14]. The system is a roller type dynamometer capable of reproducing real on road resistance by configuring the equivalent rotational inertia and applying a controlled resistive torque. The dynamometer measures two primary quantities: the roller speed, obtained using a high-resolution optical encoder, and the brake reaction force, captured by a load cell mounted on the stator. From these measurements, the system computes wheel side torque, tractive effort, mechanical power, and vehicle acceleration. Cooling and ventilation fans are used to maintain stable thermal conditions when the vehicle operates at high load. Before each test, the battery is fully charged and then allowed to rest to stabilize its temperature.

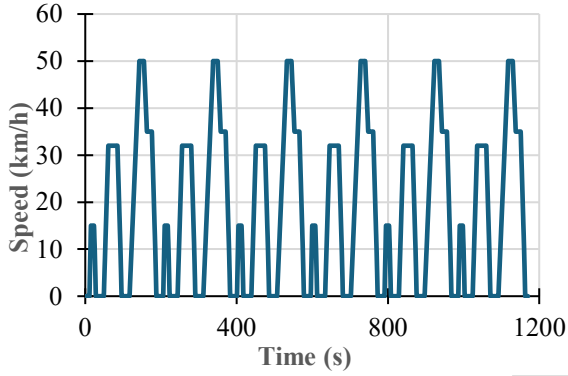


Fig. 3. ECE R40 cycle

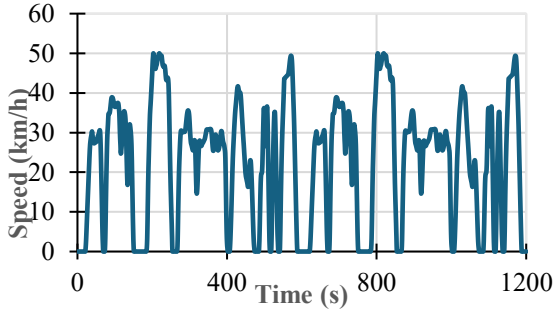


Fig. 4. WMTC cycle

In this study, two distinct driving cycles, ECE R40 and WMTC, were selected to provide a comprehensive evaluation of the 2W-EV energy performance across different regulatory and operational contexts. The ECE R40 was chosen as a benchmark for traditional, steady-state urban mobility, characterized by low speeds and frequent idling phases, which remains a widely used standard for vehicle certification in many regions. In contrast, the WMTC was implemented to represent more dynamic and realistic real-world driving conditions, as it was developed based on actual on-road driving data. By comparing these two cycles, this research aims to

address how the 2W-EV energy consumption varies between idealized urban patterns and modern, high-dynamic driving scenarios, thereby offering a holistic assessment of its efficiency for both regulatory compliance and practical use. The results are illustrated in Fig. 3 and Fig. 4.

2.3. Typical Parameters

Table 2. Typical parameters

Parameter	Sign	Unit
Battery power consumption	E_{pull}	Wh
Energy regeneration	E_{regen}	Wh
Net energy consumed	E_{net}	Wh
Average energy consumption	e_{net}	Wh/km
Total cycle distance	D	km
Regeneration rate	$Regen$	%
Average speed	V_{avg}	km/h
Maximum speed	V_{max}	km/h
Battery power	P_b	W
Tractive power	P_{pull}	W
Charging power	P_{regen}	W
Vehicle speed	$v(t)$	km/h
Voltage	$U(t)$	V
Current	$I(t)$	A

Several statistical criteria that reflect the energy consumption (EC) characteristics of the 2W-EV need to be computed in advance. The parameters listed in Table 2 are applied, including time data t_i (s), speed $v(t)$ (km/h), voltage $U(t)$ (V), and current $I(t)$ (A).

The processed input data are then configured to yield the EC, in watt-hours per kilometre (Wh/km) of travel, using the following equations:

$$P_b(t) = U(t) \times I(t) \quad (1)$$

$$P_{pull}(t) = \max(P_b(t), 0) \quad (2)$$

$$P_{regen}(t) = \max(-P_b(t), 0) \quad (3)$$

$$E_{pull} = \int \frac{P_{pull}(t) dt}{3600} \quad (4)$$

$$E_{regen} = \int \frac{P_{regen}(t)dt}{3600} \quad (5)$$

$$E_{net} = E_{pull} - E_{regen} \quad (6)$$

$$D = \int \frac{V(t)dt}{3600} \quad (7)$$

$$e_{net} = \frac{E_{net}}{D} \quad (8)$$

2.4. Calculating Driving Kinematic Parameters

Using the processed dataset, the ECE and WMTC speed traces were analyzed to derive typical driving kinematic (driving characteristic) parameters, summarized in Table 3. All metrics were computed from the 1 Hz speed profiles following the procedure described in [4].

Table 3. Typical driving kinematic parameters

No.	Parameter	Unit
1	Idling time ratio	%
2	Acceleration time ratio	%
3	Deceleration time ratio	%
4	Cruising time ratio $v \geq 5$ m/s	%
5	Creeping time ratio $v < 5$ m/s	%
6	Average speed	km/h
7	Maximum speed	km/h
8	Maximum acceleration	m/s ²
9	Minimum acceleration	m/s ²
10	Average positive acceleration	m/s ²
11	Average negative acceleration	m/s ²
12	RMS acceleration	m/s ²
13	Number of stops per kilometer	/km

2.5. Signal Pre-Processing

The signal processing framework in this study is designed to handle the high-frequency switching noise inherent in EV powertrains. Data acquisition was performed at a sampling frequency of 4 Hz, a rate optimized to balance the capture of powertrain transients with the suppression of measurement noise. The vehicle speed was acquired directly from the high-precision encoder of the chassis dynamometer. Due to the high fidelity of the encoder output, the speed signal is considered noise-free and was utilized for energy

calculations without additional digital filtering, serving as a stable and accurate reference for efficiency analysis.

The technical parameters and hardware-based filtering thresholds used in this stage are summarized in Table 4.

Table 4. Signal refinement specifications

Parameter	Value	Unit	Description
Battery configuration	16S4P x 3 (Parallel)	-	3 packs connected in parallel.
Voltage operating range	48.0 – 67.2	V	Minimum and maximum battery voltage
Max discharge current limit	105	A	Peak hardware limit (35A * 3 packs)
Max charge current limit	30	A	Max regenerative limit (10A * 3 packs)
Sampling frequency	4	Hz	Data acquisition rate during testing

3. Analysis of Results

3.1. Driving Cycle Data

The stronger acceleration-deceleration pattern observed in WMTC is consistent with its regulatory design, which aims to better represent real-world riding conditions compared to the smoother ECE R40 cycle [6, 7]. Tracking performance is quantified using the following metrics including error and absolute error ($|err|$), mean absolute error (MAE), maximum absolute error (Max $|err|$), time-share above threshold (fraction of time with $|err|$ greater than Δ), the 95th percentile absolute error (e_{95} of $|err|$), along with the kernel density estimation (KDE) of $|err|$ and trends versus reference speed (v_{ref}) and reference acceleration (a_{ref}). The results from Fig. 5 to Fig. 8 indicate that the speed tracking system achieves high quality and clearly highlights transition phases as the key area for optimization.

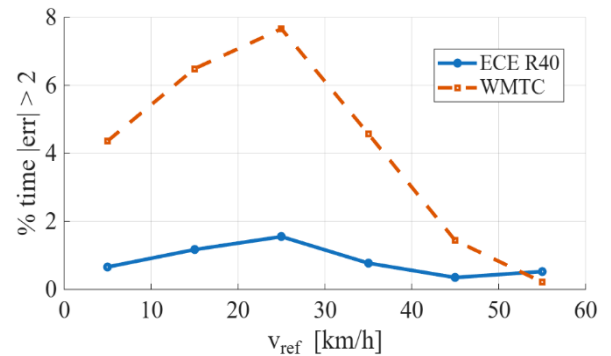


Fig. 5. Time-above-threshold ratio versus speed

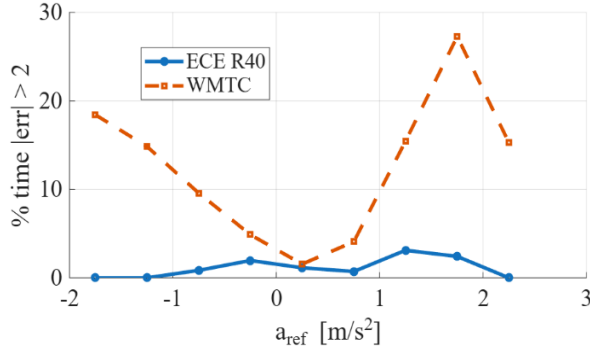


Fig. 6. Time-above-threshold ratio versus acceleration

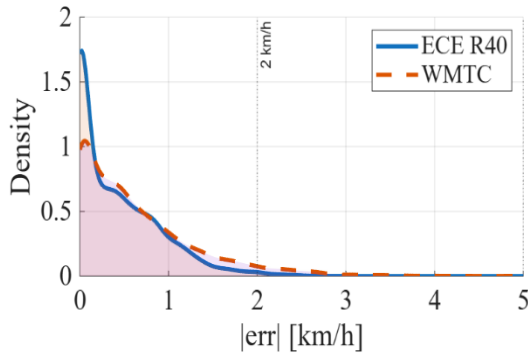


Fig. 7. Absolute error ($|err|$) distribution by driving cycle

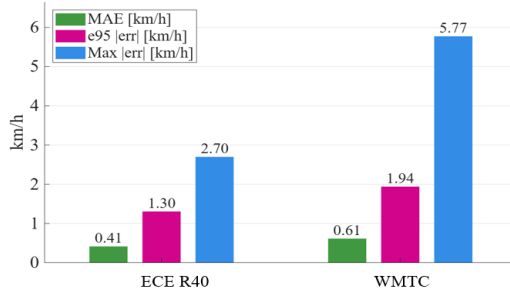


Fig. 8. Distribution of MAE, e_{95} , and maximum error by driving cycle

As shown in Fig. 7 and Fig. 8 the ECE R40 cycle all indicators are very good such as MAE equal 0.41 km/h, e_{95} equal 1.30 km/h, and $Max |err|$ equal 2.70 km/h. The KDE is strongly concentrated below 1 km/h, indicating predominantly very small errors. Compared to the data collected following the WMTC driving. Tracking remains compliant, with MAE equal 0.61 km/h, e_{95} equal 1.94 km/h (just shy of the 2 km/h threshold), and $Max |err|$ equal 5.77 km/h. The KDE shows a 2–6 km/h tail, reflecting several sharp transient phases. Conditioned analysis. Fig. 5 shows that the share of time with $|err|$ greater than 2 km/h increases markedly at 15–30 km/h (7–8%), then drops quickly above

35–45 km/h. With respect to acceleration in Fig. 6, WMTC is particularly sensitive at strong positive accelerations $a_{ref} \approx 1.5\text{--}2.0 \text{ m/s}^2$ ($\approx 25\text{--}27\%$) and hard braking $a_{ref} \approx -1.5 \text{ m/s}^2$ ($\approx 15\text{--}18\%$), whereas ECE remains mostly below $\sim 1.5\%$ across speed and below approximately 3% across acceleration. As shown in Fig. 5 and Fig. 6, the WMTC cycle consistently exhibits higher tracking errors than ECE R40. This is mainly due to its more dynamic profile, featuring frequent and sharp acceleration and deceleration phases (up to $\pm 2 \text{ m/s}^2$), which challenge the controller's response and cause larger transient deviations. In contrast, ECE R40 has smoother speed transitions, leading to smaller overall $|err|$ and lower %time ($|err| > 2$).

3.2. Data Refinement Results

The effectiveness of the pre-processing stage was evaluated across both ECE R40 and WMTC cycles. As presented in Table 5, the total percentage of refined data remained consistently low (under 3% for all test cases). The majority of the refinements addressed data gaps at zero speed, while hardware limit violations were near zero, confirming the stability of the measurement system. Notably, the speed signal, obtained directly from the dynamometer's encoder, exhibited no data loss or significant outliers throughout the testing phases. This high-precision, noise-free velocity data provides a reliable foundation for calculating the 2W-EV EC across all evaluated driving scenarios.

Table 3. Refined data summary

Metric	ECE R40		WMTC	
	(U) (%)	(I) (%)	(U) (%)	(I) (%)
Gaps at zero speed	2.778	2.778	0.427	0.427
Limit violations	0	0	0.644	0
Total	2.778	2.778	1.071	0.427

These results demonstrate that the processed dataset is physically consistent and provides a highly reliable foundation for calculating the 2W-EV efficiency. Furthermore, observed variations in the $U(t)$ and $I(t)$ profiles during deceleration phases (Fig. 9 and Fig. 10) are not measurement errors but reflect the authentic interaction between manual driving behavior (e.g., coasting) and the vehicle's control logic, with speed tracking errors maintained within the standard $\pm 2 \text{ km/h}$ tolerance.

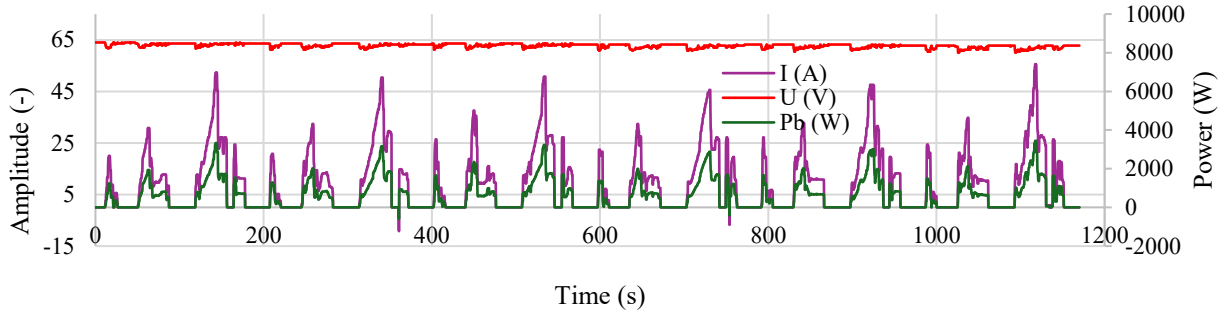


Fig. 9. Relationship among instantaneous voltage, current, and power following the ECE R40 cycle

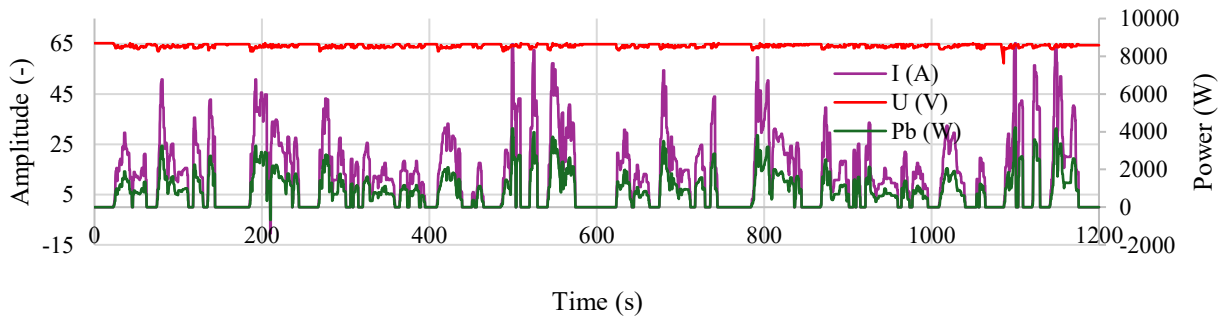


Fig. 10. Relationship among instantaneous voltage, current, and power following the WMTC cycle

3.3. Driving Kinematic Parameters

As can be seen from Table 6, a higher difference has been shown when comparing the driving features of the ECE R40 and the ones of WMTC. The analysis, following the procedure in [4], shows that the WMTC has a significantly higher average speed and larger acceleration amplitudes than the ECE R40. Following the WMTC, the driving kinematic parameters (DKP) are more dynamic than ECE as the acceleration/deceleration shares 32.4%/31.3% (ECE 25.6%/23.7%), a_{max}/a_{min} equal 1.93/−1.843 m/s² (ECE 1.28/−1.152), and Root Mean Square (RMS) a 0.557 (ECE 0.439). Average speed is higher in WMTC (23.17 km/h) and ECE (18.53 km/h, +25%), while stops per km are lower (2.33 and 3.16, −26%). ECE shows more idling (31.96%) and cruising (20.69%) than WMTC (19.58% and 18.67%). This implies that the WMTC cycle requires higher instantaneous power due to its frequent transients and thus results in higher specific EC per kilometer. The experimental analysis reveals that the peak tracking error for the system during the WMTC cycle is 1.87 km/h. Compared to the ECE R40 cycle, which exhibited a peak error of 1.44 km/h, the WMTC profile represents a 29.86% increase in tracking difficulty. This peak occurs during the high-speed transition phase, suggesting that the controller's transient response is more heavily taxed by the aggressive acceleration demands of the WMTC. Despite this localized peak, the error remains within the industry-standard tolerance of ± 2 km/h, confirming the robustness of the proposed control strategy under varying drive cycle dynamics.

In contrast, the ECE R40 cycle is more influenced by idle efficiency, as its longer low-speed and idling phases emphasize energy losses at low load. This observation aligns with previous studies, which have demonstrated that more transient driving cycles lead to higher energy and fuel consumption compared to smoother regulatory cycles, due to increased acceleration demands and power fluctuations [9, 10, 12, 13].

3.4. I – V – P_b Signatures Across Operating Phases

Fig. 9 and Fig. 10 show that the current varies more strongly and complexly, with multiple current peaks during rapid acceleration phases. The experimental results show that peak current can exceed 55–65 A, with instantaneous power reaching over 4000 W during high load transients. These results are consistent with dynamometer-based measurements reported in previous studies, validating the high-power performance of the motor [14, 15]. Furthermore, signal oscillations in instantaneous power are partly attributable to high-frequency current fluctuations, which are known to affect numerical integration accuracy if not properly filtered [16]. These considerations ensure the robustness of the energy consumption metrics calculated using (1) through (8). Compared with the ECE cycle, current/power oscillations occur more frequently and with larger amplitudes, reflecting the greater severity of the WMTC cycle. The battery voltage remains fairly stable around 65 V, with only minor voltage sag when current peaks occur. Short negative current pulses are also recorded during deceleration, and they appear more often than in ECE, indicating a higher potential for regenerative braking.

Table 4. Data driving kinematic results

Driving kinematic parameters	Units	ECER40	WMTC	Percentage difference (%) ^(*)
Idling time ratio	%	31.957	19.575	38.74
Acceleration time ratio	%	25.649	32.369	26.19
Deceleration time ratio	%	23.748	31.284	31.73
Cruising time ratio	%	20.686	18.671	9.74
Creeping time ratio	%	4.035	4.159	3.07
Average speed	km/h	18.527	23.166	25.04
Maximum speed	km/h	51.4	50.9	0.97
Maximum acceleration	m/s ²	1.28	1.93	50.78
Minimum acceleration	m/s ²	-1.152	-1.843	59.98
Average positive acceleration	m/s ²	0.422	0.434	2.90
Average negative acceleration	m/s ²	-0.453	-0.475	4.95
RMS acceleration	m/s ²	0.439	0.557	26.79
Number of stops per kilometer	/km	3.157	2.331	26.15
Peak tracking error	km/h	1.44	1.87	29.86
Total distance	km	6.019	7.722	28.29

Note: ^(*) represents the relative deviation of the WMTC value with respect to the ECE R40 baseline

In summary, the test vehicle's electric drivetrain operates stably and meets the operational requirements under the standardized cycles. The differences between the two cycles show that the ECE R40 represents a mild and idealized speed pattern, the vehicle performs stably under this condition and remains capable of following the more transient and realistic WMTC cycle with acceptable tracking accuracy. However, additional optimization is required to enhance overall energy efficiency and improve regenerative braking effectiveness, particularly at higher speeds and during rapid acceleration or deceleration phases.

3.5. Energy Consumption and Regeneration

Table 7 summarizes the values of energy consumed, regenerated energy, specific energy consumption (Wh/km), and regeneration efficiency for the three test cycles.

A comparison of the two driving cycles shows that the WMTC imposes significantly higher energy demand than the ECE R40, both in total and per distance traveled. The tractive energy consumption increases from 191.8 Wh in ECE R40 to 277.7 Wh in WMTC, while the specific energy rises from 31.85 to 35.95 Wh/km. This difference reflects the more dynamic nature of the WMTC profile, which includes higher average speed (23.17 km/h vs. 18.53 km/h) and more frequent acceleration-deceleration events, resulting in higher instantaneous power and transition losses. Such benchmarking is essential for contextualizing the draft MEPS/HEPS standards for 2W-EVs, ensuring that

energy efficiency targets reflect real-world operating conditions [5]. In contrast, the ECE R40 smoother, low-speed operation with longer idling periods leads to lower total energy use but also limits regenerative opportunities, as most braking occurs at low speeds. Despite WMTC featuring more deceleration events that could favor regeneration, the measured recovered energy remains marginal in both cases 0.049% and 0.041% of the tractive energy for ECE and WMTC, respectively due to the short activation window and low torque capability of the current regenerative braking system. This is consistent with earlier studies reporting limited regenerative potential in electric motorcycles due to short braking durations and low regenerative torque [4, 20].

Table 5. Energy consumption statistics

Metric	ECE R40	WMTC	Percentage difference (%)
Epull [Wh]	191.781	277.715	44.80
Eregen [Wh]	0.094	0.116	23.15
Enet [Wh]	191.687	277.599	44.81
D [km]	6.019	7.722	28.29
e_net [Wh/km]	31.846	35.949	12.88
Regen share [%]	0.049	0.041	14.95

4. Conclusion

From the combined analysis of kinematics, speed-tracking, energy use, and regeneration, two main conclusions can be drawn. The vehicle exhibits excellent cycle following accuracy under both driving cycles. In ECE R40, the tracking error remains extremely low ($MAE = 0.41$ km/h, $e_{95} = 1.30$ km/h), indicating a well tuned torque control and smooth driver response to the prescribed cycle. In the more transient WMTC cycle, performance remains robust ($MAE = 0.61$ km/h, $e_{95} = 1.94$ km/h), confirming the controller's capability to handle moderate transients. However, the exceedance maps show that deviations concentrate during rapid acceleration and braking phases, where torque demand changes sharply and the control loop latency or inverter response limits instantaneous compensation. These transient regions represent the main opportunity for improving the system's dynamic tracking and regenerative coordination.

Energy analysis reveals a clear increase in power demand with the higher WMTC dynamic load. The specific energy consumption increases from 31.85 to 35.95 Wh/km (+13%). This difference stems from the higher average WMTC speed (23.17 km/h) and larger acceleration amplitudes, which cause more frequent converter switching and transient torque peaks amplifying electrical and mechanical losses. Meanwhile, regenerative energy remains minimal in both cycles (0.09–0.11 Wh, $\approx 0.05\%$ of tractive energy) due to the short duration and low torque level of the regenerative phases. In WMTC, although deceleration events are more frequent, braking occurs mostly at mid to high speeds where regenerative torque is electronically limited, resulting in little actual energy recovery. Thus, future optimization should focus on extending the regenerative window and improving energy conversion efficiency during rapid transients.

In summary, this study focused on evaluating the EC characteristics of an 2W-EV using a roller-type chassis dynamometer under standardized driving cycles. The analysis confirms that standardized test cycles are effective tools for quantifying traction energy, regenerative rate, and overall drivetrain efficiency. Among them, the WMTC driving cycle proves to be the most representative of real-world riding conditions, as it includes a wide range of transient accelerations, decelerations, and steady speed phases that closely reflect actual urban and suburban operation. Therefore, future energy assessments and efficiency benchmarking for electric motorcycles should prioritize the WMTC cycle as a reference framework, enabling more realistic evaluation and targeted optimization of control and energy management strategies.

In conclusion, this study goes beyond a standard driving cycle comparison by establishing a robust, experimentally-verified benchmark for 2W-EV. Unlike conventional studies relying on numerical simulations,

this research provides high-fidelity empirical data utilizing a chassis dynamometer and a rigorous 4 Hz signal pre-processing framework. By integrating noise-free velocity data from the dynamometer's encoder with physical-constraint-based electrical filtering, the dataset's reliability was technically validated, with refinement corrections maintained strictly under 3%.

Furthermore, the observed variations in regenerative braking highlight the stochastic nature of human driving behaviors, bridging the gap between idealized certification cycles and authentic on-road performance. By focusing on the 2W-EV segment within Southeast Asia's urban mobility sector, this study provides practical insights to support regional manufacturers and regulatory bodies in improving energy efficiency under real-world operating conditions.

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