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Development of a Model-Based Development Method for Global Design Optimization Using a Cross-Domain Model

-Model development and application to vehicle development considering power management, thermal performance, vehicle motion performance, etc-

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Model-Based Development (MBD) is widely used to improve efficiency in automotive development processes. In the conceptual and early design phases, rational module selection requires simultaneous consideration of multiple performance domains such as fuel economy, vehicle dynamics, and thermal performance, etc. However, conventional 3D CAE approaches are impractical at this stage due to their high computational cost. On the other hand, existing 1D modeling approaches are often limited to specific domains and cannot easily capture cross-domain trade-offs.

This study proposes the Integrated Environment shown in Fig. 1. Which is a Model-Based Development method for global design optimization using a cross-domain physical model termed the Collective Automotive Engineering Model (CAEM). CAEM integrates power management, thermal systems, and vehicle motion performance within a unified 1D physical modeling framework. All models are controlled through a Relational Database (RDB)-based Application Programming Interface (CAEM API), which enables strict traceability and consistent handling of design variables, model parameters, and evaluation items. CAEM API allows conceptual design queries without requiring direct manipulation of low-level model parameters. The RDB explicitly defines relationships among design specifications, evaluation scenarios, model parameters, and physical quantities, ensuring both flexibility and consistency when models or evaluation methods are updated. For design exploration, Design of Experiments (DOE) is executed via CAEM API, and Response Surface Models (RSM) are constructed to approximate the high-dimensional design and performance spaces. Using RSM, tens of thousands of virtual experiments can be evaluated within seconds, enabling interactive design space exploration that would otherwise be computationally infeasible.

To enable fast and stable simulation of cross-domain phenomena, the internal model structure is reorganized by controlling eigenvalues and time constants. Vehicle dynamics models are reduced to eigenfrequencies below 50 Hz, thermal systems are modeled as first-order systems with time constants longer than 1 s, and thermal fluid behavior is simplified as forced-flow systems without pressure dynamics. Control systems are represented as continuous systems with dominant frequencies below 1 Hz, and algebraic loops are avoided to reduce computational cost. These simplifications enable time-domain simulation with Real time while preserving energy consistency.

Furthermore, Domain Mapping Matrices (DMM) are generated from DOE results to quantitatively evaluate the contribution of each design variable to individual performance metrics using explicitly defined design units. Based on the similarity of contribution vectors, Design Structure Matrices (DSM) are constructed to cluster performance metrics that should be considered simultaneously as shown in Fig. 2. This process enables systematic dimension reduction and provides quantitative support for engineering intuition regarding trade-offs and dominant design factors.

In summary, the proposed cross-domain MBD framework combines physical modeling, database-driven model management, DOE, RSM, DMM, and DSM to realize rapid and explainable global design optimization. The method enables consistent cross-domain analysis, efficient exploration of high-dimensional design spaces, and quantitative identification of dominant design variables and performance trade-offs in early vehicle development phases.

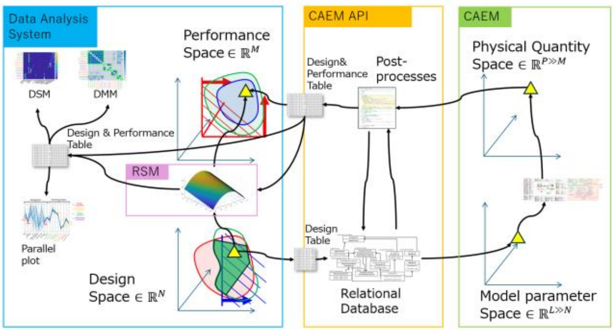

Fig.1 Design Concept of Integrated Environment

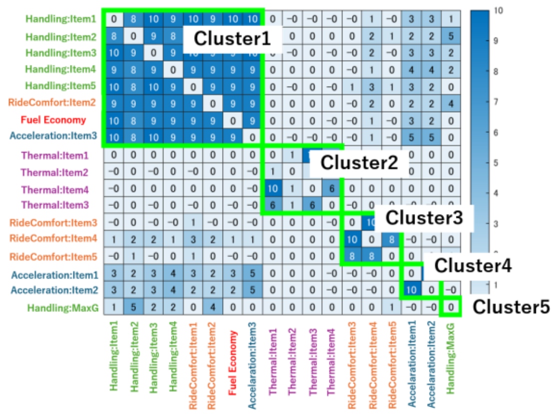

Fig.2 Parallel plot with constraints

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