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Comprehensive Modeling and Analysis of 2021 Mach-E for Battery Electric Vehicle Performance

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Executive Summary

This study analyzes the powertrain, battery, and torque distribution strategy of the 2021 Ford Mustang Mach-E using dynamometer and track test data to develop and validate a vehicle model. The powertrain and battery models were developed by using Argonne's model-based high-fidelity, forward-looking, vehicle simulation tool, Autonomie. Key parameters such as battery open-circuit voltage (OCV), internal resistance, and powertrain efficiency maps were extracted from test data and integrated into the Autonomie model. Additionally, for the Mach-E AWD, which features two motors mounted on the front and rear axles, a torque distribution strategy based on vehicle speed and required torque was analyzed. A control model for this strategy was built in Simulink and integrated into Autonomie. The accuracy of this integrated model was validated through comparative analysis across WLTP, UDDS, and HWFET cycles during duty cycle simulations. Under standard conditions (ambient temperature of 22°C), the energy consumption error was found to be within 3% range.

Keywords: modeling, battery electric vehicle, validation

1 Introduction

Argonne National Laboratory has developed a vehicle system simulation tool called Autonomie, which comprehensively models various vehicle classes, powertrains, and their components and control strategies. Autonomie has been used to model and validate a wide range of production vehicles [*1,2,3,4*]. This series of studies provides essential data for enhancing the understanding of modern vehicle control technologies and developing strategies to improve energy efficiency in the transportation sector [*5*,*6*,*7*]. Following this research direction, this study models and validates the 2021 Ford Mustang Mach-E, a fully electric vehicle. The Mach-E is equipped with an electric motor on each axle, offering a range of 270 miles. In this study, the vehicle systems, including the front and rear powertrains and high-voltage battery, were modeled using duty cycle test data from a dynamometer and tip-in/tip-out tests on a track. A detailed analysis of torque distribution between the front and rear axles provided insights into the power distribution logic, allowing for a close replication of real-world energy consumption characteristics in simulations.

2 Vehicle Model Development

Since Ford Mustang Mach-E is a battery electric vehicle (BEV), we aimed to validate the vehicle model concerning electric energy consumption, motor power requirements, and battery SOC (State of Charge) fluctuations. The efficiency map of the electric drivetrain and battery characteristics are crucial elements in developing component models. By analyzing test data, we incorporated parameters and performance and efficiency data into the component models of the vehicle model. Additionally, we developed a control module to manage motor power in the BEV model with two electric motors and sought to verify the accuracy of this module. The Mach-E, which utilizes both a front and rear motor, has varying power distribution ratios depending on driving conditions. We analyzed power distribution-related variables from test data to identify patterns in control strategies. Based on these insights, we developed a higher-level control module for the vehicle model. This control module manages power distribution between the front and rear motors during vehicle propulsion and braking.

Figure 1 below shows the system of a vehicle equipped with an electric motor on each of the front and rear axles, such as with the Ford Mustang Mach-E. Depending on driving conditions, such as driver inputs and vehicle speed, the power distribution strategy determines how power is allocated between the front and rear motors. The high-voltage battery power is then distributed accordingly to the front and rear inverters.

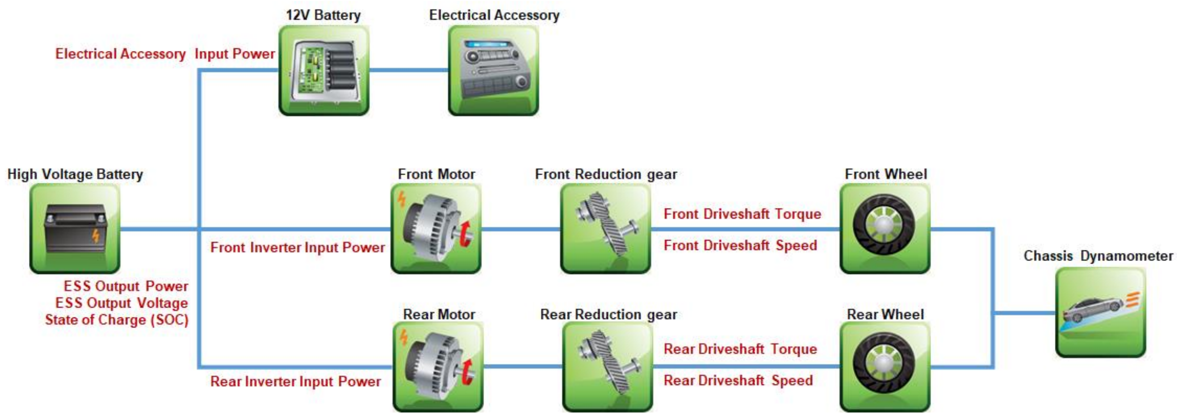


Figure 1: Two-motored vehicle system and sensor configuration

As summarized in Table 1, the front motor of the Mach-E provides a maximum power of 49 kW and a maximum torque of 165 Nm, while the rear motor delivers a maximum power of 209 kW and a maximum torque of 415 Nm. The torque generated by each motor is transmitted to the drive shafts and wheels through the front and rear reduction gears, with reduction ratios of 10.00 and 9.05, respectively.

Table 1: Parameter values used for vehicle modeling

Parameters	Values
Electric motor peak power, kW	49kW (front), 209kW (rear)
Battery Capacity, kWh	98.8 kWh
Gear ratio of the final drive and torque coupling (front axle / rear axle)	10.00 (front), 9.05 (rear)
Tire radius, m	0.357 m (front, rear)
Vehicle Test weight, kg	2,252 kg
Road load coefficient f0/f1/f2	204.6 N 0.7197 N/(km/h) 0.0358 N/(km/h)^2

As shown above in *Figure 1*, the sensor configuration and component layout used for vehicle system analysis are presented. We analyzed powertrain efficiency using the input power to the front and rear inverters and the output power of the drive shafts. By measuring the rotational speed of each component, we can also determine the reduction ratios and the effective rolling radius of the wheels.

2.1 Powertrain Efficiency Map

The powertrain analysis utilized duty cycle tests, including WLTC, HWFET, and UDDS cycles, as well as steady-state tests on a dynamometer and tip-in and tip-out tests on a track. Efficiency maps were generated based on recorded wheel speed, torque, and electrical input from the tests. The tests conducted on the vehicle included various conditions that pushed the motors to their maximum torque regions, particularly under transient operating conditions. This is useful for verifying the speed and torque characteristics of the electric machine, reduction gear, and final drive unit. The maximum torque curve of the powertrain was derived by analyzing the operating points from all these test sets. *Figure 2* below shows the powertrain map derived from the test points conducted on the dynamometer. This process allows for obtaining reliable efficiency measurements in frequently used areas of operation during testing. However, operational areas not represented well in the tests may have inaccurate efficiency values.

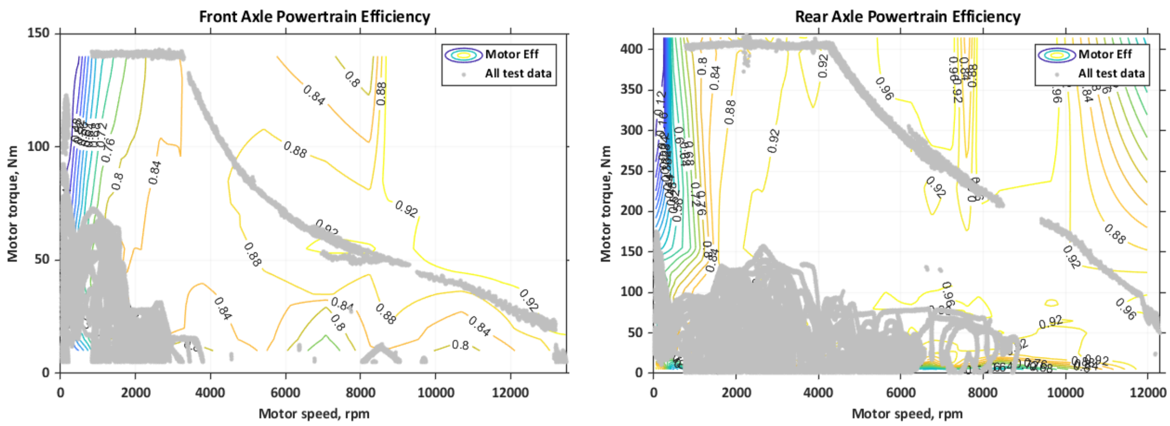


Figure 2: Estimated maps of powertrain efficiency

The efficiency map was calculated based on the mechanical output of the final drive unit and the electrical input to the motor controller. It considers the efficiencies of the motor and controller unit, torque coupling, and final drive unit. This efficiency map is not a direct efficiency analysis of the components but rather an estimated efficiency analysis result that includes various components such as the electric motor and speed reduction drive unit.

2.2 Battery Model

The key battery characteristics required for Autonomie simulation include pack capacity (total and usable), pack voltage, cell internal resistance, and charge and discharge power limits. All this information can be obtained from test data and information provided by the manufacturer. The Ford Mach-E is equipped with a battery that has a nominal voltage of 337V and a nominal capacity of 98.8 kWh, consisting of 376 cells arranged in 94 series-connected cells and 4 parallel strings.

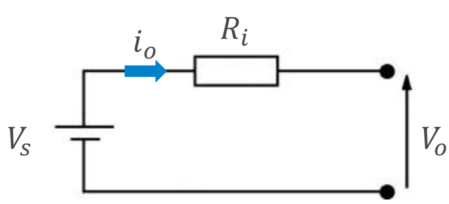


Figure 3: Battery model

Based on test data, battery parameters were estimated using a circuit model, as shown above in *Figure 3*. The battery model consists of a single internal resistance and a source voltage. V_o and i_o are the output voltage and output current measured during testing, respectively. V_s and R_i are the source voltage and internal resistance, which are the parameters to be estimated. The state equation for the equivalent circuit in *Figure 3* can be expressed as

$$V_o = V_s - i_o \cdot R_i \qquad \text{Eq. (1)}$$

Batteries and resistors have temperature-dependent internal resistance and voltage characteristics. This is because the ion mobility, chemical reaction rates, and thermal activation energy of the materials used in batteries and resistors are affected by temperature changes, which in turn affect their electrical properties. The parameters to be estimated in this study, namely V_s and R_i, are functions of SOC and the battery temperature (T). They are calculated as follows:

$$V_s = f_0(SOC, T) \qquad \text{Eq. (2)}$$

$$R_i = f_1(SOC, T) \qquad \text{Eq. (3)}$$

The same data used for powertrain efficiency estimation was applied to battery model development. Following the estimation method assuming a first-order equivalent circuit model as described in [*8,9*], the internal resistance and open-circuit voltage were estimated, as shown below in *Figure 4*. Each can be expressed as a surface function of battery temperature and SOC.

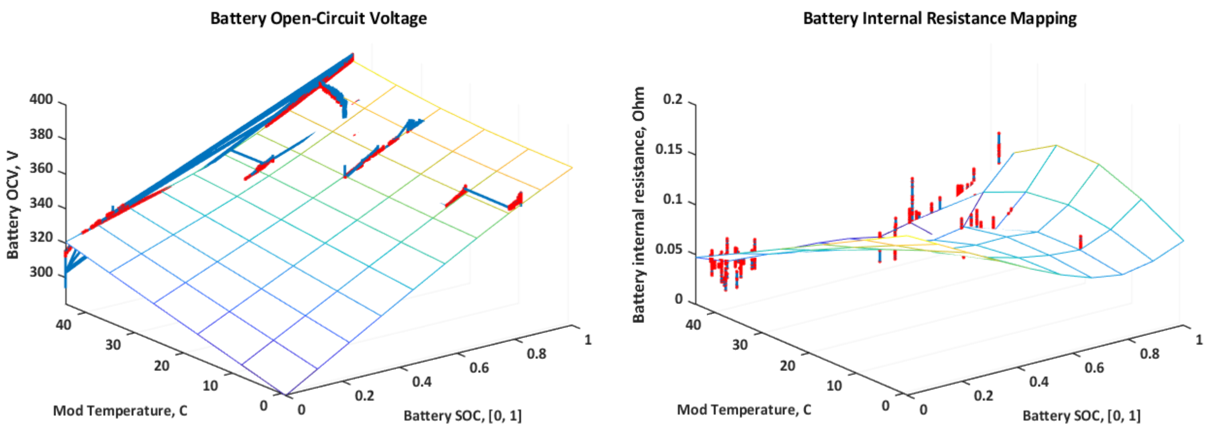


Figure 4: Estimated map of battery internal resistance and open circuit voltage

2.3 Torque Distribution Strategy Analysis

The Mach-E is a dual-motor vehicle with one motor mounted on each axle. Both motors are used for propulsion and regenerative braking, and while the vehicle features a relatively large rear motor, the power distribution between the motors varies depending on driving conditions.

Figure 5 below shows the power output of the front and rear motors for the UDDS and HWFET driving cycles. During initial acceleration, both the front and rear motors provide driving torque, but above a speed threshold, the vehicle is primarily driven by the rear motor. It also appears that there is a distribution of regenerative breaking between the front and rear motors. To analyze this power distribution, we used data from the entire driving cycle to separately analyze propulsion and regenerative braking phases.

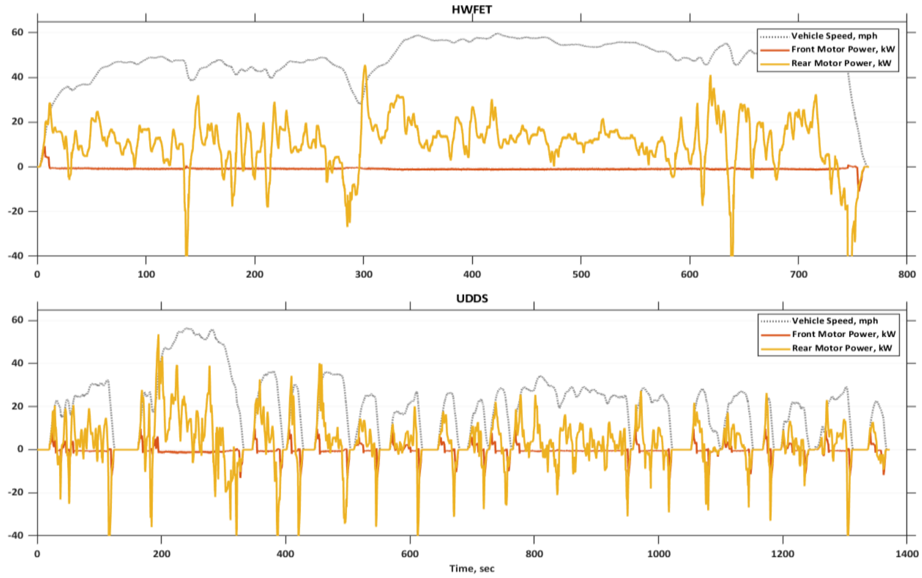


Figure 5: Power output between front and rear motors on HWFET and UDDS driving cycles

2.3.1 Propulsion control

Figure 6 below shows the torque output ratio between the front and rear motors during propulsion, highlighting a clear power distribution ratio. During propulsion, the torque ratio between the front and rear motors is controlled at 45:55, 20:80, or 0:100. Therefore, the Mach-E utilizes a total of three torque distribution ratios for propulsion control. We conducted a more detailed analysis to understand how these ratios are controlled.

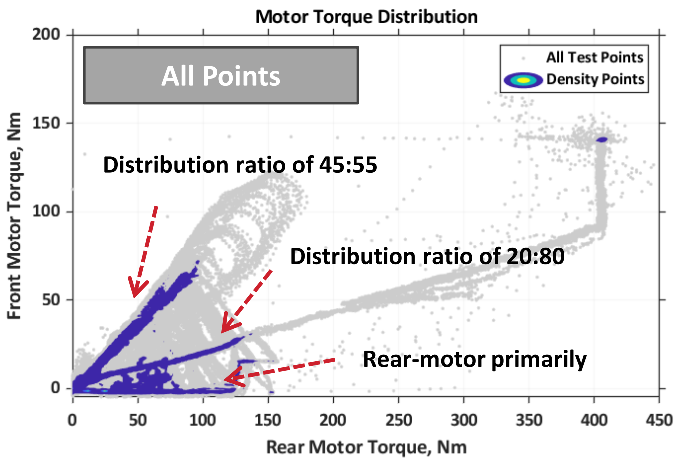


Figure 6: Operating points of electric motors in propulsion

Figure 7(a) below shows the operating points for low-speed segments where the vehicle speed is approximately below 12 mph, while *Figure 7*(b) illustrates the segment operating points for the speed range of 12-22 mph. At lower vehicle speeds, torque is generally distributed between the front and rear motors at nearly fixed ratios of 45:55 or 20:80, as indicated by the blue dashed lines. This torque distribution likely represents an optimal path for driving efficiency. Around 12 mph, the vehicle operates in a transitional zone, and as the speed increases, the torque distribution ratio gradually shifts. *Figure 7*(c) shows the torque distribution ratio when the vehicle speed exceeds 24 mph, where torque is distributed at fixed ratios of 20:80 or 0:100 depending on the driver's torque demand. When the torque demand is low (during steady-speed driving), only the rear motor is used. However, when the driver demands higher driving torque for acceleration, the front motor is also engaged, operating at approximately a 20:80 ratio. If the rear motor's maximum torque (around 410 Nm) is exceeded, the front motor assists.

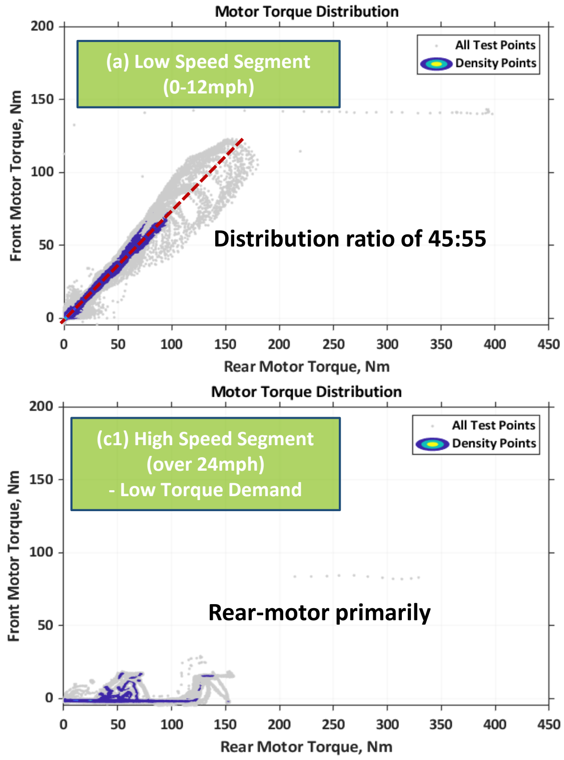


Figure 7: Torque distribution between front and rear electric motors during propulsion

2.3.2 Braking control

Figure 8(a) below shows the distribution of torque between the two motors during braking, based on all test data. When filtered by the density of operating points, it controls primarily with two distinct distribution ratios, as indicated by the blue lines. In addition, Figure 8(b) shows that as the vehicle decelerates to a speed of approximately 4 mph or below, the regenerative braking force from the rear motor becomes nearly zero, and the vehicle comes to a stop by mechanical braking force.

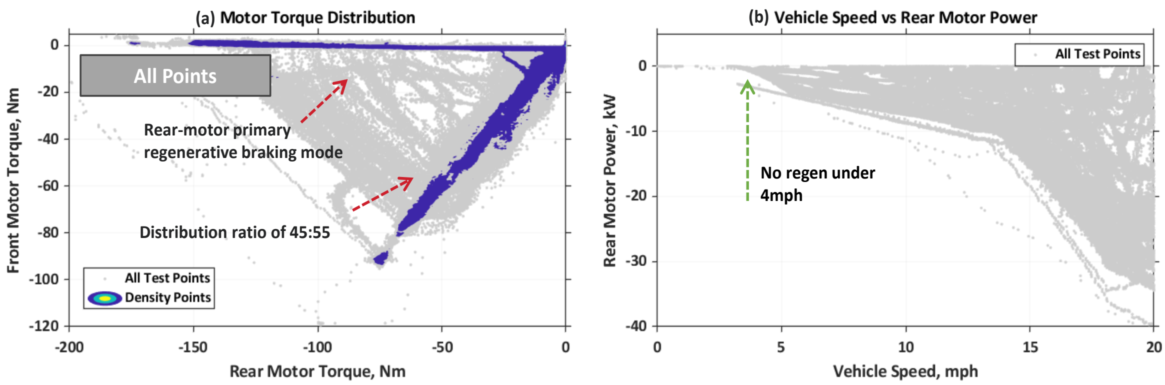


Figure 8: Operating points of electric motors in braking

Figure 9 below shows the operating points of two speed segments defined for analysis during braking situations. In the low-speed braking segment (0-14 mph), torque is distributed between the front and rear motors within a relatively narrow ratio band, similar to propulsion, but with a higher distribution to the front motor. In the relatively higher speed segment (above 18 mph), regenerative braking is primarily performed by the rear motor. The speed range of approximately 14-18 mph represents a transition zone, where the torque distribution ratio shifts as the vehicle decelerates.

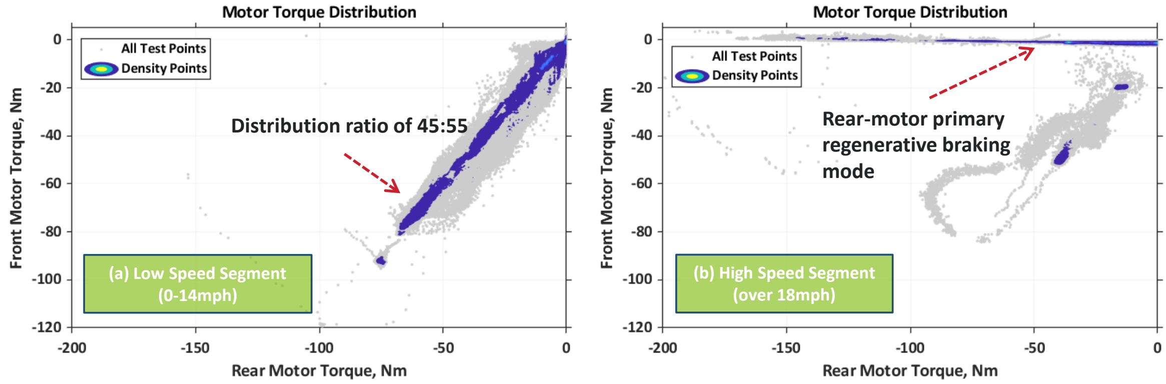


Figure 9: Torque distribution between front and rear electric motors during braking

2.4 Accessory Load

The energy consumption of the Mach-E vehicle primarily results from the combined energy usage of the motor for propulsion and various accessories. These accessories include the PTC heater, the electric compressor for air conditioning, and the 12V low-voltage battery system. When the heating, ventilation, and air conditioning systems are not in operation, the energy consumption of the accessories is minimized. Conversely, initiating the heating or air conditioning functions significantly increases the accessory power demand. *Figure 10* below illustrates the relationship between ambient temperature and accessory load. The scatter plot in this figure displays all test data points and density points representing the average accessory power usage. During vehicle testing, the interior temperature was set to be maintained at 22°C for both heating and cooling. When there is no demand for heating or cooling power, the average accessory power stabilizes at approximately 300 - 350W. When the air conditioning is in operation, the power demand can increase up to 1,400W at 45°C. On the other hand, the energy required for heating is influenced by external temperature, exceeding approximately 800W at -10°C.

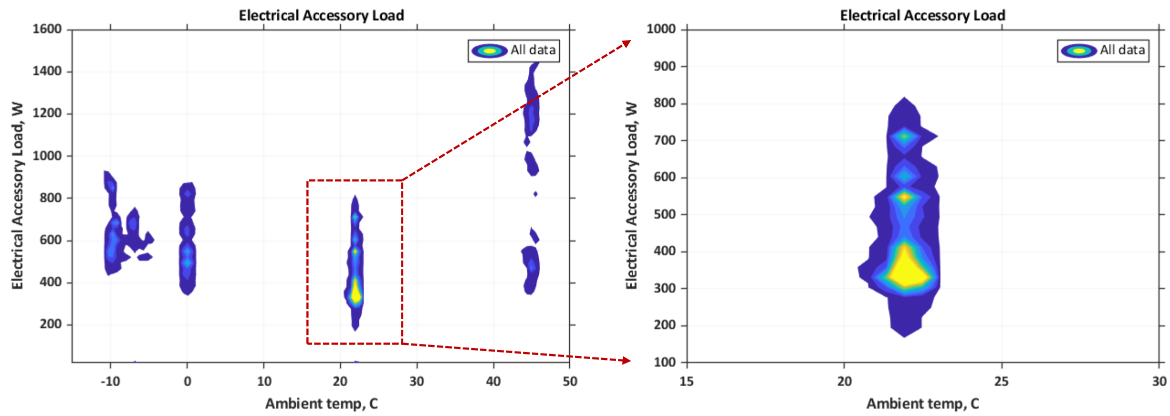


Figure 10: Accessory load depending on ambient temperature

3 Vehicle Model Validation

The component efficiency and performance data analyzed using vehicle test data, along with the vehicle control logic, were integrated into a comprehensive vehicle simulation model in Autonomie. The upper control logic handles the process of converting driver inputs into torque and brake commands for the two vehicle motors. *Figure 11* illustrates the overall validation methodology applied in this study.

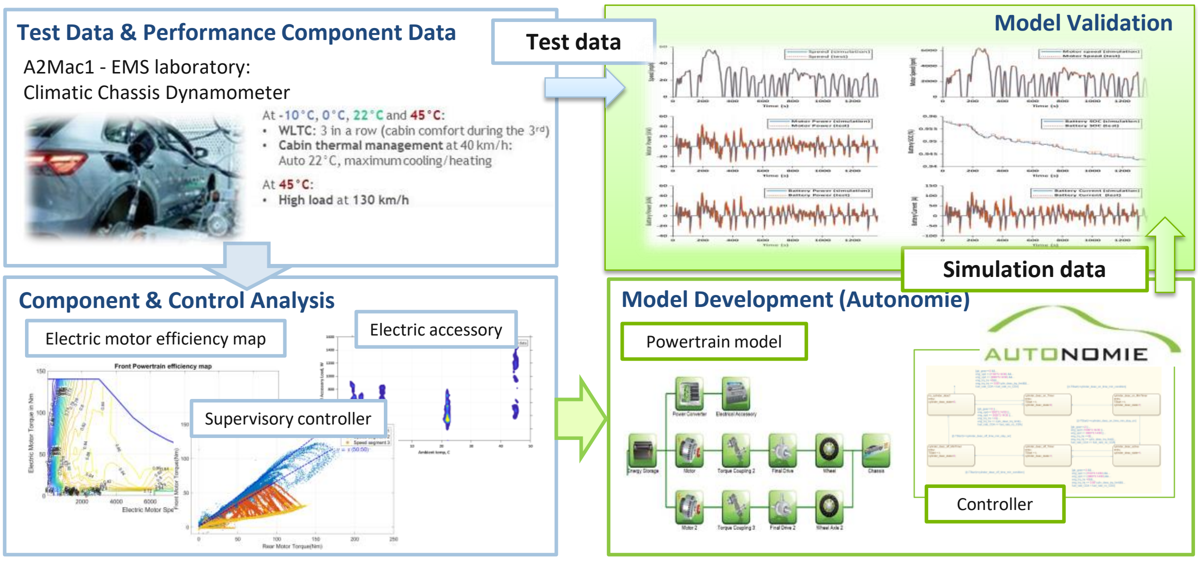
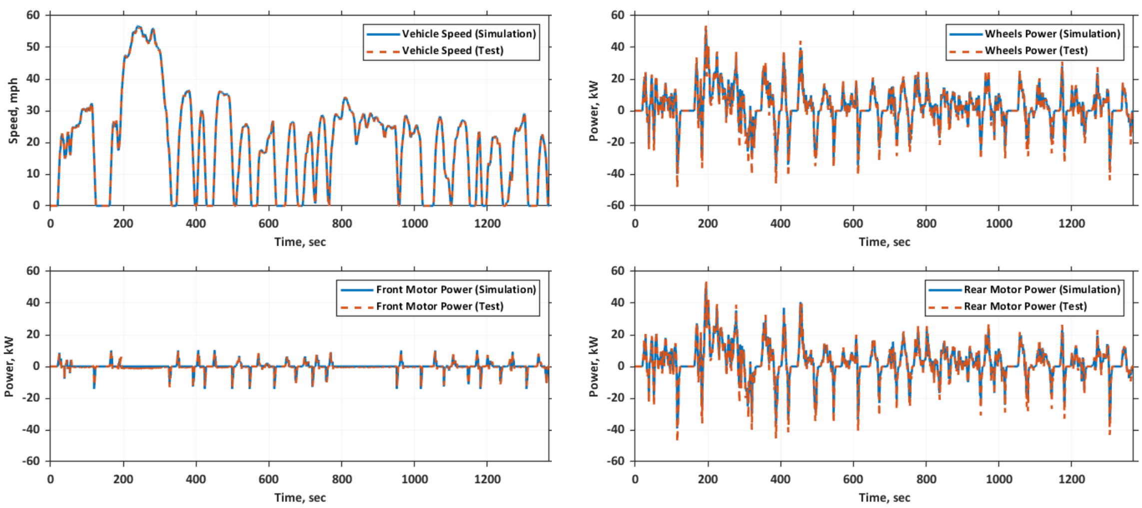


Figure 11: Validation process for Mach-E model in Autonomie

Simulations were conducted using the UDDS, HWFET, and WLTC driving cycles. The simulation results and corresponding test data for vehicle speed, wheel power, motor power, battery power, and SOC across each cycle are presented below in *Figure 12*, *Figure 13*, and *Figure 14*. To ensure that the simulation accurately predicts the actual driving behavior of the vehicle under various driving conditions, it is essential to validate the accuracy of the simulation model using the UDDS, HWFET, and WLTC cycles. The UDDS cycle represents urban driving characterized by frequent acceleration, deceleration, and regenerative braking. The WLTC cycle reflects a wider range of driving patterns with a variety of speeds and acceleration, deceleration patterns, including urban, suburban, and highway driving. By comparing the simulation results with test results for these diverse driving modes, the accuracy of the simulation can be comprehensively evaluated.



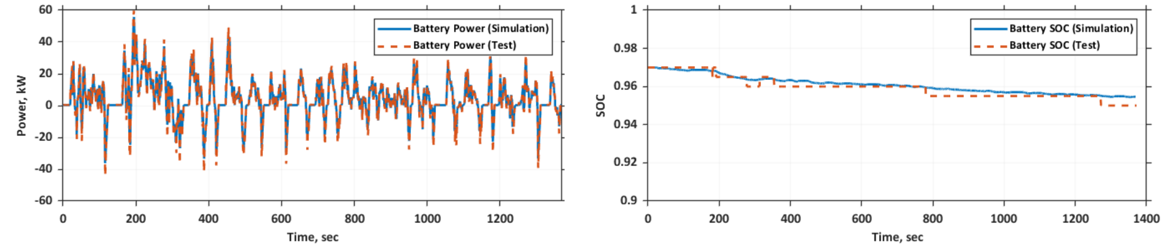


Figure 12: Simulation and test results for the UDDS cycle

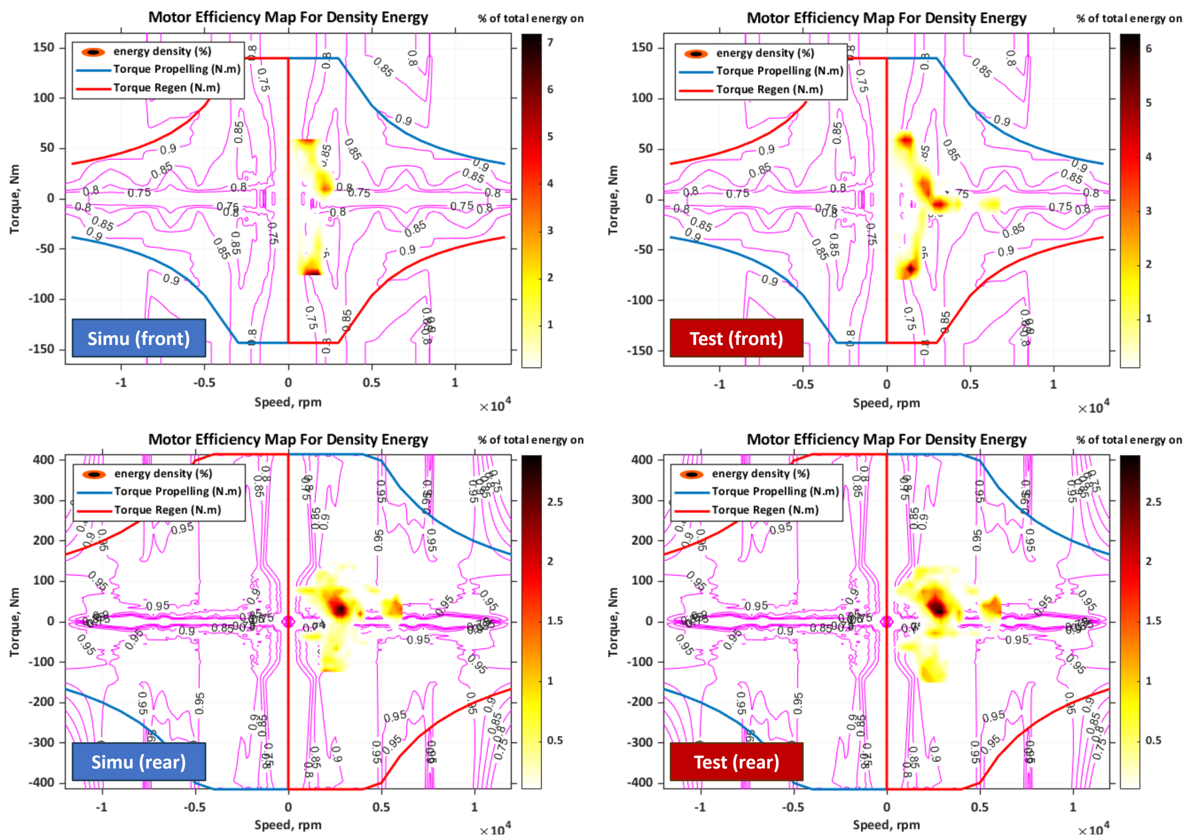
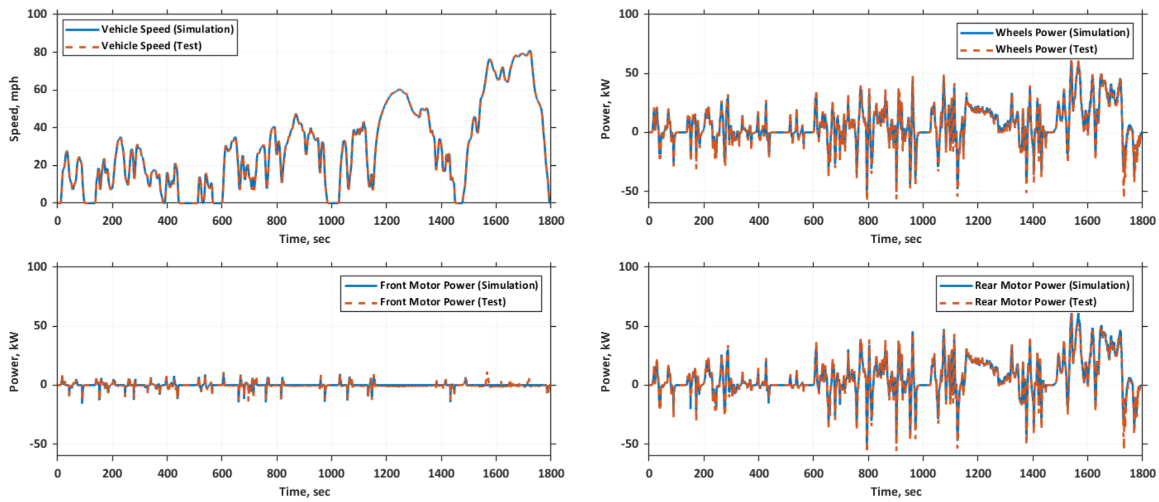


Figure 13: Energy density for front and rear motor operation in UDDS Cycle



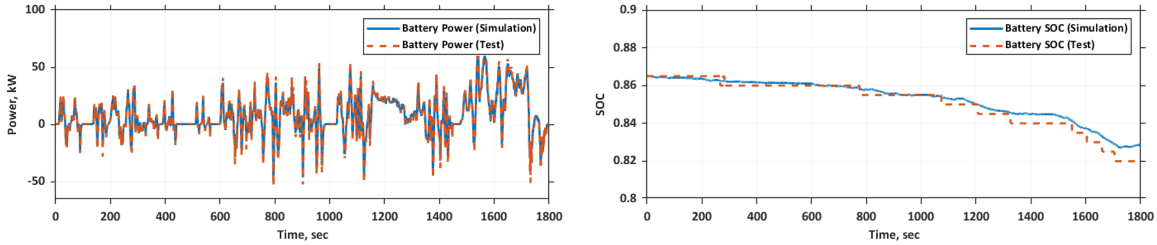


Figure 14: Simulation and test results for the WLTC cycle

The comparison results for the main component operating regions showed that the simulation results closely matched the actual test results. The simulation model demonstrated high accuracy in comparing mechanical variables such as motor torque and rotational speed, as well as electrical variables like battery SOC and motor power. These characteristics suggest that the simulation model developed in this study can accurately predict the driving parameters and energy consumption efficiency of the Mach-E.

Table 2: Energy consumption in testing and simulation of UDDS, HWFET, and WLTC cycles

DC Wh/mile	UDDS	HWFET	WLTC
Test	234.4	261.7	291.1
Simulation (error)	232.5 (-0.1%)	265.1 (1.3%)	281.2 (-3.4%)

Table 2 above compares the DC energy consumption rate simulation results with test results to validate the simulation performance. An analysis of energy consumption measured in watt-hours per mile across various driving cycles reveals insightful trends between the test and simulation data. In the UDDS cycle, which simulates urban driving conditions, the actual test recorded an energy consumption of 234.5 Wh/mi, while the simulation reported 232.5 Wh/mi, showing an almost match with a -0.1% error. In the HWFET cycle, representing highway driving, the test results indicated 261.7 Wh/mi, whereas the simulation results showed 265.1 Wh/mi, estimating that the simulation slightly overestimated energy usage. For the WLTC cycle, the test consumption was 291.1 Wh/mi, and the simulation result was 281.2 Wh/mi, showing a slight *under*estimation of 3.4%. These results demonstrate that the simulation can accurately replicate actual energy consumption within approximately a 3% margin of error across various driving conditions.

4 Conclusions

This study developed and validated a comprehensive vehicle model for the 2021 Ford Mustang Mach-E AWD using the Autonomie simulation framework. By integrating sophisticated torque distribution strategies with detailed powertrain and battery models, the model accurately replicated energy consumption characteristics across various driving cycles. The simulation results closely matched the test data, with energy consumption errors within a 3% error, demonstrating the model's precision. These results provide insight into the control strategies and energy efficiency of electric vehicles with dual electric motors, supporting the development of more efficient transportation technologies. Future research could further enhance the applicability of the model by analyzing the impact on BEV performance under various temperature conditions.

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References

1. N. Kim, E. Sabri Islam, R. Vijayagopal and M. Pamminger, "Transmission Shifting Analysis and Model Validation for Medium Duty Vehicles," SAE Technical Paper, 2023.

2. D. Park, L. Yang and N. Kim, "Validation for Ioniq EV via chassis dynamometer test," in 2019 IEEE Vehicle Power and Propulsion Conference (VPPC), 2019.

3. J. Jeong, N. Kim, K. Stutenberg and A. Rousseau, "Analysis and model validation of the Toyota Prius Prime," SAE Technical Paper, 2019.

4. J. Jeong, S. Choi, N. Kim, H. Lee, K. Stutenberg and A. Rousseau, "Model validation of the Chevrolet Volt 2016," SAE Technical Paper, 2018.

5. N. Kim, E. Sabri Islam and R. Vijayagopal, "Impact of Advanced Technologies on Energy Consumption of Advanced Electrified Medium-Duty Vehicles," SAE Technical Paper, 2024.

6. R. Al Haddad, C. Mansour, N. Kim, J. Seo and M. Nemer, "Comprehensive Thermal Modeling and Analysis of a 2019 Nissan Leaf Plus for Enhanced Battery Electric Vehicle Performance," SAE Technical Paper, 2024.

7. D. Park, J. Jung, N. Kim, E. Sabri, N. Kim and R. Vijayagopal, "Component Sizing Optimization Based on Technological Assumptions for Medium-Duty Electric Vehicles," SAE Technical Paper, 2024.

8. X. Hu, S. Li and H. Peng, "A comparative study of equivalent circuit models for Li-ion batteries," Journal of Power Sources, vol. 198, pp. 359-367, 2012.

9. N. Kim, A. Rousseau and E. Rask, "Parameter estimation for a lithium-ion battery from chassis dynamometer tests," IEEE Transactions on Vehicular Technology, vol. 65, no. 6, pp. 4393-4400, 2016.

Authors Biography

Namdoo Kim is a research engineer at Argonne National Laboratory. He graduated from the University of Sungkyunkwan, South Korea, with a Master's Degree in Mechanical Engineering in 2007. He focuses his research on the vehicle system modeling and simulation to assess the energy consumption, performance, and cost of advanced vehicle technologies across multiple classes, powertrains, components, and control strategies.

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Aymeric Rousseau is the Director of the Vehicle and Mobility Systems (VMS) Department at Argonne National Laboratory. He received his engineering diploma at the Industrial System Engineering School in La Rochelle, France in 1997 and an Executive MBA at Chicago Booth in 2019. For the past 25 years, he has been evaluating the impact of advanced vehicle and transportation technologies from a mobility, energy and economic point of view including the development of Autonomie (passenger, MD/HDT, off-road, marine and rail system simulation), Aeronomie (aviation system simulation), RoadRunner (connected and automated vehicle and powertrain control), and POLARIS (large-scale transportation system simulation).