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Interpretation of the electric vehicle operating point in real time

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Abstract

In this article, the performance parameters of the electric vehicle were investigated, and its operating point was defined using the core components (Battery, Inverter, and Motor). The test vehicle 2023 Cadillac Lyriq, provided by General Motors Inc., was driven on specified road segments, and the real-time data were retrieved using the integrated controller area network architecture. The neoVI–Fire 2 tool was connected to the vehicle system, which records the dynamic data, and Vehicle Spy software was used to convert the data into a readable format. Finally, the vector electric vehicle operating point was proposed, and the corresponding behavior was interpreted. This methodology could assist researchers in understanding the dynamic behavior of electric vehicle parameters to develop integrated techniques which augment the performance in real time.

Key words: battery operating point; CAN analyzer; electric vehicle; inverter operating point; motor operating point; Vehicle Spy

Introduction

The Lithium-Ion battery developed four decades back has penetrated every electric component of daily human usage. Among the technological advancements, the automotive industry has changed its phase to adopt the electric propulsion system ending the traditional internal combustion engines to reduce emissions (Akhtar & Patil, 2022). The performance of the combustion engines was measured using the vector engine operating point (EOP), which was traditionally accepted as an industry standard. However, the existing literature did not propose a similar concept for electric vehicles.

Kolachalama and Malik (2021, 2022) performed multiple experiments using Cadillac test vehicle segments and analyzed the vector EOP. Hence, in this article, a similar experiment was conducted using the electric test vehicle 2023 Cadillac Lyriq to investigate the properties of the performance parameters. The vector electric vehicle operating point (EVOP) was proposed, representing the performance, using the parameters relevant to the elements (Battery, Inverter, and Motor) (Zhou et al., 2015). It is engrossing for every engineer to delve into the properties of EVOP vector in real time, and a definite behavior was not investigated in the existing literature. The details of the test procedure and process adopted was presented in the following sections.

Objective

The electric vehicle performance could be analyzed more precisely by identifying the effecting parameters in real time. Despite the advancement of computational techniques, virtual simulations representing normal driving conditions, and controlled test procedures, adapting the actual scenario of a vehicle traversing any terrain in real time is challenging (Donkers et al., 2020). Hence, to investigate the properties of EVOP, it is required to drive the test vehicle (2023 Cadillac Lyriq) on multiple terrains, and real-time vehicle data must be collected to analyze the performance parameters. This article summarizes the detailed experimental procedure based on the automotive industry standards and a new problem to explore for researchers.

Methodology

The vector EOP was defined with three elements (instantaneous engine torque [IET], instantaneous engine speed, and instantaneous fuel consumption rate [IFCR]), which is an established automotive standard (Kolachalama & Lakshmanan, 2021). In this article, analogous to EOP, the EVOP was proposed with the elements (battery operating point [BOP], inverter operating point [IOP], and motor operating point [MOP]). Table 1 lists the parameters defining the EVOP, and only the direct current discharged by the battery was considered in the following analysis assuming no losses, that is, $IBAC \approx IINC \approx IMOC$. In real time, the vector EVOP is affected by multiple parameters listed in Table 2, and the steps involved in data retrieval are presented in the following section.

Abbreviations: BOP, battery operating point; IOP, inverter operating point; MOP, motor operating point.

Data retrieval

In this experimental project, the test vehicle (2023 Cadillac Lyriq) was driven on the path (Milford–Lansing) with a speed range of [0 75] MPH, as shown in Figure 1. The vehicle is equipped with a single rear motor and 100-kWh battery pack and is expected to produce 340 horsepower and 312 miles of range (Source: General Motors Inc.).

The data retrieval procedure adopted in Kolachalama and Malik (2021) and Kolachalama and Malik (2022) produced the best results for the computational model that predicted the driver behavior vector (DBV). Hence, a similar process was followed to retrieve the 2023 Cadillac Lyriq test vehicle data. The hardware tool neoVI–Fire 2 is attached to the controller area network (CAN) outlet under the vehicle's steering wheel (Figure 2) and interfaced to the machine installed with Vehicle Spy software (Jaynes et al., 2016). This setup accommodates the user to retrieve the selected vehicle data with a defined frequency of 10 Hz (Figure 3; Navet, 1998). Two datasets were retrieved in the form of *.vsb files and using the built-in

Table 1. Electric vehicle operating point (BOP, IOP, and MOP)

BOP	IOP	MOP
Instantaneous battery charge (IBAQ)	Instantaneous inverter voltage (IINV)	Instantaneous motor torque (IMOT) Instantaneous motor speed (IMOS)
Instantaneous battery current (IBAC)	Instantaneous inverter current (IINC)	Instantaneous motor current (IMOC)
Instantaneous battery temperature (IBAT)	Instantaneous inverter temperature (IINT)	Instantaneous rotor temperature (IROT) Instantaneous stator temperature (ISOT)

Table 2. Dynamic state of vehicle (body module, driver behavior, and environment)

Body module	Driver behavior	Environment
Odometer	Speed	Road curvature
Tire pressure	Longitudinal acceleration	External air temperature
Euler angles	Lateral acceleration	Gradient
Aerodynamic drag	Yaw rate	Humidity
Vehicle load	Cabin air temperature	Atmospheric pressure

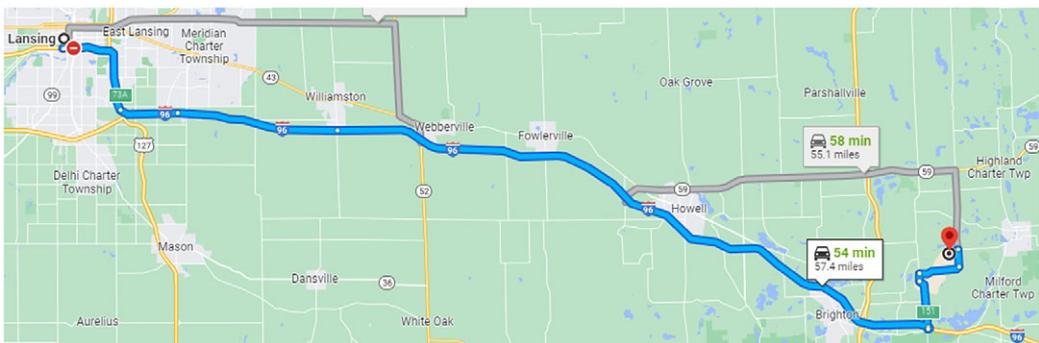


Figure 1. Path traversed—2023 Cadillac Lyriq (January 10–11, 2022).
Source: Google Maps—Michigan, USA.

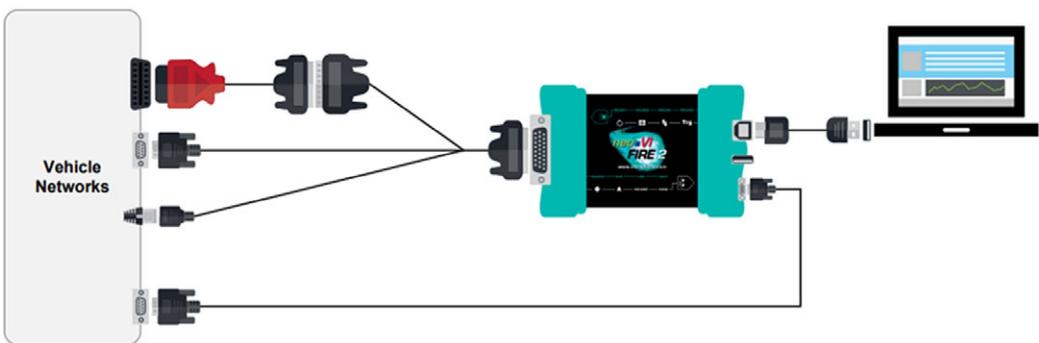


Figure 2. Test setup—Data retrieval using Vehicle Spy.
Source: Intrepid CS and General Motors Inc.

software tool Vehicle Spy, and the parameters were extracted in excel sheets (Fugiglando et al., 2018). Thus, the results were presented in the next section using the computational tool MATLAB.

Results

The functionality of the vector EVOP was investigated using the snippets of the data selected at multiple road segments for speeds ranging [0 75] MPH. The resulting plots of instantaneous [IOP, MOP] were shown in Figures S1–S12 in the Supplementary Material. The BOP was observed to be invariant for 10 s, and the analysis of the results was presented in the “Discussion” section.

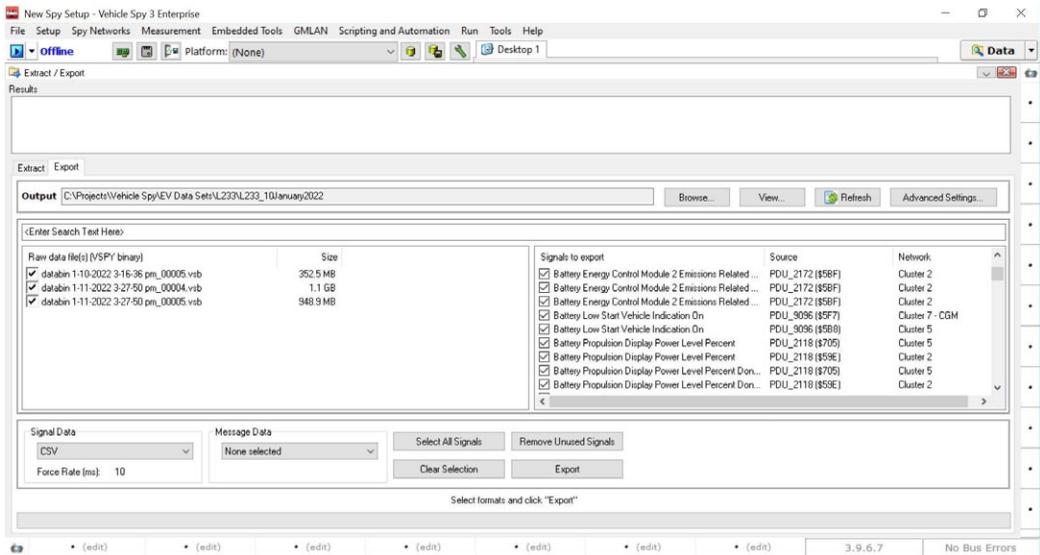


Figure 3. Vehicle Spy software—graphical user interface.
 Source: Intrepid CS and General Motors Inc.

Discussion

The test procedure was conducted using a human driver, and real-time data of the EVOP vector were retrieved using the integrated CAN architecture. The data were investigated, and the vectors [MOP, IOP] were plotted on the two-dimensional plane in the time domain. The graphs were developed for 1,000 time steps (1 time step = 100 ms), and the following details were interpreted.

A 10-s random snippet of the data was selected, and it was observed that the parameters [IBAQ, IBAT] of the vector BOP were invariant. Thus, an analogous correlation could be derived to combustion engine vehicles, where [IBAQ] reflects the level of the fuel tank, and [IBAT] corresponds to the engine surface temperature [EST]. In Kolachalama and Malik (2021), $EST \approx 194^\circ\text{F}$ was considered an optimization criterion to ameliorate HVAC functionality. Similarly, enhanced battery health could result when $IBAT = [71\ 77]^\circ\text{F}$ (Balamurugan et al., 2022).

The most exciting part of this research is the analysis of the vector [MOP] = [IMOT, IMOS, IMOC, IROT, ISOT]. In combustion engines, the values of [IET] and [IFCR] have fluctuating magnitudes due to the intricate property of the flame impingement (Kolachalama & Malik, 2022). In contrast, the curves [IMOT] and [IMOC] have smooth behavior with a direct linear relationship, except for the case Speed = 0 MPH. Similarly, the parameters [IMOS] and [Speed] are linearly related to the factor of transmission ratios of the vehicle. The $IMOT < 0$ reflects the case of regenerative braking, and thus $IMOC < 0$ represents the current directed toward the battery for recharging. The concept of regeneration is an additional advantage of electric vehicles, which is impossible in combustion engines. The [IROT, ISOT] plots depict that $IROT > ISOT$ for all the cases and the range of $IROT = [132\ 142]^\circ\text{F}$ for Speeds > 25 MPH and $EAT < 25^\circ\text{F}$. In the idling state, with Speed ≈ 0 MPH (end of the trip), the range of IROT was observed to be $[132.5\ 134.5]^\circ\text{F}$, whereas ISOT has a range of $[116\ 136]^\circ\text{F}$ in all the scenarios.

The parameter [IINT] fluctuates in the range $[43\ 95]^\circ\text{F}$ but does not have a definite relationship with Speed. The parameters [IINV] and [IINC], relevant to IOP, possess an inverse relationship, reflecting that the resistance would remain in a definite range (or constant) over time. These observations could lead to a new research pathway for engineers to investigate the vector EVOP in real time and develop performance optimization algorithms.

Conclusion

In this experiment, the concept of EVOP for battery-driven vehicles was proposed as analogous to the EOP applicable to combustion engines. In addition, the test vehicle was driven on regular terrain under normal driving conditions (human driver), and the relevant data applicable to the vector EVOP were extracted. The properties and behavior of the EVOP were well understood in real-time scenarios, and the possibility of developing empirical relationships was explored between the elements (MOP, Speed, and EAT). The results were satisfactory and could lead to the development of computational techniques for augmenting electric vehicle performance, as discussed in the “Future work” section.

Future work

The performance analysis of a vehicle in a virtual simulation environment or the setup in a plant model may not produce the accurate behavior of the proposed vector EVOP. Hence, in this work, the EVOP was measured using the real-time analysis of driving a single test vehicle with human intervention, with specific limitations of the testing scenarios (EAT < 25°F). In future work, multiple test cases could be developed with EAT > 60°F, HUM > 60%, and absolute slope > 10% to validate the observations. The investigation could be further deepened by extending the test cases with a multimotor electric vehicle (dual or triple) and utilizing the integrated adaptive cruise control feature, which provides controlled acceleration. Furthermore, selecting short snippets 10 s resulted in minimal (or zero) variance in some parameters, including [IBAQ]. Hence, the analysis could be extended for long periods where substantial changes are observed to the BOP (EAT > 60°F).

In addition, there are no abstract mathematical or empirical models in the existing literature correlating the environmental conditions, body module, and DBV with the EVOP. Thus, a customized deep learning model could be developed to predict EVOP, which could assist the researchers in altering the DBV in real time to enhance vehicle performance. The optimal performance criteria could be defined for the vectors [IMOT, IMOS, IMOC, IINV], and [IBAT, IROT, ISOT], considering the dynamic state of the system.

The adopted procedure of collecting data is not only well known in the industry, but also a tedious procedure which is the major limitation of this experiment. The vehicle was driven by connecting the neoVI–Fire 2 tool interfaced with the data collection machine (laptop) with integrated software Vehicle Spy. The data are collected in the form of *.vsb files, which are encrypted, and it is a time-taking process to retrieve the data in a readable format. The cellular connectivity feature could be used in future work to transmit the required data to the cloud. This could potentially help the engineers selectively retrieve the data in a readable format directly from the server.

Acronyms

BOP	battery operating point
CAN	controller area network
CAT	cabin air temperature
DBV	driver behavior vector
EAT	external air temperature (°F)
EOP	engine operating point
EVOP	electric vehicle operating point
HUM	relative humidity (%)
IOP	inverter operating point
MOP	motor operating point
MPH	miles per hour

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Supplementary materials. To view supplementary material for this article, please visit <http://doi.org/10.1017/exp.2022.27>.

Acknowledgment. The technical analysis was performed using the tools provided by General Motors Inc. (Vehicle Spy and neoVI-Fire 2) and the University of Michigan (MATLAB).

Data availability statement. The data used in this work are proprietary to General Motors Inc., and further details cannot be publicly available. However, the details of the test procedures can be disclosed on request.

Authorship contributions. S.K. developed the concept and performed the analysis. I.S. led the detailed test procedure, and H.M. was the principal investigator for this project.

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Conflict of interest. The authors declare that there is no conflict of interest regarding the publication of this article.

Ethical standards. The research meets all the ethical guidelines, including adherence to the legal requirements of the study country.

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Peer Reviews

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Review 1: Interpretation of the Electric Vehicle Operating Point based on the Dynamic State of the System

Reviewer: Dr. Zheshu Ma 

Date of review: 27 July 2022

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Conflict of interest statement. Reviewer declares none.

Comment

Comments to the Author: This manuscript defines the operating point of the electric vehicle system according to its dynamic state. The performance of electric vehicle systems can be analyzed more precisely by identifying affecting parameters in real-time. It is meaningful for establishing empirical models and performance improvement of electric vehicles in the future. This article is interesting and I suggest it can be considered for acceptance. However, there are some questions for the author to consider. How reliable are the collected data that need to be considered by the author? What can be improved on the electric vehicle used to collect data according to the experimental results? In addition, the acronyms in the manuscript are repeatedly explained, such as EVS, EOP and EVOP. Are the acronyms directly usable after the explanation?

Score Card

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Does the abstract correctly embody the content of the article? (25%)

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Is the objective of the experiment clearly defined? (25%)

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Analysis



Does the discussion adequately interpret the results presented? (40%)

2/5

Is the conclusion consistent with the results and discussion? (40%)

2/5

Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)

2/5

Review 2: Interpretation of the Electric Vehicle Operating Point based on the Dynamic State of the System

Reviewer: Dr. Bo Yang 

Kunming Univ Sci , China

Date of review: 03 August 2022

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Conflict of interest statement. I have no conflict of interests

Comment

Comments to the Author: More discussions should be provided for the data;
More state-of-the-art literature review should be done;
Major limitation of this work should be highlighted.

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Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)

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