

Study on Robust Optimization Design Methodology for EV Thermal Management Components Using an FMI-Based Integrated Vehicle, Drivetrain, and HVAC Model

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Optimizing vehicle-wide thermal management is critical for extending EV driving range and improving energy efficiency in extreme seasons. Although component supply to OEMs has been dominated by mega-suppliers, the EV shift and low-volume, high-mix demands are increasing opportunities for small and medium-sized enterprises (SMEs) with niche strengths to enter the supply chain. However, during early vehicle planning stages, component specifications must be decided before detailed 3D geometries are defined, making conventional 3D-CFD unapplicable. Additionally, adapting to OEM-required Model-Based Development (MBD) and ensuring Verification and Validation (V&V) for unproven components present severe barriers for SMEs lacking advanced CAE resources.

To resolve these issues, this study proposes a system simulation methodology that allows SMEs to participate in early-stage design competitions without massive investments or expert training, enabling rapid quantification of how component thermal specifications affect total vehicle energy consumption from the pre-geometry phase.

Traditional simulation methods are classified by dimensionality and discretization (Table 1). While 3D-CFD or 1D flow-network models excel at detailed validation, they suffer from high computational overhead and design confidentiality issues during the early planning phase. On the other hand, lumped-parameter (0D) models are suitable for control co-simulation but fail to represent spatial distributions of thermal capacity and resistance in cabin structures.

To bridge this gap, the proposed methodology utilizes a "1.5D multi-mass model" that defines components as a network of thermal capacities and resistances, utilizing empirical formulas (such as Nusselt numbers) for fluid heat transfer. This eliminates 3D mesh generation costs while accurately capturing structural temperature gradients. Because this model can be exported as an FMU via the FMI standard, it seamlessly integrates into higher-level 1D/0D environments (e.g., Simulink) for vehicle, drivetrain, and control systems, enabling rapid functional specification optimization during the vehicle planning phase.

Table 1 Comparison of Thermal Simulation Methods

Class.	Approach	Advantages	Disadvantages
3D	3D-CFD	Localized visualization	High cost/ Hard to validate
1D	Flow Network	Pressure & flow accuracy	Limited spatial temperature
0D	Lumped	Low cost/ Fast execution	No spatial distribution
1.5D	Proposed	Fast / Spatial heat transfer	No localized flow velocity

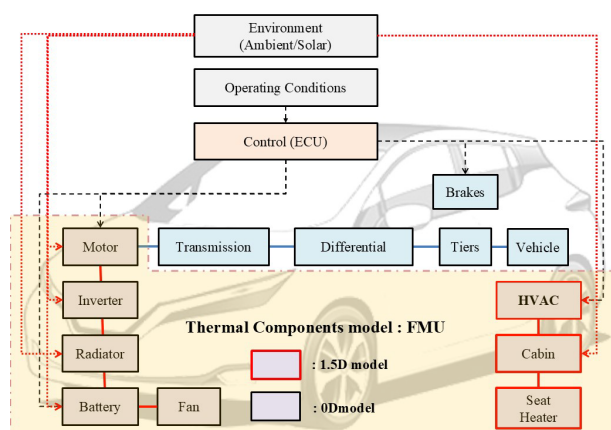


Fig. 1 Block diagram of BEV 0D+1.5D(FMU) model