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Modeling Framework for Vehicle Electrification Representation within Combat Simulations

by Greg Dogum

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14. ABSTRACT

This technical report outlines a new methodology developed by the Ground Vehicle Electrification Systems Modeling Working Group to address a gap in modeling and simulation capabilities for electrified vehicles in combat scenarios. The focus was on creating a Physical Model Knowledge Acquisition Document to define hybrid vehicle behaviors and the data requirements for an electrified battlefield. This project emphasized enhancing vehicle electrification modeling from an energy sustainment perspective, incorporating accurate energy estimation and tactical advantages such as silent mobility and watch. The methodology’s core feature is its agnostic approach, using a systems-level aggregate vehicle model adaptable to various hybridization or electrification levels. Validated through a hybrid vehicle mission profile case study, it balances accuracy and complexity, and is suitable for combat simulations. The results demonstrate improved energy estimations and operational level energy accounting, which better align with modern and future vehicle technologies. This advancement contributes to more refined combat simulations, supporting informed decisions in Multi-Domain Operations, Large-Scale Combat Operations, and contested logistics scenarios.

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Greg Dogum	(410) 278-5677

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Executive Summary

The Army modernization goals for ground vehicle electrification are aimed to significantly change the dynamics of the future battlefield environment. However, within the modeling and simulation (M&S) community there are gaps preventing adequate representation of electrified platforms in combat simulations. This project was initiated to address these gaps, under the direction of the Ground Vehicle Electrification Systems Modeling Working Group conducted by the Maneuver Battle Lab. The objective was to develop a Physical Model Knowledge Acquisition Document (PKAD) to define hybrid electric and electric vehicle behaviors and understand the system-level data requirements for an electrified battlefield.

To address these gaps, enhancements to the modeling of electrification from an energy sustainment standpoint were needed that focus on accurate energy estimation while considering the functional capabilities and potential benefits to the Warfighter. A novel approach, which can capture electrification and hybridization degrees to include a range of powertrain configurations, was proposed that can consistently characterize steady-state power rates. The proposed methodology enables accounting for the tactical advantages of advanced powertrains in future military vehicles (e.g., silent mobility and silent watch) based on the tactical operating mode (vehicle signature) while tracking battery state of charge, mobility and non-mobility power demands and establishes a rule-based framework to select appropriate power modes.

An important feature of this methodology is its agnostic modeling approach, which is facilitated by a systems-level aggregate vehicle model for an electrified platform regardless of degree of hybridization or electrification. Through a case study involving a hybrid-vehicle mission profile, the methodology was benchmarked against higher-fidelity models to illustrate its efficacy in providing a balanced trade-off between accuracy and complexity acceptable for combat simulations.

The methodology has shown promise in delivering refined point-to-point energy estimations at the operational level and improving the fidelity of energy accounting in combat simulations. It has also set the foundation for a more comprehensive and nuanced approach toward sustainment-centric energy estimations aligning with current and future vehicle capabilities that go beyond liquid fuel predictions.

This project aligns M&S capabilities that aid in mission capturing nuances for scenario-driven decisions within Multi-Domain Operations, Large-Scale Combat Operations, and contested logistics environments.

1. INTRODUCTION

The transition to electrified military ground vehicles is just beginning, with potential to revolutionize the future battlefield environment, presenting both opportunities and challenges for military operations. Ground platforms for many decades have relied primarily on liquid fuel, and the potential inclusion of diverse power and energy systems on future vehicles requires changes to platform models. As tactics, techniques, and procedures evolve in response to these new capabilities, the U.S. Army's modeling and simulation (M&S) community needs to represent these technologies with a cohesive, comprehensive, and systematic approach within combat simulations to understand the impacts of electrified platforms in acquisition-related studies. While this effort was initiated by the combat simulation community, it is also recognized that using improved M&S can enhance the decision-making process within other analytical areas as well, to include the acquisition and sustainment communities. Therefore, a substantial gap was identified in representing these types of systems. The potential impacts of an electrified battlefield are significant and multifaceted, requiring a shift in the Army's approach to M&S.

The complexity inherent in predicting system-level behaviors of electrified vehicles requires enhancement of current M&S methodologies, particularly with respect to power and energy (P&E) consumption estimations, which is the primary focus area for this effort. However, it should serve as a potential foundation to representing other domain areas that will rely on predicting system behavior and operating mode or state. Modeling the unique operating behaviors of every configuration or technology arrangement was too cumbersome for quickly representing a variety of different vehicles in combat simulations. Current models, including detailed component-level frameworks developed by the U.S. Army Combat Capabilities Development Command (DEVCOM) Analysis Center (DAC) such as the Component-Level Energy Analysis Tool (CLEAT), offer valuable insights and incredible resolution; however, they do not appropriately balance computational cost with the fidelity-level required for combat simulations. This gap indicates that current M&S practices are inadequate for representing the appropriate level of details of sustainment within combat simulations, which are critical in reflecting the true operational impacts of electrification on the battlefield.

In response to this capability gap, this methodology delineates an approach for the future development of the electrified vehicle-focused Physical Model Knowledge Acquisition Document (PKAD) algorithms and accompanying data requirements. This effort is underpinned by the construction of a simplified, yet robust, system-level framework and a rules-based algorithm. The framework is designed to facilitate the application of these algorithms to support mission scenario-driven decisions, catering to the unique demands of contested logistics environments, Multi-Domain Operations (MDO), and Large-Scale Combat Operations (LSCO).

A central objective of this project is to provide tailored, sustainment-centric energy estimates that are congruent with the capabilities of both modern and future military vehicles. By doing so, the aim is to bridge the gap in current M&S practices, ensuring that the Army's combat simulations can fully represent the tactical advantages of vehicle electrification. This introduction sets the stage for an in-depth exploration of the proposed PKAD algorithms, the system-level framework, and their practical applications in enhancing Army combat simulations.

1.1 Background

Several key motivations toward building an enhanced capability within combat simulations were identified within the working group. A general understanding of this paradigm shift associated with vehicle electrification presented the group with an opportunity to establish an innovative approach to modeling.

The study approach employed a holistic methodology to establish a system-level framework for modeling ground vehicle electrification within combat simulations. A PKAD was developed to define the algorithms and data requirements necessary to accurately represent electric and hybrid-electric vehicles.

The framework development was designed to reflect a simplified yet comprehensive model of vehicle electrification, addressing steady-state power rates, energy storage, and consumption across a range of powertrain configurations. It includes conventional, hybrid-electric, and fully electric vehicles, incorporating various technology architectures such as series hybrids, parallel hybrids, or range extenders.

The PKAD algorithms were designed using a rule-based strategy and framework focusing on battery state of charge (SoC), tactical operating mode (TOM), mobility, and non-mobility power demands. This allows for combat simulations to account for the tactical advantages of advanced powertrains, such as silent mobility and silent watch capabilities as well as their improved efficiencies.

Another consideration was to determine how to tailor these algorithms for combat simulations. The primary aim of this initiative was the creation of a unified methodology capable of accommodating the diverse levels of vehicle electrification, from partially hybridized systems to fully electric platforms. The method developed focuses on steady-state energy estimations to allow for the operational benefits and enhanced capabilities of these electrified vehicles to be captured within combat scenarios.

This methodology is flexible, designed to accurately represent vehicles across the levels of electrification, and is broadly outlined in Figure 1. The approach aligns with the Army's broader modernization objectives (MCDID, 2021), which includes the adoption of evolving commercial power and energy systems alongside a commitment to reduce logistical footprints and align with the Army's climate strategy (Department of the Army, 2022).

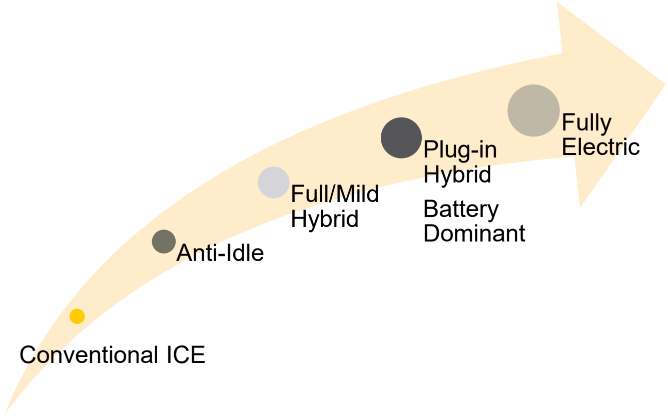


Figure 1. Increasing levels of electrification/hybridization

The approach is intended to be universally applicable to ensure comprehensive integration of future advancements in military vehicular power and energy technologies. It is also designed to refine the modeling of energy use and allocation within combat simulations. Enhancing combat simulation models will support more accurate resource distribution and tactical decision-making. This approach could improve data fusion beyond the perspective of energy consumption rates by emphasizing the tactical implications of electrification.

The transition to electrified battlefields signifies a fundamental shift in energy modeling. Electrification means a shift from concentration on fuel consumption rates to tracking electrical power rates within platforms and understanding multifaceted power and energy considerations beyond liquid hydrocarbons. The new modeling approach enhances data integration and simulation accuracy while maintaining focus on sustainment. The new methodology aims to predict energy demands with greater precision, while considering the enhanced capabilities and strategic advantages of electrified vehicles. Table 1 outlines the energy related functions, capabilities, and enabling benefits of electrified ground vehicles.

Table 1. Example capability and energy considerations for the future battlefield

Energy Considerations for MDO/LSCO/CLE	
Function/Capability	**Benefit**
Fuel powered generator to vehicle	Semi-portable charging points
Vehicle to vehicle	Flexible energy sharing
Grid to vehicle	Enhanced power capacity
Vehicle to grid	Energy load balancing
Renewable generation to energy storage	Silent charging
Energy storage to vehicle	Silent charging
Energy storage to grid	Energy load balancing
Auxiliary power unit to vehicle or energy storage	Spot generation

1.2 Network-Centric View of Battlefield Electrification

An initial step in establishing improved understanding of operational energy and its sustainment within combat simulations was to identify how systems on the future modern battlefield will act as a network to enhance Warfighter capabilities. This effort builds on this realization with a focus on hybrid-electric vehicles and fully electric ground vehicles.

Electrification allows a shift in planning for sustainment of ground vehicles as it introduces the concept of energy as a network. That is, the proposed framework foresees each entity, whether consuming, producing, or storing energy, as a node within a comprehensive energy network. This network facilitates bidirectional energy flows, optimizing resource utilization across various platforms. There are advantages to these networks and challenges in adequately modeling the new approach to energy distribution beyond traditional liquid fuel. A network perspective allows for more diverse power generation and storage methods and is important for understanding the complex interplay of energy resources on future battlefields. This framework enables the categorization of electrified assets into distinct roles—consumers, producers, suppliers, and storers.

Implementing this network-centric model is expected to significantly enhance the precision of energy supply and demand calculations, which is key for the success of modeling energy consumption in combat simulations as it pertains to MDO, LSCO, or CLE.

1.3 Mobility Calculations and Electrification Algorithms in Combat Simulations

This technical report presents an energy consumption methodology for integration within combat simulations. It does not delve into the specifics of mobility power and energy estimations, including how fuel and electrical consumption rates are calculated. These calculations form the basis for the information provided for data requests (the consumption rate lookup tables in this report). Instead, the focus of this report is how those consumption tables can be used to represent electrification.

Details on the underlying methodologies of these power rate estimations can be found in previous comprehensive reports. These include the Fuel Consumption Prediction Model (FCPM) (Dogum et al., 2019; Fisher & Mastrola, 2013; Mastrola, 2016) or the CLEAT reports (Carrier, 2021). Both are physics-based, empirically derived models developed by DAC, providing in-depth insights into the overall calculation processes. FCPM focuses on system-level steady-state fuel consumption estimates while CLEAT addresses component-level steady- and transient-state fuel and energy consumption estimates.

In a related development, efforts are underway to enhance the lower resolution model, FCPM, by incorporating electrification. This initiative parallels the work presented in this report but is not covered in detail here.

This technical report explains the application of the proposed consumption lookup tables for data request purposes, rather than exploring the foundational computational models.

2. METHODS, ASSUMPTIONS, AND PROCEDURES

This section reviews the methods, assumptions, and procedures for implementing the vehicle electrification framework and provides a comprehensive overview of the approach.

2.1 Methods

This section outlines the approach to representing system-level behavior in combat simulations across various levels of electrification employment that the Army anticipates may be developed and deployed. This section provides an introduction, and an understanding of the methodology and its potential implementation.

2.1.1 Electrification Methodology Introduction

The proposed algorithms utilize system-level representation through standardized lookup tables. These tables provide steady-state energy rates for each vehicle under different conditions; they are key to conducting power and energy analysis. Recognizing the need for greater specificity for electrified platforms, the lookup tables were modified to accommodate additional vehicle energy modes (VEMs). These enhancements allow for a more nuanced representation of each vehicle's performance based on the specified climate zones, surface conditions, terrains, and slope combinations that provide the basis for predicting maximum safe speeds. Lookup table will include not just fuel consumption rates but also battery discharge or recharge rates.

Another key aspect of this method is the identification of behaviors common to different levels of vehicle electrification. This process enables understanding of the tactical advantages and improved capabilities that electrified platforms offer to the Warfighter. It focuses on capturing a prediction of vehicle state, particularly for hybrid platforms with multiple propulsion and energy sources. The data tables developed are flexible enough to support a wide spectrum of vehicles, including traditional internal combustion engine (ICE)-based systems, hybridized, and fully electrified vehicles.

The algorithms are designed to operate via two approaches within a combat simulation: user-directed and automated. Both approaches utilize the same lookup tables, with the automated method manipulating the data to make decisions in situations or circumstances where a user-directed decision is either unknown or not specified. This allows for user control or commander decisions to attempt direction of vehicle operation from a tactical perspective based on specific situations or circumstances (e.g., requiring silent watch or silent mobility in urban maneuvers). In cases where no intended tactical behavior is specified, the algorithm can automatically select an optimized mode for electrified platforms. If the user-directed approach is used, the system can also flag whether the vehicle was able to achieve the desired mode.

The tactical decisions within this methodology are categorized by two Tactical Operation Modes (TOMs): *normal signature* or *reduced signature*. This level of decomposition simplifies the process, enabling rapid and efficient calculations. Consequently, the proposed lookup tables are expanded to cover each of these modes and speeds for each condition; they are applicable across the entire range of electrified platforms. This approach ensures an adaptable framework for analyzing a wide array of vehicle types and conditions within combat simulations. Based on either normal or reduced signature, subsequently, the algorithms can use a rules-based approach that will be defined in Section 2.3 to pick one of three VEMs: *Charge Sustaining (CS), Charge Replenishing (CR),* and *Charge Depleting (CD)*. These TOMs and VEMs will be defined in greater detail in Section 2.3.

2.1.2 Implementing Tactical Behavior Control in Vehicle Simulation

This section details the approach for implementing user-directed options for tactical control within combat simulations. This is not the only method to employ electrification within combat simulations; however, it is key to deliberate control of a vehicle's behavior. The approach is designed for intuitive use and aligns with realistic operational scenarios, ensuring flexibility and precision in simulation outcomes. This is not exhaustive but rather demonstrative of the benefits of this approach.

2.1.2.1 Tactical Behavior and Charging State Association (User-directed)

The methodology employs nuanced links between tactical behaviors and vehicle energy states. Instead of direct mappings such as "Silent Mode" to "Charge Depleting," a more abstract association enhances the simulation's tactical realism. For example, "Silent Mode" correlates with the "Reduced Signature" TOM. This alignment accurately reflects decision-making processes in real-world scenarios, dictating the vehicle's general energy management strategy and the corresponding lookup table selection—whether the VEM be charge sustaining, replenishing, or depleting.

2.1.2.2 Integration with Human-in-the-Loop (HITL) System Concepts (User-directed)

Integration with HITL systems is another opportunity for modelers to control tactical behavior. In scenarios where vehicles approach urban environments or sensitive areas, for example, an HITL can direct the vehicle to switch to a lower thermal/auditory mode and the corresponding reduced signature TOM in advance. If the Warfighter determines the absence of nearby threats, they can command the vehicle to switch to normal signature mode, allowing for dynamic decision-making that could match actual battlefield decisions.

2.1.2.3 Decision-Making in Ambiguous Situations (Automated)

In situations where the operational mode is not a distinctly “normal” or “reduced” signature, the methodology defaults to an automated decision-making process. This process considers various factors (e.g., vehicle speed, terrain, slope, and fuel level or battery SOC) to optimize operational efficiency. This option reduces the burden associated with requiring TOM decisions to be made for every situation.

2.1.2.4 Pairing Behaviors with TOM to Predict VEM

The explicit linkage of user-directed behaviors with intended TOM allows for rules-based algorithms to decide between the VEM options, which is a critical feature of this framework. This ensures that the simulation’s physical model equations accurately reflect the vehicle’s capabilities (i.e., battery SoC or power requirements) under different conditions. This approach maintains data fidelity for combat simulations, realistically depicting the vehicle’s functional capabilities.

Thus, this approach to user-directed options in vehicle simulations provides a realistic and tactical representation of operation-centric decision-making, while still allowing for a pathway for automation when operational behavior is ambiguous or unknown. It provides a framework that accommodates a wide spectrum of tactical scenarios and vehicle capabilities, while maintaining flexibility of user control. By linking user behaviors to TOMs, the methodology sets up a robust framework for accurately simulating the complexities of vehicle operations in complex combat environments. The approach provides an analytical tool that can quantify the operational value of electrification; thus, making an effective asset for potential Army modernization goals to include training, planning, and decision-making in sustainment analysis or acquisition programs. This ensures that the simulations are not only reflective of real-world conditions but also adaptable to evolving tactics, techniques, procedures, and technological advancements.

2.2 Assumptions

The need for this methodology and the process for development was based on several key assumptions:

1. **Electrification as a key modernization goal**: Electrification of vehicles will be a significant feature in the future battlefield. Ground vehicle electrification is a major aspect of the Army’s modernization goals and will substantially change the dynamics of future battlefields.

2. **Impact on M&S tools**: Existing M&S tools do not currently provide the necessary fidelity to model the operational capabilities and nuances of electrified platforms.
3. **Shift in tactical operations**: The integration of electrified vehicles will have a considerable impact on the Army's tactics, techniques, and procedures, necessitating new approaches to combat or operational strategies.
4. **Change in energy focus**: Transition to electrified battlefields requires a shift from focusing predominantly on liquid fuel consumption rates to including electrical power rates for multifaceted energy considerations.
5. **Requirement for improved energy estimations**: There exists a requirement to estimate energy more accurately, particularly in operational contexts, thereby improving the fidelity of combat simulations.
6. **Flexibility and comprehensiveness of approach**: A simplified yet comprehensive approach is assumed to be effective for modeling all levels of vehicle electrification, including traditional nonelectrified platforms.
7. **Alignment with technological and climate strategies**: The study presumes an improved understanding and integration of technological modernization objectives will substantially enhance combat simulations, particularly in the areas of Class IIIB bulk fuel sustainment and operational analyses. The study aligns with the Army's climate strategy (Department of the Army, 2022), implying a commitment to a reduced logistical footprint and the adoption of improved power and energy efficiency.
8. **Interoperability and standardization**: Electrified vehicles will need to be interoperable with existing military systems, equipment, and protocols to ensure seamless integration into current operational systems. An agnostic approach to modeling, which can be applied universally across various levels of vehicle electrification, will be required. Electrification technologies will be standardized across different platforms.
9. **User familiarity and understanding**: It is assumed that the user has an understanding and familiarity of how maximum safe speeds are calculated. This includes knowledge of the NATO Reference Mobility Model (NRMM), the Standard Mobility Model (STNDMob) Application Programming Interface, STNDMob representative vehicle bins, and the crosswalk between Mobility Lookup (MLU) codes to Surface Trafficability Group Joint Simulation System (STGJs) identifiers. All of which form the basis for the maximum safe speed determination used in the tractive force calculations and fuel and energy consumption estimates. Ultimately, these calculations and estimates are used to populate the proposed lookup tables using the DAC-developed physics-based models (e.g., CLEAT and FCPM). This process is critical to how fuel

consumption rates for specific terrain-to-vehicle combinations will be provided—to include differences based on surface conditions and climate zones.

2.3 Procedures

Section 2.3 is intended to introduce specific definitions, concepts, and terms critical to implementing the proposed vehicle electrification representation framework. These will be highlighted in bold throughout this section to indicate important definitions and concepts that will set the foundation of how hybrid-electric and electric vehicles can be represented. The process of implementing the algorithms is also provided, with results and examples following in Section 3.

2.3.1 Proposed Implementation and Framework Introduction

The proposed implementation requires some initial understanding of the problem space. Initially developed for use in combat simulations, the methodology was created to be comprehensive so that it can align with a variety of decision-making, tradespace, or requirements analyses.

2.3.2 VEM Definitions

The proposed framework is centered around providing energy consumption rates that are differentiated across three distinct energy modes for powertrain configurations associated with conventional, hybrid-electric, and fully electric vehicles. These VEMs are defined as follows and summarized in Table 2:

1. **CS**: Applicable to conventional and hybrid-electric platforms, this mode maintains the battery's SoC over time.
2. **CR**: Relevant for hybrid-electric platforms, this mode involves recharging the battery from the vehicle's own power generation capabilities on the move or while idling.
3. **CD**: Used by hybrid-electric and fully electric platforms, this mode describes scenarios where the vehicle operates on battery power until a recharge is necessary.

Table 2. VEM summary

VEM	Liquid Fuel	Battery	VEM Description
CS	Fuel Decreasing (-)	No Change	Engine provides power, no significant change to high voltage battery power consumption
CR	Fuel Decreasing (-)	Battery SoC Increasing (+)	Engine provides power and recharges the battery
CD	No Change or Fuel Decreasing (-)	Battery SoC Decreasing (-)	Battery provides power, engine off or on if required for maximum power

These three modes are intended to be holistic and represent the new proposed lookup tables for combat simulators. Inputs will be provided for all vehicles regardless of their level of electrification, from conventional platforms, anti-idle, mild/full hybrids (parallel, series, or combination), battery dominant, or fully electric platforms. For example, whether the system is characterized as a conventional, hybrid-electric, or electric-only system, the three VEMs will capture all potential operational behaviors, as summarized in Table 3. They will provide a uniform standard output; however, for some vehicles, the values will be unused (i.e., a placeholder such as –999 to indicate “not applicable” might be used).

Table 3. Application of VEM and vehicle type

Vehicle Type/System	CS	CR	CD
Conventional	Applicable	Not applicable	Not applicable
Hybrid-Electric	Applicable	Applicable	Applicable
Electric	Not applicable	Not applicable	Applicable

More specifically, each VEM will have an associated fuel (e.g., liquid fuel, hydrogen, compressed natural gas) and battery consumption rate metric:

1. **Fuel Consumption Volumetric Rate (time-based metric)**: The rate at which a vehicle consumes fuel in each mode, represented as a volumetric flow rate, such as gallons per hour.
2. **Battery Charge/Discharge Rate (time-based metric)**: The rate at which the vehicle’s battery is charged or depleted in each mode, represented in kilowatts.

2.3.3 TOM

Another key component of this methodology is the TOM. This is a key behavior to determine which specific VEM will be utilized for any given time step in the subroutine within combat simulations or other time-based power and energy simulations. A vehicle can operate in two different TOMs (normal or reduced signature), which are defined in Table 4.

Table 4. TOM summary

TOM	VEM	TOM Description
Normal Signature (NS)	- CS - CR - CD	Internal combustion engine, range extender, or other liquid/gas-based fuel energy conversion system is operating and providing power to supply mobility or non-mobility demands while moving or stationary. If system requires additional power, energy from battery and traction effort can also be applied through the motor.
Reduced Signature (RS)	- CD	Vehicle operates solely under battery and electric motor to match moving or nonmoving requirements; thus, suppling necessary mobility or non-mobility power demands electrically only.
No Preference (Automated)	- CS - CR - CD	Does not imply vehicle signature management explicitly, allowing the algorithm to dynamically decide between energy modes. Depending on conditional efficiency between the mechanical or electrical system, and remaining energy in the fuel tank or battery, an optimized selection is determined between the three VEMs.

The operating state to decide which VEM to use is determined by a set of key variables that can be driven by explicit instruction through a commander or user-driven decision, or implicitly decided automatically based on the efficiency of the hybrid-electric powertrain for a given condition.

For the explicit method, which relies on a rules-based approach, the key variables require tracking the system state through the simulation. This commander/user-driven method will be further discussed Section 3.1.

1. **Battery SoC**: The current energy level of the battery as a percentage of its total usable capacity. This requires an initial condition at the onset of the simulation. Additionally, each vehicle will be characterized by a unique battery SoC operating window (i.e., usable capacity), which will guide the simulation to stay within the system’s characteristics.
2. **TOM**: The intended operational state of the vehicle, which will affect the selection of the specific energy consumption mode (i.e., VEM). This requires explicit instruction to operate under “normal” signature mode or “reduced” signature mode. The implication of normal signature mode means the system scenario does not require or demand silent operations, whereas the reduced signature mode implies lower auditory or lower thermal signature operations.
3. **Fuel Level**: The remaining fuel in the vehicle, which can dictate the preferred operating mode. This variable is key to defining whether there can be sufficient fuel to feasibly replenish the battery energy. Below a certain threshold, these

rules will not allow the battery to be recharged by the ICE or other such method (e.g., fuel cell).

The implicit method relies primarily on a physics-based approach, and the algorithm does not require any specific input from the user on the desired or intended vehicle TOM (i.e., normal or reduced signature). Deciding which VEM to select is entirely based on the following two concepts (efficiency of fuel/motor and remaining energy in fuel/battery). This default or automated method will be further discussed in Section 2.3.4.1 and demonstrated in Section 3.1.

4. **Efficiency of Fuel or Motor for Condition**: The current efficiency of the vehicle's propulsion system based on the operating conditions.
5. **Remaining Energy Reserve**: The remaining fuel energy (e.g., JP-8, hydrogen, compressed natural gas) and battery energy.

The intent of the VEM is on providing steady-state energy predictions which can be used in combat simulations. In addition, the VEM values will be suitable for supporting the traditionally large data requests that are required to support combat simulations. Combat simulations will require the tracking of energy states (e.g., VEM values), like the current accounting of fuel tank volumes but now with the addition of battery SOC.

2.3.4 Determining VEM State

To determine the operational state of an electrified or conventional vehicle, two distinct approaches are proposed to employ these algorithms: user-directed and automated. Notably, the automated approach does not necessitate additional data beyond what is already present in the forthcoming lookup tables. The methodology effectively utilizes existing data to facilitate automated decisions for predicting the most efficient system state.

The vehicle's operational state can be established in one of two ways, which are described in greater detail in Section 2.3.4.1.

2.3.4.1 Option/Method 1: User-directed (Explicit Instructions)

The process for determining energy consumption in a combat simulation involves a rules-based strategy centered on TOM, battery SoC, fuel level, and VEM when under the user-directed explicit instruction method. The process can be described as follows:

1. **Initialization of Vehicle Data**: The first step in the subroutine that determines energy consumption for a specific period or time step within a combat simulation involves initializing vehicle data. These initial conditions include the status of the

vehicle and other operational scenario-related information. The operational scenario-related data is important for finding the appropriate entries in the provided energy lookup tables, which will guide subsequent calculations and decisions. Meanwhile, initial conditions for battery and fuel levels are required to determine the VEM using the proposed rules-based algorithm.

2. **Load Thresholds and Capacities**: The subroutine begins by loading the thresholds for the battery's operating regime, which is defined by a low and high SoC threshold. Additionally, the data is associated with the vehicle's characteristics; specifically, the battery's useable capacity and the vehicle's fuel capacity. Establishing an initial condition for the SoC and fuel level sets the stage for the decision-making process that follows.
3. **User-Directed TOM Decision**: For the user-directed portion of the simulation, a decision is required from the commander or simulator regarding the vehicle's TOM, which can be either normal or reduced signature. This choice directly influences the vehicle's energy consumption and operational behavior, given the vehicle's battery SoC or fuel level.
4. **Energy Mode Determination and Consumption Calculation**: If the SoC is above the low threshold and the vehicle is directed to operate in a reduced signature mode, the vehicle enters a charge depleting VEM. The energy consumed during this time step is calculated by multiplying the rate by the time step duration, which is then subtracted from both the battery capacity and fuel level. The SoC is subsequently updated. If the vehicle successfully achieves the desired TOM, an objective flag is raised to indicate success or pass value. However, if the SoC falls below the operating window, the vehicle enters a charge replenishing state if the fuel level is above its low threshold; otherwise, it switches to a charge sustaining mode. Both conditions result in a "fail" objective flag indicating inability to match desired TOM.
5. **Normal Mode Operations**: In scenarios where the vehicle is directed to operate in normal mode, and the battery SoC is below the upper threshold, the vehicle enters a charge replenishing state if the fuel level is above the low threshold, resulting in a pass objective flag. If the battery SoC is at or above the upper threshold, and if the vehicle is above its low fuel threshold, the vehicle operates in a charge sustaining mode. In cases where there is no fuel left for normal operation, but sufficient battery capacity remains, the vehicle will switch to a charge depleting mode. Additionally, fuel efficiency calculations are not the primary purpose of combat simulations, so the selection of normal signature mode is solely from a tactical perspective to deliberately reserve battery energy and consume fuel instead.
6. **Outcome of Rules Application**: The application of these rules ensures that at any given point in the simulation, the VEM—CD, CR, or CS—is clearly defined.

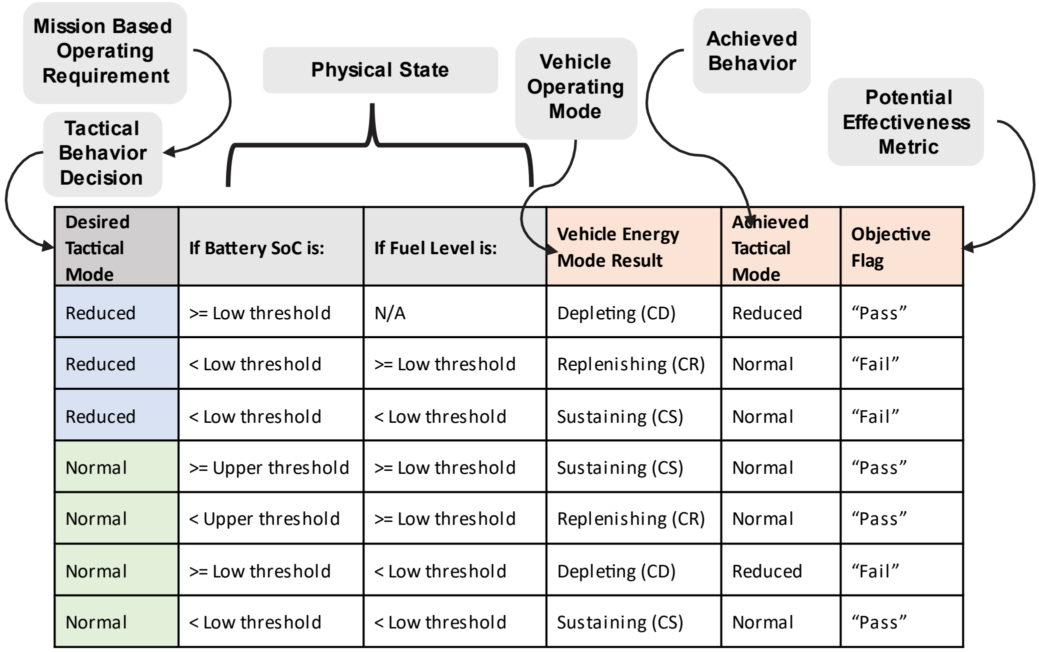
This determination is important for accurately predicting energy dynamics and tactical decisions for conventional, hybrid-electric, and electric vehicles within the combat scenario.

Through this structured procedure, the simulation accurately mirrors the energy consumption patterns of vehicles in various operational modes. It provides a realistic representation of how tactical decisions and vehicle states influence energy usage, enhancing the fidelity and operational relevance of performing these calculations in combat simulations.

In this report, we refer to the outcomes of our simulations in terms of whether the hybrid electric vehicles achieve their desired TOM. When the desired TOM aligns with the achieved TOM, we denote this as a “pass.” Conversely, when there is a discrepancy between the desired and achieved TOM, we have categorized this as a “fail.” However, it is important to note that this binary classification of “pass/fail” can be further nuanced. Alternative terminologies that may be employed to describe these outcomes include “Met/Unmet Criteria,” “Achieved/Not Achieved,” “Effective/Ineffective,” and “Operational/Non-Operational,” among others. Each of these alternatives provide a different perspective on the simulation results, emphasizing various aspects of performance and operational capability. The final choice of terminology should be guided by the specific context and objectives of the simulation, as well as by considerations of how best to communicate the performance of the hybrid-electric platform.

Within the scope of our combat simulations for hybrid electric vehicles, an important operational consideration is the vehicle’s energy management, specifically scenarios where a vehicle depletes its energy reserves and requires refueling and/or recharging. This process, important for maintaining operational readiness, can be accomplished through external or internal means, mirroring real-world logistics and support mechanisms. However, it is important to note that the specifics of refueling and recharging protocols, while integral to the sustainability of vehicle operations in a combat environment, are not directly addressed within the rule’s discussion in this report. The focus is on the evaluation of TOM achievements and the corresponding effectiveness metrics. The logistics of energy replenishment fall outside the immediate intent of the vehicle energy management algorithm but is recognized as another component of overall vehicle operational capability in combat simulations.

Figure 2 summarizes the previous description regarding the rules-based strategies employed by the proposed algorithms.



Desired Tactical Mode	If Battery SoC is:	If Fuel Level is:	Vehicle Energy Mode Result	Achieved Tactical Mode	Objective Flag
Reduced	>= Low threshold	N/A	Depleting (CD)	Reduced	“Pass”
Reduced	< Low threshold	>= Low threshold	Replenishing (CR)	Normal	“Fail”
Reduced	< Low threshold	< Low threshold	Sustaining (CS)	Normal	“Fail”
Normal	>= Upper threshold	>= Low threshold	Sustaining (CS)	Normal	“Pass”
Normal	< Upper threshold	>= Low threshold	Replenishing (CR)	Normal	“Pass”
Normal	>= Low threshold	< Low threshold	Depleting (CD)	Reduced	“Fail”
Normal	< Low threshold	< Low threshold	Sustaining (CS)	Normal	“Pass”

Figure 2. User-directed rules-based algorithm summary

2.3.4.2 Option/Method 2: Automated (Implicit Instructions)

This methodology provides a simplified approach to model and control hybrid vehicles for combat simulations. It is designed to be applicable across all types of electrified architectures and control strategies. The goal is to manage the use of fuel and electric power to balance efficiency and performance.

Two key nondimensional parameters are defined to facilitate the automated behavior process: the **Fuel-Electric Efficiency Ratio (FEER)** and the **Remaining Energy Reserve Ratio (RERR).** The first measures the relative efficiency of fuel consumption to electric consumption, while the second adjusts the remaining energy resources. Both are nondimensional parameters and are used to calculate the key metric that decides which VEM is suited for the condition and state of the vehicle’s remaining energy—the **Resource-Adjusted Consumption Ratio (RACR)**. These two parameters, FEER and RERR, are used to calculate the RACR, a measure of the relative efficiency of fuel to electric consumption (FEER), adjusted and normalized for the remaining energy resources (RERR), a nondimensional parameter.

To determine which VEM to use, the definition is expanded with additional **threshold parameters** for each of the previously introduced VEMs. That is, based on the RACR metric, the vehicle operates in one of three modes: CD, CS, or CR depending on predefined default or custom threshold parameters.

CS Mode: The conventional or hybrid-electric vehicle operates in this mode when the RACR is less than a predefined fuel-only threshold value. In this mode, the vehicle primarily uses its fuel power however electrical power can be used as required to meet mobility demands. Notably, in scenarios of negative mobility requirements (i.e., downhill driving), CS mode facilitates a regenerative braking opportunity for hybrid electric or electric vehicles, enabling the vehicle to maintain desired steady speed while harnessing a portion of the energy from the negative mobility force.

CR Mode: The hybrid-electric vehicle operates in this mode when the RACR is between the fuel-only and battery-only threshold values. In this mode, the vehicle balances the use of fuel and battery power and recharges the battery if it satisfies the battery SOC operating window.

CD Mode: The hybrid-electric or electric vehicle operates in this mode when the RACR is greater than a predefined battery-only threshold value. In this mode, the vehicle primarily uses its battery power.

However, we need to define initial threshold parameters or values to determine what level of RACR will determine which mode to operate in. These will ultimately be suggested on a per-platform basis; however, the user may increase or decrease the RACR thresholds as necessary. The midpoint of the RACR is assumed to be 1.0, with a default “gap” value of 0.33. This establishes the operating mode window thresholds/boundaries. The midpoint is given a value of 1.0 because for the specific speed, slope, and terrain condition, the amount of energy (e.g., megajoules) from the mechanical and electrical systems would be equal. The “gap” value is a sensitivity control toggle of a vehicle’s behavior with respect to selecting between the mechanical and electrical systems. This is a customizable value and can be used to tune platforms if empirical data is available, or if any bias exists between battery operation or fuel operation.

These default values (for MV and GV) serve as a practical starting point, derived from initial analyses and theoretical modeling to ensure a balanced and efficient operation across typical conditions. However, recognizing the diversity of vehicle platforms and operating environments, further testing and empirical validation are encouraged to refine these settings for optimal performance and efficiency. Additionally, the value shown here is intended to be demonstrative for the use case in this report but tailored values for distinct vehicle types can be provided in the future and encourage future users to conduct simulations to identify the configurations or values for MV and GV that best meet their specific requirements. Further examples are shown in Appendix A on the sensitivity to these key threshold parameters.

There are three bins associated with the RACR value: Fuel Only Threshold (FOT), Battery Only Threshold (BOT), and (for values between those thresholds), the Recharging Value Range. The bins by default are defined as follows:

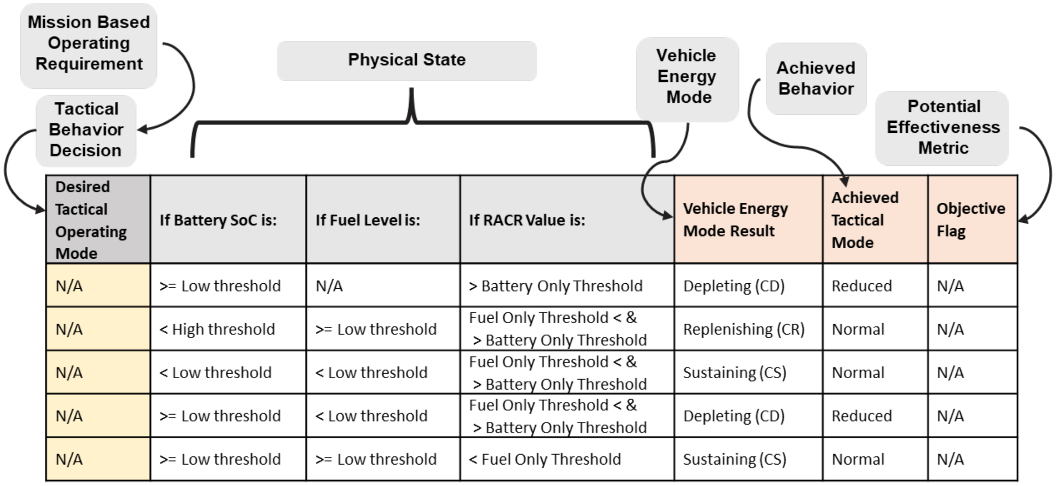
1. **FOT:** For values less than 0.67 (0.00 = < x < 0.67), the vehicle operates in CS mode, primarily using its fuel power. In CS mode, if the condition results in negative mobility requirement, then regenerative power could occur if it is a hybrid electric or electric vehicle with capacity to capture the energy based on the battery SOC.
2. **BOT**: For values greater than 1.33 (1.33 < x), the vehicle operates in CD mode, primarily using its battery power.
3. **In-between Values:** For values between 0.67 and 1.33 (0.67 = < x < = 1.33), the vehicle operates in CR mode, balances the use of fuel and battery power, and charges the battery if possible.

This methodology provides a simplified, yet effective way to control hybrid-electric vehicles. By dynamically adjusting the operating mode based on the RACR defined in this approach, optimal use of both fuel and electric power are ensured, leading to improved efficiency and performance for combat simulations when the behavior aspect cannot be defined or if no preference for operating mode exists for a simulation. Table 5 summarizes the metrics introduced in the automated process flow.

Table 5. Summary of metrics and variables for automated process

Metrics	Variables	Description/Conditions
Calculated parameters (nondimensional)	**FEER**	Measures relative efficiency of fuel to electric consumption.
	RERR	Adjusts for remaining energy in both fuel and electric sources.
	RACR	Uses FEER and RERR to calculate a measure of efficiency between fuel and electric consumption. Adjusted and normalized for remaining energy resources.
VEMs	**CS**	Operates when RACR is greater than the predefined fuel-only threshold value. Primarily uses fuel power.
	CR	Operates when RACR is between the battery-only and fuel-only thresholds. Balances the use of fuel and battery power, and recharges battery if conditions are met.
	CD	Operates when RACR is greater than the predefined battery-only threshold value. Primarily uses battery power.
Mode-specific Thresholds	**Midpoint Value (MV)**	Assumed to be 1.0 for RACR as a neutral control point. Indicates that the mechanical and electrical systems' energy output is equal given specific conditions (speed, slope, terrain, etc.). Depending on application and use case, this value can be tuned to match desired vehicle behavior.
	Gap Value (GV)	Default estimation is 0.33. Defines the sensitivity of the control between selecting the mechanical or electrical systems. Customizable and can be adjusted based on empirical data or specific operational bias.
	FOT	RACR values less than MV minus GV (e.g., 0.00 < = x < 0.67) result in charge sustaining mode. Primarily uses fuel power, unless under negative mobility condition and will capture some energy for hybrid electric or electric vehicles
	BOT	RACR values greater than MV plus GV (e.g., 1.33 < x) will result in charge depleting mode. Primarily uses battery power.
	Recharging Range (RR)	RACR values between 0.67 and 1.33 (0.67 < = x < = 1.33) result in CR mode. Balances the use of fuel and battery power and charges battery if possible.

In summary, the automated option introduces a hands-off approach for modeling and controlling hybrid-electric vehicles in combat simulations. It is designed to be universally applicable, catering to various hybrid-electric architectures and control strategies. The primary objective of this approach is to distinguish between fuel and electric power use, thereby balancing efficiency and performance while allowing the user to customize how aggressive or passive the use of fuel or battery energy is undertaken within the simulation. The dynamic adjustment of the vehicle's operating mode based on the RACR is central to this methodology. RACR ensures balanced fuel and electric power use, leading to realistic efficiency and performance in combat simulations. This approach becomes particularly useful when the behavior aspect of a vehicle cannot be specifically defined, or when there is no distinct preference for an operating mode in each simulation. Figure 3 summarizes this automated process.



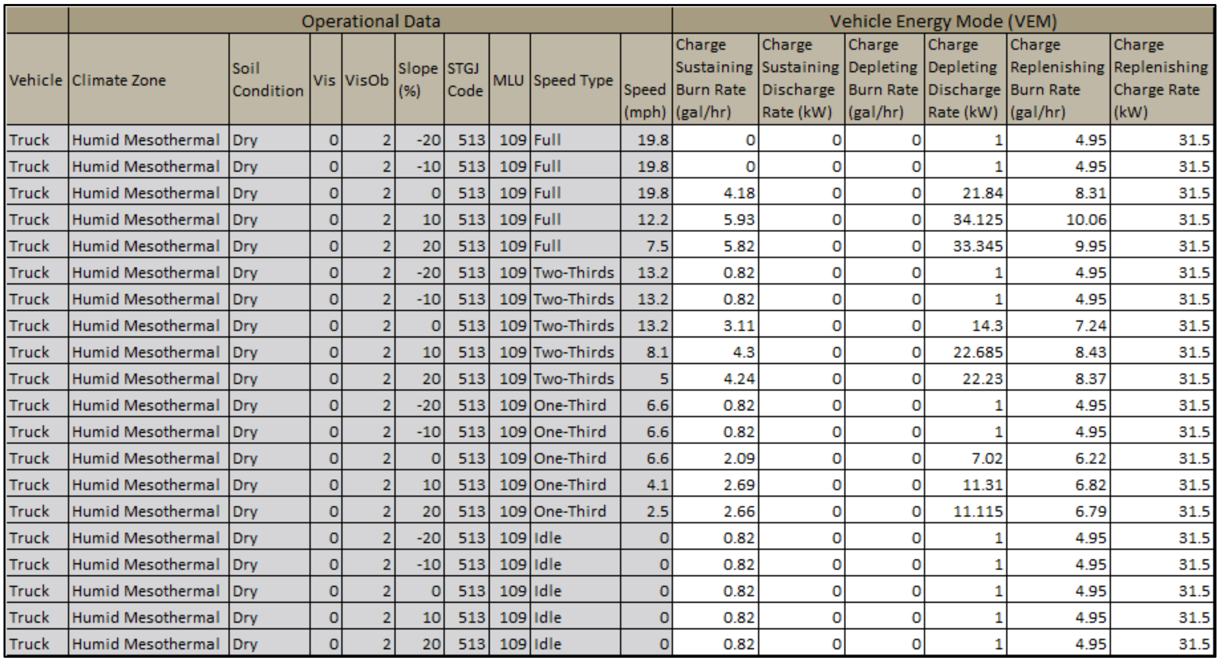
Desired Tactical Operating Mode	If Battery SoC is:	If Fuel Level is:	If RACR Value is:	Vehicle Energy Mode Result	Achieved Tactical Mode	Objective Flag
N/A	>= Low threshold	N/A	> Battery Only Threshold	Depleting (CD)	Reduced	N/A
N/A	< High threshold	>= Low threshold	Fuel Only Threshold < & > Battery Only Threshold	Replenishing (CR)	Normal	N/A
N/A	< Low threshold	< Low threshold	Fuel Only Threshold < & > Battery Only Threshold	Sustaining (CS)	Normal	N/A
N/A	>= Low threshold	< Low threshold	Fuel Only Threshold < & > Battery Only Threshold	Depleting (CD)	Reduced	N/A
N/A	>= Low threshold	>= Low threshold	< Fuel Only Threshold	Sustaining (CS)	Normal	N/A

Figure 3. Automated rules-based algorithm summary

2.3.5 Calculation Process for Option/Method 2

This section provides additional details on the automated method. The general instructions for how this method can be employed is discussed, with results shown in Section 3.

Figure 4 is a notional data request product for a vehicle operating on specified surface condition and STGJ code within a designated climate zone. Consumption rates are provided for the full slope range and for four distinct speeds (includes idle). The maximum safe speed value for the vehicle in question is calculated using the STNDMob API for each slope, STGJ, surface condition, and climate zone combination. The one-third and two-thirds speed values are in reference to this maximum safe speed.



	Operational Data									Vehicle Energy Mode (VEM)					
Vehicle	Climate Zone	Soil Condition	Vis	VisOb	Slope (%)	STGJ Code	MLU	Speed Type	Speed (mph)	Charge Sustaining Burn Rate (gal/hr)	Charge Sustaining Discharge Rate (kW)	Charge Depleting Burn Rate (gal/hr)	Charge Depleting Discharge Rate (kW)	Charge Replenishing Burn Rate (gal/hr)	Charge Replenishing Charge Rate (kW)
Truck	Humid Mesothermal	Dry	0	2	-20	513	109	Full	19.8	0	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	-10	513	109	Full	19.8	0	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	0	513	109	Full	19.8	4.18	0	0	21.84	8.31	31.5
Truck	Humid Mesothermal	Dry	0	2	10	513	109	Full	12.2	5.93	0	0	34.125	10.06	31.5
Truck	Humid Mesothermal	Dry	0	2	20	513	109	Full	7.5	5.82	0	0	33.345	9.95	31.5
Truck	Humid Mesothermal	Dry	0	2	-20	513	109	Two-Thirds	13.2	0.82	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	-10	513	109	Two-Thirds	13.2	0.82	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	0	513	109	Two-Thirds	13.2	3.11	0	0	14.3	7.24	31.5
Truck	Humid Mesothermal	Dry	0	2	10	513	109	Two-Thirds	8.1	4.3	0	0	22.685	8.43	31.5
Truck	Humid Mesothermal	Dry	0	2	20	513	109	Two-Thirds	5	4.24	0	0	22.23	8.37	31.5
Truck	Humid Mesothermal	Dry	0	2	-20	513	109	One-Third	6.6	0.82	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	-10	513	109	One-Third	6.6	0.82	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	0	513	109	One-Third	6.6	2.09	0	0	7.02	6.22	31.5
Truck	Humid Mesothermal	Dry	0	2	10	513	109	One-Third	4.1	2.69	0	0	11.31	6.82	31.5
Truck	Humid Mesothermal	Dry	0	2	20	513	109	One-Third	2.5	2.66	0	0	11.115	6.79	31.5
Truck	Humid Mesothermal	Dry	0	2	-20	513	109	Idle	0	0.82	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	-10	513	109	Idle	0	0.82	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	0	513	109	Idle	0	0.82	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	10	513	109	Idle	0	0.82	0	0	1	4.95	31.5
Truck	Humid Mesothermal	Dry	0	2	20	513	109	Idle	0	0.82	0	0	1	4.95	31.5

Figure 4. Example energy consumption lookup table for a notional hybrid-electric platform

Table 6 establishes conversion factors for liquid or gaseous fuels to make calculations in terms of joules to compare the mechanical and electrical efficiency of the system at any moment during the simulation.

Table 6. List of unit conversion factors

Fuel	Density (lb/gal)	Density (kg/gal)	Heating (btu/gal)	Heating (btu/lb)	Heating (btu/kg)	Energy (MJ/gal)	Energy (Wh/gal)
DF-2	7.107	3.224	130,319	18,451	40,678	137.5	38.2
DL-1	6.779	3.075	125,960	18,581	40,964	132.9	36.9
DL-2	7.111	3.225	131,207	18,451	40,678	138.4	38.5
JP-4	6.302	2.859	118,124	18,744	41,323	124.6	34.6
JP-5	6.826	3.096	125,270	18,352	40,459	132.2	36.7
JP-8/F-24	6.652	3.017	123,069	18,501	40,788	129.8	36.1
LH2	0.588	0.267	35,868	61,000	134,482	37.8	10.5
GH2_5kPSI	0.035	0.016	2135	61,000	134,482	2.3	0.6

The first step of the automated process is to convert consumption rates and energy resources into joules. Note: 1 kWh = 3.6 MJ.

2.3.5.1 Variables

The following list establishes the required variables extracted from the lookup table and/or derived and calculated in the subsequent conversions and equations. The values below for the charge depleting or charge sustaining power rates are all normalized for one hour of operation to remove the time component and facilitate a direct comparison of both potential VEM conditions.

Let CD_{EC} be the charge depleting energy consumption in megajoules.

Let CD_{BR} be the charge depleting battery rate in kilowatts.

Let CD_{FR} be the charge depleting fuel rate in gallons per hour.

Let CS_{EC} be the charge sustaining energy consumption in megajoules.

Let CS_{FR} be the charge sustaining fuel rate in gallons per hour.

Let $\mathrm{FR}_{\mathrm{MJ}}$ be the potential fuel energy remaining in megajoules.

Let BR_{MJ} be the potential battery energy remaining in megajoules.

Let FR_{gal} be the potential fuel energy remaining in gallons.

Let BR_{kWh} be the potential battery energy remaining in kilowatt-hours.

2.3.5.2 Energy Conversion Equations

To facilitate a direct comparison between fuel consumption rates (expressed in gallons per hour) and battery discharge rates (expressed in kilowatts), this methodology normalizes these values for one hour of steady-state operation. This normalization is important for comparing the inherent efficiencies of operating in either CS or CD modes for a given condition or duty cycle, while converting to a standard unit of energy, megajoules. Specific equations detail this conversion process for both liquid fuels and electrical power, enabling a nuanced analysis of their respective efficiencies. For instance, the energy content of diesel fuel (JP-5) is converted from a consumption rate over one hour into megajoules, and similarly, electrical power measured in kilowatts for the same duration is also converted to megajoules. A comprehensive lookup table with conversion factors for various fuels (such as JP-8 and hydrogen), is essential for this analysis. Additionally, the energy stored in fuel tanks or battery packs is converted into megajoules as shown. Through the application of Equations 1–4, all energy metrics are standardized to megajoules, establishing a coherent framework for evaluating and comparing the energy content and operational efficiencies across different fuel types and power generation methods.

$$CD_{\mathrm{EC}} = (CD_{BR} \times \ 1\ \mathrm{hr} \times 3.6\ \text{MJ/kWh}) + (CD_{FR} \times \ 1\ \mathrm{hr} \times 132.2\ \text{MJ/gal}) \tag{1}$$

$$CS_{EC} = CS_{FR} \times 1\ \mathrm{hr} \times 132.2\ \text{MJ/gal} \tag{2}$$

$$FR_{MJ} = FR_{gal} \times 132.2\ \text{MJ/gal} \tag{3}$$

$$BR_{MJ} = BR_{kWh} \times 3.6\ \text{MJ/kW} \tag{4}$$

2.3.5.3 FEER and RERR Equations

The next step calculates the nondimensional parameters. Equations 5 compares the efficiency of operating in fuel-only mode (CS) to electric-only mode (CD) and Equation 6 calculates the ratio of remaining energy resources of fuel to electric energy. Equation 5 is the FEER, a ratio that measures the relative efficiency of fuel consumption to electric consumption. Equation 6 is the RERR, a ratio that measures the remaining energy content of the fuel capacity to electric battery capacity.

$$FEER = \frac{CS_{EC}}{CD_{EC}} \tag{5}$$

$$RERR = \frac{FR_{gal}}{BR_{kWh}} \tag{6}$$

2.3.5.4 RACR Equation, FOT/BOT Thresholds, and VEM Determination

The third step is to calculate adjusted efficiency ratio to determine the operating mode (i.e., VEM). In Equation 7, the RACR is a ratio of the measure of the relative efficiency of fuel consumption to electric consumption (FEER), adjusted for the remaining energy resources (RERR). This calculation modifies the fuel-to-electric consumption ratio by accounting for the remaining energy resources, facilitating the selection of the most appropriate VEM based on the vehicle’s current state.

By manipulating adjustable inputs, users can calibrate the FOT and BOT to align with their specific application requirements or to explore different simulation scenarios. The key aspect of adjusting the FOT or BOT value is that it allows fine-tuning the balance between electric and fuel use, enabling a tailored approach to energy management within the hybrid system. Equation 8 defines the maximum value to operate in fuel only (CS), whereas Equation 9 defines the minimum value to operate with battery only (CD) and values in between result in a charge replenishing mode.

$$RACR = \frac{FEER}{RERR} \tag{7}$$

$$FOT = MV - GV \tag{8}$$

$$BOT = MV + GV \tag{9}$$

Equations 10 and 11 calculate the threshold values based on a chosen MV and GV, or default values of 1.0 and 0.33, respectively. The GV determines the size of the window range and is tunable to fit the characteristics of the specific vehicle capabilities, or to adjust the strategy on increasing the battery operating zone based on the RACR value which considers the efficiency of the duty cycle and the remaining energy in the fuel tank or battery pack. In other words, the size of the window can dictate the probability the system will lean on fuel or battery operations. These values will allow the user to control how sensitive a vehicle is for a given simulation or configuration including whether it will lean towards fuel only or battery only within the recharging range. The MV can be adjusted to shift the operating mode windows as needed.

$$Vehicle\ Energy\ Mode = \begin{cases} Charge\ Depleting\ if\ RACR > BOT \\ Charge\ Sustaining\ if\ RACR < FOT \\ Charge\ Replenishing\ if\ FOT \leq RACR \leq BOT \end{cases} \tag{10}$$

Example using given proposed default values:

$$Vehicle\ Energy\ Mode = \begin{cases} Charge\ Depleting\ if\ RACR > 1.33 \\ Charge\ Sustaining\ if\ RACR < 0.67 \\ Charge\ Replenishing\ if\ 0.67 \leq RACR \leq 1.33 \end{cases} \tag{11}$$

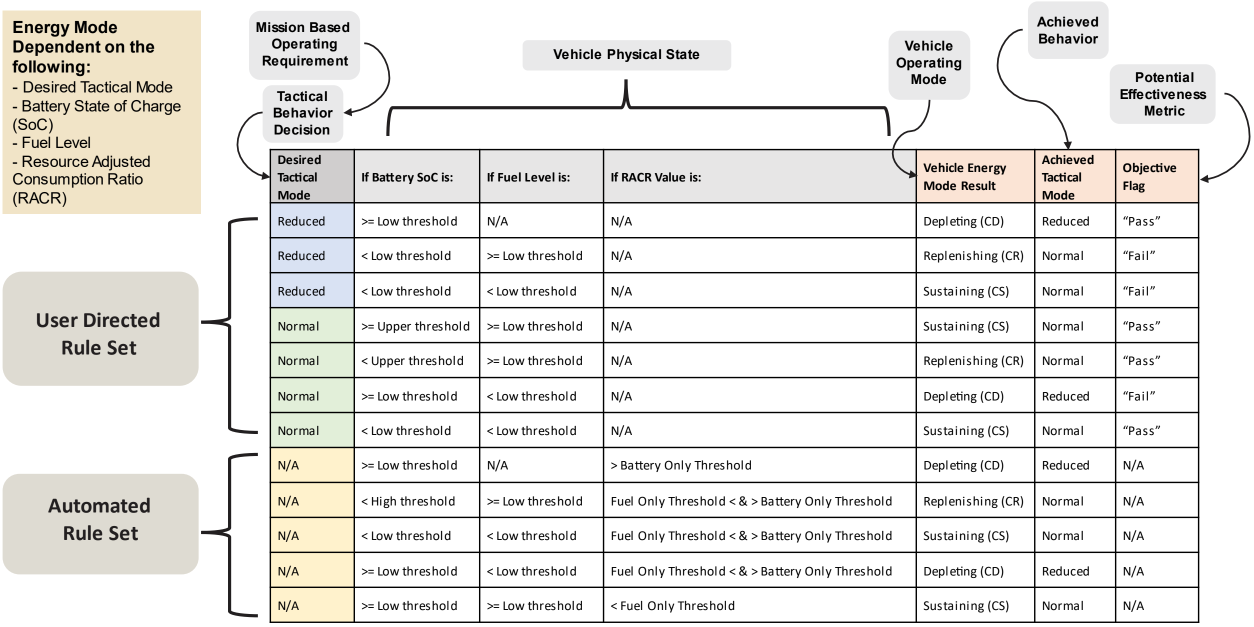
Table 7 summarizes the calculation process.

Table 7. Automated option summary of steps

Step	Objective	Key Equations, Parameters	Notes
Step 1: Unit conversion to standardize energy values & normalize power rates to 1 hour of consumption	Normalize power rates to 1 hour and convert this energy quantity and stored energy to megajoules.	- Fuel energy to megajoules - Electric energy to megajoules - Fuel tank to megajoules - Battery capacity to megajoules	- A lookup table is needed for different fuel types (e.g., JP-8, hydrogen).
Step 2: Calculate key nondimensional parameters	Compare efficiency in fuel-only and electric-only modes and calculate the ratio of remaining energy.	- **FEER** - **RERR**	- No additional data needed from lookup tables.
Step 3: Calculate key efficiency ratio and mode	Determine the vehicle's operating mode based on efficiency ratios.	- **RACR** - Threshold equations - Mode determination	- User-adjustable MV and GV - Default values: 1.0 (MV) and 0.33 (GV)

2.3.6 Combined Rules Review

Figure 5 summarizes both pathways to implementing hybrid-electric vehicle power controls in combat simulations. The original proposal for the framework design involved only the user-directed explicit controls; the automated procedure was added to solidify additional potential gaps in capturing tactical behaviors.

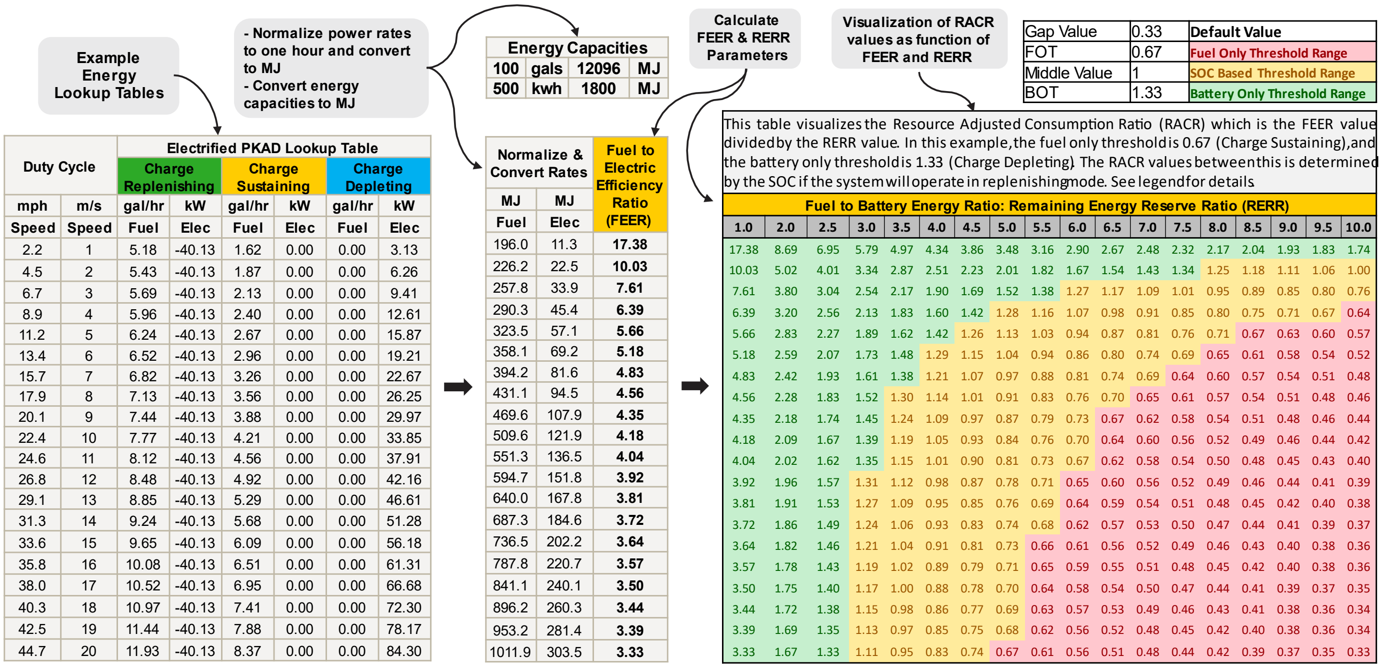


Desired Tactical Mode	If Battery SoC is:	If Fuel Level is:	If RACR Value is:	Vehicle Energy Mode Result	Achieved Tactical Mode	Objective Flag
Reduced	>= Low threshold	N/A	N/A	Depleting (CD)	Reduced	“Pass”
Reduced	< Low threshold	>= Low threshold	N/A	Replenishing (CR)	Normal	“Fail”
Reduced	< Low threshold	< Low threshold	N/A	Sustaining (CS)	Normal	“Fail”
Normal	>= Upper threshold	>= Low threshold	N/A	Sustaining (CS)	Normal	“Pass”
Normal	< Upper threshold	>= Low threshold	N/A	Replenishing (CR)	Normal	“Pass”
Normal	>= Low threshold	< Low threshold	N/A	Depleting (CD)	Reduced	“Fail”
Normal	< Low threshold	< Low threshold	N/A	Sustaining (CS)	Normal	“Pass”
N/A	>= Low threshold	N/A	> Battery Only Threshold	Depleting (CD)	Reduced	N/A
N/A	< High threshold	>= Low threshold	Fuel Only Threshold < & > Battery Only Threshold	Replenishing (CR)	Normal	N/A
N/A	< Low threshold	< Low threshold	Fuel Only Threshold < & > Battery Only Threshold	Sustaining (CS)	Normal	N/A
N/A	>= Low threshold	< Low threshold	Fuel Only Threshold < & > Battery Only Threshold	Depleting (CD)	Reduced	N/A
N/A	>= Low threshold	>= Low threshold	< Fuel Only Threshold	Sustaining (CS)	Normal	N/A

Figure 5. Summary of user-directed and automated algorithms

2.3.7 Demonstration

Figure 6 shows the sequential process to calculate the required parameters and determine the appropriate VEM given the vehicle’s energy resource state and the specific duty cycle or conditional request. It illustrates the automated process only. It begins with inputs from the standardized energy lookup tables and the consumption rates for each VEM in their standard units. These inputs feed into the next step—converting consumption rates in kilowatts and energy capacity to megajoules (to calculate both FEER and RERR). Subsequently, the RACR is visualized showing the results of this process and the VEM results. The far-right table in Figure 6 shows the balance of fuel and electric power aligning with the vehicle’s capabilities, ensuring the simulation accurately reflects real-world tactical operational decisions and energy management strategies without any user-directed or HITL behavior.



Duty Cycle		Electrified PKAD Lookup Table					
		Charge Replenishing		Charge Sustaining		Charge Depleting	
mph	m/s	gal/hr	kW	gal/hr	kW	gal/hr	kW
Speed	Speed	Fuel	Elec	Fuel	Elec	Fuel	Elec
2.2	1	5.18	-40.13	1.62	0.00	0.00	3.13
4.5	2	5.43	-40.13	1.87	0.00	0.00	6.26
6.7	3	5.69	-40.13	2.13	0.00	0.00	9.41
8.9	4	5.96	-40.13	2.40	0.00	0.00	12.61
11.2	5	6.24	-40.13	2.67	0.00	0.00	15.87
13.4	6	6.52	-40.13	2.96	0.00	0.00	19.21
15.7	7	6.82	-40.13	3.26	0.00	0.00	22.67
17.9	8	7.13	-40.13	3.56	0.00	0.00	26.25
20.1	9	7.44	-40.13	3.88	0.00	0.00	29.97
22.4	10	7.77	-40.13	4.21	0.00	0.00	33.85
24.6	11	8.12	-40.13	4.56	0.00	0.00	37.91
26.8	12	8.48	-40.13	4.92	0.00	0.00	42.16
29.1	13	8.85	-40.13	5.29	0.00	0.00	46.61
31.3	14	9.24	-40.13	5.68	0.00	0.00	51.28
33.6	15	9.65	-40.13	6.09	0.00	0.00	56.18
35.8	16	10.08	-40.13	6.51	0.00	0.00	61.31
38.0	17	10.52	-40.13	6.95	0.00	0.00	66.68
40.3	18	10.97	-40.13	7.41	0.00	0.00	72.30
42.5	19	11.44	-40.13	7.88	0.00	0.00	78.17
44.7	20	11.93	-40.13	8.37	0.00	0.00	84.30

Energy Capacities			
100	gals	12096	MJ
500	kwh	1800	MJ

Normalize & Convert Rates		Fuel to Electric Efficiency Ratio (FEER)
MJ	MJ	
Fuel	Elec	
196.0	11.3	**17.38**
226.2	22.5	**10.03**
257.8	33.9	**7.61**
290.3	45.4	**6.39**
323.5	57.1	**5.66**
358.1	69.2	**5.18**
394.2	81.6	**4.83**
431.1	94.5	**4.56**
469.6	107.9	**4.35**
509.6	121.9	**4.18**
551.3	136.5	**4.04**
594.7	151.8	**3.92**
640.0	167.8	**3.81**
687.3	184.6	**3.72**
736.5	202.2	**3.64**
787.8	220.7	**3.57**
841.1	240.1	**3.50**
896.2	260.3	**3.44**
953.2	281.4	**3.39**
1011.9	303.5	**3.33**

Gap Value	0.33	**Default Value**
FOT	0.67	Fuel Only Threshold Range
Middle Value	1	SOC Based Threshold Range
BOT	1.33	Battery Only Threshold Range

This table visualizes the Resource Adjusted Consumption Ratio (RACR) which is the FEER value divided by the RERR value. In this example, the fuel only threshold is 0.67 (Charge Sustaining), and the battery only threshold is 1.33 (Charge Depleting). The RACR values between this is determined by the SOC if the system will operate in replenishing mode. See legend for details.

Fuel to Battery Energy Ratio: Remaining Energy Reserve Ratio (RERR)

1.0	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
17.38	8.69	6.95	5.79	4.97	4.34	3.86	3.48	3.16	2.90	2.67	2.48	2.32	2.17	2.04	1.93	1.83	1.74
10.03	5.02	4.01	3.34	2.87	2.51	2.23	2.01	1.82	1.67	1.54	1.43	1.34	1.25	1.18	1.11	1.06	1.00
7.61	3.80	3.04	2.54	2.17	1.90	1.69	1.52	1.38	1.27	1.17	1.09	1.01	0.95	0.89	0.85	0.80	0.76
6.39	3.20	2.56	2.13	1.83	1.60	1.42	1.28	1.16	1.07	0.98	0.91	0.85	0.80	0.75	0.71	0.67	0.64
5.66	2.83	2.27	1.89	1.62	1.42	1.26	1.13	1.03	0.94	0.87	0.81	0.76	0.71	0.67	0.63	0.60	0.57
5.18	2.59	2.07	1.73	1.48	1.29	1.15	1.04	0.94	0.86	0.80	0.74	0.69	0.65	0.61	0.58	0.54	0.52
4.83	2.42	1.93	1.61	1.38	1.21	1.07	0.97	0.88	0.81	0.74	0.69	0.64	0.60	0.57	0.54	0.51	0.48
4.56	2.28	1.83	1.52	1.30	1.14	1.01	0.91	0.83	0.76	0.70	0.65	0.61	0.57	0.54	0.51	0.48	0.46
4.35	2.18	1.74	1.45	1.24	1.09	0.97	0.87	0.79	0.73	0.67	0.62	0.58	0.54	0.51	0.48	0.46	0.44
4.18	2.09	1.67	1.39	1.19	1.05	0.93	0.84	0.76	0.70	0.64	0.60	0.56	0.52	0.49	0.46	0.44	0.42
4.04	2.02	1.62	1.35	1.15	1.01	0.90	0.81	0.73	0.67	0.62	0.58	0.54	0.50	0.48	0.45	0.43	0.40
3.92	1.96	1.57	1.31	1.12	0.98	0.87	0.78	0.71	0.65	0.60	0.56	0.52	0.49	0.46	0.44	0.41	0.39
3.81	1.91	1.53	1.27	1.09	0.95	0.85	0.76	0.69	0.64	0.59	0.54	0.51	0.48	0.45	0.42	0.40	0.38
3.72	1.86	1.49	1.24	1.06	0.93	0.83	0.74	0.68	0.62	0.57	0.53	0.50	0.47	0.44	0.41	0.39	0.37
3.64	1.82	1.46	1.21	1.04	0.91	0.81	0.73	0.66	0.61	0.56	0.52	0.49	0.46	0.43	0.40	0.38	0.36
3.57	1.78	1.43	1.19	1.02	0.89	0.79	0.71	0.65	0.59	0.55	0.51	0.48	0.45	0.42	0.40	0.38	0.36
3.50	1.75	1.40	1.17	1.00	0.88	0.78	0.70	0.64	0.58	0.54	0.50	0.47	0.44	0.41	0.39	0.37	0.35
3.44	1.72	1.38	1.15	0.98	0.86	0.77	0.69	0.63	0.57	0.53	0.49	0.46	0.43	0.41	0.38	0.36	0.34
3.39	1.69	1.35	1.13	0.97	0.85	0.75	0.68	0.62	0.56	0.52	0.48	0.45	0.42	0.40	0.38	0.36	0.34
3.33	1.67	1.33	1.11	0.95	0.83	0.74	0.67	0.61	0.56	0.51	0.48	0.44	0.42	0.39	0.37	0.35	0.33

Figure 6. **Example demonstration of automated process**

3. RESULTS AND DISCUSSION

User-directed and automated are the two options used in this methodology to define the operational state of an electrified or conventional vehicle. A notional application of the proposed PKAD algorithms, using a hypothetical hybrid-electric truck, follows to demonstrate the process and efficacy of the approach.

3.1 Results

Using a notional 24-h mission, a light hybrid-electric 4x4 truck is used to demonstrate the proposed PKAD electrification algorithms. The mission profile incorporates cross-country terrain with slopes ranging from –20% to 20%, and a soil strength with a rating cone index of 290 in soil group no. 4. Refer to Figure 4 for the fuel consumption rate data used in this simulation example. The differences between these examples are solely in the control approaches, either user-directed or automated. The speed and slope profile, including idle time, are kept constant to make direct comparisons of the different approaches. In this example, sample rate assumes one minute time steps.

Key vehicle details and assumptions for this example are as follows:

- Hybrid-electric 4 × 4 wheeled vehicle, in parallel configuration.
- ICE = 162 kW (217 hp) using JP-8 fuel and has an equivalently sized electric motor.
- Integrated starter generator rating = 40 kW.
- Total weight = 10,000 lb.
- Silent watch power demand = 1 kW.
- It is equipped with a 250-kWh battery, with the battery’s usable range maintained between 10% to 90% SoC and has a 26-gal fuel tank.

3.1.1 Simulation Speed, Slope, and Idle Profile

Figure 7 depicts the mission profile simulated for each of the four examples, as follows:

- Reduced Signature Operation Only (User-directed)
- Normal Signature Operation Only (User-directed)
- Mixed Operations (User-directed)
- Automated Selection Algorithm

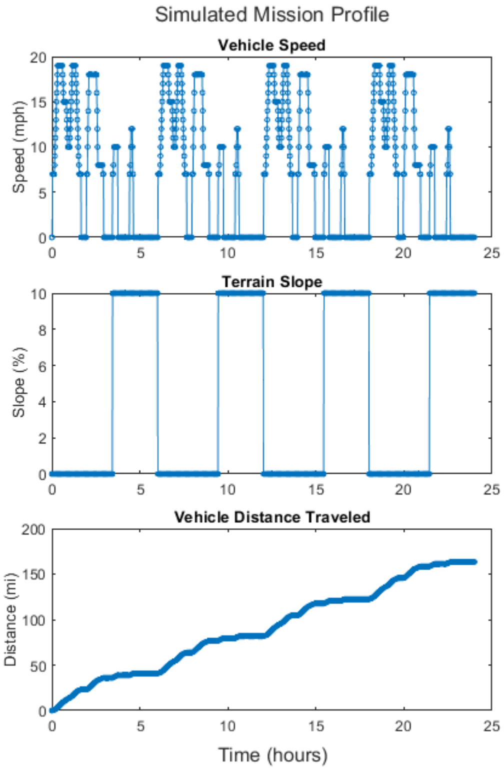


Figure 7. Simulated duty cycle and mission profile of hybrid-electric vehicle

3.1.2 Example 1: Reduced Signature Operation Only (User-directed)

In Example 1, the user directs the vehicle to operate in a reduced signature TOM throughout the mission (i.e., emphasize battery only use). Figures 8–10 demonstrate the results of the vehicle’s attempt to maintain this desired TOM, as well as when the vehicle was not able to achieve the desired objective when the battery reached a low SOC.

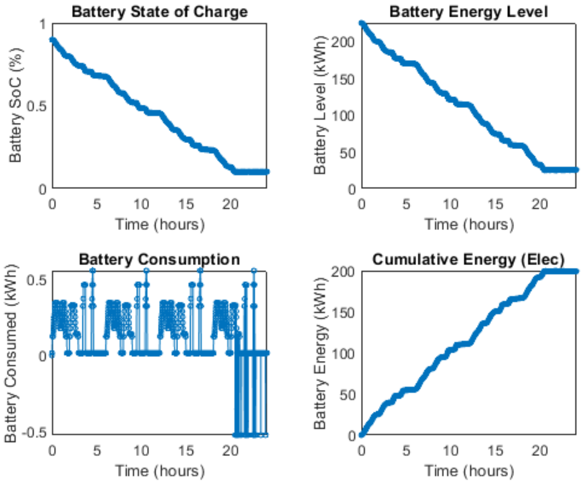


Figure 8. Example 1: battery usage and consumption profile

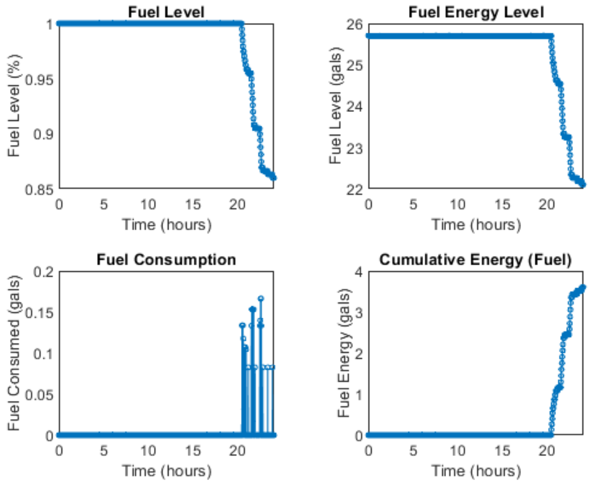


Figure 9. Example 1: fuel usage and consumption profile

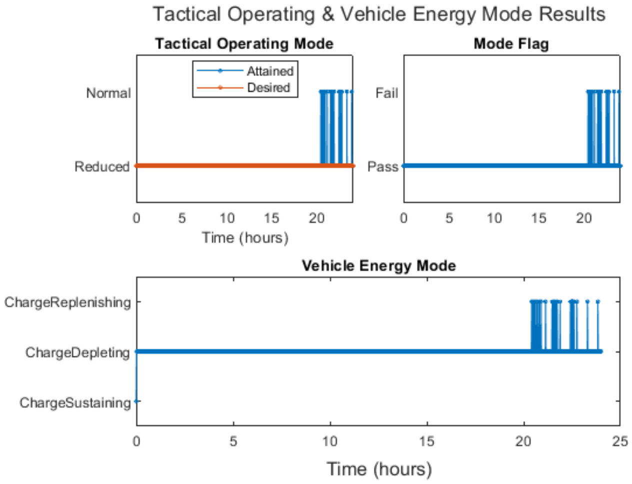


Figure 10. Example 1: TOM and VEM results

3.1.3 Example 2: Normal Signature Operation Only (User-directed)

In Example 2, the user directs the vehicle to operate in a normal signature TOM throughout the mission. Figures 11–13 demonstrate results for the vehicle’s attempt to maintain this desired TOM, as well as when the vehicle was not able to achieve the desired objective when fuel reached a low level.

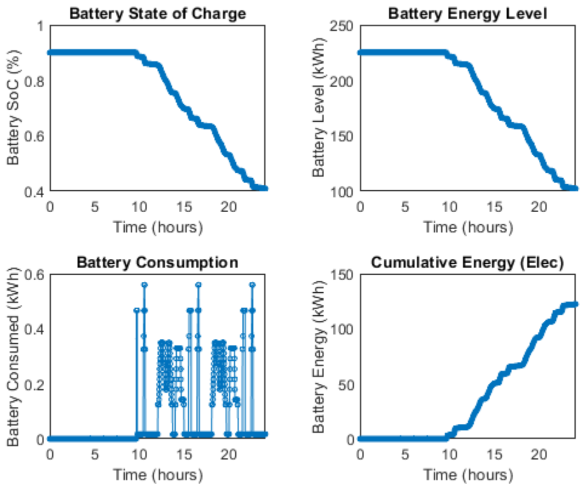


Figure 11. Example 2: battery usage and consumption profile

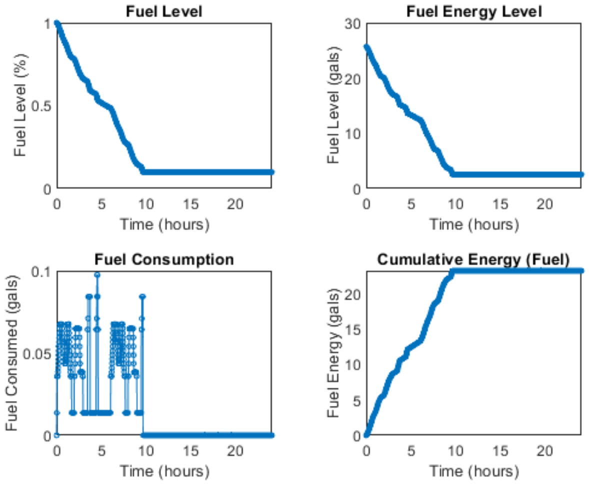


Figure 12. Example 2: fuel usage and consumption profile

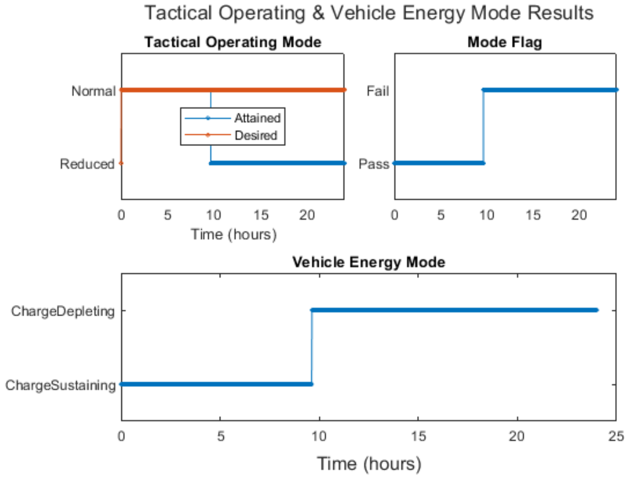


Figure 13. Example 2: TOM and VEM results

3.1.4 Example 3: Mixed Operations (User-directed)

In Example 3, the user directs the vehicle to operate in a cycle between normal and reduced signature TOM. Figures 14–16 demonstrate results of the vehicle’s attempt at maintaining these desired TOMs, as well as when the vehicle was not able to achieve the desired objective when fuel reached a low level.

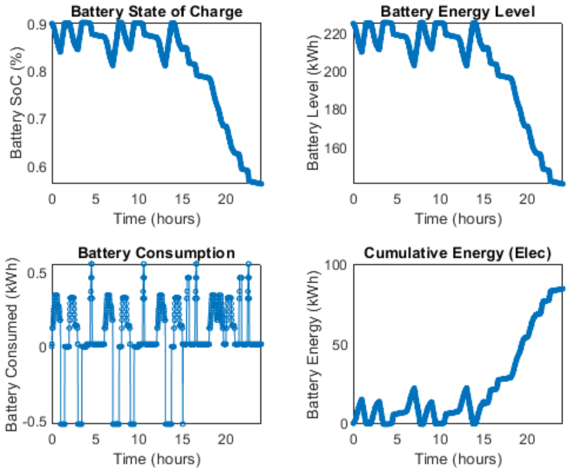


Figure 14. Example 3: battery usage and consumption profile

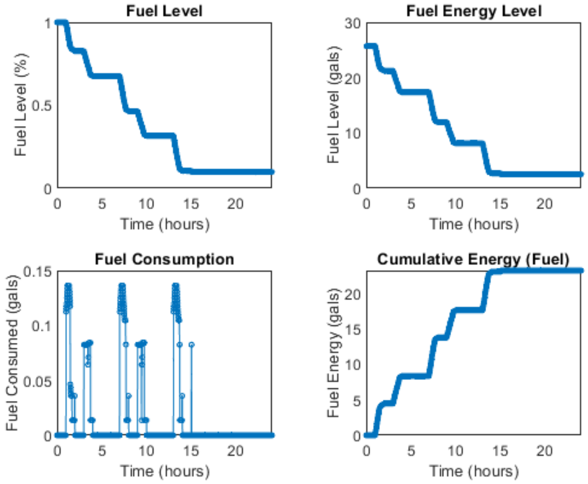


Figure 15. Example 3: fuel usage and consumption profile

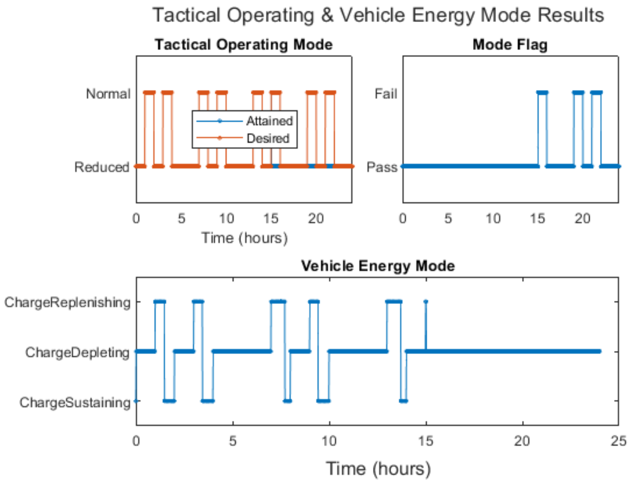


Figure 16. Example 3: TOM and VEM results

3.1.5 Example 4: Automated Selection Algorithm

In Example 4, the user has not chosen a preferred TOM, allowing the algorithm to optimize between fuel and battery mode for the mission. Because there is no desired behavior, the data does not explicitly mark whether the vehicle passed or failed since no selection is made in this simulation. Figures 17–19 show the results.

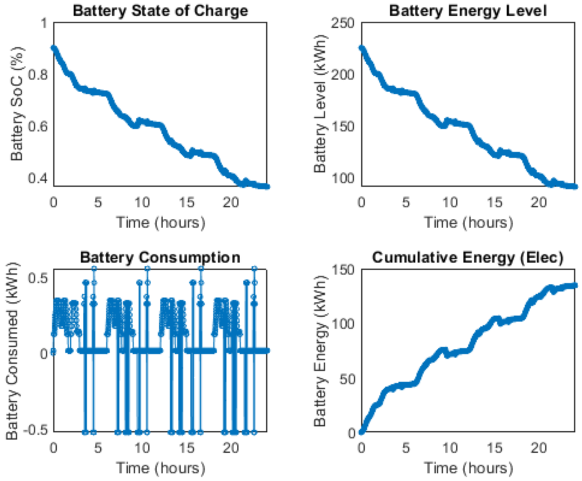


Figure 17. Example 4: battery usage and consumption profile

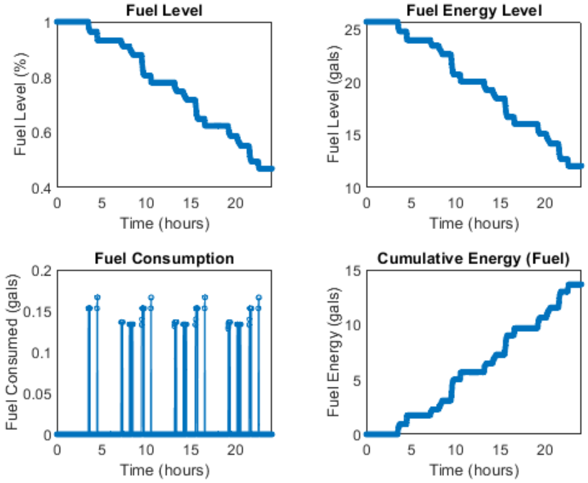


Figure 18. Example 4: fuel usage and consumption profile

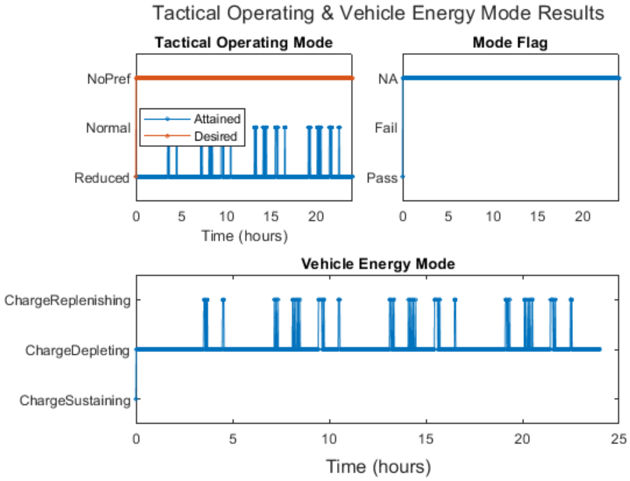


Figure 19. Example 4: TOM and VEM results

3.2 Discussion

Example 1 utilized a reduced signature mode exclusively, demonstrating how the vehicle conserved fuel while maximizing silent operation. Example 2 maintained a normal signature mode throughout, emphasizing fuel use over stealth, and consequently showed increased fuel consumption while conserving battery energy. Example 3, a mix of reduced and normal TOMs, showed the algorithm's capability to adapt to changing tactical requirements. Example 4 employed the automated process, demonstrating the algorithm's potential to make autonomous decisions without explicit user direction.

Each example showed the algorithm's responsiveness to different TOM inputs and operational considerations. However, the automated process needs additional exploration, particularly concerning the sensitivity of the algorithm to various threshold settings. These thresholds, including the MV and GV, are important since they define the fuel-only or battery-only thresholds. Their eventual calibration can dynamically alter the VEM, potentially impacting the operational effectiveness of the vehicle in combat simulations.

Further research is recommended to test the automated algorithm’s sensitivity to these parameters. Through additional examples where these threshold values are systematically varied, further insights can be gained into how the algorithm responds. This can also inform the development of a more robust and adaptable system that can seamlessly transition between energy modes, ensuring optimal performance.

This type of refinement is essential to accurately mirror the nuanced decision-making processes expected in real-world operations where the complexity of higher-fidelity modeling to address control logic is not feasible. The refinement would undoubtedly contribute to the overall goal of the methodology—to enable simulations that can estimate, predict, and capture the tactical advantages of electrification.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This technical report describes a novel and systematic approach to representing electrified vehicles in combat simulations. The methodology considers both the vehicle's energy use and mission capabilities. Using a rules-based algorithm approach that is informed by lookup tables, the methodology has demonstrated the potential to predict energy use using a framework that can work agnostically and consistently across various technologies and operational states. This methodology development, supported by a notional hybrid-electric truck example, demonstrates that this approach can draw from existing high-fidelity models while offering the expedience necessary to support a combat simulation.

This methodology, which is intended to support a future PKAD, is a significant step toward achieving and improving the Army's M&S capabilities in representing electrification in operationally relevant combat simulations. This in turn will permit the Army to move closer to its electrification goals with improved tools to support senior leader acquisition decisions. The transition to a more electrified force presents both significant challenges and opportunities that this methodology can assist in addressing. Insights from this methodology development can contribute to a better understanding of how such a force can operate more effectively and efficiently.

4.2 Recommendations

The following recommendations are proposed:

1. **Adopt PKAD Methodology**: Encourage the adoption of the PKAD methodology across M&S communities to enhance the representation of hybrid-electric and electrified vehicles in combat simulations. Increase familiarity with the new methodology across the combat simulator, acquisition, and sustainment communities alike, ensuring a smooth transition to the enhanced modeling approach.
2. **Validation**: Validate and refine the methodology against real-world data and higher-fidelity purpose-built simulations. The examples in this report can be used as a starting point to compare to higher-fidelity models representing hybrid-electric vehicle energy use and performance. Compare with physical systems to determine realistic and representative default values for model variables.
3. **Model Power Sharing Dynamics**: It is recommended to expand the modeling framework to encompass the additional aspects of power sharing and the network effects of energy distribution. This should include the interactions between various entities such as smaller autonomous vehicles, vehicle-based

microgrids, and fuel-based generators used to recharge electric vehicles. Understanding the dynamics of these energy networks is important for simulating the strategic advantages and potential vulnerabilities of a highly electrified battlefield.

4. **Develop Network-Centric Energy Models**: Improve the framework and development of these algorithms to consider a network-centric approach to energy that can simulate the bidirectional flow of energy between different assets or vehicles. These models would capture the complexity of an interconnected electrified energy network, where vehicles can act as consumers, producers, or storage nodes depending on mission demands and availability of resources.

By implementing these recommendations, the Army will advance combat simulations ability to adequately represent the capabilities and limitations of an increasingly electrified fleet. This will improve operational analysis used to inform strategic acquisition, sustainment, and analytical decisions.

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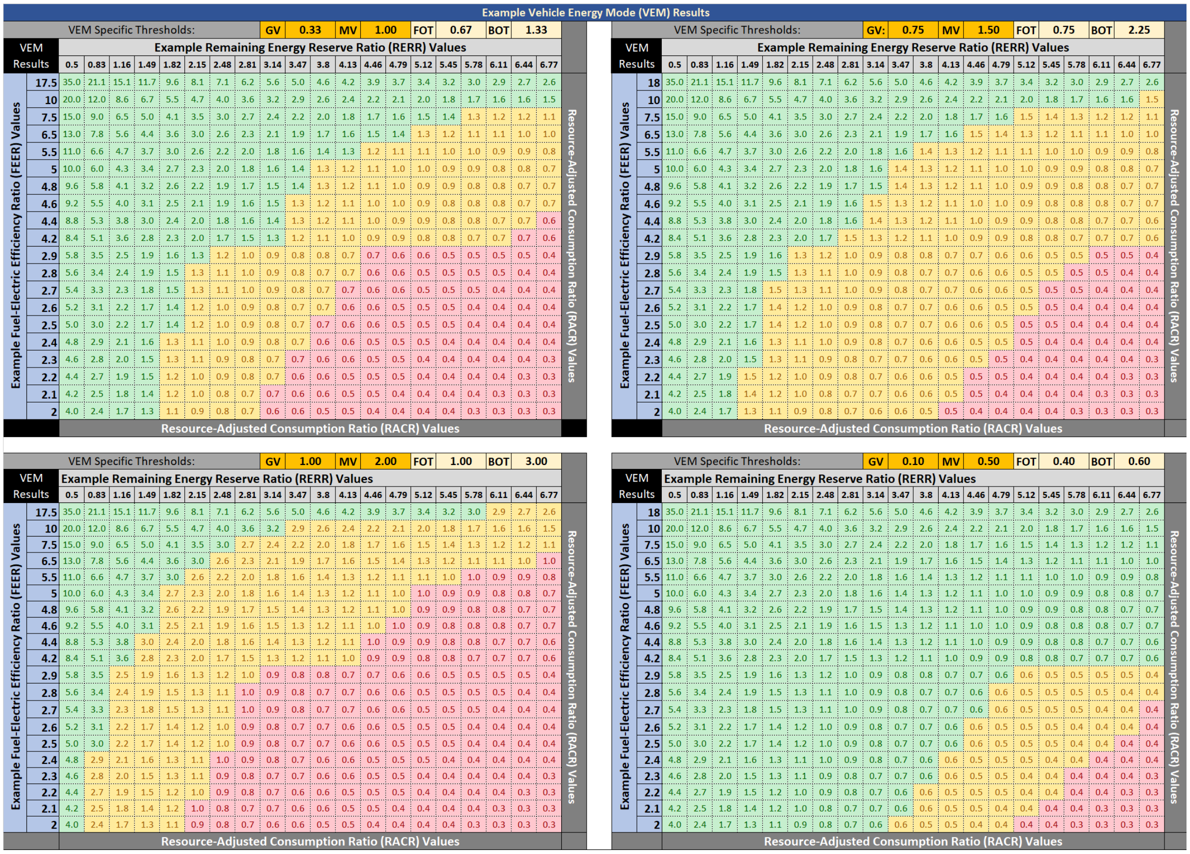
Appendix A - Automated Hybrid Algorithm Sensitivity

A.1 FIGURES AND TABLES

Figure A-1 depicts four examples that illustrate the sensitivity of a hybrid-electric vehicle's desired behavior. It highlights how the tuning and adjustment of critical control toggle variables, MV and GV, can modify the balance in system preferences across the three VEMs. Green cells or zone indicate BOT (e.g., CD), yellow cells or zone are the SOC dependent CR zone, and the red cells indicate the FOT (e.g., CS) region. Rows shown are potential FEER values, while columns are potential RERR values. The values in the table are RACR calculation results.



Example Vehicle Energy Mode (VEM) Results

VEM Specific Thresholds: GV 0.33 MV 1.00 FOT 0.67 BOT 1.33

Example Fuel-Electric Efficiency Ratio (FEER) Values

VEM Results	0.5	0.83	1.16	1.49	1.82	2.15	2.48	2.81	3.14	3.47	3.8	4.13	4.46	4.79	5.12	5.45	5.78	6.11	6.44	6.77
17.5	35.0	21.1	15.1	11.7	9.6	8.1	7.1	6.2	5.6	5.0	4.6	4.2	3.9	3.7	3.4	3.2	3.0	2.9	2.7	2.6
10	20.0	12.0	8.6	6.7	5.5	4.7	4.0	3.6	3.2	2.9	2.6	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.6	1.5
7.5	15.0	9.0	6.5	5.0	4.1	3.5	3.0	2.7	2.4	2.2	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1
6.5	13.0	7.8	5.6	4.4	3.6	3.0	2.6	2.3	2.1	1.9	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	1.0
5.5	11.0	6.6	4.7	3.7	3.0	2.6	2.2	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.1	1.0	1.0	0.9	0.9	0.8
5	10.0	6.0	4.3	3.4	2.7	2.3	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.0	1.0	0.9	0.9	0.8	0.8	0.7
4.8	9.6	5.8	4.1	3.2	2.6	2.2	1.9	1.7	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7
4.6	9.2	5.5	4.0	3.1	2.5	2.1	1.9	1.6	1.5	1.3	1.2	1.1	1.0	1.0	0.9	0.8	0.8	0.8	0.7	0.7
4.4	8.8	5.3	3.8	3.0	2.4	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.6
4.2	8.4	5.1	3.6	2.8	2.3	2.0	1.7	1.5	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.7	0.6
2.9	5.8	3.5	2.5	1.9	1.6	1.3	1.2	1.0	0.9	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4
2.8	5.6	3.4	2.4	1.9	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.4
2.7	5.4	3.3	2.3	1.8	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4
2.6	5.2	3.1	2.2	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
2.5	5.0	3.0	2.2	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
2.4	4.8	2.9	2.1	1.6	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4
2.3	4.6	2.8	2.0	1.5	1.3	1.1	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.3
2.2	4.4	2.7	1.9	1.5	1.2	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3
2.1	4.2	2.5	1.8	1.4	1.2	1.0	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3
2	4.0	2.4	1.7	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3

Resource-Adjusted Consumption Ratio (RACR) Values

VEM Specific Thresholds: GV: 0.75 MV 1.50 FOT 0.75 BOT 2.25

Example Fuel-Electric Efficiency Ratio (FEER) Values

VEM Results	0.5	0.83	1.16	1.49	1.82	2.15	2.48	2.81	3.14	3.47	3.8	4.13	4.46	4.79	5.12	5.45	5.78	6.11	6.44	6.77
18	35.0	21.1	15.1	11.7	9.6	8.1	7.1	6.2	5.6	5.0	4.6	4.2	3.9	3.7	3.4	3.2	3.0	2.9	2.7	2.6
10	20.0	12.0	8.6	6.7	5.5	4.7	4.0	3.6	3.2	2.9	2.6	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.6	1.5
7.5	15.0	9.0	6.5	5.0	4.1	3.5	3.0	2.7	2.4	2.2	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1
6.5	13.0	7.8	5.6	4.4	3.6	3.0	2.6	2.3	2.1	1.9	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	1.0
5.5	11.0	6.6	4.7	3.7	3.0	2.6	2.2	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.1	1.0	1.0	0.9	0.9	0.8
5	10.0	6.0	4.3	3.4	2.7	2.3	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.0	1.0	0.9	0.9	0.8	0.8	0.7
4.8	9.6	5.8	4.1	3.2	2.6	2.2	1.9	1.7	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7
4.6	9.2	5.5	4.0	3.1	2.5	2.1	1.9	1.6	1.5	1.3	1.2	1.1	1.0	1.0	0.9	0.8	0.8	0.8	0.7	0.7
4.4	8.8	5.3	3.8	3.0	2.4	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.6
4.2	8.4	5.1	3.6	2.8	2.3	2.0	1.7	1.5	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.7	0.6
2.9	5.8	3.5	2.5	1.9	1.6	1.3	1.2	1.0	0.9	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4
2.8	5.6	3.4	2.4	1.9	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.4
2.7	5.4	3.3	2.3	1.8	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4
2.6	5.2	3.1	2.2	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
2.5	5.0	3.0	2.2	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
2.4	4.8	2.9	2.1	1.6	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4
2.3	4.6	2.8	2.0	1.5	1.3	1.1	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.3
2.2	4.4	2.7	1.9	1.5	1.2	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3
2.1	4.2	2.5	1.8	1.4	1.2	1.0	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3
2	4.0	2.4	1.7	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3

Resource-Adjusted Consumption Ratio (RACR) Values

VEM Specific Thresholds: GV 1.00 MV 2.00 FOT 1.00 BOT 3.00

Example Fuel-Electric Efficiency Ratio (FEER) Values

VEM Results	0.5	0.83	1.16	1.49	1.82	2.15	2.48	2.81	3.14	3.47	3.8	4.13	4.46	4.79	5.12	5.45	5.78	6.11	6.44	6.77
17.5	35.0	21.1	15.1	11.7	9.6	8.1	7.1	6.2	5.6	5.0	4.6	4.2	3.9	3.7	3.4	3.2	3.0	2.9	2.7	2.6
10	20.0	12.0	8.6	6.7	5.5	4.7	4.0	3.6	3.2	2.9	2.6	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.6	1.5
7.5	15.0	9.0	6.5	5.0	4.1	3.5	3.0	2.7	2.4	2.2	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1
6.5	13.0	7.8	5.6	4.4	3.6	3.0	2.6	2.3	2.1	1.9	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	1.0
5.5	11.0	6.6	4.7	3.7	3.0	2.6	2.2	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.1	1.0	1.0	0.9	0.9	0.8
5	10.0	6.0	4.3	3.4	2.7	2.3	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.0	1.0	0.9	0.9	0.8	0.8	0.7
4.8	9.6	5.8	4.1	3.2	2.6	2.2	1.9	1.7	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7
4.6	9.2	5.5	4.0	3.1	2.5	2.1	1.9	1.6	1.5	1.3	1.2	1.1	1.0	1.0	0.9	0.8	0.8	0.8	0.7	0.7
4.4	8.8	5.3	3.8	3.0	2.4	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.6
4.2	8.4	5.1	3.6	2.8	2.3	2.0	1.7	1.5	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.7	0.6
2.9	5.8	3.5	2.5	1.9	1.6	1.3	1.2	1.0	0.9	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4
2.8	5.6	3.4	2.4	1.9	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.4
2.7	5.4	3.3	2.3	1.8	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4
2.6	5.2	3.1	2.2	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
2.5	5.0	3.0	2.2	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
2.4	4.8	2.9	2.1	1.6	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4
2.3	4.6	2.8	2.0	1.5	1.3	1.1	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.3
2.2	4.4	2.7	1.9	1.5	1.2	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3
2.1	4.2	2.5	1.8	1.4	1.2	1.0	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3
2	4.0	2.4	1.7	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3

Resource-Adjusted Consumption Ratio (RACR) Values

VEM Specific Thresholds: GV 0.10 MV 0.50 FOT 0.40 BOT 0.60

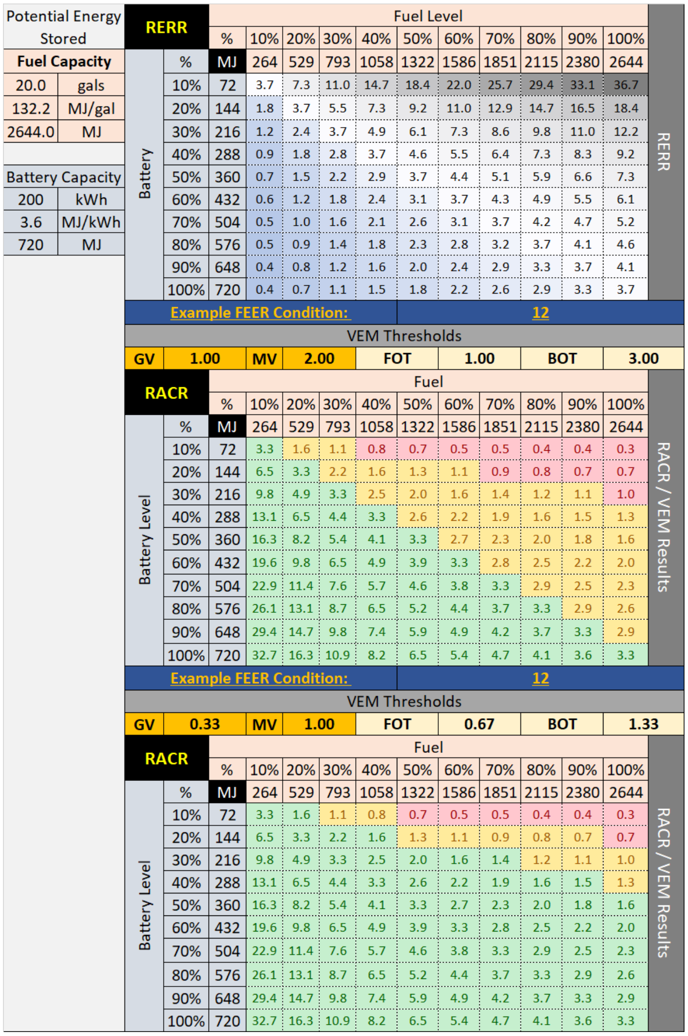
Example Fuel-Electric Efficiency Ratio (FEER) Values

VEM Results	0.5	0.83	1.16	1.49	1.82	2.15	2.48	2.81	3.14	3.47	3.8	4.13	4.46	4.79	5.12	5.45	5.78	6.11	6.44	6.77
18	35.0	21.1	15.1	11.7	9.6	8.1	7.1	6.2	5.6	5.0	4.6	4.2	3.9	3.7	3.4	3.2	3.0	2.9	2.7	2.6
10	20.0	12.0	8.6	6.7	5.5	4.7	4.0	3.6	3.2	2.9	2.6	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.6	1.5
7.5	15.0	9.0	6.5	5.0	4.1	3.5	3.0	2.7	2.4	2.2	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1
6.5	13.0	7.8	5.6	4.4	3.6	3.0	2.6	2.3	2.1	1.9	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	1.0
5.5	11.0	6.6	4.7	3.7	3.0	2.6	2.2	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.1	1.0	1.0	0.9	0.9	0.8
5	10.0	6.0	4.3	3.4	2.7	2.3	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.0	1.0	0.9	0.9	0.8	0.8	0.7
4.8	9.6	5.8	4.1	3.2	2.6	2.2	1.9	1.7	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7
4.6	9.2	5.5	4.0	3.1	2.5	2.1	1.9	1.6	1.5	1.3	1.2	1.1	1.0	1.0	0.9	0.8	0.8	0.8	0.7	0.7
4.4	8.8	5.3	3.8	3.0	2.4	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.6
4.2	8.4	5.1	3.6	2.8	2.3	2.0	1.7	1.5	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.7	0.6
2.9	5.8	3.5	2.5	1.9	1.6	1.3	1.2	1.0	0.9	0.8	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4
2.8	5.6	3.4	2.4	1.9	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.4
2.7	5.4	3.3	2.3	1.8	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4
2.6	5.2	3.1	2.2	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
2.5	5.0	3.0	2.2	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
2.4	4.8	2.9	2.1	1.6	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4
2.3	4.6	2.8	2.0	1.5	1.3	1.1	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.3
2.2	4.4	2.7	1.9	1.5	1.2	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3
2.1	4.2	2.5	1.8	1.4	1.2	1.0	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3
2	4.0	2.4	1.7	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3

Resource-Adjusted Consumption Ratio (RACR) Values

Figure A-1 Example results from tuning hybrid algorithm threshold parameters

Figure A-2 highlights a single specific FEER condition value to demonstrate outcomes based on the states of the fuel tank and battery pack's energy. This example features a vehicle equipped with a 20-gal fuel tank and a 200-kWh battery pack, and a FEER condition of 12. Two scenarios are presented: the first scenario, with an MV of 2 and GV of 1, indicates that thresholds are balanced at a RACR where the FEER is twice the value of the RERR. This setup slightly favors recharging and fuel operations. In contrast, the second scenario applies the default values (MV of 1, GV of 0.33), illustrating how a lower MV biases the system towards battery-centric operations. Furthermore, a smaller GV results in a narrower recharging window under this FEER condition.



Potential Energy Stored	
Fuel Capacity	
20.0	gals
132.2	MJ/gal
2644.0	MJ
Battery Capacity	
200	kWh
3.6	MJ/kWh
720	MJ

RERR

Fuel Level

Battery

	%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
%	MJ	264	529	793	1058	1322	1586	1851	2115	2380	2644
10%	72	3.7	7.3	11.0	14.7	18.4	22.0	25.7	29.4	33.1	36.7
20%	144	1.8	3.7	5.5	7.3	9.2	11.0	12.9	14.7	16.5	18.4
30%	216	1.2	2.4	3.7	4.9	6.1	7.3	8.6	9.8	11.0	12.2
40%	288	0.9	1.8	2.8	3.7	4.6	5.5	6.4	7.3	8.3	9.2
50%	360	0.7	1.5	2.2	2.9	3.7	4.4	5.1	5.9	6.6	7.3
60%	432	0.6	1.2	1.8	2.4	3.1	3.7	4.3	4.9	5.5	6.1
70%	504	0.5	1.0	1.6	2.1	2.6	3.1	3.7	4.2	4.7	5.2
80%	576	0.5	0.9	1.4	1.8	2.3	2.8	3.2	3.7	4.1	4.6
90%	648	0.4	0.8	1.2	1.6	2.0	2.4	2.9	3.3	3.7	4.1
100%	720	0.4	0.7	1.1	1.5	1.8	2.2	2.6	2.9	3.3	3.7

RERR

Example FEER Condition: **12**

VEM Thresholds

GV	**1.00**	**MV**	**2.00**	**FOT**	**1.00**	**BOT**	**3.00**

RACR

Fuel

Battery Level

	%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
%	MJ	264	529	793	1058	1322	1586	1851	2115	2380	2644
10%	72	3.3	1.6	1.1	0.8	0.7	0.5	0.5	0.4	0.4	0.3
20%	144	6.5	3.3	2.2	1.6	1.3	1.1	0.9	0.8	0.7	0.7
30%	216	9.8	4.9	3.3	2.5	2.0	1.6	1.4	1.2	1.1	1.0
40%	288	13.1	6.5	4.4	3.3	2.6	2.2	1.9	1.6	1.5	1.3
50%	360	16.3	8.2	5.4	4.1	3.3	2.7	2.3	2.0	1.8	1.6
60%	432	19.6	9.8	6.5	4.9	3.9	3.3	2.8	2.5	2.2	2.0
70%	504	22.9	11.4	7.6	5.7	4.6	3.8	3.3	2.9	2.5	2.3
80%	576	26.1	13.1	8.7	6.5	5.2	4.4	3.7	3.3	2.9	2.6
90%	648	29.4	14.7	9.8	7.4	5.9	4.9	4.2	3.7	3.3	2.9
100%	720	32.7	16.3	10.9	8.2	6.5	5.4	4.7	4.1	3.6	3.3

RACR / VEM Results

Example FEER Condition: **12**

VEM Thresholds

GV	**0.33**	**MV**	**1.00**	**FOT**	**0.67**	**BOT**	**1.33**

RACR

Fuel

Battery Level

	%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
%	MJ	264	529	793	1058	1322	1586	1851	2115	2380	2644
10%	72	3.3	1.6	1.1	0.8	0.7	0.5	0.5	0.4	0.4	0.3
20%	144	6.5	3.3	2.2	1.6	1.3	1.1	0.9	0.8	0.7	0.7
30%	216	9.8	4.9	3.3	2.5	2.0	1.6	1.4	1.2	1.1	1.0
40%	288	13.1	6.5	4.4	3.3	2.6	2.2	1.9	1.6	1.5	1.3
50%	360	16.3	8.2	5.4	4.1	3.3	2.7	2.3	2.0	1.8	1.6
60%	432	19.6	9.8	6.5	4.9	3.9	3.3	2.8	2.5	2.2	2.0
70%	504	22.9	11.4	7.6	5.7	4.6	3.8	3.3	2.9	2.5	2.3
80%	576	26.1	13.1	8.7	6.5	5.2	4.4	3.7	3.3	2.9	2.6
90%	648	29.4	14.7	9.8	7.4	5.9	4.9	4.2	3.7	3.3	2.9
100%	720	32.7	16.3	10.9	8.2	6.5	5.4	4.7	4.1	3.6	3.3

RACR / VEM Results

Figure A-2 Example vehicle tuning demonstration

LIST OF ACRONYMS

API	Application Programming Interface
BOT	Battery Only Threshold (RACR threshold parameters)
CD	Charge Depleting (VEM)
CLEAT	Component-Level Energy Analysis Tool
CR	Charge Replenishing (VEM)
CS	Charge Sustaining (VEM)
DAC	DEVCOM Analysis Center
DEVCOM	U.S. Army Combat Capabilities Development Command
FCPM	Fuel Consumption Prediction Model
FEER	Fuel to Electric Energy Ratio
FOT	Fuel Only Threshold (RACR threshold parameters)
GV	Gap Value (RACR threshold parameters)
HITL	Human-in-the-Loop
LSCO	Large Scale Combat Operations
M&S	Modeling and Simulation
MDO	Multi-Domain Operations
MLU	Mobility Lookup
MV	Midpoint Value (RACR threshold parameters)
NATO	North Atlantic Treaty Organization
NRMM	NATO Reference Mobility Model
NS	Normal Signature (TOM)
P&E	power and energy
PKAD	Physical Model Knowledge Acquisition Document
RACR	Resource Adjusted Consumption Ratio
RERR	Remaining Energy Reserve Ratio
RS	Reduced Signature (TOM)
SoC	State of Charge
STGJ	Surface Trafficability Group Joint Simulation System
STNDMob	Standard Mobility (model)
TOM	Tactical Operating Mode
VEM	Vehicle Energy Mode

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