

Use of an Aerodynamic Wake Emulator to Assess the Impact on a High-Performance Ground Vehicle in Close Proximity

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The interaction between ground vehicles in close proximity is currently of interest as it is known that the aerodynamic characteristics of the trailing vehicle may change significantly under the effect of a disturbed flow. The aim of this work is to map a wide range of situations where a trailing car, under racing conditions, is affected by another vehicle ahead. A sub-scale wind tunnel test in which the aerodynamic characteristics of a high-performance ground vehicle is affected by a simplified ‘wake emulator’ has been conducted. The trailing vehicle is a 35% scale model of the generic DrivAer geometry. These experiments were carried out at Cranfield University’s 8x6 Wind Tunnel facility, at a speed of 40 m/s. Several relative positions, such as longitudinal and lateral distances, together with different yaw angles have been investigated. The behavior of the trailing car is monitored with an internal balance that gathers the variations of all aerodynamic forces. Thus, a well detailed map displays the effect of close slipstreaming in high-performance cars alongside the variations due to yaw conditions. Results have shown similar trends on axial and vertical force as previous works regarding high performance vehicles. The variation on aerodynamic forces and moments are highly dependent on the relative position with the main vortices from the leading car’s wake.

I. Nomenclature

β	=	yaw angle [°]
C_{pt}	=	total pressure aerodynamic coefficient [-]
C_x	=	axial force aerodynamic coefficient [-]
C_y	=	side force aerodynamic coefficient [-]
C_z	=	vertical force aerodynamic coefficient [-]
C_{my}	=	pitching moment aerodynamic coefficient [-]
H	=	high-performance (HP) DrivAer model maximum height [mm]
HP	=	high-performance
L	=	high-performance (HP) DrivAer model length [mm]
x	=	longitudinal vehicle separation [mm], measured
y	=	lateral displacement of the leading and trailing vehicles axial center lines [mm], measured

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II. Introduction ⁽⁴⁾

Much of previously published work related to ‘drafting’ or ‘platooning’ has focused on either: (i) the potential for fuel economy improvements through aerodynamic drag reduction or (ii) the handling/stability implications for smaller/lightweight vehicles in close proximity to larger/heavier vehicles. In contrast, a motorsport application presents a specific challenge in that: (i) the interacting vehicles are normally of comparable physical size and weight, (ii) vehicle speeds are often high (potentially large variations in effective free stream dynamic pressure) and (iii) the aerodynamic characteristics of the vehicles’ wake are potentially complex with both significant ‘upwash’ and embedded longitudinal vortices. The benefits, or disadvantages, when trailing another car are highly dependent on their shape, as stated in Ref. [1]. Drag force on the trailing car can be reduced with blunt bodies whereas it can be increased with more streamlined geometries. Understanding the fundamental flow mechanisms that are relevant to the interaction can be aided with the use of a generic wake emulator that has been designed to produce a wake that exhibits the key features of the flow field.

The properties of a generic high-performance ground vehicle wake are measured, using a 35% sub-scale model of the DrivAer configuration in Ref. [2], by Soares and colleagues. An example of the total pressure distribution in a plane within the wake is reproduced in Ref. [3]. The key flow features are characterized by: (i) an upwash effect caused by diffuser-spoiler combination on the leading vehicle, (ii) the development of two trailing vortices and (iii) an inflow at the centerline close to the ground due to the low-pressure region. Similar characteristics can be found on open wheel race cars, whose turbulence intensities and velocity deficits at the wake exceed 40% and 50% respectively. These quantitative results show the relevance of the structure of the wake and how the trailing car can be highly affected when driving under these conditions.

Previous studies have stated a predicted reduction in drag of the trailing car under slipstreaming conditions making the most of the low-pressure zone created behind the leading car (from Ref. [4]). Nowadays, drafting situations are used to shorten the distance to the leading vehicle when the trailing car is within a low-pressure zone generated by the leading one, however, other consequences need to be considered. Dominy and co-authors in Ref. [4] argued that, regarding the variation of drag, downforce and its distribution between the axles on a 1990 Le Mans specification car, slipstreaming reduces both drag (14%) and downforce (17%) on the trailing car at the normalized axial location $x/L = 0.25$ compared to the reference value, also shifting the balance of downforce to the front axle, leading to unpredicted oversteering condition. Another previous study, Ref. [5], considered the effect of yaw angle at 10° , finally stating that its consequence on the trailing car is proportionally the same as without yaw angle, but in smaller magnitude.

Previous experimental and computational studies of wake emulators (generators) related to motorsport, have been related to NASCAR configurations (Ref. [6]) and Formula 1 cars (Ref. [7]), with their own flow characteristics. This study will use an existing adaptable wake emulator, as proposed by Soares in Ref. [3]. This generator (Fig. 1) can be configured to simulate a number of generic passenger vehicle “wake profiles” but the measurements reported here only use the ‘high-performance’ configuration, originally proposed by Soares which is characterized with a front splitter together with a rear diffuser and spoiler.

III. Methodology

A. Experimental Testing

1. Planning

As mentioned previously, this work will study the slipstream effect within close proximity on HP vehicles. The base geometry of a high-performance car is obtained from a DrivAer model adapted with other devices to turn it into a racing specification setup from Ref. [2] (Fig. 1). The main part of the study consists of experimental testing at Cranfield University 8x6 ft low speed and closed return wind tunnel facility with a closed test section, at a freestream speed of 40 m/s with motionless ground. Specifically, HP DrivAer model has a total length (L) of 1620 mm while the emulator is 750 mm long (47% of full car model).

The trailing car is mounted on a turning table with one six-component JR3 underfloor balances on each of the four wheels that monitors the variations of aerodynamic forces on each situation. In contrast, the emulator is manually moved and fixed to the ground to each specific position for each run. Relative positions are normalized by the vehicles’ length, with longitudinal distance (x) set between the rearmost part of the emulator and the foremost of the DrivAer (without considering the front splitter), whereas the lateral distance (y) is defined between both bodies’ centerlines. Considering these relative coordinates, the models are positioned throughout a set of points to map a wide range of possible circumstances occurred on close racing (Table 1), also displayed in Fig. 3.

⁴ This entire project is based on a master’s thesis carried out at Cranfield University, see Ref. [9].

The range of study is constrained by the test section and the proximity to the walls for all yaw angles, having a maximum longitudinal distance of $x = 648 \text{ mm}$ (i.e., $x/L = 0.4$).

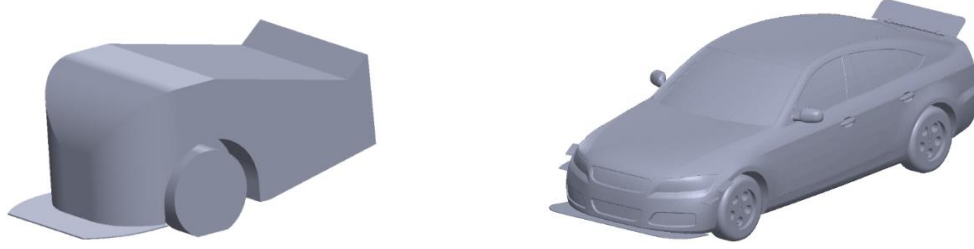


Fig. 1 Models of adaptable wake emulator in high-performance configuration from Ref. [3] (right), and HP DrivAer from Ref. [2] (left), originally proposed by Soares



Fig. 2 Testing setup at Cranfield University 8x6 ft wind tunnel

Coordinate	Abbreviation	Positions
Longitudinal distance	x/L	0.15, 0.2, 0.25, 0.3, 0.4
Lateral distance	y/L	-0.2, -0.1, 0, 0.1, 0.2
Yaw angle [°]	β	0°, 3°, 6°

Table 1. Relative positions summary

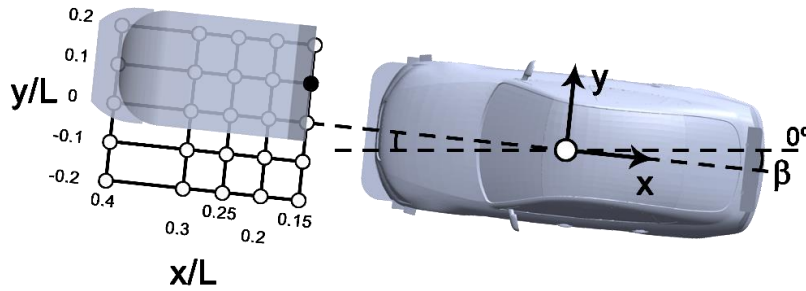


Fig. 3 Testing matrix of experimental testing

In addition to this set of positions, other relative distances are tested under no-yaw to obtain a more detailed trend:

- $x/L = 0.45$ at the centerline ($y/L = 0$).
- $y/L = \pm 0.05$ and $y/L = -0.25$ at $x/L = 0.4$.

The testing setup of the experimental analysis is displayed in Fig. 2, where the wake emulator is fixed to the ground on each case, while the DrivAer model only rotates. For instance, this means that an example of a relative position in Fig. 3 at $x/L = 0.15$ and $y/L = 0.1$ can also be understood as the trailing car is placed at $x/L = 0.15$ and $y/L = -0.1$, if the emulator was fixed and the trailing car was moving behind the leading car.

2. Corrections

The use of two different models and diverse relative positions in a constrained facility reduce the area where the flow moves through, increasing the real testing speed and dynamic pressure compared to the predicted one. Previous works stated this issue and suggested a correction of the dynamic pressure if the blockage ratio (BR), from Ref. [8], is greater than 7.5%, which considers the ratio between model frontal area over test section cross area. Namely,

$$BR [\%] = \frac{\text{model frontal area}}{\text{test section area}} * 100 \quad (1)$$

To calculate the model's frontal area, this is a function of the longitudinal distance between the bodies (x), the lateral distance (y) and yaw angle (β). To achieve the best accuracy with a simplified case, the wake emulator as well as HP DrivAer are considered as two rectangular prisms defined by the largest coordinate on each direction with following measures summarized in Table 2. In order to obtain the frontal area, it is necessary to calculate the area where models are overlapped and deduct it to the sum of both frontal areas from each model separately. As the variables on this problem are defined by 'x' and 'y', which are referenced by the gap between both models, and the distance between their centerlines. The frontal area and coordinates used to calculate it, are displayed on a planar view in Fig. 4. The definition of each length is as follows:

- h_A : vertical distance from test section symmetry line up to upper vertex of DrivAer.
- h_B : vertical distance from test section symmetry line up to midpoint on the rear of wake emulator.
- d_{min} : vertical distance from test section symmetry line up to lowest vertex of wake emulator.
- d_{ov} : overlapping vertical distance calculated from the lowest vertex of wake emulator to upper vertex of DrivAer.

Coordinate	Length [m]	Width [m]	Height [m]
Wake Emulator	x_e	y_e	z_e
	0.75	0.45	0.39
HP DrivAer	x_d	y_d	z_d
	1.62	0.62	0.50

Table 2. Models simplified coordinates values

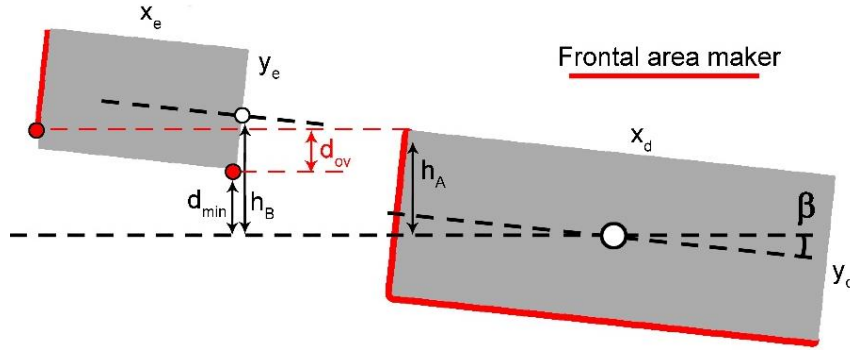


Fig. 4 Frontal area planar view coordinates sketch

In addition to these formulas, it is necessary to note that one more condition must be stated: if $d_{min} < 0$ and $d_{min} < h_A$, it means that the emulator does not stand out of the DrivAer model. Therefore, the emulator is completely in front of DrivAer and does not increase the frontal area. Hence, it is possible to calculate the frontal area for the emulator (A_e) and the HP DrivAer (A_d), as displayed in Eq. (2) and (3),

$$A_e = z_e * (y_e * \cos\beta + x_e * \sin\beta - d_s) \quad (2)$$

$$A_d = z_d * (y_d * \cos\beta + x_d * \sin\beta) \quad (3)$$

With the frontal area of each position, it is possible to calculate the correction value (ε_t) for the dynamic pressure (q) stated in Ref. [8], removing the effect of the reduction of test section cross area due to the models. This calculation is exemplified by Eq. (4) and (5). The values of H_{wt} and W_{wt} respectively define the height (1.8m) and width (2.4m) of wind tunnel cross section.

$$\varepsilon_t = \frac{1}{4} * \frac{\text{model frontal area}}{\text{test section area}} = \frac{1}{4} * \frac{A_e + A_d}{H_{wt} * W_{wt}} \quad (4)$$

$$[q_{corrected} = q_{measured} * (1 + \varepsilon_t)^2] \quad (5)$$

The complete procedure results in a variation of the blockage ratio from 7.14% up to 12.55%. Largest blockage happens at largest yaw angle (6°) and a relative position between the wake emulator and DrivAer of $x/L = 0.4$ and $y/L = 0.2$. These calculations correct the dynamic pressure due to the frontal blockage of the test section, and from all cases, the coefficients are reduced from a 3.48% on the lowest blockage case up to 6.39% on the largest one. Having seen the magnitude of the variations, it confirms the importance of considering the blockage effects on wind tunnel testing, as it could lead to more than 6% error in worse cases.

B. CFD Simulations

This section is intended to study the flow features along the wake emulator and how they can affect the trailing car through three dimensional CFD simulations which are carried out with *ANSYS Fluent v19.2* as a solving software. Model setup and preparation is done with *ANSYS Workbench* and *Space Claim* feature to do so. The input CAD geometry is created with *CATIA v5* from the drawings of the decisive wake emulator provided in Ref. [3], and the missing thickness of front splitter of 3mm. Even though the real model counts on two thin metal plates on the wheels where the body is screwed on the ground, and one strut at the front. These elements are not taken into account through this CFD study, as they do not present a significant role on the flow field behavior.

As stated in Ref. [3] and other references mentioned there, it is concluded that RANS modelling with 2nd-order and Hybrid Gauss-LSQ, Realisable k- ε is a cost-effective solution in terms of external automotive aerodynamics studies, such as the present study. k- ε model is accurate at fully turbulent areas, but this turbulence model does not capture accurately flow behavior close to the wall. For this reason, three prism layers are applied on the body to describe better the flow features around the emulator. The parameters at the time of the acquisition of experimental data used on this case are summarized in Table 3:

Property	Average Value	Units
Density	1.1642	kg/m ³
Pressure	100825	Pa
Dynamic Viscosity	1.8567x10 ⁻⁵	Pa·s

Table 3. Flow properties

Recommended CFD guidelines are also mentioned in Ref. [3], where it is stated the best domain size to capture the features of the current case. In order to show a possible asymmetry of emulator's wake, this case is run with a complete domain of 4 m width on each side without considering a symmetry plane. To better capture the wake features of the emulator, two refinement volumes have been defined around the body and its wake volume. Refinement volumes are extended symmetrically to each side of the emulator 1m and 0.6m respectively. The dimensions of the domain are shown in Fig. 5.

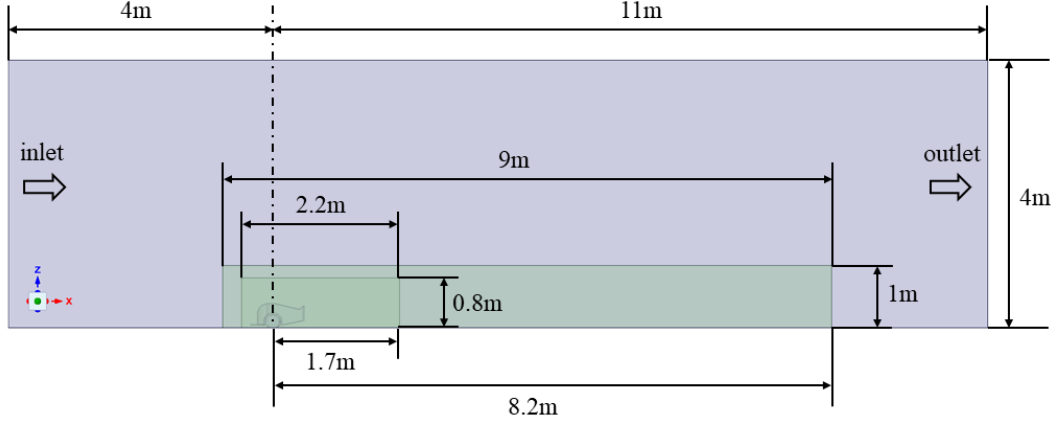


Fig. 5 CFD domain and refinement volumes dimensions

Finally, the boundary conditions are set with a velocity inlet of 40m/s, a pressure outlet with an ambient pressure of 100825 Pa together with a turbulence intensity (I) of 1%. As previous testing with the emulator and current's project conditions are with a stationary ground, this has a condition of no-slip with null velocity. Three different yaw angles are studied on this project, thus, simulation conditions are kept on all cases, as only the emulator (CAD geometry) is turned to its yaw angle on each case to simulate crossflow condition, remeshing the volume with same parameters.

Mesh is generated with *poly-hexcore* setup (mosaic mesh) and three prism layers on the body and a specific element size defined for each area. In all cases, the growth rate of mesh size is established to the standardized value of 1.2. The largest refinement volume is set with a size of 25mm and smallest volume with a size of 8mm. The main body, the wake emulator, is defined with a minimum surface mesh element size of 2mm and a maximum of 8mm, in addition to a more refined area on wheel's contact patch on the ground with a greater resolution with an element size of 1mm.

CFD simulations match the experimental data from the source in Ref. [3], as it has been summarized in section II, the main features of a high-performance wake are characterized properly. Fig. 6 shows a contour plot of total pressure coefficient (which basically represents the loss of flow energy on the wake) together with the main features on the wake with both counter rotating vortices and the central upwash (white arrows).

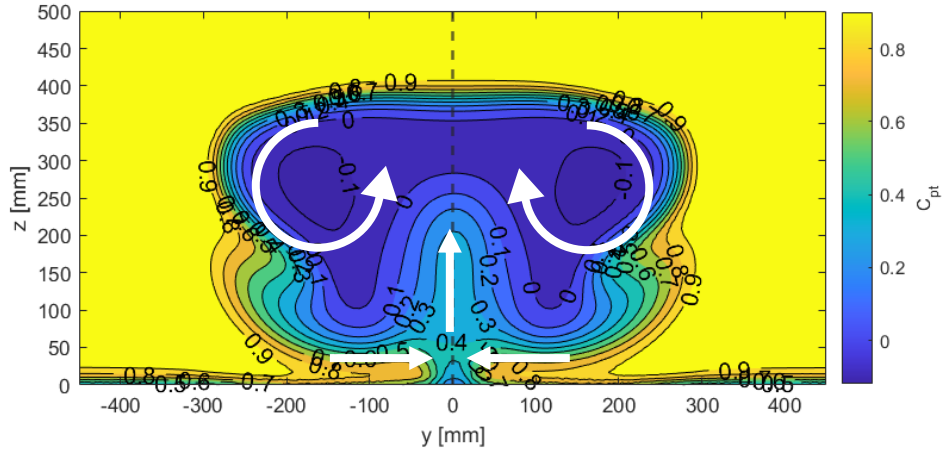


Fig. 6 C_p contour plot from CFD simulation at $x = 300$ m

IV. Presentation of Results

Each run for a specific relative position provides the values of aerodynamic coefficients on the trailing car. Throughout this work, the most relevant aerodynamic coefficients of forces and moments to be studied are the axial force (C_x), side force (C_y), vertical force (C_z) and pitching moment (C_{my}). These ones are defined with the directions stated in Fig. 7, with the 'x' axis is always aligned with model's centerline and the vertical axis going upwards.

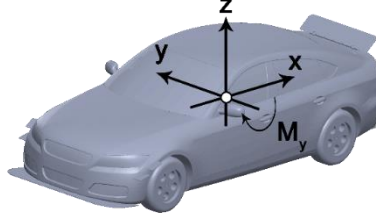


Fig. 7 Forces and moments coordinate system

Results are presented with several plots which show the evolution of a particular aerodynamic coefficient through a specific relative position. These show the increment (ΔC_i) of C_i coefficient from the reference value obtained from the HP DrivAer alone for each yaw angle, throughout a specific relative distance (x/L or y/L). For side force, vertical force and pitching moment plots, they also display other three markers which state the value where the coefficient shifts between positive to negative value. Fig. 8 show two sample plots for C_x (left) and C_z (right). To analyze all sets of plots it is important to be familiarized that positive ΔC_i shows an increment of the coefficient from the reference value, whereas a negative one shows the reduction of the same. In addition, if the values are above their respective yaw angle vertical axis marker, it represents that it has a positive value, while being below its reference line, show that it is negative.

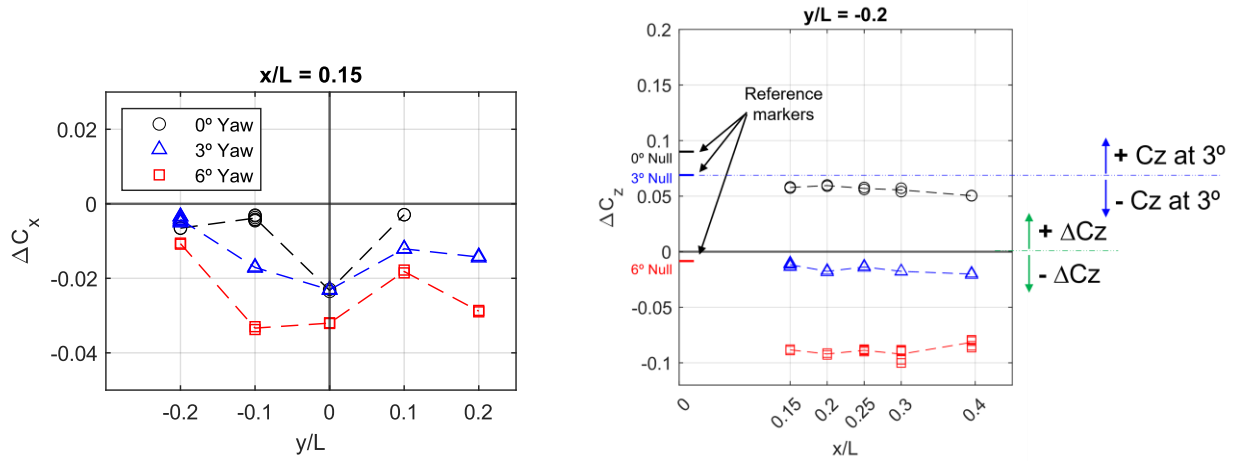


Fig. 8 Axial force sample plot (left side) and vertical force sample plot with reference markers (right side)

The first step to begin this study is to acquire the reference values of HP DrivAer and compare following tests to characterize the variations on each relative position, thus, the model is tested without the emulator for each yaw angle. From several runs and a small variation, Table 4 gathers the average values of each coefficient and yaw angle.

	C_x	C_y	C_z	C_{m_y}
0° yaw	0.3276	-0.0177	-0.0900	-0.0402
3° yaw	0.3380	0.0915	-0.0690	-0.0421
6° yaw	0.3534	0.1984	0.0084	-0.0504

Table 4. Average reference coefficients

From these values it is possible to say that axial force (C_x) is increased together with larger yaw angle. Road vehicles are designed to move along freestream, however, if there is crossflow or any disturbance which changes the direction of the freestream, the flow around the car is completely different and vehicles' shape is not optimized with this airflow, causing an earlier detachment and a larger wake (Fig. 9).

Moving onto side force (C_y), the reference at 0° yaw is slightly deviated to the expected null value. Considering the ideal case with a complete symmetry, side force with no-yaw conditions should be zero as forces applied on each side of the vehicle would compensate each other, thus it shows an asymmetry of the model or the incoming airflow. In contrast, the behavior when yawing the model is the same as predicted, side force being increased towards positive direction. Due to the larger detachment produced by crossflow condition and larger wake on the suction side (Fig. 9), the vehicle is pushed onto that direction.

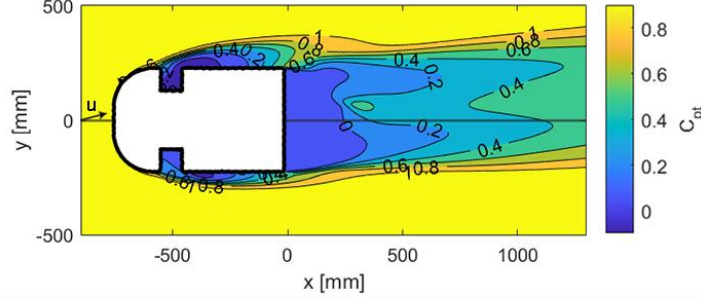


Fig. 9 C_{pt} contours at $z = 220$ mm for 6° yaw, wake asymmetry

Downforce, represented by C_z , is lost along the increment of yaw angle. Both at 0° and 3° yaw generate downforce, whereas at 6° yaw it becomes positive lift. This must be taken into consideration as racing cars highly rely on the generation of downforce to perform during competitions, and as it has been shown, the effect of crosswind significantly alters this behavior that will also affect the drivability. HP DrivAer model was developed and designed with moving ground; however, this project employs a stationary ground. This feature has a large effect on downforce generation as airflow is no longer accelerated under the vehicle, as the main responsible of creating downforce are the underfloor and the diffuser.

Finally, pitching moment (C_{my}) has the opposite trend compared to other coefficients, as it reduces along the increment of yaw angle having a greater loss of downforce at the rear axle. These values are established with negative value, describing a larger downforce at the front axle. This shift is slightly enlarged with yaw angle, transferring the loads to the front axle, alternatively, losing more downforce at the rear one.

V. Analysis of Results

A. Detailed Study Under No-Yaw Conditions

1. At the Centerline

This chapter focuses on the analysis of slipstreaming conditions without yaw angle and trailing right behind the leading car (i.e., with vehicle's centerlines aligned), representing the approach of the trailing car at $y/L = 0$ through diverse x/L (Fig. 10).

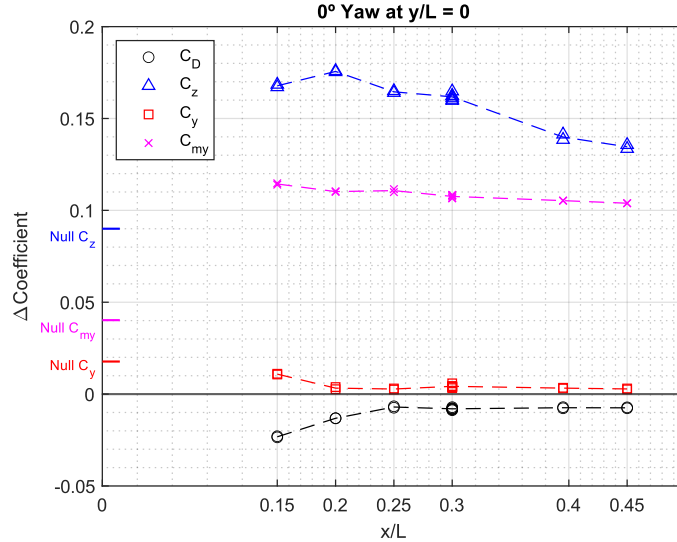


Fig. 10 Variation of coefficients at 0° yaw and $y/L = 0$

The most significant feature of axial force (C_x) is the greatest reduction at $x/L = 0.15$, the closest gap to the leading car. There is also a progressive lineal variation up to $x/L = 0.25$, however, the axial force acting on the HP DrivAer model is not affected by the emulator's wake at larger distances. Hence, the greatest interaction with leading car's wake occurs at $x/L = 0.25$. It is important to note that there is always axial force reduction when both bodies are aligned within the range of this study.

Regarding vertical force (C_z), there is a relevant increment throughout the entire range, resulting on positive lift instead of downforce at all longitudinal distances. The maximum peak of downforce's loss is found at $x/L = 0.2$, and it starts to recover from $x/L = 0.3$ onwards with nearly a linear tendency.

Side force (C_y) and pitching moment (C_{my}) are quite constant along the range although they have a slight negative slope which will converge to reference value at larger separations. Even though the vehicle is behind another body that disturbs the flow, its effect on side force is constant with a small value, apart from the peak at $x/L = 0.15$, where flow disturbances are greater. As the study is based on different longitudinal positions, the expected symmetrical behavior is kept through this range with small constant variations. As well as side force, pitching moment also shows a steady increment that represents the greater loss of downforce at the front axle in overall. Nevertheless, side force is still negative all through, while pitching moment has always a positive value, meaning that downforce is larger at the rear axle.

In overall, most significant variations on this case occur at distances smaller than $x/L = 0.25$, where the leading car's wake is much greater and the interaction with the trailing one is more relevant.

2. At Largest Longitudinal Distance

In contrast, this sub-section focuses on the study throughout diverse lateral positions (y/L) at largest longitudinal distance ($x/L = 0.4$), bringing an overview of the variations occurred on the trailing car during an overtaking maneuver, when it moves away from the rear of the leading one (Fig. 11).

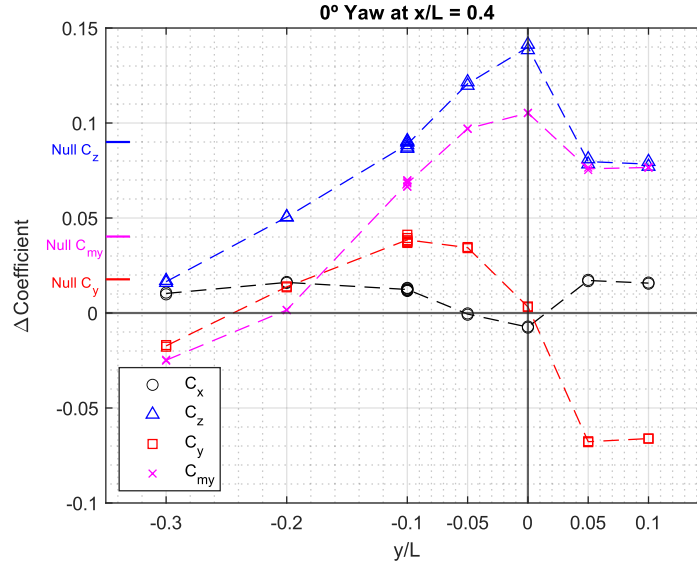


Fig. 11 Variation of coefficients at 0° yaw and $x/L = 0.4$

Firstly, results presented in Fig. 11 display an unexpected asymmetry. Both bodies are symmetrical, and study conditions are symmetrical too, however, due to unknown circumstances such as possible misalignments or asymmetrical flow features along wind tunnel's test section, it is not possible to replicate the results in both sides. The most significant representation of this lack of symmetry can be found at $y/L = \pm 0.05$, where the differences of the values are more significant.

Fig. 11 shows that there is only axial force (C_x) reduction when both vehicles are aligned with freestream flow ($y/L = 0$). In case both vehicles are not aligned and lateral distance is greater than 5% ($|y/L| > 0.05$), the axial force shifts from a beneficial reduction at the centerline to an increment within this small lateral change. From $y/L = -0.2$ and larger lateral distances, the trend is nearly constant with the smaller increment at $y/L = -0.2$ and a projected convergence to the reference afterwards.

Even though downforce ($-C_z$) is lost along all lateral distances, the most significant peak of downforce loss can be found at $y/L = 0$. Through the increment of lateral distance, downforce is rapidly recovered although it is still as positive lift until $y/L = \pm 0.1$ and shifts to the generation of downforce when $|y/L| > 0.2$.

Side force (C_y) changes significantly between $y/L = 0.1$ and $y/L = -0.1$, moving from a relevant reduction to an increment within this small range. This trend is expected to have the opposite sign as the relative position is shifted along both sides, meaning that the trailing car is pushed away from leading car's wake. Beyond $y/L = -0.1$, side force

is reduced again. However, at $y/L = -0.3$ there is a decrement of side force, showing that its effect is not constant along different lateral distances.

Like vertical force, pitching moment (C_{my}) is significantly increased at close lateral distances, showing a greater loss of downforce at the front axle, which is not recovered until $y/L = -0.2$. Furthermore, there is a change on its trend at $y/L \geq -0.2$ where the aerodynamic balance is the opposite, resulting in larger downforce at the front axle.

This case shows the importance of the variations of lateral distances during overtaking maneuver, as the trailing car will face a significant variation of aerodynamic loads that will change the behavior of the car within small distances. The next section discusses the aerodynamic forces measured under yaw conditions.

B. Analysis of Aerodynamic Forces

1. Axial Force

The evolution of axial force (Fig. 12) follows the same trend for each yaw angle, and it is also similar along diverse longitudinal distance (x/L) for all lateral distances (y/L), with an offset between each yaw angle, being the largest difference with greater yaw angles. Despite this general tendency occurs at diverse lateral distances, there is a different behavior at $y/L = -0.2$, where axial force variation is nearly the same for 0° and 3° yaw, whereas it does not follow the predicted change at 6° yaw with other variations. This could be due to a smaller loss of pressure on the right-hand side for 6° yaw as it is more affected by emulator's asymmetry under larger crosswind, compared to other yaw angles (Fig. 13).

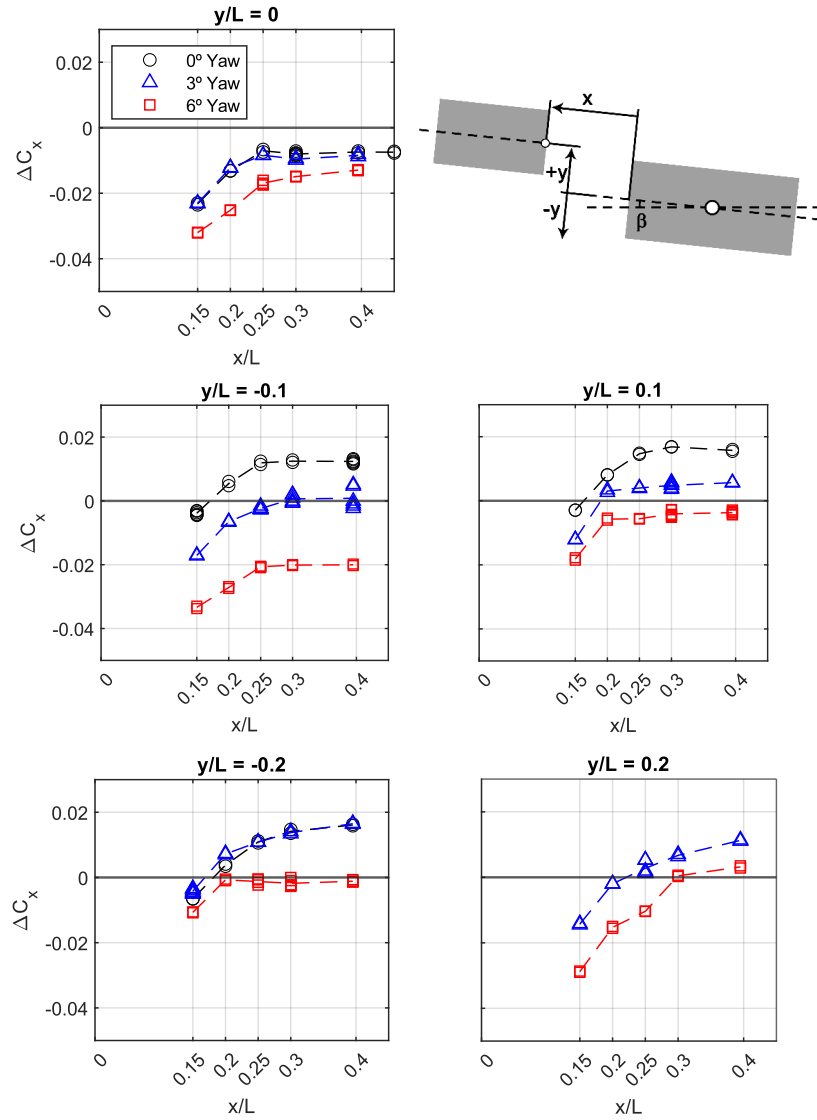


Fig. 12 Axial force coefficient variation for each yaw angle through longitudinal position (x/L)

Furthermore, the asymmetry of these configurations is visible and more relevant under no-yaw conditions, as there are greater changes here at $y/L = 0.1$ than the negative side. From 3° yaw angle, axial force variation is larger at $y/L = 0.1$ than $y/L = -0.1$, whereas the opposite happens at $y/L = 0.2$, when the variation is smaller than $y/L = -0.2$. On the other hand, axial force reduction at 6° yaw is larger at $y/L = -0.1$ than $y/L = 0.1$ while the contrary occurs at larger lateral distances, when axial force is significantly more reduced at $y/L = 0.2$ than $y/L = -0.2$. These circumstances are due to the interaction between the main vortices from emulator's wake and the trailing car (Fig. 13). Mainly, the largest low-pressure area on the wake (left hand side) is directly striking the trailing car at positive y/L , whereas the right-hand side slightly interacts with the car at negative y/L . Therefore, it is possible to say that low-pressure area on the wake reduces the axial force on the trailing car (see right picture in Fig. 13).

There is a reduction of axial force only at $y/L = 0$ along all longitudinal distances, and this is more significant at closer distances with a more abrupt change, when the trailing car faces the entire wake from the emulator. Its evolution is linear up to $x/L = 0.25$ for all y/L , and then it becomes nearly constant through larger distances. Until $x/L = 0.25$, axial force is highly influenced by the upwash circulation from emulator's diffuser, which reduces progressively the dynamic pressure on the trailing car (Fig. 14).

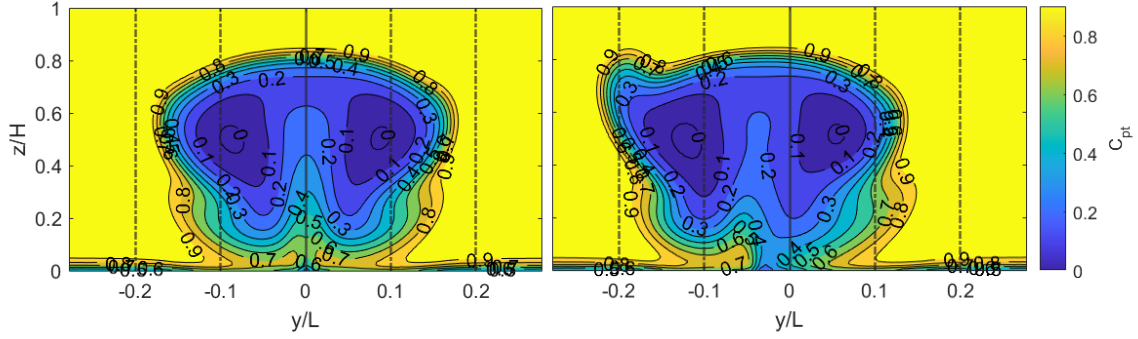


Fig. 13 C_{pt} contours at $x/L = 0.3$ for 0° yaw (left) and 6° yaw (right)

Axial force reduction always occurs for 6° yaw angle through all y/L , and also for all yaw angles at $x/L = 0.15$, always with a greater reduction at 6° yaw compared to smaller yaw angles as the wake for larger crosswind is greater too (Fig. 15). The trends of 0° and 3° yaw are quite similar regarding their increment, becoming almost the same at $y/L = -0.2$, and within small variation between each other at the centerline ($y/L = 0$) and $y/L = -0.1$.

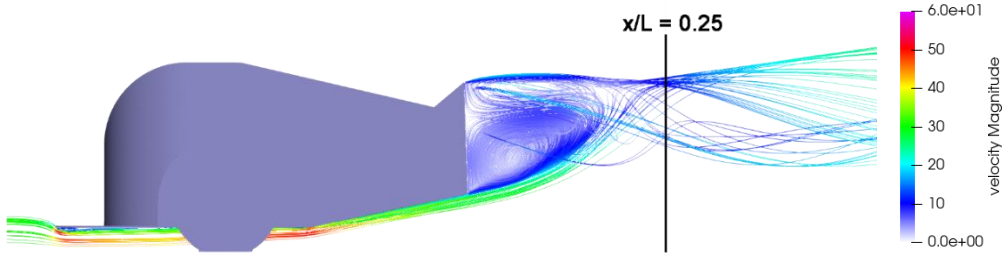


Fig. 14 Diffuser streamlines circulation at $y/L = 0$ for 0° yaw

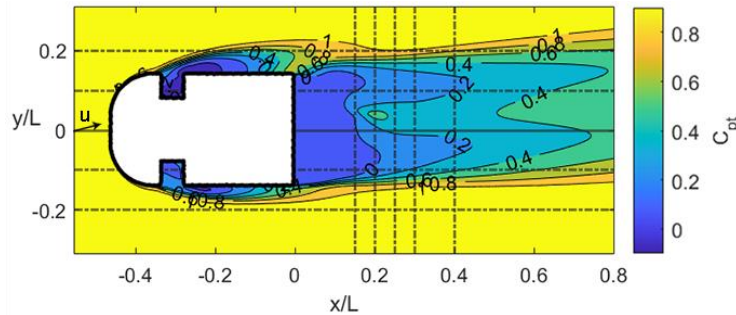


Fig. 15 C_{pt} contours at $z = 230\text{mm}$ for 0° (top) and 6° yaw (bottom), wake size

Outside the centerline ($y/L = 0$), there is an increment of axial force from $x/L = 0.2$ at $y/L = -0.1$, and before $x/L = 0.2$ at $y/L = -0.2$ for 0° and 3° yaw. In contrast, axial force variation at $y/L = 0.2$ is more abrupt than other lateral distances, becoming a more extreme situation when axial force changes rapidly along longitudinal positions. This could be due to the trailing car being hit by the stronger low-pressure area on the left-hand side, which also develops more rapidly through x/L (right picture in Fig. 13).

2. Vertical Force

The variations of vertical force coefficient through longitudinal distances are displayed in Fig. 16:

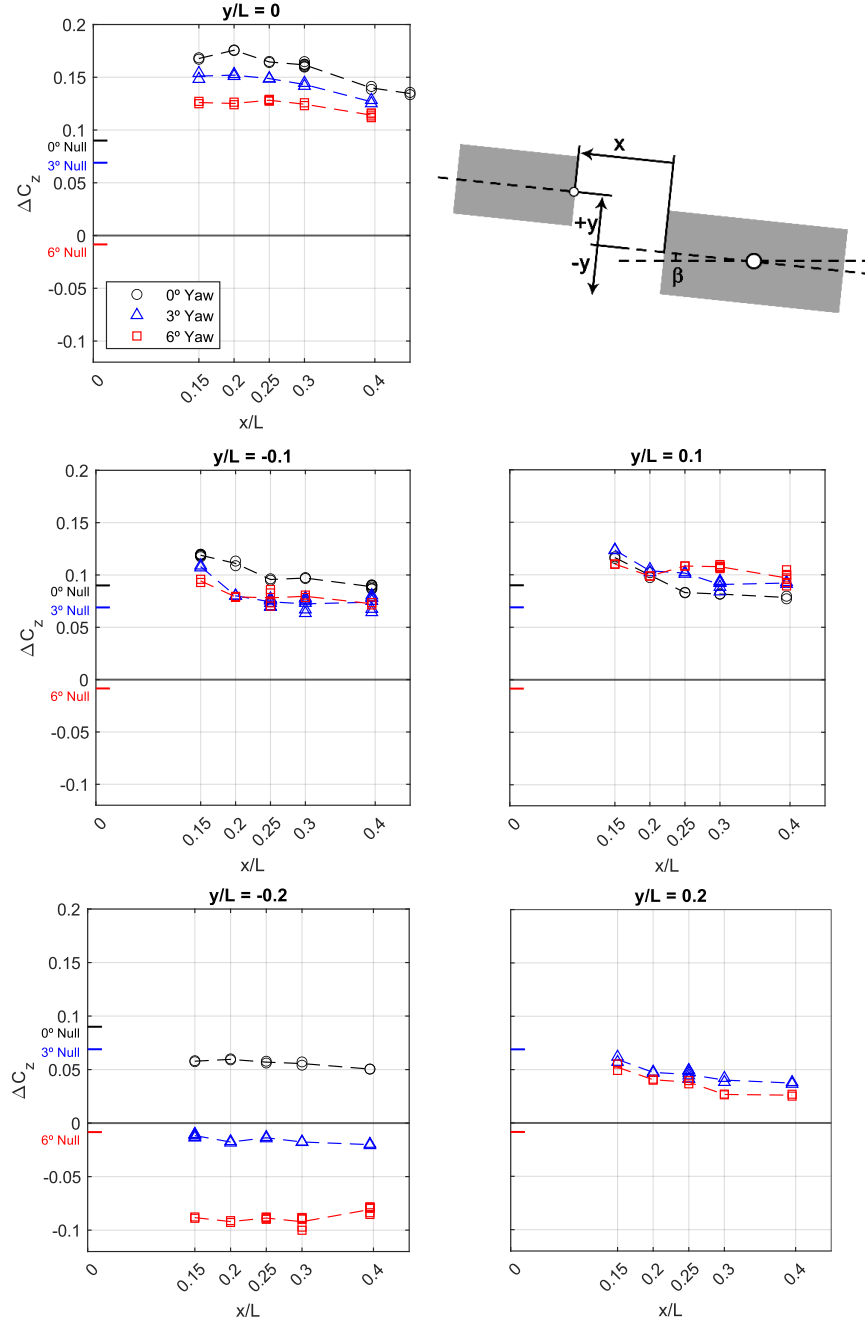


Fig. 16 Vertical force coefficient variation for each yaw angle through longitudinal position (x/L)

A clear conclusion throughout all position displayed on these plots in Fig. 16 is the general loss of downforce all through. As a general trend for all yaw angles, the greatest loss of downforce occurs at $y/L = 0$ and it slightly recovers with larger lateral distances. However, this loss is still greater at closer lateral distances ($y/L = \pm 0.1$) than larger ones ($y/L = \pm 0.2$) as the trailing car faces a smaller part of the wake. Generally, the tendency for each yaw angle is similar on each lateral distance, and drafting effect is more noticeable with 0° yaw as the change is greater than 3° and 6° yaw respectively. The main reason of the increment of vertical force is the upwash effect resulted from the two counter rotating vortices (Fig. 17).

The unique exception of downforce's loss is the case of 3° and 6° yaw at $y/L = -0.2$, when reference vertical force results on a significant increment of downforce reaching similar values between both yaw angles. Particularly this change is more relevant at 6° yaw as it shifts from positive lift to a significant generation of downforce due to a large reduction of C_z , reaching a coefficient close to the datum value with no-yaw condition ($C_z = -0.09$). This interesting feature has a completely different trend to other ones and illustrates the wide range of variation from greatest loss at $y/L = 0$ to this increment at $y/L = -0.2$.

The increment of downforce at $y/L = -0.2$ could be because the center of the trailing car directly faces the strongest downwash flow from right hand side vortex from the emulator ($U_z = -8$ m/s isoline on the right picture in Fig. 17).

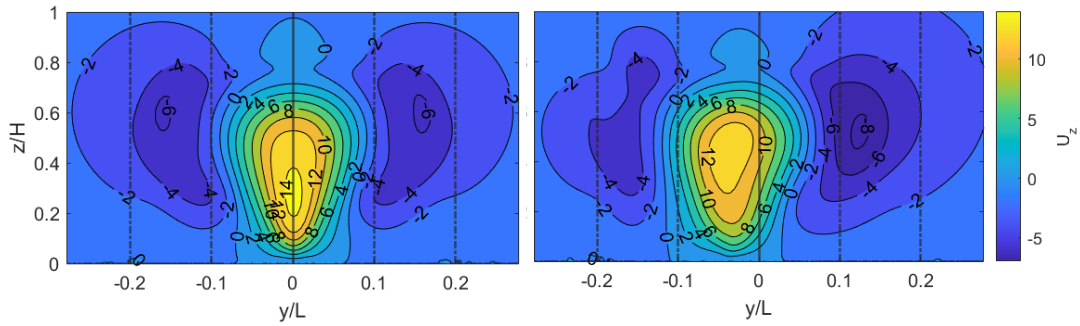


Fig. 17 U_z contours at $x/L = 0.25$ for 0° yaw (left) and 6° yaw (right) , central upwash and outer downwash due to vortices

Even though there are not enormous variations on downforce through longitudinal proximity (x/L), the largest loss occurs at closer proximity between both vehicles where the interaction with emulator's wake is higher. As both vortices develop through longitudinal distance (x/L), the central upwash is reduced together with the reduction of the downwash from the outer part of the vortices too, which compensates each other and result in a constant variation of vertical force through x/L (Fig. 18). This is visible on the size of the zones with negative vertical velocity on the right picture compared to the left one.

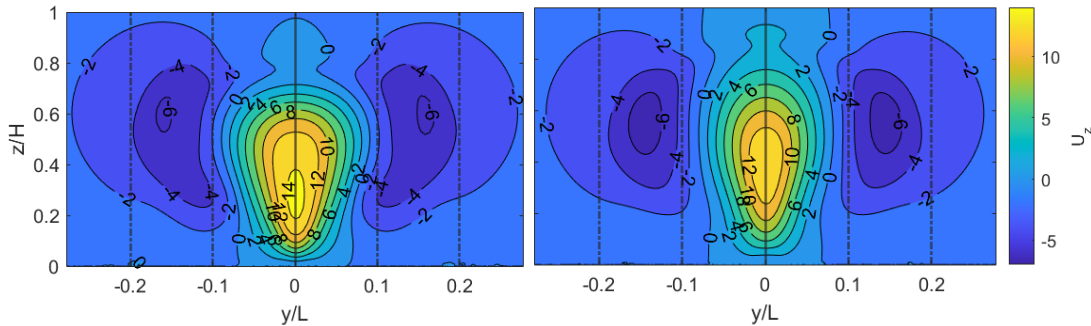


Fig. 18 U_z contours for 0° yaw at $x/L = 0.25$ (left) and $x/L = 0.4$ (right) , reduction of vertical velocity through x/L

Moreover, the values for each yaw angle are quite similar at $y/L = \pm 0.1$; particularly, but with a larger increment for 0° yaw at $y/L = -0.1$ while other yaw angles are slightly smaller here. The opposite occurs at $y/L = 0.1$ with a larger loss of downforce under crosswind conditions. Even though the left hand side of the emulator has a larger wake, most of it is caused by the circulation due to yawed body; however, this does not happen on the right side which results on a vortex that has a more coherent structure with a steady rotation that increases the vertical velocity on that area (Fig. 19).

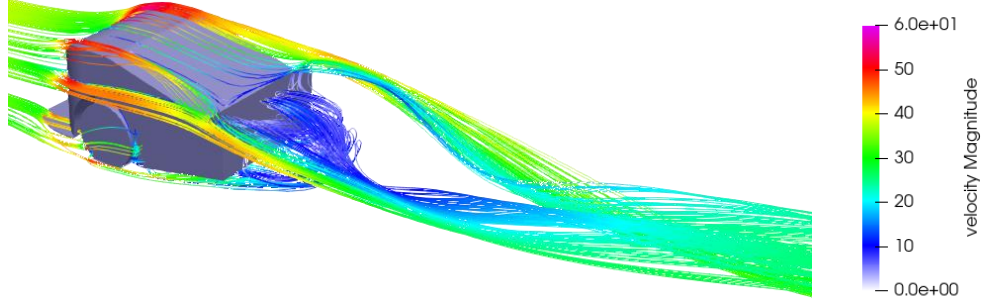


Fig. 19 Vortex streamlines at 6° yaw, difference between both sides

For 0° yaw, vertical force shifts from positive lift to downforce at $x/L = 0.4$ and $y/L = -0.1$, while this change occurs at $x/L = 0.25$ with $y/L = 0.1$. Considering a predicted ideal symmetry for 0° yaw in both lateral distances, the trends and inflexion points of vertical force should be equal, resulting in a greater similarity between all yaw angles at $y/L = \pm 0.1$. It is possible to find a special behavior at $x/L = 0.2$ on every case where the slope of vertical force evolution is modified, meaning that the development of emulator's wake has a particular impact on the rear car at this relative distance, which is more visible at 6° yaw.

Contrarily to small lateral distances ($y/L = \pm 0.1$) with similar variations for each yaw angle, the difference between each yaw angle is enlarged at $y/L = -0.2$. On the other hand, values of vertical force are nearly the same at $y/L = 0.2$, illustrating a significant difference between both sides of lateral distances under yaw conditions, as emulator's wake is larger with greater crosswind magnitude. meaning that the ideal position to overtake is at $y/L = -0.2$ in regard to downforce generation. This is due to the relative position of the trailing car and which part of the vortices from the emulator it faces directly (Fig. 20).

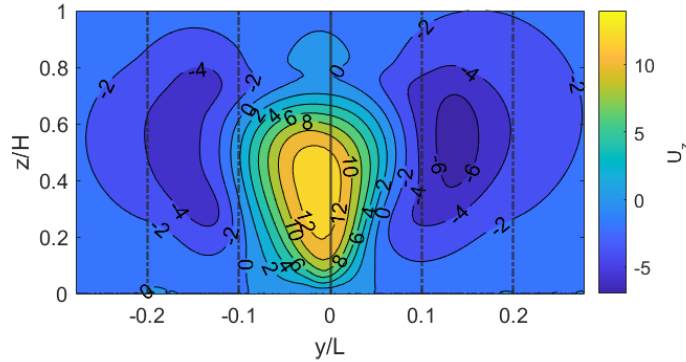


Fig. 20 U_z contour for 3° yaw at $x/L = 0.25$, vertical force asymmetry

3. Side Force

Beginning with 0° yaw, the trends of side force (Fig. 21) are fairly constant at all lateral distances (y/L) with a small variation when moving longitudinally (x/L), but it has a quicker reduction at $y/L = -0.2$. The reduction of side force at $y/L = 0$ is particularly reduced to almost null value from $x/L = 0.2$ onwards. Focusing on the differences at $y/L = \pm 0.1$, side force is reduced at $y/L = 0.1$ whereas it is increased at $y/L = -0.1$. This could be due to the lateral velocity induced by the counter rotating vortices of the wake, as most of trailing car faces a negative velocity right on its hood at $y/L = 0.1$ from the inward flow from clockwise vortex with negative lateral velocity that pushes it to the negative side of 'y' (Fig. 22).

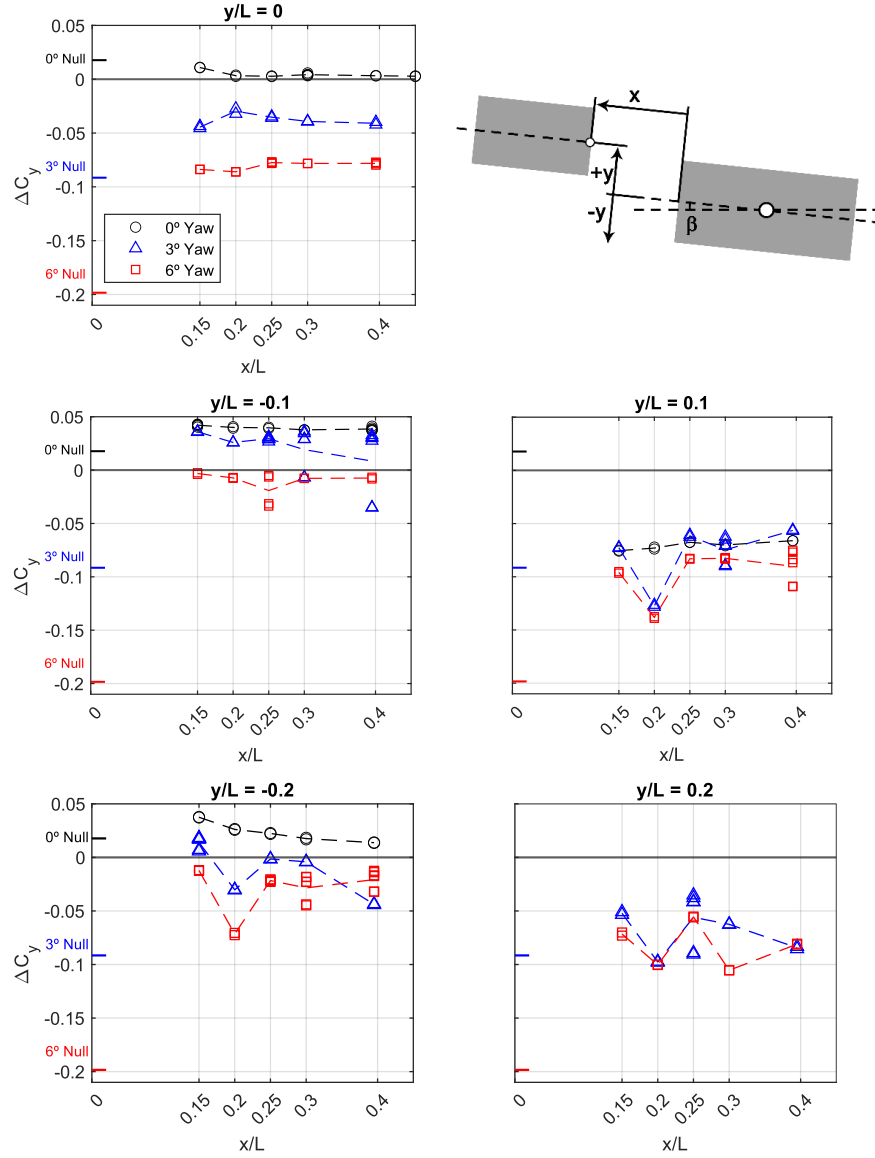


Fig. 21 Side force coefficient variation for each yaw angle through longitudinal position (x/L)

An expected antisymmetric trend between $y/L = \pm 0.1$ does not occur for 0° yaw either, as both variations would be expected to be equal but with an opposite sign, and this restates again the lack of symmetric conditions throughout the experimental testing. Resulting on a greater variation of side force in absolute value at $y/L = 0.1$ rather than $y/L = -0.1$. In the end, an increment of side force only occurs for 0° and 3° yaw at $y/L = -0.1$, in addition to 0° yaw for small x/L at $y/L = -0.2$. The most different location is at $y/L = -0.2$ where side force shifts from positive to negative value for 0° yaw at $x/L = 0.3$, completely changing the direction of the force influencing the trailing car when approaching to the leading car at this lateral distance.

Tendencies for 3° and 6° yaw are more similar each other and their resultant side force is always positive, compared to 0° yaw which has a more constant variation (unless one single point at $y/L = -0.2$ and $x/L = 0.15$ for 3° yaw). The effect of crosswind is not compensated when trailing another car and this one is always pushed towards wind direction, being a larger side force for larger yaw angles (Fig. 9).

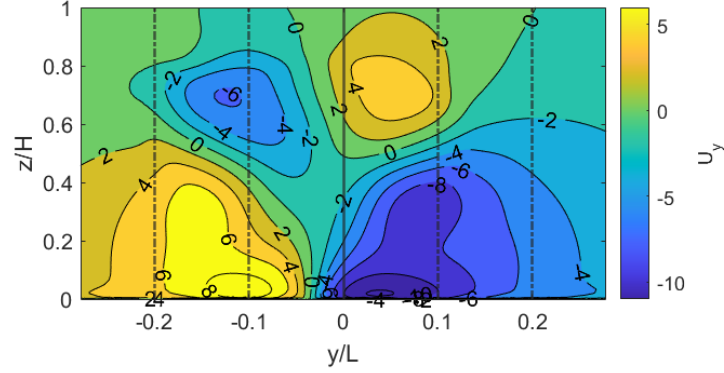


Fig. 22 U_y contour for 6° yaw at $x/L = 0.3$, inward flow from the vortices

A regular singularity that does not follow a constant trend for these yaw angles, constantly occurs at $x/L = 0.2$ for all lateral distances when side force is suddenly reduced (slightly increased for 3° yaw at $y/L = 0$). This could be due to the largest inward flow at $x/L = 0.2$ where the structure of the vortices is developed, and the effect of crosswind's detached flow is not relevant (Fig. 23). Apart from these specific points, there is also an unexpected variation for 6° yaw at $x/L = 0.3$ in $y/L = 0.2$.

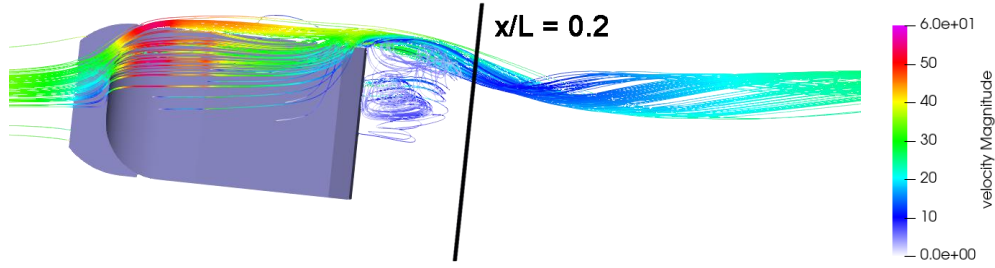


Fig. 23 Vortex streamlines at 6° yaw, maximum inward flow at $x/L = 0.2$

Another aspect to mention here are the outliers, as the plots show all testing results for truthfulness. Most of testing positions have been run more than once, in some cases particular runs are offset from the average predicted value from other repeated runs, but within a small variable range. Some of these cases are: 3° yaw at $y/L = -0.1$ and $x/L = 0.4$; and another one at $y/L = 0.2$ and $x/L = 0.25$.

4. Pitching Moment

The main aspect of these set of plots in Fig. 24 is a fairly constant variation of pitching moment with smooth changes for each yaw angle, throughout different longitudinal positions (x/L). This could be due to the proportional reduction downstream in the central upwash effect and the negative vertical velocity in the outer part of the vortices (Fig. 25), balancing the distribution of vertical force through longitudinal distance (x/L).

Most of the results show an increment of pitching moment from the reference value, apart from 0° yaw at $y/L = -0.2$ and 3° yaw at $y/L = 0.2$ which have a slight reduction of it. The effect of slipstreaming within small variations of lateral distance between vehicles ($|y/L| \leq 0.1$) result in a greater loss of downforce on the front axle, whereas at larger lateral distances ($|y/L| \geq 0.2$) it turns out to have more downforce on the front axle as the trailing car directly faces the greatest downwash velocity from emulator's vortices (Fig. 25).

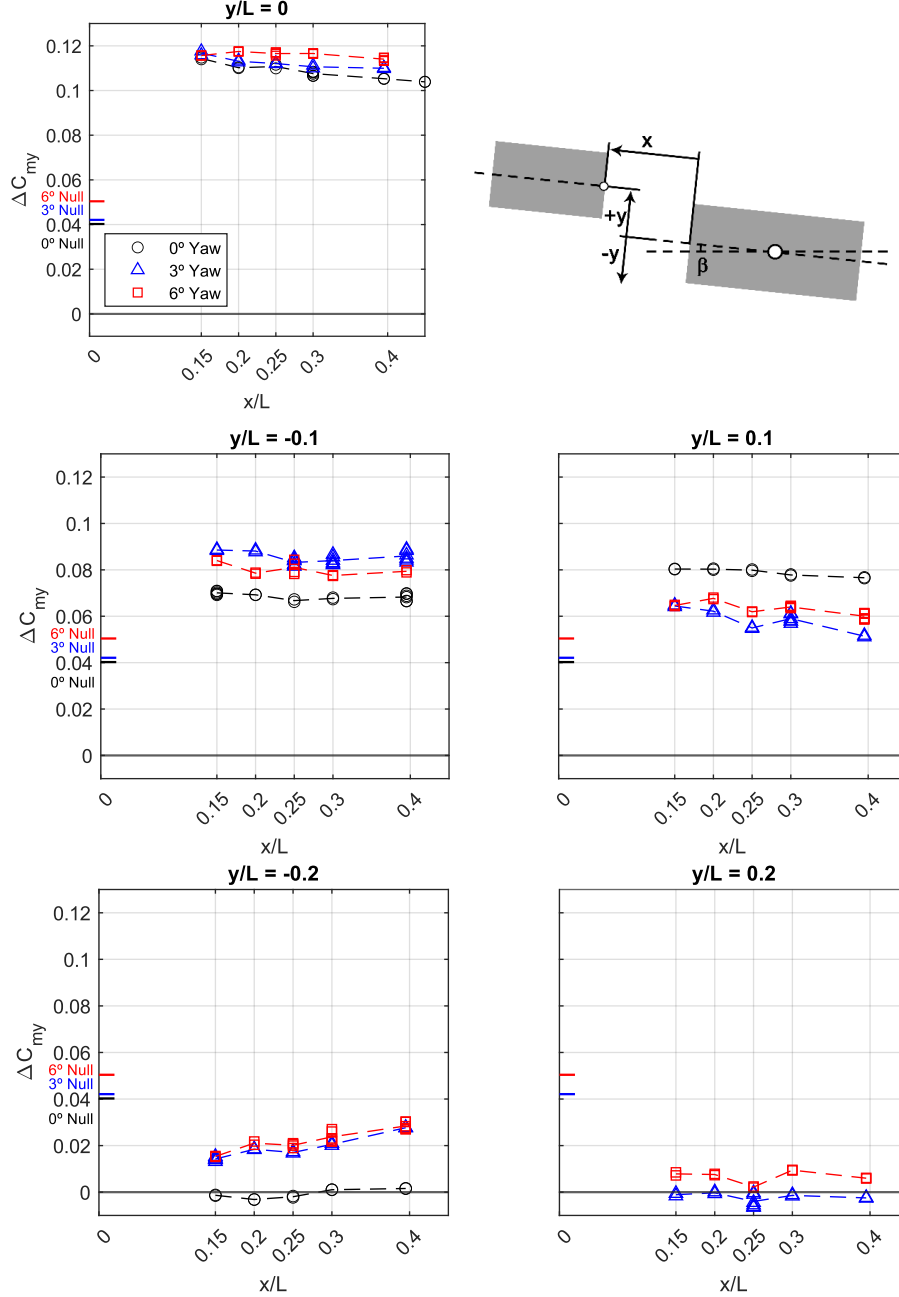


Fig. 24 Pitching moment coefficient variation for each yaw angle through longitudinal position (x/L)

When moving along diverse lateral positions (y/L), the distribution of vertical force on the axles is changed all through. On the centerline ($y/L = 0$) there is the greatest distribution moved to the rear axle, as trailing car is highly influenced by the wake. Therein, this distribution is reduced on the following lateral distance ($y/L = \pm 0.1$) even though the rear of the car has larger loads. Later, the distribution is even more reduced at $y/L = \pm 0.2$ where it reaches a load distribution shifted to the front axle. In conclusion, this variation shifts from a possible understeering to a likely oversteering. Even though variations through longitudinal distances are almost constant, for $y/L = 0$ and 0.1 , there is a tiny negative slope that reduces the pitching moment when increasing the distance to the leading car (x/L), going to a greater balance of the vertical force on both axles while reducing downforce on rear axle. In contrast, there is positive slope at $y/L = -0.2$ that also tends to balance the vertical loads on each axle while increasing the gap between both vehicles, increasing downforce on the rear axle all through. The difference between both sides of lateral distance (y/L) is not significant, although pitching moment is smaller at positive y/L .

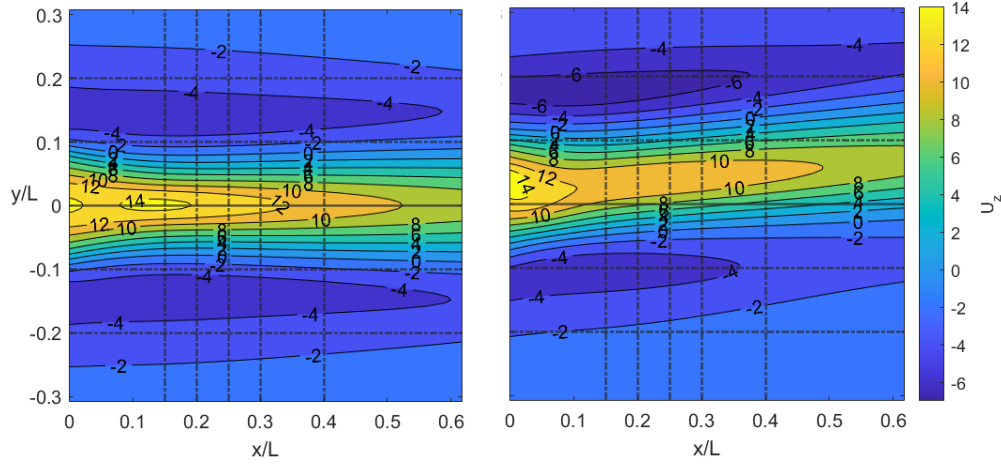


Fig. 25 U_z contour for 0° yaw (left) and 6° yaw at $z = 200$ mm, constant vertical velocity through x/L

Focusing under crosswind conditions (3° and 6° yaw angle), both yaw angles have a similar trend on each lateral distance, but the change to the marker, that shows the transition to front or rear downforce, is greater for 3° than 6° yaw and show a larger influence of small crosswind conditions on pitching moment than larger yaw angles. Additionally, there is a constant sudden tiny rise at $x/L = 0.25$ outside the centerline ($y/L \neq 0$) which changes the constant variation of pitching moment.

VI. Conclusions

A wide range of relative positions between two high-performance vehicles have been studied, making use of a shorter body replacing the leading car (wake emulator). The positions and the testing matrix for this project has been set from 8x6 ft Cranfield's wind tunnel facility, providing a detailed study of two vehicles in close proximity and small yaw angles, with the possibility to continue this work with larger distances in other facilities. For greater detail about this project, more information is available in Ref. [9].

The testing gathered a large amount of data from the interaction of a leading vehicle's wake and a trailing car, which is highly influenced by both counter rotating vortices from leading car. Therefore, it is possible to state the following general conclusions from the variation of aerodynamic forces and moments on the trailing car:

- Greatest variations occur when the trailing car is right behind the leading one ($y/L = 0$).
- The trends for all yaw angles are quite similar each other through diverse relative positions (x/L and y/L), but with different magnitudes.
- The largest variation of aerodynamic coefficients, in absolute value, is found for vertical force at $y/L = 0$, with the most significant increment.
- For vertical force, side force and pitching moment; the variations through longitudinal distances (x/L) are fairly constant, whereas they are more abrupt through lateral distances (y/L).

Going into a greater detail for each aerodynamic force and moment, the following conclusions have been found:

- Axial force:
 - A reduction is achieved at $y/L = 0$, and $x/L = 0.15$ for all cases. Additionally, it is always reduced for 6° yaw in all positions.
 - There is a progressive variation up to $x/L = 0.25$, therein, the variation remains constant.
 - For 0° yaw and $y/L \neq 0$, there is an increment for $x/L > 0.15$.
 - Variations on different lateral distances ($y/L \neq 0$) are quite similar each other.
- Vertical force:
 - There is always a loss of downforce which results in positive lift, apart from $y/L \neq -0.2$ where vertical force is reduced and results in generation of downforce.
 - Under crosswind conditions, the most beneficial variation of vertical force for the trailing car is at $y/L < 0$.
 - The variations for each yaw angle are almost the same (without considering $y/L = -0.2$ case).
 - Vertical force on the trailing car is highly influenced by leading car's vortices and their upwash and downwash velocity.

- c) Side force:
 - a. For no-yaw conditions, the trailing car is pushed away of leading car's wake.
 - b. It normally has a positive value, and this is more significant for larger crosswind conditions, although it is reduced at $+y/L$.
- d) Pitching moment:
 - a. It is increased in all cases, with largest increment at $y/L = 0$ and a progressive reduction through larger lateral distances, showing the greatest loss of downforce on the front axle.
 - b. At close lateral distances ($|y/L| \leq 0.1$), downforce balance is shifted to the rear axle.
 - c. At large lateral distances ($|y/L| = 0.2$), downforce balance is shifted to the front axle.

The main part of the project regarding wind tunnel testing has defined the interaction between both vehicles in close proximity, and results coincide with previous works. A visible difference, however, the variation of downforce and its balance on each axle differ from predicted results, what is due to the difference on the models used and the way they generate downforce.

The statistical analysis of experimental results has proved a reliability of the values with a small uncertainty. Furthermore, the repeatability of the testing has also shown that the procedure during the testing period has remained constant and there are no significant differences with diverse runs at the same position.

CFD simulations of the wake emulator have provided a useful insight to analyze the main features of high-performance vehicle's wake, and how it can affect a trailing car. The differences between no-yaw and crosswind conditions have been assessed, showing the asymmetry behavior with yaw, creating a larger wake at the left-hand side of the leading car and a stronger vortex in the right.

This project and Ref. [9] provide a large amount of information and data which can be used in future research projects. Due to the adaptable design of the wake emulator, this project also provides some guidelines to study the impact on different car's geometries (fastback, notchback and estateback). High-performance DrivAer was designed with a moving ground, however, as this testing used a stationary one, the behavior of the vehicle was also altered, resulting on a drastic loss of downforce. Finally, the conclusions on the effect of the leading car have been stated with CFD simulations with the single wake emulator, however, the flow is also altered because of the trailing car, for that reason, it will be useful to simulate both models together and characterize the real effect between both.

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Use of an aerodynamic wake emulator to assess the impact on a high-performance ground vehicle in close proximity

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