Exploratory Analysis of Operational Thermal Behavior in Electric Bus Batteries: A Diagnostic Perspective

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Abstract— **This paper presents an analysis of the thermal behavior of electric bus batteries, emphasizing diagnostic techniques to identify potential issues in the Battery Thermal Management System (BTMS). Using real-time data from a CAN interface reader, the study focuses on temperature fluctuations and patterns that pose risks to the BTMS. Key findings include instances where maximum cell temperatures exceed safe operational limits, indicating a decline in BTMS effectiveness over time. The research also highlights the importance of monitoring the temperature difference (ΔT) between cells to ensure thermal distribution efficiency. Given the often limited data provided by electric vehicle manufacturers, this methodology demonstrates that early signs of thermal anomalies can be detected, offering valuable insights for improving maintenance strategies and ensuring the safety and longevity of electric bus batteries, particularly in climates where thermal management is crucial.**

Keywords: Battery Thermal Management System (BTMS), Safety, Battery Electric Bus (BEB), Thermal Diagnostics, Real-Time Monitoring.

I. INTRODUCTION

The rapid adoption of electric vehicles (EVs) has accelerated the need for safe and efficient lithium-ion battery (LIB) management. LIBs, known for their high energy density and long cycle life, are sensitive to temperature fluctuations, especially under demanding conditions [1]. Operating temperatures outside the optimal range of 15°C to 35°C can lead to thermal runaway, a condition where battery cells overheat uncontrollably, potentially causing fires or explosions [2], [3].

Maintaining consistent temperatures within LIB modules is essential for preventing safety failures and ensuring reliability. A temperature differential of less than 5°C is recommended to avoid the spread of thermal issues across the battery pack [4]. This requirement becomes critical in applications like electric buses, where the Battery Thermal Management System (BTMS) plays a crucial role in operational safety and longevity [5].

Faulty sensors and data inaccuracies in BTMS can lead to erroneous decision-making, affecting temperature control and potentially masking real battery issues. False readings may trigger unnecessary cooling actions or, conversely, allow overheating conditions to go undetected, increasing the risk of system failure and accelerated cell degradation [1].

If left undetected, these temperature inconsistencies can degrade specific cells faster, shortening the overall battery lifespan and, under extreme conditions, causing thermal propagation—a phenomenon where an overheated cell initiates a chain reaction that impacts the entire battery pack [6], [2]. Such failures not only compromise system reliability but also present severe safety risks [2].

This study conducts a thermal diagnostic analysis of temperature fluctuation patterns in the battery cells of an electric bus during operational cycles. By employing real-time monitoring and diagnostic techniques, it examines the impact of sensor faults and BTMS decision errors on battery health. The proposed methodology, which focuses on using limited operational data to identify thermal issues, aims to improve maintenance strategies and enhance safety for electric buses operating in challenging climates [7].

II. THERMAL ANALYSIS

This section presents an exploratory analysis of the temperature patterns observed in the battery cells of an electric bus, aiming to detect thermal anomalies and evaluate the performance of the Battery Thermal Management System (BTMS). Using data from the bus's monitoring system and ambient conditions, the analysis focuses on identifying fluctuations that could impact operational safety and efficiency.

A. Setup and Data Collection

The analysis utilizes temperature data collected in 2021, 2022, and 2024 through a CAN (Controller Area Network) interface reader, which provides real-time monitoring of the electric bus operation, including battery cell temperatures. Additionally, ambient temperature data from an external source allows for a direct comparison of internal and external thermal conditions. These variables help identify which cells reach maximum and minimum temperatures, offering insights into patterns of potential overheating or cooling within the battery pack. Table I summarizes key variables, units of measurement, sampling rates, and data sources, essential for tracking thermal performance and informing BTMS decisions.

The daily operation of the electric bus at the State University of Campinas occurs in a varied urban environment with diverse infrastructure and terrain. This setting provides an appropriate context for assessing performance under typical urban conditions. Figure 1 compares SOC (State of Charge), voltage, and temperature data between 2021 and 2024. In 2021, SOC discharged continuously with temperatures below 35°C, while in 2024, maximum temperatures exceeded 35°C,

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linked to operational factors rather than ambient temperature.

TABLE I: Summary of Data Variables

Variable	Description	Unit	Rate	Source
maxprobe	Sensor ID recording the highest temperature	-	1 min	CAN Reader
tempmax	Highest temperature recorded	°C	1 min	CAN Reader
minprobe	Sensor ID recording the lowest temperature	-	1 min	CAN Reader
tempmin	Lowest temperature recorded	°C	1 min	CAN Reader
temperature	Ambient temperature	°C	5 min	Solcast (Web) [8]

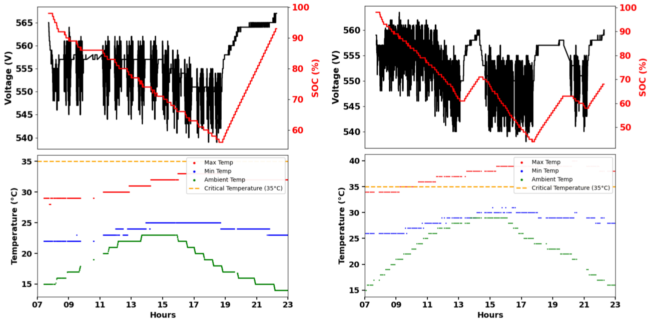


Fig. 1: Comparison of SOC, voltage, and temperature data over two days in June across different years, illustrating operational differences in battery performance: (a) 2021 (b) 2024.

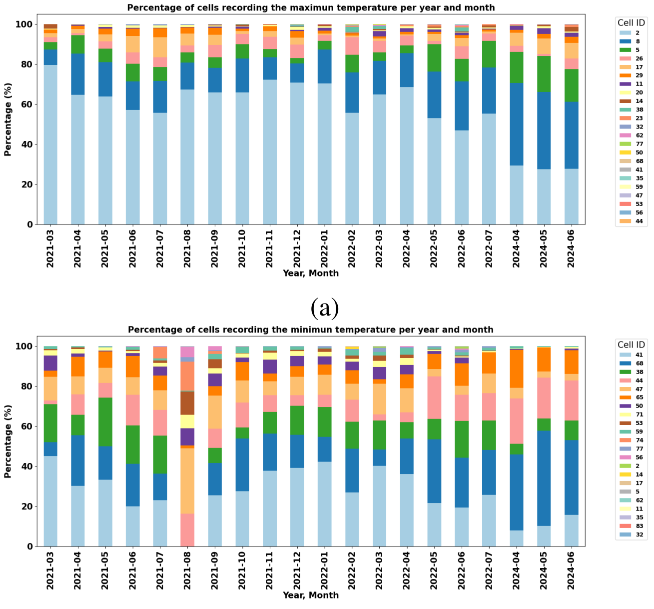
B. Thermal Activity Patterns in Active Cells

The analysis of the active cells during the years 2021, 2022, and 2024 reveals that consistently only about 13% to 15% of the total 168 LFP cells, distributed across five packs on the bus, are actively reporting temperature extremes. This is illustrated in Figure 2. Such a small subset of active cells might suggest inherent characteristics of the thermal management system or operational patterns that lead to repeated activation of the same cells.

Interestingly, a few cells, like cell numbers 2, 8, and 5 for maximum temperatures, show a high frequency of reporting, accumulating 77% to 94% of maximum temperature records. Similarly, for minimum temperatures, cells 41, 68, and 38 account for 55% to 79% of the reports. This recurrence could indicate specific operational stress or inherent design features within these cells or their positions in the battery pack. Such insights highlight the potential need for targeted analysis or maintenance to ensure balanced thermal behavior and efficient battery operation. By understanding the behavior of these consistently active cells, we gain a better understanding of the thermal dynamics within the battery pack. This could lead to improved strategies in thermal management, focusing on identified cells to enhance overall performance and longevity.

C. Comparative Analysis of Battery and Ambient Temperatures

The thermal behavior of lithium-ion batteries is influenced by various factors, including ambient temperature. While extreme cold can reduce capacity and efficiency, and extreme heat can accelerate degradation, Figure 3 demonstrates that during different months—spanning both cooler and warmer periods—the battery cell temperatures remained below the critical threshold of 35°C.



(a)

(b)

Fig. 2: Display of the percentage appearance of cells reporting extreme temperatures by month and year, highlighting variability patterns within the battery system: (a) Highest temperatures (b) Lowest temperatures.

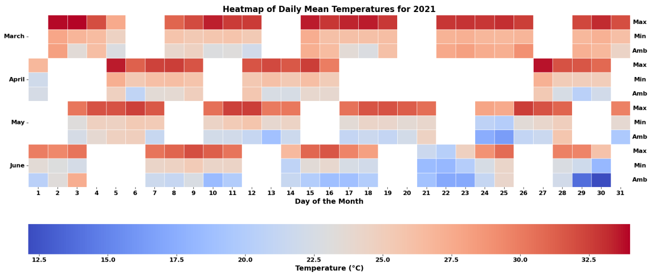


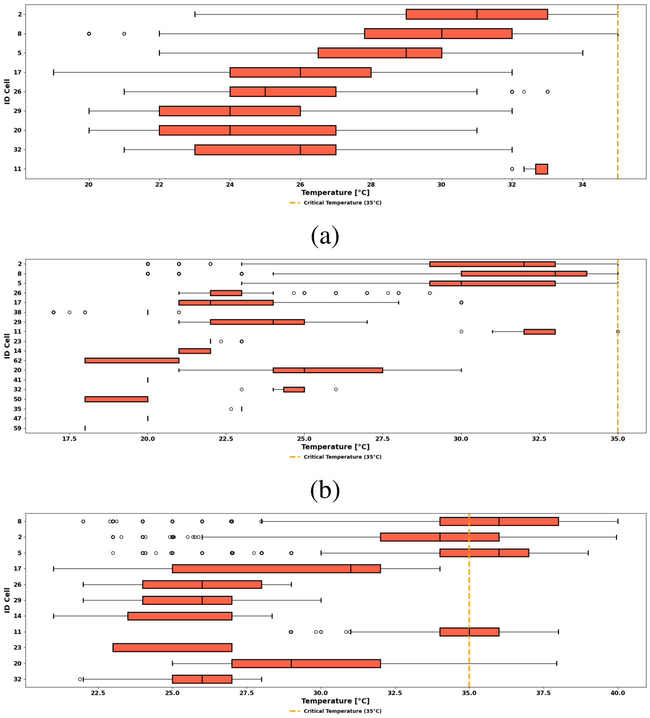
Fig. 3: Heatmap of daily mean temperatures from March to June 2021, showing maximum, minimum, and ambient temperatures. The data indicates resilient thermal management, keeping temperatures below the critical 35°C despite external variations.

The uniformity in the chromatic variation of the heatmap suggests an operational environment with relatively constant thermal conditions. This consistent pattern implies that the thermal management system has been effective in ensuring stable battery temperatures throughout different seasons. Even as the ambient temperature fluctuates, the internal battery temperatures do not exhibit significant deviations, indicating that the system is resilient to external temperature changes.

The data reveals that ambient temperature alone did not have a substantial impact on the battery temperatures. Instead, it appears that operational conditions such as driving patterns, charging cycles, and energy demand play a more significant role. The consistent temperatures near the threshold, regardless of the month, imply that the internal operations of the vehicle are more influential on thermal behavior than the external climate. This homogeneous temperature behavior can be interpreted as a sign of stability in the thermal management of the electric bus battery system.

D. *Thermal Variability Analysis*

One of the key aspects of this management is monitoring the temperature distribution across the cells, identifying any anomalies that may indicate underlying problems. In terms of safety benchmarks, it is generally recommended that battery cell temperatures should not exceed 35°C. Notably, according to Figure 4 the data from 2021 and 2022, the cells did not exceed this critical threshold, indicating that the BTMS was operating within acceptable parameters. However, the data from 2024 shows instances where this limit was exceeded, raising concerns about the system's ability to maintain safe operating conditions. This deviation underlines the importance of continuous monitoring and the need to make dynamic adjustments to the thermal management strategy to prevent potential thermal runaways or accelerated degradation.



(a)

(b)

(c)

Fig. 4: Boxplot of maximum cell temperatures by ID in June, highlighting the thermal threshold 35°C: (a) 2021 (b) 2022 (c) 2024.

The collected data shows considerable variability in cell temperatures over the years, indicating potential issues in thermal management. In 2021 and 2022, the most prominent cells (ID 2, 8, and 5) exhibit consistent variability in their interquartile ranges (Q1-Q3), oscillating between 4°C and 5°C, with temperatures ranging from 27°C to 33°C. However, in 2024, although the interquartile range variability remains similar (4°C - 5°C), the maximum temperatures reach up to 39°C and 40°C. This suggests a reduced effectiveness of the BTMS in controlling these peaks, indicating that the core issue lies in the BTMS's ability to manage these fluctuations effectively, rather than in the variability itself.

The presence of outliers and a wider range of temperatures in 2024 indicates that the thermal management system may be reaching its limit, allowing cells to reach dangerous temperatures. This situation not only accelerates cell degradation, reducing battery life, but also increases the risk of serious incidents. Therefore, temperature variability can serve as an early warning of potential issues in the BTMS, highlighting the need for constant monitoring and dynamic adjustments in the thermal management strategy.It is essential for the BTMS to effectively detect and manage these thermal variations. Failures in BTMS decision-making, whether due to inaccurate data or delayed responses, can lead to unnecessary cooling actions or, more critically, overlook conditions that could result in catastrophic failures. Additionally, sensor failures can cause false positives or negatives, compromising system accuracy.

E. *Thermal Difference Assessment*

The temperature difference (ΔT) (Equation 1) between the maximum and minimum cell temperatures serves as a key indicator of thermal stability within the battery system.

$$\Delta T = T_{max}(t) - T_{min}(t) \tag{1}$$

ΔT serves as a diagnostic tool to monitor the BTMS response to changing operating conditions. Ideally, ΔT should remain minimal, indicating an even temperature distribution across the cells. Significant deviations from this ideal state suggest potential flaws in the thermal management strategy.

Figure 5 illustrates this approach by combining a time series plot of the maximum and minimum temperatures with a heat map depicting the temperature difference (ΔT) over the month of June 2021. This method allows for a more dynamic assessment of BTMS performance, highlighting periods where the thermal variation between cells is high, potentially indicating inefficiencies in heat distribution or emerging failures within the cells.

A critical aspect to consider is the threshold for ΔT. According to the literature, a ΔT above 5°C is generally considered a risk factor for battery systems. During June 2021, we observed that although maximum cell temperatures did not exceed the critical threshold of 35°C, there were multiple instances where ΔT approached or exceeded 5°C, occasionally reaching 10°C. This suggests that while the BTMS was successful in preventing over-temperature, there were underlying issues with thermal distribution.

During periods where ΔT exceeds 5°C, significant variations in voltage occur, indicating a potential impact on battery performance. The BTMS appears to have faced challenges in maintaining uniform temperature distribution across cells during these periods, which could point to early signs of inefficiency. Had this behavior been detected earlier, it could have provided an opportunity for proactive interventions, preventing the more severe thermal management issues seen in 2024.

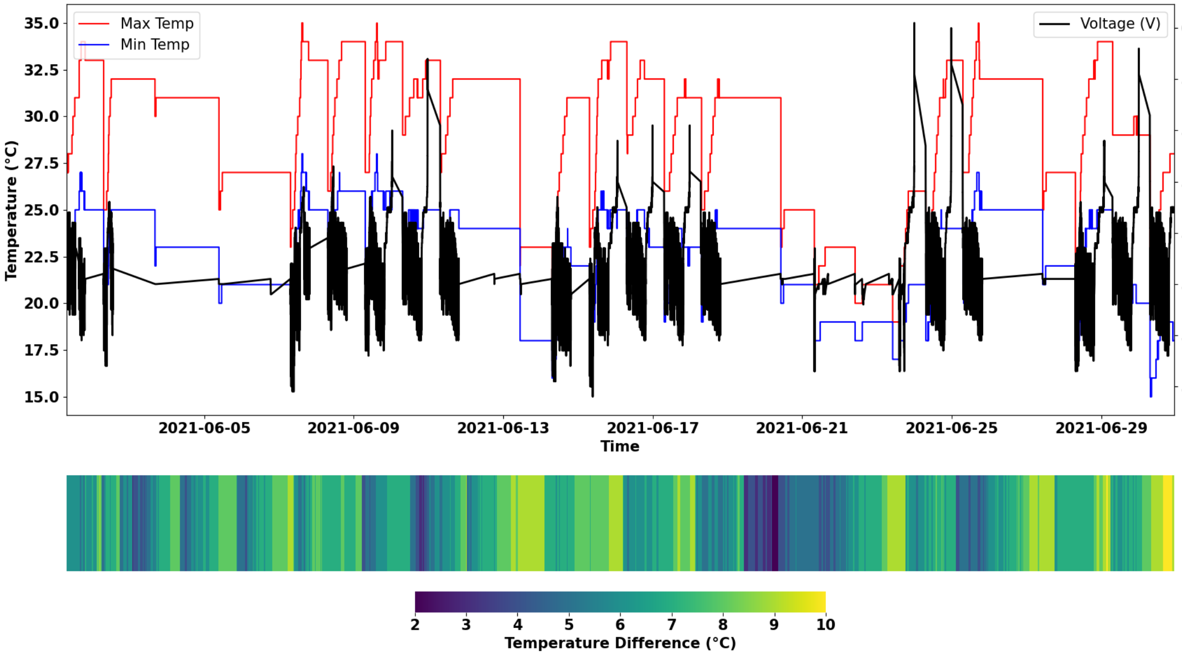


Fig. 5: Time series of maximum and minimum cell temperatures with battery voltage for June 2021, accompanied by a heatmap showing the temperature difference (ΔT).

III. CONCLUSIONS

This research offers a valuable diagnostic perspective on the thermal behavior of battery cells in an electric bus operating in Brazil's dry climate, using data obtained through a CAN reader. While thermal management principles are well-established for electric vehicle batteries, this research goes beyond ensuring functional operation; it focuses on how to monitor, identify, and anticipate failures in real time under operational conditions. Early detection of thermal anomalies is crucial for fleet operators and customers who aim to maximize the safety and durability of their assets, even when access to detailed bus specifications is limited.

A key finding from the 2020 and 2021 data was that, although the maximum battery temperature remained within the safe threshold of 35 °C, the temperature differences (ΔT) between cells indicated an irregular thermal distribution, reaching up to 10 °C. Rather than attributing battery degradation, our approach served as a preventive diagnostic tool. In 2024, maximum temperatures exceeding 35 °C were recorded, suggesting that issues related to the vehicle's cooling system may have gone unnoticed, thus increasing system stress. This underscores the importance of comprehensive monitoring of temperature differences as a deterministic diagnostic method based on specific vehicle properties.

In summary, the diagnostic methodology developed here equips electric bus fleet operators with tools to detect critical thermal issues early and improve cooling system management. This approach enhances battery safety and durability, providing a practical solution for fleet management even with limited data access.

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