Modeling Fuel Cell Electric Vehicle for Performance Prediction and Optimal Component Selection

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Abstract

This study involves modeling and simulating a Fuel Cell Electric Vehicle (FCEV) to predict whether it meets the target performance requirements. The FCEV model includes an electrified powertrain, composed of a hydrogen fuel cell, motor, battery, and controller, along with a chassis model. A test environment was also modeled to evaluate these components. Different combinations of chassis and motor candidates were examined to predict vehicle performance for each configuration and determine if the target requirements were met. The results of this study served as a reference for selecting optimal components during the development process.

Keywords: Fuel cell electric vehicle, Electrified powertrain, Model based system engineering

1 Introduction

With the increasing demand for eco-friendly vehicles, such technologies are gaining attention in various fields, including the military. Military electric vehicles, in particular, are highly regarded for their low heat emission, reduced noise, which enhances concealment, and the inherent mobility unique to electric vehicles.

According to the IP Defense Forum (2024), South Korea views the utilization of hydrogen fuel cell vehicles in military operations positively. Fuel Cell Electric Vehicles (FCEVs) are especially preferred for their rapid refueling capabilities and long driving range, further highlighting their suitability as military electric vehicles.

Additionally, the International Energy Agency (2019) predicts that hydrogen will account for 24% of the global energy mix by 2050. In response to this global trend, South Korea is actively refining its policies and regulations. Against this backdrop, FCEVs are emerging as a vital solution that meets the dual objectives of sustainable energy transition and advancements in military technology.

Model-Based Systems Engineering (MBSE) utilizing electric vehicle models can significantly streamline the design and development process, enabling more efficient achievement of target performance goals. According to Shevchenko, N. (2020), MBSE enhances traceability across requirements, design, analysis, and validation, ensuring consistency and efficiency throughout the system's lifecycle. Additionally, performance prediction through modeling supports optimal component selection and facilitates effective risk management as specifications evolve during the development process.

In this study, an electrified powertrain model comprising key components of an FCEV was developed, and simulations were conducted on various component specifications to predict performance. Through this process, optimal components were selected, and specifications were evaluated.

2 Vehicle Modeling

Vehicle models consist of a chassis, an electrified powertrain, and a brake model. In this study, two chassis models and three electrified powertrain models were created based on their specifications. By combining these, a total of four vehicle models were generated.

Table 1. Architecture combinations of each vehicles

Number	*Chassis*	*Powertrain*
1	1	1
2	2	1
3	2	2
4	2	3

2.1 Chassis

The chassis model calculates the vehicle's behavior based on vehicle dynamics, taking into account driving force, braking force, steering input, and driving resistance. Driving and braking forces are input from the powertrain and brake models, while steering input is provided by the driver model. Driving resistance is calculated through each component of the chassis model.

The chassis model comprises body, suspension, and tire models. The body model includes a mass model and an aerodynamics model, with parameters set for sprung mass, center of gravity, inertia, drag coefficient, and frontal area to calculate air resistance. For efficiency, the suspension model also adopts a lumped mass approach, focusing on wheel center position and spring and damping characteristics. The tire model includes wheel weight information and calculates rolling resistance based on a rolling resistance coefficient. In this study, two types of chassis models were created for each specification based on Vehicle Dynamics Library from *Modelon AB*(2021).

Table 2. Comparison between chassis models.

Specifications	*Chassis 1*	*Chassis 2*
GVW	+	++
Tire dynamic radius	+	++
Frontal Area	++	+

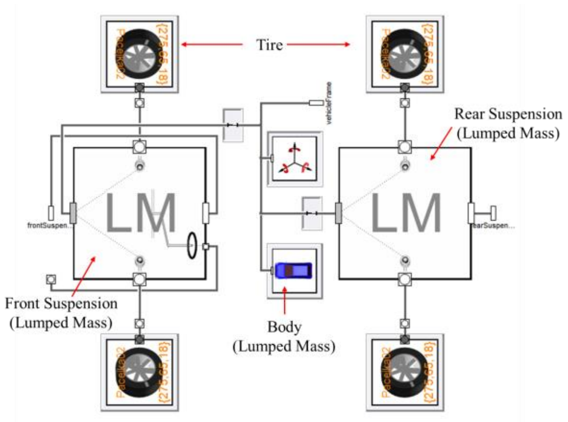

Figure 1. Chassis model.

2.2 Electrified Powertrain

The electrified powertrain model for the FCEV consists of the following subsystems. The subsystems are based on Electrification Library from *Modelon AB*(2021).

- Hydrogen Fuel Cell
- Motor
- Battery
- Controller

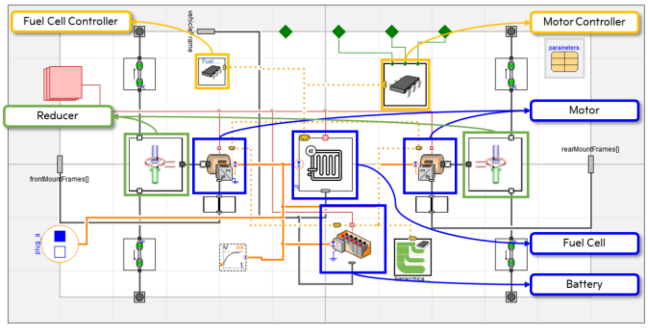

Figure 2. Electrified powertrain model for FCEV.

The hydrogen fuel cell model is designed to calculate hydrogen consumption based on the power demand, using a battery model as its foundation. The model incorporates the current-voltage characteristic curve, with resistance values tuned to reflect this curve. A tabular model with current-hydrogen consumption curve data is used to calculate hydrogen consumption according to the current level. The load model connected to the hydrogen fuel cell model simulates the power consumption of the Balance of Plant (BOP), enabling the calculation of the gross and net output of the hydrogen fuel cell.

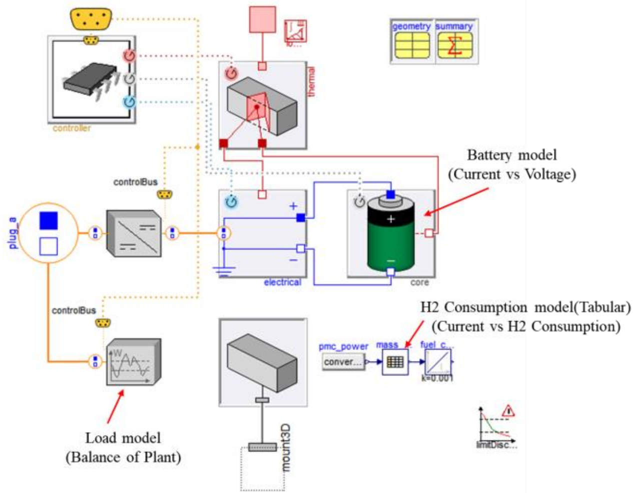

Figure 3. Simple Fuel cell model based on battery model.

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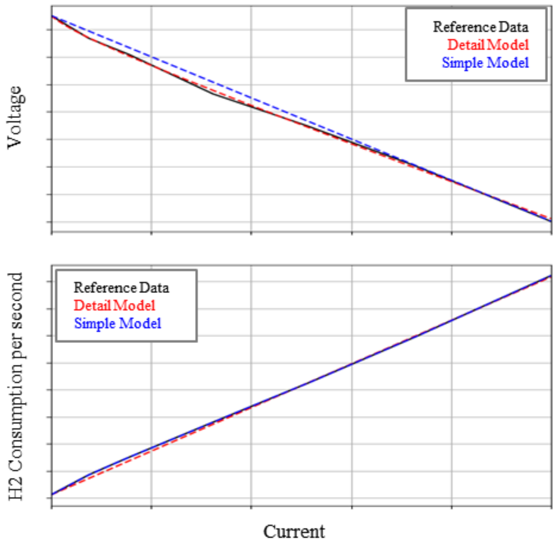

Figure 4. Fuel cell model(simple) validation.

The motor model simulates either a DC motor or an AC motor with an inverter. The motor's torque map model calculates the maximum torque based on motor speed according to the set maximum power and torque limits, restricting torque if the demanded torque exceeds the calculated maximum. The efficiency model uses efficiency values or an efficiency map to determine the power consumption based on motor output. The calculated torque is transmitted to the chassis model via a mechanical connector, while the consumed power is sent to a power source model, such as a battery or hydrogen fuel cell, via an electrical connector to calculate SOC or hydrogen consumption. Thermal losses, calculated from the difference between consumed power and mechanical output, allow the motor's temperature to be tracked within the thermal model.

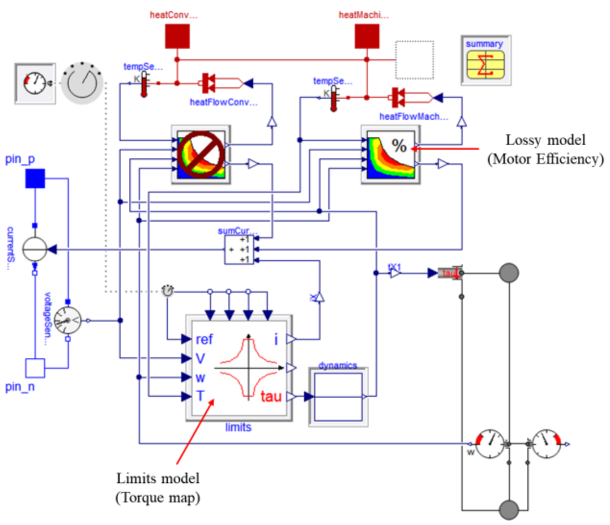

Figure 5. Electric machine(motor & generator) model.

The battery model is configured to supplement the output of the hydrogen fuel cell. The battery characteristics are modeled by setting the cell capacity, OCV curve, internal resistance properties, and cell configuration details. The capacity model calculates SOC based on the set capacity and consumed charge. The OCV model simulates the discharge characteristics of the battery according to SOC. The resistance model represents the internal resistance of the battery cells, calculating voltage drop and, through losses, determining the battery's temperature.

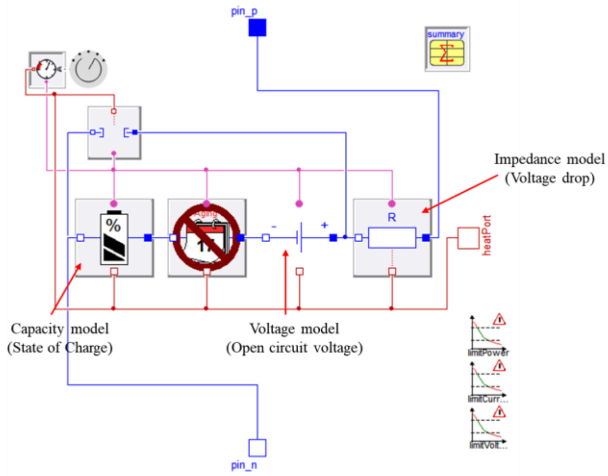

Figure 6. Battery model.

The controllers calculate the output of the motor and hydrogen fuel cell, respectively. The motor controller determines the required torque of the motor based on the accelerator pedal input, controlling the motor model accordingly. In the motor model, the output torque is determined based on the demanded torque and the torque map.

The hydrogen fuel cell system controller calculates the gross power based on the motor's required power. It then computes the BOP's power consumption according to the calculated gross power and transfers this to the load model within the hydrogen fuel cell, ensuring that the net output is supplied to the motor.

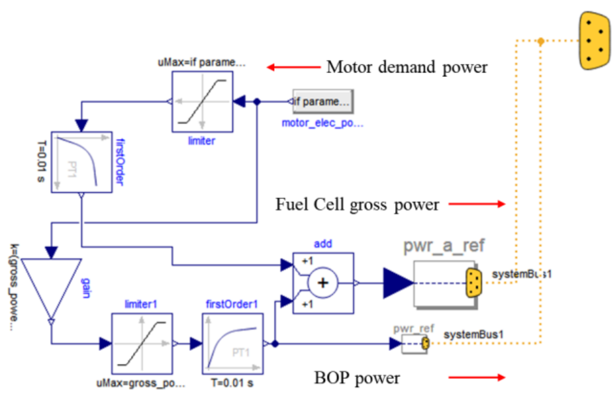

Figure 7. Fuel cell system controller

The hydrogen fuel cell system controller calculates the gross power based on the motor's required power. It then computes the BOP's power consumption according to the calculated gross power and transfers this to the load model within the hydrogen fuel cell, ensuring that the net output is supplied to the motor.

Three types of electrified powertrain models were created based on the specifications and combinations of each component.

Table 3. Comparison of electrified powertrain configurations.

Specifications	*1*	*2*	*3*
System voltage	++	+++	+
Peak power	++	++	+
Peak torque	+	+	+
Continuous power	+	+	+
Continuous torque	+	++	++
Max speed of motor	++	+	+
Reduction Ratio	+	++	++
Efficiency of powertrain	+ (Const.)	++ (Map)	++ (Map)

3 Performance Anaysis

To evaluate whether each vehicle meets the required performance, a vehicle performance evaluation environment is modeled and configured according to the test conditions for assessing each requirement. Subsequently, the performance of each vehicle, composed of various subsystem combinations, is evaluated.

3.1 Test Environment Modeling

The vehicle performance evaluation environment consists of vehicle, driver, road surface, and atmosphere models. The driver model controls the vehicle model by providing acceleration/brake pedal inputs and steering inputs. The driver model is broadly classified into open-loop and closed-loop models.

The open-loop model delivers predefined acceleration and brake pedal inputs directly into the vehicle model without any feedback control. This approach is suitable for evaluating acceleration and top speed through full-throttle scenarios.

On the other hand, the closed-loop model controls the vehicle's speed by adjusting the acceleration and brake pedal inputs to follow a predefined speed profile. By comparing the vehicle's current speed with the speed defined in the profile, the inputs are dynamically adjusted. This method is suitable for evaluating fuel efficiency or energy consumption during specific speed profile driving.

The road surface model defines the road characteristics by setting the friction coefficient and the lateral/longitudinal slope of the surface. This makes it suitable for evaluating vehicle performance in scenarios such as driving on inclined roads.

3.2 Requirements

The vehicle performance evaluation criteria include five items: acceleration performance, maximum speed, gradeability, maximum grade speed, and driving range.

Acceleration performance is evaluated by measuring the time it takes for the vehicle to reach the target performance on flat terrain using the peak performance of the powertrain.

Maximum speed is determined by assessing the highest speed the vehicle can achieve on flat terrain based on the continuous performance of the powertrain.

Gradeability tests the vehicle's ability to start from a standstill and maintain a certain speed on steep slopes, utilizing the powertrain's peak performance.

Maximum grade speed evaluates the maximum speed the vehicle can achieve on a general incline using the continuous performance of the powertrain.

Lastly, driving range is estimated by analyzing hydrogen consumption during constant-speed driving on flat terrain, using the continuous performance of the powertrain to predict the total distance the vehicle can travel.

Table 4. Performance requirements and test conditions.

Performance	*Road*	*Motor*	*Velocity Control*
Acceleration	Flat	Peak	Full throttle
Max speed	Flat	Cont.	Full throttle
Gradeability	Very steep slope	Peak	Full throttle
Max gradient speed	Moderate slope	Cont.	Full throttle
Driving Range	Flat	Cont.	Controlled for contant speed

3.3 Results

The acceleration performance evaluation results showed that all four vehicles met the requirements. Vehicles 3 and 4 demonstrated the best acceleration performance, while Vehicle 2 had the lowest acceleration performance. This is attributed to the increased reduction ratio in Vehicles 3 and 4, which provided greater torque amplification for the same motor torque output, despite their heavier weight.

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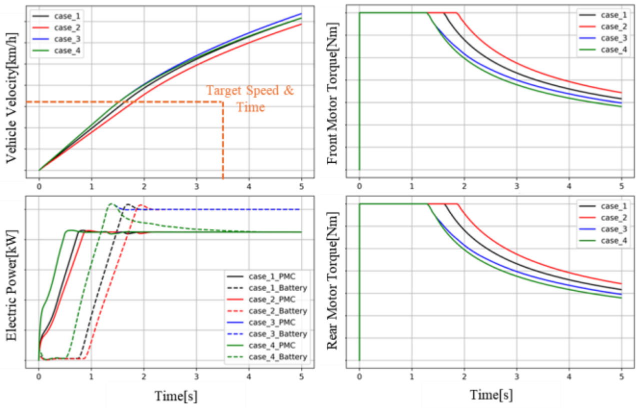

Figure 8. Result of acceleration test.

The maximum speed evaluation results showed that Vehicles 3 and 4 achieved the highest top speeds, while Vehicle 1 recorded the lowest. Although the continuous output of the powertrain was identical across all four vehicles, Vehicle 1's larger frontal area resulted in greater aerodynamic drag, leading to a lower maximum speed. In contrast, the improved aerodynamics and enhanced powertrain efficiency of Vehicles 3 and 4 contributed to their superior top speed performance.

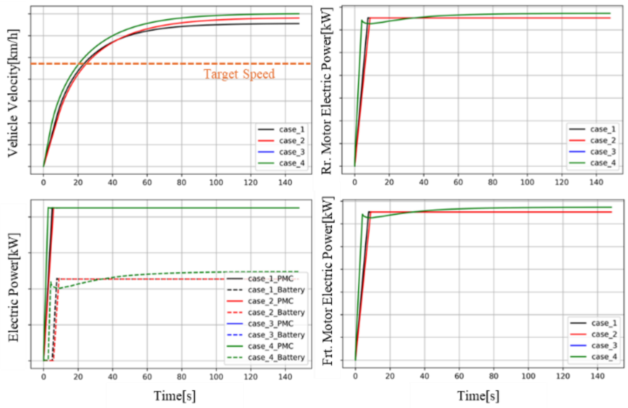

Figure 9. Result of max speed test.

The gradeability evaluation results showed that Vehicles 3 and 4 performed the best, while Vehicle 2 failed to meet the requirements. Compared to Vehicle 1, Vehicle 2 maintained the same powertrain performance but experienced increased gradient resistance due to its heavier weight. Vehicles 3 and 4 demonstrated significant improvements in gradeability, attributed to the increased reduction ratio, which amplified torque and enhanced their climbing performance.

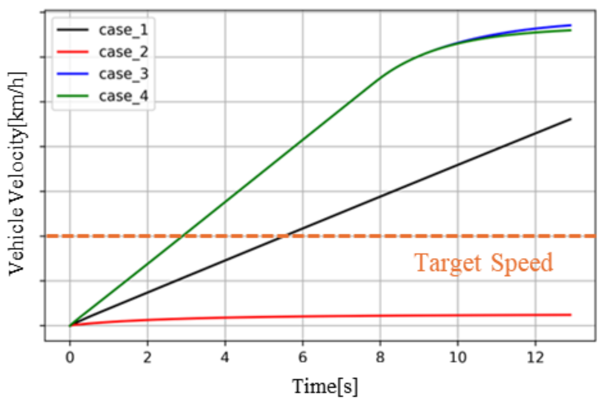

Figure 10. Result of gradeability test.

The maximum grade speed evaluation results indicated that Vehicle 2 had the lowest performance due to increased gradient resistance caused by its heavier weight. In contrast, Vehicles 3 and 4 demonstrated the best performance, attributed to the improved powertrain efficiency.

The driving range evaluation results revealed that Vehicles 3 and 4 achieved the best performance. This outcome is attributed to their superior aerodynamics and enhanced powertrain efficiency compared to the other two vehicles.

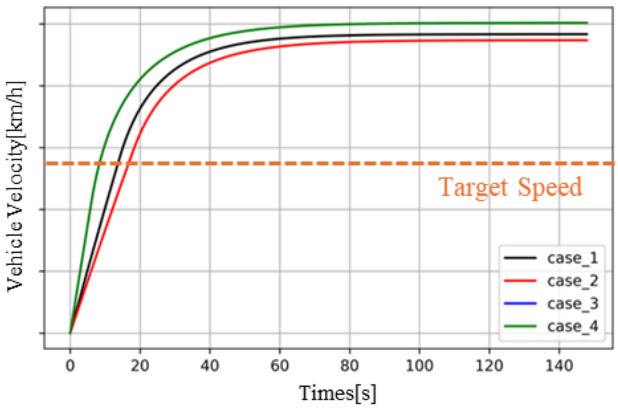

Figure 11. Result of max gradient speed test.

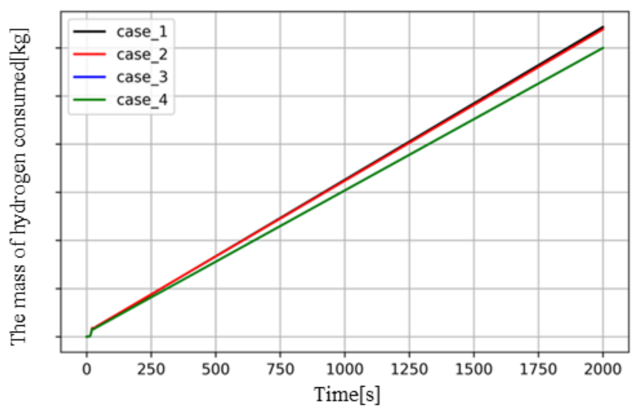

Figure 12. Result of driving range test.

Table 5. Summary of evaluation results.

Performance	*Vehicle (+: Passed / -: Failed)*			
	1	*2*	*3*	*4*
Acceleration	++	+	+++	+++
Max speed	+	++	+++	+++
Gradeability	+	-	++	++
Max gradient speed	++	+	+++	+++
Driving Range	+	+	++	++

4 Conclusion

In this study, modeling and simulation were conducted to predict the performance of FCEVs. Instead of using detailed specifications of hydrogen fuel cells, which are critical to information security, the study utilized results from component-level tests to develop a hydrogen fuel cell model. This approach provides a foundation for predicting FCEV performance and examining optimal component combinations during the early stages of design.

However, as the model does not fully reflect the physical and chemical characteristics of actual hydrogen fuel cells, further validation is required. Additionally, studies on the control of electrical flows between the hydrogen fuel cell and the battery in real FCEV systems are necessary.

Future research will focus on validating the model using test results from actual vehicles and conducting comparative validation with models incorporating detailed hydrogen fuel cell specifications and characteristics. Moreover, research will explore methods for integrating the control of electrical flows between the hydrogen fuel cell and the battery to enable more realistic performance predictions.

Acknowledgements

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