Review of state of the art in active aerodynamic control research for vehicles

Wei Gao, Xinxin Kong, Zhaowen Deng*, Wei Yu, Yongxing Wu, Jintao Luo

Key Laboratory of Automotive Power Train and Electronic Control
School of automotive engineering, Hubei University of Automotive Technology, Shiyan, China

*Corresponding author e-mail: dengzw_qc@huat.edu.cn

Abstract. Various active safety systems have been developed and applied to improve the driving safety of road vehicles under emergency scenarios. However, the functions of these active safety systems are limited due to the forces saturation between the tires and the road under high lateral accelerations or on low adhesion roads. To further enhance the safety of high-speed vehicles, the active aerodynamic control system was proposed and studied by engineers and researchers. An overview of the state of the art and present status of active aerodynamic control research for vehicles is presented in this paper. The influence of the active aerodynamic control on the dynamic properties of road vehicles, vehicle models used for active aerodynamic control systems, the control system and controller are summarized in this paper. The future research efforts are discussed. The paper is to provide some guidance for the further investigations of the active aerodynamic control system.

1. Introduction

This report, Global Status Report on Road Safety 2018 shows that the road traffic accidents cause the deaths of 1.35 million every year [1]. Most of the severe accidents are caused by the driver losing control of the car [2]. With the rapid development of the automotive technology, a variety of active safety systems have been designed to keep the car under control especially under emergency manoeuvre and improve the safety of road vehicles. These active safety systems include active front steering (AFS) [3], active rear steering [4], torque vectoring [5], differential braking [6], direct yaw-moment control (DYC) [7, 8, 9], active camber control [10], etc. Essentially, these active safety systems are based on the controlling of the forces between the tire and the road to improve the lateral stability of vehicles [11]. However, the functions of these active safety systems can’t be fully utilized due to the forces saturation between the tires and the road at high lateral accelerations or on icy slippery roads [12]. As a result, to avoid the appearance of tires saturation under limiting conditions and further enhance the safety of road vehicles, active aerodynamic control was proposed and investigated by researchers and engineers. The Active aerodynamic control of vehicles has the following advantages: 1) Under the low speed manoeuvre, it can decrease the air drag and the fuel consumption of vehicles, 2) Under the braking manoeuvre, the active wing plate is deployed to increase the windward area of the vehicle, so as to increase the drag and reduce the longitudinal braking force required by the tire, 3) Under the high speed manoeuvre, the active aerodynamic devices can increase the downforce and the working limit of the tire,
which is beneficial to improve the stability of vehicles, 4) Under high speed cornering manoeuvre, appropriately increasing the windward area on one side of the vehicle can produce additional moment of aerodynamic force couple to reduce the workload of the tire [13]. However, active aerodynamic control has been widely used in aviation and military fields. In recent years, the application of active aerodynamic control in the automotive field has gradually attracted the attention of some automotive manufacturers and scholars. But it is only applied to Super cars and racing cars, which is called Drag Reduction System (DRS). In 2011, the Drag Reduction System was first introduced in the FIA World Formula One Championship. The DRS is one of the latest technologies in racing car design. It changes the aerodynamic force of the racing car by changing the rear wing attack angle, so as to improve the performance of the car under accelerating, braking, and cornering manoeuvre [14]. In view of the aforementioned advantages of it, some sports cars designers and manufacturers are dedicated to the development of the active aerodynamic control system. For example, the active aerodynamic control system of Porsche 911 (991 Turbo) consists of a retractable front spoiler and a deployable rear wing, which can produce considerable downforce at the front and rear axle respectively during fast cornering [15]. The Porsche 918 Spyder utilizes the active aerodynamic devices for a particular range of speeds to either minimize aerodynamic drag or maximize the downforce [16]. The active front aero blades and ‘swan neck’ active rear wing of the McLaren Senna work continuously which enable it to maintain optimal aerodynamic downforce during yaw and raise cornering speeds to extraordinary levels [17]. However, the active aerodynamic control system is seldom applied in mass produced common vehicles. Therefore, to provide some guidance for the development of the active aerodynamic control system, it is necessary to summary the state-of-the art studies that have been carried out so far.

2. Influence of the active aerodynamic control on the dynamic properties of vehicles
The longitudinal, lateral, and vertical forces of road vehicles are affected by the aerodynamic forces and moments. Thus, the aerodynamic characteristic of vehicles has a great influence on its dynamic properties. This section will present the effect of the active aerodynamic control on the dynamic performance of road vehicles.

2.1. Fuel consumption
As every knows, the aerodynamic drag significantly influences the fuel economy of road vehicles, especially when the car runs at high speed [18]. For midsize vehicles at high speed, about 50% of fuel consumption is used to overcome the aerodynamic drag [19]. Fuel economy increases by 5% for every 10% decrease in air resistance [20]. It is estimated that the aerodynamic drag reduces 30%, CO2 decreases 10g/km [21]. A lot of methods were developed and used to reduce the drag of road vehicles. Kang et al. developed an active rear diffuser to reduce the drag of the car [22]. It was found that the pressure of the vehicle’s underbody flow was increased because the device produced a diffusing process. An active Drag Reduction System (DRS) was designed and used on the front and rear wings of a race car [23]. The aerodynamic performance of the DRS was conducted by numerical simulation and wind tunnel tests. The drag of race car with DRS was reduced by 54%. An adaptive adjustable rear wing system was developed by Ding Peng et al. [24]. The real car experimental results indicated that the fuel economy and braking performance of the car were significantly improved. A drag reduction system (DRS) was designed [25]. Through CFD simulation, it was found that the drag of the race car was reduced by 17.4%.

2.2. Ride comfort and road holding
Various active aerodynamic control systems have been developed to enhance the ride comfort and road holding of vehicles. The influence of aerodynamic forces on ride quality and road holding for high-speed vehicles was studied by Doniselli et al. [26]. Both simulation and experiment results showed that when the vehicle speed exceeded 40-50m/s, the aerodynamic force had a significant effect on ride comfort and road holding of vehicles. An active aerodynamic control device was proposed to reduce pitch and heave of truck cabin [27]. The results indicated that the improvement of ride performance
depended on the airfoil mounting position, dimensions, and control saturation. An active control system using both suspension and aerodynamic actuators was designed [28]. It is shown that the ride comfort of vehicles was improved, but the road holding was deteriorated slightly. In addition, the active aerodynamic surfaces were also explored to improve the ride comfort of a sport car, and the results showed that the ride comfort of the vehicle was increased by 30%, without negative effects on its road holding [29]. The new method of utilizing dual active aerodynamic control was investigated by Wu and Chen [30]. The road holding and ride comfort was significantly improved by using the dual active aerodynamic surface (DAAS). Ahmad et al [31] demonstrated that the active aerodynamic control system (AACS) can achieve good compromise between ride comfort and road holding under circular path and lane change maneuver.

2.3. Handling and stability
Active aerodynamic control has also been investigated by many researchers for improving handling and stability of road vehicles during cornering maneuver. An active aerodynamic control system was proposed to enhance the handling of a sport car [32]. The results illustrated that vehicle handling was enhanced effectively. An active split rear spoiler was developed to enhance the lateral stability of vehicles at high speeds [33]. It was shown that when the spoiler angle of attack is in the range of 10º to 15º, the high downforce and low drag could be obtained, which was conducive to enhance the lateral stability of road vehicles at high speeds. Using the CFD simulation method, the independent active rear wing was designed by Sikder et al [34]. The different downforce on each wheel was generated by the different angle of attack of the left and right rear wings. It was beneficial to improve the handling of vehicle and cornering performance. Hammad investigated the influence of 3-DOF vehicle model with the AAD system on the vehicle lateral stability [35]. The validation of the controller’s effectiveness was conducted by co-simulations. The results showed that the active aerodynamic control system enhanced vehicle lateral stability. The active aerodynamics control was integrated with other active safety system to improve the comprehensive performance of road vehicles [36].

2.4. Braking performance
For high-speed vehicles, the aerodynamic force can not only improve the car’s handling but also enhance the braking performance of vehicles. The active aerodynamic control devices were originally applied to improve the braking performance of racing cars. Such as, the 1968 Porsche 908LH mounted two flaps at the rear of the vehicle which automatically went up during braking to increase the downforce and the drag [37]. A concept car with movable aerodynamic elements was shown at the Tokyo Motor Show in 1989 [38]. The active aerodynamic devices were employed for braking by increasing the drag coefficient. An active aerodynamic control system using the aerodynamic drag to generate deceleration was developed [39]. The effect of an adjustable spoiler on the braking efficiency of the high-speed vehicle was investigated using the co-simulation [40]. The numerical results showed that the braking time and distance were reduced effectively. The braking efficiency of vehicles at high speeds significantly improved. Also, the effective braking can be provided by the spoiler under the wet and slippery road conditions.

3. Vehicle model of active aerodynamic control system
Various simplified vehicle models were selected as the reference model for the controller development of active aerodynamic control systems. A 13-DOF in-plane truck semi-trailer linear model was chosen to reduce pitch and heave of truck cabins, as shown in Fig. 1 [27]. Meijaard, et al. [28] chose a 4-DOF half-car model to improve the ride quality and comfort for vehicles, as illustrated in Fig. 2. Fig.3 shows the quarter car models that were employed to improve the ride comfort of sports vehicles [29]. As shown in Fig. 4, the quarter-car model of DAAS was applied to enhance the road holding and ride comfort of vehicles [30]. Because the above models in these studies do not represent a real-world vehicle, so more complex and accurate models were used in some active aerodynamic control systems design. Diba et al. [41] developed a 9-DOF race car nonlinear model, as shown in Fig. 5, to study the influence of the active
aerodynamic system on the performance of vehicle. In [32, 36], a 14-DOF vehicle model is shown in Fig. 6, which was employed to investigate for enhancing the stability and overall characteristics of a sports car, respectively. A 3-DOF nonlinear model was used to analyze the high-speed vehicle’s lateral stability, as shown in Fig. 7.

Figure 1. 13-DOF in-plane truck semi-trailer model [27]  
Figure 2. 4-DOF half-car model [28]  
Figure 3. Quarter car model [29]  
Figure 4. Quarter-car model of DAAS [30]  
Figure 5. 9-DOF nonlinear vehicle model [41]

4. Control system design

The control system design is crucial in the development of active aerodynamic control system. This section summaries the control system and controllers explored for active aerodynamic control system. The control system of AAS consists of four independent corner controllers, which are toned on the quarter car model. Fig. 8 shows the block diagram of one corner controller [29]. YOUN control law was applied for the DAAS control system [30]. Three different control strategies, namely full state feedback based on LQR design, open-loop control pre-filter and a combination of both were suggested to calculate the demand on the roll and yaw actuators. As shown in Fig. 9, the controller is composed of two layers,
where the upper layer is used to obtain the understeer or oversteer behavior by monitoring the vehicle condition, while the lower layer is a PID controller to compute the angle of attack of the spoilers, which control the actuators according to the vehicle status [32]. The sliding mode control (SMC) was used for the active aerodynamic control system [35]. Fig.10 shows the block diagram of the active aerodynamic controller. Fig. 11 shows the AAD control system and the controller [41].

5. Conclusion
This paper summarizes the recent researches of active aerodynamic control. The effects of the active aerodynamic control on the dynamic performance of the vehicle, vehicle models, control system, and controller are reviewed. Through summarizing the investigations of active aerodynamic control for vehicles, it can be seen that active aerodynamic control is beneficial to improve the performance of vehicles. Thus, as outlined below, extensive and in-depth studies on active aerodynamic control for vehicles still need to be further carried out.

- The criteria for choosing or designing vehicle models need to be established.
- The comprehensive comparative studies need to be conduct to evaluate the accuracy of the control algorithm and controller for active aerodynamic control system.
- The active aerodynamic control need to coordinate with other active safety systems for enhancing the comprehensive performance of vehicles. Multidisciplinary optimization design of the integrated control system need to be explored.
- To validate the effectiveness of the system, the prototype and the hardware/software in-loop simulation platform of active safety system need to be developed.
References

[1] World Health Organization. Global status report on road safety 2018. http://www.who.int/violence_injury_prevention/road_safety_status/2018/en/.

[2] A.T. van Zanten, Bosch ESP Systems: 5 Years of Experience, 2000, SAE Technical Paper, 2000-01-1633.

[3] Naser Elmi, Abdolreza Ohadi, Behzad Samadi, Active front-steering control of a sport utility vehicle using a robust linear quadratic regulator method, with emphasis on the roll dynamics, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol.227, no. 12, 2013, pp.1636-1649.

[4] Baozhen Zhang, Amir Khajepour, Avesta Goodarzi, Vehicle yaw stability control using active rear steering: Development and experimental validation, Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, vol.231, no. 2, 2017, pp.333-345.

[5] Leonardo De Novellis, Aldo Sorniotti, Patrick Gruber, et al., Comparison of Feedback Control Techniques for Torque-Vectoring Control of Fully Electric Vehicles, IEEE Transactions on Vehicular Technology, vol.63, no.8, 2014, pp.3612-3623.

[6] Taeyoung Chung, Kyongsu Yi, An investigation into differential braking strategies on a banked road for vehicle stability control, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol.221, no.4, 2007, pp.443-455.

[7] Y. Shibahata, K. Shimada, T. Tomari, Improvement of vehicle maneuverability by direct yaw moment control, Vehicle System Dynamics, vol. 22, no. 5-6, 1993, pp. 465-481.

[8] M. Abe, N. Ohkubo, and Y. Kano, A direct yaw moment control for improving limit performance of vehicle handling-comparison and cooperation with 4WS, Vehicle System Dynamics, vol. 25, no. S1, 1996, pp. 3-23.

[9] M. Nagai, Y. Hirano, and S. Yamanaka, Integrated control of active rear-wheel steering and direct yaw moment control, Vehicle System Dynamics, vol. 27, no. 5-6, 1997, pp. 357-370.

[10] Mansour Ataei, Chen Tang, Amir Khajepour, et al., Active camber system for lateral stability improvement of urban vehicles, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2019, vol. 233, no. 14, pp.3824-3838.

[11] Y. He, Design of an Actively Controlled Aerodynamic Wing to Increase High-Speed Vehicle Safety, 2013, SAE Technical Paper 0148-7191.

[12] D. T. Ayyagari and Y. He, Aerodynamic analysis of an active rear split spoiler for improving lateral stability of high-speed vehicles, International Journal of Vehicle Systems Modelling and Testing, vol. 12, no. 3-4, 2017, pp. 217-239.

[13] Yang Kang, Research on vehicle stability enhancement using active aerodynamic control system, Master Thesis, 2018, Fuzhou University, China.

[14] Wang Yuannan, Gao Feng, Development of Drag Reduction System for Formula Racing Car, Journal of Henan University of Science and Technology (Natural Science), 2017, vol.38, no. 4, 2017, pp. 30-34.

[15] https://www.stuttcars.com/porsche-models/911/991/turbo/.

[16] G.Wahl, 918 Spyder – the impulse source for future sports car concepts, in Proceedings of the 5th International Munich Chassis Symposium 2014, pp. 35–56, Springer Fachmedien, Wiesbaden, Germany.

[17] http://media.mclarenautomotive.com/en-gb/releases/531.

[18] J.Y. Wong, Theory of ground vehicles. Fourth Edition, John Wiley &Sons, Inc., Hoboken, New Jersey, 2008.

[19] Hucho, W. H. and Sovran, G., Aerodynamics of road vehicles, Annual Review of Fluid Mechanics, 1993, Vol. 25(1), pp485-537.

[20] Bellman, M., Agarwal, R., Naber, J., et al., Reducing energy consumption of ground vehicles by active flow control, ASME Paper ES2010-90363, 2010.

[21] Eulalie, Y., Gilotte, P., Mortazavi, I., Numerical study of flow control strategies for a simplified
square background vehicle, Fluid Dynamics Research, 2017, vol. 49, pp. 1-25.

[22] S.-O. Kang et al., Actively translating a rear diffuser device for the aerodynamic drag reduction of a passenger car, International Journal of Automotive Technology, 2012, vol. 13, no. 4, pp. 583-592.

[23] S. Wordley, D. McArthur, L. Phersson et al., Development of a Drag Reduction System (DRS) For Multi-Element Race Car Wings, In Proceedings of the 19th Australasian Fluid Mechanics Conference, Melbourne, 2014.

[24] Ding Peng, Ge Ruhai, Li zhi, et al., Development of a Vehicular Adaptive Adjustable Rear Airfoil System, Automotive Engineering, 2017, vol. 39, no. 8, pp. 895-899.

[25] Wang Yuannan, Gao Feng, Development of Drag Reduction System for Formula Racing Car, Journal of Henan University of Science and Technology (Natural Science), 2017, vol. 38, no. 4, pp. 30-34.

[26] C. Doniselli, G. Mastinu, and M. Gobbi, Aerodynamic effects on ride comfort and road holding of automobiles, Vehicle System Dynamics, 1996, vol.25, no. S1, pp. 99-125.

[27] A. Savkoor, S. Manders, P. Riva, Design of actively controlled aerodynamic devices for reducing pitch and heave of truck cabins, JSME Review, 2001, vol. 22, no. 4, pp. 421-434.

[28] J. P. Meijaard, A. R. Savkoor, and G. Lodewijks, Potential for vehicle ride improvement using both suspension and aerodynamic actuators, 2005, vol. 1, pp. 385-390: IEEE.

[29] M. Corno, S. Bottelli, M. Tanelli, C. Spelta, and S. M. Savaresi, Active control of aerodynamic surfaces for ride control in sport vehicles, IFAC Proceedings Volumes, 2014, vol. 47, no. 3, pp. 7553-7558.

[30] Y. Wu and Z. Chen, Improving Road Holding and Ride Comfort of Vehicle Using Dual Active Aerodynamic Surfaces, IEEE 2018 2nd International Conference on Robotics and Automation Sciences (ICRAS), Wuhan, China, 2018, pp. 151-155.

[31] Ejaz Ahmad, Y. Song, Muhammad Arshad Khan, Iljoong Youn, Attitude Motion Control of a Half car Model with Tracking Controller Using Aerodynamic Surfaces, 2019 International Automatic Control Conference (CACS), 2019.

[32] A. Hosseinian Ahangarnejad and S. Melzi, Numerical analysis of the influence of an actively controlled spoiler on the handling of a sports car, Journal of Vibration and Control, 2018, vol.24, no.22, pp.5437-5448.

[33] D. T. Ayyagari and Y. He, Aerodynamic analysis of an active rear split spoiler for improving lateral stability of high-speed vehicles, International Journal of Vehicle Systems Modelling and Testing, 2017, vol. 12, no. 3-4, pp. 217-239.

[34] T. Sikder, S. Kapoor, and Y. He, Optimizing Dynamic Performance of High-Speed Road Vehicles Using Aerodynamic Aids, 2016, pp. V007T09A060-V007T09A060: American Society of Mechanical Engineers.

[35] Mohammed Hammad, Design and Analysis of Active Aerodynamic Control Systems for Increasing the Safety of High-Speed Road Vehicles, Master Thesis, University of Ontario Institute of Technology, Canada, 2019.

[36] Arash Hosseinian Ahangarnejad, Stefano Melzi, and Mehdi Ahmadian, Integrated Vehicle Dynamics System through Coordinating Active Aerodynamics Control, Active Rear Steering, Torque Vectoring, and Hydraulically Interconnected Suspension, International Journal of Automotive Technology, 2019, Vol.20, No. 5, pp. 903-915.

[37] Krzysztof Kurec, Micha Remer, Janusz Piechna, The influence of different aerodynamic setups on enhancing a sports car’s braking, International Journal of Mechanical Sciences, 2019, vol.164, 105140.

[38] Kataoka T, China H, Nakagawa K, Yanagimoto K, Yoshida M, Numerical simulation of road vehicle aerodynamics and effect of aerodynamic devices, SAE Trans 1991, 100:722–34.

[39] Vivek Muralidharan, Abhijith Balakrishnan, Vinit Ketan Vardhan, Nikita Meena, Y. Suresh Kumar, Design of Mechanically Actuated Aerodynamic Braking System on a Formula Student Race Car, Journal of The Institution of Engineers (India): Series C, 2018, vol.99, no.2, pp.
[40] Lu Wenchang, Wang Zi, Cheng Long, et al., Adjustable-spoiler’s effect on braking efficiency at high speed, Manufacturing Automation, 2014, vol.36, no.5, pp. 59-63.

[41] F. Diba, A. Barari, and E. Esmailzadeh, Handling and safety enhancement of race cars using active aerodynamic systems, Vehicle System Dynamics, 2014, vol.52, no.9, pp.111-190.