Review of effects the rear spoiler aerodynamic analysis on ground vehicle performance

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Abstract. Recently reduce in fuel consumption and concern regarding the ground vehicle safety, automotive engineers are faced with the immediate task of introducing more efficient aerodynamic performance vehicles. Hence, the rear spoiler attached on the ground vehicle was presented. Rear spoiler is a device commonly found on road vehicle for improving their aerodynamic performance. Review on the research effects of the rear spoiler aerodynamic analysis on ground vehicle performance is reported in this paper. This review intends to enhance the stability and safety by attaching the rear spoiler on ground vehicle. The review mainly focus on aerodynamic analysis and control of the rear spoiler for different types ground vehicle in term of improving vehicle performance. Researches carried out by a number of researchers with regard to analyze and control the rear spoiler of ground vehicle and their effect on ground vehicle performance. Aerodynamic analysis i.e. computational fluid dynamics(CFD), design optimization, drag coefficient ($C_d$) and lift coefficient ($C_l$) and control methods i.e. passive control and active control had been reviewed. Meanwhile, progressive research on the rear spoiler aerodynamic analysis was observed due to its flexibility for wide range of application in the different type vehicles.

1. Introduction

Performance, handling, safety, and comfort of a car are significantly affected by its aerodynamic properties. Getting high power under the hood is not enough to judge the performance of the car. Aerodynamic properties must be considered for the purpose of studying the drag and its stability, an aerodynamic device is needed such as rear spoiler. The added spoiler can diffuse the airflow passing a vehicle, which minimizes the turbulence at the rear of vehicle, adds more downforce pressure to the back end and reduces lift acted on the rear trunk [1]. The rear spoiler is no longer just a decoration and they do have measurable effect on aerodynamic drag and vehicle stability [2].

Rear spoiler is a device commonly found on road vehicle for improving their aerodynamic performance [3]. Numerous techniques have been explored to analyze and control the rear spoiler for improving ground vehicle performance. These methods range from the use of CFD technologies to active or passive control for the rear spoiler of different forms, among the various strategies employed in the rear spoiler control for improving the stability and safety of ground vehicle. Due to wide range of application active the rear spoiler control is preferable. Thus, research effects are now focusing on the active the rear spoiler for improving ground vehicle performance.
2. Aerodynamic analysis of a rear spoiler
Aerodynamic characteristics of a race car is of significant interest in creating negative lift for stability and in reducing for achieving high speed. Typical design tools such as wind tunnel testing, computational fluid dynamics, and track testing, and their relevance to race car development, are discussed as well [4].

C. V. K. B. Murugan et al. [5] studied focuses on Computational Fluid Dynamics (CFD) based lift and drag prediction on the car body and on improvement in the design due to spoiler configurations. It was found that at the certain height of spoiler and wind collision angle, the change in $C_D$ is negligible but $C_L$ changes significantly as the speed of the racing car increases. Furthermore, the value of $C_D$ and $C_L$ increase as the height of the spoiler decreases and the angle of wind collision increases. Z. Yang et al. [6] applied automatic design and analysis process to the PACE 2008 global vehicle collaboration project, and as many as 4725 numerical cases due to the variations of five parameters were calculated using the computer program. Compared with original design, the process yielded a design with a six percent increase in downward force and a five percent decrease in drag. This result was achieved by creating script code for GAMBIT and FLUENT. Fig. 1 and Fig. 2 show their flow charts.

![Figure 1. Flow chart of GAMBIT script.](image1)

![Figure 2. Flow chart of FLUENT script.](image2)

These modifications are helpful in reducing the coefficient of drag i.e. $C_d$ which effects the fuel consumption. By these modifications the coefficient of drag is reduced by approximately 2.18% [7]. Results show that there was considerable reduction in the coefficient of drag of around 80% with the presence of rear spoiler and a very insignificant increase in the coefficient of drag of around 3% when the vehicle was fitted with a rear spoiler [8]. Numerical simulations show that the aerodynamic drag and lift on the LMV (Low Mass Vehicle) moving at 30 m/s reduce by 5% and more than 100%, respectively, when the new spoiler is attached to it [9].

M. Mashud et al. [10] demonstrated the effect of spoiler on the aerodynamic characteristics thus the drag and lift force of an airfoil through CFD (Fig. 3 and Fig. 4). The result obtained were quite satisfactory as the main functions of the spoilers were demonstrated clearly through the results. The lift coefficient for the airfoil having spoiler at any of the five positions is lower than that of the airfoil without spoiler. Simultaneously the drag force obtained with a spoiler fitted to the airfoil is higher than that of the airfoil without any spoiler.

![Figure 3. Geometry of airfoil with spoiler.](image3)

![Figure 4. Grid generated.](image4)

R. Kittipichal and W. Trutssonawin [11] demonstrated that the airfoil spoiler provided the higher angle of attack at high speed and the lower angle of attack at low speed whilst its deflection was small when their results were compared with the results of the flat plate spoiler. Therefore, this paper shows...
the success of employing MDO (Multidisciplinary Design Optimization) to search for the maximum twist angle of aeroelastic spoiler so that the spoiler wing deformation is taken in a positive way.

3. Passive control of the rear spoiler

3.1. Effects of a passive rear spoiler on the race car performance

The effect of the airfoil profile drag is negligible when compared to the effect of induced drag. This result points out that in the design of airfoils for race car wings, the focus needs to be primarily on achieving high maximum lift even if that objective results in high profile drag. The results show that higher-lift airfoils are preferred for the cornering and braking conditions [12].

M. J. Berchak and M. W. Camosy [13] addressed the question if testing wing alone configurations has a place in the design process of an open wheel race car. Data from 40% models and stand full size wings are compared to determine if wing alone testing is a good predictor of performance when the wing is mounted on the car. the results of downforce and downforce-to-drag ratio improvements relative to the clean wing suggest that a use of the counter-rotating sub-boundary layer vortex generators (CtSVG) has advantage both in downforce and efficiency under several conditions, indicating a 26% and a 10% maximum improvement of the downforce and efficiency. Meanwhile, the counter-rotating larger-scale layer vortex generators configuration indicates less efficiency than the clean wing and counter-rotating sub-boundary layer vortex generators configuration [14]. Numerical analysis has showed us that the second spoiler design provided more negative lift force than the first spoiler shape did but provided less drag reduction. It provided 6% drag reduction (dropped the drag coefficient from 0.232 to 0.217) but the negative lift force has been increased by 17% (dropped the lift coefficient from -0.222 to -0.268) [15].

When the rear-spoiler was installed at the end of the upper body (Fig. 5), it cleared away the extreme vortex produced at the upper body, and aerodynamic drag decreased and driving stability improved compared with the case without the spoiler [16]. The effect of changing the flap angle (-10, -5, 0, 5, and 10 degrees) of the rear wing on the downforce and drag was studied by using the CFD analysis. It was shown by increase the flap angles the downforce and drag was increased. It was concluded that best performance for the both wings has achieved at 5 degrees angle of attack [17].

Figure 5. Model with all add-on devices.

3.2. Effects of a passive rear spoiler on the passenger car performance

With high-speed automobiles much more common nowadays, reducing the lift coefficient to enhance stability on the road is no longer just a concern for race cars. The results indicate that using a spoiler is a promising way to reduce the lift of a vehicle. Further, the simplicity of using it on vehicles makes it an appropriate way to fulfill such a function. Moreover, the present study proves that by placing a spoiler angles on a vehicle’s aerodynamic forces [18]. The spoiler relies on two main mechanisms to reduce aerodynamic drag. First, by preventing the airflow from accelerating at the leading edge of the slant section. Second, by preventing the formation of longitudinal vortices at the side edge of the slant section [19].

S. Y. Cheng et al. [20] carried out a study, the results show that the aerodynamic lift was to decrease nearly linearly with the inclination angle of the spoiler, and was accompanied by the increment in aerodynamic drag. The high speed passenger car with new near spoiler shows that the aerodynamic drag is reduced by 1.7% and it increases negative lift [2]. This lift is induced by a series of wings attached on
the top of the vehicle. To validate the proposed method 3D model of one medium duty vehicle is modelled using SOLIDWORKS. 3D external flow analysis is performed using ANSYS FLUENT, with and without the addition of the wings. The results show that there is a considerable reduction in fuel consumption for these vehicles. Further research on the airfoil profiles which can generate more lift and reduce drag will help reduce the fuel consumption even further [21]. The addition of spoiler results in a reduction of the drag coefficient 2.02% and lift coefficient 14.06% in head-on wind [22].

The yaw angle affects the aerodynamic performance of the hatchback model negatively regardless of the presence of a spoiler. However, the impact is more pronounced with the absence of a spoiler, particularly at higher yaw angles. Most importantly, the use of a spoiler prevents the bi-stability behavior of flow which occurred in the model without the spoiler [23]. The findings show that both the drag coefficient and lift coefficient, $C_D$ and $C_L$, have increased with increasing yaw angle [24]. V. Shukla and G. Saxena [25] carried out a study, comparative results between the baseline car and car with spoiler are shown in Table 1:

| Configuration                  | Drag coefficient | Reduction from base model(%) | Lift coefficient | Reduction from base model(%) |
|--------------------------------|------------------|------------------------------|-----------------|------------------------------|
| Base model                     | 0.60             | 0                            | 0.25            | 0                            |
| Splines and rear spoiler       | 0.51             | 15%                          | 0.22            | 12%                          |

4. Active control of the rear spoiler

4.1. Effects of an active rear spoiler on the race car performance
Active wing has the potential to increase the stability of racing cars by down-force as a result of aerodynamics pressure energy. M. Salehi et al. [26] studied a novel way of wing modelling and control is introduced. The proposed model is driven by using the second and the third Newton law and is also theoretically calculated by some simple formulation. Moreover, a proof to show how the performance increases is given. There are ways to work on other aspects of the subject because it will be the first step intelligently control wings in order to increase road-holding without any special features on the road corners. Numerical and analytical arguments are considered to show step by step modeling spoiler. First the history of wing and spoiler is described then some research and improvement in the subject are given. The numerical results show the efficacy of the proposed method.

Y. Park [27] investigated adjustable spoiler for vehicle and method for controlling the same. An adjustable spoiler for a vehicle includes a pressure sensor sensing a pressure applied to an upper side of a spoiler and generating a current signal in proportion to the pressure. An electronic control unit (ECU) is configured to control an angle of a spoiler according to the current signal from the pressure sensor. The spoiler is mounted on the upper side of a vehicle body. The adjustable spoiler can be changed to the optimal position according to the pressure applied on the spoiler, and therefore the stable driving performance and the air dynamic performance of the vehicle can be guaranteed.

4.2. Effects of an active rear spoiler on the passenger car performance
M. Corno et al. [28] investigated the use of Active Aerodynamic Surfaces (AAS) to enhance ride comfort in sport vehicles (Fig. 6). Simulation validation shows that at high speed on average the use of AAS yields an improvement of 30% of the comfort performance without affecting road holding. The results show that Coanda effect can be used to reduce trailing edge separation, in order to improve the aerodynamic characteristics of the ailerons, and later to increase the aerodynamic behavior of the vehicle concerning the aerodynamic loads, drag and lift, and, consequently, stability and handling [29]. An active flow control solution by suction and blowing are tested to reduce the aerodynamic drag on reversed Ahmed body. The maximum drag reductions associated with these modifications are close to
15.83% etand the increase of suction velocity increase at $U_{sc} > 0.30U_o$ does not improve such a reduction significantly [30].

Figure 6. System layout with actuator and sensors.

The research deal with Computational Fluid Dynamic analysis and simulation to maximize down force and minimize drag during high speed of the car. Using ANSYS FLUENT software and mentoring provided by ANSYS, the results employs efficient discretization techniques and real loading conditions to study down force on rear wing of the car with drag generated by all active mounted surfaces. Wing and external surface under high velocity runs of the car are presented. Optimization of wing direct angle of degree of stability and to control during operation. Moreover to ensure more stability active aerodynamic spoiler which can adjust its height and its angle of attack according to speed [31].

4.3. Effects of an active rear split spoiler on ground vehicle performance

Active aerodynamic control can effectively enhance the lateral stability of high speed vehicles over tight cornering maneuvers. A split rear wing has been proposed. By means of manipulating the attack angles for the right and/or left parts of the split rear wing, a favorable yaw moment may be achieved to ensure the lateral stability of the vehicle. In order to examine the performance of the active split rear wing, Numerical simulation is carried out using the LQR (Linear Quadratic Regulator) based controller and a yaw-plane vehicle model designed in MATLAB. The effectiveness of the proposed actives split rear wing is demonstrated by the results derived from the numerical simulation [32].

F. Diba et al. carried out a simulation results demonstrate that the handling capabilities of the race car with an ADD (active aerodynamic) system have been enhanced (Fig. 7). Furthermore, the ADD system increases the steer ability of the vehicle and, as a result, the aero-assisted race car requires a smaller steering input to perform the specific turning manoeuvres [33]. It is disclosed that by operating the individual rear left and right spoilers, different left and right downforce and drag at the rear end of the vehicle can be achieved, which may be beneficial to the active yaw and roll moment control to improve the lateral stability of high-speed vehicles. It is also demonstrated that once the angles of attack of the individual left and right spoilers are controlled within the range of 10° to 15°, the high total downforce and low drag may be achieved [34].

Figure 7. Prototype of the ADD system with inverted wings.
M. Hammad [35] proposed a split rear wing to control the aerodynamics of high speed road vehicles to closely manipulate the dynamics of the vehicle. An SMC technique is used to design the ADD controller to control the attack angle of the wings based on the decided control objective of tracking the steady-state yaw rate. It is demonstrated that the controller is more effective to improve the lateral stability of the vehicle at higher speeds. The analysis is concluded by simulating the vehicle with different payloads, thereby proving the controller’s robustness. Independent active rear wing systems are an ideal alternative to conventional fixed wing systems as they can ensure the accepted acceleration performance and improve the directional stability of high-speed vehicles [36].

Y. He [37] presented a design of an actively controlled aerodynamic wing to increase high-speed vehicle safety (Fig. 8 and Fig. 9). Based on the CFD analysis, a wing design is chosen and real physical prototype of the actively controlled aerodynamic wing is developed. The active wing can implement limited functions under specified testing maneuvers using an open-loop control scheme.

**Figure 8.** The actively controlled aerodynamic wing and its installation on the testing vehicle

![Figure 8. The actively controlled aerodynamic wing and its installation on the testing vehicle](image)

**Figure 9.** The configuration of the actively controlled aerodynamic wing

![Figure 9. The configuration of the actively controlled aerodynamic wing](image)

5. **Summary**

The aerodynamic analysis of the rear spoiler has been carried out by a number of researchers. Based on the previous research, a new active aerodynamic control system research scheme is proposed, which is divided into aerodynamic analysis, active split rear spoiler control system design and real vehicle verification in three steps. Step 1: F1 racing car and S1223 airfoil with high lift drag ratio are taken as the research object and analyzed by CFD. Step 2: the controller is designed according to four different driving conditions (acceleration, deceleration, braking and cornering). The input signals of the controller are collected by acceleration pedal sensor, brake pedal sensor, speed sensor, steering wheel angle and rear spoiler pressure sensor. The control program system of the split rear spoiler is designed with CodeWarrior software, and the actuator composed of servo actuator and belt gear transmission mechanism is used to control the rear spoiler angle of attack. Step 3: the active rear spoiler control system is verified in rear vehicle, the stability and reliability of the system is further optimized and processed.
6. Concluding remarks
The review provides an aerodynamic analysis of the rear spoiler for improving ground vehicle performance. The lower drag and higher downforce were achieved by controlling the rear spoiler of ground vehicle. The lower drag can reduce fuel consumption and higher downforce increases tires capability to produce cornering force. In the future, more active control methods be selected for improving ground vehicle safety and stability. such as, multi-objective control, adaptive control and integrated control. The rear spoiler be applied to enhance aerodynamic performance of ground vehicle in different types vehicle.

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