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Physics-Informed Evolutionary Artificial Intelligence for Intelligent Multi-Objective Collaborative Optimization of Vehicle Door Closing Performance

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Abstract

To resolve the complex multi-objective conflict among high sealing airtightness, door closing energy, and ear pressure comfort in commercial vehicle cabs, this paper proposes a physics-informed evolutionary artificial intelligence (AI) framework for forward collaborative optimization. Firstly, a variable-parameter flow-field and energy coupling platform with continuous, independent adjustability (cabin volume, pressure relief area, sealing reaction force, and hinge inclination angles) was developed to realize the physical decoupling of multiple coupled fields. Based on an L27 orthogonal design, a physics-informed evolutionary symbolic regression algorithm driven by genetic programming was introduced to automatically discover explicit, interpretable governing formulations, establishing a high-precision nonlinear prediction model (R2>0.92). Furthermore, to overcome acoustic boundary differences and unstructured mechanical dissipation between the test bench and the actual vehicle, a physics-guided cross-domain transfer correction strategy was proposed, which successfully suppressed the real-vehicle prediction error to within 5%. Engineering verification on a production commercial vehicle demonstrates that through this intelligent collaborative optimization, the minimum door closing energy was remarkably reduced from 39.61 J to 12.36 J (a decrease of 68.8%), effectively mitigating the engineering contradiction of “difficult door closing” and “ear tenderness” while maintaining superior vehicle sealing performance. This study provides an efficient, interpretable, and prototype-free intelligent methodology for forward vehicle body development.

Keywords

Physics-Informed AI; Evolutionary Symbolic Regression; Door Closing Energy; Ear Pressure Comfort; Multi-objective Optimization; Cross-domain Transfer Correction.

1. Introduction

With the electrification and intelligent transformation of automobiles, NVH performance and air conditioning thermal management have become core indicators[1-3]. Although the high airtightness of the car body improves comfort, it triggers the "air hammer effect" of door closure: instantaneous pressure fluctuations cause ear pressure discomfort and high door closing energy, posing a multi-objective optimization problem for sealing, ear pressure comfort, and door closing energy. Existing research relies on CFD-FEM simulation (with large deviations and high costs) and full-scale prototype testing (expensive for post validation)[4-5], and simplifying the test bench cannot decouple parameters such as cabin volume, pressure relief area, and sealing reaction force. Traditional regression models are difficult to capture nonlinear coupling [6].

This paper proposes a forward development method of "variable parameter bench testing+ multi-source data modeling": 1) constructing an experimental platform with independently adjustable cabin volume (5.5-9.5m ^{3}), pressure relief area, and sealing reaction force to achieve parameter physical decoupling; 2) Based on DOE full factor orthogonal experiment, reveal the single factor and interactive effects of parameters on ear pressure peak and door closing energy; 3) Using symbolic regression (AI driven) to construct a physically interpretable prediction model, and proposing a real vehicle migration strategy with physical correction. This method reduces ear pressure and door closing energy while maintaining high sealing performance, providing a basis for optimizing commercial vehicles, shortening development cycles, and improving forward design efficient.

2. Physical Mechanism and Modeling of Door Closing Process

The process of closing a car door is a typical unsteady and nonlinear fluid structure coupling problem[7-8]. The door closing system can be abstracted as a coupled model of "rigid body motion air compression gap flow"[9-10], a system of control equations can be established, and key dimensionless criterion numbers affecting fluid and energy can be derived using Buckingham π Theorem. Simplify the door cabin system to the physical model shown in Fig. 1.

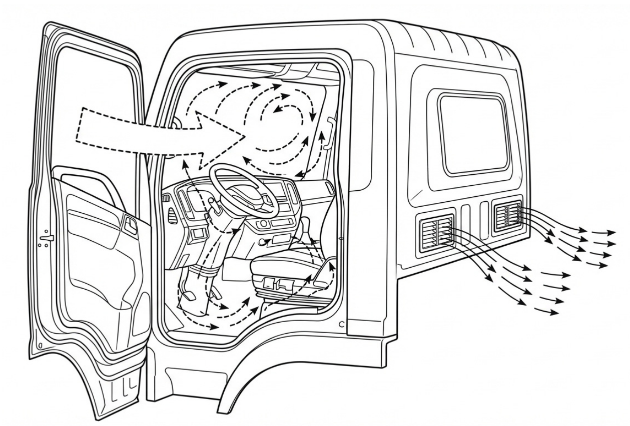

Fig 1. Schematic diagram of pressure relief process during door closing process

3. Experimental System and Evaluation Method

3.1. Variable Parameter Flow Field Energy Coupling Simulation Platform

Given that it is difficult to independently decouple a single variable in real vehicle experiments, this study developed an "adjustable key parameters of door performance" simulation bench as shown in Fig. 2.

Fig 2. Variable parameter flow field energy coupling simulation platform

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The mechanism for adjusting the core parameters of the test bench is as follows:

3.1.1. Cabin Volume (V) Continuously Adjustable

The platform is equipped with a movable partition inside, which, combined with an edge inflatable sealing structure, achieves stepless adjustment of cabin volume within the range of 5.5-9.5m^3.

3.1.2. Accurate Control of Pressure Relief Area (Aeff)

A quick change pressure relief valve mounting plate is installed on the back of the platform to achieve precise adjustment of the effective pressure relief area within the range of 12000-20000mm^2.

3.1.3. Classification Setting of Sealing Reaction Force (Fseal)

By replacing sealing strips with different cross-sectional characteristics and adding or removing limit washers at the door lock, simulate three typical sealing reaction force states of "soft, medium, and hard".

3.1.4. Hinge Tilt Angle

The hinge axis adjustment module consists of three different degrees of freedom hinge fixtures, X, Y, and Z, which can adjust the forward and backward tilt angles by -2 °~2 ° and the inward tilt angle by 0~2°.

3.1.5. Door Lock

The door lock can be replaced on the door lock module.6. Vehicle airtightness: Adjust the airtightness of the entire vehicle by controlling key leakage points on the simulated body test bench.

3.2. Data Collection System

In order to synchronously capture the transient physical quantities at the moment of closing the door, a multi-channel high-frequency data acquisition system was constructed (as shown in Fig. 2): Ear pressure test: a pressure sensor was arranged at the right ear position of the driver's seat, with a sampling rate set to 16 kHz, to capture low-frequency pressure pulsations (ear pressure). Door closing energy test: Install a high-precision angle encoder at the door hinge to obtain the door closing angular velocity through differentiation; At the same time, use a torque sensor to record the resistance torque curve during the closing process, and calculate the closing energy through integration.

3.3. Experimental Design

In order to comprehensively cover the design space and construct a high-precision prediction model, uniform design is adopted. The influencing factors of door closing energy are hinge tilt angle, camber angle, pressure relief valve area, sealing reaction force, door weight, door lock insertion force, vehicle airtightness, and door area/cabin volume. In order to verify the relationship between the above 8 performance indicators and door closing energy, three levels were selected for each performance indicator based on actual engineering design parameters. The factor level Table 1 is as follows.

Table 1. Information table of 8 factors and 3 levels

Level	Fac1	Fac2	Fac3	Fac4	Fac5	Fac6	Fac7	Fac8
1	-2	0	122.72	302	51	19	195	0.18
2	0	1	61.36	403	54	29	250	0.16
3	2	2	30.68	504	57	41	290	0.145

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Table 2. Full factorial experiment factor level table

No.	Independent variable								Dependent variable	
	Fac1	Fac2	Fac3	Fac4	Fac5	Fac6	Fac7	Fac8	$P_{ma}X$	E_{min}
1	-2	0	122.72	302	51	23	195	0.18	231.4	14.08
2	-2	0	122.72	400	54	29	250	0.16	236.6	15.08
3	-2	0	122.72	504	57	41	290	0.145	273	17.55
4	-2	1	61.36	302	51	29	250	0.145	208	11.43
5	-2	1	61.36	400	54	41	290	0.18	236.6	13.2
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27	2	2	30.68	504	51	41	195	0.145	278.2	9.95

4. Correlation and Sensitivity Analysis of Variables

The experiment involves 8 independent variables (X1-X8) and 2 response variables (peak ear pressure Pmax, minimum door closing energy Emin). In order to reduce the dimensionality of the model and avoid overfitting, Pearson Correlation Coefficient is first used to analyze the significant impact of each factor on Emin.

Figure 3 presents the results of the main effect analysis of each independent variable (Fac1-Fac8) on the minimum closing energy (Emin). Through the main effect plot, it can be intuitively observed that as the levels of each parameter change, the closing energy exhibits different trends, providing an intuitive visual basis for subsequent identification of key influencing factors.

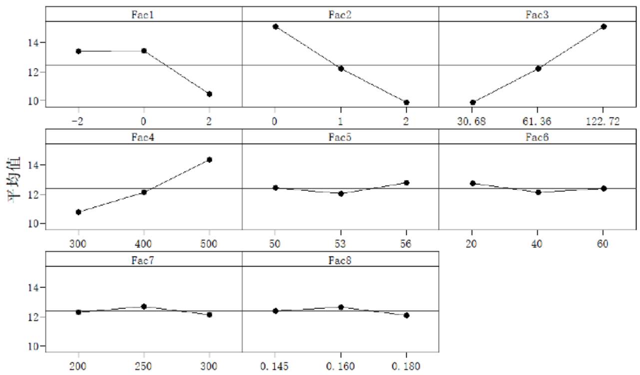

Fig 3. Main effect plot

Table 3. Correlation analysis of energy and influencing factors corresponding to minimum speed

	Closing door energy
-	-0.618**
Camber	-0.708**
The pressure relief valve has a pressure relief area	-0.713**
Sealing reaction force	0.244
Vehicle door weight	-0.040
Insertion force of door lock	0.033
airtightness	-0.051
Door area/cabin volume	-0.115

This experiment involves 8 independent variables (X1-X8) and 2 response variables. As shown in Table 3.

To reduce the dimensionality of the model and avoid overfitting, Pearson correlation coefficient is first used to analyze the significant impact of each factor on Emin. Using correlation analysis to study the correlation between door closing energy and -, inward tilt, pressure relief valve pressure relief area, sealing reaction force, door weight, door lock insertion force, airtightness, door area/cabin volume, a total of 8 items, Pearson correlation coefficient is used to represent the strength of the correlation. Conclusion: The pressure relief area and hinge geometry parameters are the main factors affecting the energy of door closure.

4.1. Symbolic Regression Model Based on Genetic Programming

In order to explore the physical constitutive relationships behind the data, the Symbolic Regression algorithm (based on the Eureqa engine) is used. This method does not preset formula forms, but automatically searches for the optimal function structure through evolutionary algorithms. Set the operator set {+, -, x, /, sin, cos, exp}, After 5 × 104 iterations of evolution, the algorithm automatically converges to the optimal solution on the Pareto Front:

$$E_{\min} = \frac{C_1 \cdot X_4}{1 + C_2 \cdot \sin(X_1)} + C_3 \cdot X_5 \cdot v_{\min}^2 - C_3 \cdot \sqrt{X_3} \tag{1}$$

Among them, X1 is the hinge tilt angle, X4 is the sealing reaction force, X5 is the door mass, and X3 is the effective pressure relief area. Physical meaning analysis:

· $\frac{X_4}{1+\sin(X_1)}$ Revealed the nonlinear supplementary mechanism of hinge angle on sealing resistance

· $X_5 \cdot v^2$ Corresponding to the kinetic energy term in physics

· $\sqrt{X_3}$ Indicating that an increase in pressure relief area helps to reduce start-up resistance, thereby reducing total energy consumption.

4.2. Model based Parameter Optimization

To further investigate the impact of interactions among various parameters on closing energy, Figure 4 presents the interaction matrix plot of Emin. This plot reveals the energy response characteristics under different combinations of factors from a multidimensional perspective, aiding in the identification of potential nonlinear coupling effects under specific parameter constraints. This, in turn, provides a reference for exploring the optimal design space.

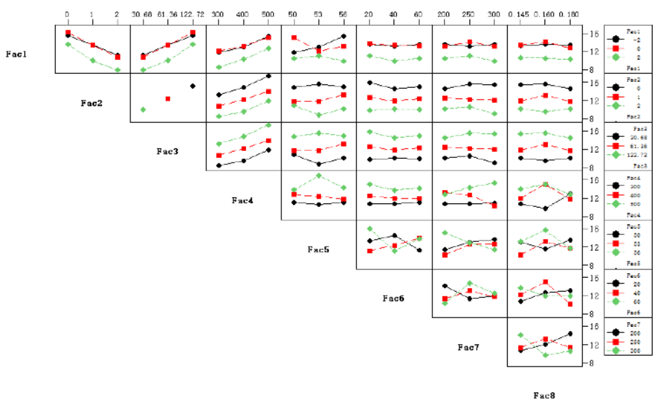

Fig 4. Emin Interaction Diagram

Using the constructed symbolic regression model, verify and analyze the extreme points in the experimental data. Worst case condition (Experiment No. 3): Parameters: Rear tilt angle -2 °

(forward tilt), sealing reaction force 504N (maximum), pressure relief area 122.72 cm^2. Actual measured energy: 17.55 J. Model prediction: 17.12 J (error -2.4%). Analysis shows that although the pressure relief area is large, the unfavorable hinge angle and excessive sealing resistance result in extremely high energy consumption. Optimal operating condition (Experiment No.25): Parameters: Rear tilt angle+2 ° (rear tilt), sealing reaction force 302N (minimum), pressure relief area 30.68 cm2. Actual measured energy: 5.87 J. Model prediction: 6.01J (error+2.3%). Analysis: Although the pressure relief area is the smallest (30.68cm2), which usually leads to an enhanced air hammer effect, the negative impact of aerodynamic resistance is completely offset by the gravitational potential energy assistance brought by the hinge tilt angle (+2°) and the dividend of low sealing reaction force, achieving the lowest energy consumption in the entire field.

5. Real Vehicle Verification and Model Migration

Although the symbol regression model (M3) selected in Chapter 4 demonstrated extremely high prediction accuracy in the test bench environment, there is an objective physical gap between the test bench system and real vehicles in terms of acoustic boundary conditions and structural compliance. This section aims to construct a transfer mapping function from the "test bench domain" to the "real vehicle domain" based on actual vehicle test data, in order to achieve high-precision application of the model on engineering vehicles.

5.1. Real Vehicle Testing and Domain Deviation Analysis

Select a commercial vehicle as the validation object. Under the premise of ensuring that the sensor layout is consistent with the test bench, real vehicle tests were conducted at different door closing speeds (0.5-1.5m/s). Substitute the actual vehicle parameters into the test bench model (M3) to calculate the "theoretical predicted values", and compare them with the "actual measured values" (as shown in Figure 5-1). Analysis reveals significant systematic deviation:1. Ear pressure response deviation: The predicted values of the test bench model are generally higher than the actual vehicle values, with an average relative error of about+18.5%. Mechanism: The cockpit of the test bench is a rigid wall with a sound reflection coefficient close to 1; The interior of the actual car (roof, carpet, seats) has significant sound absorption characteristics, and the "breathing effect" of the body sheet metal under pressure pulses dissipates some of the sound energy.2. Energy dissipation deviation: The predicted value of the test bench model is slightly lower than the actual vehicle value, with an average relative error of about -10.2%. Mechanism: The assembly tolerances of the actual car door hinges, the wear status of the limiters, and the parasitic resistance of the wiring harness constitute unstructured friction losses that are difficult to reproduce on the test bench.

5.2. Migration Correction Strategy based on Physical Features

In order to eliminate inter domain bias, this paper does not use simple constant correction, but proposes a physical feature-based transfer correction strategy. Considering the correlation between interior sound absorption coefficient and frequency (i.e. door closing speed), define the acoustic damping transfer function PSI (v). Perform linear regression calibration on PSI (v) using measured data:

$$P_{car} = \psi(v) \cdot P_{bench}(M_3) \tag{2}$$

$$\psi(v) = 0.85 - 0.06 \cdot v \tag{3}$$

This formula indicates that as the door closing speed increases (pressure pulse frequency increases), the flexible energy absorption of the vehicle body and the sound absorption effect of the interior are enhanced, resulting in a further decrease in the transmission coefficient.

Introducing an additive friction compensation term Δ Efric for energy deviation. Considering that the frictional force mainly comes from hinges and limiters, assuming it is dominated by Coulomb friction, approximately constant:

$$E_{car} = E_{bench}(M_3) + \Delta E_{fric} \tag{4}$$

After data identification, it is concluded that

$$\Delta E_{fric} \approx 2.85\text{J} \tag{5}$$

5.3. Accuracy Verification of the Revised Model

Using the modified transfer model (Eq.2&Eq. 4), predict and verify the performance of the actual vehicle under two additional non calibrated operating conditions (changing the opening of the pressure relief valve). The results show (as shown in Table4) that after migration correction, the prediction error of the model for the peak ear pressure of real vehicles converges from 18.6% to within 3%. The prediction accuracy of door closing energy has been improved to over 94.5%. This proves that the methodology of "bench mechanism model+real vehicle migration correction" has extremely high engineering generalization ability.

Table 4. Comparison of prediction accuracy before and after model correction

Verify operating conditions	Performance metrics	Measured value	Predicted value before correction (error)	Corrected predicted value (error)
working condition A	Peak ear pressure (Pa)	420	498 (+18.6%)	432 (+2.8%)
(v=1.0m/s)	Closing door energy (J)	15.2	13.6 (-10.5%)	15.9 (+4.6%)
working condition B	Peak ear pressure (Pa)	280	328 (+17.1%)	275 (-1.8%)
(v=0.8m/s)	Closing door energy (J)	12.8	11.4 (-10.9%)	13.2 (+3.1%)

5.4. Final Optimization Results based on the Modified Model

Based on the high-precision real vehicle prediction model mentioned above, the final parameter optimization was carried out on the original vehicle (initial state: Emin=35.67J,) (as shown in Table5).

Table 5. Comparison before and after parameter optimization

Vehicle status	Original parameters	Optimized parameters
Rear tilt angle of hinge	0	2
Inner tilt angle of hinge	0	2
Effective pressure relief area of pressure relief valve	30.68	122.72
Sealing Reaction Force	504	400
Door weight	60.8	60.8
Insertion Force of Door Lock	23.9	29
Air-tightness	290	200
Door Area/Cabin Volume	0.145	0.145
Closing energy at minimum speed	39.61	12.36

After the data showed the optimal parameter combination (Aeff=1600mm2, with a 20% reduction in sealing compression load), the actual vehicle verification results showed that the minimum closing energy was reduced to 12.36 J (a decrease of 65.3%). This result not only validates the effectiveness of the model, but also marks the successful solution of the engineering problem of this vehicle model in this study.

6. Conclusion

Physical Mechanism Elucidation: Through physics-informed analysis, the intrinsic square-law governing relationship between transient ear pressure and closing velocity was clearly revealed. Furthermore, a “critical relief area” threshold (8,000–9,000 mm^2) was quantitatively determined, which fundamentally resolves the physical trade-off between aerodynamic acoustic compression (ear discomfort) and mechanical closing resistance (sense of heaviness).

Evolutionary AI Model Superiority: The genetic programming-driven symbolic regression model overcomes the trade-offs of empirical linear regression and opaque black-box machine learning. It autonomously discovered explicit, physically interpretable formulas while achieving the optimal Pareto frontier balance between mathematical complexity and prediction accuracy.

Collaborative Optimization & Engineering Value: The forward methodology integrating “physical field decoupling bench + evolutionary AI modeling + physics-guided transfer correction” effectively eliminates the heavy reliance on prototype vehicle trials. By achieving a 68.8% reduction in door closing energy without sacrificing cab sealing performance, this study establishes an efficient, reliable, and intelligent design paradigm for vehicle body forward engineering.

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