Effects of Battery State of Charge on Fuel Economy of Hybrid Electric Vehicles: An Analysis Using the UN ECE R101 Method

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Effects of Battery State of Charge on Fuel Economy of Hybrid Electric Vehicles: An Analysis Using the UN ECE R101 Method

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Abstract: Indonesia is currently embracing electric vehicle technology for widespread use and mass production, with hybrid vehicles serving as a crucial intermediary in the transition towards full electric vehicle adoption, as outlined in the roadmap established by the Indonesian Government through the Ministry of Industry. Hybrid vehicles integrate an internal combustion engine and an electric motor as the powertrain system, enabling the charging of the battery through the combustion engine while also serving as the primary mover, with charging and discharging cycles contingent upon the vehicle's operational conditions. This research investigates the impact of battery conditions on the fuel economy of two hybrid vehicles during a UN ECE R101 test cycle. This research focusing on two specific battery conditions: a state of charge (SoC) of 50% and 100%. Remarkably, the results indicate that vehicles with a SoC of 100% exhibit a noteworthy enhancement in fuel economy, achieving an improvement of up to 16% compared to those with a SoC of 50%. These findings shed light on the significant role that battery conditions play in optimizing fuel efficiency within hybrid vehicles, ultimately contributing to the ongoing advancements in sustainable transportation and the realization of the Indonesian Government's electric vehicle roadmap.

Keywords: Hybrid vehicle, fuel economy, UN ECE R101, state of charge (SoC)

1. Introduction

Developing countries, such as Indonesia and other Asian countries, have seen a fast increase in their energy usage and the amount of carbon dioxide released into the atmosphere[1,2]. Through Kyoto Protocol and Paris Agreement, the Indonesian government has committed to reduce CO_2 emissions, and hence to reduce global warming by 29% with its efforts, or even by 41% if there is international cooperation by 2030[3,4]. Energy in the transportation sector is one of the targets in increasing efficiency to achieve this goal. The Indonesian government has issued policies to encourage energy efficiency by applying tax deductions for electric vehicles, hybrids, biofuel-based vehicles, green gasoline, and green diesel technology[5]. Usage of electric vehicles in Indonesia is now accelerated improve efficiency, security, and conservation of energy in the transportation sector through Presidential Regulation number 55 of 2019 [6,7]. In 2017 EV sales globally reach 3,000,000 units[8,9]. It is predicted that electric vehicle users will reach more than 500,000 units for Indonesian government institution by 2030 [10]. One of the strategies implemented by Indonesia and current trend in the automotive industry toward this target is through the transition of technology from internal combustion engine (ICE) technology to full battery technology through a combination of ICE and battery (Hybrid) technology[11,12]. The use of this hybrid vehicle will have an impact on reducing carbon dioxide gas emissions and reducing fuel consumption by up to 50%. This is because light vehicle is the dominant share in global transportation[13,14] and also the hybrid car can optimize the electric motor to reduce fuel use so that the portion of ICE that produces CO_2 emissions can be suppressed[15–17]. In general, there are 3 modes in hybrid vehicle technology: full hybrid, mild hybrid, and plug-in hybrid[18,19]. Hybrid vehicles use batteries to store energy and run electric motors for propulsion coupled with ICE. Different battery states of charge (SoC) will result in different driving modes. It will, in turn, affect the emissions and fuel consumption[20]. The differences between full hybrid and plug-in hybrid is that the plug-in can recharge the battery through off-board source, while the full hybrid can recharge only from the engine[21,22].

Yang et al. researched the plug-in hybrid electric bus vehicle running in its actual condition, which showed that different battery SoC at the beginning of the test would result in different. There was an increase in fuel consumption (decreased fuel economy) as the battery level was lowered at the beginning of testing[23]. Duarte et al research showed that there was fuel consumption effect due to SoC of the car. Lower SoC increased the fuel consumption. The highest consumption was observed on the range of 40 - 50% battery SoC [24]. Both experiments were conducted on real driving conditions.

The various results of the study show that hybrid vehicles supported by electric motor technology still need optimization in accordance with the real conditions of their operation to reduce CO_2 emissions and optimum fuel economy[25–28]. Cubito et al found higher CO_2 emission by using World Harmonized Light Duty Test Procedure (WLTP) than using New European Driving Cycle (NEDC)[29]. One of the optimizations that can be done is to adjust the condition of the SoC battery and charge the battery during a cycle. In this initial study, the SoC battery is studied for its effect on fuel economy and the emissions produced. To the best author knowledge, there was lack of work to study the effect of SoC of the electrical battery towards to carbon emission and fuel economy. Two-types hybrid electric car of type M passenger vehicles available in the Indonesian market. Measurement of fuel economy and vehicle exhaust emissions under two SoC battery was carried out using the UN ECE R101 method, which has been adopted by the Indonesian Government for the tax deduction program for its low-cost green car program[30]. The cycle of operation is the New European Driving Cycle (NEDC), with the maximum operational speed at 120 km/h.

2. Methods

2.1 Car Specification

Table 1. Hybrid vehicle test specifications

Parameter	Unit	Car A	Car B
Reference weight	kg	1,810	1,470
Cylinder capacity	cc	1,999	1,798
Number of cylinders		4	4
ICE power	hp	123	99
ICE torque	Nm	168	142
Electric motor power	hp	174	82
Electric motor torque	Nm	320	207

The study was conducted using two types of hybrid vehicles, designated as the car A and car B, with different cylinder capacities but having similar technology to the technical specifications shown in Table 1. Both cars belong to the same classification of hybrid vehicles in which the electric motor works series-parallel with ICE. The electric motor operates at low speeds or low loads. Under high loads, the motor functions as an assist for the engine. The ICE use for propulsion of vehicle and generate electricity for the battery by generator[31,32]. The test vehicles are products of two different manufacturers, and hence, different energy management systems. The command to activate either battery, engine, or both, follows different criteria in each car.

2.2 Experimental Procedure

The experiment was conducted on a chassis dynamometer in accordance with the UN ECE R101 standard. The test was conduct on Laboratory of Thermodynamic, Engine, and Propulsion in National Research and Innovation Agency in Indonesia. The Lab is national accredited and as one of the official equipment for emission test in Indonesia. The test car was securely positioned on the dynamometer to facilitate the measurement of exhaust gas emissions. Subsequently, these emissions were diluted with ambient air and directed into a dedicated collection container referred to as a "bag." The bag served as a reservoir for collecting emissions throughout each segment of the NEDC (New European Driving Cycle) procedure, with separate bags used for different parts of the cycle. Notably, the bag contained a mixture of emissions and ambient air, with the ambient air serving as the initial reference point or "zero" value. Additionally, real-time data logging was employed to continuously record emission levels during the entire testing process. The specific emissions being analyzed included carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO2).

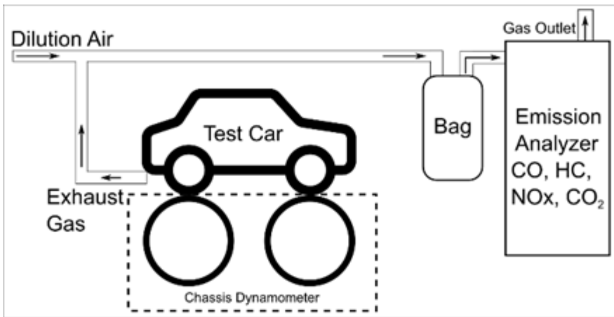

Fig 1. Test schematic diagram[33]

Both cars were tested on a chassis dynamometer with the NEDC procedure. This cycle test consists of two main cycle testing. The first part is an urban mode, in which car operates to simulate the urban areas condition with a maximum speed of 50 km/h. it is known as the Urban Driving Cycle (UDC). The first cycle testing consists of four times UDC. The second part is Extra Urban Driving Cycle (EUDC), in which the car is operated to simulate driving on the highway or interconnecting city at maximum speed about 120 km/h. In total, the duration for whole test was carried out for 1,180 seconds or about 20 minutes[30].

Table 2. Matrix of testing

Test Sample	Methods	SoC Level
Car A	R101	100%
		50%
Car B	R101	100%
		50%

Furthermore, each car test was conducted twice with difference in battery level at the beginning of the test i.e., at 50% capacity and at full capacity as shown in Table 2. During the test, exhaust emission data were essential key to determine fuel economy data. In this test, the ICE and electrical control systems were based on optimization conditions carried out by vehicle manufacturers without modifications during the testing process.

To obtain the initial condition of the battery as desired, the car was driven on a chassis dynamometer and conditioned so that the battery was charged while the car was operated and stopped when the battery reached the desired condition which was at 50% state of charging condition of the battery. SoC level of each car according to display on dashboard of the car. Then the car was prepared to carry out test in accordance with the UN ECE R101 standard. The calculation of the fuel economy was carried out with the carbon balance method for both car A and car B with the formula shown in Equation (1)[30].

$$FE = \frac{100}{(0.1154/D)\cdot[(0.866\cdot HC)+(0.429\cdot CO)+(0.273\cdot CO_2]} \qquad (1)$$

where FE stands for fuel economy in km/l; D denotes for density of fuel at 15°C in kg/m^3; HC, CO, and CO_2 represent the measured emission of hydrocarbon, carbon monoxide and carbon dioxide in g/km, respectively. In addition to measuring the fuel economy, this test also measured gas emissions in accordance with the R83-05 standard, which has been implemented in Indonesia since 2018.

3. Results and Discussion

3.1 Emission Analysis

Fig 2 depicts the cumulative CO_2 emissions for car A. The dashed line represents the NEDC cycle, as indicated by the variation of car speed shown in the righthand vertical axis. the thick orange and grey lines illustrate the cumulative CO_2 emissions as indicated in the lefthand vertical axis, both for a SoC of 100% and 50% respectively. It is observed that car A, operating at a SoC of 100%, exhibits an earlier CO_2 emission compared to the other car. The engine is activated when the car reaches a speed of 50 km/h. Conversely, for the car with a SoC of 50%, the engine is only activated during the final UDC cycle. As a result, upon entering Part II or EUDC, the cumulative CO_2 emissions for the 100% SoC exceed those for the 50% SoC. However, due to the higher SoC, when the car is accelerated to achieve 120 km/h, the engine emits a lower quantity of CO_2. Consequently, the final cumulative CO_2 emissions for the car with a 50% SoC are higher than those for the 100% SoC.

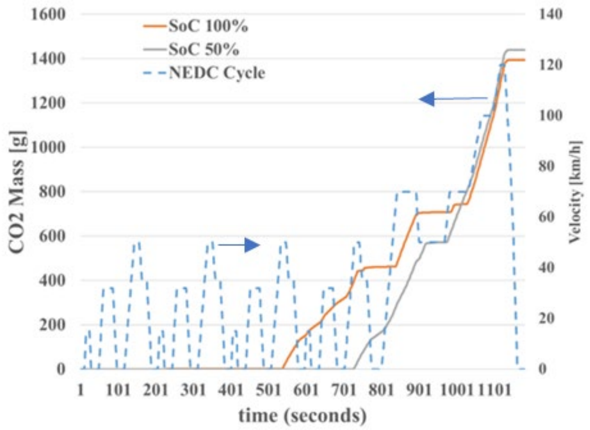

Fig 2. CO_2 mass accumulative for car A during test

The common characteristic observed in both tests is the absence of engine operation during the initial stages of Part I until the second UDC. The car relied solely on electric motor power, resulting in the absence of CO_2 emissions when the ICE was not yet engaged to assist in propulsion. This behaviour is heavily influenced by the vehicle's control system, specifically the Engine Control Unit (ECU). It is plausible that the vehicle's control strategy prioritizes maintaining the SoC at the highest feasible level. Typically, hybrid vehicles operate in two distinct modes: charge-depleting mode, where the electric motor solely propels the vehicle while the ICE remains inactive, and charge-sustaining mode, where the ICE operates to sustain the SoC within a predefined range[34]. The emissions data presented in the Table 3 were acquired from these two operational modes.

Table 3. Emission results for car A

Parameter	Unit	1st cycle testing	2nd cycle testing	Total
		SoC 100%		
HC	g/km	0.040	0.007	0.019
CO	g/km	0.354	0.037	0.153
CO_2	g/km	111.842	131.604	124.387
		SoC 50%		
HC	g/km	0.048	0.014	0.027
CO	g/km	0.289	0.124	0.184
CO_2	g/km	32.494	186.555	130.412

Table 3 presents the emissions of car A during the NEDC test under two different SoC conditions: 100% and 50%. By examining the operating conditions and the cumulative values in Figure 1, it is evident that the CO2 emissions with a 100% SoC are higher in Part I due to the earlier activation of the ICE compared to the 50% SoC condition. However, when considering the total emissions, the CO2 emissions with a 100% SoC are lower compared to the 50% SoC condition.

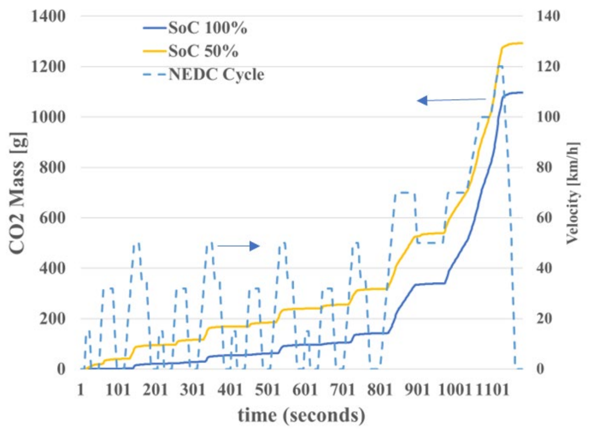

Fig 3. CO_2 mass accumulative for car B during test

Fig 3 shows the cumulative CO_2 emission values for car B under two distinct SoC conditions: 50% and 100%. The NEDC cycle is represented by the dashed line, while the thick yellow and blue lines depict the cumulative CO_2 emissions for the 50% and 100% SoC respectively. In contrast to car A, car B exhibits immediate CO_2 emissions right from the beginning of the test. Notably, the tests conducted with a 100% SoC consistently yield lower CO_2 emissions compared to those with a 50% SoC. Observing the 100% SoC scenario, the ICE remains active when the car attains a speed of 50 km/h, whereas in the case of a 50% SoC, the ICE is engaged at a speed of 30 km/h. Detailed emission data for car B can be found in the Table 4.

Table 4. Emission results for car B

Parameter	Unit	1st cycle testing	2nd cycle testing	Total
		SoC 100%		
HC	g/km	0.009	0.004	0.006
CO	g/km	0.023	0.016	0.019
CO_2	g/km	34.204	134.926	98.321
		SoC 50%		
HC	g/km	0.004	0.004	0.004
CO	g/km	0.009	0.017	0.014
CO_2	g/km	79.411	137.231	116.552

Table 4 presents the emission results of car B under 100% and 50% SoC conditions. The table reveals that during the Part I testing phase, the 100% SoC scenario yields significantly lower CO_2 emissions, with a reduction of approximately 56% compared to the 50% SoC condition. However, in Part II, the CO_2 emissions for both tests display marginal disparity. This disparity signifies that under the 100% SoC condition, the car predominantly relies on electric motor power, especially at lower speeds or in urban settings. Conversely, under the 50% SoC condition, the car operates more frequently at lower speeds, potentially serving the dual purpose of powertrain propulsion and battery recharging. This inference is bolstered by the higher end-of-test battery condition observed in the 50% SoC testing in comparison to the initial battery condition.

Both vehicles demonstrate a rise in CO2 emissions when tested under a 50% State of Charge (SoC) condition. This observation is consistent with the findings of Cubito et al., who also reported an increase in CO2 emissions when conducting tests on a hybrid vehicle under lower SoC conditions. In their study, they evaluated a single hybrid vehicle with both fully charged and fully discharged scenarios[29].

3.2 Fuel Economy

Once the vehicle's exhaust gas emission data was acquired, it was utilized to calculate the fuel economy values during the testing phase using the equation (1). The derived fuel economy values are presented in the Table 5.

Table 5. Fuel economy result

Parameter	FE [km/l]
Car A	
SoC 100%	19.152
SoC 50%	18.260
Differences	0.892 (4.6%)
Car B	
SoC 100%	24.277
SoC 50%	20.283
Differences	3.994 (16.4%)

Table 5 presents the fuel economy results for both cars under 50% and 100% SoC conditions. Both cars demonstrate lower fuel consumption with higher battery conditions. For car A, there is a fuel savings of up to 4.6% when the battery SoC is at 100%, while car B achieves greater fuel savings of up to 16.4% under the 100% SoC condition.

When calculating fuel economy based on CO, HC, and CO_2 emissions, it is apparent that HC emissions have the highest constant value. However, due to the significantly lower magnitudes of HC emissions compared to CO_2, it is the CO_2 parameter that plays a more substantial role in determining the final fuel economy result. This observation is particularly evident in the case of car B, where the SoC 100% condition exhibits higher HC and CO emissions. Surprisingly, despite these higher emissions, car B achieves a higher fuel economy due to its lower CO_2 emissions. These fuel economy findings contribute to the existing research conducted by Cubito et al., which primarily focuses on examining emissions and SoC conditions during testing using the NEDC and WLTP methods[29)]. Therefore, this study expands upon the existing literature by emphasizing the significance of CO_2 emissions in determining fuel economy, especially when evaluating hybrid vehicles under different SoC conditions.

4. Conclusion

In conclusion, the analysis of both cars emissions and fuel economy under different SoC conditions provides valuable insights into their performance. Car A, operating at a 100% SoC, exhibits earlier CO_2 emissions compared to the 50% SoC condition, but its cumulative CO_2 emissions are ultimately lower due to reduced emissions during acceleration. On the other hand, car B shows immediate CO_2 emissions from the start of the test, with consistently lower emissions and higher fuel economy under the 100% SoC condition. The car operating with a 100% SoC exhibited greater fuel efficiency compared to the car with a 50% SoC, with a 4.6% improvement for Car A and a 16.4% improvement for Car B. The absence of engine operation during the initial stages of the test for both cars, relying solely on electric motor power, confirms the effectiveness of their control systems.

Furthermore, the results indicate that CO_2 emissions play a crucial role in determining fuel economy, as higher HC and CO emissions in car B do not hinder its overall fuel efficiency due to significantly lower CO_2 emissions. This finding supports the importance of considering CO_2 emissions when evaluating fuel economy for hybrid vehicles under varying SoC conditions.

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Contributorships

KFAS and LS are the research conceptor and design. KFAS, AS, DTW, and MY contribute to the data collection data and experiment. KFAS, LS, AS, DTW, AM, and MY contribute to the data analysis and interpretation. KFAS writes the initial manuscript. LS, SY, AM and MPH perform the critical revision of the article. KFAS, LS, SY and MPH ensure final approval of the article.

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