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Thru-life impacts of driver aggression, climate, cabin thermal management, and battery thermal management on battery electric vehicle utility

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HIGHLIGHTS

- Applies real-world climate and driver data, validated vehicle and battery models.
- Quantify effects of climate, driver aggression, HVAC, and battery thermal management.
- Cold-climate BEV utility challenged by inefficient cabin heating systems.
- Hot-climate BEV utility challenged by high peak battery temperatures and excessive degradation.
- Active cooling required for aggressive drivers in hot climates.

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ABSTRACT

Battery electric vehicles (BEVs) offer the potential to reduce both oil imports and greenhouse gas emissions, but have a limited utility that is affected by driver aggression and effects of climate—both directly on battery temperature and indirectly through the loads of cabin and battery thermal management systems. Utility is further affected as the battery wears through life in response to travel patterns, climate, and other factors. In this paper we apply the National Renewable Energy Laboratory's Battery Lifetime Analysis and Simulation Tool for Vehicles (BLAST-V) to examine the sensitivity of BEV utility to driver aggression and climate effects over the life of the vehicle. We find the primary challenge to cold-climate BEV operation to be inefficient cabin heating systems, and to hot-climate BEV operation to be high peak on-road battery temperatures and excessive battery degradation. Active cooling systems appear necessary to manage peak battery temperatures of aggressive, hot-climate drivers, which can then be employed to maximize thru-life vehicle utility.

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1. Introduction

Battery electric vehicles (BEVs) offer the potential to reduce both oil imports and greenhouse gas emissions, but have a limited range and require significantly more time to recharge than the time required to refuel a conventional vehicle (CV). These factors reduce the achievable number of vehicle miles traveled (VMT), negatively impacting the potential for BEVs to displace gasoline consumption, reduce greenhouse gas emissions, and minimize total cost of ownership of the vehicle. Calculating the extent of this effect is complicated by the fact that the range of the vehicle is sensitive to many factors. Each trip's acceleration and speed characteristics have a direct impact on vehicle efficiency—more aggressive trips will consume more energy from the battery for each mile driven. Use of cabin climate control (e.g., air conditioning and heating) can add considerably to auxiliary load demands placed upon the battery. Battery temperature can affect efficiency and available energy. Further, the battery's ability to store energy degrades in response to these and other factors throughout its service life.

With support from the Vehicle Technologies Office in the U.S. Department of Energy, the National Renewable Energy Laboratory (NREL) has developed BLAST-V—the Battery Lifetime Analysis and Simulation Tool for Vehicles. BLAST-V is an evolution of NREL's Battery Ownership Model, designed to evaluate the total cost of ownership and address other challenges associated with the

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lifecycle performance of electric drive vehicles. The Battery Ownership Model has been applied to study the effects of electric range and charge strategies on both BEVs and plug-in hybrid electric vehicles in past studies [1–4]. BLAST-V improves the resolution of drive patterns to the individual trip level, considering both the temporal and spatial distribution of trips, and adds additional capability to account for the effects of driver aggression, local climate, vehicle cabin thermal management systems, and battery thermal management systems (BTMSs). Future development will allow BLAST-V to analyze electrical, electrochemical, and thermal performance variations between cells within a pack. In this paper, we apply BLAST-V's capabilities to examine the sensitivity of BEV utility to driver aggression and climate effects over the life of a vehicle.

2. Approach

BLAST-V is an electric vehicle simulator focused on computing long-term effects of complex operational scenarios on vehicle utility and battery performance. It considers the vehicle powertrain, battery control strategy, driving and charging patterns, local climate, the vehicle-battery-environment thermal system, battery chemistry, and other factors in computing short-term vehicle and battery performance (e.g., vehicle range, battery voltage, state of charge (SOC), and temperature) and long-term vehicle utility and battery degradation. An approximate graphical representation of the key elements and flow of data within BLAST-V is illustrated in Fig. 1.

Vehicle performance and sizing via standard drive cycle simulation (e.g., UDDS, HWFET, US06) is completed in NREL's Future Automotive Systems Technology Simulator (FASTSim), also developed under funding provided by the Vehicle Technologies Office in the U.S. Department of Energy [5].

2.1. Climate data

Hourly ambient temperature and solar irradiance data from NREL's National Typical Meteorological Year Database [6a] is integrated into BLAST-V for 100 cities. These cities were selected as the 100 largest markets for hybrid electric vehicles as of 2010 [6]. Example data for the cities of Los Angeles, California; Phoenix, Arizona; and Minneapolis, Minnesota, are shown in Figs. 2 and 3. In this study, Los Angeles is selected as a baseline case for its mild climate and history of rapid adoption of hybrid electric vehicles. Phoenix is selected to represent an environment capable of rapidly degrading battery performance due to its high ambient temperature and solar irradiance. Minneapolis is selected to represent an environment requiring aggressive use of cabin climate control systems due to its cold winters and hot summers.

2.2. Vehicle thermal model

A thermal model of the vehicle cabin and battery is utilized for calculating both cabin heating, ventilation and air conditioning (HVAC) loads and battery temperature. A lumped capacitance thermal network approach as illustrated in Fig. 4 is used for computational efficiency. Effective heat transfer coefficients and other model properties are calculated to fit the response of this model to test data recorded for a 2005 Toyota Prius [7].

This testing did not include operation of vehicle cabin thermal management systems, however. Here we apply data recorded from cabin pull-up and pull-down tests performed on a 2010 Nissan LEAF [8]. For cabin heating, we find that a positive thermal coefficient (PTC) thermistor heater model with a 4-kW electrical load capable of delivering 4 kW of heat directly to M_c produces cabin temperatures and electrical responses representative of the recorded test data. For comparison, we also model an alternative heat pump (HP) system capable of delivering the same 4 kW of heat to the cabin but at a reduced electrical load of 1.6 kW (implying a coefficient of performance of 2.5 [9–11]). For cooling, we find that a model of an air conditioning (AC) system capable of extracting 4.5 kW of heat from the cabin and an electrical load of 1.8 kW (implying a coefficient of performance of 2.5) reproduces the test data well when K_{ac} is increased by 1500 W K^{-1} when T_c is greater than T_a. This modification is representative of the mass transfer effects between the cabin and the ambient air when the cabin air temperature exceeds the ambient air temperature from either the

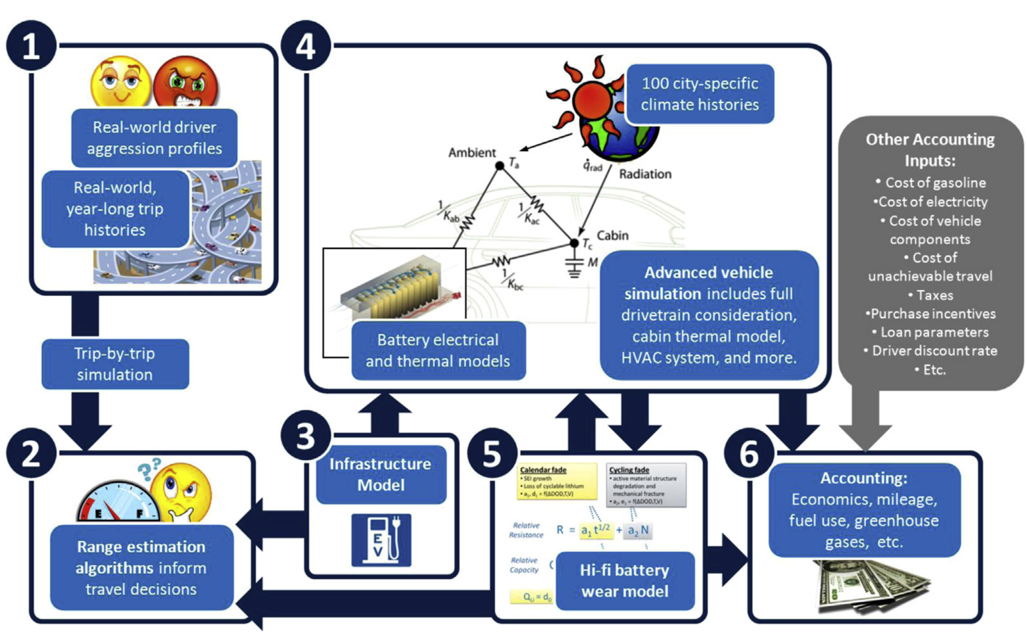

Fig. 1. Graphical illustration of BLAST-V simulation algorithms.

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