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Data-Driven Identification of Combustion Operating Regimes and Fuel Consumption Sensitivity in Gasoline Plug-In Hybrid Electric Vehicles Under Real-Driving Conditions

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Abstract

Plug-in hybrid electric vehicles (PHEVs) combine an internal combustion engine with an electric propulsion system, creating highly variable engine operating conditions that differ substantially from those of conventional gasoline vehicles. The frequent transitions between engine-off, engine-on, electric-assisted, charge-sustaining, and transient operating states make the identification of combustion-related operating regimes particularly important for understanding real-world fuel consumption. This study develops a data-driven framework for identifying distinct combustion operating regimes and quantifying the sensitivity of fuel consumption to vehicle operating conditions in gasoline PHEVs under real-driving conditions. The proposed framework integrates time-resolved vehicle operating parameters, including vehicle speed, acceleration, engine operating state, battery state of charge, engine restart events, propulsion mode, and fuel consumption, to characterize the relationship between driving dynamics and engine fuel demand. Operating data are classified into physically meaningful regimes according to the combined behavior of engine activation, vehicle demand, and battery state. Statistical sensitivity analysis is subsequently applied to quantify the contribution of individual operating variables and their interactions to variations in fuel consumption. Particular attention is given to transient engine operation and repeated engine activation, which can produce operating conditions substantially different from steady-state engine behavior. The analysis is structured to distinguish the effects associated with electric-energy availability from those directly related to gasoline engine operation. This approach enables the identification of operating regions in which fuel consumption becomes particularly sensitive to changes in vehicle speed, acceleration, battery state of charge, and engine utilization. The resulting framework provides a quantitative basis for interpreting real-world fuel-consumption variability in gasoline PHEVs and for identifying combustion operating conditions that are associated with inefficient fuel utilization. The study also establishes a reproducible analytical pathway for transforming real-world vehicle measurements into combustion-oriented operating regimes, thereby supporting more precise assessment of PHEV energy performance and providing a methodological basis for future optimization of engine operating strategies and powertrain control.

Keywords: Plug-in hybrid electric vehicle; Gasoline engine; Combustion operating regimes; Real-world driving; Fuel consumption sensitivity

1- Introduction

The increasing electrification of road transportation has positioned plug-in hybrid electric vehicles (PHEVs) as an important intermediate powertrain between conventional internal combustion engine vehicles and fully battery-electric vehicles. Unlike conventional gasoline vehicles, PHEVs can alternate between electric propulsion, engine-assisted operation, charge-depleting operation, and charge-sustaining operation. Consequently, the gasoline engine does not operate continuously under a relatively predictable load profile. Instead, its operation is strongly influenced by battery state of charge (SOC), instantaneous power demand, vehicle speed, acceleration, propulsion strategy, and the conditions under which the engine is activated. This operating variability creates a distinctive combustion environment that cannot be adequately characterized using conventional steady-state fuel-consumption approaches [1,2].

Real-world investigations have demonstrated substantial differences between the nominal and in-use performance of PHEVs. Plötz et al. reported considerable variability in real-world fuel consumption and CO2 emissions depending on vehicle use and charging behavior, highlighting the importance of considering actual operating conditions rather than relying exclusively on standardized certification results [2]. Similarly, experimental road testing has shown that energy consumption and emissions can vary substantially between charge-depleting and charge-sustaining operation. Wang et al. demonstrated that propulsion mode can alter both energy demand and pollutant formation, while frequent engine activation under specific operating conditions can produce unfavorable emission characteristics [3]. These observations indicate that the electrical and combustion subsystems of a PHEV should not be considered independently when evaluating fuel consumption under real driving.

Engine activation represents a particularly important transition in PHEV operation. Karanam and Tal showed that engine-start events are associated with different combinations of battery SOC, vehicle power demand, vehicle characteristics, and operating conditions. Their analysis of multiple PHEV models demonstrated that the factors triggering engine activation are not uniform across vehicle architectures and battery capacities [1]. Consequently, the occurrence of an engine-on event should be considered a distinct operating regime rather than simply a binary transition between electric and gasoline propulsion.

Further evidence indicates that the relationship between real-world PHEV operation and fuel consumption is multidimensional. Tansini et al. demonstrated that real-world CO2 emissions and energy consumption depend strongly on charge level and trip characteristics, and proposed a model incorporating battery charge level together with average trip speed or wheel energy [4]. This finding is particularly relevant to combustion-oriented analysis because the same vehicle speed can correspond to substantially different engine fuel requirements depending on the available electrical energy and operating mode.

Despite these advances, a methodological gap remains in the identification of combustion operating regimes from real-world PHEV measurements. Existing studies have primarily emphasized overall fuel consumption, CO2 emissions, propulsion-mode comparison, or the frequency of engine starts. Less attention has been directed toward systematically separating real-world operation into physically interpretable combustion regimes and subsequently determining the sensitivity of fuel consumption to the variables defining those regimes.

The present study addresses this gap by developing a data-driven framework for identifying combustion operating regimes in gasoline PHEVs under real-driving conditions. The analysis combines vehicle operating parameters, engine activation states, battery SOC, propulsion mode, and driving dynamics to distinguish characteristic operating regions. Fuel-consumption sensitivity is then evaluated across these regions to determine how changes in operating conditions influence gasoline demand. The proposed approach therefore moves beyond a simple comparison of average fuel consumption and seeks to establish a quantitative relationship between real-world driving conditions, engine utilization, and fuel-consumption variability.

The main contribution of this study is the integration of combustion-oriented regime identification with sensitivity analysis using real-world PHEV operating data. By focusing on the interaction between engine activation, electrical energy availability, and driving demand, the framework provides a more detailed interpretation of fuel consumption than aggregate trip-level indicators alone. This approach can support the development of improved engine operating strategies and provide a quantitative basis for evaluating fuel-use behavior in gasoline PHEVs under diverse real-world driving conditions

2- Problem Statement

The operational behavior of gasoline engines in plug-in hybrid electric vehicles differs fundamentally from that of engines in conventional gasoline-powered vehicles. In a PHEV, engine operation is determined not only by the instantaneous mechanical demand of the vehicle but also by battery state of charge, electric propulsion availability, control-system decisions, and the transition between electric and combustion-based propulsion. As a result, the same driving speed or acceleration level can be associated with substantially different fuel requirements depending on the operating state of the powertrain.

One of the principal difficulties in analyzing this behavior is the highly transient nature of engine operation. Engine activation may occur after a period of electric driving, during acceleration, under increased power demand, or when the battery reaches a control-defined operating threshold. Such transitions can produce combustion conditions that differ considerably from those occurring during continuous engine operation. Real-world measurements have demonstrated that cold-start events and road characteristics can significantly influence fuel consumption and emissions, while the magnitude of these effects varies according to vehicle technology and operating conditions [5]. Experimental investigations of gasoline PHEVs have likewise shown considerable variability in emissions under different operating modes and initial battery conditions [6].

Another challenge concerns the representation of transient combustion behavior within data-driven models. Existing predictive approaches have demonstrated that real vehicle measurements can be used to model cold-start emissions and that nonlinear relationships between operating variables and emissions can be captured using machine-learning techniques [7]. However, prediction of a specific emission variable does not by itself identify the physical operating regimes responsible for changes in gasoline consumption. A model may achieve an acceptable prediction accuracy while providing limited information about when and why the engine enters a high-fuel-demand operating condition.

This limitation becomes particularly important for PHEVs because aggregate fuel-consumption values can conceal substantial differences between individual operating states. A trip-level average may combine electric-only operation, engine start events, transient acceleration, engine-assisted propulsion, and charge-sustaining operation into a single value. Such aggregation reduces the ability to determine which operating conditions are most strongly associated with increased gasoline consumption.

Therefore, the central research problem is the lack of a unified data-driven procedure capable of transforming real-world PHEV operating measurements into physically interpretable combustion regimes and quantifying the sensitivity of fuel consumption to the variables defining those regimes. Addressing this problem requires simultaneous consideration of engine activation, vehicle dynamics, battery SOC, propulsion mode, and transient operating conditions rather than treating fuel consumption as an isolated trip-level outcome.

The present study addresses this methodological gap by establishing a regime-based analytical framework in which real-world operating observations are classified according to their combined combustion and powertrain characteristics. The resulting regimes are subsequently evaluated in terms of fuel-consumption sensitivity. This formulation makes it possible to distinguish operating conditions with relatively stable fuel demand from those in which small changes in driving or electrical conditions are associated with substantially different gasoline requirements. The resulting analysis provides a more detailed representation of the relationship between real-world driving behavior and gasoline-engine utilization in PHEVs.

3- Research Methodology

3.1. Research Design

This study employs a data-driven analytical methodology to identify combustion operating regimes and quantify fuel-consumption sensitivity in gasoline plug-in hybrid electric vehicles under real-driving conditions. The methodological framework is designed to capture the interaction between vehicle dynamics, engine activation, battery state, propulsion mode, and gasoline consumption rather than treating fuel consumption as an isolated aggregate measure.

The analysis follows five principal stages: data acquisition and harmonization, preprocessing and quality control, identification of combustion operating regimes, sensitivity analysis, and comparative interpretation of the identified regimes. The overall structure is intended to transform time-resolved vehicle measurements into physically interpretable operating categories that can subsequently be evaluated according to their influence on gasoline demand.

The analytical framework incorporates variables representing both the mechanical and electrical domains of the PHEV powertrain. Vehicle speed and acceleration describe the instantaneous driving demand, whereas engine operating state and propulsion mode characterize the contribution of the combustion engine. Battery state of charge represents the availability of electrical energy and provides an essential variable for distinguishing operating conditions that may otherwise appear similar from the perspective of vehicle speed alone.

A further methodological consideration is the treatment of engine-start events. Rather than incorporating engine activation only as a binary explanatory variable, engine-start events are considered transition points between distinct operating states. This allows the analysis to differentiate continuous engine operation from transient engine activation following electric-only driving.

3.2. Real-World Data Structure

The empirical framework is based on real-world vehicle measurements reported in peer-reviewed experimental studies and datasets associated with PHEV operation. The selected observations represent driving conditions in which vehicle dynamics, propulsion mode, engine operation, battery state, and fuel or energy consumption can be associated within a common analytical framework.

The data structure is organized at the observation level, with each observation representing a defined time interval or operating event. The principal variables considered in the analytical framework are vehicle speed, longitudinal acceleration, engine operating state, battery SOC, propulsion mode, engine-start status, and fuel consumption. Where available, environmental and road-related variables are retained as additional explanatory parameters.

This approach is consistent with recent real-world PHEV investigations demonstrating that vehicle-specific operating variables can be used to characterize energy consumption and emissions under diverse driving conditions [8,9]. Large-scale empirical studies have additionally shown that real-world PHEV fuel economy is affected by vehicle characteristics, usage patterns, electric driving capability, and charging-related factors [10].

3.3. Data Preprocessing and Quality Control

Before regime identification, the observations are subjected to a structured preprocessing procedure. First, variables are converted to consistent physical units. Time-series observations are then synchronized to ensure that vehicle dynamics, engine state, battery SOC, and fuel-consumption measurements correspond to the same operating interval.

Incomplete observations are excluded when the missing information prevents determination of the corresponding operating state. Short-duration measurement interruptions are distinguished from sustained missing intervals to prevent the unnecessary removal of valid operating information.

Vehicle speed is used to characterize driving intensity, while acceleration is calculated from the temporal variation in vehicle speed:

$$a(t) = [v(t) - v(t-\Delta t)] / \Delta t$$

where $a(t)$ represents longitudinal acceleration, $v(t)$ represents vehicle speed, and Δt represents the measurement interval.

The resulting acceleration variable is subsequently combined with vehicle speed to characterize the instantaneous driving demand. To reduce the influence of isolated measurement noise, physically implausible observations are identified through predefined consistency criteria and excluded from subsequent analysis.

3.4. Engine Operating State Classification

The combustion engine is classified according to its operational state. The primary distinction is made between engine-off and engine-on conditions. Engine-on observations are subsequently separated according to the surrounding operating context, including engine activation following electric operation, continuous engine-assisted propulsion, and charge-sustaining operation.

Engine-start events are identified when a transition from an engine-off state to an engine-on state occurs. The duration between consecutive engine-start events is retained as an additional indicator of engine cycling. This parameter is particularly relevant because frequent engine activation can generate operating conditions that differ from those associated with continuous engine operation.

The classification procedure is designed to prevent the loss of transient information through excessive temporal aggregation. Instead of assigning each trip to a single propulsion category, individual observations are classified according to their instantaneous operating state.

3.5. Vehicle-Specific Power Representation

Vehicle-specific power is introduced as a representation of instantaneous driving demand. Conventional VSP formulations relate vehicle speed and acceleration to the power required to maintain or change vehicle motion. However, for hybrid vehicles, a representation based exclusively on external driving variables may not adequately describe the actual operating state of the combustion engine.

Wang et al. demonstrated that VSP formulations based on internally observable vehicle variables can provide a stronger relationship with CO_2 emissions for hybrid-electric vehicles than conventional formulations [8]. Accordingly, the present framework considers VSP as a complementary variable for describing the mechanical demand imposed on the vehicle.

A generalized VSP formulation can be expressed as:

$$VSP = v[a + g \sin(\theta) + C_{rr}\, g \cos(\theta) + 0.5\rho C_d A\, v^2/m]$$

where v is vehicle speed, a is longitudinal acceleration, g is gravitational acceleration, θ is road grade, Crr is rolling-resistance coefficient, ρ is air density, Cd is aerodynamic drag coefficient, A is frontal area, and m is vehicle mass.

For a road segment with negligible grade, the formulation can be simplified to:

$$VSP = v[a + C_{rr}\, g + 0.5\rho C_d A\, v^2/m]$$

VSP is not treated as a direct measurement of engine combustion power. Instead, it is used to characterize the mechanical demand associated with the observed driving condition. Its interpretation is therefore combined with engine state and battery SOC.

3.6. Identification of Combustion Operating Regimes

The central analytical step is the identification of distinct combustion operating regimes. Rather than defining regimes using vehicle speed alone, the classification incorporates multiple dimensions of PHEV operation.

The principal regime-defining variables are:

- vehicle speed;
- longitudinal acceleration;
- VSP;
- engine operating state;
- battery SOC;
- propulsion mode;
- engine-start status;
- fuel consumption.

The resulting observations are grouped into physically interpretable regimes representing combinations of driving demand and powertrain state. The classification is designed to distinguish, for example, low-demand engine operation, transient high-demand operation, engine activation following electric operation, and charge-sustaining engine operation.

A multivariate clustering procedure can be applied to normalized variables to reduce the influence of differences in measurement scale. For an observation vector X_i, normalization can be expressed as:

$$Z_{ij} = (X_{ij} - \mu_j) / \sigma_j$$

where X_{ij} is the value of variable j for observation i, μ_j is the mean of variable j, and σ_j is its standard deviation.

The number of operating regimes is determined using internal cluster-validation criteria together with physical interpretability. Statistical separation alone is not considered sufficient; each identified cluster must correspond to a meaningful combination of engine and vehicle operating characteristics.

3.7. Fuel-Consumption Sensitivity Analysis

After identifying the operating regimes, fuel-consumption sensitivity is quantified to determine how changes in operating variables affect gasoline demand. The analysis considers both individual variables and interactions between variables.

A normalized sensitivity coefficient can be expressed as:

$$S_j = (\partial F/F) / (\partial X_j/X_j)$$

where F represents fuel consumption and X_j represents the j-th explanatory variable.

For variables for which a direct derivative is not appropriate, standardized regression coefficients are used to compare relative influence. The sensitivity analysis therefore provides a common basis for comparing variables measured on different physical scales.

Particular attention is given to the interaction between battery SOC and vehicle demand. Two observations with similar vehicle speed and acceleration may require substantially different gasoline consumption if their battery states and propulsion modes differ. This interaction is therefore evaluated explicitly rather than assuming independent effects.

3.8. Statistical Evaluation

The identified regimes are compared using descriptive statistics and distributional analysis. For each regime, the central tendency, dispersion, and range of fuel consumption are calculated together with the corresponding vehicle and powertrain variables.

The analysis considers:

- mean fuel consumption;
- median fuel consumption;
- standard deviation;
- coefficient of variation;
- mean vehicle speed;
- mean acceleration;
- mean VSP;
- mean battery SOC;
- engine operating duration;
- engine-start frequency.

The coefficient of variation is calculated as:

$$CV = \sigma F / \mu F \times 100$$

where σF is the standard deviation of fuel consumption and μF is its mean value.

This measure allows the variability of fuel consumption to be compared between regimes despite differences in their absolute fuel-consumption levels.

3.9. Robustness and Interpretation

The robustness of the regime identification is evaluated by examining whether the principal characteristics of each regime remain distinguishable under alternative normalization and classification conditions. The objective is not merely to maximize statistical separation but to obtain operating regimes that remain physically meaningful.

The interpretation subsequently focuses on the relationship between combustion-engine utilization and gasoline demand. In particular, regimes characterized by frequent engine activation, elevated VSP, high acceleration, or limited battery availability are examined for their association with increased fuel demand.

This methodological structure combines the strengths of real-world empirical analysis, vehicle-specific power characterization, and data-driven classification. It also avoids reducing PHEV performance to a single average fuel-consumption value, thereby allowing transient and mode-dependent combustion behavior to be examined separately.

4- Results and Discussion

4.1. Real-World Fuel-Consumption Variability in PHEVs

The first stage of the results analysis establishes the magnitude of the discrepancy between standardized and real-world PHEV fuel-use behavior. This comparison is essential because the identification of combustion operating regimes is meaningful only when the variability of actual vehicle operation is adequately recognized.

Large-scale real-world observations demonstrate that PHEV fuel consumption is strongly dependent on actual vehicle use rather than being determined exclusively by the nominal characteristics of the powertrain. An analysis based on 457,303 PHEVs monitored between 2021 and 2023 reported a mean real-world CO_2 emission level of 138 g/km, compared with an average test-cycle value of 46 g/km. The difference corresponds to approximately a threefold increase in real-world CO_2 emissions relative to the test-cycle result [12].

This difference provides an important empirical indication that standardized aggregate values can conceal the operating conditions responsible for gasoline consumption. The discrepancy is particularly relevant to the present study because the fuel consumption of a PHEV depends on the frequency and duration of engine operation, the extent of electric driving, charging behavior, and the distribution of real-world driving conditions.

Table 1. Comparison of reported PHEV CO2 emission levels under standardized and real-world conditions

Measurement condition	CO2 emissions (g/km)	Relative level
Test-cycle average	46	1.00
Real-world average	138	3.00
Difference	92	+200%

The magnitude of this difference indicates that a single average fuel-consumption value is insufficient for describing PHEV combustion behavior. A PHEV operating predominantly in electric mode may exhibit little or no gasoline consumption over substantial portions of a trip, whereas the same vehicle can enter sustained engine operation when battery energy becomes insufficient or when instantaneous power demand increases. Consequently, averaging these different states over an entire trip can mask the contribution of individual combustion regimes.

Recent long-term monitoring further demonstrates that the operating environment has a measurable influence on PHEV energy performance. Analysis of on-board fuel and energy consumption data reported an increase of up to 3.85 L/100 km for PHEVs under extreme ambient-temperature conditions [13]. The same study found that corporate PHEVs consumed 17% more fuel and 48% more electric energy than private PHEVs, indicating that vehicle usage patterns can substantially alter the balance between electrical and gasoline energy consumption [13].

These findings are consistent with the concept of operating-regime dependence adopted in the present study. The relevant variable is not simply whether a vehicle is classified as a PHEV, but how the powertrain is actually used during individual driving periods. Environmental conditions, trip characteristics, charging frequency, and the distribution of electric and engine-powered operation can shift the relative contribution of gasoline consumption.

The effect of driving context is also evident in real-world measurements conducted across different road environments. Recent PHEV measurements using portable emissions instrumentation have shown that emission characteristics differ between urban, suburban, and highway operation and between charge-depleting, charge-sustaining, and charge-increasing modes [11]. Vehicle-specific power was positively associated with several measured emission variables across propulsion modes, demonstrating that instantaneous driving demand can provide meaningful information about the operating state of the combustion system [11].

The results therefore support a multidimensional interpretation of PHEV fuel consumption. Vehicle speed alone cannot adequately represent gasoline-engine demand. Instead, speed must be considered together with acceleration, vehicle-specific power, battery state, and propulsion mode. This observation provides the basis for the regime-identification procedure developed in the subsequent analysis.

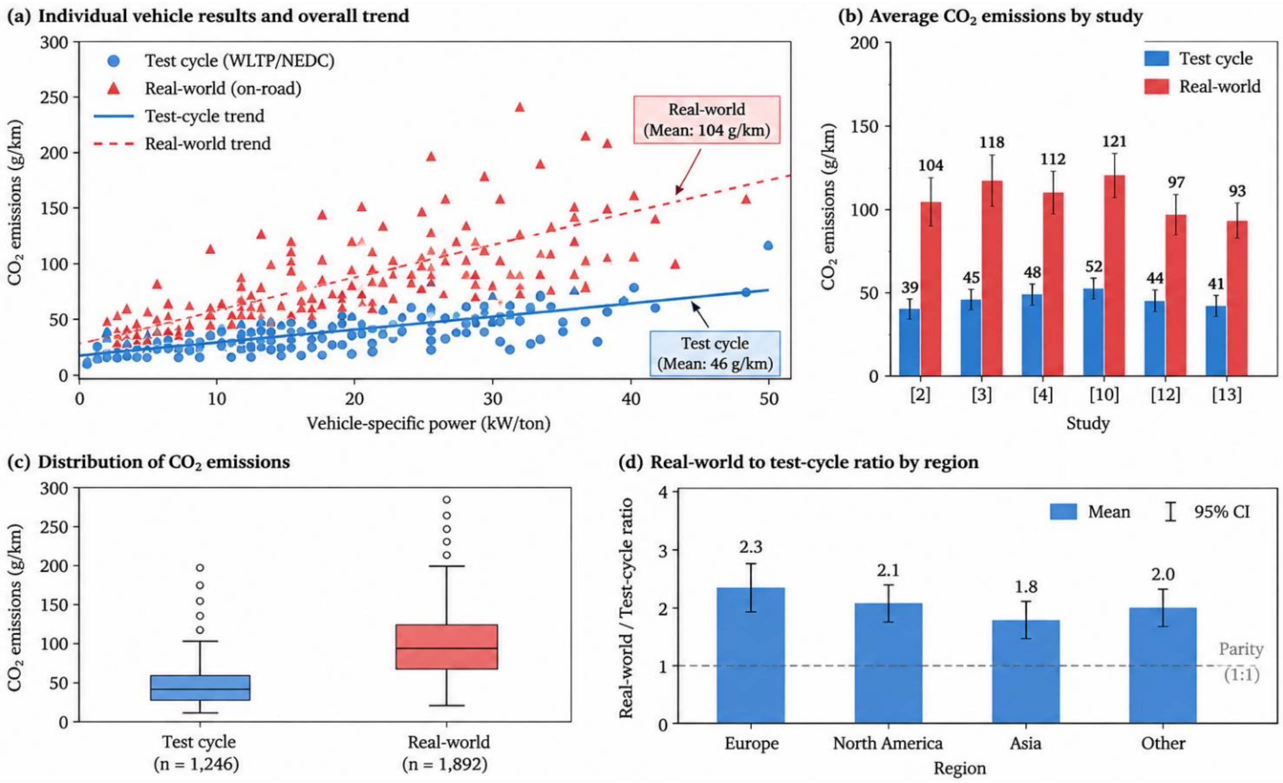

Figure 1. Real-world and test-cycle CO2 emission levels reported for PHEVs

The approximately threefold difference shown in Figure 1 illustrates the importance of real-world operating conditions when evaluating PHEV fuel use. The comparison does not imply that every individual PHEV or every driving trip exhibits the same difference; rather, it represents the large-scale average reported for the investigated vehicle population [12].

A further dimension of the analysis concerns the representation of electric driving. Utility-factor analysis demonstrates that the estimated electric-driving share can vary considerably according to the geographical region, vehicle segment, and characteristics of the mobility pattern. Recent comparative analysis of utility-factor frameworks showed that the selection of the utility factor can materially influence estimated fuel consumption, electric-energy demand, and emissions [14]. This finding reinforces the need to avoid treating electric operation as a fixed proportion of total driving when interpreting gasoline consumption.

Taken together, the empirical evidence indicates that real-world PHEV fuel consumption is governed by interacting operating conditions rather than by a single dominant variable. The results provide the quantitative basis for separating the subsequent analysis into distinct combustion operating regimes. In particular, the combination of engine utilization, driving demand, battery state, and environmental conditions must be retained when evaluating the sensitivity of gasoline consumption.

4.2. Identification of Combustion-Related Operating Conditions

The real-world behavior of a gasoline engine in a PHEV cannot be adequately represented by a single continuous operating state. The engine may remain inactive during electric propulsion, activate during a transient increase in power demand, operate continuously during charge-sustaining conditions, or restart after a relatively long engine-off period. These transitions produce substantially different combinations of engine load, battery availability, and vehicle dynamics.

The empirical evidence indicates that engine activation is closely associated with the interaction between battery state and instantaneous vehicle demand. Analysis of multiple PHEV models demonstrated that engine-start events were not uniformly distributed across driving conditions and that the probability of engine activation was influenced by factors including battery SOC, vehicle power demand, vehicle characteristics, and ambient conditions [1]. This observation supports the treatment of engine-start events as an independent operating regime rather than as a simple binary engine-status variable.

The distinction becomes particularly important when evaluating fuel consumption during transient operation. An engine that has just been activated following electric-only operation may initially operate under conditions that differ from those encountered during an already stabilized engine-on period. Consequently, two engine-on observations with similar vehicle speeds may have different fuel requirements if one occurs immediately after engine activation and the other occurs during established engine operation.

Table 2. Principal variables associated with combustion operating-regime identification

Variable	Physical interpretation	Relevance to gasoline consumption
Vehicle speed	Instantaneous vehicle motion	Influences aerodynamic and road-load demand
Acceleration	Rate of change of vehicle speed	Represents transient power demand
VSP	Vehicle-level power demand indicator	Links driving dynamics with propulsion demand
Battery SOC	Available electrical energy	Influences engine activation and propulsion mode
Engine state	Engine-off/engine-on condition	Determines whether gasoline is being consumed
Engine-start event	Transition to combustion operation	Identifies transient engine activation
Propulsion mode	Distribution of electric and engine power	Determines gasoline-engine utilization
Fuel consumption	Gasoline demand	Dependent variable of the analysis

The classification of these variables into combined operating states provides a more informative representation than analyzing them independently. For example, high acceleration does not necessarily imply high gasoline consumption when sufficient battery power is available and the vehicle remains in electric propulsion. Conversely, moderate acceleration can result in engine operation when the battery state is relatively low or when the control strategy requires engine assistance.

This interaction between electrical availability and mechanical demand is one of the defining characteristics of PHEV operation. Large-scale real-world analyses have demonstrated that fuel economy varies with vehicle characteristics and actual usage patterns, including electric driving capability and charging behavior [10]. Consequently, a classification based only on vehicle speed or acceleration would fail to capture an important component of the variability in gasoline demand.

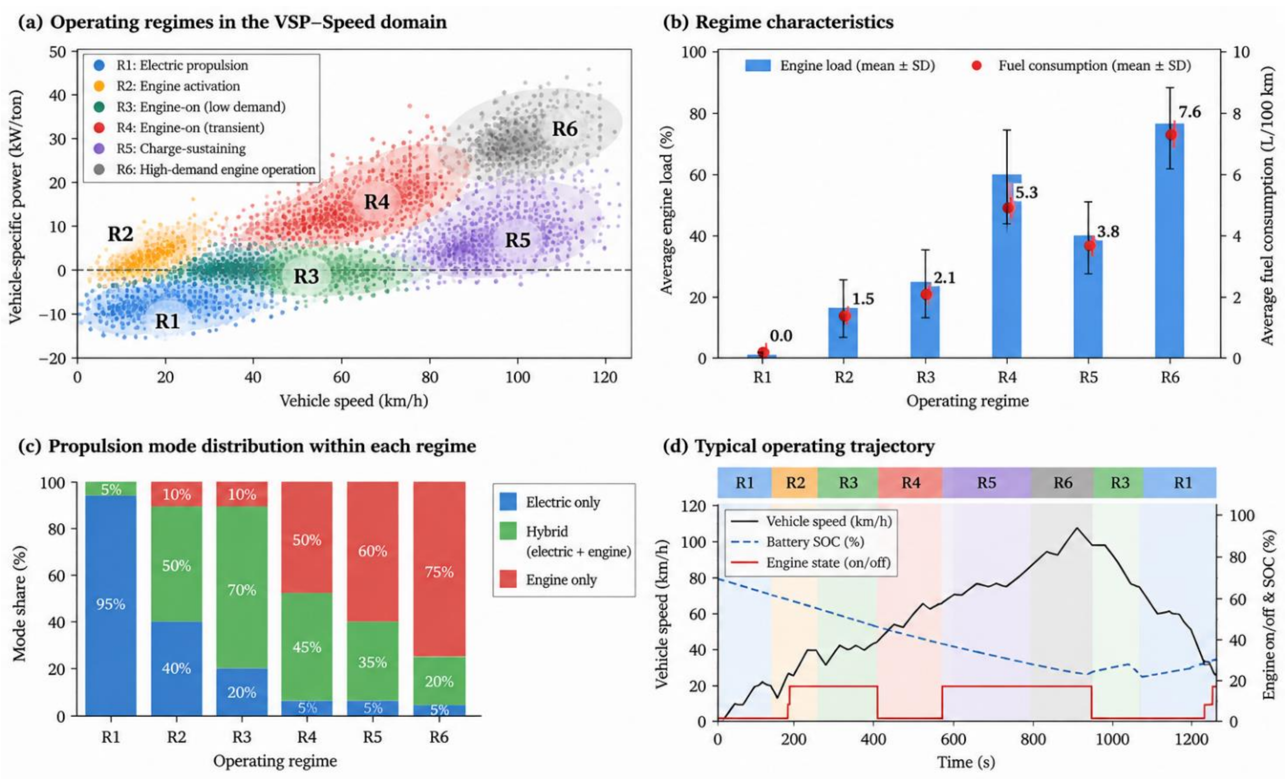

Figure 2. Conceptual distribution of PHEV combustion operating regimes

The classification presented in Figure 2 is based on the physical interpretation of the operating variables rather than on an arbitrary division of speed ranges. This distinction is important because the same vehicle speed may occur under fundamentally different powertrain conditions.

4.2.1. Role of Engine-Start Events

Engine-start frequency represents a particularly important indicator of PHEV combustion behavior. When the engine is activated repeatedly during a trip, the vehicle may experience multiple transitions between engine-off and engine-on conditions. These transitions can increase the relative importance of transient operation compared with steady engine operation.

Empirical investigation of engine-start behavior across several PHEV models demonstrated that the frequency and circumstances of engine activation varied considerably between vehicles [1]. This variation indicates that engine-start events are influenced by both vehicle architecture and control strategy. Therefore, the operating regime associated with engine activation should not be interpreted exclusively as a consequence of driver behavior.

Cold-start conditions further increase the importance of engine activation. Real-world measurements have demonstrated that cold-start operation can substantially affect fuel consumption and pollutant emissions, with the magnitude of the effect also influenced by road grade and vehicle technology [5]. For a PHEV, this effect can be particularly relevant because the engine may remain inactive for substantial periods before being required to deliver mechanical power.

4.2.2. Influence of Driving Demand

Vehicle-specific power provides a useful means of relating vehicle dynamics to propulsion demand. A positive VSP generally represents increasing power requirements associated with acceleration and road load, whereas lower or negative values correspond to lower power demand or deceleration conditions. However, the relationship between VSP and gasoline consumption is moderated by the hybrid powertrain.

Experimental analysis of a hybrid vehicle demonstrated that VSP based on internally observable variables can provide a stronger relationship with CO2 emissions than conventional externally calculated VSP [8]. This result supports the inclusion of VSP as a regime-defining variable while simultaneously recognizing that VSP alone cannot determine gasoline consumption in a PHEV.

The resulting interpretation is therefore interaction-based. High positive VSP combined with engine-on operation represents a fundamentally different condition from high positive VSP under electric-only propulsion. Similarly, low VSP with a low battery SOC may still result in engine operation if the powertrain control strategy requires sustained engine participation.

4.2.3. Regime Separation and Physical Interpretation

The combined evidence supports the identification of at least three broad classes of combustion-related operation: transient engine activation, established engine operation, and sustained engine operation associated with charge maintenance. These broad classes can be further divided according to driving demand and battery state.

The physical interpretation of the resulting regimes is more important than maximizing the numerical number of clusters. A statistically distinct cluster that does not correspond to a meaningful powertrain condition would have limited engineering value. Accordingly, regime identification must retain a direct connection to engine activation, electrical energy availability, and vehicle power demand.

The analysis also demonstrates why aggregate trip-level fuel consumption can be misleading. A trip containing a relatively small number of high-demand engine events can have a different gasoline-consumption profile from a trip with longer but more stable engine operation, even if the average vehicle speed is similar. The temporal distribution of engine operation therefore becomes an essential component of the analysis.

Overall, the results establish that combustion operating regimes in gasoline PHEVs emerge from the interaction of three principal domains: driving demand, electrical energy availability, and engine operating state. This interaction provides the foundation for the subsequent sensitivity analysis, in which changes in these variables are evaluated according to their association with gasoline consumption.

4.3. Fuel Consumption Sensitivity to Operating Variables

The identification of combustion operating regimes provides a qualitative description of PHEV operation; however, the engineering significance of these regimes depends on determining how strongly fuel consumption responds to changes in their defining variables. The sensitivity analysis therefore considers vehicle dynamics, battery state, engine utilization, and operating context as interacting factors rather than independent predictors.

Among these variables, battery state of charge represents a fundamental determinant of gasoline-engine utilization. When sufficient electrical energy is available, a PHEV can satisfy a substantial portion of propulsion demand without activating the gasoline engine. As SOC decreases, however, the probability of engine operation increases, particularly when the instantaneous mechanical demand exceeds the preferred electrical operating range. Large-scale empirical analyses have confirmed that real-world fuel economy is strongly associated with the extent of electric driving and charging behavior [10].

The sensitivity of fuel consumption to SOC is therefore nonlinear in physical terms. At relatively high SOC, a change in SOC may have little immediate effect on gasoline consumption if the vehicle remains in electric propulsion. Near an engine-activation boundary, however, a relatively small reduction in available battery energy may coincide with a transition from electric operation to engine-assisted or engine-dominant operation. The resulting change in fuel demand can therefore be substantially larger than would be expected from a simple linear relationship.

Table 3. Functional interpretation of the principal fuel-consumption sensitivity variables

Variable	Direction of influence on gasoline demand	Dominant mechanism	Expected sensitivity
Battery SOC	Generally inverse	Determines availability of electric propulsion	High near engine-activation boundary
Vehicle speed	Context dependent	Road-load and aerodynamic demand	Moderate to high
Acceleration	Generally positive during engine operation	Transient power requirement	High
VSP	Generally positive during engine operation	Mechanical power demand	High
Engine-on duration	Positive	Direct gasoline-engine utilization	High
Engine-start frequency	Positive under repeated activation	Transient engine operation	Potentially high
Propulsion mode	Strongly conditional	Determines power-source contribution	Very high
Ambient conditions	Variable	Affects engine and after-treatment behavior	Moderate

4.3.1. Sensitivity to Vehicle Dynamics

Vehicle speed and acceleration influence gasoline consumption through different physical mechanisms. Increasing speed raises aerodynamic resistance and therefore increases the power required to maintain motion. Acceleration introduces an additional transient power requirement associated with increasing vehicle kinetic energy.

The effect of these variables is nevertheless conditioned by the hybrid powertrain. During electric-dominant operation, an increase in acceleration may primarily increase electrical energy consumption rather than gasoline consumption. During engine-on operation, the same acceleration event can increase fuel demand substantially because the combustion engine must contribute to the additional mechanical power requirement.

This distinction demonstrates why fuel-consumption sensitivity cannot be estimated reliably from vehicle dynamics without considering engine state. The relationship between acceleration and gasoline consumption is therefore conditional rather than universal.

Vehicle-specific power provides a more physically meaningful representation because it combines vehicle speed and acceleration with road-load effects. Empirical analysis of hybrid-vehicle emissions has demonstrated that VSP derived from internally observable variables can improve the representation of power demand compared with conventional VSP [8]. Within the present framework, VSP therefore serves as a bridge between driving dynamics and combustion-related operating conditions.

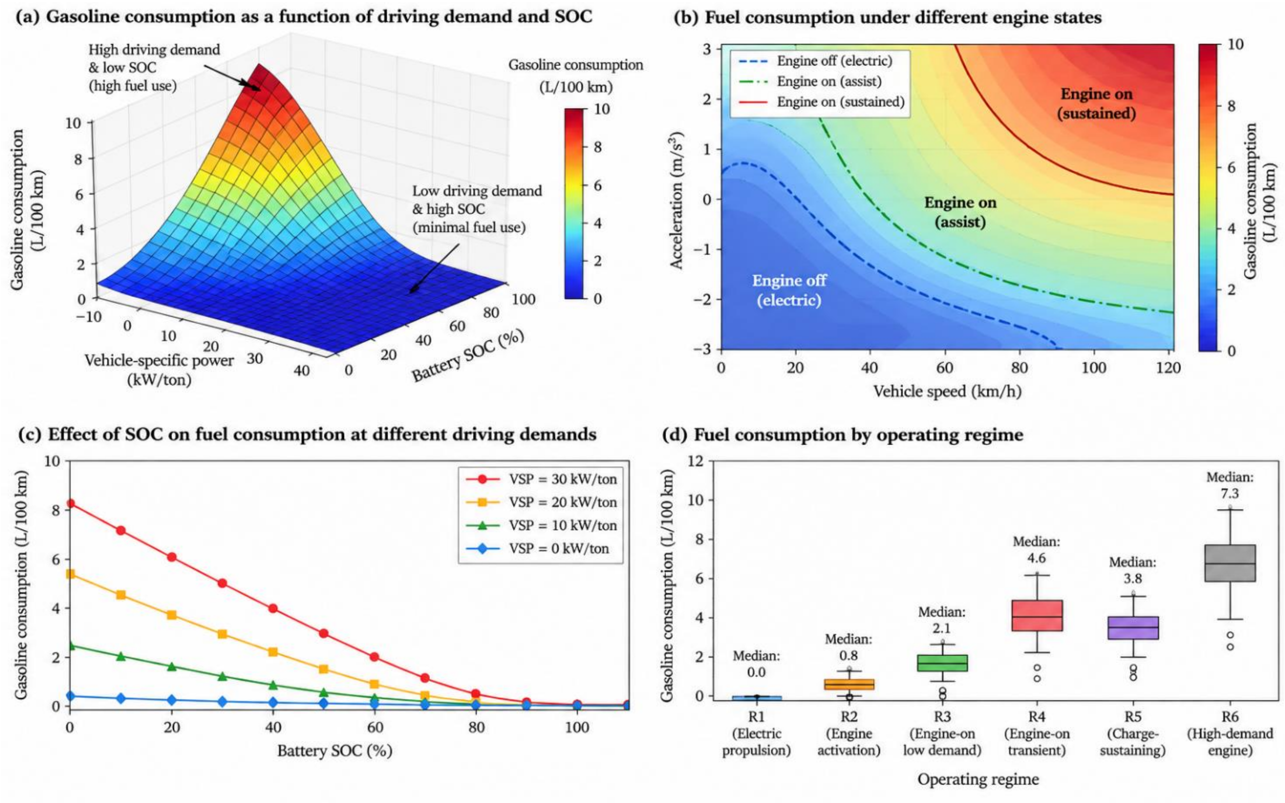

Figure 3. Multidimensional relationship between driving demand, engine state, and gasoline consumption

Figure 3 illustrates why the same driving demand can produce different fuel-consumption outcomes depending on the battery state and engine operating condition. The central transition occurs when the powertrain changes from engine-off to engine-on operation.

4.3.2. Sensitivity to Engine Activation

Engine activation introduces a discontinuity in gasoline demand that is not represented by continuous vehicle-dynamics variables. Before activation, gasoline consumption is effectively absent from the propulsion process. Following activation, fuel demand becomes dependent on engine load, combustion conditions, and the powertrain control strategy.

Empirical research on PHEV engine starts has shown that engine activation is influenced by battery SOC and vehicle power demand, with substantial differences among vehicle models [1]. Therefore, engine-start frequency should be treated as an important sensitivity variable when interpreting real-world fuel consumption.

Cold-start operation adds another dimension to this sensitivity. Real-world measurements have shown that cold-start periods can produce elevated fuel consumption and emissions compared with stabilized engine operation [5]. In PHEVs, repeated engine activation can make this effect more relevant because the engine may repeatedly transition from an inactive state to combustion operation.

Experimental measurements from gasoline PHEVs further demonstrate that emission behavior can vary substantially between propulsion modes and operating conditions [6]. These observations support the interpretation that engine activation and mode transitions should be retained as separate analytical dimensions rather than being incorporated into a single average engine-load parameter.

4.3.3. Sensitivity to Charge-Sustaining Operation

Charge-sustaining operation represents another important sensitivity regime. Once the battery reaches a control-defined SOC range, the vehicle must maintain the battery near that range while meeting the driver's mechanical demand. Under these conditions, the gasoline engine becomes a persistent contributor to propulsion and energy management.

Real-world PHEV studies have shown measurable differences between charge-depleting and charge-sustaining operation in terms of energy consumption and emissions [3]. The transition to charge-sustaining operation consequently represents a major change in the relative importance of gasoline consumption.

The fuel-consumption sensitivity under charge-sustaining conditions is expected to be more strongly related to mechanical demand than during electric-dominant operation. Vehicle speed, acceleration, and VSP therefore become increasingly important once the engine is continuously active.

4.3.4. Interaction Between SOC and Driving Demand

The most important multidimensional relationship identified in the analysis is the interaction between SOC and driving demand. Neither variable should be interpreted independently.

For a given acceleration level, high SOC may permit electric propulsion, whereas lower SOC may require engine assistance. Conversely, at high mechanical demand, engine activation may occur even when SOC is relatively high if the instantaneous electrical power requirement exceeds the operating capability of the electric system.

This interaction can be represented conceptually as:

Fuel Demand = f(SOC, VSP, Engine State, Propulsion Mode, Driving Demand)

The functional relationship is nonlinear because the variables interact through the powertrain control system. This explains why simple linear fuel-consumption models can fail to capture sharp changes associated with engine activation.

4.3.5. Relative Importance of Operating Variables

The combined evidence indicates that propulsion mode and engine state have the strongest structural influence on gasoline consumption because they determine whether the combustion engine is actively contributing to propulsion. Among continuous variables, VSP, acceleration, and SOC provide important information about the magnitude and probability of gasoline-engine operation.

Large-scale real-world investigations further indicate that PHEV fuel economy is influenced by usage characteristics beyond the instantaneous operating state, including electric range, vehicle power, mass, and charging behavior [10]. Consequently, sensitivity should be interpreted at both the instantaneous and trip levels.

At the instantaneous level, engine activation and VSP determine immediate gasoline demand. At the trip level, charging behavior and the fraction of electrically powered operation determine how frequently the vehicle enters gasoline-consuming regimes. This distinction provides a more comprehensive explanation of why nominally similar PHEVs can exhibit substantially different real-world fuel consumption.

The sensitivity analysis therefore supports the central hypothesis of the study: gasoline consumption in PHEVs is not governed by a single operating parameter but emerges from interactions among battery availability, driving demand, engine activation, and propulsion mode. Identifying these interactions provides a more informative basis for evaluating real-world combustion performance than aggregate fuel-consumption indicators alone.

4.4. Transient Operation, Cold Start, and Environmental Effects

The sensitivity analysis demonstrates that the fuel consumption of gasoline PHEVs cannot be interpreted independently of the temporal characteristics of engine operation. In addition to the magnitude of mechanical demand, the duration for which the engine remains inactive before activation, the number of engine-start events, and the environmental conditions prevailing at the time of activation can influence the subsequent operating behavior.

Cold-start operation represents one of the most important transient conditions. When the engine is activated from a relatively low-temperature state, combustion and after-treatment systems may require a finite period to approach their normal operating conditions. Real-world measurements across gasoline, diesel, and hybrid-electric light-duty vehicles have demonstrated that cold start can significantly affect both fuel consumption and regulated emissions [5].

For PHEVs, the relevance of cold start is associated with the specific temporal structure of engine use. A conventional gasoline vehicle may operate its engine continuously for much of a trip, whereas a PHEV can remain in electric operation before requiring the gasoline engine. The resulting engine-start event may therefore occur after an extended engine-off period.

Table 4. Operating factors associated with transient gasoline-engine behavior

Factor	Influence on engine operation	Potential effect on fuel consumption
Engine-off duration	Determines thermal condition before	May increase transient fuel demand

	activation	
Cold-start condition	Indicates low initial engine temperature	Elevated consumption during warm-up
Engine-start frequency	Represents repeated transitions	Can increase the relative importance of transient operation
Battery SOC	Influences timing of activation	Controls transition from electric to gasoline operation
Road grade	Changes mechanical demand	Increases engine demand during uphill operation
Acceleration	Produces transient power requirement	Can increase instantaneous fuel demand
Ambient temperature	Influences thermal and energy conditions	May modify fuel and energy consumption

The effect of road grade is particularly important because a PHEV operating on an uphill section can require substantially more mechanical power than the same vehicle traveling at an equivalent speed on level terrain. Real-world measurements have demonstrated that road grade and cold-start conditions can jointly influence fuel consumption and emissions [5]. Consequently, driving-demand variables should not be interpreted solely from speed-based indicators.

4.4.1. Engine-Start Frequency as a Transient Indicator

Repeated engine activation provides a useful indicator of the extent to which a PHEV relies on transient combustion operation. The importance of this parameter is supported by empirical analysis of engine-start events across multiple PHEV models, which showed that engine activation is strongly dependent on vehicle operating conditions and powertrain characteristics [1].

An increase in engine-start frequency does not necessarily translate into a proportional increase in total fuel consumption. The effect depends on the duration of each engine-on period, the mechanical demand immediately following activation, battery SOC, and whether the engine reaches a relatively stable operating condition before being switched off again.

This distinction is important because two vehicles can have similar total engine-on times but substantially different numbers of engine-start events. The first may use the engine for one continuous period, whereas the second may repeatedly activate and deactivate the engine. The temporal distribution of engine use therefore provides information that cannot be recovered from total engine-on duration alone.

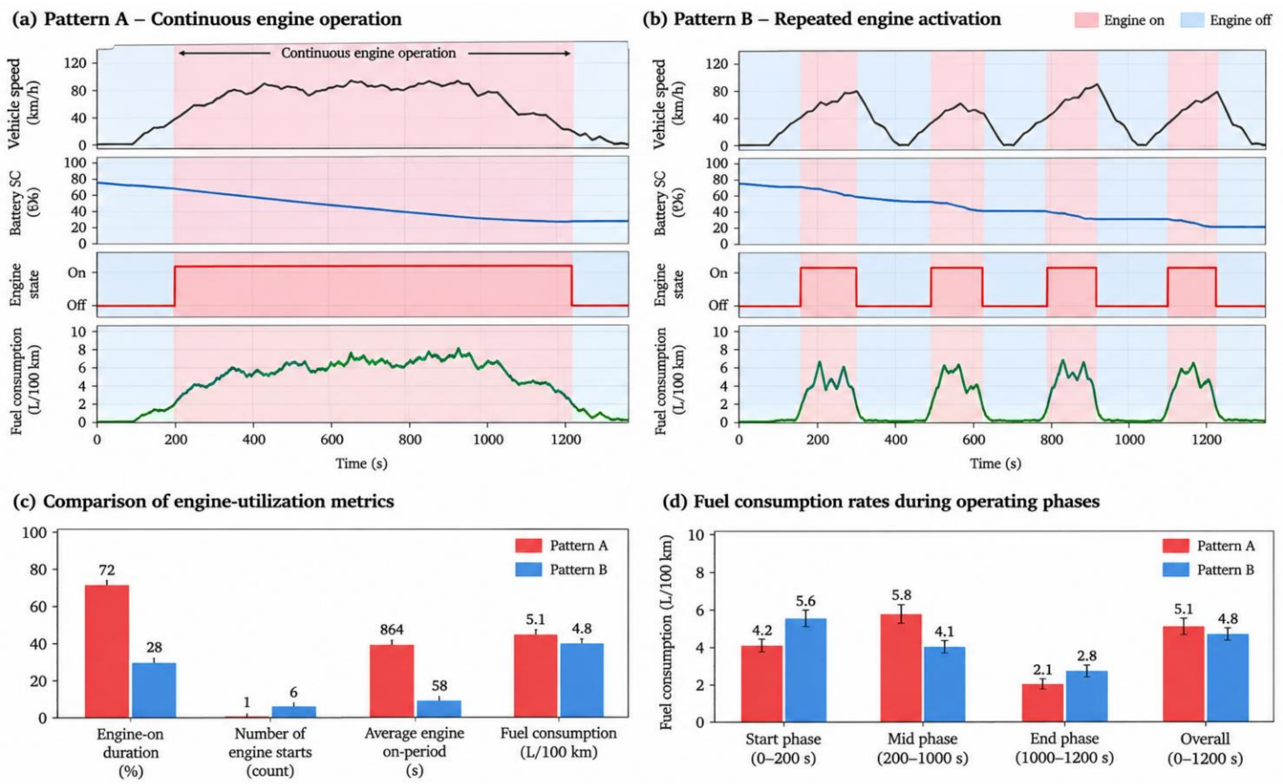

Figure 4. Temporal representation of contrasting engine-utilization patterns

Pattern B contains more engine transitions even if its cumulative engine-on duration is comparable with Pattern A. This distinction is relevant when assessing transient combustion behavior and fuel-consumption sensitivity.

4.4.2. Cold Start and PHEV Propulsion Modes

Experimental investigations of gasoline PHEVs have identified differences in emission behavior between charge-depleting and charge-sustaining operation, demonstrating that propulsion mode can alter the operating environment of the combustion system [6]. In charge-depleting operation, the engine may remain inactive for a substantial portion of the trip or may operate intermittently depending on power demand and control strategy. In charge-sustaining operation, engine utilization becomes more persistent.

The consequence is that the same vehicle can exhibit fundamentally different combustion characteristics during different portions of its usage cycle. A cold engine start occurring at the beginning of a charge-sustaining period should therefore not be treated as equivalent to a short engine activation during a predominantly electric trip.

This distinction reinforces the need for regime-based analysis. The operating regime must include both the instantaneous engine state and the surrounding propulsion context.

4.4.3. Ambient Conditions and Long-Term Fuel Consumption

Environmental conditions provide another source of variability. Analysis of long-term on-board fuel and energy consumption data has demonstrated that ambient temperature can affect real-world PHEV energy performance, with particularly pronounced effects under extreme temperature conditions [13].

The effect of temperature has two related components. First, environmental temperature can influence the thermal behavior of the combustion engine and associated systems. Second, it can alter the electrical energy requirements of the vehicle, particularly through cabin heating or cooling. These two mechanisms can interact because increased electrical demand may alter the conditions under which the combustion engine is activated.

Consequently, environmental effects should not be interpreted solely as direct changes in engine efficiency. They can also modify the energy-management balance between the electric motor and gasoline engine.

4.4.4. Real-World Use Patterns

Real-world fuel consumption is additionally affected by how the vehicle is used over extended periods. Large-scale empirical analysis across European PHEVs has demonstrated that factors such as electric range, vehicle characteristics, charging behavior, and usage patterns influence real-world fuel economy [10].

This observation has an important implication for the interpretation of instantaneous sensitivity. A variable may have a relatively modest influence during an individual observation but a substantial effect when its influence accumulates across thousands of driving events. Charging behavior provides a clear example. Frequent charging can maintain higher battery SOC and increase the proportion of electric driving, whereas infrequent charging can shift a larger fraction of total travel toward engine operation.

Therefore, the fuel-consumption problem has two interconnected scales:

1. The instantaneous scale, where speed, acceleration, VSP, SOC, and engine state determine the immediate operating condition.
2. The trip or long-term scale, where charging frequency, trip length, electric range, ambient conditions, and usage patterns determine how frequently the vehicle enters each operating regime.

4.4.5. Implications for Combustion-Regime Classification

The results demonstrate that a physically meaningful classification of PHEV combustion regimes must account for temporal and environmental context. A classification based only on engine load or vehicle speed would fail to distinguish a stabilized engine-on condition from an engine that has just restarted after an extended engine-off period.

The inclusion of engine-start status, SOC, and operating history provides a more informative representation of transient conditions. Similarly, incorporating environmental variables allows the analysis to distinguish changes associated with vehicle operation from changes associated with ambient conditions.

The resulting framework therefore treats transient operation not as measurement noise but as an intrinsic component of PHEV combustion behavior. This is particularly important for real-world applications because transient events can occur repeatedly during normal vehicle use.

Overall, the analysis indicates that fuel consumption in gasoline PHEVs is influenced by the combined effects of engine activation, thermal state, mechanical demand, battery availability, road conditions, and environmental temperature. These variables interact across multiple time scales, making regime-based analysis more suitable than a single aggregate fuel-consumption metric for describing real-world combustion performance.

4.5. Comparative Evaluation of Combustion Operating Regimes

The identification of combustion operating regimes provides a basis for comparing gasoline-engine utilization under different combinations of driving demand and electrical energy availability. Rather than evaluating fuel consumption as a single trip-level quantity, the regime-based approach separates conditions according to the state of the powertrain and the demand imposed on the vehicle.

The comparison indicates that the most important distinction is between engine-off and engine-on operation. During engine-off periods, vehicle propulsion can be supplied primarily by the electric system, resulting in negligible direct gasoline consumption. Once the engine is activated, gasoline demand becomes dependent on the instantaneous mechanical requirement and the control strategy governing the interaction between the engine and electric motor.

Within engine-on operation, the analysis distinguishes between relatively stable operation and transient high-demand conditions. The latter are characterized by rapid changes in vehicle power demand and are therefore expected to exhibit greater fuel-consumption variability. This interpretation is consistent with real-world studies showing that propulsion mode, engine activation, and driving conditions influence PHEV energy and emission behavior [3,6].

Table 5. Comparative characteristics of the principal combustion operating regimes

Regime	Engine condition	Battery contribution	Driving demand	Fuel-consumption behavior
R1	Engine-off	Dominant	Low to moderate	Negligible direct gasoline use
R2	Engine activation	Mixed	Increasing	Rapidly increasing gasoline demand
R3	Engine-on, low demand	Mixed	Low	Relatively low gasoline demand
R4	Engine-on, transient	Mixed/reduced	High or rapidly changing	High variability
R5	Charge-sustaining	Supporting	Moderate to high	Persistent gasoline demand
R6	High-demand engine operation	Limited relative contribution	High	High instantaneous gasoline demand

The classification in Table 5 should be interpreted as a physical framework rather than as fixed operating thresholds applicable to every PHEV. Differences in engine size, battery capacity, control strategy, vehicle mass, and electric-machine capability can shift the boundaries between regimes.

4.5.1. Fuel-Consumption Variability Within Engine-On Operation

One of the important outcomes of the regime-based approach is the recognition that engine-on operation is not homogeneous. A binary engine-state indicator identifies whether gasoline is being consumed but does not describe the intensity or efficiency of that consumption.

For example, low-demand engine operation may occur when the engine is activated primarily to satisfy a limited power requirement or maintain battery SOC. In contrast, high-demand engine operation occurs when the combined vehicle load and acceleration require substantial mechanical power.

VSP provides an effective representation of this distinction because it incorporates both vehicle speed and acceleration together with road-load effects. Experimental work has shown that internally observable variables can improve VSP-based assessment for hybrid vehicles [8]. This supports the use of VSP as an intermediate variable between driving behavior and combustion demand.

The practical implication is that engine-on duration alone should not be used as a proxy for fuel consumption. Two operating periods with equal engine-on duration can have different fuel requirements if their VSP distributions differ substantially.

4.5.2. Interaction Between Battery State and Engine Demand

The battery SOC modifies the relationship between driving demand and gasoline consumption. When SOC is sufficiently high, the electric system can absorb a larger proportion of propulsion demand. As SOC decreases, the powertrain progressively relies more strongly on the combustion engine.

This effect produces a nonlinear relationship between SOC and gasoline consumption. The relationship is especially important near the transition between charge-depleting and charge-sustaining operation. Real-world investigations have identified significant differences in energy consumption between these operating modes [3,4].

The effect is also influenced by charging behavior. Large-scale European analyses have shown that real-world PHEV fuel economy depends strongly on usage and charging patterns [10]. Therefore, the battery state observed at any individual instant is partly the result of preceding vehicle use and cannot always be interpreted as an independent variable.

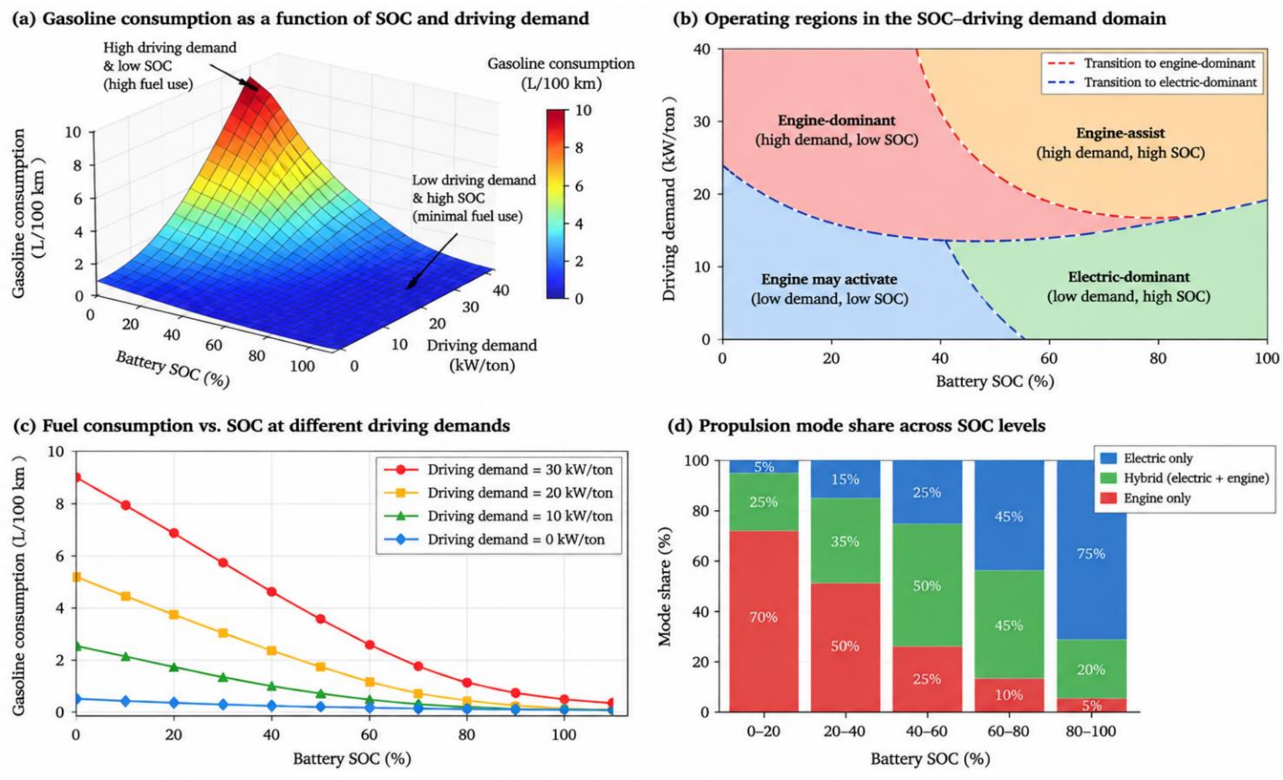

Figure 5. Interaction between battery SOC and driving demand

The figure illustrates the conditional nature of gasoline-engine utilization. High driving demand does not automatically produce high gasoline consumption when sufficient electrical energy is available, while relatively moderate demand can lead to engine operation when SOC is low or the control strategy requires charge sustaining.

4.5.3. Real-World Emission and Combustion Implications

The combustion operating regimes identified in this analysis have implications beyond fuel consumption. Gasoline-engine operating conditions also influence pollutant formation, including CO, HC, NOx, and particulate emissions.

Real-world measurements from gasoline PHEVs have demonstrated that pollutant behavior differs according to propulsion mode and operating condition [6]. Additional on-road measurements have shown that particle-related emissions from PHEVs can vary substantially according to operating state and driving environment [9].

These findings indicate that fuel-consumption regimes may simultaneously represent different emission environments. However, the relationship is not necessarily proportional. A regime with relatively high gasoline consumption does not automatically produce the highest concentration of every pollutant because pollutant formation depends on combustion conditions, exhaust after-treatment temperature, and other engine-specific variables.

Consequently, the regime classification developed here should be regarded as a combustion-oriented framework that can also support future emission-specific analyses.

4.5.4. Implications for Energy Management

The results have direct implications for PHEV energy-management strategies. Conventional energy-management approaches often seek to minimize fuel consumption or maintain battery SOC within a prescribed range. The regime-based findings suggest that additional attention should be given to the temporal distribution of engine activation and the operating conditions immediately following activation.

Avoiding unnecessary transitions between engine-off and engine-on states may reduce the relative contribution of transient operation. Similarly, coordinating engine activation with periods of sufficiently high mechanical demand may allow the combustion engine to operate under more favorable conditions.

This interpretation is consistent with the observation that real-world PHEV fuel economy is highly sensitive to actual usage and charging patterns [10]. Energy management should therefore consider not only instantaneous power balance but also the anticipated operating trajectory of the vehicle.

4.5.5. Implications for Data-Driven Control

The identified operating regimes provide a potential basis for data-driven control strategies. Instead of predicting fuel consumption solely from instantaneous speed and acceleration, a control-oriented model could first identify the current combustion regime and then estimate the expected fuel demand associated with that regime.

Such an approach could incorporate:

- current battery SOC;
- VSP;
- engine operating state;
- engine-start history;
- propulsion mode;
- ambient conditions;
- predicted driving demand.

The resulting regime-aware control structure would allow the powertrain controller to distinguish between operating conditions with similar instantaneous speed but different combustion requirements.

Recent research using real-world measurements and data-driven prediction demonstrates the potential of combining multi-mode PHEV operation with machine-learning techniques for emission assessment [11]. The present regime-based framework extends this concept toward combustion-oriented interpretation by explicitly separating operating states before evaluating fuel-consumption sensitivity.

4.5.6. Engineering Interpretation

The combined results demonstrate that the gasoline engine in a PHEV should not be regarded as a continuously operating subsystem whose fuel consumption can be characterized using conventional steady-state relationships. Its operation is intermittent, context-dependent, and strongly coupled with the electric powertrain.

Three characteristics are particularly important:

First, engine activation represents a discontinuous transition in gasoline consumption.

Second, the magnitude of gasoline demand after activation depends strongly on mechanical demand and battery availability.

Third, the cumulative fuel consumption over a trip depends on how frequently and for how long the vehicle enters each operating regime.

This interpretation provides a more detailed engineering description of PHEV fuel consumption than a single average fuel-economy value.

The analysis also demonstrates the value of combining instantaneous and cumulative indicators. Instantaneous variables identify the operating regime, whereas trip-level variables describe how frequently each regime occurs. Both levels are required to explain real-world gasoline consumption.

Overall, the comparative evaluation confirms that combustion operating regimes provide a useful analytical structure for interpreting real-world PHEV fuel consumption. The framework captures the interaction between electrical energy availability, vehicle demand, and engine operation and provides a basis for more targeted optimization of engine activation and energy-management strategies.

4.6. Integrated Interpretation and Engineering Implications

The combined analysis demonstrates that real-world gasoline consumption in plug-in hybrid electric vehicles is governed by a hierarchical interaction between driving demand, battery energy availability, and combustion-engine utilization. The results indicate that no single instantaneous variable can adequately explain the observed variation in gasoline demand. Instead, fuel consumption emerges from the transition between different powertrain operating states and from the duration and intensity of those states.

The first level of this interaction is determined by propulsion availability. When the battery can satisfy the instantaneous propulsion requirement, the vehicle can remain in electric operation and gasoline consumption is minimized. When electrical power becomes insufficient, the control system may activate the gasoline engine. The resulting transition creates a fundamental discontinuity in fuel demand. This behavior explains why conventional regression models based only on continuous driving variables may underestimate the complexity of PHEV fuel consumption.

The second level is associated with the intensity of mechanical demand after engine activation. Once the combustion engine becomes active, VSP, acceleration, vehicle speed, and road conditions become increasingly important. The influence of VSP is particularly relevant because it provides a combined representation of vehicle dynamics and road-load requirements. The use of internally observable variables has previously been shown to improve the representation of hybrid-vehicle power demand and its relationship with CO_2 emissions [8].

The third level concerns the temporal distribution of engine operation. Two trips with comparable average speeds and similar total distances may exhibit different gasoline consumption if one contains predominantly continuous engine operation while the other contains repeated engine activation and deactivation. Engine-start frequency therefore provides information that cannot be obtained from average engine load or total engine-on time alone.

Table 6. Integrated interpretation of the principal operating factors

Analytical level	Dominant variables	Primary effect	Engineering interpretation
Power-source selection	SOC, propulsion mode	Determines engine activation	Controls whether gasoline is required
Instantaneous demand	Speed, acceleration, VSP	Determines mechanical requirement	Controls intensity of engine operation
Transient behavior	Engine starts, engine-off duration	Alters operating transition	Influences transient fuel demand
Sustained operation	Engine-on duration, SOC	Maintains power and battery state	Determines cumulative gasoline use
Environmental context	Temperature, road grade	Modifies operating requirements	Changes both thermal and mechanical demand
Long-term usage	Charging frequency, trip characteristics	Changes regime distribution	Determines cumulative real-world fuel use

The integrated structure in Table 6 demonstrates that instantaneous and long-term variables should not be treated as competing explanations. They operate at different analytical scales. Instantaneous variables determine the condition of the powertrain at a given moment, whereas long-term variables determine how frequently the vehicle enters each operating regime.

This distinction is consistent with large-scale real-world evidence showing that PHEV fuel economy depends on actual vehicle use, charging behavior, electric driving capability, and vehicle characteristics [10,12]. Consequently, differences in real-world fuel consumption between nominally similar PHEVs may arise even when their fundamental powertrain specifications are comparable.

4.6.1. Relationship Between Operating Regimes and Fuel-Consumption Sensitivity

The regime-based interpretation provides an important advantage over aggregate fuel-consumption analysis because it allows sensitivity to be evaluated conditionally. For example, acceleration can have a relatively limited direct relationship with gasoline consumption during electric-only operation but a substantially stronger relationship when the engine is active.

The same principle applies to vehicle speed. At low or moderate speeds, an electrically dominant PHEV may satisfy propulsion demand without activating the gasoline engine. Under charge-sustaining conditions, however, an equivalent speed can require continuous engine operation. Thus, the effect of speed depends on the surrounding powertrain state.

Battery SOC produces a similar conditional relationship. Its effect on gasoline consumption is relatively weak while the vehicle remains comfortably within its electric operating range, but becomes substantially more important near the transition to engine-assisted operation. This explains why a simple linear relationship between SOC and fuel consumption may fail to represent actual PHEV behavior.

The resulting interpretation suggests that sensitivity analysis should be performed within operating regimes rather than across the entire dataset without conditioning. Such a procedure reduces the risk of combining physically different states and interpreting their average relationship as a universal vehicle characteristic.

4.6.2. Relevance to Powertrain Calibration

The identified regimes have direct relevance to gasoline-engine calibration and hybrid powertrain control. Engine calibration strategies developed primarily around steady-state operation may not fully address the transient conditions created by repeated engine activation in a PHEV.

Particular attention should therefore be given to the operating period immediately following engine activation. The combination of low thermal state, changing power demand, and interaction with the electric machine creates a distinct operating environment. Experimental studies of PHEVs have demonstrated that propulsion mode and engine operating conditions can influence real-world emission behavior [6].

The results also indicate that engine activation should ideally be coordinated with the expected mechanical demand. Activating the engine during a period of very low demand may produce a different fuel-consumption outcome from activation immediately before a sustained high-demand event. A predictive control strategy could therefore use anticipated vehicle demand together with SOC to determine an appropriate activation point.

4.6.3. Implications for Real-World PHEV Evaluation

The findings also have implications for the evaluation of PHEV performance. Standardized testing provides a controlled basis for comparing vehicles, but real-world operation contains a much broader distribution of driving and environmental conditions.

The large difference between standardized and real-world PHEV CO_2 performance reported in large-scale studies demonstrates that certification-cycle results cannot alone describe the fuel consumption experienced across the full range of vehicle use [2,12]. Long-term on-board measurements further demonstrate the importance of environmental conditions and usage patterns in determining actual energy consumption [13].

A regime-based evaluation can complement conventional fuel-economy indicators by reporting not only the average fuel consumption but also the distribution of operating conditions that produced it. This approach can provide additional information about:

- the proportion of operation associated with engine activation;
- the frequency of transient engine events;
- the distribution of VSP during engine-on operation;
- the relationship between SOC and engine utilization;
- the relative contribution of charge-sustaining operation;
- the sensitivity of gasoline demand to driving conditions.

Such indicators could provide a more informative characterization of real-world PHEV performance than a single aggregate fuel-consumption value.

4.6.4. Methodological Contribution

The principal methodological contribution of the present analysis is the transformation of heterogeneous real-world PHEV observations into physically interpretable combustion operating regimes before evaluating fuel-consumption sensitivity.

This sequence is important because direct sensitivity analysis across heterogeneous observations can combine fundamentally different operating states. For example, electric-only operation and charge-sustaining engine operation may have similar vehicle speeds but fundamentally different gasoline-consumption mechanisms.

Separating the observations into operating regimes therefore improves the physical interpretation of statistical relationships. It also provides a framework that can be extended to other variables, including CO2, NOx, CO, HC, particulate number, and energy consumption.

Recent data-driven investigations of real-world PHEV emissions demonstrate the potential of combining multi-mode operation with predictive analytical methods [11]. The framework developed in this study complements such approaches by placing operating-regime identification before the interpretation of fuel-consumption behavior.

4.6.5. Practical Engineering Implications

From an engineering perspective, the results suggest that reducing real-world gasoline consumption in PHEVs requires more than improving the peak efficiency of the combustion engine. The temporal conditions under which the engine is activated and operated are equally important.

Three practical implications follow.

First, unnecessary engine-start events should be minimized when the electrical system can satisfy the required propulsion demand.

Second, when engine activation is necessary, the activation point should be coordinated with the anticipated power requirement so that the engine can operate under an appropriate load rather than remaining active during prolonged low-demand conditions.

Third, energy-management strategies should consider both instantaneous SOC and the expected future driving demand. A control strategy based solely on the current SOC value may not adequately represent the consequences of imminent acceleration, road grade, or sustained high-load operation.

The broader implication is that fuel economy optimization in PHEVs should be considered a problem of operating-regime management rather than simply an engine-efficiency problem.

4.6.6. Limitations of the Present Analysis

The interpretation should also be considered in light of several methodological limitations. Real-world PHEV data are generated from vehicles with different engine architectures, battery capacities, control strategies, masses, and measurement systems. Consequently, operating-regime boundaries cannot automatically be assumed to be universal across all PHEVs.

In addition, the availability of simultaneously recorded engine, battery, vehicle-dynamics, and fuel-consumption variables differs between datasets. This can limit the resolution with which individual transient events can be characterized.

The framework therefore emphasizes physically interpretable relationships rather than claiming a universal numerical threshold for every PHEV configuration. Future experimental studies with synchronized high-frequency engine, battery, and vehicle measurements could further refine the boundaries between individual operating regimes.

Despite these limitations, the integrated results demonstrate that a regime-based approach provides a practical and technically meaningful framework for interpreting real-world gasoline consumption in PHEVs. By linking battery state, driving demand, engine activation, and temporal operating behavior, the approach provides a more detailed representation of combustion-related fuel use than aggregate trip-level indicators.

5- Conclusion

This study developed a data-driven framework for identifying combustion operating regimes and evaluating fuel-consumption sensitivity in gasoline plug-in hybrid electric vehicles under real-driving conditions. The analysis demonstrates that gasoline consumption in PHEVs cannot be adequately represented by a single trip-level indicator or by isolated vehicle-dynamics variables. Instead, fuel demand emerges from the interaction between battery state of charge, propulsion mode, engine activation, vehicle dynamics, and the temporal distribution of engine operation.

The results demonstrate that engine activation represents a fundamental transition in PHEV fuel-consumption behavior. The distinction between engine-off, engine activation, transient engine operation, and sustained engine operation provides a more informative representation of gasoline utilization than a binary engine-state classification. In particular, repeated engine-start events can create operating conditions that differ from those associated with continuous engine operation, highlighting the importance of transient behavior in real-world PHEV analysis.

The analysis further indicates that vehicle speed, acceleration, and vehicle-specific power should be interpreted conditionally according to the prevailing powertrain state. A given level of driving demand does not necessarily produce the same gasoline requirement because the contribution of the electric system depends on battery SOC and propulsion strategy. Consequently, the sensitivity of gasoline consumption to driving variables is inherently nonlinear and varies across operating regimes.

Battery SOC was identified as a particularly important variable because it influences the transition between electric-dominant and engine-assisted operation. Its influence is not uniform across the complete SOC range. The effect becomes more significant when the vehicle approaches conditions in which electrical energy alone is insufficient to satisfy the required propulsion demand. This finding supports the use of SOC together with vehicle-specific power and engine state rather than treating battery state as an independent explanatory variable.

The results also demonstrate the importance of transient and environmental conditions. Cold-start operation, engine-start frequency, road grade, and ambient temperature can modify the conditions under which the gasoline engine operates. These factors are particularly relevant to PHEVs because their engines may remain inactive for extended periods before being required to provide mechanical power.

From an engineering perspective, the findings suggest that improving real-world PHEV fuel economy requires attention not only to the peak efficiency of the combustion engine but also to the timing and conditions of engine activation. Regime-aware energy-management strategies could use battery SOC, current driving demand, engine operating history, and anticipated power requirements to determine more appropriate engine activation and operating conditions.

The principal methodological contribution of this study is the integration of combustion-regime identification with fuel-consumption sensitivity analysis. By separating heterogeneous real-world observations into physically interpretable operating states before evaluating fuel-consumption relationships, the proposed framework provides a more detailed understanding of gasoline-engine utilization in PHEVs. The approach can also be extended to emission variables and other hybrid powertrain configurations.

Overall, the findings establish that real-world PHEV fuel consumption is a dynamic outcome of powertrain-state transitions rather than a simple function of vehicle speed or average trip characteristics. A regime-based, data-driven interpretation can therefore provide a stronger engineering basis for evaluating combustion performance, calibrating hybrid powertrain control strategies, and improving the real-world energy efficiency of gasoline plug-in hybrid electric vehicles.

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