

Subject: Physics

Analyzing the relationship between Speed and Downforce, and Drag in a race car

RQ: How does a velocity of a car affect the aerodynamic drag and downforce acting on the rear wing with an Angle of Attack at 21.4° ?

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Contents

1	Introduction	3
1.1	Source of motivation	3
1.2	Research Question	3
2	Background Knowledge	3
2.1	The origin and behaviour of aerodynamic forces	4
2.2	Observation of aerodynamic principals in an isolated environment	7
2.3	Why is angle of attack important?	8
2.4	Computational Fluid Dynamics	9
3	Hypothesis	11
4	Methodology	11
4.1	Variables	11
4.2	Simulation Software 1: Assetto Corsa (AC)	11
4.3	Simulation Software 2: OpenFOAM	12
4.4	Procedure -Data collection from Assetto Corsa	12
4.5	Procedure -Data collection from OpenFOAM	12
5	Raw Data	13
5.1	Processing of Raw data	13
6	Data analysis	15
7	Further analysis	16
8	Conclusion	19
9	Evaluation	20
9.1	Quantitative Uncertainties	21
9.2	Qualitative Uncertainties	22
9.3	Possible Improvements	23
10	Further research	23

1 Introduction

1.1 Source of motivation

I have been fascinated by cars ever since I was a child. I enjoyed learning about the mechanical engineering that goes behind car manufacturing, let alone making a race car. But what specifically caught my interest was the shape of these vehicles. It is quite known that cars that are sleeker move faster than cars with orthogonal geometries. But looking at the car structures in a Formula 1 race, I noticed that although their general shape is very similar, looking closely at the body, front wing, rear wing very slight changes can be seen. Every slight change in curvature of the body could result in significant changes in performance.

Aerodynamics can be very helpful, not only in terms of faster race cars and better racing which improve the entertainment sector, but also improving efficiency of cars, boats and planes. Car manufacturers, implement the knowledge gained from their motorsports division and apply it to their production vehicles. Making cars not only go faster but improving the economy of the car. These changes have been a major factor in the evolution of road cars over the years. Additionally, understanding the relationship between drag and car velocity could help to design a clever engine cooling system. Production cars are usually cooled by the air intake from the front grill, but the block shaped parts of the engine can significantly increase drag. Understanding the latter relationship helps decide to what extent can one increase the drag coefficient of the car without resulting in loss of performance.

The aim of this experiment is to understand how the fundamental aerodynamic forces acting on a race car can affect its performance. This research aims to answer the following research question:

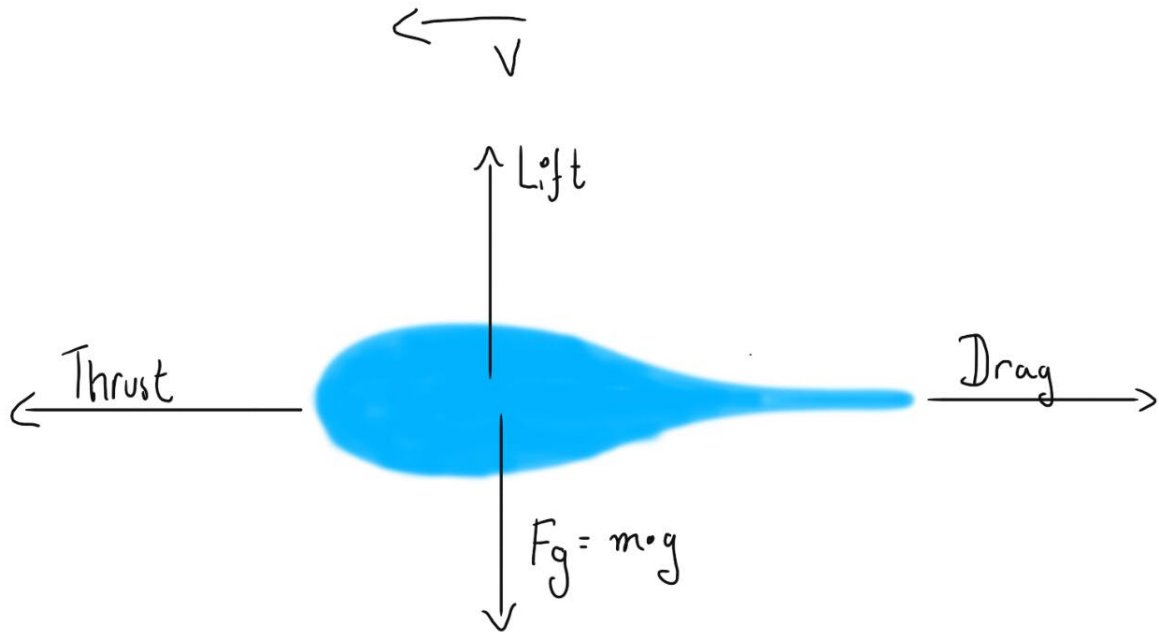
1.2 Research Question

How does a velocity of a car affect the aerodynamic drag and downforce acting on the rear wing with an Angle of Attack at 21.4° ?

2 Background Knowledge

When an object is moving through space 4 specific forces act on it. These forces are Thrust, Gravitational force Drag force and Lift/Downforce. *figure 1* represents a freebody diagram of these forces acting on a teardrop-shaped object moving through air with a constant velocity.

Figure 1: Free Body Diagram of teardrop object moving with



2.1 The origin and behaviour of aerodynamic forces

Thrust: Thrust is the force that pushes a physical object to move in the direction it is applied. It can be from a car's engine or a jet engine.

In an airplane, the propeller sucks air from the front of the plane and exerts it behind the propeller, which creates a high pressure area behind the propeller and low pressure in front of the propeller. This pressure difference pushes the plane ahead.

In cars, the Internal Combustion Engine (I.C.E) applies a torque to the wheels, and due to Newton's III law and traction on the road, the car moves in a specific direction.

Downforce/Lift: Downforce and Lift are forces of the same origin but acting in different directions. Lift is actually caused by introducing a shape into a streamlines airflow, which curves the airflow and introduces pressure difference. Low pressure on the upper surface and high pressure on the lower surface pulls the object upward. [6]

Just like how wind flows below the object, it also flows above the object but stays attached to the surface due to the coanda effect. The coanda effect is the tendency of a fluid to stay attached to a convex surface can be seen

Downforce is observed due to the pressure below the object is lower than above, which pulls the object downward. Downforce can simply be achieved by turning the wing upside down.

The formula for downforce is

$$F_{DF} = \frac{1}{2} C_{DF} \rho A v^2 \quad (1)$$

where $F_{DF}[N]$ stands for the downforce. $\rho[\frac{kg}{m^3}]$ is the density of the fluid interacting with the object. C_{DF} is the coefficient of downforce, and $v[\frac{m}{s}]$ is the relative speed of collision of the object with the medium. $A[m^2]$ is the cross-sectional area of the object. This formula is derived from the formula for lift since they are the same force in different directions [7].

Drag: Drag can be thought of as aerodynamic friction. Drag is the force that acts in a direction opposite to the object's motion and is created by the difference in air pressure between the front and the rear of the car. It slows the car down and makes it difficult to maintain high speed.

Streamlined air can be thought of as a medium with multiple layers. When an airfoil is introduced into this streamlined airflow, the air particles in contact with the object will slow down due to frictional forces. This causes the second layers which is in contact with the first layer to slow down, but to a lesser extent. Every next layer would follow the same trend. This effect is illustrated in *figure 2*, where the more dotted the line is the slower that layer of air is. A CFD simulation (see *section 2.4*) of this effect can also be seen in *figure 3* where the gradient from red to blue represents the dotted line in *figure 2*. This continues until the speed of a layer is the same as before an airfoil was introduced.

The formula for drag is the similar as the equation for downforce

$$F_{DR} = \frac{1}{2} C_{DR} \rho A v^2 \quad (2)$$

except the coefficient C_{DR} , which stands for the coefficient of drag [8].

Figure 2: Effect on streamlined flow [left to right] upon the introduction of an airfoil, the more dotted the line the lower the velocity of wind

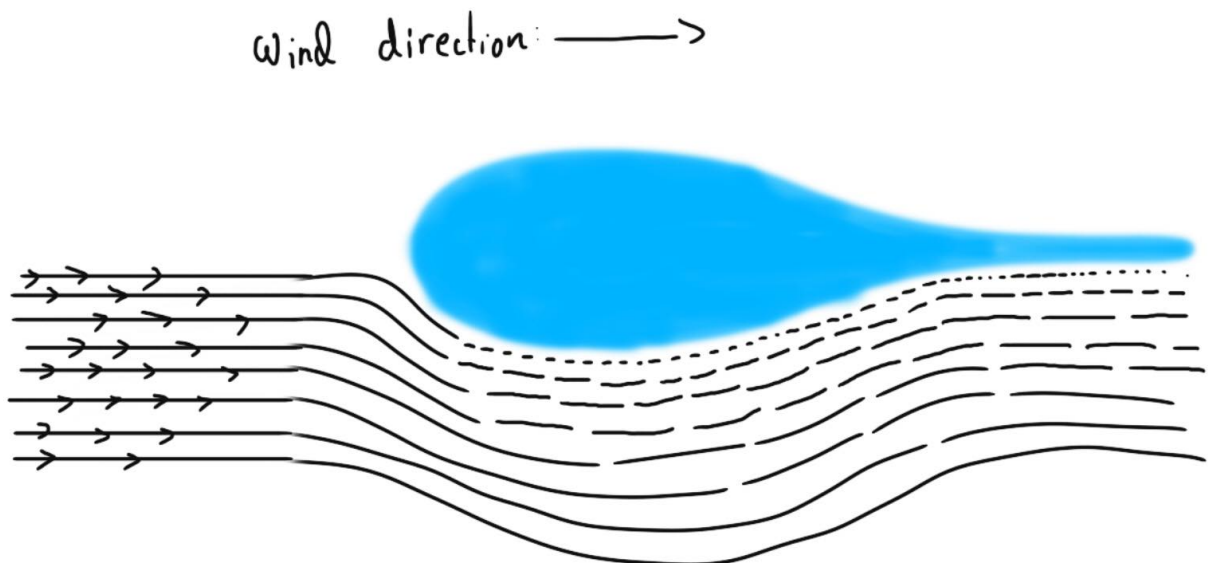
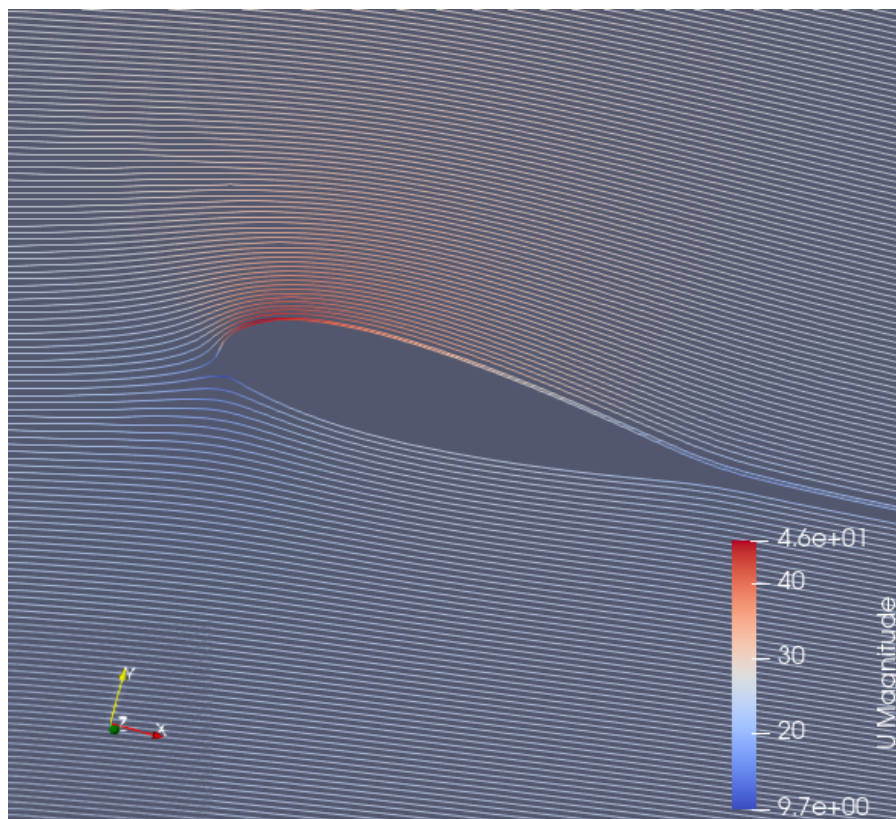


Figure 3: Simulation of a 2D airfoil in a streamlined airflow. U magnitude is the magnitude of wind velocity

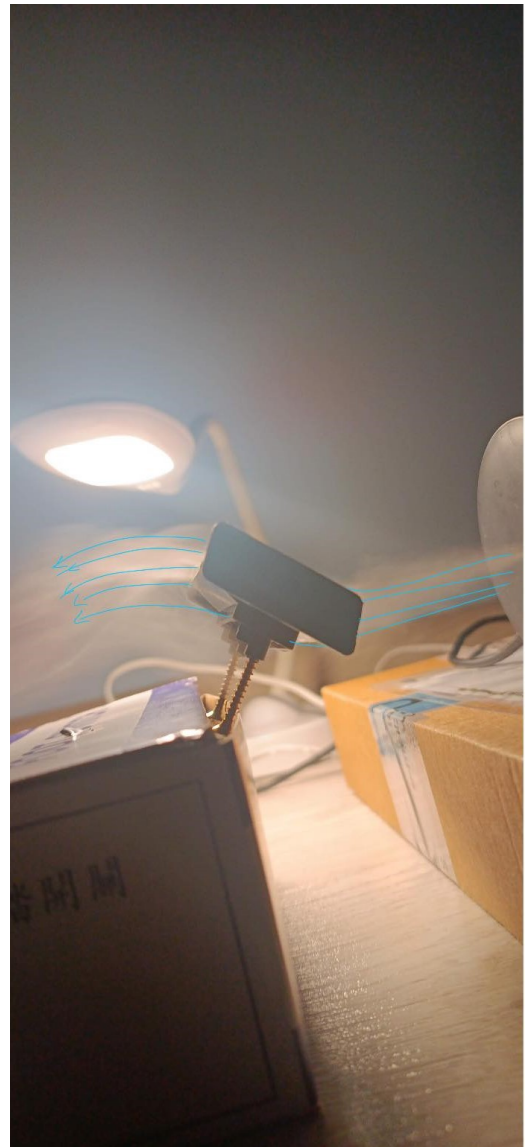


It should be noted that, this EE uses the aerodynamic interpretation of how forces are generated. Another possible interpretation is using the collision theory, that gas particles will collide with the object more frequently and transfer momentum and thus kinetic energy.

2.2 Observation of aerodynamic principals in an isolated environment

For a better visualization of the coanda effect at different AoA, an experimental setup was created. This setup included a water humidifier, a powerful fan and a rear wing from a toy car. The humidifier had an ultrasonic speaker attached to a water reservoir,0 that vibrated to create fine particles of water. On the other end of the setup, a 12V DC fan was set-up to pull the air with the water particles to create a moderately streamlined flow. A rear wing from a toy car, representing an airfoil, was placed between the fan and humidifier.

Figure 4: Observation of Bernouli's principle on low (left) and high (right) Angle of Attack

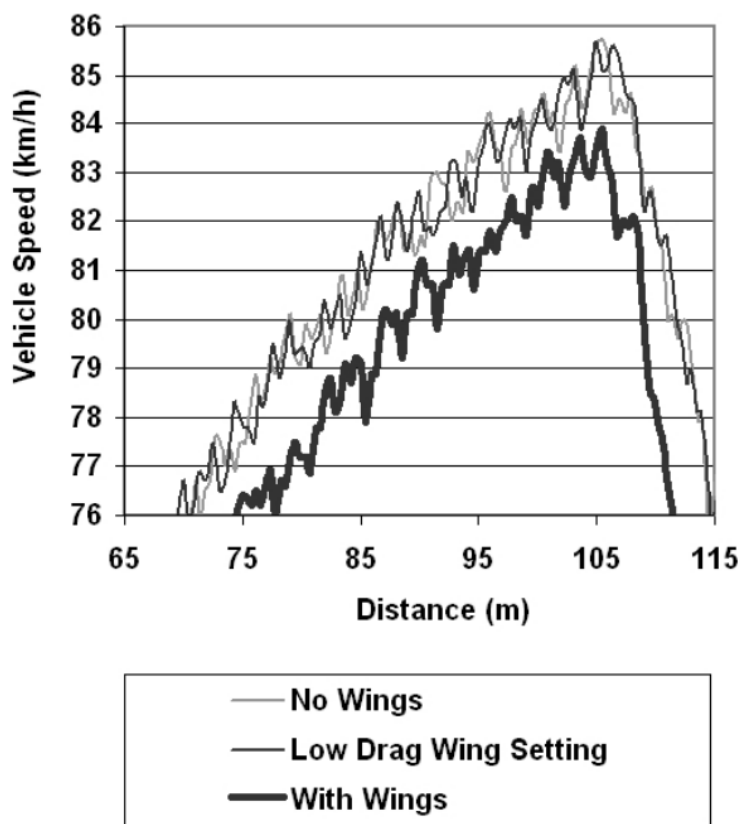


In the high AoA in *figure 4*, the coanda effect. Despite the AoA the wind follows the curvature of the wind. In *figure 4* it is shown that increasing the AoA creates more disruption in the streamlined flow.

2.3 Why is angle of attack important?

The Angle of Attack (AoA) can be increased to create more downforce at the cost of drag, or it could be decreased to create less drag at the cost of downforce. Using high AoA creates a high downforce-drag wing while using a low AoA creates a low downforce-drag wing. According to a study conducted in 2007[2], there is a significant difference in acceleration and braking between high downforce-drag setups and low downforce-drag setups. Acceleration was much slower while the braking distance was much shorter [2] *figure 5*.

Figure 5: Difference between No-wing, low-drag-wing and Full-wing, while acceleration and braking [2][figure 7]



Throughout the course of this experiment, the AoA must be a controlled variable as it is heavily influencing the forces acting on the car, which in turn affect the acceleration and velocity.

2.4 Computational Fluid Dynamics

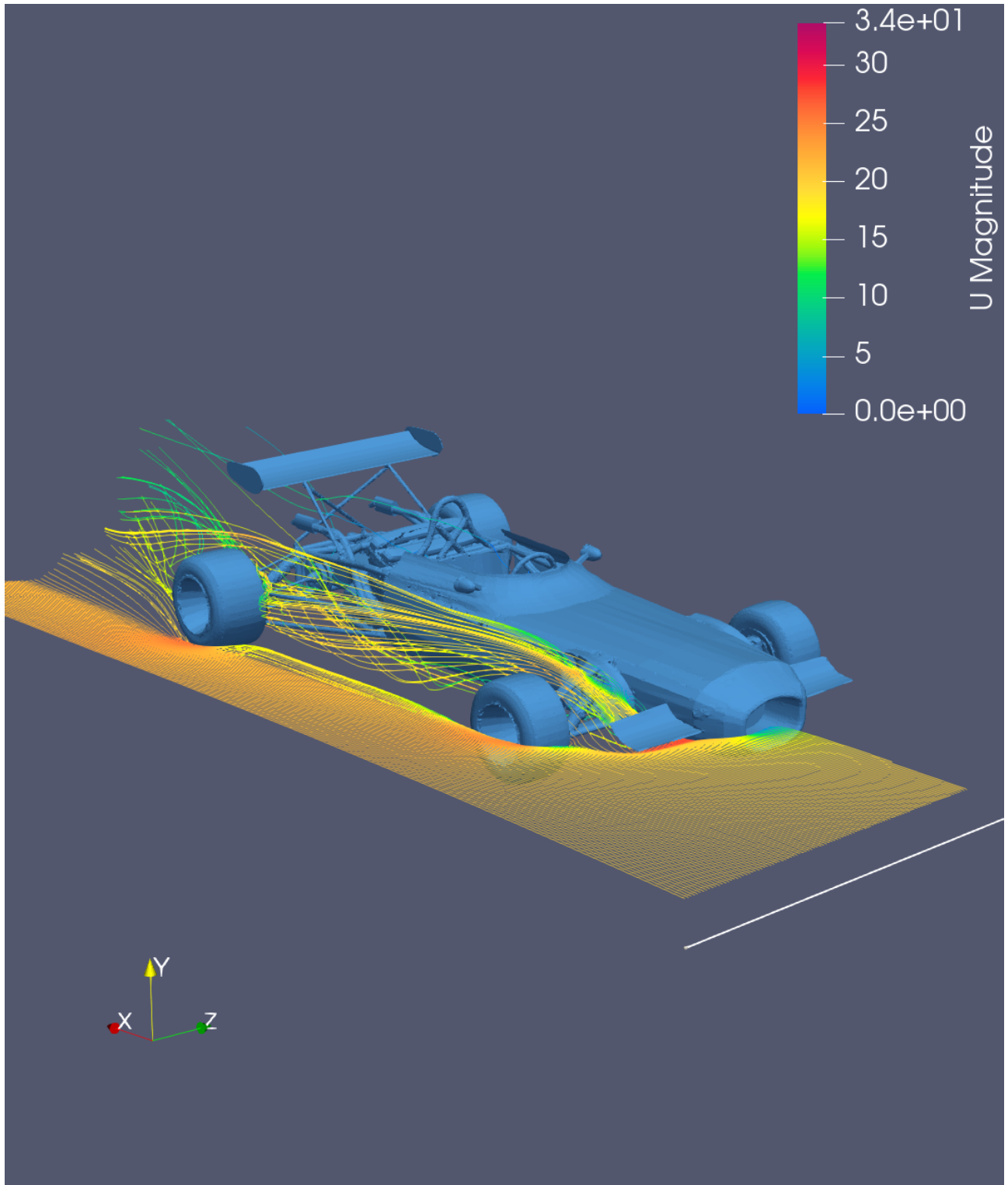
Computational Fluid Dynamics or CFD is the process of predicting physical fluid flow by solving the Navier-Stokes equation. The equations are as follow [5]:

$$\nabla \vec{u} = 0$$

$$\rho \frac{\partial \vec{u}}{\partial t} = -\nabla + \rho \nabla^2 \vec{u} + F$$

The first equation just states that the mass should be conserved. The second equation states Newton's 2nd law. Using an Open source software called OpenFOAM, these equations can be solved using the help of a computer. These equations have been proven to work with a very high accuracy in many situations as long as the object is a 2D shape. OpenFOAM runs a program on a 3D object that creates a 2D mesh of the object that wraps around the 3D object. Using ParaView to visualize the results, the force acting on it at a particular fluid speed can be extracted and compared or in some cases replaced with practical experiments. *Figure 6* shows a CFD simulation demonstration the huge turbulence created by other parts of a car.

Figure 6: Observation of vortices created by the front wing and the body in CFD simulation



For that reason, the rear wing is isolated from other downforce generating structures.

3 Hypothesis

According to *Equations (1) and (2)*, the aerodynamic forces increase proportionally to v^2 (given v is sufficiently large), of the object at a fixed AoA. As F_{DF} increases the grip levels of the car should also increase which is reflected by higher acceleration.

4 Methodology

4.1 Variables

Independent Variable: Car velocity, Relative wind speed (RWS)

Dependent Variable: Aerodynamic Forces: Drag force: F_{DR} and Downforce: F_{DF} acting on the rear wing

Controlled Variables:

- Absolute wind speed (AWS): Variable wind speed induces inconsistent change in aerodynamic forces. A constant wind speed throughout each simulation allow it to be comparable to the car speed.
- The grip level of the car that are affected by factors other than downforce can influence the progression of velocity over time. Factors that can affect grip level are **Tire compound**, **Tire Temperature** and **Tire Pressure**. These variables were kept constant throughout the experiments. Changes in these variables between trials hampers the comparison of downforce and velocity.
- Although evolution of F_{DR} and F_{DF} over time is expected to be similar, the ranges of these variables can be influenced by factors such as air temperature and humidity. Higher car body temperature increases the Drag coefficient of the body which influences the magnitude of the resultant force [4]. Additionally, higher humidity (density of air) and changing altitude (change in air pressure) results in increased magnitude of the drag force.

4.2 Simulation Software 1: Assetto Corsa (AC)

Software: [3] parameters:

Car: Open Wheeler Car, Mass: 495kg

Aero setup: Front wing: disabled, rear wing: enabled, $AoA = 21.4^\circ$

Driver aids: Auto clutch

Tyres: Pressure: 12psi, temperature: 90°

Track Features: elevation: 0°, Air temperature: 26°, Track temperature: 25°

4.3 Simulation Software 2: OpenFOAM

OpenFOAM [1] is an open source computational fluid dynamics software. It can simulate, airflow, waterflow, heat flow and electromagnetic fields. This research uses the airflow simulation by simulating a constant wind speed for 0.3 seconds.

4.4 Procedure -Data collection from Assetto Corsa

1. A track was chosen which has no turns and no elevation, only a very long straight road. An experiment is done by going from 0km/h to the top speed. A console showing the velocity of the car, the downforce and coefficients (C_{DF} , C_{DR}) is displayed.
2. Set the AWS to $w_A = 0m/s$, every second, the velocity is exported until $t = t_f = 35s$. The car reaches the top speed well before t_f . Additionally C_{DF} and C_{DR}
3. This simulation is done for $w_A = 4.86m/s$ and $w_A = 7.92m/s$ for which the velocity every second is extracted. The coefficients of Drag and Downforce are also triple checked and confirmed to be constant.
4. The car is exported as a 3D object and using OpenFOAM, computational fluid dynamics is performed for a constant wind speed of 20m/s, 30m/s and 40m/s.

4.5 Procedure -Data collection from OpenFOAM

1. The car from the AC simulation is exported as a Wavefront .obj file.
2. Using a 3D object editor, only the rear wing of the car is exported.
3. A new openFOAM project is created where this rear wing .obj file is placed.
4. The boundaries of the simulation area are manually defined. And a software is run to create a 2D mesh of the surface of the rear wing.
5. SimpleFOAM is run to simulate airflow over the rear wing for 0.3s for constant wind speed at 20m/s, 30m/s and 40m/s. This takes about 4 hours to compute.
6. After computation, the data is opened in paraView to visualize the streamlined airflow. This software also calculates the surface area of the wing, the downforce and the drag for each wind speed.

5 Raw Data

5.1 Processing of Raw data

Using equation (1) and (2), knowing the constants and the wind speed, the downforce and drag can be predicted. In this simulation, the fluid is air and the density of air is $\rho = 1.293 \text{ kg/m}^3$. In the AC simulation when the $w_A = 0 \text{ m/s}$, the speed of the fluid is the same as the speed of the car. The cross-sectional area would be the same as the surface area of the wing: $A = 1.13 \text{ m}^2$. From the AC simulation, it is known that $C_{DR} = 0.11$ and $C_{DF} = 0.28$. Lastly, the acceleration can be calculated using $v(t+1) - v(t)$ for t from 1s-35s.

The (Table 1) shows an excerpt from sheet 1 of the collected data. The rows for Time and Velocity were extracted from the AC simulation, then the Force was calculated using the force coefficients, and acceleration was calculated using $a = v(t+1) - v(t)$. This table only shows a section of the data collected when AWS=0m/s, but the complete data set contains also the data when AWS=4.86m/s and AWS=9.72m/s.

Note: DF stands for Downforce, DR stands for Drag

Table 1: Excerpt from Sheet 1

Time [s]	$v[\text{m/s}]$ (0m/s)	F_{DF} [N] (0m/s)	F_{DR} [N] (0m/s)	$a[\text{m/s}^2]$ (0m/s)
0	0	0	0	
1	0.556	0.0630	0.0247	8.33
2	8.89	16.1	6.33	6.91
3	15.8	51.2	20.1	4.50
4	20.3	83.9	33.0	3.60
5	23.9	116	45.8	3.90
6	27.8	157	61.9	2.50
7	30.3	187	73.5	3.30
8	33.6	231	90.6	2.50

For the second sheet: sheet 2, in the first column was velocity from 0- 225 km/h (Maximum wind speed achieved: top speed of car+ speed of headwind), incrementing every 1km/h. The values were then converted to m/s. Then using equation (1) and (2), the downforce and drag was calculated. Then using google sheets, a quadratic trendline was computed. And their derivatives were calculated

$$\begin{aligned}
 F_{DF} &= 0.204v^2 - 1.05 * 10^{-3}v + 7 * 10^{-3} \\
 F_{DR} &= 0.0802v^2 - 4.16 * 10^{-4}v + 2.78 * 10^{-3}
 \end{aligned}
 \tag{3}$$

$$\begin{aligned}\frac{d}{dv}F_{DF} &= 0.408v - 1.05 * 10^{-3} \\ \frac{d}{dv}F_{DR} &= 0.1604v - 4.16 * 10^{-4}\end{aligned}\tag{4}$$

$$\Delta \frac{dF}{dv} = \frac{d}{dv}F_{DF} - \frac{d}{dv}F_{DR}\tag{5}$$

equations 2, 3 and 4 were also noted into a table.

Table 2: Sheet 2: Downforce

Velocity [m/s]	Downforce [N] t1	Drag [N] t1
0	0	0
0.278	0.0157	0.00619
0.556	0.0630	0.0247
0.833	0.142	0.0557
1.11	0.252	0.0990
1.39	0.394	0.155
1.67	0.567	0.223
1.94	0.772	0.303
2.22	1.01	0.396
2.50	1.28	0.501

Table 3: Sheet 2: Derivatives

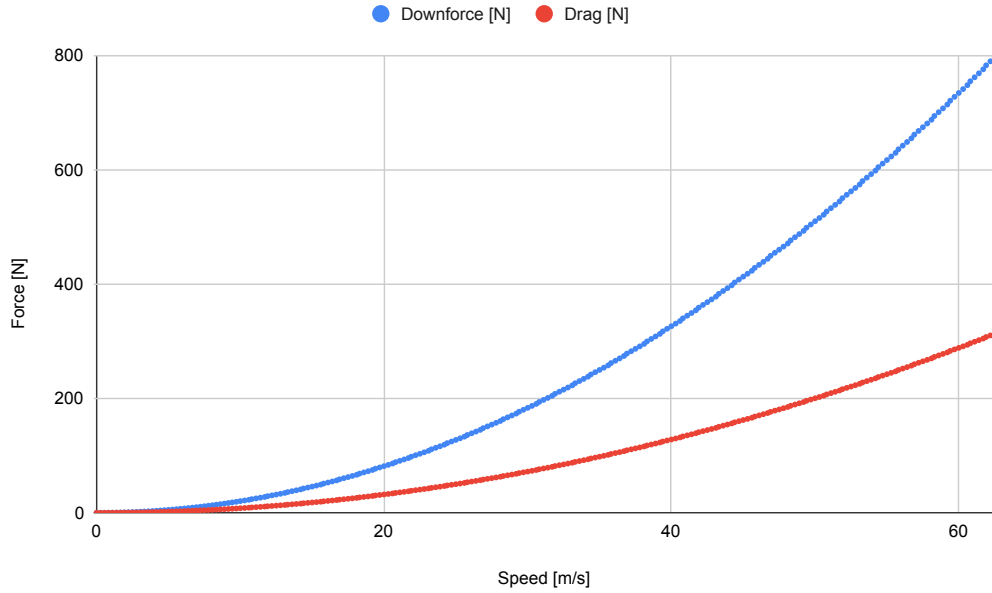
F_{DF} Derivative	F_{DR} derivative	Δ Derivative($F_{DF} - F_{DR}$)
0	0	0
0.112	0.0442	0.0682
0.226	0.0888	0.137
0.339	0.133	0.206
0.452	0.178	0.274
0.566	0.223	0.343
0.680	0.267	0.413
0.790	0.311	0.480
0.905	0.356	0.549
1.02	0.401	0.618

The tables 2 and 3 shows the excerpt from Sheet 2.

6 Data analysis

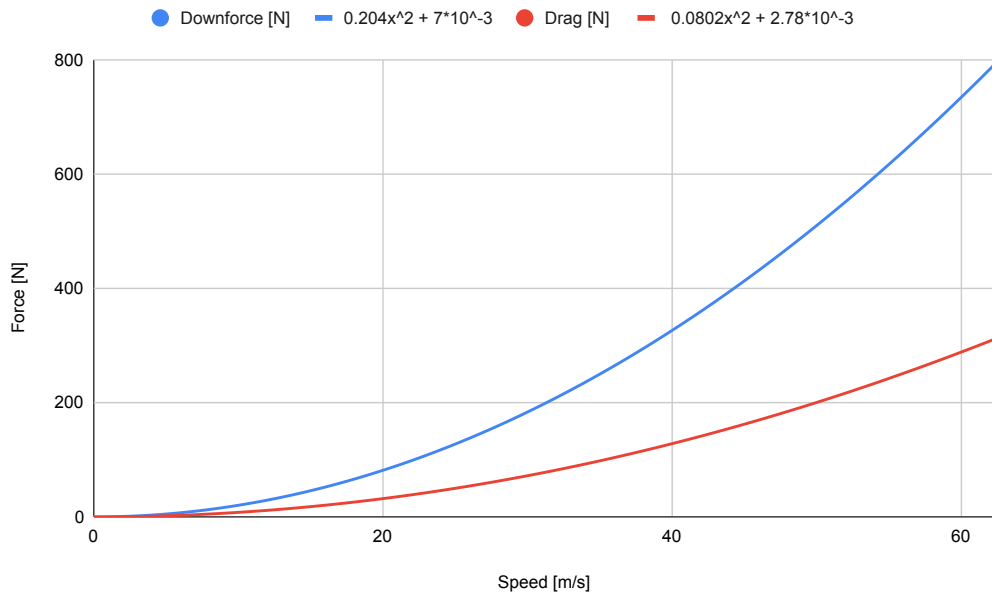
From *table 2* the graph of forces acting on the wing against the speed of wind was plotted.

Figure 7: **Graph of raw values of F_{DR} [N] and F_{DF} [N] vs car speed [m/s]**



A trendline using Google sheets was plotted with this data. A quadratic trendline was chosen due to equation (1) and (2) of downforce and drag respectively.

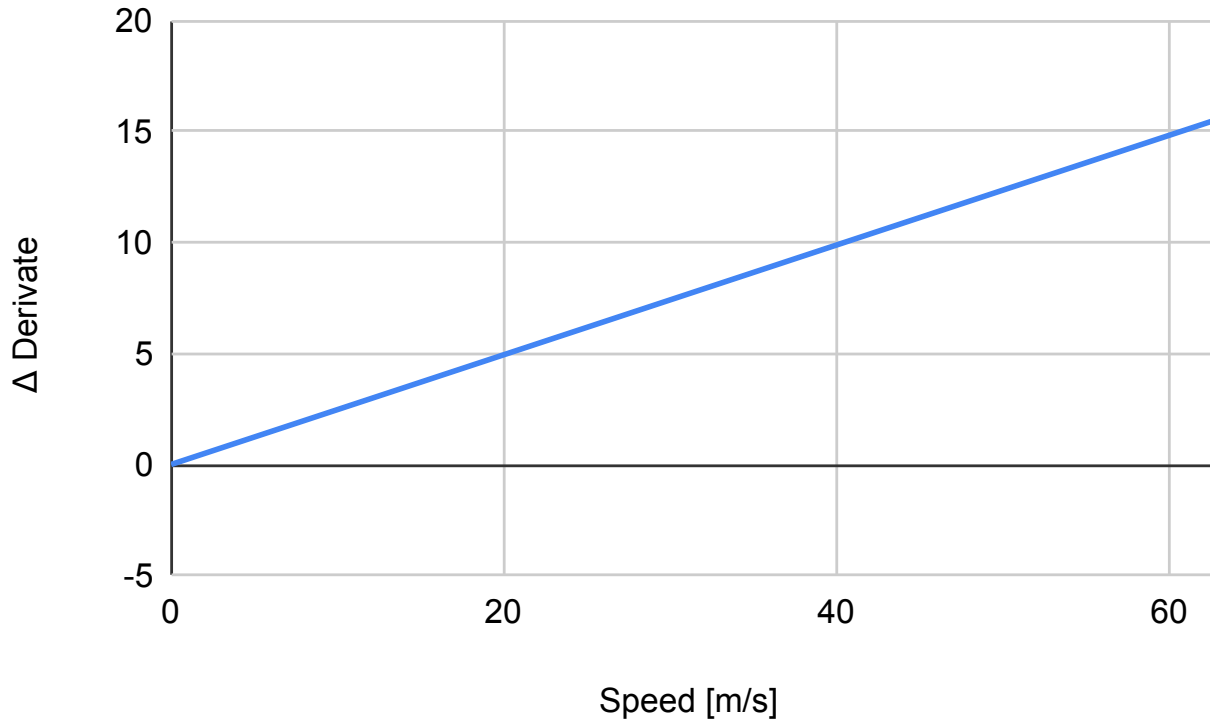
Figure 8: **Graph of trendlines of F_{DR} [m/s] and F_{DF} [m/s] vs car speed [m/s]**



In both graphs *figures 7 and 8*, the drag seems to be increasing linearly for small wind speeds. This linear velocity dependence happens due to the viscosity of the liquid being the dominant resistive force rather than turbulence. $F_{DF} \propto v$ [9]

Plotting *figure 9* the Δ Derivatives from *table 3* shows that the rate of change of downforce with respect to velocity, is higher than of drag.

Figure 9: **Graph of Δ derivative from Sheet 3**



7 Further analysis

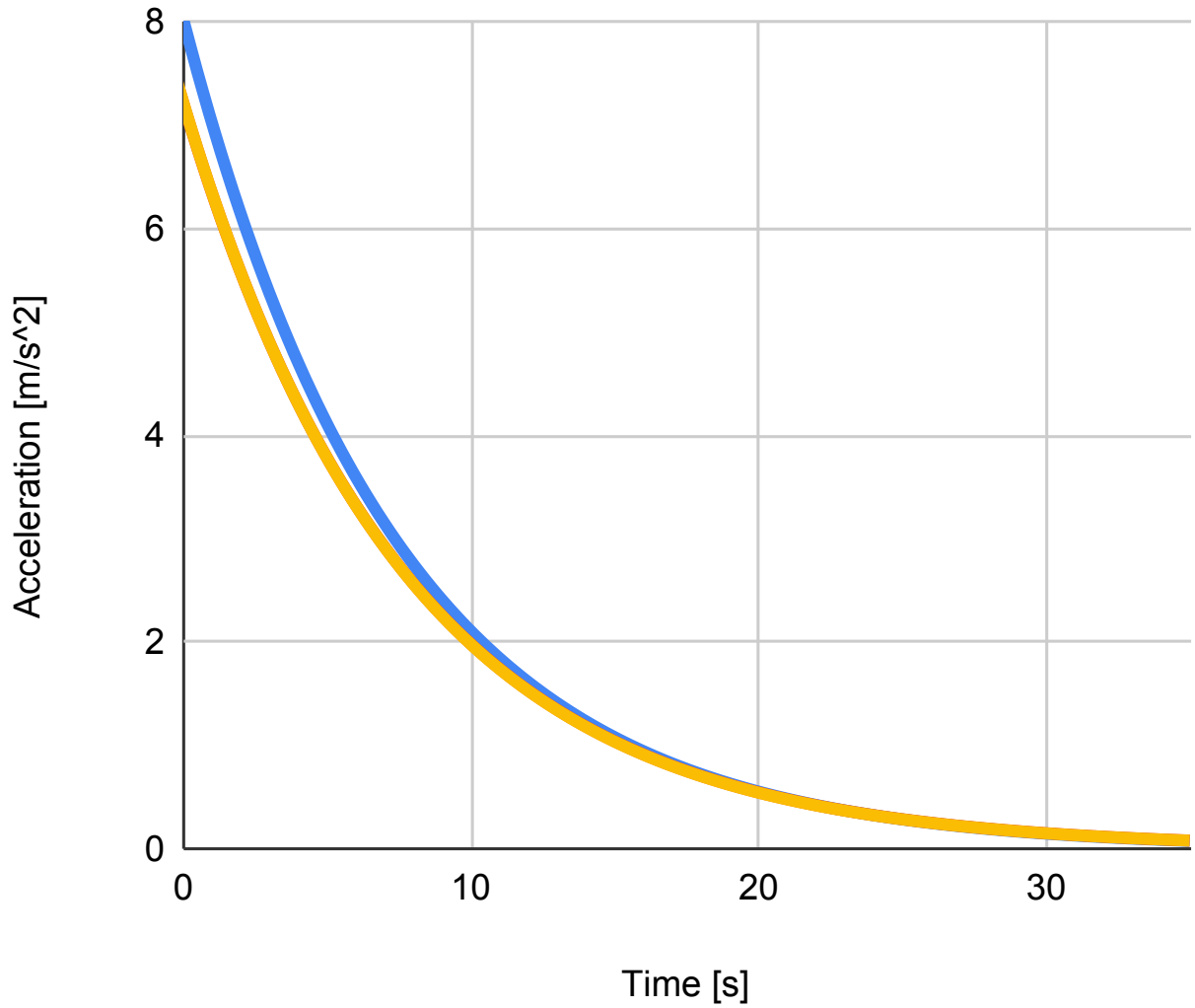
An increase in F_{DF} , results in increased grip, this increased grip results in a higher acceleration. In (*Table 1*), the last column of acceleration was observed to also be affected by the headwind. The excerpt shows only acceleration for when $AWS = 0m/s$, but data for $AWS = 4.86m/s$ and $AWS = 9.72m/s$ was calculated.

The data from Sheet 1 was plotted and a polynomial trendline was calculated using google sheets.

Table 4: Excerpt from Sheet 1

Time [s]	$a[m/s^2]$ ($0m/s$)	$a[m/s^2]$ ($4.86m/s$)	$a[m/s^2]$ ($9.72m/s$)
0			
1	8.33	8.06	8.03
2	6.91	5.30	5.30
3	4.50	3.90	4.40
4	3.60	4.10	3.70
5	3.90	3.10	2.70
6	2.50	3.00	3.40
7	3.30	2.80	2.20
8	2.50	2.00	2.5

Figure 10: **Trendline of Acceleration $a[m/s^2]$ vs. Time $t[s]$ from Table 4**



The graph shows that as the car begins to accelerate, the initial acceleration is higher when the headwind is the lowest ($AWS = 0m/s$). As for $AWS = 4.86m/s$ and $AWS = 9.72m/s$ the progression of acceleration over time is similar. The reasons for these results are likely due to increased

drag. Higher headwind speeds increase the drag component of the force. Although I was expecting this effect to be counterbalanced by the increased grip, it seems that the drag component was dominant.

The drag and downforce component of the force acting on the car were also analysed against time to identify the rate of change of each.

Figure 11: **Evolution of F_{DR} for different AWS (value in round brackets)**

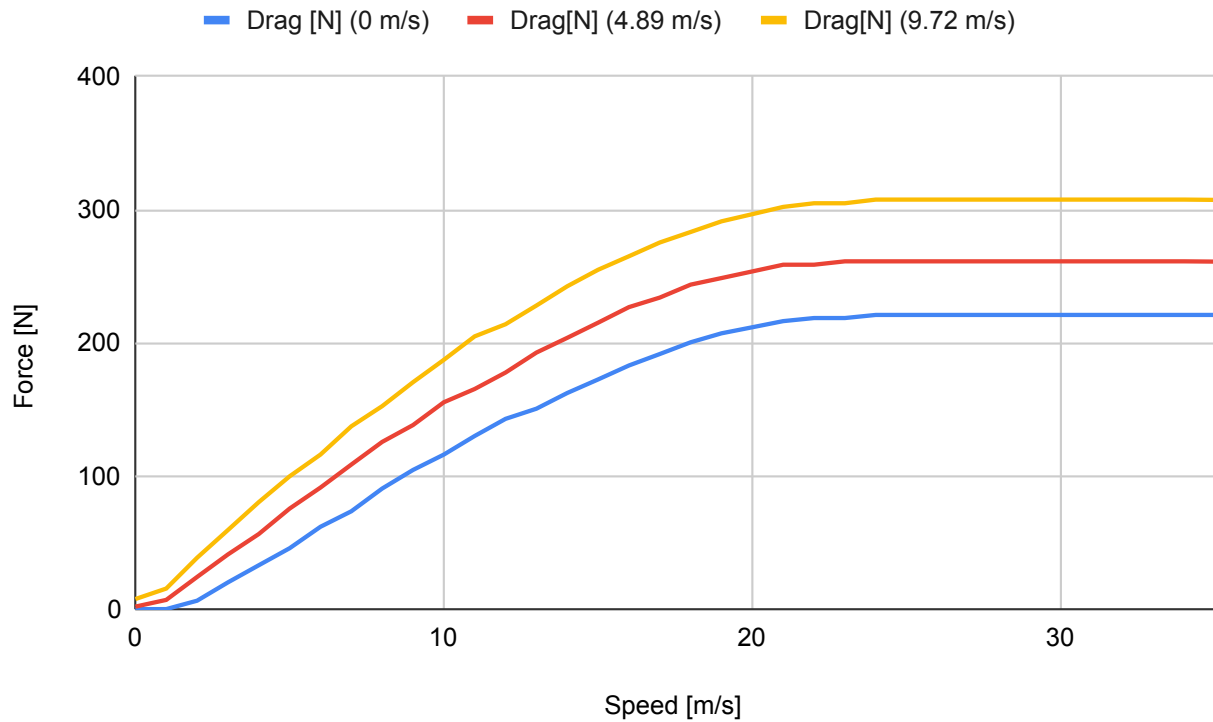
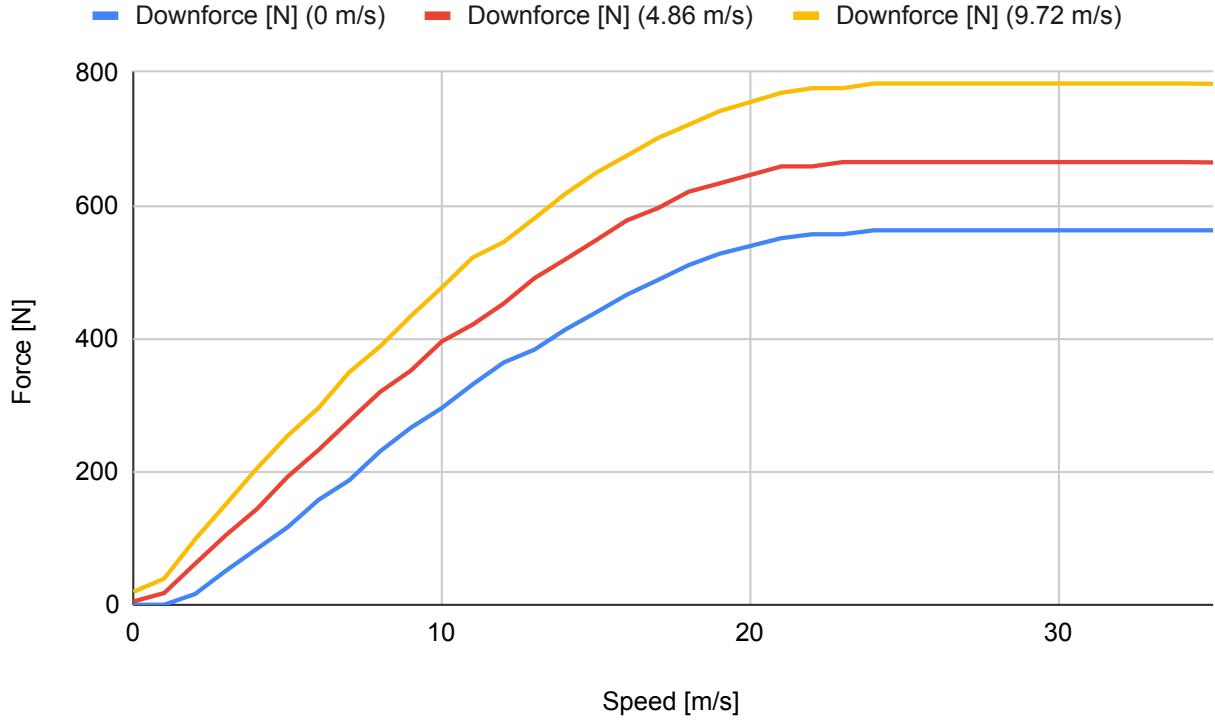


Figure 12: Evolution of F_{DF} for different AWS (value in round brackets)



The graphs *graph 11 and 12*, show how at different headwinds the downforce changes over time. For $AWS = 0\text{m/s}$ the drag is the lowest, while for $AWS = 9.72\text{m/s}$ the drag is the highest. A similar trend is observed for downforce where the speed of the headwind seems proportional to the rate of change of downforce and maximum downforce. This explain the findings for why acceleration was similar for $AWS = 4.86\text{m/s}$ and $AWS = 9.72\text{m/s}$. The is likely due to the grip starting to play a more dominant role.

8 Conclusion

The analysis of the data above show that both drag and downforce, increase linearly for very slow speed but for higher speeds the force increases quadratically. This shows that if a driver wants to utilize the full aerodynamic capabilities of their car then they must go fast. This suggest that if a drivers were to drive at 10m/s and brake down to 1m/s for a turn, they would be slower than if they drove at 20m/s and would brake down to 2m/s . Since the downforce would provide a significant amount of downforce the cars have more grip as they go faster, and are able to take the turn at higher speeds.

Another conclusion is that since the rate of change of downforce is higher than the rate of change of drag, the manufacturers should set up the wing with a higher Angle of Attack, as that would increase downforce. This strategy can only be applied to racing circuits such as Monaco and Zandvoort. This is because, in such circuits with lots of turns and small straights having higher downforce can lead to taking turns faster and hence overall lap times. The drag is less prioritized since taking the corners faster is more beneficial than going faster on the straights.

Conclusions devised from the further analysis section, are based on speculations. These findings lead to the hypothesis that after a certain threshold of headwind speed, the higher AWS is, the faster the car accelerated initially. To confirm these findings, experiments with higher headwinds must be performed. This is out of the capabilities of Assetto Corsa as the simulation allow up to $AWS = 9.72m/s \approx 35km/h$. Although, racecars are likely to not race in such extreme speeds due to safety reasons, headwind higher than these are achieved when as the car gains velocity. As then the headwind would be equal to the $AWS +$ the car's velocity.

9 Evaluation

This experiment was performed under idealistic conditions, such as non-turbulent air, which resulted in certain strengths and limitations.

One strength of this research was the use of researcher triangulation. To show the Bernoulli's effect on a wing, an experimental wind test was performed to show the theory working in practice, and a CFD 2D airfoil experiment was performed to numerically show the Bernoulli's principal.

Another strength was the use simulations. As calculations are done by the computer, multiple times per second, the accuracy of data is high enough for the propagation of uncertainty withing a particular simulation is low enough to be disregarded. Additionally, due to the theoretical nature of the experiment the experimental conditions were controlled to a high degree. This allowed for a clear cause and effect to be observed.

There are also several limitations to this experiment.

Firstly, there is a small risk of circular reasoning. The formulas deduced from the AC simulations might have been the formulas used to make this simulation. Due to AC being a closed source simulation, this cannot be verified. This is likely to not be the case in OpenFOAM, as it utilizes the

Navier-Stokes equations, which is quite unlikely for Assetto Corsa to be able to calculate in real time.

Secondly, the assessment of uncertainties is difficult to make without comparison to real life values through performing experiments or evaluating other research. Performing an on track experiment requires a lot of finance and time. The experiments done by other motorsports teams aren't published due to their proprietary nature. This creates a lack of literature values to compare to.

Albeit the lack of literature values to compare to, it can be assumed that CFD experiments are comparable to real life experiments to a certain degree. In (*section 9.1*), these uncertainties are calculated and compared

9.1 Quantitative Uncertainties

Performing a streamlined flow of air experiment using CFD on the rear wing of the car chosen, the downforce F_{DF} and drag F_{DR} on the wing were calculated. The 3 different wind speeds were 20m/s, 30m/s and 40 m/s. The uncertainties were calculated using the following formula:

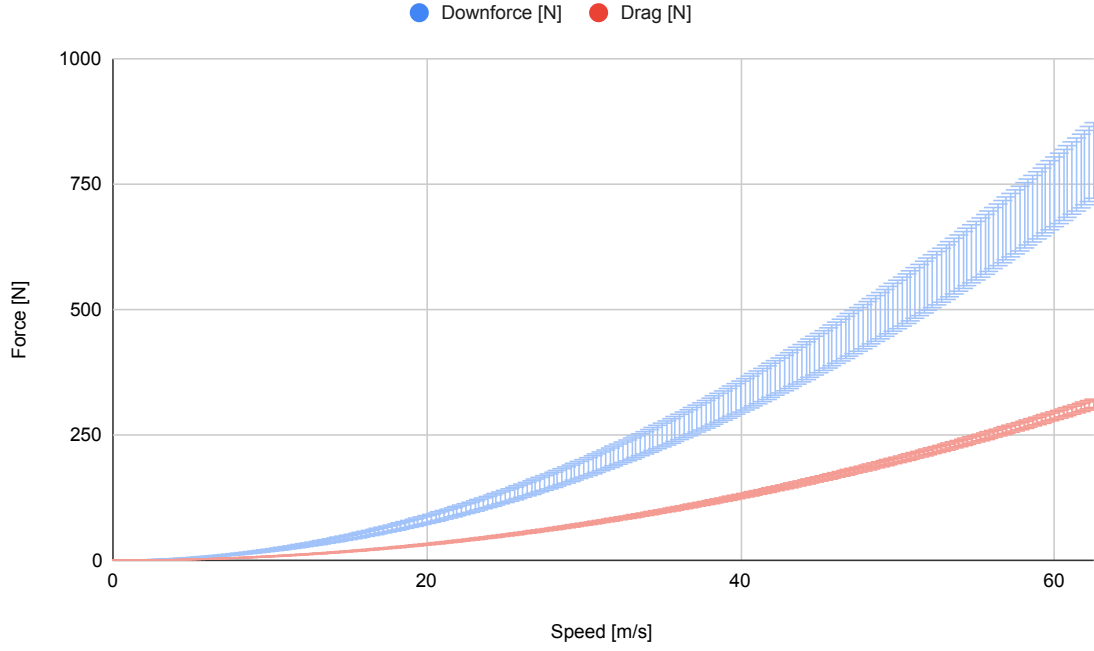
$$err\% = \left| \frac{theo-exp}{theo} \right| * 100\%$$

The theoretical values *theo* are from the Assetto Corsa simulation from *sheet 2* and the experimental values *exp* are from CFD. Then the average of 3 uncertainties $err\%$ was taken:

	Downforce	Drag
Average Uncertainty %	9.46%	2.65%

This error data can be plugged into the graph *figure 8* to get the error zone of the forces acting on the wing.

Figure 13: $F_{DF}[N]$ and $F_{DF}[N]$ vs Speed $[m/s]$ with a zone of error



The c

The blue and red areas show the error region of the downforce and drag at a particular velocity. This accuracy difference could be due to a number of reasons. One reason is the optimization of Assetto Corsa. The 3 CFD simulations took up to 12 hours, while Assetto Corsa does the calculations in real time. The increased speed of calculations could be at a cost of accuracy. Since, Assetto Corsa is a closed source software, only assumptions of its mechanisms can be made. One such assumption is that AC uses pre-trained models that are optimized to run in real time.

Another reason for the uncertainties could be attributed to human error. When the researcher was driving the car, they tried to keep the car in a straight line, but minor hand movements might have caused the car to go slightly diagonally. In this situation the headwind turns to a crosswind. This could explain the relatively small uncertainty observed, as the car moved diagonally for very little time and distance.

9.2 Qualitative Uncertainties

Apart from Quantitative Uncertainties, there are many other factors that can introduce an uncertainty in the handling and performance of the car. In a real life race scenario, the race track goes through multiple altitude changes which results in difference in air density and gravitation playing a more important role in grip level at certain parts of the track. Additionally, the track and air temperature are likely to change throughout the course of the race. Since air temperature is a direct measure of

the Kinetic energy of air particles, variations in magnitude of forces can be observed.

This EE assumes ideal conditions where variables like humidity and elevation are kept constant. In practice, the controlled variables in this EE are not constant

Experiments such as one performed in this research, allow the teams to understand the potential of their car. This experiment only measures airflow with headwind, whereas professional teams that have the resources and time, perform experiments multiple directions of wind, with different air densities and different temperature conditions. This narrows down the uncertainty window and allows for a more predictable behaviour from the car.

9.3 Possible Improvements

One improvement that can be made, is performing the experiment for different headwinds with a shorter interval. The *figures 12* and *11* are performed only for 3 different *AWS*, whereas performing for more would have allowed for a more accurate trend between the headwind and the rate of change of aerodynamic forces to be observed.

Another improvement can be made to reduce **Qualitative Uncertainties** by performing the experiment on a real life track with a real vehicle. This can be rather financially and time demanding. Simulating the car in conditions that accurately reflect real life, comes with a lot of complications. Apart from the huge number of variables and their combinations, the simulation software may not model certain factors like humidity and temperature accurately.

10 Further research

The use of simulations and a theoretical approach of this experiment shows that, racing teams can slowly shift towards completely simulating their race cars by creating simulation models that reflect real life conditions. Although creating such models is very time consuming, once its results are assessed and are fine-tuned to reflect real life, manufacturers can save resources by eliminating the need to test in wind tunnels. This could greatly benefit the environment and also promote technical advancements.

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