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A Comparative Analysis of PHEV and BEV on Fuel Economy, Greenhouse Gas Emissions, and Annual Cost

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***Abstract*—The accelerating pace of urbanization and growing concerns about climate change underscore the urgency of sustainable transportation solutions. This study compares the performance of a Battery Electric Vehicle (BEV) and a Plug-in Hybrid Electric Vehicle (PHEV) across different drive cycles and road conditions, including a real-world steep-terrain cycle with significant elevation changes. By leveraging GT-SUITE simulations for fuel economy assessment, the GREET model for life cycle emissions analysis, and cost evaluations, the findings demonstrate that the BEV outperforms a series PHEV across various conditions. BEVs achieve a fuel consumption range of 1.68–2.55 Le/100 km and produce nearly 50% lower life cycle emissions when charged by electricity generated from near-zero GHG sources. Additionally, over the evaluated cycles they offer annual cost savings between $370 to $1,750 compared to the PHEV. The results also indicate that standardized testing protocols do not fully capture real-world vehicle performance in challenging terrain. These findings highlight the environmental and economic advantages of BEVs, reinforcing their pivotal role in advancing sustainable urban transportation.

***Keywords-component*—Battery Electric Vehicles, Plug-in Hybrid Electric Vehicles, Life Cycle Emissions**

I. INTRODUCTION

Recent challenges in the transportation sector, including fluctuations in global petroleum supply and the significant environmental impacts associated with petroleum consumption, have amplified the demand for more efficient vehicle technologies. The Environmental Protection Agency (EPA) identifies personal vehicles as the primary contributors to greenhouse gas emissions within the transportation sector, underscoring the urgent need to enhance vehicle efficiency [1].

Road traffic generates noise and emits pollutants that impact both air quality and climate. While advancements have reduced carbon monoxide (CO) and hydrocarbons (HC) in newer vehicles, diesel particulate matter (PM) and nitrogen oxides (NO_x) remain challenges. Technologies such as diesel particulate filters (DPFs) for PM reduction and selective catalytic reduction (SCR) with diesel exhaust fluid (DEF) for NO_x control help but introduce cost, maintenance, and efficiency trade-offs [2]. Despite these advancements, road traffic remains a major contributor to greenhouse gas (GHG) emissions, accelerating climate change [3].

Although regulatory measures, such as stricter emission standards like the Corporate Average Fuel Economy (CAFE) standards in the U.S. and the EU's fleet-wide CO_2 targets—have been implemented [4], these alone address only a portion of the challenges posed by the transportation sector. Optimizing vehicle efficiency through powertrain electrification offers a transformative solution. As a result, the development and adoption of hybrid and fully electric vehicles have emerged as promising strategies to address these issues comprehensively [5].

To advance the sustainability of road traffic, it is essential to evaluate the benefits and limitations of Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) early in their adoption phase. This requires a holistic analysis across their entire life cycle, encompassing production, usage, electricity generation, disposal, and recycling. Studies indicate that the usage phase is a major contributor to life cycle emissions [6], with key factors such as fuel economy, the electricity generation mix, and vehicle efficiency playing pivotal roles. Additionally, economic assessments offer critical insight into the feasibility of transitioning to these technologies. This paper contributes to this discourse through the following analyses:

- An in-depth evaluation of energy consumption across various speed and grade profiles, offering insights into real-world vehicle fuel economy.
- An analysis of environmental impacts spanning production, use and end-of-life phases, with a particular

emphasis on the electricity generation mix for vehicle charging.
- An economic assessment of the operation of PHEV and BEV, informing the financial choices to adopt these technologies.

II. Methodology

A. Vehicle Data

To conduct a comprehensive and equitable comparative assessment of Tank-to-Wheel Efficiency (TtW-efficiency) between BEVs and PHEVs, it is imperative to standardize them in terms of various factors [7]. To fulfill this objective, data from commercially available PHEV and BEV, specifically from the KIA Niro (2024) series has been employed to size the vehicle and powertrain components [8] - [9], as given in Table I.

TABLE. I
Vehicle Specifications for KIA PHEV & BEV Niro

Specifications	PHEV	BEV
Gross Vehicle Weight - Kg	2,040	2,169.98
Drag Coefficient - C_d	0.29	0.29
Frontal Area - m^2	1.95	1.95
Rolling Resistance Coefficient	0.015	0.015
Lithium Ion Battery Size - Ah	30.8	180.9
Motor Power Rating - kW	62	150

B. Drive Cycles

The TtW efficiency of vehicles is significantly influenced by their drivetrain concepts. While BEVs demonstrate relatively stable TtW efficiency across different conditions, internal combustion engine-based designs show notable variations depending on the speed profile. To investigate this phenomenon, a range of drive cycles is employed, including one simulating urban driving conditions, another representing highway scenarios, and a third derived from the measurements of an actual real-world drive cycle for comprehensive evaluation. The details of the drive cycles are given in Table II.

TABLE. II
Drive Cycle Data

	FTP-75	HWFET	SFU-EDC
Time - s	1874	765	3096
Distance - Km	16.51	16.45	31.07
Speed - Km/h	77.57	77.7	36.14
Average Absolute Grade - %	0.51	1.42	8.2

a) Urban Drive Cycle - EPA Federal Test Procedure (FTP-75 - Light Duty): This is a standardized protocol used for the certification of emissions and testing of fuel economy in light-duty vehicles within the United States. Distinguished by its complexity, the FTP-75 is said to simulate real road conditions with more accuracy in an urban setting [10]. To simulate a realistic driving scenario, the model incorporates the standard GT-Suite urban grade for this drive cycle.

b) Highway Drive Cycle - EPA Highway Fuel Economy Test (HWFET - Light Duty): This is a chassis dynamometer driving schedule devised by the US EPA specifically for evaluating the fuel economy of light-duty vehicles under highway conditions. It mimics a blend of rural and interstate highway driving and is used to replicate typical longer journeys characterized by free-flowing traffic without any stops [11]. The model incorporates a user-defined grade based on a segment of the Coquihalla Highway [13] for this cycle. The corresponding elevation profile is illustrated in Fig. 1.

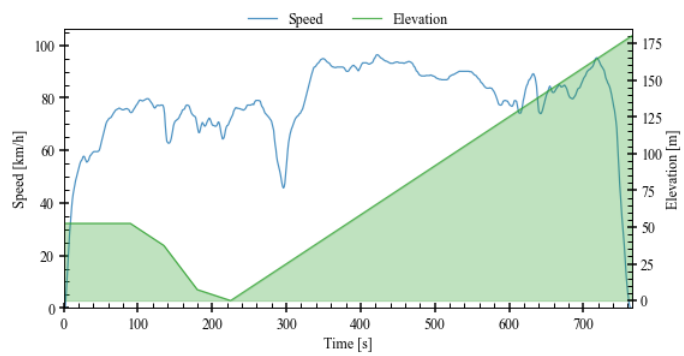

Figure. 1. *HWFET Drive Cycle with Elevation*

c) Real World Drive Cycle - SFU-EDC: This real-world drive cycle was created based on measurements obtained using the Teltonika FMC003 vehicle telematics device [12]. The device was installed in a light-duty vehicle, which was driven through urban settings with low and high speed sections. The journey began at Simon Fraser University's Surrey campus, starting in an urban environment, transitioning onto the high-speed section, stopping briefly at the SFU Burnaby campus on Burnaby Mountain, then descended back into an urban area before concluding its route in New Westminister, as shown in Fig. 2. This drive cycle features traffic stops with frequent braking along with stretches of free-flowing traffic and spanned a duration of one hour. The elevation data was also measured using the vehicle telematics device, and the grade was calculated accordingly. The corresponding road elevation of SFU-EDC drive cycle is shown in Fig. 3. This realistic drive cycle offers a practical framework for comparing the performance of PHEVs and BEVs under real-world conditions.

C. Drivetrain Modeling

1) BEV Modeling: The BEV model in GT-Suite has been customized to match the specifications in Table I. The battery is sized as per Table I , with internal resistance and open-circuit voltage maps guiding charging and discharging. State of Charge (SOC) is calculated based on power flow direction, indicating remaining capacity. A battery limiter manages power exchange with vehicle electronics, ensuring that power demands remain within limits. The traction motor uses efficiency maps to link input power with speed and torque, while static maximum braking torque is estimated based on similar vehicle studies [14]. The minimum and maximum braking

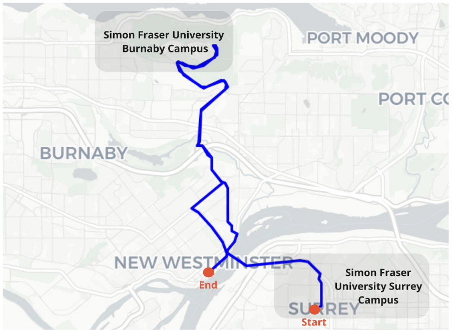

Figure. 2. *SFU-EDC - Surrey-Burnaby Route.*

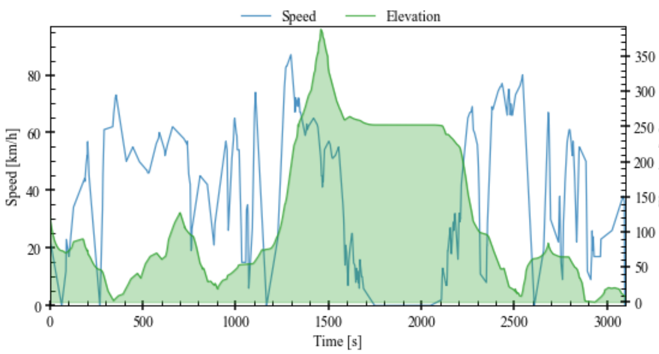

Figure. 3. *SFU-EDC Drive Cycle with Elevation.*

torque curves are defined from [15]. The DC-DC converter operates at 95% efficiency, and the driver mode targets speed using GT-Suite's default settings.

2) PHEV Modeling: The GT-Suite PHEV model was modified from the standard series hybrid model to match the specifications in Table I. While most current PHEVs, including the Kia Niro, use parallel or power-split configurations, for this work the series configuration is used to reduce control complexity. The traction motor and generator use map-based methods to relate input power to speed and torque with efficiency maps. Two controllers manage motor and generator operations based on control strategies. The static braking torque is estimated from similar vehicle data [14], with torque curves defined in [16]. Supervisory control includes four states based on SOC to manage ON/OFF status and the speed of the internal combustion engine (ICE) (Fig. 4). The engine remains OFF until the SOC drops below 32%, with hysteresis preventing frequent state changes. Unlike in modern PHEVs, the GT model uses regenerative braking only when the SOC is below 70%.

D. Life Cycle Emission Analysis

A life cycle analysis has been conducted to evaluate the emissions of the modeled PHEV and BEV using the GREET 2022 model as the assessment tool. The analysis considers electricity generation from the British Columbia electrical grid [17] and evaluate each vehicle's equivalent fuel economy performance based on GT-Suite data, using a distribution of

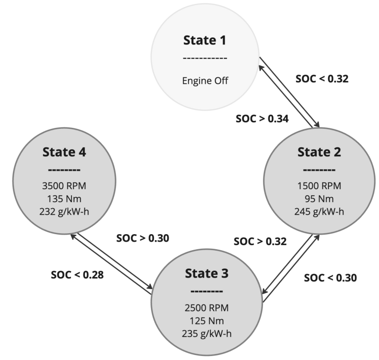

Figure. 4. *State Diagram of the Supervisory Control for the PHEV Model, Depicting Engine Speed, Brake Torque, and Brake-Specific Fuel Consumption (BSFC) for Each Operating Mode.*

30% highway and 70% urban driving conditions. The analysis assumes a consumption of energy of 50 kWh per kWh of capacity for battery production, with emissions accounting for material extraction, refining, and assembly. Each vehicle is modeled with a lifespan of 278,660 Km, including one battery replacement over its lifetime. For PHEV, the study considers a driving distribution of 70% EV mode and 30% mixed mode. In addition, all materials used for battery fabrication are sourced from virgin materials. Battery recycling and second-life applications are excluded, assuming end-of-life disposal emissions without material recovery benefits.

E. Case Studies

To enable performance comparisons, several numerical simulations are performed, covering the following case studies:

1) Case I: Initial battery SOC at 0.85.
2) Case II: Initial battery SOC at 0.5.
3) Case III: BEV with reduced battery capacity and weight.

III. Results

A. Case I: Initial Battery SOC Level at 0.85

For the BEV, the vehicle speed closely matches the target speed across all drive cycles, including urban, highway, and SFU-EDC. The SOC levels in all cases consistently remain above 0.75 throughout. The performance summary for SFU-EDC is illustrated in Fig.5.

For the PHEV, a similar pattern to the BEV is observed, with the vehicle speed profile closely matching the target speed in both urban and highway conditions. During these drive cycles, the ICE remains inactive since the battery SOC does not fall below the 0.32 threshold required to initiate charge-sustaining mode (0.52 in FTP-75 and 0.47 in HWFET). Consequently, when fully charged, a PHEV functions similarly to a BEV during short drive cycles. For the SFU-EDC drive cycle, deviations occur in the actual speed from the target speed during periods of rapid acceleration when the traction motor cannot fully meet the power demand due to grade, as shown in Fig. 6. This is a result of the simplified series-hybrid configuration used in the model. Approximately midway through the drive

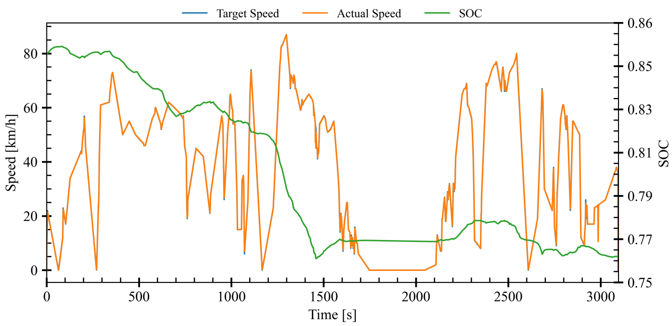

Figure. 5. *Case I - BEV Performance under SFU-EDC Drive Cycle*

cycle, the battery depletes below the 0.32 SOC threshold, prompting the ICE to activate to state 3 and provide the necessary power. However, due to the regenerative braking effect during downhill sections on the Burnaby Mountain, the battery recharges, raising its SOC above 0.34, temporarily turning off the engine. The ICE reactivates later as the SOC decreases again, cycling through various RPM stages based on the PHEV's supervisory control strategy and the level of battery depletion.

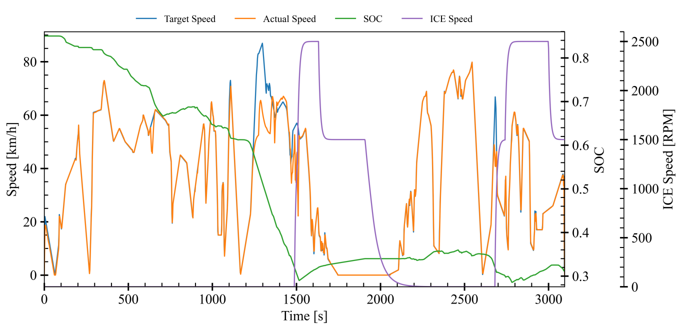

Figure. 6. *Case I - PHEV Performance under SFU-EDC Drive Cycle*

B. Case II: Initial Battery SOC Level at 0.5

When the BEV is simulated with an initial SOC of 0.5, the vehicle speed consistently follows the specified drive cycles for urban, highway and SFU-EDC driving conditions, with SOC levels remaining above 0.35 throughout.

When simulating a PHEV with an initial battery SOC of 0.5, the vehicle's speed closely aligns with the prescribed drive cycle, showing only minor deviations under SFU-EDC. In all scenarios, the ICE engages when the battery SOC drops below 0.32. As illustrated in Fig. 7, during the FTP-75 cycle the PHEV transitions from State 2 to State 4 within the charge-sustaining mode (Torque and RPM) due to battery depletion during sustained acceleration around 1200 seconds. In the SFU drive cycle, the ICE alternates between ON and OFF states depending on the terrain, which includes numerous uphill and downhill segments. As shown in Fig. 8, the ICE remains in State 4 for an extended period (1200 s to 2300 s) to assist with a prolonged climb, later recharging the battery to a target SOC of 0.34 when the PHEV is stationary or descending.

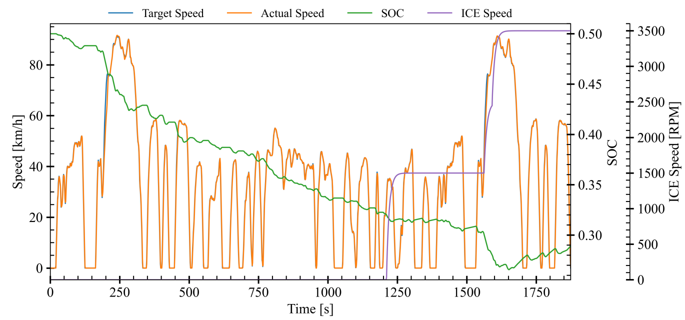

Figure. 7. *Case II - PHEV Performance under FTP-75 Cycle*

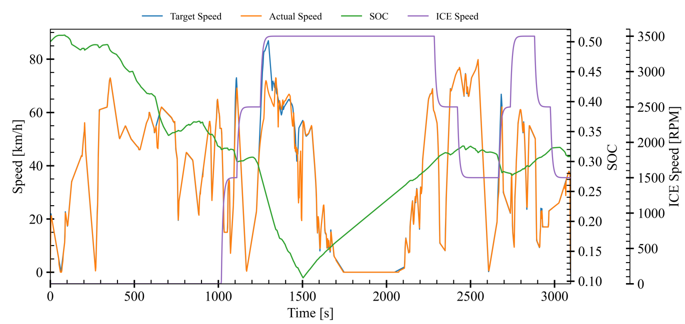

Figure. 8. *Case II - PHEV Performance under SFU-EDC Drive Cycle*

C. Case III: BEV with reduced Weight & Capacity

The BEV was simulated with a reduced weight of 1573 kg and a 111 Ah battery, using the Nissan Leaf's battery configuration as a reference [18]. Despite the smaller battery, the BEV showed minimal depletion over extended drive cycles and completed trips without recharging. A full charge allowed the BEV to complete 4 SFU EDC cycles without reaching critical battery levels compared to 6 cycles with the larger battery in Case I.

IV. Analysis

To ensure a fair comparison, the fuel economy of both drivetrains under specified drive cycles and road conditions is measured on the same scale of liters equivalent per 100 kilometers (Le/100km), as depicted in Fig. 9. The results highlight the superior efficiency of the modeled BEV compared to the PHEV. The BEV exhibits energy consumption ranging from 1.68 to 2.55 Le/100km, whereas the PHEV shows a broader and less efficient range of 2 to 7.96 Le/100km, depending on the drive cycle and the battery's initial state of charge (SOC). The consistently high efficiency of the BEV is attributed to the inherent advantages of electric motors, particularly in urban environments. In such settings, the BEV capitalizes on regenerative braking and optimal motor performance at lower speeds, further enhancing its energy efficiency. Additional improvements are observed when the BEV operates with reduced battery capacity and weight, as lower energy demand and minimized roundtrip losses during regenerative braking contribute to overall performance gains.

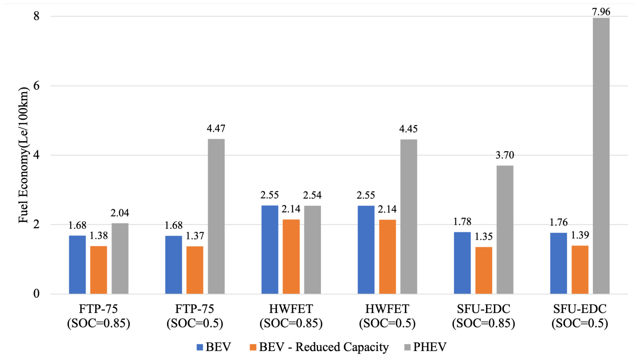

Figure. 9. *Fuel Economy Comparison – BEV vs PHEV*

In contrast, the fuel economy of PHEVs is highly dependent on their operating mode. In EV mode, the modeled PHEV achieves fuel economy comparable to the BEV, as demonstrated in Case I with an initial SOC of 0.85. However, during mixed-mode operation, the PHEV experiences significantly lower efficiency due to energy conversion losses inherent in series hybrid systems, where energy generated by the ICE must first be converted to electricity. While PHEVs perform reasonably well in steady-state, high-speed highway driving (2.54 - 4.45 Le/100km) due to the ICE's efficiency under such conditions, their performance declines substantially in more demanding cycles like the SFU-EDC. The BEV retains its performance in this scenario (SOC = 0.5), achieving consumption as low as 1.76 Le/100km. In contrast, the PHEV demonstrates poor fuel economy, reaching up to 7.96 Le/100 km, as rapid battery depletion at lower SOC forces greater reliance on ICE or combined modes. This effect is particularly pronounced in demanding drive cycles like SFU-EDC, which feature steep terrain that accelerates battery depletion. When SFU-EDC is run without grade with 0.5 SOC, the fuel economy improves significantly to 4.93 Le/100 km, highlighting the impact of elevation changes on economy. Furthermore, in mountainous terrain, the added weight of the battery and electric motor exacerbates fuel consumption, often negating the efficiency benefits of electrification. Under such conditions, PHEVs can occasionally perform worse than conventional ICE vehicles, underscoring their limitations in high-load, elevation-intensive environments. Overall, the modeled PHEV demonstrates 21% to 350% lower fuel economy compared to the BEV, with variations depending on the drive cycles, the terrain and the design of the vehicle.

When comparing the simulated fuel economy of the modeled PHEV and BEV with the manufacturer's figures for the KIA Niro (Table III), the BEV closely matches the reported values, while the PHEV shows notable deviations due to the different propulsion system configuration in the model,

TABLE. III
MANUFACTURER FUEL ECONOMY PERFORMANCE [8] - [9]

Fuel Economy	BEV	PHEV
Energy Consumption - City (Le/100km)	1.9	-
Energy Consumption - Highway (Le/100km)	2.3	-
Energy Consumption - Combined (Le/100km)	2.1	2.1

as the Niro employs either a parallel or a more advanced power-split configuration, which is anticipated to achieve significantly higher efficiency than a series hybrid, particularly on grades. While standardized drive cycles such as FTP-75 and HWFET include acceleration and deceleration patterns, they may not fully represent real-world driving conditions that involve prolonged stops, significant grade variability and mountainous terrain, as highlighted by the SFU-EDC drive cycle. Additionally, the reported PHEV fuel economy (2.1 Le/100km) assumes an operational scenario of 70% battery mode and 30% combined mode. In real-world conditions, this largely depends on driving style. As observed in Case II under SFU-EDC, low initial SOC leads to frequent mode switching and greater reliance on the ICE, ultimately reducing overall efficiency. Since specific details about the PHEV's supervisory control system were unavailable, the simulated results may not fully represent a modern PHEV. However, this highlights the need for more realistic benchmarks that account for diverse driving scenarios and better reflect the real-world performance of vehicles.

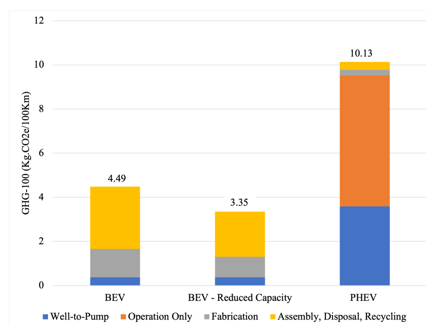

Figure. 10. *Life Cycle Emissions Comparison – BEV vs PHEV*

A life cycle emission analysis of the BEV and PHEV using the GREET model shows that the BEV's total emissions are half those of the PHEV (Fig.10). For BEVs, the majority of emissions arise from assembly, fabrication, recycling, and disposal, while the operational phase remains emission-free at the vehicle. However, BEV fabrication produces five times more emissions compared to PHEV, emphasizing the significant production-related lifecycle emissions. Reducing the BEV battery capacity decreases life cycle emissions by 34%, highlighting the impact of design optimization, though it also proportionally reduces the vehicle's range. In contrast, a substantial portion of PHEV emissions is linked to the operational phase, with PHEV exhibiting higher Well-to-Wheel emissions, primarily due to leakages and emissions during transmissions and manufacturing. The analysis also emphasizes the sensitivity of lifecycle emissions to the electricity mix. British Columbia's 99% clean energy mix results in minimal emissions, while regions with coal or natural gas-based electricity experience higher life cycle emissions. This study uses BC's average grid emissions (15.7 g.CO_2e/kWh), but in some cases marginal electricity production could play a role, as peak demand may be met by sources with variable emissions, influencing net use emissions.

From a cost perspective, the average annual travel distance for Canadians is estimated at 15,000 km [19], with 30% of driving on highways and 70% in urban settings. Under these conditions, a BEV owner can save approximately $370 per year compared to a PHEV owner, depending on fuel and electricity prices in BC, excluding maintenance costs. On more demanding drive cycles, such as SFU-EDC, annual savings increase to $1,750. However, it is important to consider that BEV battery replacements are significantly more expensive, which may offset some of these savings.

While this study focuses on vehicle performance, it highlights the need for a more comprehensive analysis across diverse drive cycles and terrains. The SFU-EDC cycle, with its steep elevation changes, is particularly demanding and may not reflect typical commutes, emphasizing the role of terrain in fuel economy. Expanding the study to include ICEVs and HEVs would offer a broader perspective on powertrain performance. Additionally, further research on charging infrastructure is essential to understanding its impact on BEV and PHEV practicality. Battery range remains a key factor, particularly in cold climates and high-speed driving, where usability may be affected. Exploring the relationship between battery range, range anxiety, and user experience could provide valuable insights into improving EV practicality and adoption. A deeper understanding of various drive cycle demands is also crucial for optimizing performance and efficiency.

V. Conclusion

In conclusion, this study highlights the advantages of the BEV attributed by excellent fuel economy and lower life cycle emissions. The GREET model shows that the modeled BEV produces nearly half the emissions of the modeled PHEV, with higher production emissions offset by significantly lower operational emissions. Optimizing battery size can further reduce the BEV's life cycle emissions by 34%, highlighting the potential for design improvements. Cost analysis indicates annual savings of $370 to $1,750 for BEV owners. While the modeled PHEV achieves comparable efficiency in EV mode, its fuel economy declines once the battery depletes, relying on an internal combustion engine having lower efficiency, with the series hybrid configuration further contributing to this drop. This effect is particularly evident in demanding drive cycles, where increased ICE usage further increases fuel economy. Although the SFU-EDC cycle may not reflect typical commuting patterns, it emphasizes the limitations of standard certification cycles in capturing real-world driving conditions. A more comprehensive study covering diverse driving conditions would make these findings more universally applicable. Overall, this study reinforces the environmental and economic advantages of electrified vehicles while underscoring the importance of drive cycle considerations in performance assessments.

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