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From driving cycle analysis to understanding battery performance in real-life electric hybrid vehicle operation

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Abstract

This paper proposes a methodology and approach to understand battery performance and life through driving cycle and duty cycle analyses from electric and hybrid vehicle (EHV) operation in real-world situations. Conducting driving cycle analysis with trip data collected from EHV operation in real life is very difficult and challenging. In fact, no comprehensive approach has been accepted to date, except those using standard driving cycles on a dynamometer or a track. Similarly, analyzing duty cycle performance of a battery under real-life operation faces the same challenge. A successful driving cycle analysis, however, can significantly enhance our understanding of EHV performance in real-life driving. Likewise, we also expect similar results through duty cycle analysis for batteries. Since 1995, we have been developing tools to analyze EHV and power source performance. In particular, we were able to collect data from a fleet of 15 Hyundai Santa Fe electric sports utility vehicles (e-SUVs) operated on Oahu, Hawaii; from July 2001 to June 2003 to allow driving and duty cycle analyses in order to understand battery pack performance from a variety of EHV operating conditions. We thus developed a comprehensive approach that comprises fuzzy logic pattern recognition (FL-PR) techniques to perform driving and duty cycle analyses. This approach has been successfully applied to EHV performance analysis via the creation of a compositional driving profile called "driving cycle profile" (DrCP) for each trip. The same approach was used to analyze battery performance via the construction of "duty cycle profile" (DuCP) to express battery usage under various operating conditions. The combination of the two analyses enables us to understand both the usage profile of EHV and battery performance in synergetic details and in a systematic manner using a pattern recognition technique.

Keywords: BEV; Driving cycle analysis; Pattern recognition; Fuzzy logic; Vehicle performance analysis; Battery stress factors

1. Introduction

Conducting driving cycle analysis using trip data collected from vehicles dispatched in real-life operation is very challenging; e.g., [1–18]. Although numerous attempts have been made in the past, no consistent approach has been accepted to allow a systematic, detailed characterization of driving cycles for engineering analysis and comparison, except those standard driving schedules conducted on dynamometers or well-documented tracks, mimicking real-life situations, to permit vehicle performance analyses or other urban and emission studies [3–5,7–9,14–20]. Besides standard driving schedules, sometimes regional driving cycles have to be developed [8,14–18] to emulate real-world conditions in certain regions to enable adequate analyses. Even so, these traditional approaches are still unable to handle extremes that are beyond test capabilities. Therefore, these conventional assessments offer limited success.

For traction power sources such as batteries in electric and hybrid vehicle (EHV) applications, assessments on their performance are, most of the time, conducted in laboratories. Similar to standard driving schedule tests and analyses, these laboratory tests and duty cycle analyses have constraints in their validity to real-life operation. A main issue exists in both cases due to the problem with real-life operation where, even under specific driving cycles or duty cycles, energy consumption strongly depends on ambient operating conditions that are typically uncontrolled. Thus, a systematic, comprehensive analysis of both driving cycles (for vehicle) and duty cycles (for power sources) in real-life operation is highly desirable.

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In the literature, depending on the context of discussions by different authors, driving cycle, duty cycle, and driving pattern may present different meanings. It is therefore essential to define the terminology used by this paper to ensure clarity. A "driving cycle" in this paper refers to a history of driving, typically represented by a speed versus time curve. A "duty cycle" refers to a history of power usage of a device, typically depicted by a power versus time curve. A "driving pattern" is used to describe a driving condition, taking into account both road condition (e.g., road type) and driving behavior.

The lack of comprehensive driving and duty cycle analytical tools to allow benchmarking both vehicle and battery performance might have undermined the development and commercialization of battery-powered electric vehicles (BEVs) in the 1990s. Significant technology barriers, such as limited driving range and the lack of battery charging infrastructure, prevented widespread use of BEVs during that period. On the other hand, the lack of adequate tools to afford a rapid integration of powertrain components and a quantitative benchmark of technology advancements could have hampered BEV's market penetration. These barriers persist to date. Although the on-going success in commercializing hybrid electric vehicles (HEVs) and the introduction of plug-in hybrids by Toyota and a handful other automakers raise some hope to transform our future automobile and transportation industry to a more efficient and environmentally-friendly operation, a better assessment can only accelerate this process.

Consistent driving and duty cycle analyses are very desirable to allow us correlate between battery performance and EHV usage in real-world situations. The approach that we used in this work relies on a suite of fuzzy logic pattern recognition (FL-PR) techniques that tend to be comprehensive and quantitative to allow (vehicle) driving and (powertrain/battery) duty cycle analyses. In this paper, we explain how the FL-PR technique works to allow driving and duty cycle analyses using trip data collected from a fleet of 15 Hyundai Santa Fe battery-powered electric sports utility vehicles (e-SUVs) in real-world driving conditions. This approach should be quite useful, for instance, for future plug-in hybrids in assessing vehicle and battery performance.

2. Data collection

The fleet of 15 Santa Fe e-SUVs was delivered by Hyundai Motor Company (HMC) of South Korea to Hawaii in July 2001. Fig. 1 shows pictures of one of the Santa Fe e-SUVs and on-board data acquisition device. The vehicles are designed to be purely battery-powered for roadworthy tests. Each vehicle comes with a 60 kW AC inductive motor and power controller with a Panasonic 95 Ah nickel metal hydride EV battery pack (315 V nominal). These vehicles can accept AC charging directly from electrical wall outlets or fast DC charging with a 60 kW PosiCharge™ made by AeroVironment (Monrovia, CA). Trip and charging data are recorded by automated on-board data acquisition system in a flash memory card during vehicle operations or charging periods. All trip and charging data were time-stamped. The data includes information from motor controller, auxiliary power unit (APU), and battery management system on a second-by-second basis, including pack voltage, current, power, motor RPM and many other critical parameters that can afford driving and duty cycle analyses. The database comprised data from more than 255,000 km in 25,000 trips. The data were transferred periodically to a separate collecting medium, filtered, validated, and then recorded into a database for analysis.

The vehicles were dispatched to four primary organizations on Oahu, Hawaii, for a variety of use from July 2001 to June 2003. The vehicles dispatched to Hickam Air Force Base (HAFB) were typically used for security patrol and errands. Hawaiian Electric Company (HECO) and City and County of Honolulu (C&C) used the vehicles for commutes and performing service duties. The vehicles retained at the Hawaii Electric Vehicle Demonstration Project (HEVDP) office, now Hawaii Center for Advanced Transportation Technologies (HCATT), were used for commutes and errands. It is worth noting that drivers at HAFB have to observe strict speed limits (mostly at 25 mph or 40 km h^{-1}), therefore the driving cycles from these vehicles are often different from those of the other locations.

3. Technical approach: analyses, results, and discussion

3.1. Driving cycle analysis

Fuzzy logic pattern recognition is a relatively well-accepted technique for many technology applications, e.g., [21–26]; due to its merit often associated with the need for linguistic, qualitative expression and knowledge in handling non-fuzzy numerical data. This ability is of particular interest to us in dealing with driving cycle analysis, arising from the qualitative nature and need for linguistic expression of driving cycles in such an analysis. Interestingly, few have reported using fuzzy logic or

Fig. 1. Hyundai's Santa Fe e-SUV and on-board data acquisition system.