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Aerodynamic Drag Effects of Externally Mounted LiDAR on Vehicles

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Abstract. With the development of autonomous driving technology, onboard sensor systems have gradually become an essential component of intelligent vehicles. However, externally mounted sensors, particularly Light Detection and Ranging (LiDAR) systems, can alter the original aerodynamic geometry of a vehicle. This can potentially cause flow separation, wake enhancement and increased aerodynamic drag. Then, energy efficiency and driving range will be affected. This paper focuses on the influence of LiDAR on the aerodynamic performance of autonomous vehicles. First, the basic working principles and major types of LiDAR, including mechanical spinning and solid-state LiDAR, are introduced. Also, their importance in environmental perception for autonomous driving is discussed. Subsequently, based on the theory of aerodynamic drag, the effects of LiDAR installed at different locations(such as the roof, front, side, and rear of the vehicle)on the external flow field, pressure distribution, and wake structure are analysed. Furthermore, the main approaches for reducing the aerodynamic impact of LiDAR are summarised, such as sensor shape optimisation, low-profile design and streamlined structural design. In the future, with the development of solid-state LiDAR and intelligent optimisation technologies, sensors are expected to become increasingly compact, integrated and collaboratively optimised. It will enable a better balance between environmental perception performance and vehicle aerodynamic efficiency.

Keywords: Aerodynamic effect, externally mounted LiDAR, Autonomous Vehicles

1. Introduction

Before the emergence of autonomous driving technology, automotive aerodynamic research mainly focused on the influence of the overall vehicle shape on aerodynamic performance. With the continuous advancement of autonomous driving technology and its expanding applications in logistics and low-speed public transportation, the number of onboard sensors has increased. The aerodynamic drag induced by these sensors has begun to attract increasing attention. Consequently, energy efficiency and driving range have become important factors limiting vehicle performance. Many external sensors, such as LiDAR, are key components of the environmental perception system in autonomous vehicles. However, they may disrupt the vehicle's original aerodynamic profile, deteriorate the car's overall aerodynamic performance, increase energy consumption and adversely affect vehicle operating efficiency and driving range. Gawron, J. H., Keoleian, G. A., De Kleine, R.

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D., Wallington, T. J., and Kim, H. C. [1] mentioned this question early . Therefore, reducing the additional aerodynamic drag induced by externally mounted sensors has become an important issue for further research.

At present, collaborative optimisation strategies, which seek to reduce aerodynamic drag through integrated design while satisfying both sensor functional requirements and vehicle aerodynamic performance, have gradually become an important research direction. Researchers have combined computational fluid dynamics (CFD) with wind-tunnel experiments to parameterise sensor geometries. Such approaches can reduce the total aerodynamic drag and drag coefficient of autonomous vehicles to help alleviate limitations related to driving range and energy efficiency. They therefore provide a feasible approach with potential engineering applications.

2. Different kinds of LiDAR

LiDAR is one of the most important environmental perception sensors in autonomous driving systems. Its primary function is to emit laser pulses and receive reflected signals to obtain three-dimensional spatial information about the surrounding environment [2]. Yoo, J. H., et al. [3]. According to different technological implementations, LiDAR can be broadly classified into mechanical rotating and solid-state types.Among these, mechanical spinning LiDAR uses a motor to rotate the laser transmitting and receiving components to enable wide-range spatial scanning through rotational motion. Solid-state LiDAR, on the other hand, achieves scanning using semiconductor or optical devices. It includes optical phased array (OPA) LiDAR, MEMS-based hybrid solid-state LiDAR and Flash LiDAR.This is one of the ways to classify them.

3. Aerodynamic effect of LiDAR

3.1. Total instruction

For a vehicle travelling at high speed, aerodynamic drag can be expressed as

$$C_D = \frac{F_D}{\frac{1}{2}\rho v^2 A} \tag{1}$$

Where F_D is the aerodynamic drag force, ρ is the air density, v^2 is the square of vehicle speed relative to the surrounding air, C_D is the aerodynamic drag coefficient, and A is the vehicle's frontal projected area.

The influence of externally mounted LiDAR can be found from the equation easily, because it can increase the effective frontal area of the vehicle. The aerodynamic drag may increase when other conditions remain unchanged. Besides, the School of Automotive Engineering, Wuhan University of Technology [4] showed that externally mounted sensors such as LiDAR can disrupt the continuity of the vehicle surface, inducing local flow separation. Through CFD simulations, wind-tunnel experiments, and sensor-shape optimisation, a reduction in the vehicle drag coefficient under steady-state conditions can be achieved.

To understand this more directly, taking the frontal projected area of the baseline vehicle as the reference area, the aerodynamic drag coefficient can be shown as CD≈CD vehicle + CD sensor + CD interference. where CD vehicle represents the aerodynamic drag coefficient of the original vehicle model without externally mounted sensors, CD sensor represents the drag contribution generated by the LiDAR itself when considered as an isolated object exposed to the airflow and CD

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interference represents the additional drag caused by the aerodynamic interaction between the sensor flow field and the vehicle flow field after the LiDAR is mounted on the vehicle surface.

This equation provides a framework for analysing the additional aerodynamic drag induced by externally mounted sensors, such as LiDAR, on autonomous vehicles. It helps distinguish the different sources of aerodynamic drag and highlights the importance of the aerodynamic coupling between the sensor and the vehicle body. It should be noted that this expression is intended as a conceptual decomposition and does not imply a strict numerical additive relationship among the three components.

3.2. The installation location of LiDAR

LiDAR sensors can be designed in various shapes, such as cylindrical and box-shaped configurations. In addition, LiDAR sensors can be mounted at different locations on the exterior of a vehicle. In general, the installation locations can be divided into the roof, front, rear, and side regions. LiDAR sensors installed at different locations often serve different functions and can have different effects on the aerodynamic drag of the vehicle. At present, most studies have focused primarily on the aerodynamic effects of LiDAR sensors mounted on the roof and at the front of the vehicle.

3.2.1. Roof-mounted LiDAR

The roof is located in a relatively high-energy region of the external flow field and originally contributes to maintaining the continuity of the vehicle's streamlined flow. Therefore, roof-mounted LiDAR not only generates additional drag itself but also significantly alters the external flow structure around the entire vehicle. The aerodynamic interference induced by LiDAR mainly depends on its geometric characteristics and mounting position. For externally mounted LiDAR sensors with a large protrusion height, large frontal area or poor streamlining, their structures can disturb the development of the original vehicle boundary layer, causing flow deceleration and boundary-layer thickening near the leading edge. Then it may induce flow separation under the adverse pressure gradient near the rear edge [5]. The resulting wake and pressure redistribution can perhaps reduce pressure recovery efficiency, increase pressure drag, and ultimately affect the overall vehicle CdA. In contrast, the interference effects can be significantly reduced when LiDAR is designed with a low profile, streamlined geometry, or integrated into the vehicle body.

Li et al. [6] investigated the effects of a roof-mounted sensor system on the aerodynamic and aeroacoustic characteristics of an intelligent vehicle using LES and the Acoustic Perturbation Equation (APE), combined with aerodynamic experiments . The results showed that, compared with the baseline vehicle without a roof-mounted sensor system, the installation of the sensor system increased the overall vehicle drag coefficient by 23.4%. The study suggested that the incoming-flow impact on the front of the sensor system and the flow separation generated downstream disrupted the original flow field around the vehicle. The resulting increase in pressure drag was identified as the primary cause of the increase in overall vehicle drag.

3.2.2. Front-mounted LiDAR

To avoid seriously disturbed flow regions, front-mounted LiDAR is commonly installed around the bumper, front grille, headlamp area or integrated into the front fascia. However, as the front of the vehicle is the first region to encounter the incoming airflow, the LiDAR is directly exposed to high-

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speed airflow, leading to increased local pressure gradients and flow separation and wake structures behind the sensor. Due to the aerodynamic interference between the sensor and the flow field around the vehicle front, front-mounted LiDAR not only generates additional drag itself but also alters the downstream flow characteristics, so the overall aerodynamic drag of the vehicle increases.

3.2.3. Side-mounted LiDAR

Side-mounted LiDAR is always installed near the vehicle doors, fenders or side mirrors. Its aerodynamic influence is mainly manifested as a disturbance to the boundary-layer flow along the vehicle side. Because the side region is less directly exposed to high-speed incoming airflow, the overall aerodynamic drag produced by side-mounted LiDAR is generally lower than that of roof- and front-mounted LiDAR. However, externally exposed side-mounted LiDAR can alter the pressure distribution over the vehicle surface, generate local flow separation and vortex structures behind the sensor. It can also enhance turbulence around the side windows and A-pillar. These effects can increase aerodynamic noise as well. In addition, the aerodynamic interference between the sensor and the vehicle body can further affect the overall aerodynamic performance of the vehicle.

3.2.4. Rear-mounted LiDAR

Rear-mounted LiDAR is typically installed on the rear bumper, tailgate or rear fascia of the vehicle. Its aerodynamic effect depends on the specific mounting position and geometric dimensions of the sensor, as well as the flow characteristics around the rear of the vehicle. When the LiDAR is placed outside the high-speed flow separation region at the rear of the vehicle, its direct frontal drag is relatively limited because the local airflow velocity is comparatively low, but when the sensor is relatively large, protrudes substantially from the vehicle surface or is located close to the rear pressure-recovery region, it may cause disturbance of the original wake structure and pressure recovery process of the vehicle. This makes local flow separation and vortex formation around the sensor occur, thereby altering the pressure distribution at the rear of the vehicle and increasing pressure drag. Therefore, the effect of rear-mounted LiDAR on the overall aerodynamic performance is not determined solely by its frontal area, but also depends primarily on its aerodynamic coupling with the flow field around the rear of the vehicle [7].

4. Solution

4.1. Improvement of shape

To reduce the aerodynamic effects of externally mounted LiDAR at different locations, an approach is to improve the geometric shape of the LiDAR itself. A low-profile design can reduce the frontal area through a reduction in the height, width, and exposed portions of the sensor. This can directly reduce aerodynamic drag

$$C_D = \frac{F_D}{\frac{1}{2}\rho v^2 A} \tag{2}$$

Zhao et al. [8] investigated a passenger-car-level autonomous vehicle equipped with externally mounted sensors. In related studies, the original vehicle configuration with externally mounted sensors is generally used as the baseline . Methods such as sensor geometric parameterisation, the

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Free-Form Deformation (FFD) method, Kriging surrogate models, and CFD numerical simulations are then employed to optimise the sensor geometry and mounting parameters. The results showed that, while maintaining the sensor functions and installation conditions, the optimised sensor structure reduced the overall vehicle drag coefficient by approximately 5.22% and the lateral force coefficient by approximately 4.58% under the same operating conditions. It should be noted that these reductions represent changes in the overall aerodynamic performance relative to the baseline vehicle with the original externally mounted sensor configuration, rather than reductions in the aerodynamic drag generated by the sensor itself.

In addition, streamlined housing design is another significant approach for reducing the aerodynamic influence of sensors. For high-drag geometries such as conventional box-shaped and cylindrical structures, streamlined geometries such as elliptical, teardrop-shaped, and rounded-front/sharp-rear profiles can be adopted to improve the flow around the sensor, for example, by increasing the leading-edge fillet radius, introducing continuous surface transitions, and optimising the rear-edge contraction angle.

4.2. Other possible improvements

In addition to sensor shape optimisation, the aerodynamic drag induced by LiDAR can be reduced through sensor–vehicle body integration as well, installation layout optimisation, and aerodynamic–perception co-design. By integrating the LiDAR structure with the curved surface of the vehicle body, disturbances to the development of the boundary layer caused by exposed protrusions can be reduced, thereby weakening local flow separation and wake intensity. One research team proposed integrating LiDAR inside the windshield to minimise exposed sensor structures and improve both the vehicle's exterior appearance and aerodynamic performance [9, 10]. Meanwhile, optimising the sensor mounting position to avoid high-speed flow regions or regions that are sensitive to pressure gradients can further reduce aerodynamic interference drag.

5. Conclusion

This paper analysed the effects of LiDAR on the aerodynamic performance of autonomous vehicles. The working principles and application characteristics of different types of LiDAR were introduced. In addition, the aerodynamic effects of LiDAR installed at different locations, including the roof, front, side, and rear of the vehicle, were discussed in combination with different sensor geometries, such as cylindrical and box-shaped configurations. Particular attention was given to their effects on the vehicle flow-field structure and aerodynamic drag characteristics.

To address the aerodynamic problems caused by externally mounted LiDAR, current research mainly focuses on sensor shape optimisation, low-profile design, and sensor–vehicle body integration. By combining CFD simulations, wind-tunnel experiments, and intelligent optimisation algorithms, researchers can efficiently and accurately optimise parameters such as the curvature of the LiDAR housing, protrusion height, and flow transition between the sensor and vehicle body. These approaches have demonstrated the feasibility of reducing aerodynamic interference and improving the overall aerodynamic performance of autonomous vehicles.

In the future, LiDAR aerodynamic optimisation is expected to develop toward integration, miniaturisation, and intelligent co-optimisation. With the continued development of solid-state LiDAR technology, sensors are expected to gradually shift from externally protruding structures toward integrated vehicle-body designs, thereby reducing frontal area and flow separation. Furthermore, while satisfying requirements for sensing range, detection accuracy, and field of view

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(FOV), aerodynamic performance should be incorporated into the sensor layout and integration process. Achieving coordinated optimisation between perception performance and aerodynamic performance will therefore become an important direction for sensor integration in future autonomous vehicles.

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