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Article

Assessment of the On-Road Performance of Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs) in Urban Road Conditions in the Philippines

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Abstract: This current and pioneering work aimed to assess the on-road performance of selected hybrid electric vehicles (HEVs) and electric vehicles (EVs) in local urban road conditions following the World Harmonized Light Vehicles Test Procedure (WLTP) and the chase car protocol. An experimental research design was also implemented to investigate the effects of the different payload conditions on vehicle performance, and corresponding drive cycle patterns for the test vehicles were generated from each on-road test. From the series of these on-road tests, it was revealed that there was high variability in speed profiles, and vehicle speed was generally found to be inversely related to payload weight. The variations in the state of charge, fuel fill-up, and fuel and energy parameters exhibited no significant differences in terms of payload conditions. When compared to both the Canada fuel consumption guide and the US fuel consumption guide, the resulting fuel consumption and energy consumption indicated that the Mitsubishi Outlander PHEV and Mitsubishi iMiEV exceeded energy efficiency standards, unlike the Toyota Prius. Meanwhile, in terms of CO_2 emissions, all vehicles demonstrated around 40–70% lower emissions compared to conventional vehicles according to the 2023 estimates of the US Environmental Protection Agency. Being the first of its kind in the Philippines, this study on the on-road performance assessments of HEVs and EVs is essential because it provides empirical data on these vehicles' actual performance in everyday driving conditions. The data are important for evaluating the potential to address environmental concerns, promote sustainable transportation solutions, influence consumer adoption, and shape government policies. With ongoing improvements in technology and expanding charging infrastructure, HEVs and EVs are poised for significant adoption in the coming years.

Keywords: on-road performance test; hybrid electric vehicle (HEV); electric vehicle (EV); carbon emissions; alternative transport solutions; World Harmonized Light Vehicles Test Procedure (WLTP)

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1. Introduction

The growing concerns about price fluctuation, depletion of fossil fuel resources, global warming, and health and environmental impacts have caused a significant increase in interest in hybrid and electric vehicles. In the Philippines, the price of gasoline has been volatile in recent years, making it difficult for motorists to budget for their fuel costs. The average price of gasoline has increased by more than 66% since 2019 and is currently at its highest level in history. Hybrid electric vehicles (HEVs) and electric vehicles (EVs) are not directly affected by price fluctuations, as they use electricity or a combination of electricity and gasoline. They are promising technologies that can help decrease our dependence on fossil fuels and reduce emissions. HEVs and EVs could cut greenhouse gas emissions by up to 80% and eliminate most urban air pollution and oil imports [1]. They are more energy-efficient than conventional vehicles, improving fuel economy by up to 40% [2]. They can also provide vehicle-to-grid services to improve the efficiency of electric grids [3]. Moreover, the environmental benefits of EVs depend on how electricity is generated; they produce the fewest emissions when charged with renewable energy [4,5]. In areas with more renewable energy, EVs produce the greatest benefits, while in areas reliant on coal, EVs could initially increase some emissions until more renewable energy is added but can provide the greatest overall benefits in these areas [5].

However, many barriers prevent the widespread adoption of hybrid electric vehicles (HEVs) and electric vehicles (EVs). High upfront costs, the cost of batteries, and limited range are among the biggest technological barriers [6,7]. Long charging times and lack of charging infrastructure are also major barriers, as limited range cannot be separated from the lack of charging points [8–10]. In Asian countries such as India and Sri Lanka, economic factors, lack of knowledge about EVs, and policy issues are significant barriers to EV adoption [9,10], while in Thailand, the same issues of a lack of charging infrastructure, battery life concerns, and high costs are major barriers to EV adoption [10]. Nevertheless, studies found positive perceptions and intentions to adopt HEVs and EVs. The positive views of the environmental benefits, cost-effectiveness, advanced technology, consumers' environmental concerns, and their preference regardless of the lack of knowledge on these vehicles positively influence intentions to adopt.

In the Philippines, electric jeepneys and tricycles can now be seen on the streets of major metropolitan areas like Metro Manila and popular tourist destinations such as Boracay in Aklan. This shift towards electric vehicles is being facilitated by various government initiatives, including the public utility vehicle modernization program, e-tricycle projects, fiscal incentives, and other policies. The Electric Vehicle Industry Development Act (EVIDA), or RA 11697, which lapsed into law on 15 April 2022, was predicted to create a significant impact on the adoption of HEVs and EVs in the country by creating a more favorable environment through tax incentives, infrastructure development, and research and development while raising public awareness.

Following the trends in the adoption of HEVs and EVs, several studies have been conducted that focus on the on-road performance of these modern vehicles. Such studies conducted in local settings are lacking but remain critical before governments and consumers widely adopt these vehicles. With this in mind, the current work aimed to assess the on-road performance of selected hybrid electric vehicles (HEVs) and electric vehicles (EVs) in local urban driving conditions in the Philippines based on a procedure adopted from the World Harmonized Light Vehicles Test Procedure (WLTP) and the chase car protocol. Although HEVs and EVs undergo rigorous testing based on universally accepted methods, understanding how they perform in site-specific, real-world conditions will help develop efficient energy management systems and performance optimization standards, so that consumers will be able to gain the maximum benefits as they shift towards these alternative transport solutions. From the on-road tests, drive cycle patterns were developed and were used to determine the fuel consumption, fuel economy, energy consumption, energy economy, and estimated carbon emissions.

2. Materials and Methods

2.1. Pre-Survey of the Test Site

The road test adhered to the chase car protocol and each trial covered a route spanning 24 km (Figure 1). The duration of these trials varied, ranging from 60 to 120 min, depending on the prevailing traffic conditions. The designated test route was situated in Bonifacio Global City (BGC), Taguig City, Philippines, in proximity to the Department of Energy

(DOE)-Energy Center office. Both the starting and ending points were located at the same coordinates: 14° 33′ 17.6904″ (latitude) and 121° 3′ 23.6376″ (longitude).

Figure 1. Aerial view of the test route digitized in Google Maps.

2.2. Protocol for the On-Road Performance Test

The protocol for the road performance test was adopted from the World Harmonized Light Vehicles Test Procedure (WLTP) [11]. This testing procedure is based on an approximation of the test conditions to real-world circumstances, which implies that the values determined will also have greater relevance to reality. A summary of the test parameters are listed in Tables 1 and 2.

Table 1. Summary of test parameters and values.

Parameter	Value
number of test cycles	Up to 4
cycle time	30 min
cycle distance	23–25 km
driving phase	4 (more non-urban use)
highest speed	131 kph
impact options	Yes
gear shift	Variable
test temperature	23 °C

Table 2. Classification of WLTP cycles based on power-to-mass ratio (PMR).

Category	PMR	Speed Phase
Class 1	PMR ≤ 22	Low, middle
Class 2	34 ≥ PMR ≥ 22	Low, middle, high
Class 3	PMR > 34	Low, middle, high, extra-high

In light of the previously mentioned conditions, the test cycles for the test vehicles primarily comprised a low phase (Low_3), a medium phase ($Medium_{3\text{-}2}$), and a high phase ($High_{3\text{-}2}$). The extra-high phase (Extra $High_3$) was not included due to the potential of exceeding the speed limit in the test route.

2.3. Experimental Design

During the road tests, variations in the performance of the test vehicles under different payload conditions were observed. The payloads for both the test vehicle and the chase vehicle, excluding the driver, were 50 kg (Treatment 1), 100 kg (Treatment 2), or 150 kg (Treatment 3), with each treatment being repeated three times. For each repetition, the following factors were observed and determined: (a) fuel economy (measured in km/L), (b) energy economy (measured in kWh/km), (c) fuel consumption (L/100 km), and (d) energy consumption (kWh/100 km).

2.4. Data Collection Procedure

Before conducting the road test, a comprehensive inspection of all vehicles was carried out. The inspection encompassed a thorough examination of various components, including the battery, lights, oil, water, brakes, air system, gas system, engine, tires, and tire pressure. In addition, before and after the road test, the following parameters were also recorded: (a) initial and final readings of the odometer, (b) the total distance covered during the test cycle in kilometers; (c) the duration of the test cycle in minutes, (d) the initial and final state of charge (SOC) for hybrid vehicles expressed as a percentage, (e) the amount of energy recharged for hybrid vehicles and for the electric vehicle, and (f) the quantity of fuel refilled in liters.

During the road test, two on-board diagnostic (OBD) devices with data-logging capabilities were implemented to record real-time driving data. For the hybrid vehicles, a Launch X431 Pro 3 OBD tool was used to record data on vehicle speed (kph) and SOC with an average data logging interval of 3 s. Meanwhile, for the chase vehicle, a Bluetooth-enabled OBD scanner (BlueDriver Bluetooth® Pro OBDII Scan Tool) was implemented to collect the same data with an average data logging interval of 0.8 s.

2.5. Analysis of Drive Cycle Patterns

Drive cycle patterns were generated for each trip. To understand the drive cycle pattern, a representative driving cycle was chosen from various patterns developed during road tests, and corresponding line graphs were created. The drive cycle patterns displayed the speed, acceleration, deceleration, and time elapsed for each trip. The information derived from these drive cycle patterns was examined using descriptive statistics that included the mean, median, standard deviation, variance, skewness, kurtosis, minimum, maximum, range, and interquartile range.

To determine whether significant differences exist between trip duration, average speed, SOC, fuel fill-up, fuel efficiency, energy recharge, energy consumption, and energy economy parameters, the Kruskal–Wallis H-test was applied, followed by the Dwass–Steel–Critchlow–Fligner method as a post hoc test. The post hoc test (for pairwise comparison) helped identify which observations account for the significant differences.

Ultimately, visual representations of speed profiles were presented using box-and-whisker plot and histograms.

2.6. Determination of Fuel and Energy Consumption and Fuel and Energy Economy

Fuel consumption gives consumers reliable information about the relative fuel efficiency of vehicles expressed in liters per 100 km (L/100 km). Fuel economy, on the other hand, is the reciprocal of the fuel consumption expressed in km/L. These parameters were computed using the equations below:

$$\text{fuel consumption} = \frac{\text{refuel amount (L)}}{\text{cycle distance (km)} \times 100} \tag{1}$$

$$\text{fuel economy} = \frac{\text{cycle distance (km)}}{\text{refuel amount (L)}} \tag{2}$$

The Mitsubishi Outlander PHEV and the Mitsubishi iMiEV were operated in a charge-depleting mode. Starting with an initial SOC of 80%, these vehicles were permitted to discharge their batteries throughout the test cycle before being recharged back to the original SOC. The quantity of energy recharged (measured in kWh) was documented for each trial to calculate energy consumption (kWh/100 km) and energy efficiency (km/kWh). These calculations were performed using the following equations:

$$\text{energy consumption} = \frac{\text{energy recharged (kWh)}}{\text{cycle distance (km)} \times 100} \quad (3)$$

$$\text{energy economy} = \frac{\text{cycle distance (km)}}{\text{energy recharged (kWh)}} \quad (4)$$

2.7. Estimation of Greenhouse Gas Emissions

Carbon dioxide (CO_2) emissions resulting from passenger vehicles were quantified in CO_2 emissions units [12]. To approximate the quantity of the greenhouse gas that was being discharged during combustion, as well as the quantity emitted due to electricity consumption, the following emission factors and mathematical expressions were employed:

for gasoline-powered vehicles,

$$\text{Tailpipe emissions per km} = \frac{CO_2 \text{ emissions per liter}}{\text{Fuel economy rating}} \quad (5)$$

$$\text{Total tailpipe emissions} = \text{Tailpipeemissionsperkm} \times \text{distance travelled} \quad (6)$$

for hybrid vehicles that use electricity,

$$\text{Emissions per km} = \frac{\text{Emission factor}}{\text{Energy economy rating}} \quad (7)$$

$$\text{Total emissions} = \frac{\text{Emission factor}}{\text{Energy economy rating}} \times \text{total distance travelled} \quad (8)$$

where CO_2 emissions per liter of gasoline = 2347.7 g; fuel economy rating, km/L; emission factor = 4.33×10^{-4} metric tons CO_2/kWh; energy economy rating, km/kWh; and distance traveled, km.

3. Results and Discussion

3.1. Statistics on the Duration of Trips during the On-Road Tests

Tables 3–6 present information about the average duration of trips for different vehicles during the on-road tests. For instance, with the Mitsubishi iMiEV, the briefest trip lasted 86.43 min while the longest lasted 154.08 min. The Mitsubishi Outlander PHEV similarly had a range of 61.03 to 119.25 min, and the Toyota Prius experienced trips ranging from 79.79 to 107.18 min. Comparing their average trip durations, the Toyota Prius displayed the shortest mean at 91.68 min, followed by the Mitsubishi Outlander PHEV at 95.39 min, and the Mitsubishi iMiEV at 106.92 min.

Table 3. Statistics on the duration of trips for Mitsubishi iMiEV.

Test Date	Mean Duration of Trip (min)	Minimum Value (min)	Maximum Value (min)	Coefficient of Variation	Standard Deviation
1	123.67	93.25	154.08	0.35	43.01
2	100.64	86.43	118.97	0.17	16.66
3	96.45	91.90	99.75	0.04	4.07
Mean	106.92			0.19	21.25

Table 4. Statistics for the duration of trips of Mitsubishi Outlander PHEV.

Test Date	Mean Duration of Trip (min)	Minimum Value (min)	Maximum Value (min)	Coefficient of Variation	Standard Deviation
1	90.14	61.03	119.25	0.46	41.17
2	92.69	87.12	99.60	0.07	6.35
3	103.33	85.92	129.20	0.22	22.84
Mean	95.39			0.25	23.45

Table 5. Statistics on the duration of trips for Toyota Prius.

Test Date	Mean Duration of Trip (min)	Minimum Value (min)	Maximum Value (min)	Coefficient of Variation	Standard Deviation
1	90.40	82.99	94.51	0.07	6.43
2	91.80	86.75	97.17	0.06	5.22
3	92.85	79.79	107.18	0.15	13.74
Mean	91.68			0.09	8.46

Table 6. Summary of the trip information for the three vehicles.

Vehicle Type	Mean Duration of Trips ^{NS} (min)	Coefficient of Variation	Standard Deviation
Mitsubishi iMiEV	106.92	0.19	21.25
Mitsubishi Outlander PHEV	95.39	0.25	23.45
Toyota Prius	91.68	0.09	8.46

NS = Difference in mean values is not significant.

Overall, the data underscore that the average trip duration for all three car models hovered around 90 min. This information can provide insights into probable traffic conditions during these trips. The average trip duration can serve as an estimate for the time a journey might take under normal traffic circumstances. For example, if operating a Mitsubishi iMiEV, one could anticipate a trip lasting around 123 min without traffic disruptions. Conversely, the standard deviation helps gauge the potential variability in trip times due to traffic. For instance, using the same Mitsubishi iMiEV, there is a chance the trip time for the same distance could range from 85.67 to 128.17 min.

3.2. Drive Cycle Patterns

A representative drive cycle pattern for each test unit is shown in Figure 2. Following these drive cycle patterns, the average speeds (in kph) were recorded for the test vehicles under the effects of varying payload. The highest speeds were reached by the Mitsubishi Outlander PHEV at 100 kph, followed by the Mitsubishi iMiEV at 96 kph and the Toyota Prius at 94 kph. In terms of speed variability, the Mitsubishi iMiEV exhibited the lowest variability (379.40), followed by the Toyota Prius (450.79) and the Mitsubishi Outlander PHEV (481.39).

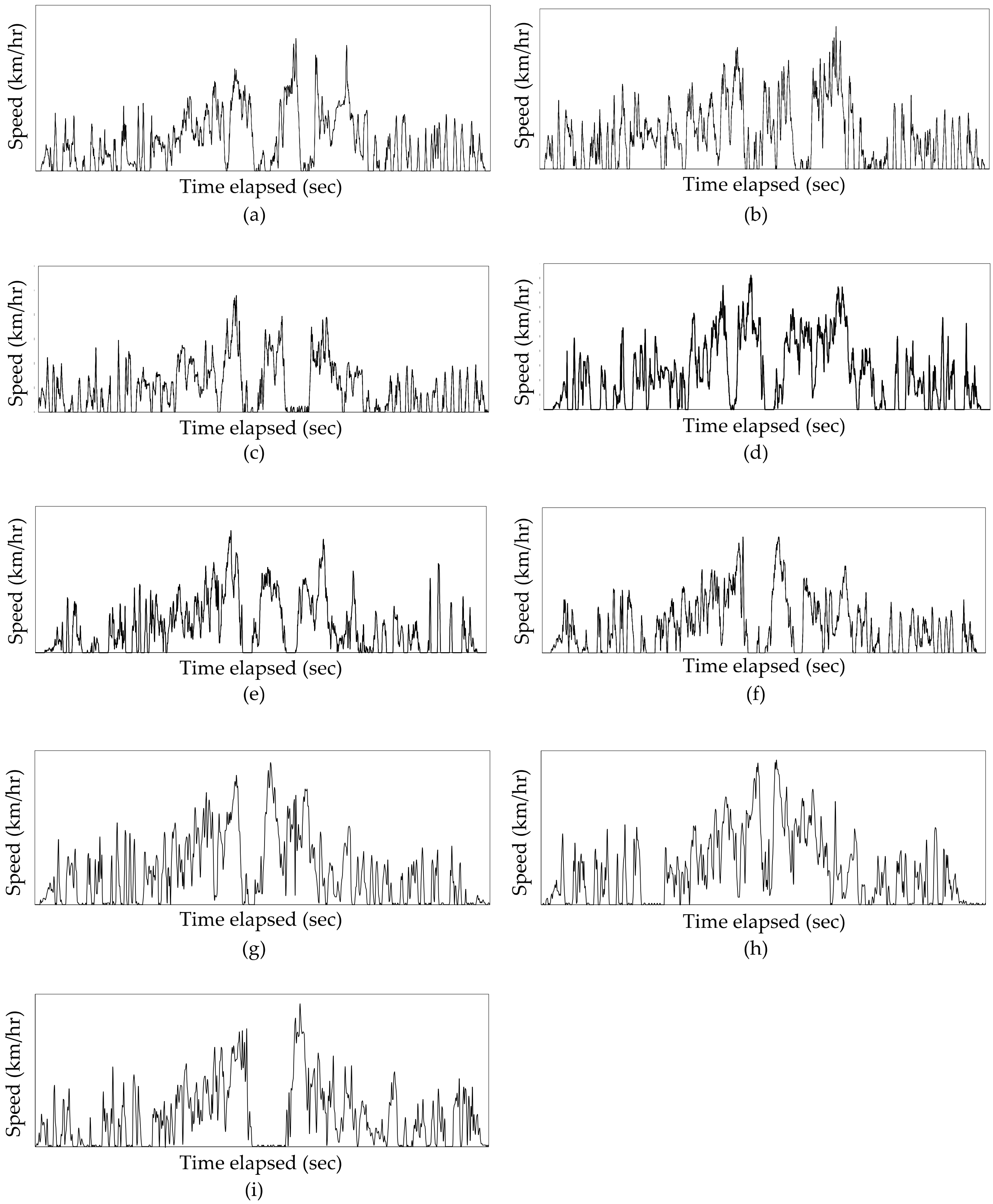

Figure 2. Drive cycle patterns of the test units with different payloads: (**a**) Mitsubishi i-MiEV with 50 kg payload; (**b**) Mitsubishi i-MiEV with 100 kg payload; (**c**) Mitsubishi i-MiEV with 150 kg payload; (**d**) Mitsubishi Outlander PHEV with 50 kg payload; (**e**) Mitsubishi Outlander PHEV with 100 kg payload; (**f**) Mitsubishi Outlander PHEV with 150 kg payload; (**g**) Toyota Prius with 50 kg payload; (**h**) Toyota Prius with 100 kg payload; (**i**) Toyota Prius with 150 kg payload.

In essence, these drive cycle patterns suggest a city environment with frequent stops, accelerations, and decelerations, indicative of substantial urban traffic conditions. Despite adhering to standard test procedures, it remains challenging to control both traffic conditions and vehicle speeds, resulting in rapidly changing patterns. Driving cycles should match real-world conditions but existing methods may not capture their complexity [13]. A related study shows that an analysis of driving cycles in Indian cities also revealed frequent stopping, accelerating, and decelerating due to traffic and intersections, confirming substantial traffic conditions [14,15].

Meanwhile, the analysis of the speed parameters obtained from the drive cycle patterns is also presented in Table 7. The statistical analysis revealed that there are highly significant differences in the average speeds of the vehicles, particularly the Mitsubishi iMiEV and Mitsubishi Outlander PHEV. Furthermore, the pairwise comparisons revealed that for both vehicles, the mean speeds under a 50 kg payload differ significantly from those under 100 kg and 150 kg payloads. However, the mean speeds for these two vehicles when loaded with 100 kg and 150 kg are quite similar. It can also be observed that the vehicle speed generally decreases as the load increases and vice versa.

Table 7. Statistics of the speed data for the test vehicles.

Speed Data (kph)	Vehicle Load (kg)								
	50	100	150	50	100	150	50	100	150
	A **	B **	C **	A **	B **	C **	A	B	C
Mean	20.13 ^{ab}	19.14 ^{a}	18.98 ^{b}	23.80 ^{ab}	20.17 ^{a}	20.76 ^{b}	20.63	21.91	19.02
Median	16	16	15	19	13	15	15	16	14
Standard Deviation	0	0	0	0	0	0	0	0	0
Variance	393.22	357.95	387.02	493.73	482.65	467.79	463.73	497.13	391.52
Skewness	0.94	0.87	1.02	0.69	1.06	0.98	1.20	1.18	1.15
Kurtosis	0.22	−0.05	0.53	−0.52	0.33	0.35	0.61	0.63	0.78
Minimum	0	0	0	0	0	0	0	0	0
Maximum	96	89	96	92	100	96	92	94	93
Range	96	89	96	92	100	96	92	94	93
IQR	31	31	31	39	34	35	29	31	29

Note: A—Mitsubishi iMiEV; B—Mitsubishi Outlander PHEV; C—Toyota Prius. IQR—interquartile range. ** Difference on mean speed is highly significant at 1% level. ^{a,b} Means with the same letter are highly significantly different at 1% level.

The median speed values for all vehicles were close to each other and the IQRs were also quite similar, suggesting that the variability in speed data is consistent across these vehicles.

There are similar findings on the relationship between vehicle load and speed. As the proportion of heavy vehicles increased on a highway, average traffic speed decreased [16]. However, speed deviation between vehicles also decreased, showing that heavy vehicles forced other vehicles to travel at similar speeds. In addition, as vehicle load increased, dynamic loads on the vehicle increased, requiring lower speeds [17]. Conversely, decreasing vehicle load allows for higher speeds. Evidence shows that lighter vehicle loads decrease the forces on a vehicle, allowing it to corner at higher speeds [18].

The box-and-whisker plot in Figure 3 illustrates the 25th, 50th, and 75th percentiles of the speed values, the interquartile range, and the minimum and maximum speeds. These histograms in Figure 4 reveal information on skewness, wherein the speed distribution is skewed to the left for all three vehicles. This indicates that there is a higher concentration of data points are at lower speeds compared to higher speeds. Remarkably, among the three vehicles, the speed distribution for the Mitsubishi iMiEV exhibits the most pronounced left skew, while the Toyota Prius displays the least. The left skewness in the speed distribution of the Mitsubishi iMiEV also suggests that this vehicle is more influenced by the weight of the load than the other two vehicles.

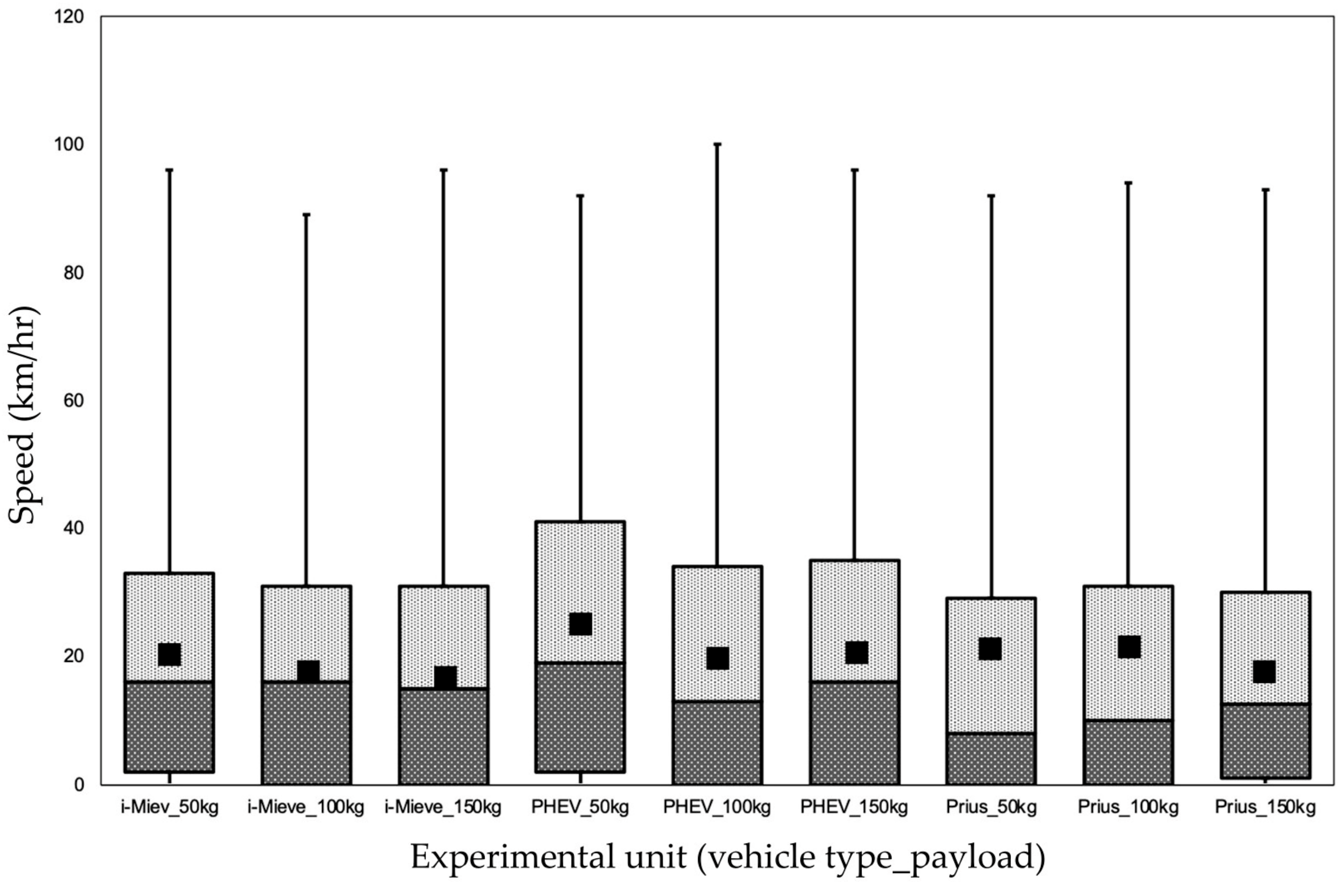

Figure 3. Box-and-whisker plot of the speeds of the test vehicles under different loading conditions during the road test. The black squares represent the mean.

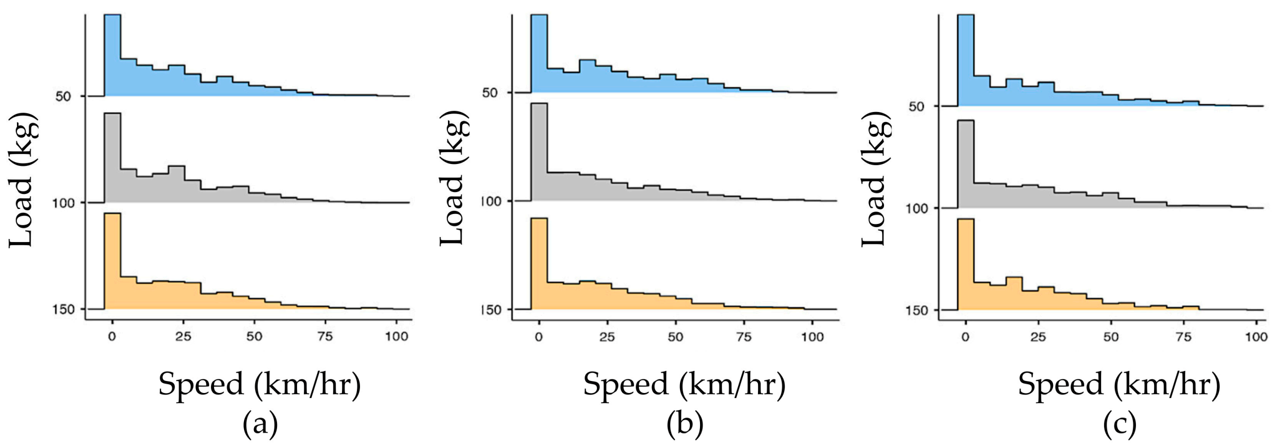

Figure 4. Histogram of the speed values of the test vehicles based on the drive cycle pattern: (**a**) Mitsubishi iMiEV; (**b**) Mitsubishi Outlander PHEV; (**c**) Toyota Prius.

3.3. Fuel and Energy Consumption and Economy

Tables 8–10 present a summary of the road test data for the test vehicles, which encompasses the total distance covered per trip, SOC, fuel fill-up, fuel efficiency, energy recharged, energy consumption, energy economy, and charging time. Mitsubishi iMiEV, being a fully electric vehicle, does not have values for fuel fill-up and fuel efficiency. On the other hand, the Toyota Prius does not have values for energy recharged, energy efficiency, and charging time.

Table 8. Summary of road test information for Mitsubishi iMiEV.

Test Date	Distance Traveled (km)	Difference in SOC (%)	Fuel Fill-up (L)	Fuel Economy (km/L)	Energy Recharged (kWh)	Energy Consumption (kWh/100 km)	Energy Economy (km/kWh)	Charging Time (min)
1	24.00	37.50	NA	NA	2.40	10.00	10.00	10.58
2	24.00	34.17	NA	NA	4.30	17.92	5.61	15.29
3	24.00	32.67	NA	NA	4.23	17.64	5.68	14.34

Table 9. Summary of road test information for Mitsubishi Outlander (PHEV).

Test Date	Distance Traveled (km)	Difference in SOC (%)	Fuel Fill-up (L)	Fuel Economy (km/L)	Energy Recharged (kWh)	Energy Consumption (kWh/100 km)	Energy Economy (km/kWh)	Charging Time (min)
1	24	37.17	3.33	9.33	3.43	14.30	16.63	18.29
2	24	55.00	1.41	17.11	4.93	20.56	4.86	19.00
3	24	55.00	1.20	21.00	4.93	20.56	4.86	18.36

Table 10. Summary of road test information for Toyota Prius.

Trial	Distance Traveled (km)	Difference in SOC (%)	Fuel Fill-up (L)	Fuel Economy (km/L)	Energy Recharged (kWh)	Energy Consumption (kWh/100 km)	Energy Economy (km/kWh)	Charging Time (min)
1	24	−2.62 ‡	2.43	10.14	NA	10.14	NA	NA
2	24	−0.91 ‡	1.45	17.73	NA	6.04	NA	NA
3	24	2.49	1.80	17.54	NA	7.50	NA	NA

Note: NA = not applicable. ‡ Negative value (−) denotes increase in battery charge after the trip.

Statistically, the differences in the SOC percentage among all test units per type of vehicle do not vary significantly (Mitsubishi iMiEV, p-value = 0.819; Mitsubishi Outlander PHEV, p-value = 0.395; Toyota Prius, p-value = 0.079). Similarly, the differences in fuel fill-up, fuel efficiency, energy recharge, energy consumption, and energy economy for all vehicles were also not significant. One study argues that the relationship between vehicle mass and fuel economy is more complex for hybrid and electric vehicles than for conventional vehicles [19,20]. While reducing mass typically improves fuel economy for conventional vehicles, HEVs can achieve significant fuel economy improvements with little or no change in mass. Once a vehicle has switched to a hybrid or electric powertrain, further mass reductions provide diminishing fuel economy benefits.

Table 11 offers a more simplified yet comprehensive overview of key performance metrics for test vehicles. First, take note that the Mitsubishi iMiEV operates as a pure electric vehicle; thus, the inclusion of standard fuel consumption values is irrelevant. Moreover, the Toyota Prius has no value for energy economy. Interestingly, the Mitsubishi iMiEV demonstrated an average energy consumption of 15.80 kWh/100 km, a figure below both the Canadian standard of 16.9 kWh/100 km and the US EPA standard of 20.50 kWh/100 km. This suggests that the iMiEV excels in energy efficiency under real-world driving conditions. Conversely, the Mitsubishi Outlander PHEV exhibited an average fuel consumption of 8.25 L/100 km, which falls slightly under the Canadian standard of 9.2 L/100 km and the US EPA standard of 9.0 L/100 km. These results indicate that the Outlander PHEV is not only energy-efficient but also exhibits fuel efficiency that aligns with established standards. However, the Toyota Prius recorded an average fuel consumption of 7.89 L/100 km. This implies a lower fuel efficiency than the specified standards of 5.7 L/100 km for Canada and 6.2 L/100 km for the US EPA. The data suggests that the Prius falls short of its hybrid counterparts in terms of fuel efficiency during real-world usage.

Table 11. Summary of fuel fill-up and recharge data for the test vehicles during the road test.

Vehicle Type	Fuel Consumption (L/100 km)	Fuel Economy (km/L)	Energy Consumption (kWh/100 km)	Energy Economy (km/kWh)	Standard Fuel Consumption (L/100 km)		Standard Energy Consumption (kWh/100 km)	
					Canadian *	US DOE **	Canada *	US DOE **
Mitsubishi iMiEV	NA	NA	15.18	7.10	-	-	16.9 [b]	20.50 [b]
Mitsubishi Outlander PHEV	8.25	15.81	18.47	8.79	9.2 [a]	9.0 [a]	-	-
Toyota Prius	7.89	15.14	7.89	NA	5.7 [a]	6.2 [a]	-	-

Note: NA = Not applicable. * Data obtained from the Canada Fuel Consumption Guide (2023 or 2017 version). ** Data obtained from the US Fuel Economy Guide (2022 or 2017 version). [a] Data were obtained from the 2023 Fuel Consumption/Economy Guide. [b] Data were obtained from the 2017 Fuel Consumption/Economy Guide. Mitsubishi iMiEV is no longer included in the later versions of the fuel consumption/economy guide.

In general, the above information underscores the superior energy and fuel efficiency of the Mitsubishi iMiEV and Mitsubishi Outlander PHEV in comparison to established standards. Meanwhile, the Toyota Prius appears to lag in fuel efficiency when assessed under actual driving conditions. It is also important to note that the fuel consumption and energy consumption of a vehicle can vary depending on several factors, including the driving conditions, the weight of the vehicle, and the driving habits of the driver.

Several studies have found that the Prius fails to meet its advertised fuel economy and emissions standards in real-world driving conditions. While the Prius IV spent a high percentage of time operating in zero-emission mode in urban driving, its overall fuel economy was lower than advertised, achieving only 5.9 L/100 km compared to Toyota's claim of 4.4 L/100 km [21,22]. In addition, a model of the 2010 Prius achieved fuel consumption 5% higher than advertised after simulating real-world driving conditions [22]. The Prius's fuel economy advantage is highly dependent on driving conditions wherein fuel economy benefit was 60% lower in urban driving but only 40% lower at higher speeds, nearly reaching that of a diesel vehicle at 95 [23]. Some studies have found that the standard regulatory drive cycles, which fail to capture real-world variability, overestimate the Prius's fuel economy by up to 23% compared to more aggressive supplemental cycles [24].

The adoption of hybrid electric vehicles (HEVs) and electric vehicles (EVs) is increasing, but at a slower rate than many predictions and government targets, which makes it hard to predict its socio-economic impacts. Several factors are contributing to the difficulty in predicting adoption rates and associated fuel savings. Government incentives and policies aim to encourage consumers to purchase HEVs and EVs, but their effectiveness is unclear. In Asia, economic factors like high upfront costs and lack of consumer incentives are barriers to adoption. Consumers were only willing to pay EUR 1645 more for a HEV, which is much less than the actual price premium [25]. While some studies found government incentives increased adoption [26], others found little impact [27]. The timing, magnitude, and type of incentive seem to influence their success, but more research is needed [26]. However, public charging infrastructure reduces "range anxiety" and eases the transition to EVs, especially battery EVs (BEVs) [26,28], but the direction of causality is uncertain regarding whether infrastructure may drive adoption or vice versa [26].

Nevertheless, there is significant evidence that hybrid electric vehicles (HEVs) and electric vehicles (EVs) will play an increasingly prominent role in the future of transportation. Multiple studies found that HEVs and EVs produce fewer emissions than traditional internal combustion engine vehicles (ICEVs), making them more environmentally friendly. Governments worldwide are implementing policies and incentives to encourage the adoption of HEVs and EVs to meet emission reduction targets and combat climate change [29,30]. Technological improvements are also making HEVs and EVs more affordable, higher-performing, and competitive with ICEVs. Advancements in batteries, power electronics, and electric motor designs are enhancing range, efficiency, and power [30–32].

Although HEVs and EVs currently represent a minority of vehicles on the road, numerous specialists anticipate a substantial increase in their adoption in the coming decade. HEVs and EVs are projected to capture a significant portion of the market as their costs decrease and their performance is enhanced, charging infrastructure expands, and a wider range of models becomes accessible.

3.4. Estimated Carbon Emissions

The estimated carbon emissions of the test vehicles are shown in Table 12. On average, the combustion of one gallon of gasoline results in the release of 8887 g of CO_2 (2347.7 g/L). Using this emission factor, the Mitsubishi Outlander PHEV was found to emit 148.49 g of CO_2/km, totaling 3563.87 g, and the Toyota Prius emitted 155.07 g/km, totaling 3721.58 g. These translate to estimated annual CO_2 emissions of 2.748 metric tons (MT) and 2.8790 MT, respectively. These values are remarkably 40% lower than the average emissions of a typical US passenger vehicle, which emits 4.6 MT of CO_2 per year.

Table 12. Estimated CO_2 emissions of the test vehicles.

Vehicle Type	CO_2 Emissions	Total CO_2 Emissions [d]	Estimated Annual Emissions [e] (MT CO_2)
Mitsubishi Outlander PHEV	148.49 g/km [b]	3563.87 g	2.748
Toyota Prius	155.07 g/km [b]	3721.58 g	2.870
Mitsubishi iMiEV [a]	6.09859×10^{-5} [c] MT CO_2/km	1.463662×10^{-3} MT CO_2	1.130

Note: All estimates are based on values from the US Environmental Protection Agency [12]. [a] Emission is based on energy recharged or kilowatt hours of energy consumed. [b] Emission factor for gasoline is 2347.7 g/L. [c] Emission factor for electricity consumed = 4.33×10^{-4} metric tons CO_2/kWh. [d] Total emissions based on the 24 km driving distance during the road test. [e] Estimated annual emissions based on 18,507.456 km driven per year (mileage).

On the contrary, the Mitsubishi iMiEV does not produce tailpipe emissions, but its electricity consumption in kilowatt hours can be converted into CO_2 emissions. With an emission factor of 4.33×10^{-4} metric tons of CO_2 per kilowatt hour, the estimated vehicle's annual CO_2 emissions are 1.463662×10^{-3} MT CO_2 or 1.13 MT per year.

It is challenging to predict the long-term CO_2 reduction of the increased adoption of HEVs and EVs, but there is a consensus among researchers that estimating CO_2 emissions from vehicles is crucial to understanding their environmental impact [33–40]. Considering emissions from manufacturing, operation, and end-of-life phases, life cycle assessment is a commonly used method to evaluate CO_2 emissions. Studies show that while HEVs and EVs produce lower emissions during operation due to their efficient powertrains and renewable energy usage, their manufacturing phases generate higher emissions due to battery production [34,35,39]. Overall, most research finds that HEVs and EVs have lower life cycle CO_2 emissions compared to ICEVs [33–35,38]. EVs were estimated to reduce life cycle CO_2 emissions by 11–50% compared to ICEVs. Meanwhile, for EVs to have lower emissions than ICEVs, the emissions from generating their electricity should be around 320 g/kWh or less. Studies also show that the source of electricity used to charge EVs significantly impacts their emissions, and renewable energy can help maximize environmental benefits.

4. Conclusions

The fuel consumption and energy consumption results indicated that the Mitsubishi Outlander PHEV and Mitsubishi iMiEV exceeded energy efficiency standards, while the Toyota Prius fell short. In terms of CO_2 emissions, all vehicles demonstrated lower emissions compared to conventional vehicles, with the Mitsubishi iMiEV having the lowest fuel emissions.

Despite currently representing a minority of vehicles on the road, experts anticipate a significant rise in the adoption of HEVs and EVs over the next decade. As their costs decrease, performance improves, charging infrastructure expands, and a wider range of vehicle models becomes accessible, HEVs and EVs are poised to capture a substantial portion of the automotive market. Although hybrid electric vehicles (HEVs) and electric vehicles (EVs) are still emerging technologies, the public tends to have a positive view of them and believes in their potential to contribute to a sustainable future in transportation. Overcoming the remaining barriers to their widespread adoption can be achieved through a combination of policy initiatives, incentives, educational efforts, and ongoing technological advancements.

With all these findings, the team recommends further research on market analysis, the correlation between demographics and fuel economy, the development of comprehensive test protocols, on-road testing in different settings, exploration of climate effects on vehicle performance, and a life cycle analysis of HEVs and EVs. For policymakers, addressing adoption barriers through policies, incentives, education, and technological advancements is crucial for their continued growth in the automotive market. With ongoing improvements in technology and expanding charging infrastructure, HEVs and EVs are poised for significant adoption in the coming years.

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