International Baccalaureate

Extended Essay

Investigating the Influence of Winglength in Aerodynamic Downforce in a Porsche 911 RSR Scale Model

Research Question:

How does changing the length of a model Porsche 911 RSR car's wing affect the magnitude of downforce it generates?

Physics

Group 4: Sciences

Word Count: 3997

Table of Contents

1. Essay Overview

Aerodynamics play a decisive role in the world of motorsport performance, where even small design changes can significantly influence lap times, stability and driver control. One of the most essential aerodynamic factors is downforce, the vertical force that presses the car onto the track, increasing grip during acceleration, braking and cornering (Katz, 2016). This force is heavily influenced by the design of key aerodynamic components such as the rear wing, which modifies airflow to create a pressure difference between its upper and lower surfaces.

This essay addresses the research question “How does changing the length of a model Porsche 911 RSR car's wing affect the magnitude of downforce it generates?” The aim is to quantify the relationship between wing length and downforce, using wind tunnel measurements as well as to calculate the negative lift coefficient ($-C_L$), Reynolds numbers and identify the scaling effects.

To achieve this, wind tunnel tests will be conducted on a scale model Porsche 911 RSR fitted with five different wing lengths, while keeping flow speed, air density, and wing profile constant inside the scaled down windtunnel.

The first step of this investigation involves measuring the amount of weight that presses on the reading scale for each wing using a high precision jewelry weighing scale, then converting these readings from grams to Newtons. These values will be further processed in order to find graphs, tables and other measurements.

The second stage examines the Reynolds number for each wing length, calculated from the chord length, air velocity and kinematic viscosity. By calculating all the values of the Reynolds number which will be explained further on, the flow regime in which the car is will be determined. Operating under laminar conditions introduces boundary layer instability, laminar separation and separation bubbles, which reduce aerodynamic stability which will be explained in the background.

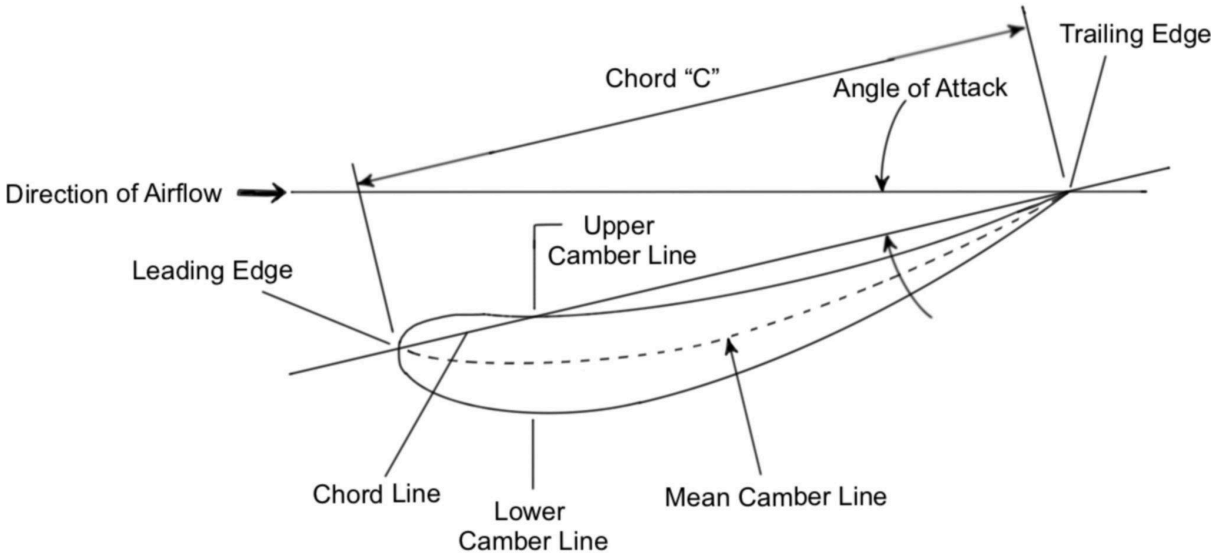
Since the experiment uses a small-scale model of the Porsche 911 RSR, scaling effects must be considered when interpreting the results. In particular, the lower Reynolds numbers of the model compares to the full scale car due to differences in boundary layer behaviour, turbulence and flow separation. These differences can affect the relationship between wing size and downforce, meaning the trends observed in the model may not directly match those of a real racing car. Therefore, conclusions drawn for this lab will be limited to the experimental conditions of the model, however they will still be similar to the real life scenarios.

2. Background

Downforce is the aerodynamic force that acts in the opposite direction to lift. While lift is what allows planes to ascend, downforce is what keeps race cars pressed to the ground. Without the required downforce cars would lose grip, especially at high speeds and could

endanger the safety of the drivers as well as the lap times (Katz, 2016). Downforce is generated by redirecting air to flow over, under or around aerodynamic surfaces such as wings, spoilers or diffusers. Airfoils are designed to lift planes up, however, since the aim of rear wings is to keep the car grounded, they're inverted to have this effect. This is why it will be referenced as inverted airfoil or rear wing, which are the same. The shape of the wing, the camber (curvature) and the angle of attack determine how the air flows across it, which affects the pressure distribution (Edgar, 2023). A longer wing increases the surface area that's exposed to airflow and can therefore generate more downforce, assuming the shape and angle remain constant, which is true for this experiment. For this experiment however, the geometry of the wing will stay the same.

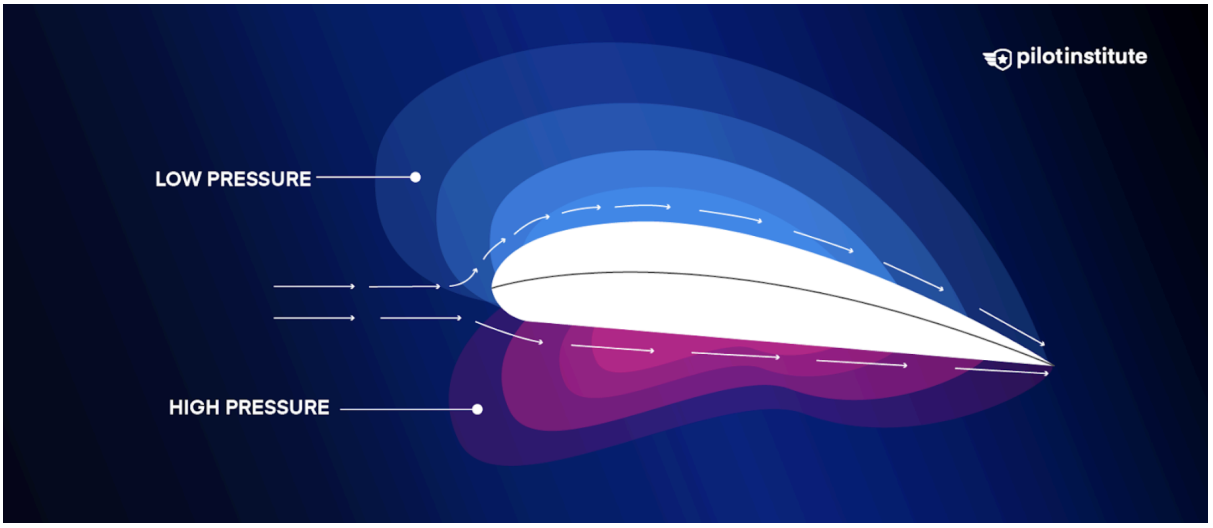
Figure 1 - Components of an Inverted Airfoil



Bernoulli's principle states that an increase in the speed of a fluid occurs simultaneously with a decrease in pressure (Bernoulli's Principle | SKYbrary Aviation Safety, 2021). If you simplify this, it basically means that fast airflow leads to lower pressure, and

slower airflow leads to higher pressure. In an inverted airfoil, the air moves slower over the top and faster beneath it, this creates a zone of low pressure underneath the wing and high pressure on top, pushing the car down (Serway & Jewett, 2018). In the real world this isn't always the case, as aerodynamics involve more complicated airflow behaviour, and Bernoulli's model assumes ideal laminar flow, which often does not occur in real life racing environments. (Serway & Jewett, 2018).

Figure 2- Areas of low and high pressure on airfoil



(Pilot Institute, 2024)

Figure 2 shows the areas of pressure an airfoil experiences. This is not an inverted airfoil so in this figure lift is generated not downforce.

Newton's third law states that for every action there's an equal and opposite reaction. This law also gives another explanation to downforce. A rear wing, because of its shape, deflects air upwards, therefore, in return, the air pushes the wing downward, generating downforce. A longer wing surface deflects more air, which results in a greater force pushing downwards. (Giancoli, 2008). This concept applies more to what actually happens during high speed motion than Bernoulli's, and helps explain why increasing wing length improves

the vehicle's downforce. To find the downforce generated we need to modify *Equation 1*, the force lift equation.

Equation 1

$$F_L = C_L(\frac{1}{2}\rho v^2)A$$

Where:

F_L= Lift force	N
ϱ= Air density	$kg.m^{-3}$
v= Air velocity relative to object	$m.s^{-2}$
A= Area of wing*	m^2
C_L= Coefficient of lift	

Note:

*Variable “A” in this equation refers to the surface area of the “upper camber line.” depicted in Figure 1. Not to be confused with the “A” from *Equation 3* which means the frontal area of the wing.

However, since we know downforce acts in the opposite direction of force lift, we have to modify the equation. We could do this by maintaining all the variables the same and making F_L be negative, or making the Coefficient of Lift (C_L) negative. This would make more sense in the context of our experiment as we’re inverting an airfoil, which would mean that the coefficient of lift would be negative. Since the only dimension that's being changed is the length of the wing, we can also separate Area into Length times width in order to help us further on. By doing these changes, we get *Equation 2* which is the equation for downforce.

Equation 2

$$F_{Down} = (-C_L)(\frac{1}{2}\rho v^2)(L \times W)$$

Where:

F_{Down} = Downforce	N
ϱ = Air density	$kg.m^{-3}$
v = Air velocity relative to object	$m.s^{-1}$
$-C_L$ = Negative coefficient of lift	
L = Length of wing	m
W =Width of wing	m

One drawback from larger wings though is the increased drag, which is a resistive force that acts opposite to the direction of the motion and in the same direction of airflow. The equation for drag force is given in *Equation 3.*

Equation 3

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

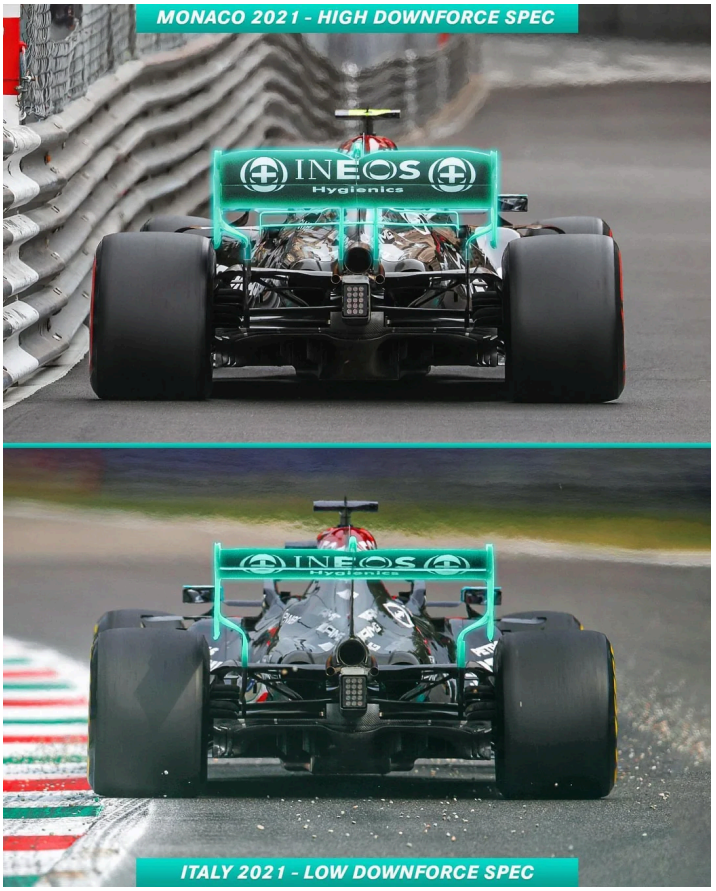
Where:

F_D = Force drag	N
ϱ = Air density	$kg.m^{-3}$
v = Velocity	$m.s^{-1}$
A = Frontal Area	m^2
C_D = Drag coefficient	

Increasing the wing's area increases both the downforce and the drag it generates as both frontal area and area of wing increase. The more drag a car has the more it reduces the car's top speed in straight lines. That's why you don't see cars with huge spoilers. In professional racing teams, engineers have to analyze and find the sweet spot to ensure top speed, and maximum downforce. In sports such as Formula 1, engineers change their set ups depending on the track. Tracks such as Monaco require a lot of downforce as cornering

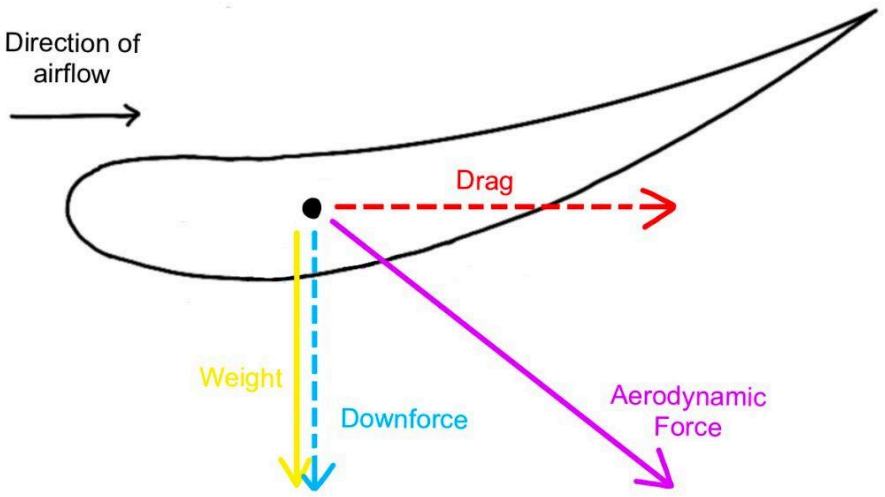
speed is critical for the best lap times, therefore teams use large, high angled wings. In other tracks such as Monza, labeled “The Temple of Speed” its few corners and long straights require little downforce and more top speed, making teams have smaller wings. This is shown in the figure below.

Figure 1- Difference of wings in Monaco vs Monza



(*Reddit - the Heart of the Internet*, 2021)

Figure 3 - Free body diagram of the forces acting on a wing



Note:

Vectors are not to scale, only directions are represented.

Another factor to consider is the Reynolds number. This is a value that's used to predict patterns in fluid dynamics. It helps explain whether the flow regime in which the wing is at in this case. Three flow regimes exist, laminar, transitional and turbulent. In this experiment these values ranged from ~2,300 to ~7,100, ensuring all the wing configurations all operated far below the critical threshold, placing them well into the laminar flow regime. This is because the critical Reynolds number typically lies between 100,000 and 500,000 when talking about airfoils (Koning et al., n.d.). The Reynolds number is calculated by the medium of *Equation 4.*

Equation 4

$$Re = \frac{\rho v L}{\mu}$$

Where:

Re = Reynold number

ϱ = Fluid density kg.m^{-3}

υ = Fluid velocity relative to object m.s^{-1}

L = Characteristic length (chord length of wing) m

μ = Dynamic viscosity N.s.m^{-2}

In small scale models, the Reynold number is much lower than in real cars so airflow behaves differently, this includes laminar separation and separation bubbles. A laminar separation bubble occurs when smooth laminar airflow detaches from the surface of the wing and reattaches further downstream, trapping a small pocket of air between. This trapped pocket changes the pressure on the wing and makes the behaviour less stable. These behaviours, due to the laminar regime the wing is found in, mean that model tests may not predict perfectly what happens in real world conditions with 1:1 scale; Which is an important limitation in this experiment, nevertheless findings will still match trends in real life scenarios.

3. Research Question

Research Question:

How does changing the length of a model Porsche 911 RSR car's wing affect the amount of downforce it generates?

Justification:

While the basic principle that as you increase wing surface area tends to increase downforce is already established, the exact relationship can be affected by other aerodynamic factors, especially at low Reynolds numbers found in scale model testing. This makes the question relevant for understanding how length impacts performance under model-scale conditions, and how these results may vary from full size racing scenarios. However, as explained previously in the background, having a larger wing also generates more drag therefore finding the right balance between downforce and drag is essential and can vary from circuit to circuit.

4. Methodology

4.1 Experimental Setup

Figure 4 - Labeled drawing of set up

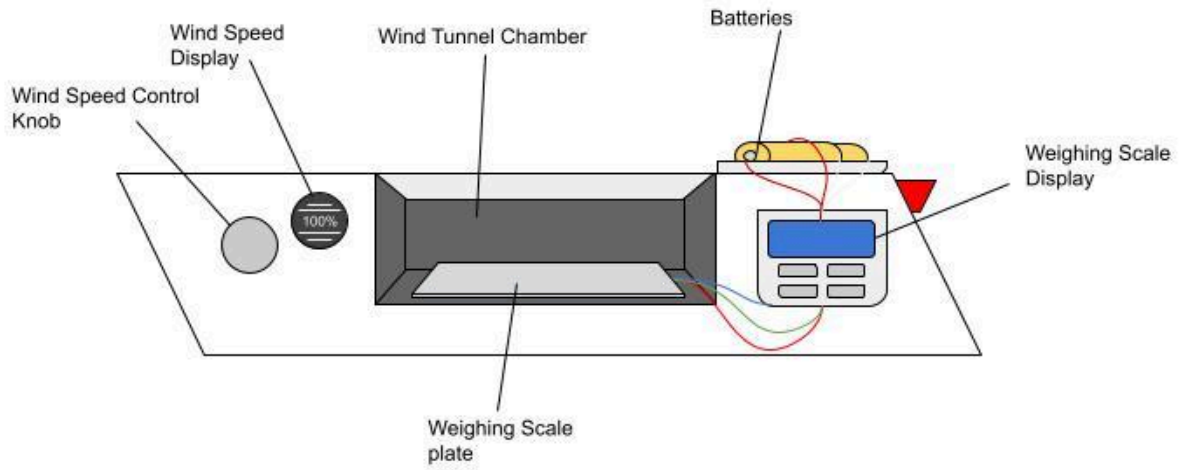


Figure 5- Experimental setup picture

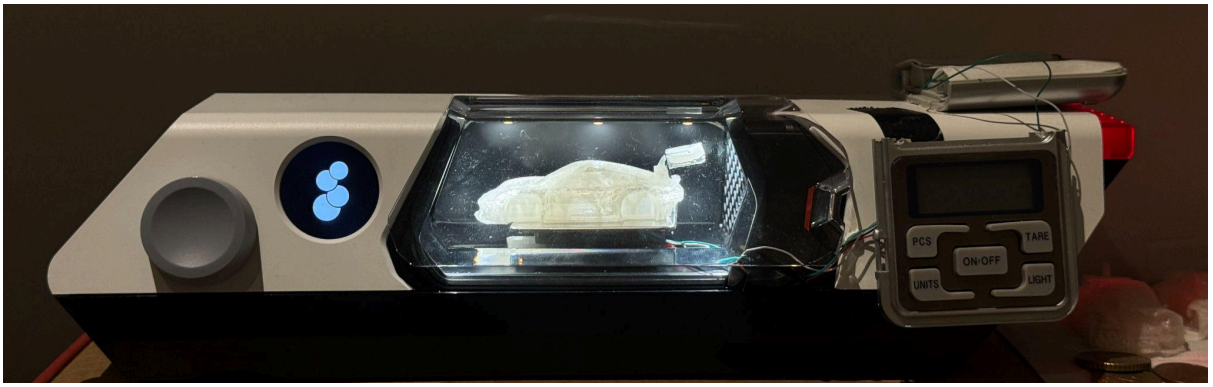
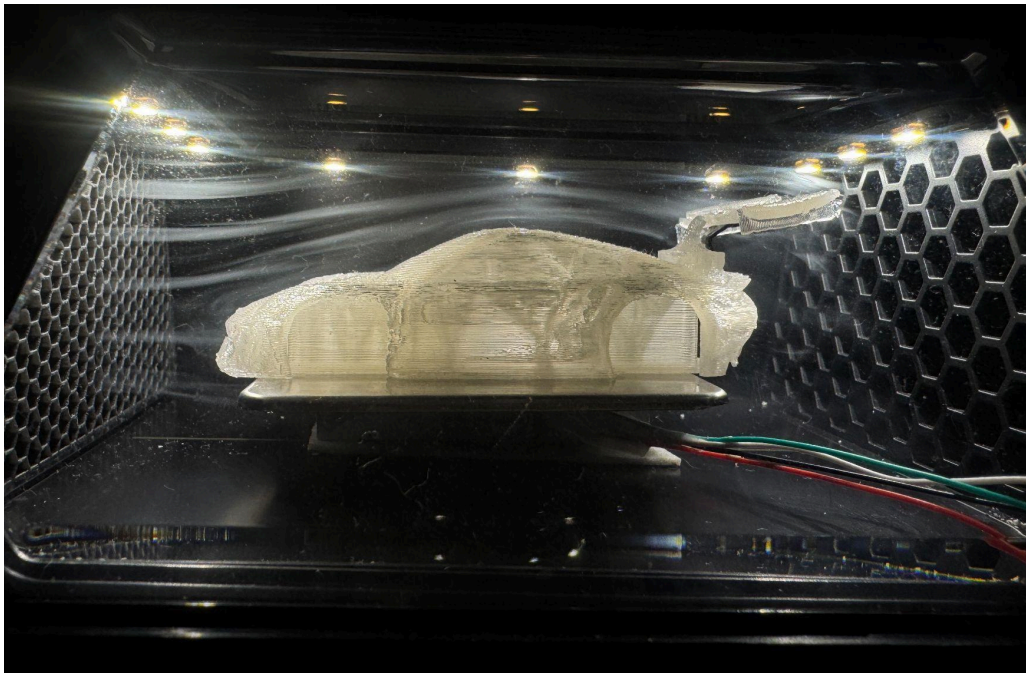


Figure 6 - Setup in action



4.2 Materials List

Materials List

- Windsible 1:64 Wind Tunnel
- Mengshen Digital Pocket Jewelry Scale
- Porsche 911 RSR model

- Different wing sizes (5.150 mm, 7.725mm , 10.300mm, 12.875mm, 15.450mm)

4.3 Variables

Independent variable

- The length of a model Porsche 911 RSR car's wing

Dependent variable

- The magnitude of downforce the car generates

Control variables

- 100% wind speed (6.75 $m.s^{-1}$)
- Weighing Scale Plate Used
- Windsible Windtunnel
- Constant pressure (Room Pressure)
- Car position
- Angle of wing (Θ)
- Same model car used
- Same environment
- Same direction of airflow
- Air density (1.255 $kg.m^{-3}$)
- Room Temp (25°C)

4.4 Procedure

Method

1. Load the fogger* with fog fluid
2. Attach nozzle with multiple streamlines
3. Insert fogger with the nozzle into its corresponding spot
4. Select the model with the wing size you want to use (5.150 mm, 7.725mm , 10.300mm, 12.875mm, 15.450mm).
5. Place base model on weighing scale
6. Tare the scale
7. Turn wind speed control knob until wind speed display shows 100% speed
8. Look at the weighing scale display and wait for reading to stabilize for three seconds
9. Record reading
10. Repeat steps 5-9 seven* times total per wing
11. Select different wing size and repeat steps 4-10

Notes:

*The fogger is the simply the official name the company that created the windtunnel gives to the cartridge in which the fog fluid is stored.

*The amount of trials per wing is seven as it ensures that at the end when averaging the results, fluctuations and random error are as minimal as possible. With only 2 or 3 trials one bad reading could skew the results significantly. No more than 7 trials were made because the fog fluid is limited, and getting more fog fluid that's compatible for this machine is not only

pretty expensive, but would also take time to ship from China. This would mean conditions might vary when doing the trials.

Hypothesis

As the wing of the Porsche 911 RSR increases in length, so does the downforce it generates as we can see from Equation 2 that the force is directly proportional to the area of the wing.

The independent variable will be controlled, measured and changed by using different model cars. These model cars are identical to each other, the only thing differentiating them is the length of the wing. Each of the 5 model cars has one size wing (eg. 7.725mm) and is being used for all seven trials to ensure there are no discrepancies in the data due to changes in that car or the setup in general.

The dependent variable is going to be measured with the weighing scale, and the reading of the digital display of the weighing scale will be the way we measure the dependent variable.

All trials were done as close to each other as possible, meaning they were all made in under an hour to ensure all external factors that are uncontrollable at a home lab, such as air pressure from the weather or room temperature, that can fluctuate are as similar as possible for all trials. The wind speed was always at 100% (6.75 $m.s^{-1}$) in order to make sure this is an easy number that can be repeated multiple times, this wind speed was also used in order to get the highest possible readings and therefore more precise results, specially in the smaller wing sizes. To keep the same weighing scale for all trials, I made sure the scale had a battery at all times, and was always functioning properly in order to be able to use it in

future trials. The windsible 1:64 wind tunnel was used in all the trials as this is the only way we could measure the downforce that was generated by different model cars. To ensure a constant pressure across all trials, the windtunnel was used in the same room and environment with the plastic lid closed, and to ensure it was fully sealed with no gas that could maybe depressurize the chamber we sealed all the edges of the lid with electrical tape. During testing of the windtunnel, previous to the testing of the actual lab we found out that if used with the plastic lid open the weighing scale would not measure anything, even if wind was blowing.

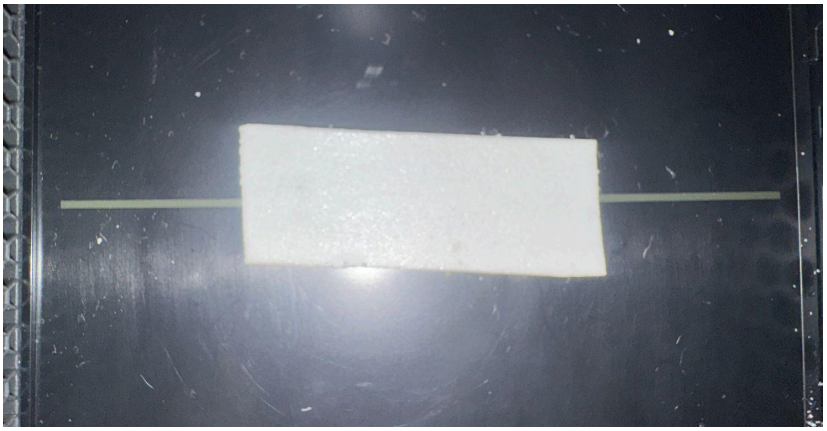
The position of the car in the chamber is important as the wind only hits in a straight line, so if the car was slightly rotated, or shifted to the point where the center of the car isn't aligned with the center of the direction of the airflow, the air could potentially hit less surface area or potentially entirely miss the wing giving us faulty results or none at all.

For the same model car used, we didn't actually use the same object itself, rather I 3D printed 5 completely identical model cars, which I then glued the different side wings to. This way I know that the model cars are not a source of error for the data, and if it does affect the data, it's a systematic error that affects the data of all the trials for or the wing lengths, not just for one specific wing length. The direction of airflow can be changed with relation to the windtunnel, and can only go straight, however, it can be changed in relation to the car and the angle of the car. By ensuring the direction of airflow is parallel to the direction of the car we aligned it with the factory center line* that indicates the direction of airflow and the center of that airflow.

Note:

*The factory center line is a thin white line inside the chamber that is directly in the center of where the airflow hits the model car, as shown in the image below.

Figure 7 - The factory center line on the floor of the chamber



5. Data Collection and Processing

Raw Data

The raw data consists of 35 total measurements, seven for each of the five wing configurations. The recorded values display a small amount of variability, which is expected due to changes in the airflow and imprecisions in the small scale measurement of force. The weighing scale resolution is ±0.01 g.

Table 1- Raw Data with Average

Length (mm)	Reading In Weighing Scale ± 0.01 g							
	T1	T2	T3	T4	T5	T6	T7	Average
5.150	0.04	0.04	0.05	0.04	0.03	0.03	0.04	0.039
7.725	0.05	0.07	0.06	0.05	0.07	0.06	0.04	0.057
10.300	0.08	0.07	0.06	0.09	0.08	0.07	0.07	0.074
12.875	0.11	0.09	0.10	0.11	0.09	0.10	0.10	0.100
15.450	0.12	0.12	0.13	0.14	0.11	0.12	0.14	0.126

Data Processing and Calculations

To make sense of the raw data, several calculations were made, such as the mean, the uncertainty, the force conversion and the uncertainty in Newtons.

For each wing size, the average of the seven trial values was calculated. This gives us a more precise value to work with that we can use across all the different wing sizes.

The uncertainty was determined by using *Equation 5*, which is the one used for calculating resolution uncertainty.

Equation 5

$$Uncertainty_{Resolution} = \frac{Resolution}{2}$$

Note:

Resolution is the scientifically correct way of saying the smallest number a measuring instrument can read to. For example, the digital weighing scale in this experiment measures up to 0.01 grams. Therefore the resolution is 0.01.

Sample calculation:

$$Uncertainty_{Resolution} = \frac{0.01}{2} = 0.005$$

The difference from the mean was calculated in order to find how spread out my results are, which is essential for evaluating the uncertainty. If the difference from the mean is larger than the uncertainty the difference from the mean will be used rather than the uncertainties

For each wing, the average difference from the mean was calculated in Table 2.

Table 2 - Difference From the Mean Reading in Weighing Scale

Wing Length (mm)	**Difference From the Mean Reading in Weighing Scale (g)**							
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**Average**
5.15	0.001	0.001	0.011	0.001	0.009	0.009	0.001	0.0049
7.725	0.007	0.013	0.003	0.007	0.013	0.003	0.017	0.0090
10.3	0.006	0.004	0.014	0.016	0.006	0.004	0.004	0.0078
12.875	0.010	0.010	0.000	0.010	0.010	0.000	0.000	0.0057
15.45	0.006	0.006	0.004	0.014	0.016	0.006	0.014	0.0094

An example of the difference from the mean calculation for wing 5.150 mm is as follows.

Sample Calculation:

$$|0.04 - 0.039| = 0.001$$

As we can see, the average difference from the mean is larger in wing sizes than the resolution uncertainty. Therefore, this is what's going to be used as our uncertainty moving forward.

The reading from the scale was then converted from grams into Newtons in order for it to be used in further equations and for it to actually be a force. This was by using Newton's second law of motion (Law of Force an acceleration) which is represented by *Equation 7.*

Equation 7

$$F = ma$$

However, since our data is in grams and the equation requires it to be in kilograms the formula is modified to look like *Equation 8.*

Equation 8

$$F = (\frac{m_g}{1000})a$$

Where:

F = Downforce	N
m = Reading In Weighing Scale	g
a = Acceleration (gravity)	$m.s^{-2}$

Finally, the uncertainty is propagated the same way ($\Delta F = \frac{\Delta m_g}{1000} \times a$) to convert it into Newtons.

Sample Calculations:

$F = (\frac{0.03857}{1000})9.81 = 0.000378$

$\Delta F = \frac{0.005}{1000} \times 9.81) \approx 0.00005$

Reynolds Number

The Reynolds number was calculated using Equation 4.

$$Re = \frac{\rho v L}{\mu}$$

Where:

$\rho = 1.225$	$kg.m^{-3}$
$\nu = 6.75$	$m.s^{-1}$
L = chord length	m
$\mu = 1.81 \times 10^{-5}$	$N.s.m^{-2}$

Sample Calculation (5.150 mm wing):

$$Re = \frac{1.225 \times 6.75 \times 0.00515}{1.81 \times 10^{-5}} = 2,335$$

All this data was summarized in Table 3 in order to make it more clearly visible and understandable for the reader.

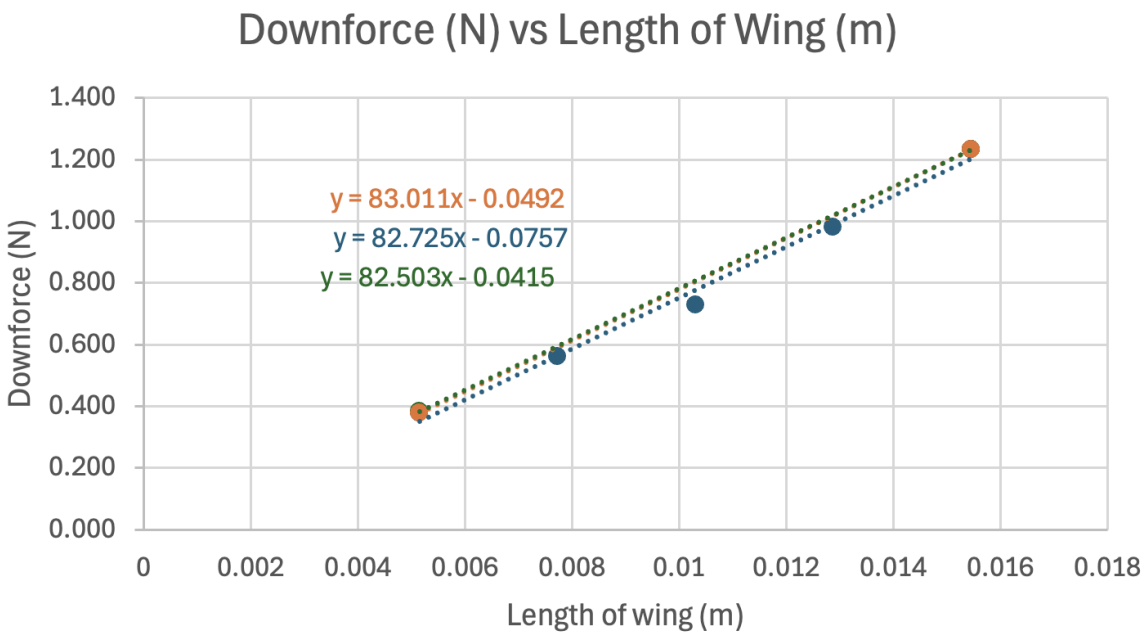
Table 3- Processed Data Values

Length (mm)	Avg Reading In Weighing Scale (g)	± Uncertainty (g)	Downforce (N)	± Uncertainty (N)	Surface Area (mm^2)	Reynolds Number
5.150	0.039	0.005	0.000378	0.00005	149.8	2,355
7.725	0.057	0.009	0.000561	0.00009	224.7	3,532
10.300	0.074	0.008	0.000729	0.00008	299.5	4,709
12.875	0.100	0.006	0.000981	0.00006	374.4	5,886

15.450	0.126	0.009	0.001233	0.00009	449.3	7,062

Graphical representation and Interpretation

Graph 1- Length of wing vs Downforce



Note:

For the graphs we can see length was changed from millimeters to meters since it's what's used in the calculations. (1 mm = 0.001 m).

Also note, uncertainties are too small to be seen.

By finding gradient, m, in Graph 1, we can solve for the $-C_L$, the maximum $-C_L$ and the minimum $-C_L$ as well as the Uncertainty in $-C_L$. We know the equation for m is:

$$m = \left(\frac{1}{2}\rho v^2\right)(w)(-C_L)$$

So the negative lift coefficient is found by

$$-C_L = \frac{m}{\left(\frac{1}{2}\rho v^2\right)(w)}$$

We then plug our m values in to find out the $-C_L$, the max $-C_L$ and the minimum $-C_L$.

Sample Calculation:

$$-C_L = \frac{82.725}{\left(\frac{1}{2}(1.225)(6.75)^2\right)(29.08)} = 0.1019$$

Finally we calculate the uncertainty $-C_L$ by taking the (Maximum-Minimum)/2.

$$Uncertainty\ (-C_L) = \frac{Max-Min}{2}$$

Sample Calculation:

$$Uncertainty\ (-C_L) = \frac{0.1023-0.1017}{2} \approx 3 \times 10^{-4}$$

Giving us $\approx 3 \times 10^{-4}$ as the uncertainty ($-C_L$) for this lab and this Table 5 to summarize our $-C_L$ values.

Table 5 ($-C_L$) values

$-C_L$	Max ($-C_L$)	Min ($-C_L$)	Unc ($-C_L$)

0.1019	0.1023	0.1017	3×10^{-4}

6. Results Analysis

6.1 Downforce vs Wing Length

The first analysis focuses on the direct relationship between wing length and the measured downforce. As expected, the downforce values in Newtons increased consistently as the wing length increased from 5.15 mm to 15.45mm. This aligns with the aerodynamic theory that a longer wing provides a greater surface area for deflecting air and therefore increasing the magnitude of the downward force acting on the car.

Graph 1- shows a clear trend, with downforce rising linearly across the five wing lengths tested. This indicates that within the range of lengths tested, the effect of the wing length on downforce is direct and almost proportional to the amount of downforce it generates. Minor deviations from a perfect linear trend can be assumed to be from random errors in measurement or small inconsistencies in wind tunnel airflow, but the general trend strongly supports the hypothesis that longer wings will produce greater downforce. The reason why the graph does not show a completely proportional relationship is because the values don't go through the origin. even though according to theory it should. We can see

that the y-intercept in the graph is below zero, which means there is lift being generated by the model car. Since this lab includes the body of the car too in the trials, the force measured is not explicitly of the wing, but also of the body of the car. Therefore air wraps around the car too, generating aerodynamic forces too. In this case is 0.0757 N of lift, which is relatively smaller than the downforce generated by the wing.

6.2 Scaling Effects

Another important factor when interpreting these results is the effect of scaling. The Reynolds number numbers found in these experiments (max 7,062) are orders of magnitude lower than the ones that a full scale Porsche 911 RSR experiences in actual racing conditions. The critical chord based Reynolds number for conventional airfoils is typically between $1 \times 10^5$and 5×10^5, so every configuration happens in the laminar flow regime, in which early separation and laminar separations affect the results (Edgar, 2023). At such high Reynolds numbers, airflow over the wing would be fully turbulent, producing more stable and predictable aerodynamic behaviour.

On the other hand, the model used in this experiment is in a laminar airflow regime. This could explain small deviations from the perfect theoretical predicted values. Surface roughness in the model has also had a larger effect on this experiment than it would on an actual race car. Full size race cars are completely smooth relative to the roughness of the model car we use.d This leading to further deviations and inconsistencies from expected behaviour.

7. Conclusion

The aim of this investigation was to determine how changing the rear wing length of a model Porsche 911 RSR affects the amount of downforce generated. The hypothesis predicted that increasing wing length would increase the downforce, and this was supported by the data collected.

Across the five wing lengths, the average measured downforce increased from 0.00038 ± 0.00005 N for the 5.150 mm wing to 0.00123 ± 0.00009 N for the 15.450 mm wing. This shows a clear and consistent trend of higher downforce with longer wings. The linear graph of wing length vs downforce confirmed this relationship, with only minor deviations around the line of best-fit. The reliability of this trend is also supported by the relatively small uncertainties compared to the measured forces.

From the gradient of Graph 1, the negative lift coefficient was determined to be $-C_L$ = 0.1019 ± 0.0003. This value lies in the expected order of magnitude for these small scale aerodynamics tests. The uncertainty used in this coefficient was obtained by calculating the maximum and minimum possible slopes, which were between a narrow range from 0.1017 to 0.1023. This depicts that even though small fluctuations were present in the trials, the results are still precise.

In conclusion, the experiment successfully demonstrated the predicted trend: increasing wing length leads to a greater magnitude in downforce. The data produced a reliable estimate of the negative lift coefficient. The hypothesis was confirmed within the

range of measurements of the Thai experiment, but the results cannot be directly applied to full-scale conditions without accounting for scaling effects when talking about the Reynolds number or the surface texture.

8. Evaluation

Even though every effort was made in order to maximize the precision and accuracy, uncertainties coming from human error and limitations in the lab set up are simply bound to happen in an at-home lab such as this one. Even though the experiment underwent multiple iterations in order to perfect it, there were still clear sources of error and uncertainties in the lab.

The surface of the model car was another limitation. In real race cars, surfaces are manufactured to be perfectly smooth to improve aerodynamics. However, the 3D printed model had ridges proportionally significant to the size of the car, even after sanding. Achieving a near perfect smooth wing by sanding would've changed the geometry of the wing without a consistent factor, causing inconsistencies across the testing of different wing lengths. It is highly probable that the ridges affected the aerodynamics, therefore potentially contributing to the inconsistent lift coefficient values.

Finally, the number of trials per configuration gave enough data for averages and standard deviations, but more repetitions would've likely improved the reliability of the

results. Increasing the number of trials would have most likely not changed the downforce vs wing length trend, which was already clear and positive. However, it could have revealed more variations to lift coefficient. These could have been linked to the formation of laminar separation bubbles and the disappearance of them in places they had previously been.

Improvements

Many improvements could be made to strengthen this investigation. A calibrated anemometer should be used to measure wind speed, which would verify the wind speed the company gave us after contacting them. Producing models with smoother surfaces such as resin printing or precision machining would reduce the roughness of the model caused by the 3D printed filament and therefore give results closer to the real aerodynamic behaviour. All of these improvements together would reduce the uncertainties and depict more consistent and clear trends.

9. Bibliography

Wang, J., Li, H., Liu, Y., Liu, T., & Gao, H. (2018). Aerodynamic research of a racing car based on wind tunnel test and computational fluid dynamics. *MATEC Web of Conferences*, *153*, 04011. https://doi.org/10.1051/matecconf/201815304011

Hassan, S. M. R., Islam, T., Ali, M., & Islam, M. Q. (2014). Numerical Study on Aerodynamic Drag Reduction of Racing Cars. *Procedia Engineering*, *90*, 308–313. https://doi.org/10.1016/j.proeng.2014.11.854

Katz, J. (2005). AERODYNAMICS OF RACE CARS. *Annual Review of Fluid Mechanics*, *38*(1), 27–63. https://doi.org/10.1146/annurev.fluid.38.050304.092016

Flow, L. (2021, November 8). *Calculating Laminar Flow Reynolds Number and Its Limits*. Cadence.com. https://resources.system-analysis.cadence.com/blog/msa2021-calculating-laminar-flow-reynolds-number-and-its-limits

Reynolds Number. (2025). Nasa.gov. https://www.grc.nasa.gov/www/k-12/airplane/reynolds.html

Chen, X. D. (2019). Laminar-to-Turbulence Transition Revealed Through a Reynolds Number Equivalence. *Engineering*, *5*(3), 576–579. https://doi.org/10.1016/j.eng.2018.09.013

Koning, W., Natalia Perez Perez, B., & Cummings, H. (n.d.). *PRELIMINARY AIRFOIL DESIGN FOR LOW REYNOLDS NUMBERS*. Retrieved August 27, 2025, from

https://ntrs.nasa.gov/api/citations/20220006782/downloads/1570_Koning_050422.pdf?

Pilot Institute. (2024, February 29). *How Airplane Lift Works - Pilot Institute*. Pilot Institute. https://pilotinstitute.com/the-curious-story-of-airplane-lift/

Edgar, J. (2023). Vehicle Aerodynamics - Testing, Modification & Development: For road, racing and alternative transport.

Reddit - The heart of the internet. (2021). Reddit.com. https://www.reddit.com/r/formula1/comments/pm4eg3/comparison_between_the_mercedes_rear_wing_at/

TOTAL WORD COUNT: 5218