

Active Aerodynamic Designs in Automobiles

Yuming Wang

Chongqing DEPU Foreign Language School, Chongqing, China

a1332871531@outlook.com

Abstract. Faced with pressures from environmental regulations and consumer demands for efficiency and performance, active aerodynamics has become a core technology for optimizing vehicle performance. This paper examines the technical system of automotive active aerodynamics, focusing on dynamic adjustable components, integration with energy recovery systems, and intelligent control algorithms. Dynamic adjustable components including diffusers, active grilles, and active spoilers, achieve real-time aerodynamic optimization through multi-mode adjustments. The integration of active aerodynamics with energy recovery systems breaks traditional design limitations. It reduces energy consumption of electrified vehicles via high-speed drag reduction and maintains battery/motor temperature stability through targeted airflow control, reducing efficiency loss caused by extreme temperatures. Additionally, multi-source sensor data fusion solving single-sensor limitations and deep learning-based short-term condition prediction (e.g., LSTM and CNN-LSTM models) upgrade aerodynamic systems from “passive response” to “proactive adjustment”, enhancing control precision.

Keywords: Active Aerodynamic Designs, Dynamic Adjustable Components, Energy Recovery System, Intelligent Control Algorithms.

1. Introduction

In the contemporary automotive industry, the dual pressures of environmental regulations and consumer expectations have driven a paradigm shift toward technologies that enhance both efficiency and performance. Active aerodynamics, defined as the real-time adjustment of vehicle components to modulate airflow [1], has emerged as a critical solution to reconcile these often-conflicting demands. Unlike passive aerodynamic designs, which remain fixed, active systems adapt to dynamic driving conditions—such as speed, acceleration, and terrain—thereby optimizing aerodynamic performance across diverse scenarios.

Dynamic adjustable components form the core of active aerodynamic systems, with diffusers, active grilles, and active spoilers each contributing uniquely to airflow management. Diffusers, located at the vehicle’s rear underbody, accelerate airflow exit to reduce pressure drag and generate downforce, a function particularly valuable in high-speed cornering. Active grilles, positioned at the front fascia, regulate air intake into the engine bay: closing at high speeds to minimize drag and opening under low-speed or high-load conditions to ensure adequate cooling [2]. Active spoilers, mounted on the rear decklid or roof, adjust their angle or position to balance downforce (for stability) and drag reduction (for efficiency) [3].

The integration of active aerodynamics with energy recovery systems represents a frontier in sustainable mobility. In hybrid and electric vehicles, where energy efficiency is paramount, aerodynamic adjustments can complement brake energy recovery (BER) systems. For instance, reducing drag during steady cruising directly lowers energy consumption, while strategic downforce generation during braking can enhance tire grip, improving BER efficiency [4]. However, this integration poses significant challenges, including the need for seamless communication between aerodynamic control modules and energy management systems, as well as the mitigation of weight and cost penalties associated with additional hardware.

Thermal management, often overlooked in aerodynamic studies, plays a pivotal role in maintaining energy recovery efficiency. Batteries and electric motors in electrified vehicles are sensitive to temperature fluctuations; thus, aerodynamic designs must not only reduce drag but also channel airflow to critical components, ensuring optimal operating temperatures. This dual function—drag

reduction and thermal regulation—requires sophisticated design trade-offs, such as optimizing vent positions and duct geometries to balance conflicting demands [5].

Real-time control algorithms are the key factors enabling effective active aerodynamics. These systems rely on multi-source sensor data fusion, integrating inputs from speedometers, accelerometers, steering angle sensors, and even cameras or LiDAR for environmental awareness. By processing the data, the algorithms can accurately recognize driving conditions, such as highway cruising versus urban stop-and-go traffic. Furthermore, deep learning techniques have enabled short-term condition prediction, allowing aerodynamic components to pre-adjust before a maneuver—such as extending a spoiler in anticipation of a sharp turn—thereby enhancing responsiveness and effectiveness [6].

This review synthesizes current research on active aerodynamic technologies, with a focus on dynamic adjustable components, integration with energy recovery systems, and control algorithms. By examining key advancements, practical challenges, and performance metrics, this paper aims to provide a comprehensive overview for researchers and engineers. Ultimately, it seeks to highlight pathways toward more efficient, safe, and sustainable vehicles through the advancement of active aerodynamics.

2. Dynamic Adjustable Components

Dynamic adjustable components are core modules of active aerodynamic systems, which realize real-time optimization of vehicle aerodynamic performance by changing structural parameters according to driving conditions. Typical components include diffusers, active grilles, and active spoilers [7].

2.1. Diffusers

Diffuser is usually located at the rear part of the vehicle chassis, its core mechanism based on Bernoulli's principle:

$$P + \frac{1}{2}\rho v^2 = C \quad (1)$$

Where P is static pressure, ρ is air density, and v is airflow velocity.

When the vehicle is moving forward, air flows from the front end of the chassis. Since the clearance between the chassis and the ground is small, the compressed airflow increases in speed and decreases in pressure. The inlet of the diffuser is of the convergent type, which efficiently collects high-speed and low-pressure airflow. Then, the airflow enters a diverging channel. Downforce generated by diffuser can be simplified computed as follows:

$$F = \rho v^2 C_d A \quad (2)$$

Where F_d is downforce, C_d is the diffuser's downforce coefficient, and A is the effective cross-sectional area of the diffuser.

As the cross-sectional area of the channel increases, airflow velocity decreases while static pressure rises, achieving two key effects: (1) The underbody downforce is primarily generated by a suction region formed via the Venturi effect—a phenomenon that is significantly enhanced when a diffuser is incorporated. This airflow behavior is analogous to the fluid movement through a narrowed tube, as illustrated in Fig. 1. Essentially, the diffuser functions to restore the low air pressure beneath the vehicle to the ambient atmospheric pressure [8]; (2) Minimizing airflow stagnation at the rear underbody, reducing wake drag and optimizing the overall aerodynamic performance [9].

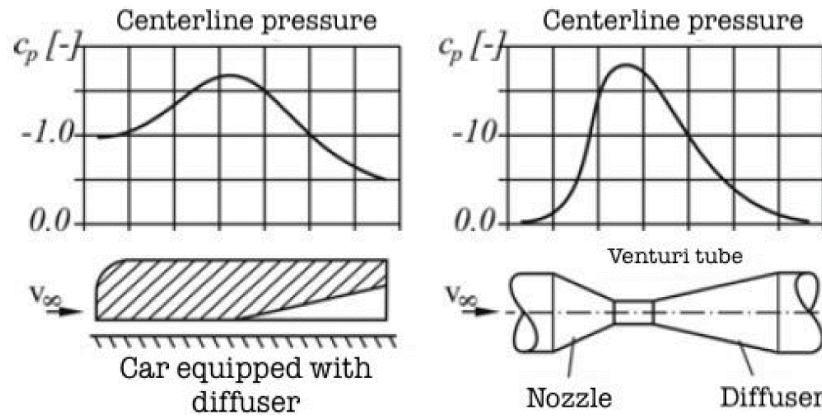


Figure 1. Pressure distribution along the centerline of a generic body of car with an underbody diffuser and a Venturi tube [8]

Active diffusers adopt multiple adjustment methods to adapt to different working conditions, with specific parameters and effects shown in Table 1.

Table 1. Adjustment Modes and Performance Effects of Active Diffusers

Adjustment Mode	Implementation Method	Applicable Scenarios	Performance Effects	Reference
Inlet Angle Adjustment	Motor/hydraulic actuator drives the deflector to change the inlet divergence angle	High-speed cruising ($120+$ km/h), cornering	- High-speed: Angle reduced by 5° – 10° , C_d decreased by 0.01–0.03 - Cornering: Angle increased by 15° – 25° , downforce enhanced by 20%–40%	[10]
Ground Clearance Adjustment	Linked with air suspension to adjust the distance between diffuser and ground	High-speed (≥ 100 km/h), low-speed (≤ 40 km/h)	- High-speed: Clearance reduced by 30–50 mm, downforce increased by 15%–25% - Low-speed: Clearance increased by 20–40 mm, avoiding ground scraping	[10]
Outlet Area Adjustment	Telescopic baffles at the outlet change the effective area of airflow discharge	BEV fast charging, high-speed cruising	- Fast charging: Area increased by 20%–30%, cooling efficiency enhanced by 15%–20% - High-speed: Area reduced by 10%–15%, wake drag decreased by 8%–12%	[11]
Synergy with Other Components	Coordinated adjustment with active spoilers (e.g., spoiler angle increases with diffuser angle)	Extreme handling (track cornering)	Downforce distribution optimized, lateral stability improved by 10%–15%	[8]

2.2. Active Grilles

Active grilles are consisting of grating blades, drive mechanism (electric motor/hydraulic device), seals and control system. The blades are mostly arranged horizontally or vertically and are installed in the grille area of the vehicle's front. The function of grilles is that their opening/closing or angle

adjustment directly regulates the airflow into the engine compartment or battery pack. The seals reduce air leakage, optimizing the efficiency of aerodynamics and thermal management [12].

The control logic of active grilles relies on multi-sensor data fusion, with decision-making rules based on vehicle speed, component temperature, and load. Table 2 summarizes the key control strategies and triggering conditions.

Table 2. Active Grilles - Control Logic

Working Condition	Triggering Conditions	Blade State	Control Objectives	Reference
High-speed Cruising	Speed ≥ 100 km/h, engine/battery temperature $\leq 80^{\circ}\text{C}$ (ICE)/ 35°C (BEV)	Fully closed ($\geq 90\%$ closure rate)	Reduce aerodynamic drag, C_d decreased by 0.02–0.04, fuel consumption reduced by 1.7%–2.4%	[13]
High-load Heat Dissipation	Engine load $\geq 70\%$ (ICE), BEV fast charging (current ≥ 100 A), component temperature $\geq 95^{\circ}\text{C}$ (ICE)/ 45°C (BEV)	Fully open ($\geq 85\%$ opening rate)	Maximize airflow, cooling efficiency improved by 25%–35%, preventing overheating	[13]
Cold Start	Ambient temperature $\leq 5^{\circ}\text{C}$, engine/battery temperature $\leq 40^{\circ}\text{C}$	Fully closed (0% opening rate)	Retain heat, shorten engine warm-up time by 30%–40%, battery warm-up time by 20%–30%	[13]
Urban Low-speed Driving	Speed ≤ 60 km/h, engine/battery temperature 60°C – 85°C (ICE)/ 25°C – 40°C (BEV)	Partially open (30%–50% opening rate)	Balance heat dissipation and drag reduction, avoiding unnecessary energy loss	[13]

2.3. Active Spoilers

Active spoilers are classified into three types based on structural characteristics, with distinct designs and application scenarios in Table 3. Their adjustment mechanism relies on real-time data from multiple sensors (speed, steering angle, brake pressure, yaw rate) and the vehicle control unit (VCU) to implement dynamic control.

Table 3. Classification and Characteristics of Active Spoilers

Type	Structural Design	Key Features	Typical Models
Retractable Active Spoiler	Fully retracts into the trunk/roof at low speed; horizontally/vertically at high speed	For Low-speed, no impact on vehicle streamlines For High-speed, fast response(0.5-1.0s extension time)	Porsche 911 Turbo S, Mercedes- AMG GT
Angle-Adjustable Active Spoiler	Fixed main body, motor drives blades to rotate (adjustment range: 0° – 45°)	Precise angle control (adjustment accuracy: $\pm 1^{\circ}$) Adaptable to multi-scenarios (crusing, cornering)	Tesla Model S, BMW M3 Competition

Multi-stage Active spoiler	2-3 sets of independent blades, each adjustable in angle/extension length	Optimizes airflow separation and downforce distribution) Suitable for extreme handling (high-speed cornering)	Lamborghini Aventador SVJ, Ferrari SF90 Stradale
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The VCU determines the adjustment strategy based on driving conditions:

(1) For high-speed cruising (≥ 120 km/h, no aggressive maneuvering): Spoiler angle adjusted to 5° – 10° or retracted, reducing drag by 8%–12%;

(2) Cornering (steering angle $\geq 15^\circ$, yaw rate $\geq 5^\circ/\text{s}$): Angle increased to 25° – 45° , downforce enhanced by 30%–50%, improving tire grip;

(3) Emergency braking (brake pressure ≥ 800 kPa): Angle rapidly increased to the maximum (40° – 45°), shortening the 100–0 km/h braking distance by 1–2 meters (Porsche Engineering Report, 2021).

Some high-end models (e.g., Audi RS e-tron GT) integrate navigation data to predict road conditions (e.g., upcoming corners) and adjust the spoiler in advance, reducing the response delay to 100–200 ms and further enhancing handling stability.

The Bugatti Veyron stands as a contemporary benchmark for high-performance road cars, distinguished by its multifaceted approach to aerodynamic optimization. Its design encompasses not only movable aerodynamic elements but also active suspension systems that enable precise adjustments to ground clearance and body pitch, facilitating dynamic control over the vehicle's aerodynamic interaction with the road surface [7]. Furthermore, the rear spoiler is engineered with an auxiliary aerodynamic braking function, which is engaged automatically at velocities exceeding 200 km/h. When the brake pedal is depressed, the spoiler rapidly elevates and articulates to a 55-degree angle within a timeframe of 0.4 seconds (Fig. 2).

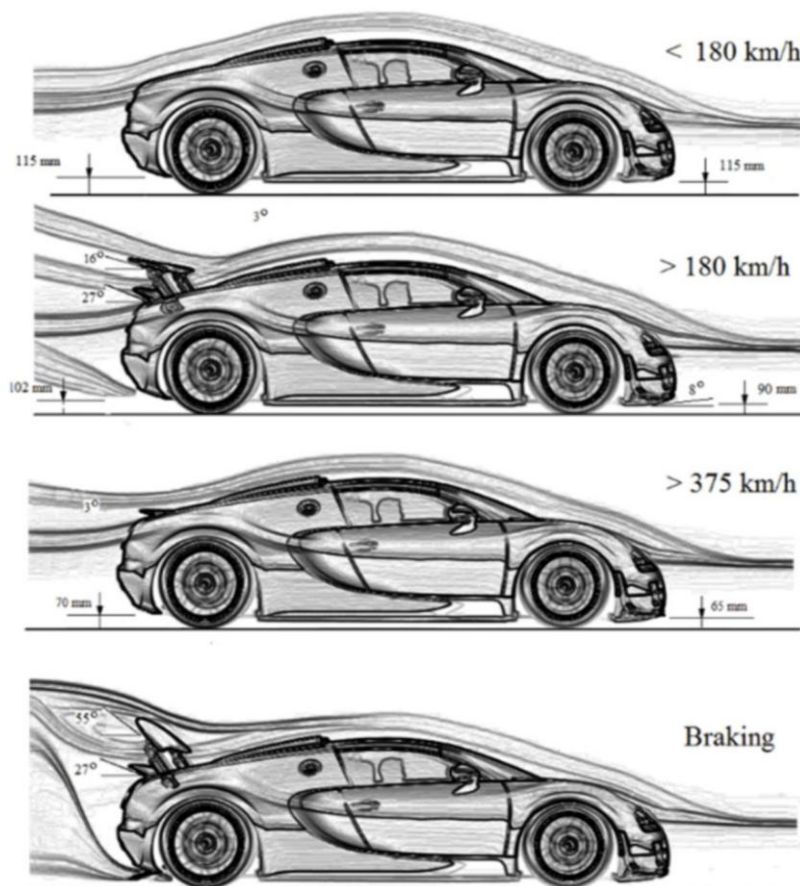


Figure 2. Bugatti Veyron operation modes [7]

3. Integration of Energy Recovery with Aerodynamic Systems

3.1. Optimization of Aerodynamic Drag Reduction and Braking Energy Recovery

The principle of collaborative optimization lies in dynamically adjusting aerodynamic drag reduction and braking energy recovery based on the real-time operating conditions of the vehicle. During the braking phase, active aerodynamic components play a critical role. The active rear wing increases the angle of attack, and the diffuser expands its diffusion degree, both of which can generate additional aerodynamic braking force. According to the research findings in reference [14], when a specific type of vehicle is in the braking phase, an additional 10% to 20% of braking force can be obtained through the reasonable adjustment of aerodynamic components. This alleviates the load of mechanical braking to a certain extent, reduces the kinetic energy lost as heat energy during the braking process, and thereby creates conditions for the efficient operation of the braking energy recovery system.

However, under working conditions such as high-speed cruising without braking, operations like the closure of active grilles and retraction of the rear wing can effectively reduce the aerodynamic drag when the vehicle is moving, thereby cutting down on energy consumption. When the aerodynamic drag of a moving vehicle:

$$F_d = \frac{1}{2} \rho v^2 C_d A \quad (3)$$

Where F_d is aerodynamic drag, C_d is the aerodynamic drag coefficient of the car, A is vehicle's frontal area, ρ is air density, and v is airflow velocity.

As the aerodynamic drag be reduced, the vehicle's energy consumption decreases accordingly. This indirectly supports the energy recovery system and alleviates the subsequent energy replenishment pressure on it.

This relationship between drag and energy consumption is supported by industry data: for battery electric vehicles (BEVs), a 0.01 reduction in C_d typically lowers energy consumption by 2%-3% under steady high-speed cruising [10]. Critically, the synergy relies on real-time control synchronization—vehicle control units (VCUs) integrate brake pressure and speed sensor data to adjust aerodynamic components (e.g., rear wing angle) and regenerative torque simultaneously, with a response delay controlled [15]. For mass-produced models like the Tesla Model S, this synergy reduces highway energy consumption by 4.5% compared to passive aerodynamics.

For example, Mercedes-Benz presented the Concept Intelligent Aerodynamic Automobile (Concept IAA). With all the active features enabled, the drag coefficient drops from 0.25 to 0.19.

3.2. Thermal Management Aerodynamic Design for Energy Recovery Efficiency

Energy recovery systems (brake energy recovery, battery storage) depend on stable temperatures: lithium-ion batteries lose 10%-30% recovery efficiency at $<0^\circ\text{C}$ or $>45^\circ\text{C}$, while PMSM motors see conversion rate drops at $>120^\circ\text{C}$. Active aerodynamics balances two goals—reducing drag and guiding airflow for thermal regulation—to stabilize recovery efficiency.

Component-specific airflow control is key to balancing heat dissipation needs and aerodynamic performance. For battery packs, adjustable underbody diffusers activate during high-speed driving or fast charging, guiding airflow through cold plates to lower battery temperature. In low-temperature environments, front aerodynamic baffles close to trap hot air from motor radiators, reducing battery warm-up time [16]. For motors and inverters, under high-load conditions, active grilles open to a specific angle and wheel arch vents adjust its angles—this synergy lowers inverter temperature [18].

To resolve the conflict between "drag reduction" and "heat dissipation," condition-based adjustment strategies are adopted (Table 4).

Table 4. Condition-based Aerodynamic Adjustment Strategy [17]

Operating Condition	Aerodynamic Component State	Regulation Target
High-speed Cruising	Active grille opening: 10%–20%; Wheel arch vent angle: 5°–10°; Underbody diffuser: Retracted	Aerodynamic drag coefficient (C_d) reduction: 0.015–0.02; Battery temp stability: 25°C–35°C
Fast Charging	Active grille opening: 85%–95%; Wheel arch vent angle: 25°–30°; Underbody diffuser: Fully open	Battery cooling efficiency improvement: 40%–50%; Charging temp control: $\leq 45^\circ\text{C}$
Low Temperature ($<5^\circ\text{C}$)	Active grille opening: 0% (fully closed); Wheel arch vent angle: 0° (fully closed); Front aerodynamic baffle: Closed	Battery warm-up time reduction: 30%; Motor heat retention rate: $\geq 80\%$

The practical value of this thermal-aerodynamic design has been validated in real-world mass-produced vehicles. Take the Tesla Model 3, for instance: its integrated system, combining active grilles with underbody air deflectors, keeps battery temperature fluctuations within the 28°C–35°C range during the NEDC cycle. This translates to an energy recovery efficiency that is 8%–10% higher than that of BEVs relying on conventional passive heat dissipation methods [18].

4. Control Algorithms

4.1. Multi-source Sensor Data Fusion and Dynamic Working Condition Identification

Multi-source sensor data fusion integrates inputs from speedometers, brake pressure sensors, battery thermometers, and airflow meters. This fusion solves "single-sensor limitations"—e.g., a speedometer alone cannot distinguish "high-speed cruising" from "high-speed braking"—while dynamic working condition identification classifies scenarios in real time (Table 5). Together, they enable accurate adjustment of aerodynamic components and energy recovery systems [19].

To translate the functional value of multi-source sensor data fusion into practical application, its technical implementation follows a hierarchical framework, specifically categorized as the following Data Fusion Methods [20]: (1) Level 1 (Data Preprocessing): Filters noise via Kalman filtering (e.g., reduces speed sensor fluctuations from ± 3 km/h to ± 0.5 km/h); (2) Level 2 (Feature Fusion): Fuses "speed + brake pressure" to judge braking intensity—e.g., speed ≥ 100 km/h + brake pressure ≥ 500 kPa = "high-speed emergency braking".

Table 5. Dynamic Working Condition Classification for BEVs [21]

Working Condition	Sensor Threshold Combination	Identification Goal
Urban Low-Speed Driving	Speed: ≤ 60 km/h; Brake frequency: ≥ 3 times/min; Battery temp: 25°C–35°C; Airflow rate: ≤ 5 m ³ /s	Trigger partial opening of active grilles (40%–50%) to balance cooling and low-speed drag reduction
Highway Cruising	Speed: 90–120 km/h; Brake frequency: ≤ 1 time/5 min; Battery temp: 30°C–40°C; Airflow rate: 8–12 m ³ /s	Close active grilles (10%–20%) to minimize drag coefficient (C_d) and stabilize energy recovery
High-Speed Emergency Braking	Speed: ≥ 100 km/h; Brake pressure: ≥ 500 kPa; Motor speed: ≥ 3000 rpm; Battery temp: $\leq 42^\circ\text{C}$	Open rear aerodynamic vents (80%–90%) to enhance heat dissipation during intense energy recovery
Fast Charging	Speed: 0 km/h (parked); Charging current: ≥ 150 A; Battery temp: 35°C–45°C; Airflow rate: 10–15 m ³ /s	Fully open active grilles (90%–100%) to cool battery pack and prevent overheating-induced recovery efficiency loss

For example, Tesla Model Y uses 12+ fused sensors: it identifies "high-speed cruising" (speed ≥ 110 km/h + battery temp 30°C – 38°C) in 0.3s, triggering active grille closure (opening 15%) to cut drag. For "urban stop-and-go" (speed ≤ 60 km/h + brake frequency ≥ 2 times/min), it keeps grilles partially open (40%) to balance cooling and efficiency, improving energy recovery stability by 6%–8%.

4.2. Short-term Working Condition Prediction Based on Deep Learning

Short-term working condition prediction—covering a 10–60 second time horizon—tackles the “delayed adjustment” issue that plagues aerodynamic components. Take a practical scenario: if we can forecast an upcoming highway cruising phase 30 seconds in advance, active grille shutters can be pre-adjusted from a 40% opening to just 15%. This proactive tweak avoids the unnecessary drag loss that would otherwise occur if the shutters closed too late. To enable such predictions, deep learning (DL) models—such as long short-term memory (LSTM) networks and hybrid CNN-LSTM architectures—leverage patterns gleaned from historical sensor data [22]. A visual breakdown of this process is provided in Fig. 3, which outlines the DL-based workflow for predicting battery electric vehicle (BEV) working conditions.

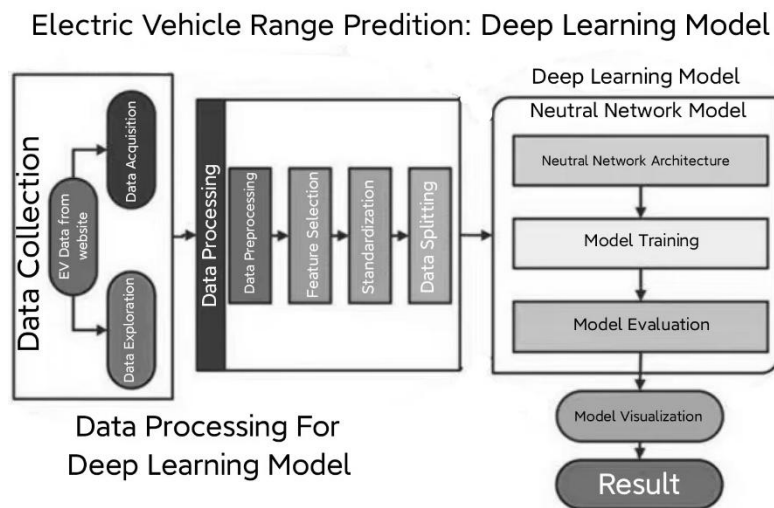


Figure 3. DL prediction workflow for BEV conditions

For BEV working condition prediction model selection, alignment with core requirements is essential: accurately capturing time-series patterns (e.g., vehicle speed, battery temperature) and accounting for multi-dimensional correlations from sensor spatial distribution. Therefore, mainstream solutions center on two deep learning models.

The Long Short-Term Memory (LSTM) network, leveraging its strong fitting capability for time-series data, serves as the fundamental choice for processing single-dimensional time-series. It can stably achieve a prediction accuracy of over 85% for working conditions 30 seconds ahead, thereby meeting the pre-judgment needs of most regular driving scenarios [23]. In contrast, the CNN-LSTM (Convolutional Neural Network-LSTM) model extracts spatial features related to sensor positions through convolutional layers, and then combines with LSTM layers to process time-series information, enabling "spatial-temporal" dual-dimensional data fusion. Compared with the single LSTM model, it further reduces prediction errors and improves accuracy by 5%–8%, making it more suitable for scenarios with complex sensor layouts and frequent working condition switches (e.g., alternating driving between urban roads and highways) [24].

5. Conclusion

This review conducts a comprehensive overview of active aerodynamic technologies in automobiles, clearly presenting the complete technical context from core components and system collaboration to intelligent control. Dynamic adjustable components are the key carrier for

implementation. It achieves aerodynamic performance optimization of vehicles in scenarios such as high-speed cruising for drag reduction and intense handling for stability enhancement. This is accomplished through the diffuser's precise regulation of downforce and wake drag, the active grille's adaptive opening and closing under different working conditions, and the active spoiler's millisecond-level angle response, with their design fully adapting to the complex needs of dynamic vehicle driving. The integration of active aerodynamics and energy recovery systems breaks the single dimension of traditional design: it not only reduces energy consumption of electric-driven vehicles through high-speed drag reduction but also ensures the temperature stability of batteries and motors via directional airflow regulation, effectively alleviating the attenuation of energy recovery efficiency under extreme temperatures. Moreover, the application of multi-source sensor fusion and deep learning prediction algorithms upgrades aerodynamic components from passive response to forward-prediction adjustment, significantly improving system adaptation accuracy.

In the future, this field needs to focus on overcoming bottlenecks in hardware light weighting and cost control, and further enhance the precision of multi-system collaborative control. With the maturity of intelligent driving technology, integrating active aerodynamic systems with environmental perception and path planning will surely realize dynamic optimization of full-scenario aerodynamic strategies, continuously promoting the automotive industry toward high efficiency, low carbon, and intelligence, and providing core technical support for the high-performance and sustainable development of next-generation vehicles.

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