Monitoring of High-Voltage Components of Hybrid Electric Vehicle Using OBD Diagnostics Device in Several Modes and Road Conditions

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ABSTRACT

This paper presents hybrid electric vehicles (HEVs) utilize both high-voltage battery system and internal combustion engine to reduce fuel consumption and hazardous emissions. However, the operational performance of high-voltage powertrain components varies considerably with driving modes and road profiles, necessitating real-time monitoring to evaluate their system behavior under dynamic operating conditions. This study evaluates motor torque, motor-generator rotational speed (RPM), inverter temperature, battery temperature, and state of charge (SoC) across Eco and Sport modes on flat, uphill, and downhill roads. Real-time telemetry was acquired using a Launch X431 Pro diagnostic scan tool connected to the OBD-II interface of a Toyota Prius Gen 3 under controlled driving trials. The experimental results show that on flat roads, Eco mode yields steady energy consumption, with an SoC reduction of 2% to 4% and minimal thermal fluctuations, whereas Sport mode incurs higher torque demand, approximately 2.5 times higher and an accelerated battery discharge rate, an SoC reduction between 5% and 8%. During uphill ascent, increased mechanical loads elevate energy consumption SoC decreases by approximately 6% to 10% in Eco mode and 10% to 15% in Sport mode. Moreover, higher thermal stress on the inverter, energy consumption increases by 30% to 50% in Sport mode. On downhill descents, regenerative braking recovers kinetic energy, restricting SoC variation between 0% and 2%, plus stabilizing component temperatures.

Keywords: Hybrid electric vehicle, motor generator, inverter, high-voltage battery, real-time monitoring, OBD-II diagnostics

INTRODUCTION

The persistent growth in global fuel consumption and increasingly stringent emission regulations have accelerated the adoption of energy-efficient vehicle powertrains, particularly hybrid electric vehicles (HEVs) [1]. HEVs combine an internal combustion engine (ICE) with an electric motor to lower fuel consumption and tailpipe emissions while maintaining acceptable dynamic vehicle performance [2, 3]. Because an HEV coordinates distinct power sources and selectable operating modes, overall powertrain efficiency depends fundamentally on how energy is dispatched and managed under real-world driving environments [4].

The physical operation of an HEV powertrain is inherently complex because dynamic power splits must be continuously negotiated among the high-voltage (HV) battery, power inverter, and electric motor-generators across diverse driving conditions [5, 6]. Variations in user-selected driving modes, vehicle speed profiles, and road gradients significantly influence motor torque demands, high-voltage battery state of charge (SoC), and thermal behaviour [7, 8]. Ineffective tracking or poor thermal and energy management of these components can degrade system efficiency and shorten component service life. Consequently, accurate real-time monitoring of high-voltage component states under transient loading is critical for optimizing hybrid control strategies and evaluating vehicle durability.

On-board diagnostics (OBD) technology provides an accessible, non-invasive method for tracking powertrain performance and detecting operational faults [9]. Contemporary OBD-II communication networks allow live parameter streaming of internal variables, including motor rotational speeds, torque outputs, battery pack temperatures, inverter module temperatures, and battery SoC [10, 11]. Prior investigations have validated that OBD-based monitoring can effectively evaluate in-use energy consumption, thermal management performance, and powertrain operating characteristics under real-world driving conditions [12, 13]. Hence, OBD-II telemetry presents a reliable, cost-effective framework for characterizing the operational profiles of high-voltage components in HEVs.

RESEARCH METHODOLOGY

Vehicle Selection and Diagnostic Setup

A third-generation Toyota Prius was selected for this study due to its established series-parallel (power-split) hybrid architecture and recognized fuel efficiency. The powertrain integrates an internal combustion engine with two high-voltage alternating current (AC) synchronous machines, which are the Motor-Generator 1 (MG1) and Motor-Generator 2 (MG2). This configuration enables comprehensive logging of high-voltage battery SoC, inverter temperatures, motor torques, rotational speeds (RPM), and traction battery pack temperatures.

Real-time parameter extraction was performed using a Launch X431 Pro diagnostic scan tool connected directly to the vehicle's standard SAE J1962 OBD-II data link connector. The device provides high-frequency data logging and parameter interrogation directly from the hybrid vehicle control electronic control unit (ECU), providing a robust empirical record for dynamic analysis.

Monitored Parameters

The diagnostic routine captured high-voltage powertrain operational metrics at three times sampling intervals:

a) High-voltage battery state of charge (SoC, %)

b) Rotational speeds of MG1 and MG2 (rpm)

c) Output torques of MG1 and MG2 (Nm)

d) Inverter module temperatures for MG1 and MG2 (°C)

e) High-voltage battery pack temperature (°C)

Driving Modes, Road Profiles, and Speed Variations

To analyse powertrain responsiveness and energy distribution, testing was performed under two selectable driving programs: Eco mode and Sport mode. Eco mode alters throttle mapping to prioritize fuel economy and smooth power transitions, whereas Sport mode sharpens throttle sensitivity to maximize combined torque delivery.

Powertrain performance was evaluated across three distinct topographical road conditions: flat, uphill with approximately +5% road gradient, and downhill, about -5% road gradient. Within each driving mode and topographic condition, controlled acceleration and deceleration cycles were executed across five target speed benchmarks: 20 km/h, 30 km/h, 40 km/h, 50 km/h, and 60 km/h. These discrete speed variations simulate urban and sub-urban operating cycles, allowing systematic comparison of electrical loads and regenerative dynamics.

Test Route and Experimental Protocol

Testing was performed on straight test section to ensure operational consistency. Flat-road trials were conducted on level roadway with negligible road grade. Inclined driving trials were carried out along

continuous uphill and downhill grades to isolate gravitational resistance and regenerative braking effects. All test runs took place under dry pavement and clear weather conditions with recorded temperature between 30 to 35 degree Celsius and humidity about 80 to 85%, to prevent traction anomalies or ambient variations from confounding the telemetry data.

RESULTS

Flat Road Conditions: High Voltage Battery, State of Charge

Figure 1 show the HV SoC changes in Eco driving modes on flat road in acceleration. During acceleration along flat roadway in Eco mode, the high-voltage battery SoC decreased steadily and moderately across all test speeds. Across baseline trials, initial SoC values ranged between 41% and 46%. As vehicle speed advanced toward each target increment, the recorded SoC displayed a gradual, linear decline. This stable profile demonstrates the conservative energy-release logic executed by the hybrid control unit in Eco mode. An initial low-speed tractive force from MG2 is strictly regulated, followed by an early blending of internal combustion power to preserve battery reserves and mitigate thermal stress.

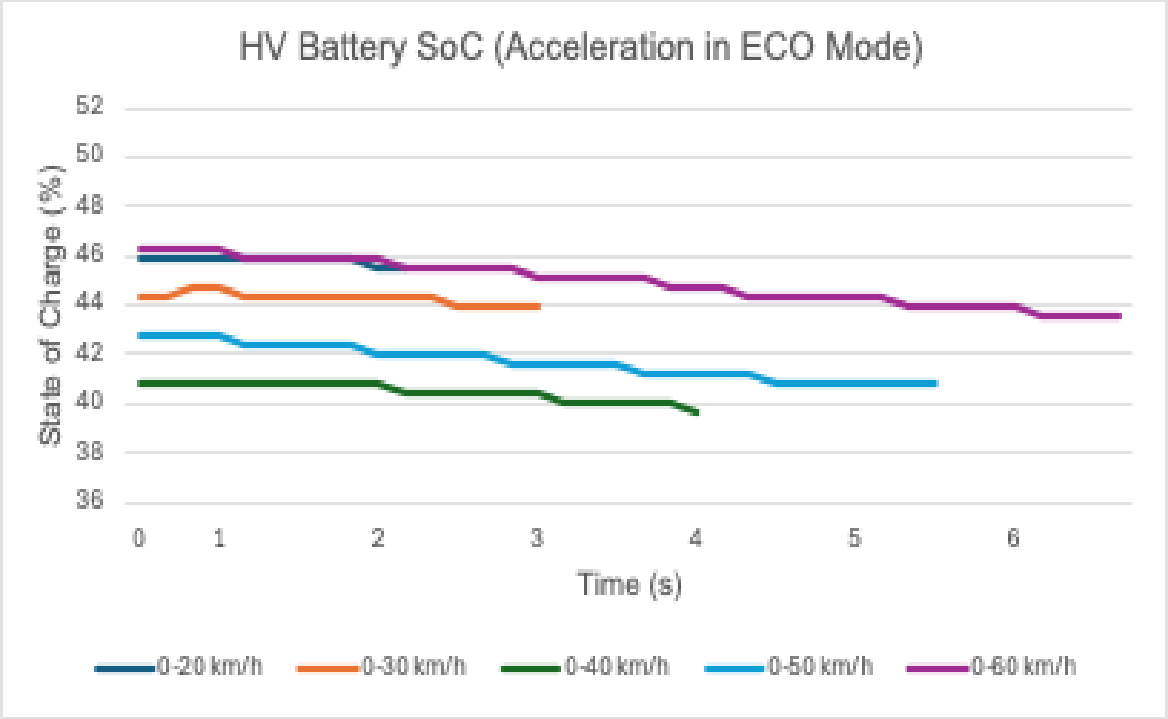


Figure 1. HV Battery SoC During Acceleration in Eco Mode on Flat Road

Uphill Road Conditions: Battery Depletion and Motor Speeds

Figure 2 show the HV SoC changes in Sport driving modes on uphill road in acceleration. When accelerating on an uphill gradient in Sport mode, the battery SoC exhibited rapid depletion across all target speeds. Over the course of the hill climb, the battery SoC dropped sharply from initial values between 41% and 50%. This pronounced discharge rate represents the most severe electrical loading measured in this study, caused by the simultaneous demand for maximum mechanical torque to overcome gravitational resistance and the aggressive throttle mapping of Sport mode.

Concurrently, MG1 and MG2 rotational speeds rose sharply under uphill acceleration in Sport mode as shown in Figure 3. MG2 operated consistently in the 3,500 to 4,500 RPM range to supply continuous tractive effort to the drive wheels. Concurrently, MG1 accelerated rapidly to manage power-split planetary gearing and balance generator loading. This response highlights the ability of the power-split transaxle to provide responsive torque multiplication under high mechanical load, albeit at the cost of higher battery discharge and increased inverter heat generation.

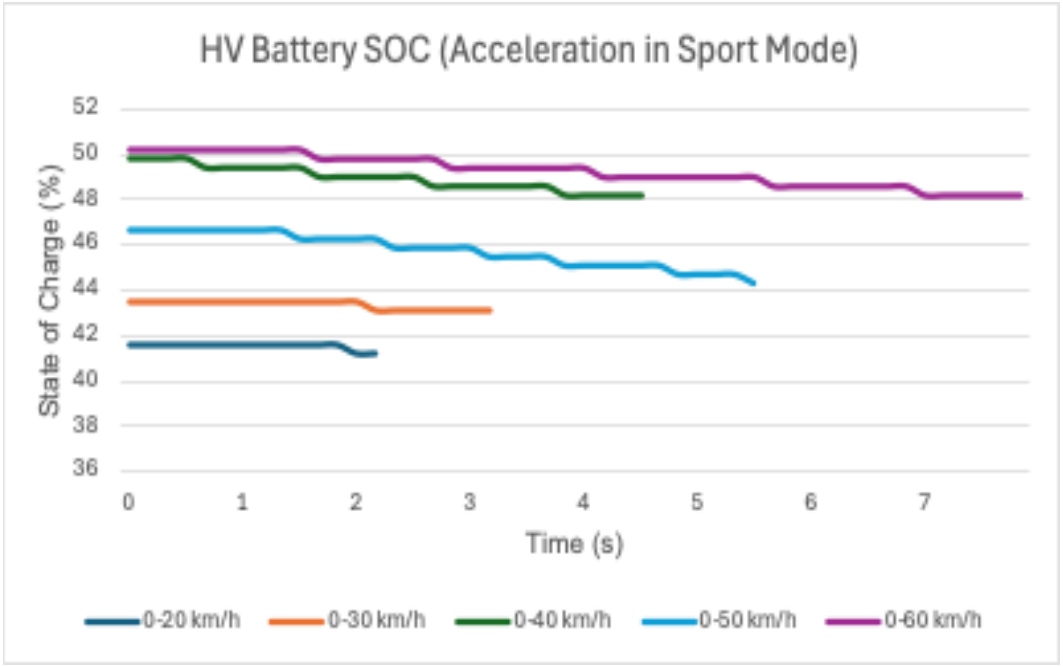


Figure 2. HV Battery SoC During Acceleration in Sport Mode on Uphill Road

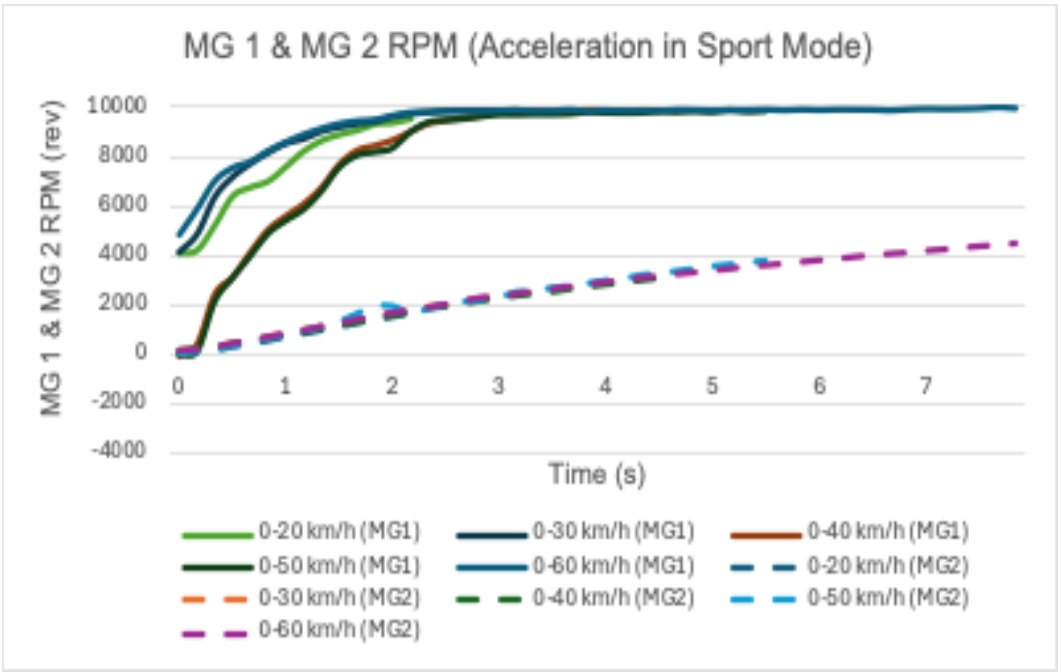


Figure 3. MG1 and MG2 (rpm) During Acceleration in Sport Mode on Uphill Road

Downhill Road Conditions: Regenerative Braking and Torque Split

Figure 4 compares the torque response of the MG1 and MG2 in Eco driving modes on downhill road in deceleration. During downhill deceleration in Eco mode, MG2 produced sustained negative torque to harvest kinetic energy and feed charge back into the high-voltage battery via regenerative braking. Concurrently, MG1 maintained minor torque adjustments to stabilize engine braking speed and balance transaxle torque distribution. This coordinated torque management provided predictable vehicle deceleration while maintaining battery SoC stability within an optimal range of 0% to 2% variation window, preventing over-temperature conditions in the high-voltage pack.

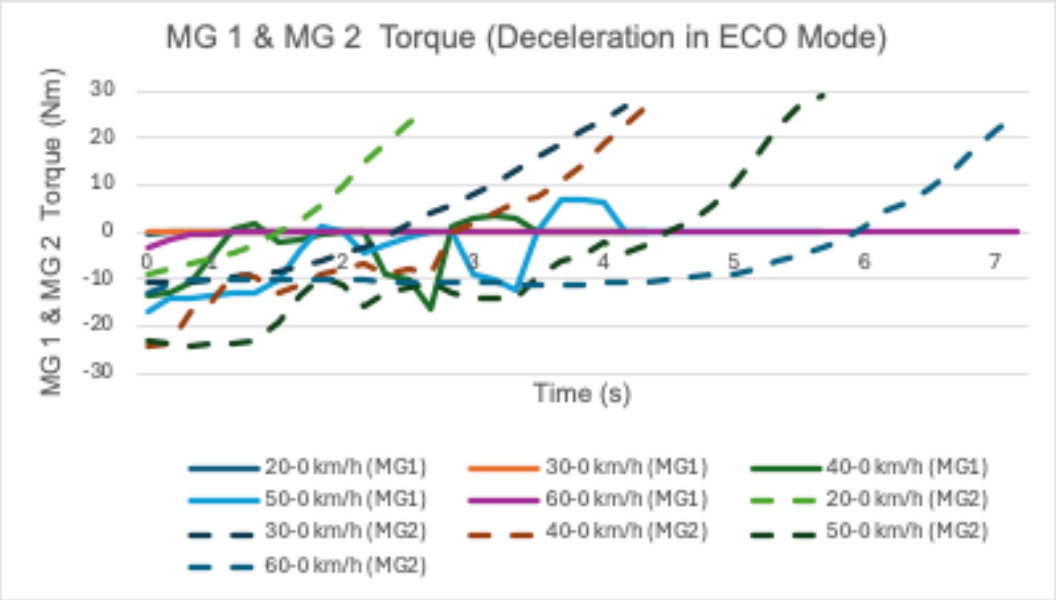


Figure 4. MG1 and MG2 Torque During Deceleration in Eco Mode on Downhill Road

Uphill Road Conditions: Inverter and HV Battery Temperature

Figure 5 shows the temperature response of key inverter components in Sport mode on uphill road in acceleration. The inverter temperature rises more rapidly due to the steep incline and performance-oriented settings. In this situation, the inverter temperature typically reaches 85°C to 95°C. This temperature rise reflects the high electrical stress resulting from the combined demands of steep road inclines and strong acceleration. Despite the heavy load, the inverter temperature tends to stabilize once the engine provides most of the drive torque.

When accelerating uphill in Sport mode, the battery temperature rises noticeably as shown in Figure 6. Depending on the vehicle speed, the temperature typically fluctuates between 35.5°C and 39°C. Despite the temperature increase, it remains within a safe range. As the engine assumes a greater driving load, the battery temperature quickly stabilizes. Overall, this performance demonstrates excellent thermal management capabilities, even under high power demand.

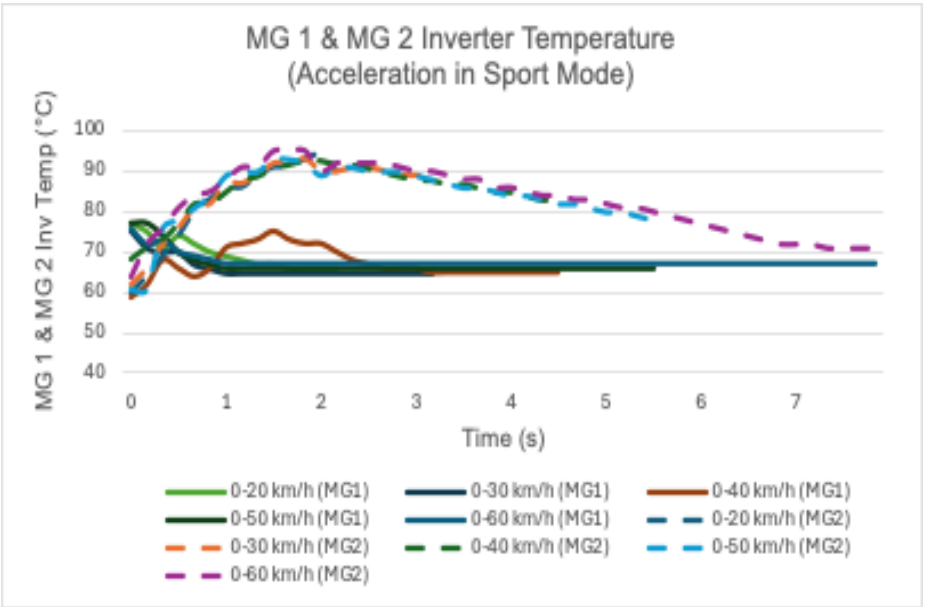


Figure 5. MG1 and MG2 Inverter Temperature During Acceleration in Sport Mode on Uphill

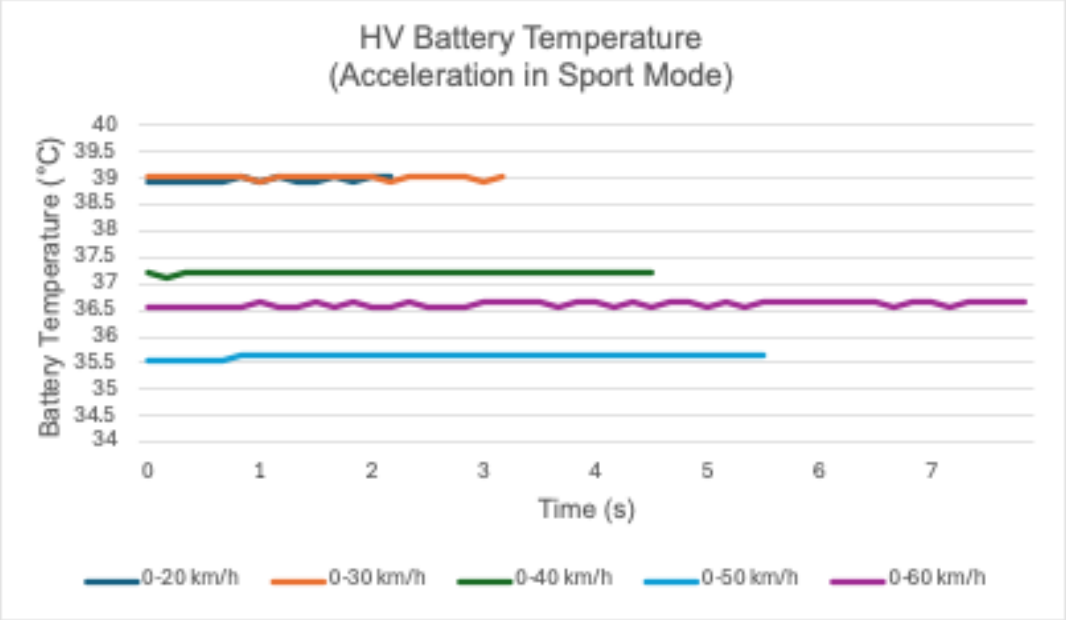


Figure 6. HV Battery Temperature During Acceleration in Sport Mode on Uphill Road

DISCUSSION

The observed trends confirm that operating modes and topographic profiles heavily govern hybrid powertrain loading. Eco mode enforces disciplined energy management across all elevations, keeping electrical discharge rates low, smoothing torque transitions, and minimizing thermal buildup in both the inverter and battery cells. Conversely, Sport mode mobilizes combined battery and engine reserves to deliver peak mechanical power, resulting in higher electrical current draw and elevated component temperatures. Importantly, even during demanding uphill hill climbs in Sport mode, component temperatures remained safely within OEM thermal safety thresholds.

These findings establish that live telemetry obtained via an OBD-II diagnostic tool (such as the Launch X431 Pro) offers an accurate, cost-effective method for quantifying high-voltage component behaviour under actual road loading. This non-intrusive diagnostic workflow provides actionable data for hybrid vehicle state-of-health assessments, control strategy calibration, and fleet maintenance diagnostics.

CONCLUSIONS

This study experimentally investigated the operational behaviour of high-voltage components in a third-generation Toyota Prius under Eco and Sport driving modes across flat, uphill, and downhill road conditions. Using a Launch X431 Pro OBD-II diagnostic tool, the study monitored motor-generator torque, rotational speeds, inverter temperatures, high-voltage battery temperature, and battery SoC.

The results demonstrated that driving mode and road gradient significantly influenced the electrical loading and thermal behaviour of the hybrid powertrain. During flat-road acceleration, Eco mode exhibited a relatively stable battery SoC profile and moderate energy demand, whereas Sport mode resulted in higher torque demand and faster battery depletion. During uphill driving, the increased mechanical load led to greater battery discharge and elevated inverter and battery temperatures, particularly in Sport mode. In contrast, downhill deceleration enabled regenerative braking, allowing MG2 to recover kinetic energy and maintain relatively stable battery SoC. The findings highlight the relationship between driving conditions, powertrain energy management, and the operational behaviour of high-voltage components. OBD-II telemetry provided a practical, non-invasive means of observing ECU-reported parameters under real-world driving conditions. However, the findings are specific to the tested vehicle and experimental conditions, and independent measurement validation was not conducted.

Future research should incorporate repeated driving cycles, additional hybrid vehicle models, and independent measurement validation to improve the reproducibility and generalizability of the findings. Further investigation using longitudinal data and advanced analytical methods could also support the development of more reliable diagnostic and predictive maintenance strategies for hybrid electric vehicles.

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