

Development of a Virtual Performance Evaluation Model for New Multi-Mode Hybrid Powertrain System with RCP-HIL Validation

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Multi-mode hybrid powertrains combine an internal combustion engine, multiple electric motors, and a multi-speed transmission to improve fuel efficiency and vehicle performance. However, the interaction among these components requires coordinated control and systematic verification, particularly during driving-mode transitions and transmission shifting. This study develops a virtual performance evaluation model for a new multi-mode hybrid powertrain consisting of a 1.6 L GDI engine, a P1 motor (MG1), a P3 motor (MG2), and a dog-clutch type two-speed transmission.

The proposed system supports three driving modes: Electric Drive (EV), Series Hybrid (S-HEV), and Parallel Hybrid (P-HEV). EV mode uses the electric motors for propulsion, S-HEV mode operates the engine as a generator, and P-HEV mode combines engine and motor torque for vehicle propulsion. The target vehicle is a compact SUV-class HEV with a curb weight of 1,360 kg. The development targets are a maximum speed of 160 km/h, a 0-100 km/h acceleration time within 11 s, and an EV-mode grade ability of 37%.

The virtual model integrates the vehicle's longitudinal dynamics, engine, transmission, two electric motors, battery, and controller models. The plant and controller subsystems were separated into independently executable blocks with bus-based signal interfaces. This structure enables the model to be used for both offline simulation and real-time hardware-based evaluation. The controller architecture consists of the Hybrid Control Unit (HCU), Transmission Control Unit (TCU), Engine Control Unit (ECU), two Motor Control Units (MCUs), Battery Management System (BMS), and Brake Control Unit (BCU).

As shown in Fig.1, the real-time evaluation environment was constructed using two Speedgoat target machines connected through a CAN bus. The HCU was deployed on the Rapid Control Prototyping (RCP) target machine, while the vehicle plant and the remaining controller models were executed on the hybrid-system target machine. The two machines exchanged vehicle states, torque/speed commands, battery signals, and transmission information in real time. This configuration enabled closed-loop validation of the complete multi-mode hybrid powertrain control system.

The HCU selects the driving mode according to vehicle speed, battery state of charge (SOC), driver torque demand, and clutch position, and coordinates the torque commands of the engine, MG1, and MG2. The TCU controls the dog-clutch type two-speed transmission in P-HEV mode through a six-step shifting sequence consisting of torque reduction, clutch release, motor-speed synchronization, clutch engagement, and torque recovery. The ECU regulates engine operation according to the requested torque from HCU. The MCUs control motor operation and regenerative braking, and the BMS manages battery power, SOC, and energy flow.

The developed model and control logic were evaluated using FTP-75 and HWFET drive cycles in the closed-loop RCP-HIL environment. The simulated vehicle speed showed high agreement with the reference profiles, with R-squared values of 0.9990 for FTP-75 and 0.9993 for HWFET. The 0-100 km/h acceleration time was 10.00 s, the EV-mode grade ability was 39.14%, and the maximum speed reached 168.7 km/h. The maximum speed was sustained for 2 km with less than 5% variation in P-HEV mode.

All development targets were therefore satisfied or exceeded. These results demonstrate that the proposed virtual model and constructed RCP-HIL architecture can effectively verify mode transitions, engine-motor torque coordination, and shifting control before physical prototype testing. The developed approach provides a practical foundation for further optimization and validation of advanced multi-mode hybrid powertrain systems.

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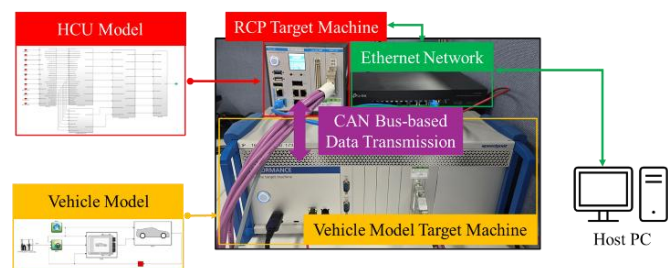


Fig.1 RCP-HIL Virtual Evaluation Environment Configuration