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Control Analysis and Model Validation for Hyundai Ioniq 5 based on Dynamometer Test Data

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Executive Summary

In this study, the electric vehicle simulation model of the Hyundai Ioniq 5 was validated using dynamometer test data. The vehicle was tested under various speed profiles of standard driving cycles on a 4-wheel-drive (4WD) dynamometer at Argonne National Laboratory to analyze its propulsion control strategy and energy consumption. For vehicle modeling, the components such as motor and battery were configured using test data obtained from dynamometer testing performed under constant temperature conditions. Ioniq 5 features a dual motor system, for which a motor power distribution control strategy was analyzed based on the dynamometer test data and developed in the simulation model to emulate its production control. Furthermore, in the Vehicle Propulsion Controller (VPC), both propulsion and brake systems were developed and integrated. The simulation model was implemented into Autonomie. As a result, discrepancies in electric energy consumption were within 5%, and simulation signals, including state of charge, were matched the test data well.

Keywords: Electric Vehicles, Electric Motor Drive, Vehicle Motion & Stability Control, Modeling & Simulation, Advanced control of EVs

1 Introduction

Recently, interest in electric vehicles has grown significantly, leading to increased research on various types of electrified vehicles, including battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in HEVs (PHEVs), and fuel cell electric vehicles (FCEVs). Argonne National Laboratory (ANL) has conducted extensive research across a wide range of vehicles, from traditional internal combustion engine vehicles to advanced electric vehicles. Argonne's commitment to advancing vehicle technology is reflected in its comprehensive research efforts and the development of state-of-the-art simulation tools including Autonomie [1]. Autonomie is a high fidelity, forward-looking vehicle simulation tool that can estimate various types of vehicle performance, including fuel economy performance. In addition to developing simulation tools, Argonne has tested various types of vehicles using its 2-wheel-drive (2WD) and 4-wheel-drive (4WD) dynamometer facilities and released that dataset, the Downloadable Dynamometer Database (D3) [2].

The following steps outline the process of developing a high-fidelity forward-looking vehicle simulation model in Autonomie, based on test data from D3. First, the raw test data is imported into Autonomie's format, while calculating some signals that are not directly measurable. For example, front and rear wheel torque, which are difficult to measure with sensors, can be estimated using motor output torque and vehicle dynamics. Second, powertrain component models, such as those for the battery, electric motor, and engine, are developed based on the test data. For instance, a motor efficiency map can be created using the motor's operating speed, torque, current, and battery voltage data. Additionally, the supervisory vehicle control system is analyzed using the imported test data. For example, the power distribution between the front and rear electric motors of the two-motor-driven 4WD electric vehicle, based on vehicle speed, power demand, and battery state of charge, is analyzed and developed into a control model. Finally, all component models and control systems are integrated and simulated. The simulation results are then compared with the test data, and steps 2 and 3 are repeated if adjustments are required [2-5]. Based on the process, in this paper, we developed a simulation model of the 2023 Hyundai Ioniq 5 and compared it with data collected from the chassis dynamometers, electric sensors, and other components via Controller Area Network (CAN) communication [6-8].

2 Development of the Vehicle Powertrain Model

The Ioniq 5, an All-wheel-drive (AWD) pure electric vehicle, is built on the Electric-Global Modular Platform (E-GMP). It features a dual motor system for powerful performance and driving stability. The dual motor system not only enhances performance but also contributes to the vehicle's overall energy efficiency by optimizing power distribution. Additionally, the Ioniq 5 is equipped with the Disconnector Actuator System (DAS), which efficiently switches between AWD and 2WD based on driving conditions [9], and Vehicle-to-Load (V2L) technology, enabling the car to serve as a power source for charging and powering various electronic devices inside and outside the vehicle [10]. The powertrain model of the Ioniq 5 is composed of key components such as the chassis, wheels, motors, battery, as shown in Figure 1. To analyze energy efficiency, a forward simulation model of the Ioniq 5 was developed and implemented in Autonomie.

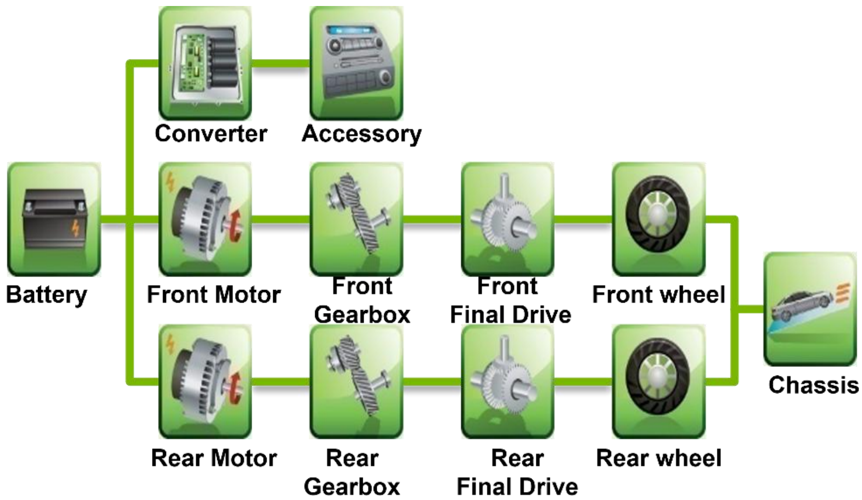

Figure 1: Vehicle configuration of the 2023 Hyundai Ioniq 5 in Autonomie

The powertrain model can be formulated based on the following equations, which describe the flow of energy from the battery through the motors and transmissions to the wheels and chassis. First of all, the battery State-of-Charge (SOC) can be represented based on equivalent circuit modeling as shown in equation (1).

$$\dot{SOC} = -\frac{V_{OCV} - \sqrt{V_{OCV}^2 - 4P_{bat} \cdot R_{bat}}}{2Q_{bat} \cdot R_{bat}} \tag{1}$$

where V_{OCV} is the battery open circuit voltage, R_{bat} is the battery internal resistance, and Q_{bat} is the battery capacity. Here, the battery power P_{bat} can be represented as shown in equation (2).

$$P_{bat} = \begin{cases} P_{bat,acc} + T_{mot,1} \cdot \omega_{mot,1} \cdot \eta_{mot,1}^{sgn(T_{mot,1})} + T_{mot,2} \cdot \omega_{mot,2} \cdot \eta_{mot,2}^{sgn(T_{mot,2})} & if\ E_{DAS,1} = 1 \\ P_{bat,acc} + T_{mot,2} \cdot \omega_{mot,2} \cdot \eta_{mot,2}^{sgn(T_{mot,2})} & else \end{cases} \quad (2)$$

where $P_{bat,acc}$ is the accessory power, $T_{mot,1}$ and $T_{mot,2}$ are the front and rear motor torque. $\eta_{mot,1}$ and $\eta_{mot,2}$ are the front and rear motor efficiency, $\omega_{mot,1}$ and $\omega_{mot,2}$ are the front and rear motor speed. During propulsion, the Disconnector Actuator System (DAS) engages the front motor to the powertrain ($E_{DAS,1} = 1$). Otherwise, during deceleration, the front motor is not connected to the driveline. The front final drive torque $T_{fd,1}$ and rear final drive torque $T_{fd,2}$ can be represented as shown in equation (3).

$$T_{fd,1} = T_{mot,1} \cdot r_{fd,1} \cdot \eta_{fd,1}^{sgn(T_{mot,1})}, \quad T_{fd,2} = T_{mot,2} \cdot r_{fd,2} \cdot \eta_{fd,2}^{sgn(T_{mot,2})} \quad (3)$$

where $r_{fd,1}$ and $r_{fd,2}$ are the front and rear final drive gear ratio, $\eta_{fd,1}$ and $\eta_{fd,2}$ are the front and rear final drive efficiency. The traction force F_{trac} can be represented as shown in equation (4).

$$F_{trac} = \frac{T_{fd,1}}{r_{whl}} + \frac{T_{fd,2}}{r_{whl}} \quad (4)$$

where r_{whl} is the wheel radius. The vehicle acceleration a_{veh} can be represented as shown in equation (5).

$$a_{veh} = \frac{F_{trac} - F_{load}}{m_{veh}}, \quad F_{load} = f_0 + f_1 \cdot v + f_2 \cdot v^2 \quad (5)$$

where m_{veh} is the vehicle test weight, v is the vehicle speed, and F_{load} is the road load force based on road load coefficients. The parameters of the powertrain components, such as vehicle test weight and road load coefficient, were derived from chassis dynamometer test data collected under controlled conditions. The parameters used in the simulation model are presented in Table 1.

Table 1: Vehicle model parameters

Battery capacity	77.4 kWh
Motor power	239 kW (Front: 74 kW, Rear: 165 kW)
Motor torque	605 Nm
Vehicle test weight	4,750 lbs.
Final drive gear ratio	10.65
Wheel radius	0.363 m
Road load coefficient	f_0: 116.67 N f_1: 3.21 N/(m/s) f_2: 0.48 N/(m/s^2)

3 Development of the Vehicle Control Logic

Since the Ioniq 5 has two motors-one in the front and one in the rear-it is important to understand how the vehicle's control strategy distributes power demand between the two motors under different conditions. The motor power distribution strategy is analyzed and then implemented in the simulation model to allocate motor power between the front and rear motors based on driving conditions.

Firstly, during the vehicle's deceleration (braking), to assess whether the rear motor could satisfy the power demand, the total motor power was compared with rear motor power, as shown in Figure 2. It was observed that regenerative braking energy is collected solely from the rear electric motor, while the front electric motor does not regenerate any energy. On the other hand, during the vehicle's acceleration, Ioniq 5 driving mode can be divided into four modes. The four modes switch according to vehicle speed and power demand as shown in Figure 3. Here, Mode 1 and Mode 2 can be determined based on the vehicle speed as illustrated in Figure 4. First, Mode 1 is defined as the initial driving phase, in which the vehicle starts to move from a stop and remains in this mode until it reaches a reference speed of 7 m/s. In this mode, motor power is distributed evenly between the front and rear motors with a power distribution ratio of 0.5:0.5, as shown in Figure 5. Second, Mode 2 begins after Mode 1, once the vehicle exceeds the reference speed of 7 m/s, resulting in a transition of the propulsion system from Mode 1 to Mode 2, as shown in Figure 4. Mode 2 serves as a transient phase during which the vehicle shifts from Mode 1 to Mode 3. In this mode, priority is given to the rear motor, although the front motor is still utilized with a front-to-rear motor power ratio of 0.2:0.8. Third, the transition from Mode 2 to Mode 3 occurs after the vehicle remains in Mode 2 for 10 seconds and maintains a speed greater than 7 m/s but less than 30 m/s. In Mode 3, only the rear motor is used for vehicle propulsion, optimizing efficiency under these conditions. Last, Mode 4 is activated from either Mode 2 or Mode 3 when the demand torque exceeds the rear motor's maximum torque, the vehicle speed exceeds 33 m/s,

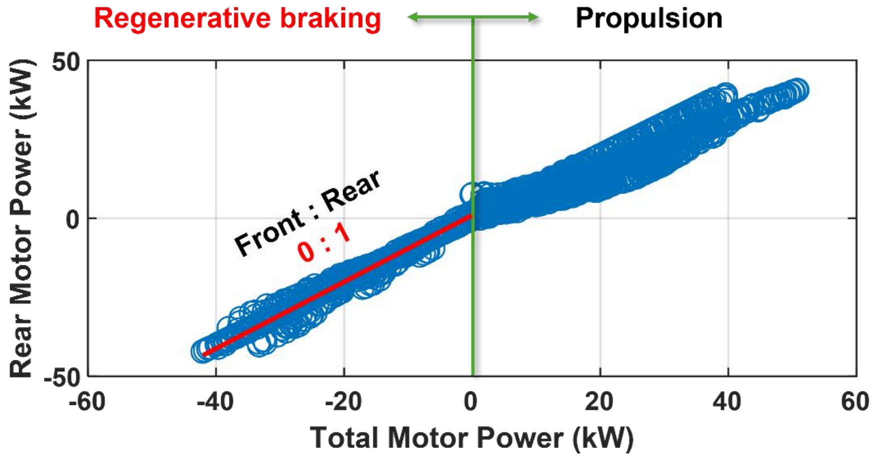

Figure 2: Rear motor power distribution according to the total motor power demand during braking

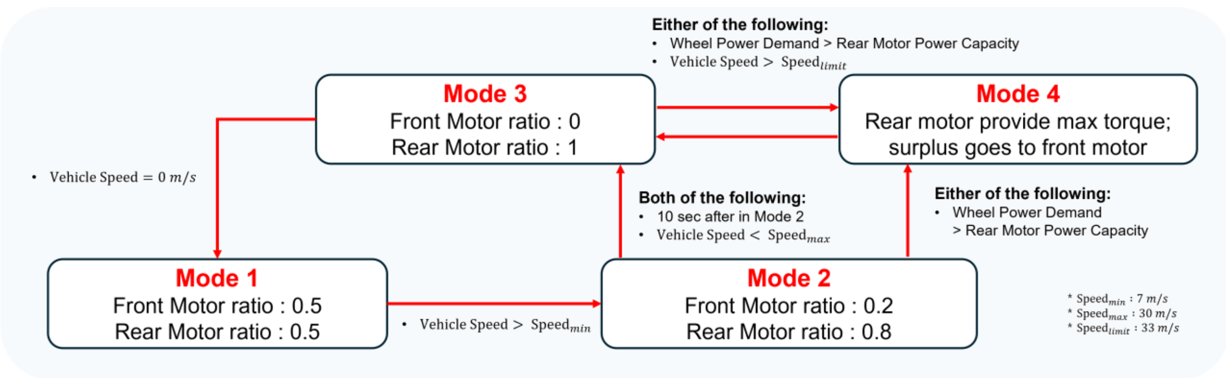

Figure 3: State flow diagram for the four modes

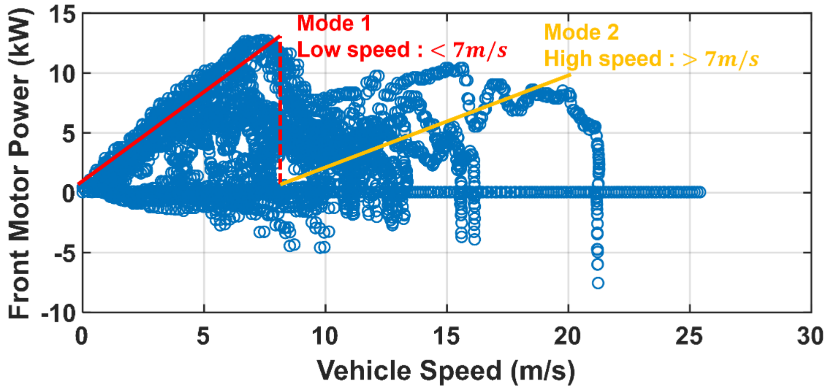

Figure 4: Mode 1 and mode 2 differentiation during propulsion

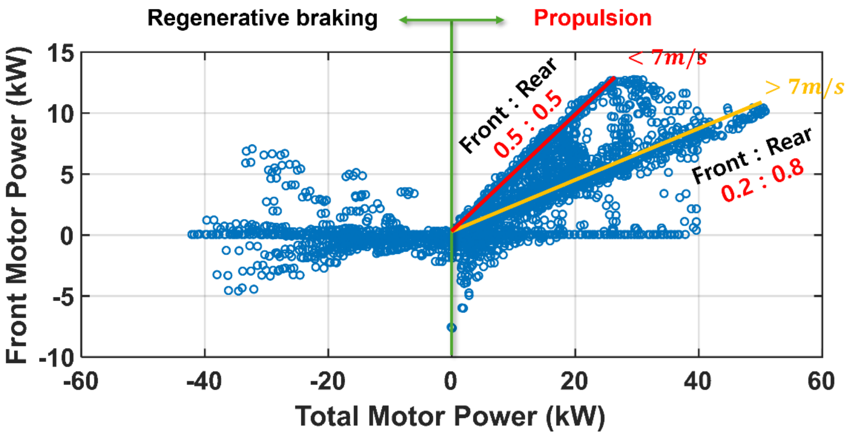

Figure 5: Front and rear motor power distribution during propulsion

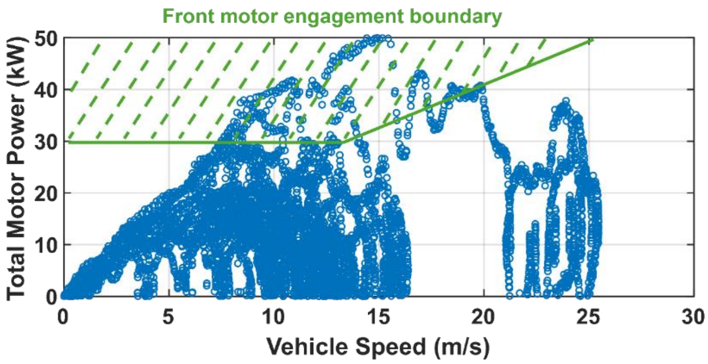

Figure 6: Mode transition condition from mode 2 or mode 3 to mode 4: Front motor engagement condition with respect to wheel power demand

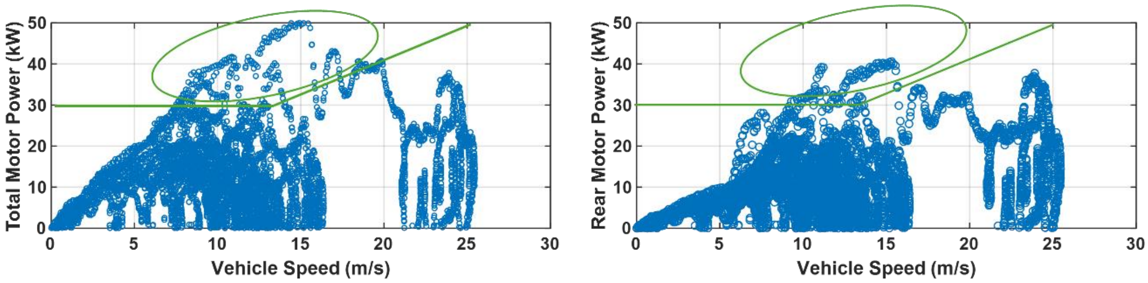

Figure 7: Comparison of total motor power and rear motor power for mode transition

or when conditions necessitate the engagement of the front motor as shown in Figure 6. In Figure 6, the boundary indicates the conditions under which the front motor becomes engaged. As illustrated in Figure 7, a comparison between the total power and the rear motor power clearly indicates that the rear motor cannot solely meet the demand power. This demonstrates that the front motor provides the additional power required beyond the rear motor's capacity. Therefore, in Mode 4, the front motor supports the portion of the power demand that cannot be fulfilled by the rear motor. Additionally, the return from Mode 3 to Mode 1 occurs when the vehicle speed drops to 0 m/s (initial condition).

4 Simulation Results

Validation was conducted across 6 driving cycles, including the Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Test (HWFET), and Connected and Automated Vehicles (CAVs) at speeds of 20, 30, 40, and 50 mph. The CAV cycles were specifically designed by Argonne to more accurately reflect the driving behavior and energy consumption of CAVs. These cycles are assumed to incorporate future traffic signal information to reduce aggressive acceleration and braking [11].

The simulation results alongside test data are presented in Figure 8-10, comparing vehicle speed, battery state-of-charge (SOC), front motor power, and rear motor power for each cycle. For the UDDS, HWFET, and CAV 40mph cycles, the simulation results for vehicle speed, rear motor power, and batter SOC closely match the corresponding dynamometer test data. However, discrepancies in the front motor power are observed between the simulation and test data, indicating that additional analysis regarding the operating points of the front motor power is required. The powertrain models and control algorithms implemented in Autonomie have demonstrated high accuracy, with vehicle dynamics and powertrain operations in simulation closely matching the test results. The close alignment between simulation and test data underscores the robustness of our modeling approach and the accuracy of the Autonomie simulation tool. Energy consumption for each of the 6 cycles in the simulation is within 5% of the test results, as detailed in Table 2. Especially compared to the test results, the HWFET cycle result shows the lowest discrepancy of 0.26%, and the UDDS cycle result also shows a low discrepancy of 1.40%. For the CAV 20 mph cycle, further tuning of the motor efficiency at low motor speeds is required; nevertheless, these results provide confidence in the model's ability to predict real-world performance, making it a valuable tool for future research and development.

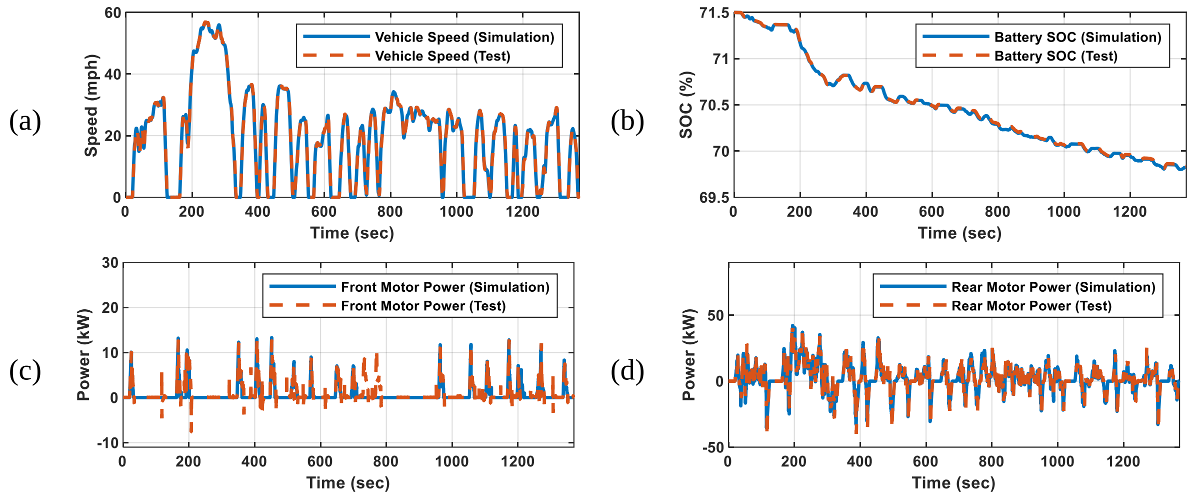

Figure 8: UDDS cycle results: (a) Vehicle speed, (b) Battery SOC, (c) Front motor power, (d) Rear motor power

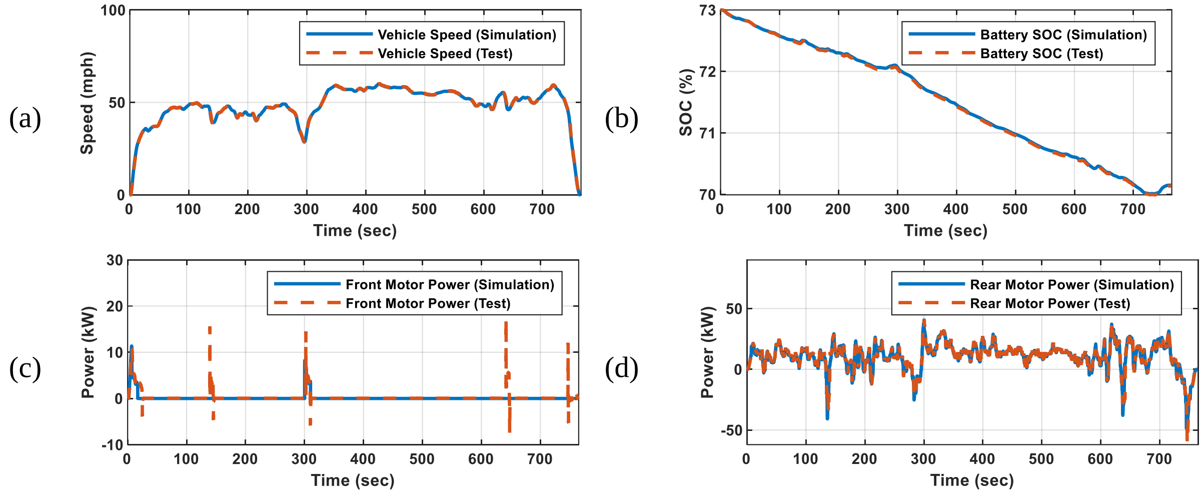

Figure 9: HWFET cycle results: (a) Vehicle speed, (b) Battery SOC, (c) Front motor power, (d) Rear motor power

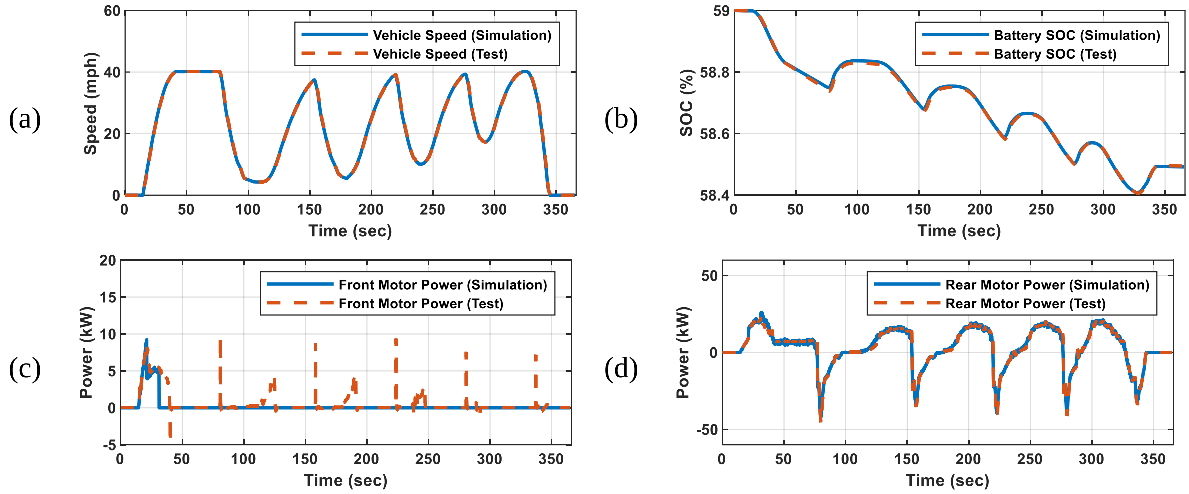

Figure 10: CAV 40mph cycle results: (a) Vehicle speed, (b) Battery SOC, (c) Front motor power, (d) Rear motor power

Table 2: Energy consumption for each cycle (kWh/mile)

Cycle	UDDS	HWFET	CAV 20 mph	CAV 30 mph	CAV 40 mph	CAV 50 mph
Test	185.6	232.8	128.3	153.2	180.8	218.7
Simulation (error)	188.2 (1.40 %)	232.2 (-0.26 %)	122.1 (-4.83 %)	151.2 (-1.31 %)	187.8 (3.84 %)	224.2 (2.51 %)

5 Conclusions

A high-fidelity simulation model of the Hyundai Ioniq 5 was successfully developed and validated by comparing simulation results with test data obtained from a chassis dynamometer. As part of the validation process, a motor power distribution control strategy for the Ioniq 5 simulation model was developed. The results demonstrated that discrepancies in energy consumption were within 5%, and other key metrics, such as vehicle speed and battery SOC, closely matched the test data. The validated simulation model is versatile and can be applied in various scenarios, including autonomous driving environments. The Ioniq 5 simulation model is designed for pre-evaluation of energy savings through advanced controls in simulation before conducting actual vehicle-in-the-loop tests. It also supports the optimization of powertrain controls by providing necessary variables.

By conducting simulations prior to actual tests, researchers can save significant time and effort while gaining reliable estimates of future test results. The insights gained from this study will inform future advancements in electric vehicle technology and contribute to the broader understanding of energy-efficient vehicle design. It is anticipated that the Ioniq 5 simulation model will be utilized in large-scale studies to assess the energy impact of electric vehicles and to evaluate the energy implications of CAVs and their advanced controls under various conditions. By leveraging high-fidelity simulation models, researchers can explore a wide range of scenarios and optimize vehicle performance before physical testing, thereby accelerating the development process.

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Presenter Biography

Hyunjoong Kim received B.S. degree in Mechanical Engineering from Dankook University, Korea, in 2023. He is currently in graduate school, pursuing M.S. degree in Mechanical Engineering at Dankook University, Korea. His research interests include Reinforcement Learning, Modeling and Simulation of Intelligent Vehicle.