PERFORMANCE ANALYSIS OF THERMAL MANAGEMENT SYSTEMS IN ELECTRIC VEHICLES: A CASE STUDY ON CHEVROLET BOLT 2020, NISSAN LEAF 2019 PLUS AND TESLA MODEL 3 2020.

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ABSTRACT

As the demand for Battery Electric Vehicles (BEVs) with extended driving ranges grows, it's crucial for manufacturers to optimize their efficiency. One major challenge is managing the energy required for cabin climate control and battery temperature regulation. These needs can drastically decrease a vehicle's range, sometimes causing energy use to surge over 50% in extreme weather. This study focuses on investigating how weather affects energy consumption and the range of compact and midsize size electric vehicles by taking the 2020 Chevrolet Bolt, 2019 Nissan Leaf plus and 2020 TESLA Model 3 as reference models. This research aims to deepen the understanding of thermal management in BEVs. It introduces an advanced thermal management system (TMS) model, coupled with detailed models for both cabin and battery thermal conditions. These models are integrated into a 2020 Chevrolet Bolt, 2019 Nissan Leaf plus and 2020 TESLA Model 3 framework, developed using Autonomie software, to thoroughly examine how weather conditions affect the vehicle's range. Our approach includes a mono-zonal model for the cabin, estimating temperature, humidity, and heat requirements. For the battery, a thermal model specific to pouch-type cells is used, employing a 2D discretization method within a nodal structure for temperature estimation. Two distinct TMS were implemented, varying with the vehicle under study. The Chevrolet Bolt 2020 features a dual evaporator vapor compression cycle and PTC heater to ensure thermal comfort in cabin and a secondary coolant loop with a PTC resistor to ensure precise battery temperature control. In contrast, the 2019 Nissan Leaf Plus and Tesla Model 3 employ a heat pump system with a Positive Temperature Coefficient (PTC) heater for cabin heating and cooling, and a conventional air-cooling system for the battery. Using Autonomie Software, this study thoroughly tests and compares the developed models. It examines various ambient temperatures (35°C, 22°C, -7°C, and -18°C). The simulation models effectively capture the impact of thermal conditions on energy consumption across the Nissan Leaf, Chevrolet Bolt, and Tesla Model 3 compared to the experimental results. Significant increases in energy consumption were observed at -18°C and -7°C, ranging from 131% to 244% across the three vehicles.

Keywords: Thermal Management System, Electric Vehicles, Energy Consumption, Ambient Temperature, Simulink

1 INTRODUCTION

BEVs are increasingly popular worldwide, supported by governments' policies encouraging their adoption. Over 26 million electric cars were on the road in 2022, up 60% relative to 2021 and more than 5 times the stock in 2018 (IEA, 2023). Numerous countries and territories are moving towards banning the sale of new internal combustion engine (ICE) vehicles from 2030 to 2040, including the European Union (Xu & Arjmandzadeh, 2023). However, as EVs continue to develop, they encounter significant thermal management issues. These include maintaining temperature comfort within the vehicle, ensuring battery thermal safety, managing heat in electric motors, and integrating TMSs (Dan

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et al., 2023). Addressing these problems is crucial, requiring innovative thermal management techniques to enhance the safety, dependability, and efficiency of EVs.

As the automotive industry moves toward BEVs, the importance of thermal management for BEVs becomes increasingly critical to their performance, especially in harsh weather conditions. BEVs do not have the natural heat generation capabilities of ICE vehicles, which affects cabin heating, and their electrical components must meet strict thermal requirements (Shelly et al., 2021). The TMS manages the temperature of the vehicle's cabin, battery, electric motor, and power electronics to ensure they perform optimally and avoid damage (Shelly et al., 2021). The energy usage of the TMS in BEVs significantly impacts the vehicle's range and overall energy efficiency, accounting for about 20% of the driving range. This percentage can increase to as much as 60% in urban settings or under severe weather conditions (Steinstraeter et al., 2021).

An overview of the most relevant studies in the literature investigating the impact of the weather conditions and the TMS architectures on compact sized BEVs is presented. Given that the purpose of this study is to enhance the understanding of the performance of the BEV at different temperatures, the literature review was geared toward (1) identifying the different approaches adopted by studies to assess the impact of the weather conditions, as well as (2) identifying the types of modes and TMS architectures studied and compared. Other publications investigating the advancement in the thermodynamic cycle, the system components, or the selection of the working fluid were disregarded.

A variety of studies in the literature covered this topic to examine the impact of weather conditions on BEVs using numerical dynamic modelling. Shelly et al. (2021) assessed six Integrated TMSs for BEVs in temperatures ranging from -20°C to 40°C and found that Waste Heat Recovery systems could enhance the vehicle range by up to 13.5% in colder climates by managing thermal loads effectively. This research, which did not include experimental validation, developed dynamic models that incorporated various components such as the drivetrain and battery. Another study by Xu & Arjmandzadeh (2023), using a similar modeling approach, concentrated on Tesla Model S and Tesla Model 3 to evaluate how different thermal management strategies impact vehicle range. This work also lacked experimental validation but provided detailed simulations based on several variables, including air conditioning use and ambient temperature effects on the vehicles' performance.

Several studies have incorporated real driving data and experimental findings to assess the influence of ambient conditions on electric vehicles. Al-Wreikat et al. (2022) analyzed real-world driving data from a major UK metropolitan area over four years, revealing increased specific energy consumption (SEC) and variability in BEV performance at lower temperatures. Another research based on over 125 trips around Munich indicated that cold climates could reduce BEV range by up to 50%, suggesting the use of electrothermal recuperation to counteract the effect of ambient temperature (Steinstraeter et al., 2021). Finally, a report by the International Council on Clean Transportation utilized data from over 140,000 vehicles in China, finding that cold temperatures and high speeds notably decrease range and energy efficiency, with drivers showing a preference for slow charging (Jin et al., 2023).

Some research has advanced the understanding of weather impacts on BEVs by combining numerical modeling with experimental validation. A study on the Nissan Leaf used a quasi-steady backward-looking model to quantify how ambient temperatures decrease BEV range, confirmed through real-world data, emphasizing the strain of cabin heating at low temperatures (Iora & Tribioli, 2019). Another project developed a detailed model of a Renault Zoe where Ramsey & Bouscayrol (2021) accounts for both driving mechanics and Heating, Ventilation and Air Conditioning (HVAC) impacts on energy consumption. Experiments showed that cold weather could lead to a dramatic increase in energy needs, with HVAC use in winter raising energy consumption by as much as 248% over summer levels (Ramsey & Bouscayrol, 2021). These studies highlight the critical role of thermal management in BEV efficiency and the necessity of incorporating thermal comfort into EV energy evaluations.

Overall, the following limitations and gaps in recent literature that the authors covered are found:

- Lack of a generic TMS applicable to different types of TMS and modes in compact BEVs.
- Scarcity of comparative studies that utilize both numerical simulations and experimental data to evaluate different TMSs within the same class of BEVs.

Based on what is presented, the contribution of this paper is summarized as follows:

- A numerical modelling of a generic TMS in addition to a detailed thermal model of the cabin and battery integrated into a complete electric vehicle model calibrated using experimental data

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and applied in Autonomie, the vehicle system simulation tool developed at Argonne National Laboratory.

- Experimental Test-Bench results: a complete performance test in terms of energy consumption and driving range at ambient temperatures of -18°C, -7°C,22°C and 35°C for 2019 Nissan Leaf Plus, 2020 Chevrolet Bolt, and 2020 Tesla Model 3 (Jehlik et al., 2023b, 2023a; Stutenberg et al., 2023).
- Experimental validation of the complete electric vehicle numerical model at different ambient temperatures and driving cycles.
- Assessment of the impact of the weather conditions on the BEVs consumption.
- Assessment of the TMS architecture and operating modes on the BEVs consumption.

This paper is split into 3 main sections. Section 2 delves into the TMS model in electric vehicles (EVs), encompassing a generic thermal management configuration, cabin model, and battery model. Section 3 presents a case study on the three BEVs: 2019 Nissan Leaf Plus, 2020 Chevrolet Bolt, and 2020 Tesla Model 3, offering an overview of each vehicle and detailing the experimental testbench setup. Finally, Section 4 discusses the results, focusing on the validation of the models, the impact of weather conditions on BEVs' energy consumption, and a comparative analysis across the studied vehicles.

2 TMS MODEL IN EV

The TMS in electric vehicles is crucial for maintaining optimal performance and safety. It plays a key role in regulating the temperatures of vital components such as the battery and the cabin, ensuring efficiency, range, and longevity of the vehicle. In this section, the generic TMS model is described, and the corresponding models are explained. The different functions, modes, and modelling schemes are presented. In addition, a brief explanation is given for the cabin and battery thermal models.

2.1 Generic TMS:

Generic TMS is a framework developed for system-level analysis of different configurations, operating modes, and control algorithms, all in one simulation model using a consistent thermal architecture. The generic TMS acts as a parent configuration from which all other configurations can be tested and analyzed with minimal changes and development time. It is intended to be used as an upfront analysis tool for EV TMS designs to obtain valuable insights and perform mass simulations.

The generic TMS model mainly covers all the possible operating modes of thermal management in the current compact sized electric vehicles. During winter, the system comprises a heat pump mode (Mode 1), Heat Pump (HP coupled with a Positive Temperature Coefficient (PTC) resistor (Mode 2), or a PTC only mode using a coolant loop and a heater core (Mode 3), the deployment of which depends on the requisite heat load or the available architecture in the studied compact BEV. Conversely, in summer conditions, the TMS utilizes a vapor compression cycle functioning in a refrigeration mode to cool the cabin. Direct air cooling is the most common cooling technique in compact size EV. A detailed schematic representation of this system is provided in Figure 1.

Table 1: Operating modes of the Generic TMS considered

Function	Possible Modes
Cabin Cooling	Vapor Compression Cycle (VCC)
Cabin Heating	**Mode 1:** HP **Mode 2:** HP / Heater core + PTC **Mode 3:** Heater core + PTC
Battery Cooling	**Mode 4:** Chiller **Mode 5:** Direct air cooling **Mode 6:** Water Cooling

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Battery Heating	**Mode 7:** PTC

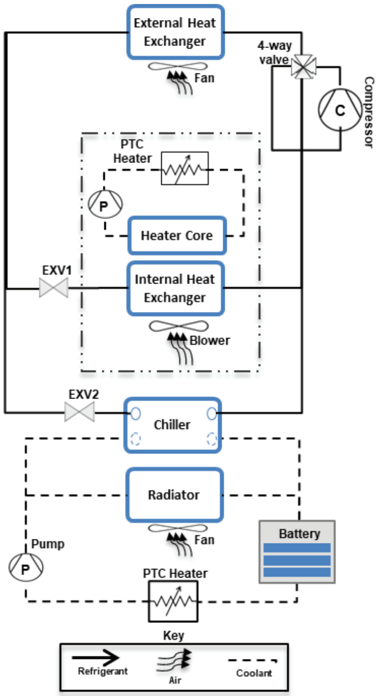

Figure 1: Generic TMS Architecture Configuration

The main characteristics and functions of the generic TMS system are presented in Table 1.
The HVAC system model adopted is a simplified lumped model, focusing on its function for both cooling and heating through a thermodynamic cycle. This cycle calculates the system's load capacity and its efficiency, denoted by the coefficient of performance (COP), based on ambient temperature. This approach is further explained in (Lemort et al., 2023). For cooling, the model sets the condenser and evaporator temperatures relative to ambient and interior air temperatures. In heating mode, these temperatures adjust relative to cabin air and external conditions. In the heat pump thermodynamic cycle, the condenser and the evaporator temperatures are assumed respectively higher than the blowing temperature of 4°C and lower than the ambient temperature of 7°C. When engaging the vapor compression cycle in cooling, the condenser and evaporator temperatures are assumed respectively higher than the ambient temperature of 7°C and lower than the blowing temperature of 4°C. Further details on the numerical model are available and presented in our previous work (Al Haddad et al., 2024). HVAC control adjusts the air flow rate automatically, aiming for the desired cabin temperature, with a specific strategy for managing the air flow to efficiently reach and maintain this target. In the basic on/off control approach, the HVAC system toggles heating or cooling based on cabin temperature. When this temperature falls within a predefined comfort range, the system remains off to conserve energy. Conversely, deviations outside this range trigger the system to activate heating or cooling, aiming to realign the cabin temperature with the established comfort threshold.

2.2 Cabin Thermal Model:

The cabin thermal model, as part of the framework proposed, predicts the vehicle cabin's need for thermal energy. This model, inspired by Brèque and developed using Simulink (Brèque, 2017; Brèque & Nemer, 2017), includes temperature points for the cabin's structure, windows, air inside, and internal objects. It uses a single-zone approach to represent the air temperature evenly across the cabin. The model is designed to accurately simulate the changing temperatures during short trips, considering the cabin's materials like seats and dashboards and the heat from passengers.

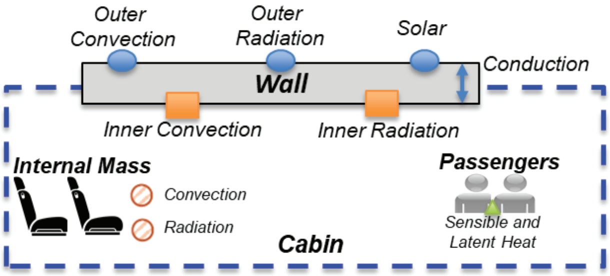

Figure 2: Schematic of the types of heat transfer within the cabin

This model examines heat exchange in different situations, including between the cabin and the outside environment, the occupants, and within the cabin itself. It takes into consideration the radiation, convection, and conduction happening through the walls and considers the effect of sunlight entering through the windows, as shown in Figure 2. The walls of the vehicle are made of materials like glass and metal. Besides, it looks at how heat is transferred within the cabin, considering both the objects and passengers inside. It even accounts for body heat and moisture from passengers. By applying a method that groups various components together (lumped-parameter modeling), the model uses energy and mass conservation principles to understand and predict the cabin's thermal conditions, whether changing or constant (Al Haddad et al., 2024).

2.3 Battery Thermal Model:

Including a thermal model of the battery is essential when considering a study on the impact of the TMS on performance. During charging and discharging cycles, heat is generated within the battery. This phenomenon leads to an increase in the temperature and potentially accelerates the aging process. The cell temperature is a function of the ambient temperature, the cooling mechanism, and the vehicle operation. Different undesirable effects occur when the cell temperature is beyond acceptable levels and when the temperature is not uniform within the cell.

Three types of battery cells are currently used: pouch, cylindrical, and prismatic. Because of their high surface area to volume, pouch cells seem to be the most adapted for effective thermal management (Hosseinzadeh et al., 2018). A 2D thermal model is developed to predict the transient response of the surface thermal distribution of the pouch cell, due to the large size and small thickness. Because of the high dependency of the internal resistance as function of state of charge, current rate, and working temperature, the proposed thermal model has been associated with the 1D electrical battery model. Considering the small thickness of the used lithium-ion pouch battery the heat distribution in the y-direction has been neglected. Therefore, a two-dimensional transient model has been developed. A transient heat conduction equation is sufficient to describe the thermal phenomena in the battery and the convective term inside the battery (electrode-electrolyte) can generally be neglected. Detailed equations and methodology of the discretization are presented in (Al Haddad et al., 2024).

2.4 Electric Vehicle System – Autonomie/Amber (Software):

The vehicle model is completed by integrating all the powertrain components and the controller into the system model. Autonomie, which is a software developed by Argonne for vehicle system simulations, is used to integrate all the component models, and the vehicle models and sub-models are validated with the test data(Argonne National Laboratory, 2023). All the models are developed using Simulink as sub-components and integrated together to develop a complete EV model.

3 CASE STUDY: NISSAN LEAF 2019 PLUS, CHEVROLET BOLT 2020 AND TESLA MODEL 3 2020

In this section, the developed models of the TMS and the complete EVs are adapted on a case study of three of the most selling compact vehicles, which are the Nissan leaf, Chevrolet Bolt and Tesla Model 3. The vehicle's specifications and characteristics are presented and the TMS and modes available in

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each vehicle are described. The test bench used to assess the performance of the mentioned vehicles is presented and the different test conditions are explained.

3.1 Vehicles Overview:

This research aims to examine the energy efficiency and operational performance of BEVs under various operational conditions and ambient temperatures. To ensure a comprehensive understanding of the differences in performance across different brands and technologies, this study encompasses vehicles from several leading electric vehicle manufacturers. Specifically, the vehicles selected for this work represent the top three best-selling electric vehicles in the United States for the calendar year 2019, as identified in Gohike & Zhou (2022). This selection strategy allows us to focus on models that significantly contribute to the electric vehicle market, as detailed in Figure 3, highlighting the market share of these top manufacturers.

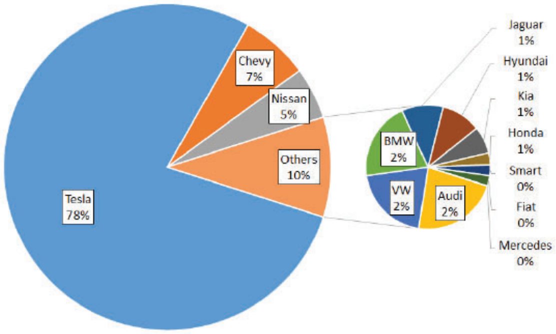

Figure 3: Comparison of vehicle sales data of EV ending in year 2019

The three vehicles chosen for evaluation include the Tesla Model 3, Chevrolet Bolt, and Nissan Leaf. Experimental testing, analysis, and model development were performed on these vehicles to provide detailed information on key powertrain systems, advanced technologies, and related energy consumption to ensure that the component information gained through the testing is updated in Autonomie. All the technical specifications of the three selected vehicles are described in Table 2.

Table 2: Technical specifications of 2019 Nissan Leaf Plus, 2020 Chevrolet Bolt, and 2020 Tesla Model 3

Test Vehicle	Nissan Leaf Plus	Chevrolet Bolt	TESLA Model 3
Model Year	2019	2020	2020
Electric Powertrain	Single Motor - front wheel drive	Single Motor - front wheel drive	Dual Motor - All wheel drive
Battery	Air-Coold Li-Ion Pouch Cell 360 V, 62 kWh (nominal)	Liquid Cooled Li-ion Pouch Cell 360 V, 66 kWh (nominal)	Liquid cooled Lithium-Ion Cylindrical cells (370 V - 75 kWh)
Motor	Permanent magnet motor/generator (160 kW,340 Nm)	Permanent magnet motor/generator (150 kW,360 Nm)	Front: 3 phase, induction, four pole, 147 kW electric Rear: 3 phase, internal permanent magnet, six pole, 188 kW
Final RR	8.139:1	7.05:1	9.04:1
Climate Control	Heat Pump + PTC	VCC + Heat core + PTC	VCC +Heat core + PTC
Curb /Test Weight	1761 kg/ 1928 kg	1616 kg/ 1757 kg	1847 kg/ 1928 kg

The TMSs across three different electric vehicles, summarized in Table 3, vary as follows:

- For the Nissan Leaf, cabin cooling is managed by a Vapor Compression Cycle (VCC), while cabin heating combines a Heat Pump (HP) with Positive Temperature Coefficient (PTC) heating elements. The battery is cooled by air, and there is no active heating system for the battery.
- The Chevrolet Bolt also uses a VCC for cabin cooling and solely relies on PTC heating for warming the cabin. The battery cooling is more complex, involving a chiller and radiator system. Similarly, battery heating is achieved through PTC elements.
- The Tesla Model 3 employs a VCC for cabin cooling and PTC elements for cabin heating, mirroring the Chevrolet Bolt's approach. Its battery thermal management is identical to Bolt's, utilizing a chiller and radiator for cooling and PTC for heating.

Table 3: Operating modes of the TMS in 2019 Nissan Leaf Plus, 2020 Chevrolet Bolt, and 2020 Tesla Model 3

Function	Nissan Leaf	Chevrolet Bolt	Tesla Model 3
Cabin cooling	VCC	VCC	VCC
Cabin Heating	HP + PTC	PTC	PTC
Battery Cooling	Air Cooling	Chiller + Radiator	Chiller + Radiator
Battery Heating	-	PTC	PTC

3.2 Testbench Overview:

A benchmark study is performed on a 2019 Nissan Leaf Plus electric vehicle, the Chevrolet Bolt 2020 EV, and Tesla Model 3 2020 EV, shown in Figure 4. Tests were performed at the Argonne's Advanced Mobility Technology Laboratory chassis dynamometer (Stutenberg et al., 2021), in a controlled laboratory environment, across a range of certification drive cycles, and other testing conditions that support model development and validation. The evaluation focused on understanding the use of critical powertrain components and their impact on vehicle efficiency over a series of charge-depleting cycles. Specific focus was given to the impacts of cold and hot ambient temperatures on consumption and range. The vehicle was instrumented to provide data for analysis, model development, and validation. Focused testing was performed to characterize the performance of different powertrain components.
The main goal of the performance analysis for thermal model development is to determine the impact of temperature on the energy consumption and driving range of the EV. The modified cycle consists of the Urban Dynamometer Driving Schedule (UDDS), HighWay (HWY), and US06 city cycles, coupled with steady-state depletion cycles.

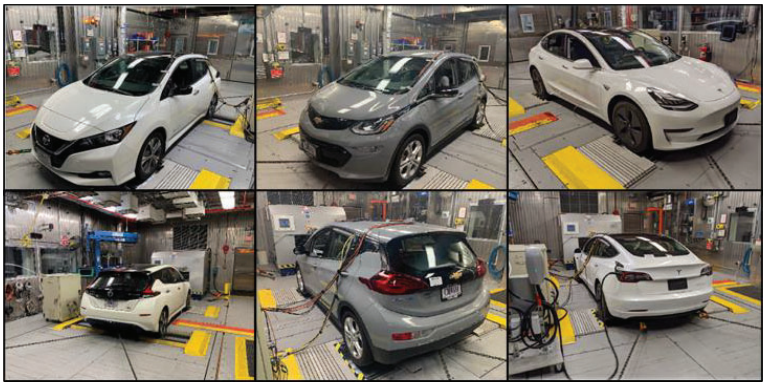

Figure 4: 2019 Nissan Leaf Plus 2020 Chevrolet Bolt test 2020 Tesla Model 3 test vehicle mounted for full testing inside the AMTL 4WD chassis dynamometer

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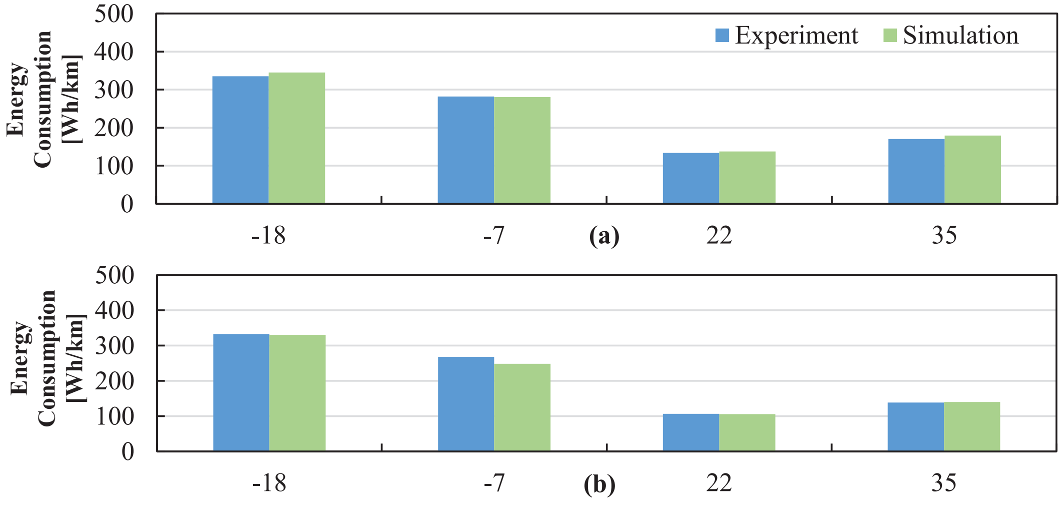
4 RESULTS AND DISCUSSION

In this section, a thorough comparison between the performance of the three selected vehicles and their respective TMSs will be presented. First, the numerical models will be validated on the UDDS cycle which is the start-up cold/hot state. Second, the three vehicles will be compared and assessed to understand the impact of the operating mode on the energy consumption of the EV in each vehicle at each temperature.

4.1 System Validation:

The comparison results for the UDDS cycle show that the simulation models can represent the impact of the thermal conditions on the total energy consumption across the vehicle configurations quite well, as presented in Figure 5. It is important to note that the cabin and battery temperatures are equal to the ambient temperature at the start of the simulation as in the experiment. In other words, in winter conditions, the battery and cabin are in cold start condition and in summer conditions the battery and cabin are in hot start condition. The operating modes and the inputs to the TMS are modified based on the selected vehicle. For example, the operating maximum power of the PTC varies between one vehicle and another. An additional powertrain heater is present the Tesla Model 3, that heats up the front and rear motor and battery through a separate coolant loop in extreme weather conditions.

For the Nissan Leaf, at -18°C, the experimental consumption is 334.85 Wh/km, which is slightly lower than the simulation at 344.86 Wh/km, resulting in an error of 3%. At -7°C, the experimental value is marginally higher than the simulation, leading to a negligible error of 0.66%. At 22°C, the experimental consumption is 133 Wh/km, again lower than the simulation, with an error of 3%. At 35°C, the experiment shows a more significant decrease from the simulation, with a 5.8% error. For the Chevrolet Bolt, at -18°C, the experimental value is slightly higher than the simulation, with an error of 0.82%. At -7°C, the experimentally measured consumption is significantly higher than the simulation, with a 7.42% error, the largest observed error for the Bolt. At 22°C, the experimental and simulation values are almost the same, with a negligible error of 0.98%. However, at 35°C, the experimental value is lower than the simulation, with an error of 0.98%. Lastly, for the Tesla Model Y, at -18°C, the experiment reports higher energy consumption than the simulation, with an error of 5.85%. At -7°C, the experimental value is lower, resulting in an error of -3.88%. The error flips at 22°C, where the experimental value is higher, resulting in an 8.33% error. At 35°C, the experimental measurement is again higher, with an error of 6.21%.



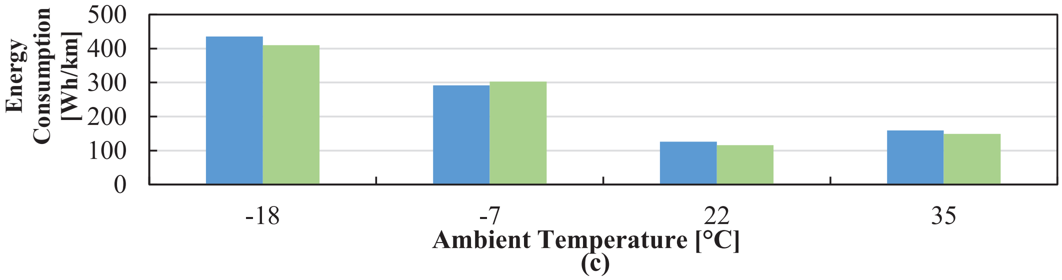


Figure 5: Total energy consumption function of ambient temperature for (a) 2019 Nissan Leaf Plus, (b) 2020 Chevrolet Bolt EV, and (c) 2020 Tesla Model 3 on UDDS Cycle using simulation and experimental results

For the total energy consumption, the error varies between 2 and 8.5% between -18°C and 35°C with solar radiation respectively. The error in energy consumption could be attributed to the control of the air conditioning system varying between the three vehicles and the simulation model. Also, the discrepancy in energy consumption could also be attributed to the lack of modeling temperature-dependent performance variations in the powertrain component (e.g. battery, motor, or wheels). This aspect could be mentioned as a subject for future research. Additionally, differences between experimental measurements and the simulation could stem from any inherent inaccuracies in the data collection process during the tests. These findings could be crucial for refining simulation models and understanding vehicle performance in different environmental conditions.

4.2 TMS and vehicle performance at different Ambient Temperatures:

The comparison of total consumption among the studied vehicles under different ambient temperatures and driving cycles (UDDS and HWY) is illustrated in Figure 6 (a) and (b). This comparison considers both transient and steady-state thermal behaviors. The UDDS cycle represents the initial startup phase, either cold or hot, during which the vehicles' consumption is observed as they reach the desired temperature. The HWY cycle, on the other hand, depicts subsequent trips where the cabin and battery temperatures stabilize at the setpoint.

In Tesla, the data indicates a substantial rise in energy consumption during the UDDS cycle, particularly when starting from cold conditions at lower ambient temperatures. Specifically, at -18°C and -7°C, energy consumption spiked by 244% and 131%, respectively, over the baseline established at 22°C, as presented in Figure 6 (a). These increases are attributed to the additional energy demands of heating the cabin, higher losses in powertrain components, and limited energy recovery through regenerative braking due to the low temperature of the high-voltage battery. At a higher ambient temperature of 35°C, excluding the HVAC system's load, the energy consumption is lower than at the 22°C baseline. This reduction is due to the higher temperatures of powertrain components, which improve their efficiency. The first cycle with solar loading sees a 26% increase in energy consumption. Once the setpoint temperature is reached the increase in the consumption between the baseline temperature and , -18°C, -7°C and 35°C decreases to reach 69.3%, 46.4%, and 3.313% respectively, as seen in Figure 6 (b).

The Nissan Leaf data shows a significant energy consumption penalty for heating the cabin during the first UDDS cycle at -7°C, at 116% more energy compared to when the PTC heater is not used. This penalty decreases to 72% once the cabin has warmed up. At an ambient temperature of 35°C, the inclusion of solar loading increases average energy consumption by 24% due to additional cooling requirements to maintain a comfortable cabin temperature. In a steady state, this increase is reduced to 14.7%.

For the Chevrolet Bolt, the increase in energy consumption is most pronounced during the first UDDS cycle due to the need to cool the cabin rapidly, which is 35% higher with solar loading and 21% without it. Over the steady state HWY cycle at 35°C with solar loading, the average increase in energy consumption is 2.9%. In winter conditions, a pronounced increase in energy consumption under the UDDS cycle, especially when initiating from a cold start at lower ambient temperatures. Specifically,

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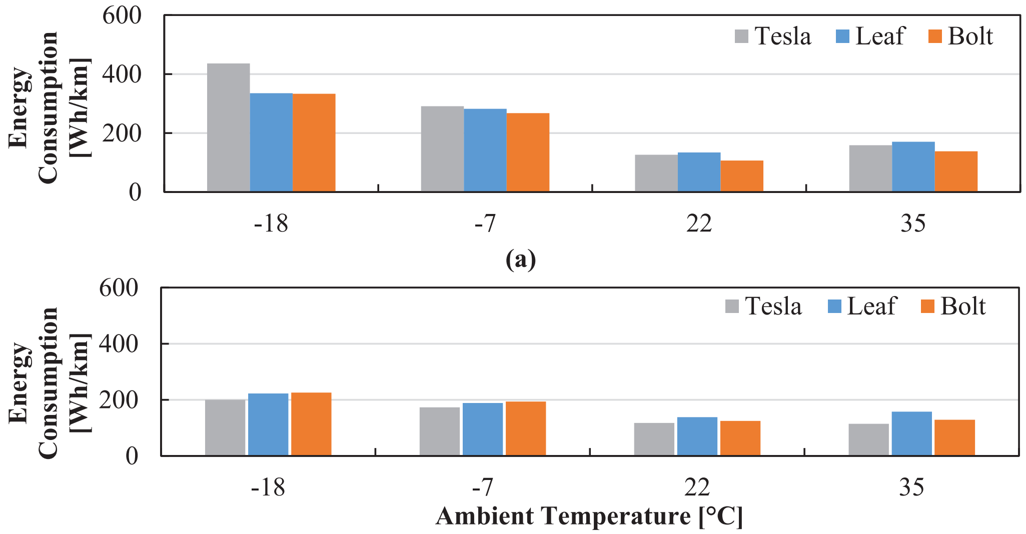
energy consumption surged by 212% at -18°C and by 134% at -7°C, in comparison to the baseline energy consumption observed at 22°C, as depicted in Figure 6 (a). However, once the interior reaches the set temperature, the difference in energy consumption relative to the baseline and at temperatures of -18°C and -7°C stabilizes at increases of 73% and 54% respectively, as illustrated in Figure 6 (b).



(a)

(b)

Figure 6: Total energy consumption function of ambient temperature for 2019 Nissan Leaf Plus 2020, Chevrolet Bolt EV, and 2020 Tesla Model 3 on (a) UDDS Cycle (Transient State) (b) HWY Cycle (steady state)

To understand the increase in consumption at -18°C and -7°C for the Tesla Model 3 compared to other vehicles in the transient state over the UDDS cycle, as depicted in Figure 6 (a), Figure 7 describes the distribution of power among the HP, cabin heater, and powertrain heater under transient state conditions. Among the vehicles studied, the Tesla Model 3 is unique in its utilization of the powertrain heater during extreme weather to warm the front and rear motors and battery. This additional power consumption amounts to an increase of 2.2 to 2.5 kW, depending on weather conditions. In contrast, the Nissan Leaf and Chevrolet Bolt do not employ this option, and the experimental results do not indicate battery heating in such extreme weather conditions. However, once the setpoint temperature is attained and the Tesla operates in a steady state, the power required by the PTC to heat the powertrain is significantly reduced. Consequently, energy consumption by the Tesla is lower compared to other vehicles across all studied ambient temperatures, as shown in Figure 6 (b). Hence, the powertrain heating mode of the Tesla Model 3, activated at extreme cold ambient temperatures, enables a reduction in consumption under steady-state conditions, as evidenced by the results.

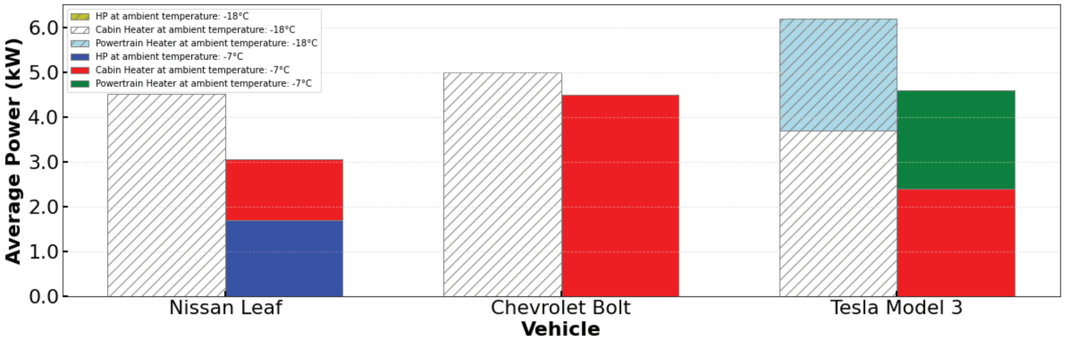


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Figure 7: Average power consumed by the HP, Cabin heater, and powertrain heater at -18°C and -7°C for the 2019 Nissan Leaf Plus, 2020 Chevrolet Bolt, 2020 Tesla Model 3

5 CONCLUSION

This comprehensive study has explained the significant impact of ambient temperature on the energy efficiency of BEVs. A numerical model of a generic TMS is presented in addition to cabin and battery thermal model. Those models were adapted using Autonomie on three compact sized electric vehicles. Experimental tests were conducted on 2019 Nissan Leaf Plus, 2020 Chevrolet Bolt EV, 2020 Tesla Model 3 at ambient temperatures: -18°C, -7°C,22°C, and 35°C. The TMSs are compared and their impact on the performance of the BEV is analyzed at each temperature.

The results demonstrate that the simulation models effectively capture the impact of thermal conditions on energy consumption across different vehicle configurations, with maximum error reaching 8.33%. Notably, the Tesla Model 3's unique powertrain heating system significantly affects its energy consumption, particularly in extreme cold conditions, increasing energy consumption by 244% and 131% at -18°C and -7°C, respectively, during the UDDS cycle. However, this system reduces overall consumption in steady-state conditions, with increases of only 69.3% and 46.4% at -18°C and -7°C. The Nissan Leaf and Chevrolet Bolt exhibit substantial increases in energy consumption during cold starts and initial UDDS cycles, with the Leaf showing a 116% increase at -7°C and the Bolt showing a 212% increase at -18°C. Errors between experimental and simulation data are most notable at certain temperatures due to HVAC control differences and potential temperature-dependent performance variations in powertrain components.

The findings underscore the importance of integrating such sophisticated thermal management strategies to maintain optimal battery health and ensure cabin comfort, thereby enhancing the overall range and performance of BEVs. Future developments of this work will include using the developed models and running mass simulations on a city level to study the impact of the weather conditions, battery size and different commuter types on the electricity grid and the charging behavior of different driver behaviors. Understanding the detailed impact of thermal conditions on energy consumption can guide the development of more efficient thermal management systems in EVs, potentially leading to significant energy savings and improved performance in extreme temperatures. Also, those models allow us to apply new control strategies and investigate new architectures to enhance the performance of the TMS and increase the driving range of the BEV.

NOMENCLATURE

EV	Electric Vehicle
UDDS	Urban Dynamometer Driving Schedule
VCC	Vapor Compression Cycle
TMS	Thermal Management System
BEV	Battery Electric Vehicle
HVAC	Heating,Ventilation, and Air Conditioning
HP	HeatPump
HWY	Highway drive cycle

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