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Preemptive degradation-induced battery replacement for hybrid electric vehicles in sustained optimal extended-range driving conditions

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ABSTRACT

This research assesses the potential of a preemptive battery replacement strategy designed to curtail the escalation of hybrid electric vehicle (HEV) operating costs when approaching terminal degradation conditions. These long-term repercussions materialize whilst an optimal plug-in hybrid electric vehicle (PHEV) active component degradation management process is applied over an extended length of time. The proposed methodology leverages a lithium-ion battery pack, a hydrogen-fueled polymer electrolyte membrane fuel cell (PEMFC) and plug-in grid recharge capabilities to achieve an economically-optimal Markov chain-generated 100-mile extended autonomy scenario during the entirety of a PHEV's useful lifecycle. Proposed results demonstrate the long-term transitional response of the optimal process when burdened with decreasing component performance. A marked shift between battery and fuel energy priority is observed during late stages of component degradation. This delayed evolution suggests the feasibility of a preemptive component replacement strategy whose potential is analyzed according to performance and economic metrics.

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1. Introduction

Rechargeable battery packs hold a prime position at the forefront of the next generation of vehicles due to their inherent usefulness as efficient energy accumulators. However, an inexorable flaw of electrochemical energy carriers such as lithium-ion batteries and polymer electrolyte membrane fuel cells (PEMFCs) is their degradation [1,2]: a spectrum of phenomena strongly dependent on usage conditions that gradually erodes their potential until end-of-life (*EoL*) conditions render them unfit to accomplish their intended function, after which point they must be replaced at significant cost. On the other hand, an ideal electric vehicle (EV) remains elusive; most EV solutions are built around the hybrid electric vehicle (HEV) concept: an assembly of energy-carrying technologies designed to capitalize on each other's strengths and weaknesses and ultimately achieve satisfactory vehicle operation [3]. By leveraging typical HEV architectures, it is possible to exert an active control over several of the aforementioned sensitive components' operating conditions using contrivances already on-board most HEVs and in turn mitigate their rate of decay, for a price. This research first proposes a macroscopic exploration of the long-term dynamics encountered when HEV component degradation is managed in such a fashion during the entirety of a vehicle's useful, a timescale that is seldom undertook in currently available optimized PHEV management proposals. Furthermore, our results expand on negative late-stage performance degradation-induced transitional responses to study the impacts of preemptive HEV battery pack replacement, i.e. ahead of terminal *EoL* conditions; such belated evolutions are only

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highlighted in the course of the proposed long-term approach and cannot be extrapolated from typical short-term results.

These results are obtained through numerical optimization using a discrete dynamic programming (DDP) technique aimed at optimizing the operating cost of a plug-in hybrid electric vehicle (PHEV) submitted to a long-distance Markov chain-generated 100-mile autonomous benchmark driving scenario carried repeatedly over the entirety of the vehicle's years-long useful lifetime, which ends when either one of its main energy carriers (lithium-ion battery pack or PEMFC) reaches *EoL* conditions. This optimal DDP process uses an economy-based criteria, balancing fuel, grid-powered recharge capabilities as well as both battery and fuel cell usage-sensitive degradation rates to achieve the absolute minimal operating cost during each consecutive daily cycle, where PEMFC degradation and fuel expenses are tallied during active driving intervals while grid-based recharge systematically occurs during inactive periods in-between each driving cycle; battery degradation is estimated at all stages of the vehicle's lifetime. This article offers constructive additions to the scientific field revolving around HEV-centric component degradation management issues by addressing specific points of interest:

- The identification of significant transitional patterns during the later stages of optimally-managed PHEV component degradation that result in increased costs and hastened battery degradation rates.
- A study on the economic and component efficiency gains achievable through a preemptive battery replacement strategy intended to mitigate the aforementioned late-stage degradation-induced rise in operating costs.
- A macroscopic study of the long-term repercussions that arise when a PHEV in extended-range driving conditions is submitted to a component degradation-focused energy management process over the entirety of its useful lifetime.

This article adheres to the following structure: the current section articulates the motivation behind this research and highlights the relevant scientific literature, Section 2 outlines the PHEV models necessary for its realization, Section 3 condenses the optimal process as well as its functional structure, Section 4 investigates the outcomes stemming from the optimal process and Section 5 concludes on our findings and their implications for future research. A complete glossary of the mathematical symbols used within this article is found in the end of the introductory section.

1.1. Literature overview

Component degradation study is a relatively well-researched field that has seen much development due to the heightened interest in efficient transportation and energy storage technologies; as such, lithium-ion batteries [4–6] and PEMFCs [7] have been the subject of many studies in recent years, ranging from modeling [8–10] to microstructure analysis [11,12]. Nevertheless, given the inherent immaturity of these emerging technologies, most of these efforts remain limited in scope [13]. In turn, direct application of ageing phenomena to HEV energy management endeavours remains limited in literature [14–16] and efforts taking an economy-focused approach is rarer still [17–19]. Of the many techniques available to address HEV energy management optimization, discrete dynamic programming (DDP) has proven to be an effective tool [20,21] that carries proof of absolute global optimality by definition [22]. A common aspect of active degradation management efforts found in literature is the short timescale on which they are conducted, which is often limited to a few minutes [23,24] representative of standard driving cycles [25]; conversely, typical HEV component degradation develops in non-linear fashion over several years' time [26], a significant aspect of this issue that few research efforts fully take into account. Our own published research has covered various aspects of the issue, such as lead-acid battery degradation modeling [27], the impacts of economic fluctuation on optimal PHEV energy management outcomes [28], optimal PHEV energy management within finite battery-dependent driving ranges from both short single-cycle [29] and long-term perspectives [30]. The proposed paper is consonant with the latter publication but eschews the boundaries of restrictive PHEV battery capacities to achieve a full 100-mile (161 km) driving scenario, a common benchmark for HEV autonomy extension [31].

Symbol	Unit	Description
P	%	State transition probability matrix
i, j	n/a	State index values
n_1, n_2	n/a	Damaging event counter
V'_1, U'_{load} V'_2	μV cycle^{-1}	Instantaneous voltage degradation [2]
	μV h^{-1}	Voltage degradation rate [2]
$V_{nom,cell}$	V	Nominal fuel cell voltage
EoL	%	Battery end-of-life condition [32]
EoL_{FC}	%	Fuel cell end-of-life condition [2]
k	n/a	Discretization step
Δt	s	Step length
V_b	V	Battery voltage
I_b	A	Battery current
E_m	V	Battery electromotive force [33–35]
SOC	%	State-of-charge
θ_b	°K	Battery electrolyte temperature
R_0	Ω	Battery pole resistance [33–35]
R_1	Ω	Battery internal resistance [33–35]
I_m	A	Battery main branch current
τ_1	s	Battery time delay factor [33–35]
t	s	Simulation time
Q_e	Ah	Battery charge
C_δ	Ah	Degraded battery capacity
ϕ_{DOD}	n/a	Discharge level stress factor
κ	Ah	Battery instantaneous lifetime capacity
κ_{max}	Ah	Battery maximal lifetime capacity
A	n/a	Exponential prefactor
E_a	J mol^{-1}	Activation energy for degradation reactions
R	J mol °K^{-1}	Universal gas constant
$\theta_{b,ref}$	°K	Battery reference electrolyte temperature
λ_b	years	Estimated battery lifetime [26]
x_i	*var.*	State variable
H_2	kg	Hydrogen fuel
$\delta_{b,I}$	%	Battery cycling degradation
$\delta_{b,\theta}$	%	Battery calendar degradation
δ_b	%	Battery cumulative degradation
δ_{FC}	%	Fuel cell degradation
x_{min}	*var.*	Minimal state admissible value
x_{max}	*var.*	Maximal state admissible value
u_R	n/a	Control variable
C_i	$\$CAN$	Performance criteria
J	$\$CAN$	Objective function
N	n/a	Final discretized step

2. Numerical models

This section provides condensed modeling information to foster reader engagement, with supplemental attention given to specific additions to the current paper; interested readers can access fully detailed mathematical descriptions of the models abridged here in [29,30]. As a general rule, in order to accommodate the calculation-heavy constraints of the optimal process and the macroscopic, economy-focused scope of our objectives, the models presented in this research lean towards straightforward, concise representations.

The modeled PHEV's general specifications [36] are that of a 1721 kg mid-sized sedan built according to a series architecture,

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