Aerodynamic Analysis of Formula Race Cars Under Queues

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Abstract. In the case of a Formula Race car following another car, the aerodynamic package of the car at the front generates turbulence in its wake, and the difference in the incoming flow will have a great impact on the aerodynamic efficiency of the car at the back of the queue. This paper takes Formula Student as an example to study its aerodynamic efficiency in the queue. Based on CFD simulation analysis, the airflow velocity and pressure cloud can be analysed in the queue with different distances between the front and rear cars. By analysing the aerodynamic efficiency of the rear vehicle at different distances, the regions that are affected by the aerodynamics of the front vehicle under the queue are found. Finally, based on the experimental findings obtained, this study makes recommendations to Formula Race Cars drivers and race organisers to ensure that safety during races is further emphasised and improved. At the same time, this study also looks forward to further investigations into the role of aerodynamics in the car queue when driving daily.

Keywords: Aerodynamics, Queue, Formula Race

1 Introduction

Motorsports originated from the end of the 19th century, and after more than a hundred years of development, has become a professional, commercial, and globalized sports event. There are also diversified types of racing. Formula racing, as the most representative racing car, has developed more advanced. Aerodynamics has played an epoch-making role in the development of formula racing.

As early as the middle of the 20th century, aerodynamic research on single formula cars had already begun to take shape, and with the first use of ground effect in Lotus (Colin Chapman) and the continuous development of wind tunnel and computational fluid dynamics technology, aerodynamics has entered a stage of comprehensive development.

With this background, aerodynamic research on the single racing car is far from being sufficient, and more and more attention is being paid to the different aerodynamic characteristics during vehicle following.

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Racing cars' aerodynamic analysis has been developed very well, including how it improves race car performance and wind tunnel experiments. However, the actual results are still different compared to experiments and simulations [1]. Due to the difficulty of conducting aerodynamic experiments in a car-following situation, with the rapid development of CFD technology, more studies can be conducted by simulation. While most of the existing research has focused on the distance of the longitudinal vehicle queue, some researchers have turned to the lateral distance of the vehicle spacing. These studies mainly consider the fuel economy [2]. How a following car influences a cyclist's drag has already been studied in sports. CFD simulations and wind tunnel tests have been used in the research [3].

Nowadays, with the development of aerodynamics in Formula Cars, following a car becomes more and more difficult, with the turbulence created by the rear of the car interfering with the aerodynamics of the car behind it, especially the downforce. This phenomenon causes overtaking to become more difficult and reduces the spectacle of Formula Racing motorsport. As a competitive entertainment event, this problem is one that FIA needs to address urgently. It also leads to many dangerous accidents, which can threaten drivers' lives.

For example, in Formula Student Races, when the rear car is approaching the front car, the front car needs to give way. It's for security reasons. However, there is no definitive study on at what distance the rear vehicle will be affected by the vehicle in front. This study is necessary because it can be more detailed to ensure the spectacle and safety of the game.

As a result, this research aims to study the aerodynamic characteristics of a race car in the longitudinal direction of the vehicle queue. The most stable region during vehicle following would be found out, and how the latter car can be made safer would be analysed. Normal cars would be simulated in the same situation as a comparison with formula cars. It can provide a good reference value for the position selection in the case of car following, which can ensure a better competitive level. The safest areas for driving a car in everyday life would also be analysed.

The research will be based on CFD simulation technology and interpolation. A Formula Student race car will be used to find out race cars aerodynamic characteristic. Then, two pieces of it will be put in a vehicle queue for further analysis of both aerodynamic characteristics for front and rear vehicles at different relative positions.

2 Method

2.1 Formula Student Car's Aerodynamic Analysis

The most basic and major component of a racing aerodynamic kit is the airfoil. Formula Student racing cars (Fig. 1) use a combination of air foils to increase the upper limit of the downforce gained by the air foils [4]. However, in practice, these relationships are complex and do not show a clear linear relationship with the downforce generated, which makes the design a multivariate problem.

Fig. 1. A Formula Student Race Car (Picture credit: Original)

STAR-CCM+, which is produced by SIEMENS, is used as the simulation software in this case. A 2024 Formula Student Race Car is taken as an example to analyse the aerodynamic characteristics of the isolated car. The model is shown in Fig. 2.

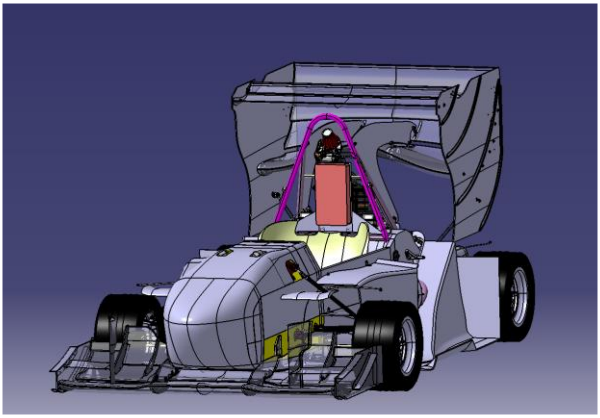

Fig. 2. The model of the Formula Student Race Car (Picture credit: Original)

Since the model is nearly symmetric in the horizontal direction, the half-vehicle model in Fig. 3 is taken in order to reduce the amount of computation as well as the computation time of the simulation [5].

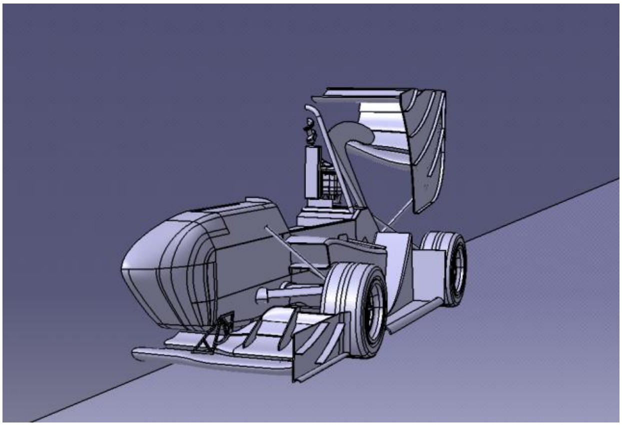

Fig. 3. The half-vehicle model (Picture credit: Original)

The length of the computational domain is 10 times the length of the tailplane, and the height of the computational domain is 5 times the half-width of the airfoil, to ensure that there is no reflux, and thus to ensure the accuracy of the analysis.

After processing the mesh of the model in STAR-CCM+, the boundary layer and fluid domain are set as follows. (Fig. 3) The boundary types are Inlet, Outlet, Symmetry, and Wall. The inlet is set as a Velocity inlet, the turbulence intensity of the Velocity inlet is 0.5%, the turbulence rate = 4× area of the computational domain/perimeter of the computational domain, and the flow velocity u is 14m/s. The outlet is set as a Pressure outlet, the turbulence intensity of the Pressure outlet is set as 0.5%, and the turbulence rate = 4× area of the computational domain [6]. To make the simulation closer to reality, the ground is set as a sliding wall with a sliding speed of 14m/s, and the wheels are set as a rotating wall, which are purely rolling on the ground. The medium is set as air.

2.2 Analysis of the range of vehicles affected by queue aerodynamics

An identical race car is placed directly behind the original vehicle. The aerodynamic downforce on the car and its airflow field are analysed to compare the aerodynamic effects on the car compared to when there is no vehicle in front of it.

Then, change the relative distance between the two cars as Fig. 4 shows.

Based on the results, interpolation analysis is carried out, and plots are obtained to represent the range of vehicles affected by queue aerodynamics.

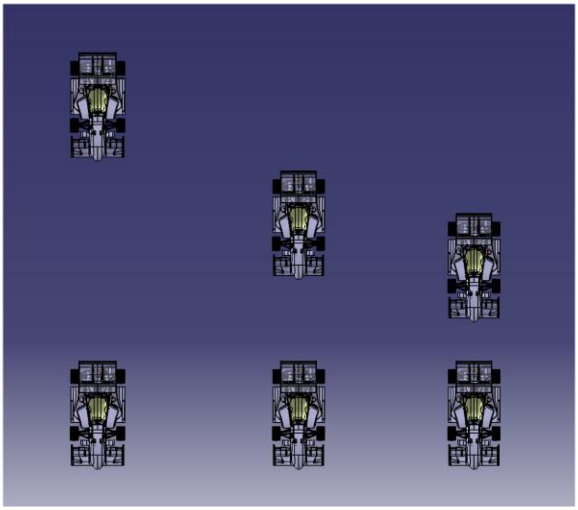

Fig. 4. Different distances between the two cars (Picture credit: Original)

2.3 Compared with Normal Cars

The Formula Student racing car used was replaced with a model of an ordinary family car to analyse the sensitivity of the aerodynamic effects to which the family car is subjected when following the car, as opposed to a Formula Student car. The sensitivity maps of the two are compared and analysed to see if the family car is unsafe when following a car.

3 Results

3.1 Isolated Formula Student Car's Aerodynamic Analysis

According to the result, the downforce of different parts of the Formula Student car has been shown in Fig. 5. It can be found that the downforce of the car is approximately 510n when the velocity is 14m/s.

It is certified that the aero bias is 45:55 when the Formula Student car is in the clean flow. With clean airflow, the rear of a car on a straightaway is subject to more downforce than the front of the car. This is to improve the handling stability of the car at high speeds.

	CLA	L_overall(N)	L_fwing(N)	L_rwing(N)	L_diffuser(N)
TR24	4.55	-239.078	-86.6077	-74.7638	-90.552

Fig. 5. Aerodynamic features of a single Formula Student car (Picture credit: Original)

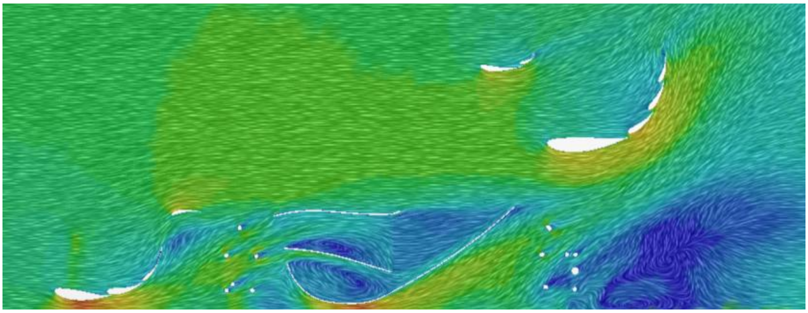

Fig. 6. Formula Student Racing's Flow Field (Picture credit: Original)

It can be found in Fig. 6 that the flow field at the rear of the car is very chaotic, forming a vacuum area, which not only produces a large pressure difference resistance to the car itself, but also causes a certain distance behind the vehicle to change the state of the air flow, so that the car behind the car is affected by the situation and may appear out of control.

3.2 Analysis of the range of vehicles affected by queue aerodynamics

The simulation was carried out by varying the longitudinal distance between the front and rear cars. It was possible to obtain data on the aerodynamic downforce on the rear vehicle at different distances. The data were plotted in Fig. 7 and compared with 100 per cent downforce data and 80 per cent downforce data for the vehicle in front.

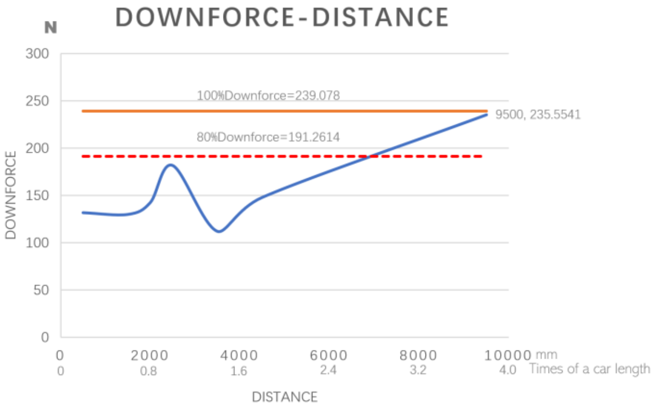

Fig. 7. The aerodynamic downforce on the rear vehicle at a distance from the front vehicle (Picture credit: Original)

Compare the distance between the two vehicles with the length of the entire vehicle. The figure of the aerodynamic downforce on the rear vehicle at a distance from the front vehicle is then combined. It is possible to obtain the area where the aerodynamic downforce on the rear vehicle is influenced by the front vehicle.

From the images, the following phenomenon can be found when the rear vehicle is more than 4 times the length of the front vehicle, the aerodynamic downforce on the vehicle is close to that of the front vehicle, and it can be regarded as not being affected by the front vehicle.

The vehicle is more affected by the vehicle in front when the following distance is within 4 times the vehicle's length. The aerodynamic downforce on the rear vehicle is about 50 per cent of that on the front vehicle. However, at a specific distance of one time the length of the vehicle, the aerodynamic downforce on the rear vehicle increases, approaching 80 per cent of the downforce on the front vehicle.

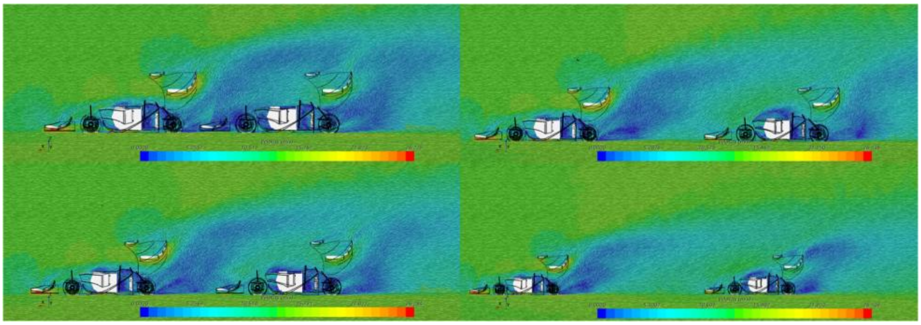

Fig. 8. Different airflow velocity: 0.2\0.6\1\1.4 times of a car length (left up\left down\right up\right down) (Picture credit: Original)

From the map of different airflow velocity (Fig. 8), it can be found that: in the case of too close proximity to the vehicle in front, the rear vehicle is in the area of the front vehicle's wake. The airflow velocity is affected by the turbulence in the wake of the vehicle in front, and there is a significant deceleration. It can be concluded through Bernoulli's principle that the lower the airflow velocity, the lower the pressure difference obtained.

At one vehicle length from the front, the rear front wing can access the higher velocity airflow induced by the front rear diffuser. In this case, the aerodynamic downforce on the rear car is significantly increased.

However, at greater distances, the lower rear wing of the rear car creates airflow separation and does not provide sufficient downforce.

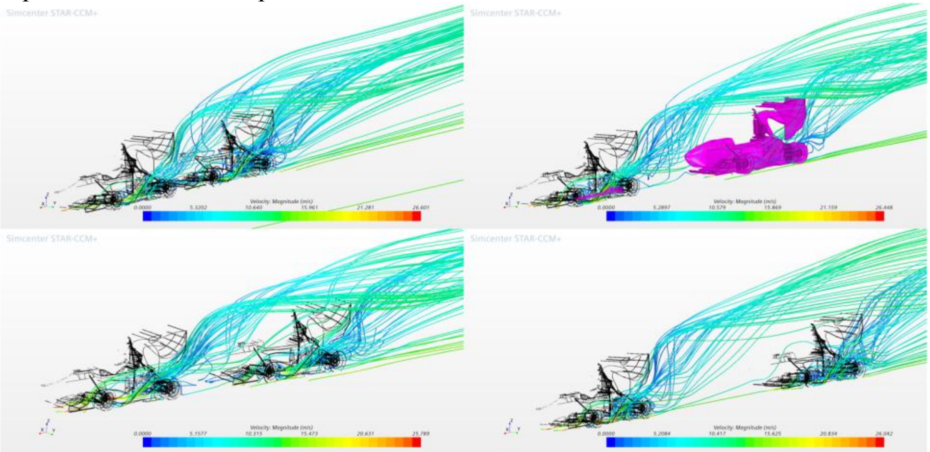

Fig. 9. Different airflow turbulence: 0.2\0.6\1\1.4 times of a car length (left up\left down\right up\right down) (Picture credit: Original)

It shows that the turbulence of the latter car is messy when the distance between the two cars is too small, from Fig. 9. However, there is a lifting of the air near the ground due to the diffusion effect caused by the aerodynamic components of the front car. The aerodynamic downforce on the rear vehicle is therefore significantly affected. From the pressure scene in Fig. 10, it can also be identified that a difference in the downforce at different distances.

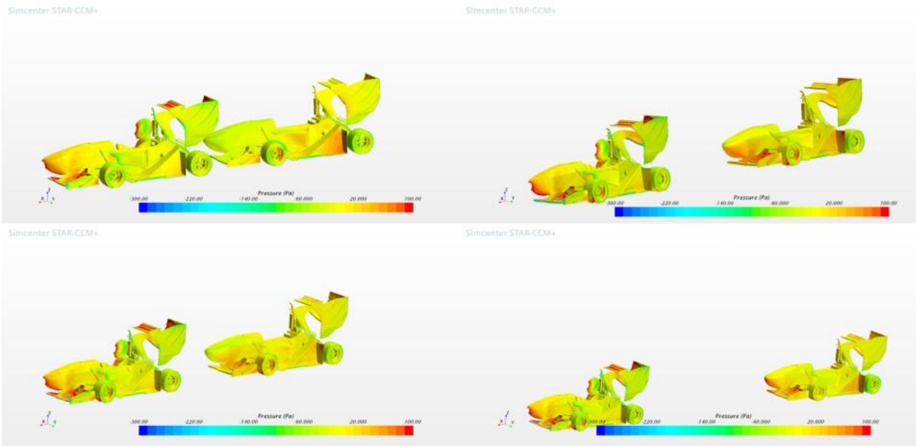

Fig. 10. Different pressure: 0.2\0.6\1\1.4 times of a car length (left up\left down\right up\right down) (Picture credit: Original)

4 Discussion

4.1 The most stable region during Vehicle Following

When a vehicle is following another vehicle in a queue, the distance between the two vehicles is greater than four body lengths, ensuring that the aerodynamic effects on itself are not unduly affected.

In everyday life, passenger cars are not sensitive to the aerodynamic down force of a following situation, and there are times when it may be possible to reduce the downforce on the vehicle [7]. Although the magnitude of this effect is negligible, it is a major factor in ensuring safe driving in extreme conditions, such as icy roads, slippery roads, and windy conditions [8].

But on a formula track, the air becomes turbulent due to the influence of the car in front. The aerodynamic effects on the rear car in a following situation will be different from those in wind tunnel test conditions. The overall downforce of the vehicle tends to decrease, but the change in drag is not significant. The unstable aerodynamics will give the vehicle an unstable driving experience, which will lead to an increased chance of losing control of the vehicle and a decrease in safety.

Therefore, when building racing cars and family cars, it is important to consider the aerodynamic stability of the vehicle under the following conditions, thus ensuring the safety of the vehicle in front and behind [9].

4.2 The reason why different types of cars perform differently

According to the result of the sensitivity maps of different types of cars, it is found that the rear wing of the car will lead to great interference with the following car.

As you can see from the trace diagram, the wingtip vortices created by the tailplane endplates and the tailfins can make the wake flow at the rear of the car more chaotic. At the same time, the vortex will wrap around the clean airflow, making the car wake flow affect a longer distance.

But among family cars, the streamlined bodywork manages the rear turbulence well while reducing drag. This makes following a car in everyday life safer and easier [10].

5 Conclusion

It can be found that in the case where the distance between the front and rear cars is more than four times the car length, the car at the back of the queue can avoid its aerodynamic efficiency, the downforce, being affected by the aerodynamic package of the front car.

When the distance between the front and rear cars is less than four times the length of the car, the aerodynamic downforce on the rear car is, in most cases, less than 50%. Since race cars are designed to be highly coupled in pursuit of greater performance, a large lack of aerodynamic downforce can lead to a malfunction in the handling of the entire car. This is very dangerous for the racing car at the back of the queue, trying to catch up with the front car. The simulation shows that the aerodynamic downforce of the rear car is not linearly related to the distance from the front car, and in the case of doubling the length of the front car, the downforce even rises to 80% of the original.

As a result, the driver of the car at the back of the queue, when approaching within four times the body length of the car in front of him, needs to do more to maintain concentration to ensure driving safety and better control of the car.

At the same time, this phenomenon also proves that race organisers need to formulate relevant rules to avoid such safety hazards as much as possible. This is to ensure that in Formula Student races, the cars at the back of the queue can give way when approaching a suitable distance from the car in front.

In the simulation process, due to the complexity of the structure of the Formula Student car, the simulation resources required are very large. Therefore, when selecting the simulation model, the model is simplified for a single Formula Student car.

In addition, this phenomenon is also a guide for everyday driving. In everyday life, family cars are also driven in a queue, and the aerodynamic effects of the car in front on the car behind need further attention. In addition to focusing on the effect of increased drag on fuel economy, it is also necessary to study the lift change and analyse the flow field of vehicles in a queue to ensure the safety of daily driving.

References

1. Katz, J.: Aerodynamics of race cars, Annu. Rev. Fluid Mech., 38(1), 27–63(2006)
2. Lei, L., Li, Z., Zhou, H., et al.: The effect of lateral offset distance on the aerodynamics and fuel economy of vehicle queues, Fluid Dyn. Mater. Process., 2024, 20, (1)
3. Blocken, B., Toparlar, Y.: A following car influences cyclist drag: CFD simulations and wind tunnel measurements, J. Wind Eng. Ind. Aerodyn., 145, 178–186(2015)

4. Dharmawan, M.A., Ubaidillah, Nugraha, A.A., et al.: Aerodynamic analysis of Formula Student car, Proc. AIP Conf., 1931(1), 030048(2018)
5. Jackson, F.F.: Aerodynamic optimisation of Formula Student vehicle using computational fluid dynamics, Fields: J. Huddersfield Student Res., 4(1), 40–65(2018)
6. Gil Gonzalez, A.: Aerodynamic design of the front wing of a Formula Student car, MSc thesis, Universitat Politècnica de Catalunya, 2024
7. Watkins, S., Vino, G.: The effect of vehicle spacing on the aerodynamics of a representative car shape, J. Wind Eng. Ind. Aerodyn., 96(6–7), 1232–1239(2008)
8. Diedrichs, B., Berg, M., Stichel, S., et al.: Vehicle dynamics of a high-speed passenger car due to aerodynamics inside tunnels, Proc. Inst. Mech. Eng. F: J. Rail Rapid Transit, 221(4), 527–545(2007)
9. Kanda, I., Uehara, K., Yamao, Y., et al.: A wind-tunnel study on exhaust-gas dispersion from road vehicles—Part II: Effect of vehicle queues, J. Wind Eng. Ind. Aerodyn., 94(9), 659–673(2006)
10. Kurec, K., Remer, M., Broniszewski, J., et al.: Advanced modelling and simulation of vehicle active aerodynamic safety, J. Adv. Transp., 2019, 2019, Article ID 7308590