

An Inverse Design Method Considering Design Constraints for Automotive Aerodynamic Development

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Growing diversity in customer needs has driven demand for accelerated automotive aerodynamic development in recent years. Achieving target aerodynamic performance in automotive development typically requires numerous iterative CFD (Computational Fluid Dynamics) simulations. The number of design iterations required to achieve the target performance has a greater impact on the overall development period than the duration of an individual iteration. Therefore, it is essential to identify promising design directions within design-modifiable regions at an early stage and reduce trial-and-error processes.

To address this issue, we propose a design-knowledge-informed inverse design approach using statistically constrained PCA (Principal Component Analysis) space. Vehicle shapes are first projected onto a PCA space. The PCA model is constructed using a dataset of 180 vehicle designs, and the first 100 PCA components are retained to represent shape variations. A statistically constrained region is then constructed from predefined design datasets. A ridge regression surrogate model is also constructed to predict aerodynamic performance. Candidate shapes are generated by Gaussian sampling around the baseline vehicle within the statistically constrained PCA space. The resulting aerodynamic responses are used to determine promising performance improvement directions for the baseline vehicle. The sampling covariance is defined by the variances of the PCA components derived from the selected design dataset. This allows the shape variability represented in the selected datasets to be reflected in the exploration region around the baseline vehicle. Among the generated candidates, the one with the highest surrogate-predicted aerodynamic performance is selected to determine the improvement direction. Figures 1 and 2 show examples of shape variations generated from the front-bumper and the rear-bumper design datasets, respectively. The upper rows show representative shape variations extracted from each dataset. The lower rows compare the baseline vehicle with the generated shape under design constraints. Shape modifications are limited to the corresponding regions represented in each dataset. This confirms that shape exploration is restricted to the design region defined by the selected dataset. Furthermore, this method combines multiple aerodynamic improvement directions derived from individual design datasets. A genetic algorithm is then used to optimize the weights assigned to each direction. The optimized weights determine the shape with the highest surrogate-predicted aerodynamic performance across multiple design regions. As a result, inverse design can be performed within the range of shape variability represented in the selected datasets. Figure 3 compares the drag coefficients (C_D) of the baseline vehicles (gray bars) and the generated shapes (blue/orange bars). CFD simulations were conducted on 30 SUV and MPV vehicle cases using shapes generated from multiple design datasets. The generated shapes achieved lower C_D than the baseline vehicles in 28 of the 30 cases. The average reduction in C_D was 4.2%.

This method can derive shape modification directions that effectively improve aerodynamic performance. These directions are consistent with the range of shape variability represented in the design datasets. Based on these results, this method has the potential to reduce the number of design iterations required to achieve the target aerodynamic performance, contributing to a shorter development period.

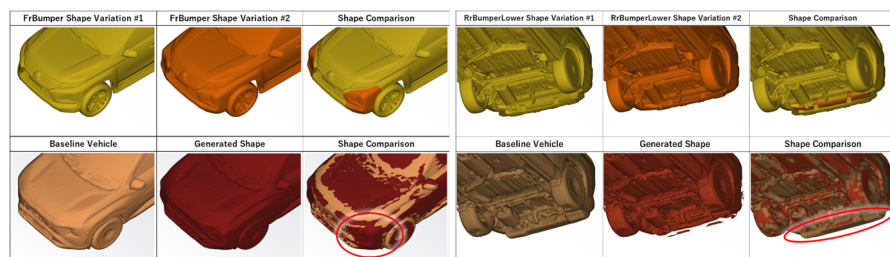


Fig.1 Generated front bumper design around the baseline vehicle

Fig.2 Generated rear bumper design around the baseline vehicle

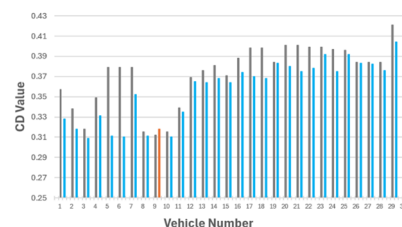


Fig.3 Comparison of C_D values between baseline vehicles and generated shapes