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A Well-To-Wheel Analysis of Greenhouse Gas Emissions for Electric Vehicle (EV) and Internal Combustion Engine Vehicle (ICEV)

Nur Anis Safiei[1], Norirda Mohamed[1]*

[1] *Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA*

*Corresponding Author: norirda@uthm.edu.my
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Abstract

The transportation industry plays a significant role in generating greenhouse gas (GHG) emissions, largely due to the prevalence of internal combustion engine (ICE) vehicles. As climate change concerns intensify, electric vehicles (EVs) are increasingly viewed as a viable solution to lower emissions. This study aims to compare the GHG emissions Carbon Dioxide (CO2) between Internal Combustion Engine Vehicles (ICEVs) and Electric Vehicles (EVs) using a comparative Life Cycle Assessment (LCA). This study aims to compare the GHG emissions Carbon Dioxide (CO2) between Internal Combustion Engine Vehicles (ICEVs) and Electric Vehicles (EVs) using a Life Cycle Assessment (LCA). Additionally, this study will also provide the environmental impact of using the existing mixed sources of electrical energy for an EV. The analysis follows a Well-to-Wheel approach which capture the life cycle of the chosen vehicles during the production of energy (petrol and electricity) and their use phase. Two mathematical equations are used to calculate the GHG emissions. Volvo XC40 ICE and Volvo XC40 Recharge from C-segment car models are chosen to conduct the analysis. The analysis shows that EV model produces lower GHG emissions (16974 g CO2 eq./km) when compared to ICE model (38339 g CO2q eq/km) with 55.72% of CO2 reduction. The results also show that using coal as the source for electricity generation produce the highest GHG emissions compared to natural gas, oil, nuclear, hydropower and renewables. This comparison emphasizes the potential for EVs to help decrease transportation-related emissions, even in areas like Malaysia that rely on a relatively high-carbon electricity mix. This study will enlighten the society on the importance of the adoption of low-emission vehicles.

1. Introduction

The automobile industry is a cornerstone of modern transportation, enabling economic growth, urbanisation, and global connectivity. In Malaysia, the sector is expanding, and in 2023, it is expected to reach a record high of over 700,000 units for the second year in a row [1]. However, transportation is one of the major contributors to several environmental burdens such as Greenhouse gas (GHG) emissions [2]. These trends show an increasing pattern in the demand for petrol and diesel, raising issues with energy security and urban air quality and climate change [3]. A significant emphasis has been placed on decarbonising the transportation sector, according to M. Zackrisson et al. [4], with electric vehicles (EVs) emerging as a practical solution to decrease dependence on fossil fuels. EVs, along with plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs), are increasingly recognised as more sustainable alternatives due to their potential to lower greenhouse gas (GHG) emissions and reduce overall energy consumption [5]. Although EVs emit zero tailpipe emissions, producing electricity to power the vehicle still produces significant environmental emissions.

There are a few studies that analyse the greenhouse gas (GHG) emissions linked to electric vehicles (EVs) based on a specific country's electricity generation mix. According to Y. Wu et al. [6], switching from a gasoline internal combustion engine vehicle (ICEV) to a battery electric vehicle (BEV) for a year in France and Brazil can decrease CO2 emissions by 2834 kg and 2823 kg, respectively. On the other hand, a study by J. Woo et al. [7] indicates that BEVs tend to have the highest GHG emissions in countries that heavily depend on fossil fuels for electricity, such as South Africa, with emissions ranging from 102.7 to 149.5 g CO_2eq/km. Other nations with significant fossil fuel reliance include Australia, India, and China. In contrast, various studies have evaluated GHG emissions between EVs and ICEVs to identify the best option for reducing overall emissions. Research conducted by Veza I. et al. [8] found that EVs produce the lowest emissions of carbon monoxide (CO) and carbon dioxide (CO_2), showing a reduction of around 20%. Furthermore, hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) also contribute to lower emissions than traditional ICE vehicles. This research utilised GREET software to assess energy consumption, air pollutant emissions, greenhouse gas emissions, and water usage associated with different vehicle technologies. Additionally, D.C. Rosenfeld et al. [9] concluded that EVs generate lower emissions than ICEVs when analysed from a Well-to-Wheel perspective. Thus, the author argues that EVs are the more environmentally friendly choice overall.

By using a Well-to-Wheel analysis, this paper aims to compare the greenhouse gas (GHG) emissions for electric vehicles (EV) and internal combustion engine vehicles (ICEV). By using C-segment car models, the study will observe the carbon dioxide (CO2) emissions associated with the two different models while encompassing the fuel life cycle of petrol per litre, electricity per kWh, and usage of the vehicles.

2. Methodology

2.1 Life Cycle Assessment

A Life Cycle Assessment (LCA) was used in this study to evaluate the potential environmental impacts of products or services during their entire life cycle, including the production, distribution, use, and end-of-life phases. Life cycle impact assessment (LCA) covers all relevant environmental inputs, including ores and crude oil, water, land use and emissions into air, water and soil such as carbon dioxide and nitrogen oxides.

2.1.1 Goal and Scope

This study aims to evaluate and compare the emissions of two distinct vehicle types with equivalent specifications: the internal combustion engine vehicles (ICEV) and the electric vehicles (EV). For this analysis, we selected the Volvo XC40 ICE and the Volvo XC40 Recharge, both from the C-segment and designed to seat five passengers. Variations of the same car model powered by different propulsion systems, serve as an excellent basis for assessing the environmental impact of traditional fossil fuel vehicles in contrast to electric vehicles, ensuring that factors such as size, weight, and overall design are controlled for. The study's scope includes a life cycle analysis of petrol consumption per litre, the national electricity supply per kWh, and fuel usage during a 100 km drive for both the ICE and EV.

2.1.2 System Boundary

The system boundary, as shown in Figure 1, included the fulll fuel cycle, necessitating a thorough evaluation of the entire fuel production life cycle (from well to wheel) to accurately assess the global implications of fuel consumption. The well-to-wheel (WTW) analysis provides a comprehensive understanding of vehicle energy consumption and efficiency, encompassing all aspects from fossil fuel extraction or electricity generation to vehicle operation. The functional unit was defined based on the distance traveled (per kilometre), with greenhouse gas (GHG) emissions reported in grams of CO2 equivalents (g CO2 eq/km). Specifically, this study utilised a functional unit reflective of driving 100 km in a vehicle.

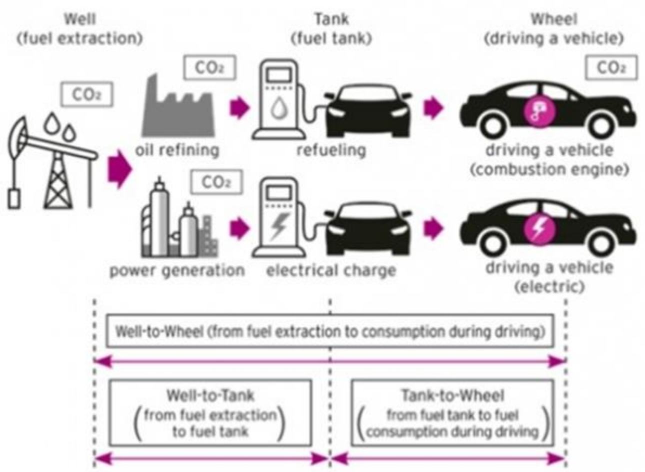

Fig. 1: System Boundary of the study [10]

2.2 Analysis Method

2.2.1 Mathematical Equation

The GHG emissions of ICEVs from the well-to-wheel viewpoint are the sum of the GHG emissions of the combined processes of well-to-tank and tank-to-wheel. This was calculated by using Eq. (1) as follows:

$$ICEV\_GHG_{WtW} = (GHG_{WtT} + GHG_{TtW}) \times FE \text{ [7]} \quad (1)$$

Where,
$ICEV\_GHGWtW$ = Total GHG emissions from well-to-wheel, $g\ CO2eq/km$
$GHGWtT$ = Total GHG emitted in the well-to-tank, $g\ CO2eq/L$
$GHGTtW$ = Total GHG emitted in the tank-to-wheel, $g\ CO2eq/L$
FE = Fuel efficiency, L/km

In contrast, the Well-to-Wheel GHG emissions of an EV was calculated by using Eq. (2).

$$EV\_GHG_{WtW,i} = \{\sum P_{e,1} \times (GHG_{WtT} + GHG_{TtW})\} \times VE \text{ [7]} \quad (2)$$

Where,
$EV\_GHG_{WtW,i}$ = Total GHG emissions from well-to-wheel, $g\ CO2eq/km$
$\sum P_{e,1}$ = Ratio of the power source e in the electricity generation mix of country i
GHG_{WtT} = Total GHG emitted in the well-to-tank, $g\ CO2eq/kW\ h$
GHG_{TtW} = Total GHG emitted in the tank-to-wheel, $g\ CO2eq/kW\ h$
VE = Electricity Efficiency, kW h/km

2.3 Inventory Analysis

The data on specifications including the fuel efficiency of both Volvo XC40 ICE and Volvo XC40 Recharge were collected and tabulated as in **Appendix A.** Then, the emission factor for 1 L of petrol and 1 kW h per electricity were also provided in Table 1. The data in the table were multiplied with the corresponding fuel efficiency to obtain the emissions during the usage phase for each model. To calculate Well-to-Wheel GHG emissions of the ICE model, data on emissions produced during the production of the petrol fuel (well-to-tank) and the emissions during the driving of the car (tank-to-wheel) were used as tabulated in Table 2. The total GHG emissions were calculated by using Equation (1).

Table 1: Emissions factors for calculating the usage emissions [11]

Unit	1 L of Petrol	1 kW h of electricity
g CO2eq	2918	802

Table 2: Data assumptions on Well-to-Tank and Tank-to-Wheel of an ICE [12]

Well-to-tank (g CO2 eq/ L)	Tank-to-wheel (g CO2/L)
2333.88	2918

There are two datasets used to calculate the well-to-wheel GHG emissions of an EV using Eq. (2). First is the GHG emission data of each power source in the well-to-wheel process which is presented in Table 3 and the other is the electricity generation mix data for each country exclusively for Malaysia, China and United States which is presented in Table 4.

Table 3: Well-to-Tank GHG emissions of EV driven with electricity generated solely with each power source [13]

Sources	Well-to-Tank (g CO2eq/kW h)
Coal	1310
Natural gas	891
Renewables	179
Oil	935
Hydropower	237
Nuclear	130

Table 4: Well-to-Tank GHG emissions of EV driven with electricity generated solely with each power source [14], [15], [16]

Country	Total net Electricity Generation (Billion kwh)	Coal	Natural gas	Hydropower	Renewables
Malaysia	187	47%	34.30%	16.6%	1.8%
China	8950.64	62%	3%	15.1%	15.35%
US	4180	16%	43%	5.7%	15%

3. Results and Discussion

The results of this analysis focus on four parts of GHG emissions associated with an electric vehicle (EV) and an internal combustion engine vehicle (ICEV). The unit used to evaluate the emission is grams CO2 equivalent per km (g CO2 eq/km). The first part is the GHG emissions of an ICEV drive for 100 km followed by GHG emissions of an EV considering generation mix in different countries, comparison of Well-to-Wheel emissions between ICEV and EV and validation of findings.

3.1 GHG Emissions (g CO2 eq/km) of ICEV

Figure 2 illustrates the GHG emissions of an ICEV driven for 100 km through three phases including, Well-to-Tank (WTT), Tank-to-Wheel (TTW) and Well-to-Wheel (WTW). Based on the figure, the WTT emission is 2333.88 g CO2 eq/km encompassing the process of extraction, refining and transportation of fuel (petrol). The emissions produced from the high-energy intensive activities associated with fossil fuel production such as oil drilling and refining, result in significant amount of GHG emissions. However, the TTW emissions produced up to 2918 g CO2 eq/km, 20% higher than WTT emissions, indicating that direct emissions were produced during fuel combustion in the engine. Overall, the WTW emissions are 38339 g CO2 eq/km, offering a comprehensive perspective on the GHG emissions generated per kilometre driven, while considering the entire fuel lifecycle.

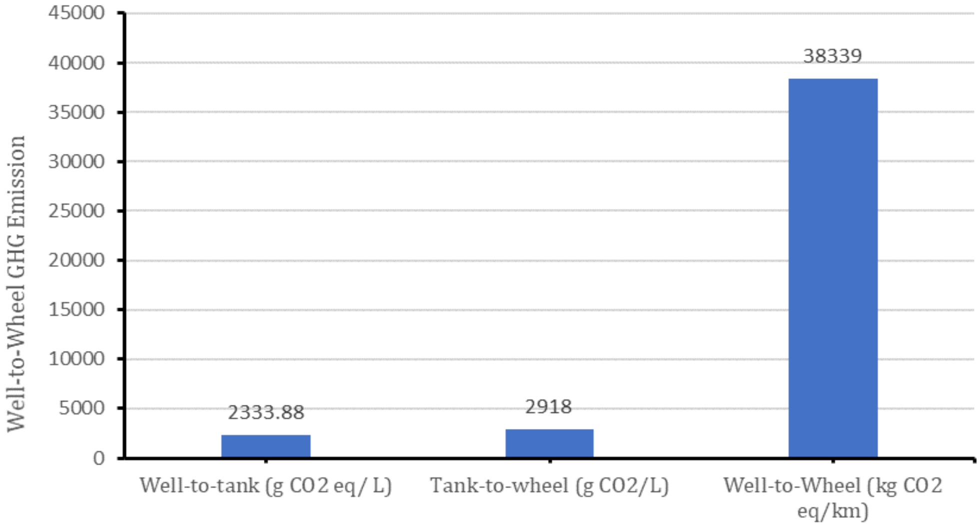

Fig. 2: GHG Emissions (g CO2 eq/km) of ICEV

3.2 GHG Emissions (g CO2 eq/km) of EV Considering Generation Mix in Different Countries (2022)

Figure 3 shows the GHG emissions of an EV when using a generation mix in different countries, which are Malaysia, China, and the United States, in 2022. EVs in Malaysia exhibit the highest emissions at 16974 g CO_2 eq/km, driven by a fossil fuel-dominated electricity generation mix with 46.8% coal, 34.3% natural gas, 0.5% oil, 16% hydropower, and 1.8% renewables, with a total electricity generation of 187,298 GWh. This high emission intensity is primarily driven by the reliance on coal and natural gas as major sources of electricity generation, coupled with minimal contributions from renewable energy sources. As for China, an EV produces 16004 g CO2 eq/km using the country's electricity generation mix. The emissions are slightly lower than Malaysia's but still show a significant value of GHG emissions. China also depends highly on coal, which accounts for 61% of the total net electricity of 895064 GWh. A higher dependency on cleaner energy sources results in lower GHG emissions during the well-to-wheel process of EVs. Lastly, an EV emits the lowest emissions of 11634 g CO2 eq/km when considering the electricity generation mix in the United States. The United States still faces difficulties in lowering emissions from its vast transportation network and reliance on private automobiles, despite the country having moved from coal to natural gas and having a rising proportion of renewable energy in its electricity generation mix.

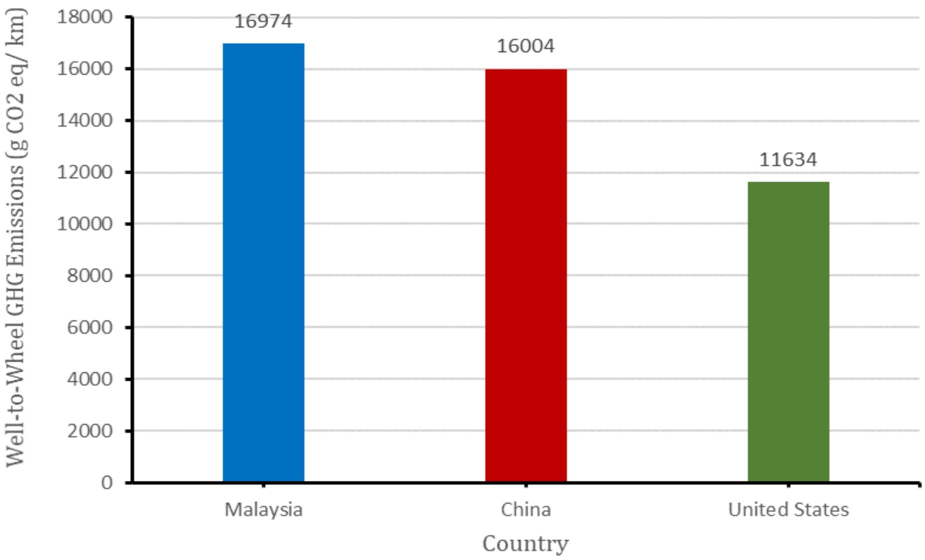

Fig. 3: GHG Emissions (g CO2 eq/km) of EV Considering Generation Mix in Different Countries in 2022

3.3 Comparison of Well-to-Wheel GHG Emissions (g CO2 eq/km) between ICEV and EV

Figure 4 offers a comparison of the well-to-wheel (WTW) greenhouse gas (GHG) emissions for the Volvo XC40 internal combustion engine (ICE) model and the Volvo XC40 Recharge electric vehicle (EV). The analysis breaks down emissions into three phases: WTT, TTW, and the overall WTW total. The findings show that the WTT emissions of the Volvo XC40 Recharge are significantly higher at 3552 g CO_2 eq/km, compared to 2333.88 g CO_2 eq/km for the internal combustion engine (ICE) model. This difference is mainly due to the carbon-intensive electricity generation required for charging EV batteries, which produces 34% more greenhouse gas emissions than refining petrol for ICE vehicles. Thus, the sustainability of EVs heavily relies on the energy mix used for electricity production. In areas with coal-dominant grids, higher WTT emissions can undermine some of the environmental advantages of electric vehicles.

The TTW phase highlights a significant difference between the two models. The ICE model releases 2918 g CO_2 eq/L representing a large portion of its total emissions. This direct CO_2 discharge is a fundamental characteristic of the operational phase of internal combustion engines. In contrast, the Volvo XC40 Recharge has zero TTW emissions since it operates solely on stored electrical energy, completely avoiding combustion and related greenhouse gas emissions.

The cumulative well-to-wheel (WTW) emissions assess the environmental impact of both models. The ICE model emits 38339 g CO_2 eq/km, while the Volvo XC40 Recharge emits 16974 g CO_2 eq/km, representing a 55.72% reduction in emissions. Despite higher well-to-tank (WTT) emissions, the EV's absence of tank-to-wheel (TTW) emissions significantly lowers its carbon footprint. This highlights the environmental advantages of electric vehicles (EVs), even in fossil fuel-dependent energy grids.

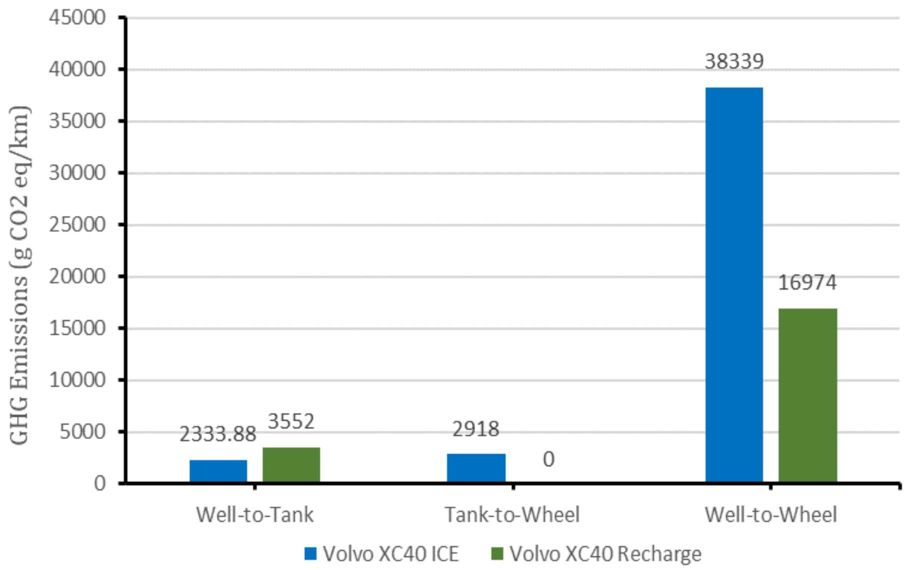

Fig. 4: Comparison of Well-to-Wheel GHG Emissions (g CO2 eq/km) between ICEV and EV

3.4 Validation

Figure 5 compares GHG emissions between the Volvo XC40 ICE and Recharge models derived from this study and those reported by Volvo. The study estimates the emissions of the Volvo XC40 ICE at 38339 g CO_2 eq/km, while Volvo reports a figure of 20500 g CO2 eq/km. The study estimates emissions at 169.184 g CO2 eq/km, for the Recharge model, compared to Volvo's reported value of 14000 g CO2 eq/km. These discrepancies are likely attributed to differences in data sources and methodologies, where this study applied equations from previous research, whereas Volvo utilised Gabi software. Despite the limitations in the data, both datasets affirm that the Recharge model exhibits significantly lower emissions than the ICE model, highlighting the environmental benefits of electric vehicles. Future research should aim to incorporate more accurate data and advanced analytical tools to enhance the reliability of these assessments.

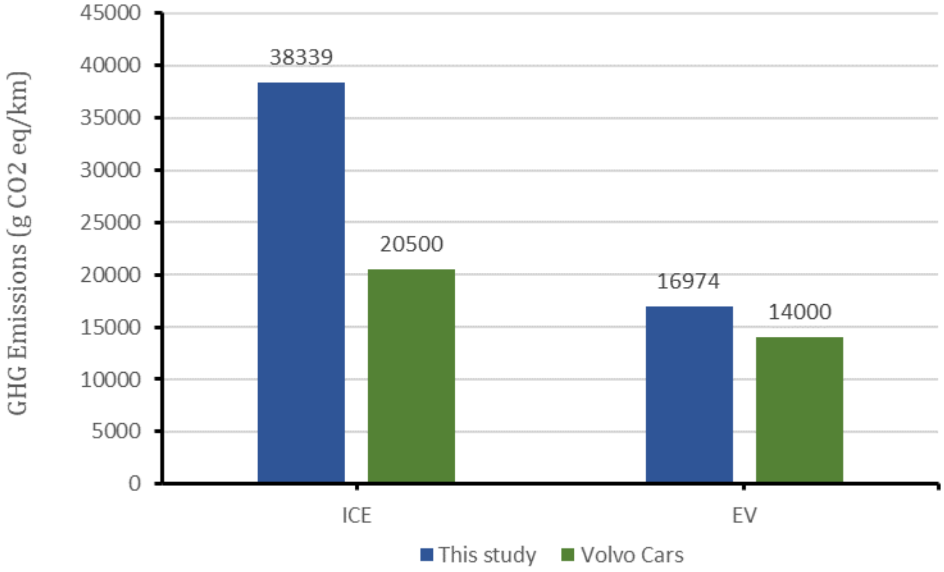

Fig. 5: Results comparison between this study and the Volvo report

Conclusion

This study investigates greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), from electric vehicles (EVs) compared to internal combustion engine vehicles (ICEVs). It highlights how emissions from EVs vary based on the electricity supply and energy mix in different countries. For example, in Malaysia, an EV emits 16974 g CO_2 eq/km, which is higher than emissions in China and the United States, largely due to Malaysia's reliance on fossil fuels. However, the Volvo XC40 Recharge shows a 55.72% reduction in well-to-wheel (WTW) emissions compared to its ICE counterpart, demonstrating EV potential even in carbon-intensive grids. The analysis also reveals that in regions reliant on coal, GHG emissions from electricity production for EVs can exceed those from gasoline for ICEVs. This highlights the need to shift away from high-carbon energy sources so that EVs can fully realise their environmental benefits. In conclusion, transitioning to EVs and decarbonising electricity grids are crucial for reducing transportation-related emissions. Policymakers should prioritise renewable energy investments like solar, wind, and hydropower to maximise EV benefits in mitigating GHG emissions.

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Appendix A: Specifications of Volvo XC40 ICE and Volvo XC40 Recharge

Table 5: Well-to-Tank GHG emissions of EV driven with electricity generated solely with each power source [17]

	ICEV	EV
	Volvo XC40 ICE	Volvo XC0 Recharge
Size (Length x width x height) (mm)	4440 x 1873 x 1652	4440 x 1873 x 1647
Acceleration (0-100km/h) (s)	6.4	4.8
Max engine power (kW)	183	308
Top speed (km/h)	180	180
Weight (kg)	2132	2534
Max torque (Nm)	670	350
Fuel tank capacity (L)	54	
Battery Capacity (kWh)	-	82
Electric Range (km)	-	541
Fuel Efficiency (L/kWh/100km)	7.3	17.6

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