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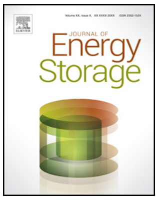

Battery cycle life test development for high-performance electric vehicle applications

Quirin Kellner[a,*], Elham Hosseinzadeh[a], Gael Chouchelamane[b],
Widanalage Dhammika Widanage[a], James Marco[a]

[a] WMG, University of Warwick, Coventry, CV4 7AL, UK
[b] Jaguar Land Rover, Banbury Road, Warwick, CV35 0XJ, UK

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ABSTRACT

High Performance (HP) battery electric vehicle (BEV) and racing applications represent significantly different use cases than those associated with conventional consumer vehicles and road driving. The differences between HP use cases and the duty-cycles embodied within established battery test standards will lead to unrepresentative estimates for battery life and performance within a HP application. A strategic requirement exists to define a methodology that may be used to create a representative HP duty-cycle. Within this paper two methods HP duty-cycle design are evaluated and validated. Extensive simulation results into the electrical performance and heat generation within the battery highlight that the new HP duty-cycles provide a more representative duty-cycle compared to traditional battery test standards. The ability to more accurately predict the performance requirements for the battery system within this emerging and strategically important BEV sector will support a range of engineering functions. In addition, the ability to more accurately define the use-case for a HP-BEV will underpin ongoing experimentation and mathematical modelling to quantify the associated cell ageing and degradation that may occur within HP vehicle applications.

1. Introduction

High Performance (HP) battery electric vehicles (BEV) and electric vehicle (EV) racing applications represent significantly different use cases than those associated with conventional consumer EVs and road driving. Such HP-BEVs are typically driven to the performance limits of the vehicle or the capabilities of the driver. Asus et al. [1,2] conducted extensive tests on a series hybrid racing car to develop a detailed mathematical model of the vehicle that characterised its dynamic behaviour and could underpin drive-cycle prediction. The authors present experimental data, including driver pedal input and system power demands, for the vehicle being driven on the Magny-Cours racing circuit in France. Their analysis highlight significant proportions of time spent at peak demand (full-throttle), in addition to rapid transitions from vehicle acceleration and braking. For a BEV, such a usage profile would translate to extended periods of time when the battery system is under full electrical load for charging or discharging.

By comparing the data presented within [1,2] with that found in studies into urban driving, e.g. [3,4] one of the unique measures of HP driving is not just the high amplitude power demands placed on the vehicle's powertrain, but also the relative time that the vehicle spends at peak-power. In contrast, peak power demand in urban driving is rare, of short duration and interspaced with extended periods of low demand. For HP applications, a complete energy discharge of the battery pack may occur within less than a single hour. Conversely, with a conventional EV it may take many hours or even days to deplete the energy content of the battery pack [5].

International standards and best-practice guides exist that address the performance evaluation requirements for EV lithium ion battery (LIB) systems. Each standard addresses different requirements for performance, robustness and safety and how

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Abbreviations: BEV, battery electric vehicle; CDF, cumulative distribution function; C-rate, current rate; DOD, depth of discharge; DST, Dynamic Stress Test; eCDF, empirical cumulative distribution function; ECM, equivalent circuit model; EV, electric vehicle; FFT, fast fourier transform; FTP-75, federal testing procedure; HP, high-performance; HP-BEV, high-performance battery electric vehicle; HP-MSC, high-performance multisine cycle; HP-RPC, high-performance random pulse cycle; iCDF, inverse cumulative distribution function; IECC, IEC 62660-1 cycle life test profile A; LFP, lithium-iron-phosphate; LIB, lithium ion battery; MSC, multisine cycle; OEM, original equipment manufacturer.

* Corresponding author.
E-mail addresses: q.kellner@warwick.ac.uk (Q. Kellner), e.hosseinzadeh@warwick.ac.uk (E. Hosseinzadeh), gchouch3@jaguarlandrover.com (G. Chouchelamane), dhammika.widanalage@warwick.ac.uk (W.D. Widanage), james.marco@warwick.ac.uk (J. Marco).

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testing should be undertaken at either a cell (i.e. IEC 62660-1 [6]), module (i.e. ISO 12405-2 [7]) or system level (i.e. Department of Energy battery test manual for electric vehicles [8]). Within [8] the Dynamic Stress Test (DST) is a simplified version of the electrical loading associated with a EV traversing the Federal Testing Procedure (FTP-75) drive-cycle [9]. The ISO and IEC standards contain comparable duty-cycles that are often employed by vehicle original equipment manufacturers (OEMs) and system suppliers for component selection and battery system evaluation. However, as reported within [10,11], the underpinning drive-cycles that are used as the basis for the design of the battery load-profile are known to be unrepresentative of a number of different vehicle types, driving styles and environmental conditions. The authors assert that the differences between HP and standardised duty-cycle profiles are likely to influence performance requirements of the battery systems and the rate of degradation that may occur within the cells that comprise the HP vehicle battery system.

Although the causality between cell degradation and the external environment and electrical load is known to vary considerably between different cell types, chemistries and form factors, there is a range of common ageing mechanisms that underpin many degradation modes for a variety of LIB chemistries. The topic of LIB degradation and associated ageing mechanisms is the subject of considerable academic and industrial research [12–16] and therefore a full explanation will not be repeated. For completeness, Table 1 summarises those key ageing factors that are most pertinent to this study. Given the increased intensity of ageing mechanisms such as electrical current and cell operating temperature associated with HP driving or EV racing, it is expected that the performance requirements and degradation profile of batteries employed within HP applications may not correspond well with experimental results from standardised tests and from existing research that is focussed on consumer BEVs and urban driving.

To progress the research into better understanding the performance requirements and cell degradation models associated with HP-BEV use, the first strategic requirement is to define a methodology that may be used to define a representative duty-cycle that, in turn, can be used to underpin subsequent experimentation and mathematical modelling.

This paper is structured as follows. Section 2 presents two methods of duty-cycle design. The first, extends the traditional process employed for drive-cycle construction within the time domain. The second exploits recent innovations in battery test case design within the frequency domain. Within Sections 3 and 4 the new duty-cycles are evaluated through three case studies that firstly compare the new HP duty-cycles against the battery power demand for a real-world race-circuit. Secondly, results are presented that quantify the differences in performance requirements for the battery based on HP duty-cycles compared to traditional test standards. Finally, results from a thermal modelling simulation are reported that highlight the level of heat generation within the battery under HP-BEV applications and compares this to that predicted using established battery test methods. Conclusions from this research are presented in Section 5.

2. Methods for duty-cycle development

One existing area of research engaged in the development of testing profiles that preserve traits in the source data is that of driving cycle design. The underlying principle of driving cycle construction is to develop a cycle whose properties match specific criteria extracted from a database. As such, the methods explored in this field lend themselves to the construction of HP duty-cycles.

Another approach to duty-cycle design is to construct the HP duty-cycle based on a desired amplitude spectrum and inverse cumulative distribution function (iCDF) [24]. The amplitude spectrum of a duty-cycle is its representation in the frequency domain and thus contains information of the amplitudes and frequencies that the battery would be subject to. The iCDF is the mathematical representation of a cumulative histogram and describes how much time is spent within each amplitude range. Recent publications by Widanage et al. have shown that the consideration of target amplitude spectra during characterization tests can positively affect the representativeness of testing procedures [25,26], while concurrently reducing the time required to undertake the experimental evaluation. This research describes a method for superimposing the Pulse Power Current (PPC) test profile as described in the IEC 62660-1 standard [6] with a multisine signal. The result is a charge sustaining test-profile called a pulse-multisine which approximates the amplitude spectrum of a duty-cycle derived from a driving cycle. Within [26], the pulse-multisine was successfully employed to characterise a number of different cell-types and provide the necessary dataset to parameterise an equivalent circuit model (ECM) representation of the cells. The research highlights that the validation accuracy of the ECM improved when estimated with the pulse-multisine as compared to characterisation tests undertaken in accordance with established methods in [6]. The improved accuracy was attributed to the ability of the pulse multisine to better emulate the frequency bandwidth and amplitude of the electrical loading experienced by the battery system throughout the target drive-cycle. A similar improvement in HP degradation and modelling is therefore expected by designing a HP duty cycle with the appropriate frequency bandwidth and histogram that represent a HP duty cycle database.

Table 1
Duty-cycle conditions and resulting degradation pathways.

Cause/Aggravating factor	Affects	Causes	Ref
High Current	Anode	Lithium plating during charging, especially at high state of charge (SOC) and subsequent solid-electrolyte interface (SEI) growth at locations where lithium metal is exposed to electrolyte	[13,17,18]
		Volume changes resulting in contact loss of active material particles and particle cracking, exposing fresh graphite to the electrolyte and subsequently further SEI growth	[13,17]
	Cathode	Volume changes, and tensile and compressive stresses causing particle cracking	[19,20]
High Temperature	Anode	Decomposition of electrolyte resulting in gassing and further SEI growth	[13,16,17,21]
		Increased rate of parasitic side reactions which includes SEI growth	[13]
		Decomposition of binder causing mechanical instability	[13]
	Cathode	Decomposition of electrolyte resulting in gassing	[17,22,23]
		Increase in phase changes in active material	[17]
		Dissolution of transition metal which may result in material phase change, and its re-deposition on anode	[13,16,17,19]
High Depth of Discharge (DOD)	Anode	Volume changes causing mechanical stresses and particle cracking with subsequent SEI growth	[13]
	Cathode	Volume changes causing mechanical stresses	[13,17]
		Crystal structure disorder causing particle cracking	[17]