MONASH MOTORSPORT

FINAL YEAR THESIS COLLECTION

Formula SAE Aerodynamic Package; Design, Development and Validation

Luke Phersson - 2009

FORMULA SAE AERODYNAMIC PACKAGE; DESIGN, DEVELOPMENT AND VALIDATION

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Summary

This project covers four main areas, the first outlines the measurement of a number of physical attributes governing vehicle dynamics with and without an aerodynamic package, subsequently, analysis is performed with ChassisSim to quantify the effects these parameters have on vehicle performance at the Formula SAE competition. Further, the simulations performed with ChasissSim are correlated with experimentally determined data to validate their accuracy.

Secondly, an improved method for manufacturing composite aerofoils is presented, providing a 32% weight saving over the previous method as well as increased dimensional accuracy.

Thirdly, a numerical and physical analysis of both 2008 and 2009 Monash Formula SAE car aerodynamic packages is performed, providing a number of parameters used in the initial modelling section as well as providing a solid basis for further 3D CFD development.

Finally a preliminary analysis of the 2010 vehicle is presented, to assess the applicability of an aerodynamic package. The findings of this analysis are that 2009 aerodynamic package will still provide a significant performance advantage.

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..1 INTRODUCTION

The Formula SAE competition involves a team of university students who conceive, design, manufacture, and compete with formula style race vehicles in both dynamic and static events. The competition can trace its origins to the early 1980's when it was hosted by the University of Texas, Austin, USA. Since then the competition has spread throughout Europe, Asia, South America, and Australasia with hundreds of teams and thousands of students competing worldwide.

Monash University has competed in Formula SAE since the inaugural Australasian competition in 2000 with mixed success. Our third car, the 2002 entry, was equipped with a full aerodynamic package, including front and rear wings in addition to a diffuser. This was an Australian first, and in the words of Carroll Smith (head judge of the Formula SAE competition and motorsport legend), Monash was only the third team in the world with *"an intelligent use of downforce"* (Australasia Formula SAE Competition, 2002).

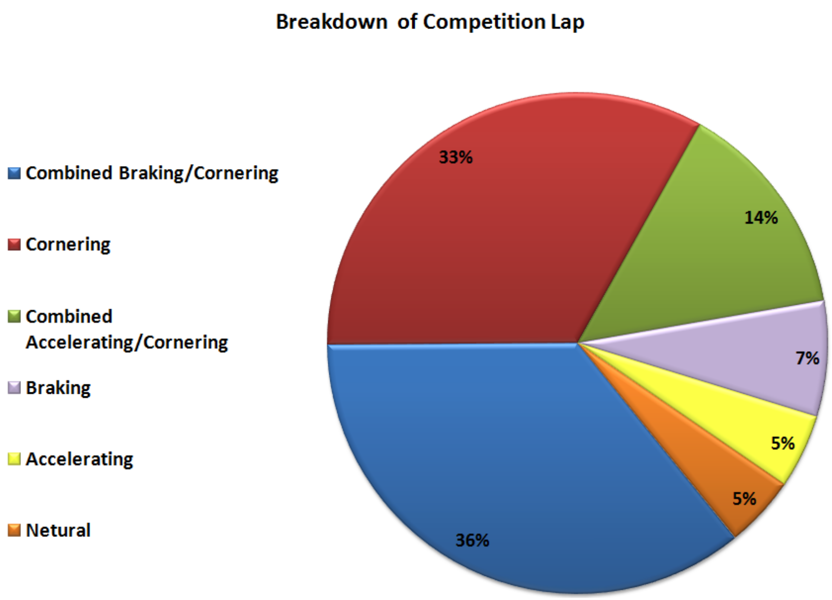


Figure ..1.1 - Breakdown of modes seen in 2008 competition (Juric, 2009)

Formula SAE events heavily favour small and nimble cars due to the low speed, tight and corner intensive nature of the tracks (See Figure ..1.1, showing relative significance of cornering). To be competitive, vehicles are required to have excellent transient cornering potential rather than outright maximum speed in a straight line. The controlling factors influencing cornering potential are weight and available lateral grip. If a car's available lateral grip can be increased for only a small weight penalty, then the car will usually be faster on a Formula SAE specification track.

At present, only a few cars world-wide have implemented a cohesive aerodynamic package to increase their cornering potential. This is likely due to a number of reasons including insufficient resources available to the team, additional weight and complexity to the vehicle, as well as a wide spread opinion that due to the relative low speeds seen in Formula SAE, wings are not effective enough to justify their weight. This is disputed by the late motorsport great, Carroll Smith who is quoted saying – "*As you* *know, for at least 12 years I've been saying the first car to intelligently apply 'download' at this competition will dominate, and Monash is pretty close*" (Australasia Formula SAE Competition, 2002).

Additional static weight due to aerodynamic devices has a three stage effect on cornering potential. Most obvious is the additional lateral force required of the tyres to resist the centrifugal acceleration (inertia) induced by the wing mass. Secondly, the vehicle's centre of gravity (CG) height will usually increase as a consequence of the addition of wings, which are commonly located above the CG height of the bare vehicle. This will facilitate more weight transferring to the outside laden wheels during cornering, and due to load sensitivity effects, this can result in a decrease of the average coefficient of friction for the four wheels (Smith, 1978). Thirdly, and of particular importance for transient response, is the increase in yaw inertia (vertical polar moment about the centre of the car) caused by wing mass located away from the vehicle's centre of rotation. This increased inertia slows the response of the car, particularly in fast slaloms by resisting rapid changes of direction and slowing down the car's response to driver inputs (Milliken & Milliken, 1995).

Detrimental effects from the addition of aerodynamic devices have the potential to be offset through the enhanced grip produced by downforce generation. Downforce increases the normal force acting on the tyres resulting in an increase in total lateral grip. It is this balance that requires an aerodynamic package to be specifically designed for a certain environment to optimise the performance benefits gained.

A thorough investigation on the performance benefits achieved due to wings has not been performed since the vastly dissimilar 2003 car, thus there is no quantifiable data suggesting the current wing package on the 2008 car is beneficial. This paper aims to address this by comprehensive analysis using the Monash Wind Tunnel facility to determine the aerodynamic characteristics of the car with and without wings. Physical changes to the dynamic properties of the vehicle as a whole will also be analysed, specifically the effect upon vehicle centre of gravity height and yaw inertia with the addition of wings. This data will then be applied to vehicle dynamic simulators to predict the gains or losses incurred in the various dynamic events of the competition. Based upon these results it will be possible to make an informed decision regarding the inclusion of an aerodynamics package on the 2009 car.

With the aid of the information gathered through wind tunnel testing, the 2008 aerodynamic package will be further developed, primarily in regards to weight and construction technique as well as improving endplate design under yaw conditions. Further development will be limited as the current design philosophy employed for the 2008/2009 cars is at the end of its development cycle, resources will be primarily invested on the 2010 car. The 2010 vehicle will follow a new design philosophy, focusing on weight reduction and increasing fuel efficiency as a direct result of a Formula SAE rule change resulting in a 100% increase in fuel efficiency weighting.

..1.1 Project Objectives

The objectives of this project are as follows:

- Testing and subsequent analysis of the 2008 aerodynamic package, to determine if a net performance increase will be seen in the Formula SAE competition, and thus make a decision about its' inclusion on the 2009 vehicle.
- Develop 2008 aerodynamic package for use on 2009 vehicle
- Improve manufacturing technique for 2009 aerodynamic package
- Perform preliminary design of an aerodynamic package for the 2010 vehicle and subsequent re-evaluation of the potential benefits by inclusion on the 2010 vehicle.

..2 LITERATURE REVIEW

The purpose of this section is to present information pertinent to the understanding of effects aerodynamics have on a race vehicles performance, as well as to review the dynamic events of the Formula SAE competition.

..2.1 Competition Scoring

The Formula SAE competition is judged on a teams combined score from both static and dynamic events, each event weighting is shown below in Table ..2.1, scoring formulae can be found appended.

Table ..2.1 - Competition event scoring

	Event	Max. Score
Static Events	**Presentation**	75
	Cost and Manufacturing	100
	Design	150
Dynamic Events	**Skid pan**	50
	Acceleration	75
	Autocross	150
	Endurance	300
	Fuel Economy	100
	Total	1000

..2.1.1 Skid pan

The skid pan event tests a vehicles ultimate steady-state cornering potential around a constant radius turn. Performance in this event is typically dictated by vehicle tyre properties, suspension geometry, vehicle balance and any aerodynamic downforce.

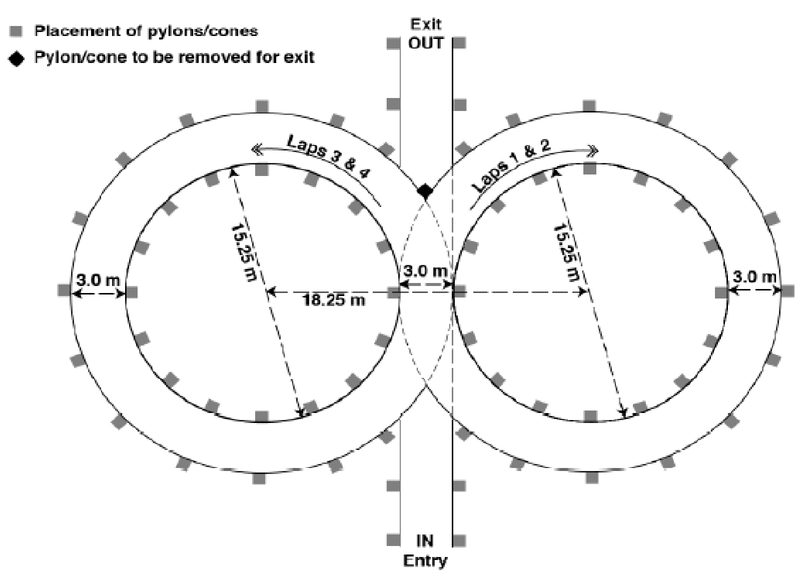


Figure ..2.1 - Skid pan layout

Vehicles enter perpendicular to the figure eight, performing one full lap of the right circle to establish steady-state turning, the second lap around the right circle is timed. Immediately following the completion of the second lap of the right circle, the car enters the left circle establishing steady-state cornering in the opposite direction; once again the second lap is timed. The elapsed times for both right and left circles are averaged to give a time in the event.

..2.1.2 Acceleration

The acceleration tests vehicles straight line acceleration potential. Performance in this event is typically dictated by rear wheel traction, engine power, vehicle tyre properties, and vehicle mass.

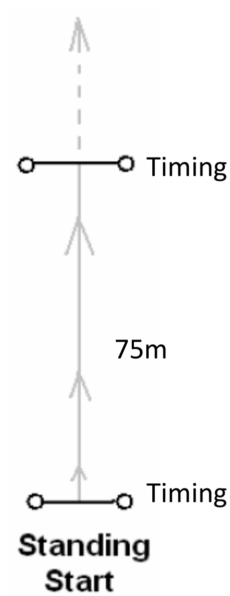


Figure ..2.2 - Acceleration event layout

Vehicles are staged just before a timing light, once a go-ahead signal is given the car accelerates in a straight line for 75m passing a second timing light. The elapsed time between the vehicle breaking the first timing light and the second is the acceleration time given.

..2.1.3 Autocross

The autocross event evaluates the car's maneuverability and handling qualities on a tight course without the hindrance of competing cars. The autocross course will combine the performance features of acceleration, braking, and cornering into one event.

A number of specifications for the autocross course are given in the Formula SAE rule book (SAE-A, 2009):

Table ..2.2 - Autocross Specifications

Track Component	Specification
Straights	No longer than 60 m with hairpins at both ends (or) no longer than 45 m with wide turns on the ends.
Constant Turns	23 m to 45 m diameter.
Hairpin Turns	Minimum of 9 m outside diameter (of the turn).
Slaloms	Cones in a straight line with 7.62 m to 12.19 spacing
Miscellaneous	Chicanes, multiple turns, decreasing radius turns, etc. The minimum track width will be 3.5 m.

The vehicle is timed to complete one flying lap of the course laid out to the above specifications.

..2.1.4 Endurance and Fuel Economy

The endurance event evaluates the overall performance of the car as well as testing the durability and reliability. The vehicles fuel economy is measured in conjunction with the endurance event to give an indication as to how well the vehicle has been tuned for the competition. Track specifications differ slightly from the autocross event, with the track being marginally more open.

Table ..2.3 - Endurance and Fuel Economy event specifications

Track Component	Specification
Straights	No longer than 77 m with hairpins at both ends (or) no longer than 61 m with wide turns on the ends. There will be passing zones at several locations
Constant Turns	30 m to 54 m diameter.
Hairpin Turns	Minimum of 9 m outside diameter (of the turn).
Slaloms	Cones in a straight line with 9 m to 5 spacing
Miscellaneous	Chicanes, multiple turns, decreasing radius turns, etc. The minimum track width will be 4.5 m.

This event requires 2 drivers, the first must complete 11 laps of the course, after which the vehicle is brought into the driver change area. The two drivers have 3 minutes in which to change places before the timing is restarted, the second driver then must complete an additional 11 timed laps. Once the combined 22 laps have been completed, the vehicles fuel consumption is measured.

..2.2 Vehicle Performance

A brief overview of vehicle performance is presented below, with a list of parameters that affect stability and response as well as cornering potential with the addition of wings.

..2.2.1 Stability and Response

As a result of the tight transient nature of typical autocross and endurance circuits, competitive Formula SAE vehicles must be nimble, providing instantaneous response to control inputs. A low CG height will minimise both lag time and pitching moments, similarly increasing vehicle roll resistance and damping whilst minimising suspension compliance will lead to an increase in vehicle response. Perhaps the greatest contribution to vehicle manoeuvrability and response are the polar moments of inertia about the X (roll), Y (pitch), and Z (yaw) axes (Smith, 1978).

..2.2.2 Cornering Potential

The basic factors governing the speed at which any car can be driven through a given corner, or series of corners, are the coefficient of friction of the tyres and the vertical loading on the tyres. The major factors affecting the coefficient of friction will be lateral and diagonal weight transfer. Lateral load transfer is governed by track width, CG height, roll centre height and roll resistance. Understeer/oversteer balance of the vehicle is governed by the relative front to rear lateral load transfers and the direction of the tyre forces, a typical practice to achieve a neutral oversteer/understeer balance is to use anti-roll bars to tune relative front to rear roll resistance (which governs lateral weight transfer).

..2.2.3 Major parameters varying with the addition of wings

The following parameters varying with the addition of wings, important for stability and response, as well as cornering potential, are listed below:

Table ..2.4 - Major parameters varying with the addition of wings

Parameter	Discussion
Vehicle Mass	The wings add mass to the vehicle
Polar moments of inertia	Polar moment will increase due to wing mass located away from the vehicle centreline
CG height	CG height will typically increase as a consequence of wings
Roll resistance	Roll resistance has the potential to be affected by 'unsprung' wing mounting (as used on the Monash car), effectively coupling left and right wheels
Downforce	Wings characteristically provide extra downforce

..3 MODELLING

This chapter describes the physical analysis of the 2008 Formula SAE car to quantify changes in physical characteristics with the addition of front and rear multi-element wings. The changes are further analysed using ChassisSim to quantify changes in terms of performance in each dynamic event of the competition. ChassisSim is widely used in high level motor sport (A1 GP, Indy car, Lemans etc) and is one of the few simulators that correctly models transient conditions and incorporates detailed aerodynamic mapping (static margin migration, chassis yaw effects etc).

..3.1 Physical Testing

It was concluded in Section ..2 that the primary attributes governing vehicle dynamics with the addition or removal of an aerodynamics package is the changes in overall mass, yaw inertia, CG height and roll resistance. Methods for measuring these changes were obtained from Rouelle (2003) and Valkenburgh (2000).

..3.1.1 Yaw Inertia Testing

Figure ..3.1 - 2008 Vehicle without wings suspended on platform

Yaw inertia testing was conducted utilizing a technique based on the concept of a trifilar pendulum (Rouelle, 2003). Essentially the car was placed on a triangular platform which was suspended via a strap attached to each point of the triangle, the car and platform was then oscillated about the vertical axis and the time taken for the oscillations was then measured. The moment of inertia is obtained with equation 3.1 (derived by solving the equation for potential energy and kinetic energy), linking the mass of the car and platform, the period of oscillation and the geometry of the platform.

$$I = \frac{m_{car}.g.r^2.T^2}{4.\pi^2.L} + \frac{m_i.g.r^2}{4.\pi^2.L}.\left(T^2 - T_i^2\right) \qquad 3.1$$

m_{car}: Mass of Vehicle

g: Gravitational Constant

r: Horizontal distance from the center of the platform to pickup points

L: Length of each strap

T: Period of oscillation of vehicle and platform combined

m_i: Mass of bare platform

T_i: Period of oscillation of bare platform

The frequency of oscillation is independent of the amplitude (angular displacement), thus in the interest of accuracy, timing occurred over 10 consecutive oscillations with the final time divided by 10 to give the period. Small initial angular displacements were used to initiate the oscillation; this minimized the angular velocity and thus lessened the effect aerodynamic drag had on the integrity of the results.

Table ..3.1 - Yaw Inertia testing results

	No Wings	Wings	Δ
Yaw Inertia	110 kgm^3	123 kgm^3	+12%

Three independent tests were performed for each configuration. Times were consistent between tests with the largest coefficient of variation under 4%. With the addition of the front and rear wings the tests showed an increase in the yaw inertia of 12% to 123kgm^3, these results are of the same order as a similar test performed on the 2003 Vehicle by Wordley & Saunders (2005), giving confidence in the results.

..3.1.2 CG Height Testing

Figure ..3.2 - 2008 Vehicle with front raised on load cells.

The CG height of the 2008 vehicle with and without wings was determined using a method developed in Valkenburgh (2000), utilizing load cells the team possessed. The front of the vehicle is raised with the increase in rear wheel load measured and recorded. Valkenburgh presents an equation (Equation 3.2) relating the height of the front wheels to the change in rear wheel load, allowing center of gravity height to be determined (see ..9.9 for illustration).

$$h = \frac{\Delta W.L.\sqrt{L^2 - x^2}}{W.x} \qquad 3.2$$

h: Distance from axle line to CG

ΔW: Change in weight over the rear wheels with the front raised

L: Vehicle Wheelbase

x: Height front wheels are raised to

W: Total vehicle weight

An SAE paper by Winkler (1992) discusses how error in this technique can be minimized, stating that for greater resolution the front wheels should be raised at least 400mm from their static height. Additionally, steel ‘dummy’ dampers were used in place of the Ohlins ST44’s to prevent unwanted suspension movement which would affect the integrity of the results below.

Table ..3.2 - CG Height test results

	No Wings	Wings	Δ
CG Height	282 mm	304 mm	+8%
CG Height inc. Driver	288 mm	306 mm	+6%

Three independent tests were performed for each vehicle configuration, with a maximum coefficient of variation below 3%. A 22mm (8%) increase was seen with the addition of the wings over the bare care configuration, this difference was reduced to only 6% with the addition of an 80kg Driver which concentrated more mass marginally above the bare vehicles centre of gravity.

..3.1.3 Roll Resistance Testing

Figure ..3.3 - 2008 Vehicle on load cells with diagonal wheels shimmed

Roll resistance changes were measured using the teams load cells once more. The roll resistance for each configuration was determined by first recording the static weight distribution with all four wheels on the load cells, then two diagonal wheels are raised a known displacement (25.4mm), representative of typical wheel travel in cornering modes (Juric, 2009). The change in weight distribution between the four wheels and a known track width allows a torque about the front and rear axle lines to be calculated, this torque combined with a known angular displacement (from the shims under the wheels) gives a roll resistance in Nm/degrees.

The tests were performed with front and rear wings, no rear wing, no front wing and no wings. Initially the tests were executed without a driver for greater resolution on the affects of the wings; an 80kg driver was then added to observe the affects under more representative conditions.

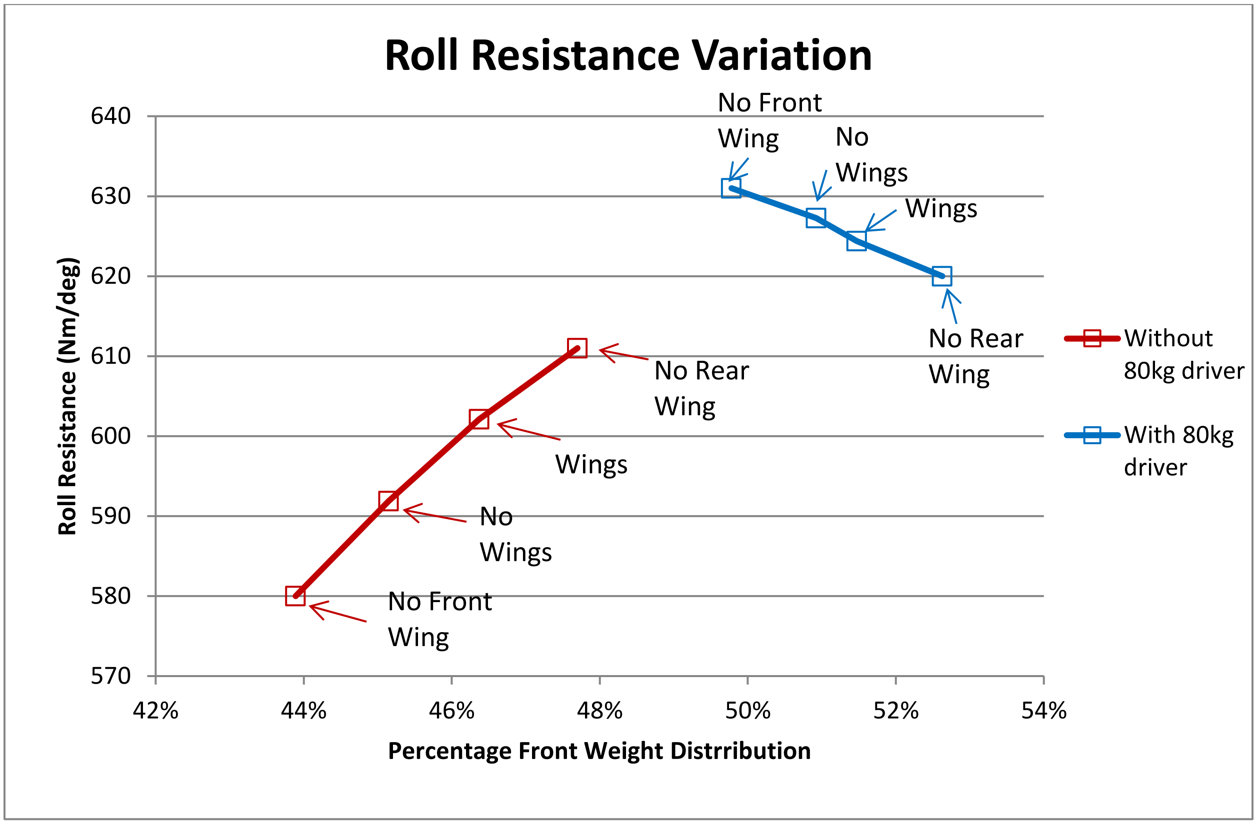


Figure ..3.4 - Effect wings have on vehicle roll resistance

Figure 3.4 shows that addition of wings only affects roll resistance due to changes in static weight distribution front to rear, rather than acting as an anti-roll bar, coupling left and right wheels. Roll resistance was observed to decrease as the cars weight distribution moved away from 50:50, this occurs due to the fact the suspension operates essentially as two springs in parallel (in roll mode). As the weight distribution moves away from 50:50, more of the cars mass is reacted by a single spring rather than sharing the load equally between the two (which will provide greatest roll resistance).

The negligible affect observed of wings on roll stiffness, besides changes in weight distribution, can be attributed to the small wheel displacements used and the small motion ratios seen between components. As the wing mounts utilise rod end bearings for all pickups, any displacement caused in roll can be taken up in bearing 'slop'.

Adjustment of corner weights to achieve close to 50:50 weight distribution can be achieved via movement of suspension platform height and/or a re-think of component packaging, thus these tests conclude an unsprung aerodynamics package does not contribute directly to vehicle roll stiffness and can be ignored in later analysis

..3.1.4 Summary

A summary of physically measured parameters that vary with the addition of wings is presented below:

Table ..3.3 - Parameters varying with the addition of wings

	No Wings	Wings	Δ	Effect?
Weight	313 kg	330 kg	17 kg (5%)	Bad
Yaw Inertia	110 kgm3	123 kgm3	13 kgm3 (12%)	Bad
Roll Resistance	Adjustable	Adjustable	-	Unchanged
CG Height	288 mm	306 mm	18 mm (6%)	Bad
Frontal Area	0.75 m^3	1.1 m^3	0.35 m^3 (47%)	Bad
CD **	0.68	1.2	0.52 (76%)	Bad
CL **	0.23	-2.4	-2.63 (1140%)	Good

* - All values include an 80kg driver.

** - Coefficients of lift and drag are obtained in section 0.

..3.2 Analysis

This section employs the parameters obtained through physical testing in section ..3.1 to develop transient vehicle dynamics simulations using ChassisSim, the simulations are then utilised to quantify changes in performance for the following scenarios: 0-75m Acceleration, Braking 80-40km/h, Skid Pan, and an Autocross/Endurance flying lap.

..3.2.1 ChassisSim Setup

Table ..9.2 gives a full summary of the additional data used to construct the ChassisSim vehicle model. ChasissSim uses G-G (lateral and longitudinal acceleration) and wheel speed data to construct the vehicle path or 'track'. The G-G and wheel speed data was obtained using the MoTeC Advanced Dash Logger (ADL) at the 2008 Competition, the vehicle was outfitted with a number of data acquisition sensors.

Table ..3.4 summarises the sensors used to obtain the required data with their logging rates and accuracy.

Table ..3.4 - Data Acquisition Sensors utilised on 2008 Vehicle

Measurement	Sensors Type	Logging Rate	Accuracy
Wheel Speed	Honeywell Hall-effect	100 Hz	**+/- 1.02%**
Vehicle Z&Y Acceleration	Crossbow LP 3-axis Accelerometer	100 Hz	**+/- 0.20%**

Distance is a function of the MoTEC Dash Logger and an internal calculation is based on the Wheel Speed, with a quoted error for the distance calculation of 1%.

The model was 'tuned' to correlate with acceleration, braking, skid pan and autocross data (Figure ..3.5 to Figure ..3.8) by adjusting driver skill (% of vehicle grip limit utilised), engine power and torque curves (Figure ..9.1**)** and tyre parameters which were based off results obtained from Trevorrow (2006).

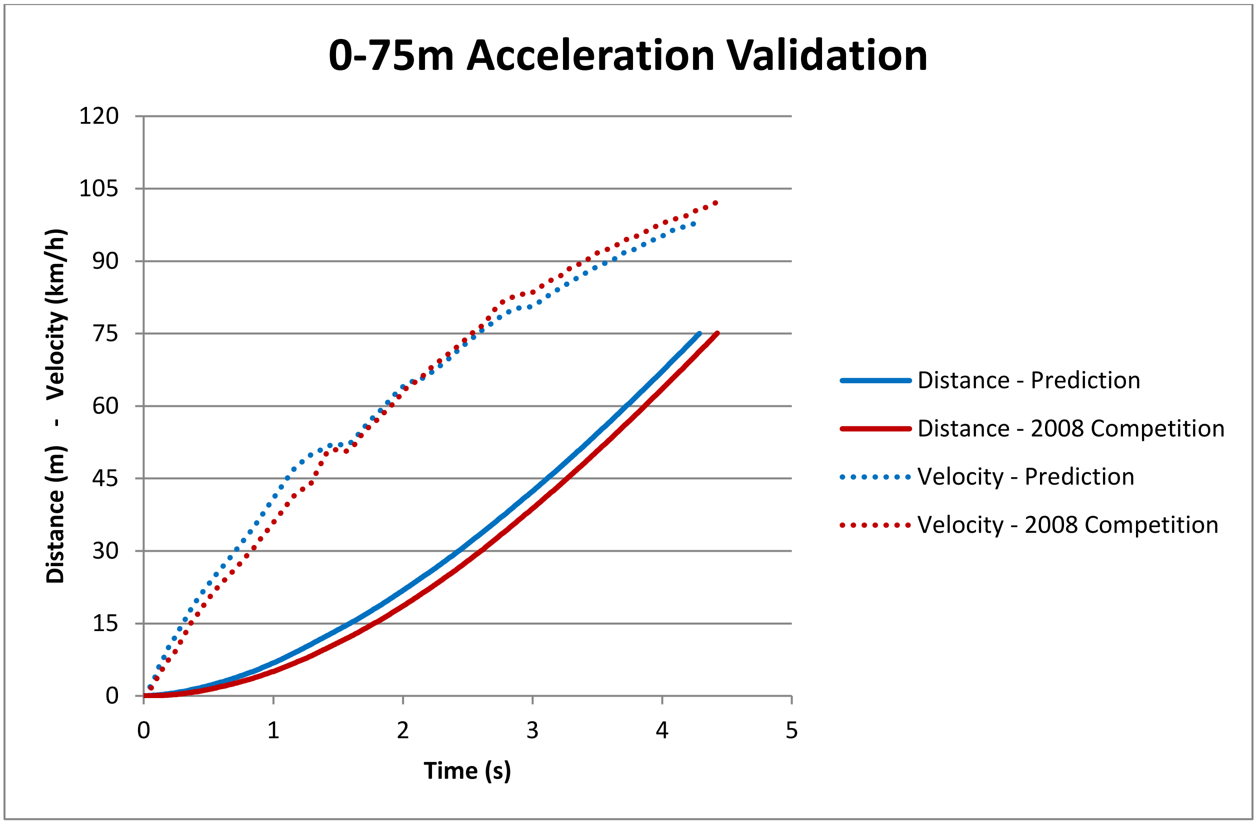


Figure ..3.5 – ChasissSim correlation with 2008 competition acceleration data

Acceleration data obtained from the 2008 Formula SAE competition was utilised for the initial stage of the ChassisSim correlation, as the acceleration event is comparatively independent of driver skill, relying more on tyre parameters and vehicle torque curves. Torque and power curves for the engine (Figure ..9.1**)** were obtained using a steady state water brake dynamometer; any variance in these curves seen at the 2008 Competition can be primarily attributed to changes in ambient air temperature and humidity, as well as drive train losses.

The major discrepancy between predicted and logged data occurs during the initial 1.5 seconds of acceleration, this has been credited to the inaccuracies in ChassisSims tyre model predicting tyre behaviour under sudden acceleration, which is notoriously difficult to do (Trevorrow, 2006). Due to this difficulty in predicting initial tyre performance, an accumulated error after 75m comes to 0.1 seconds, which was minimised by varying the engine torque curve to affect the higher velocity portion of the velocity curve, and varying tyre thermal properties to affect the initial curve.

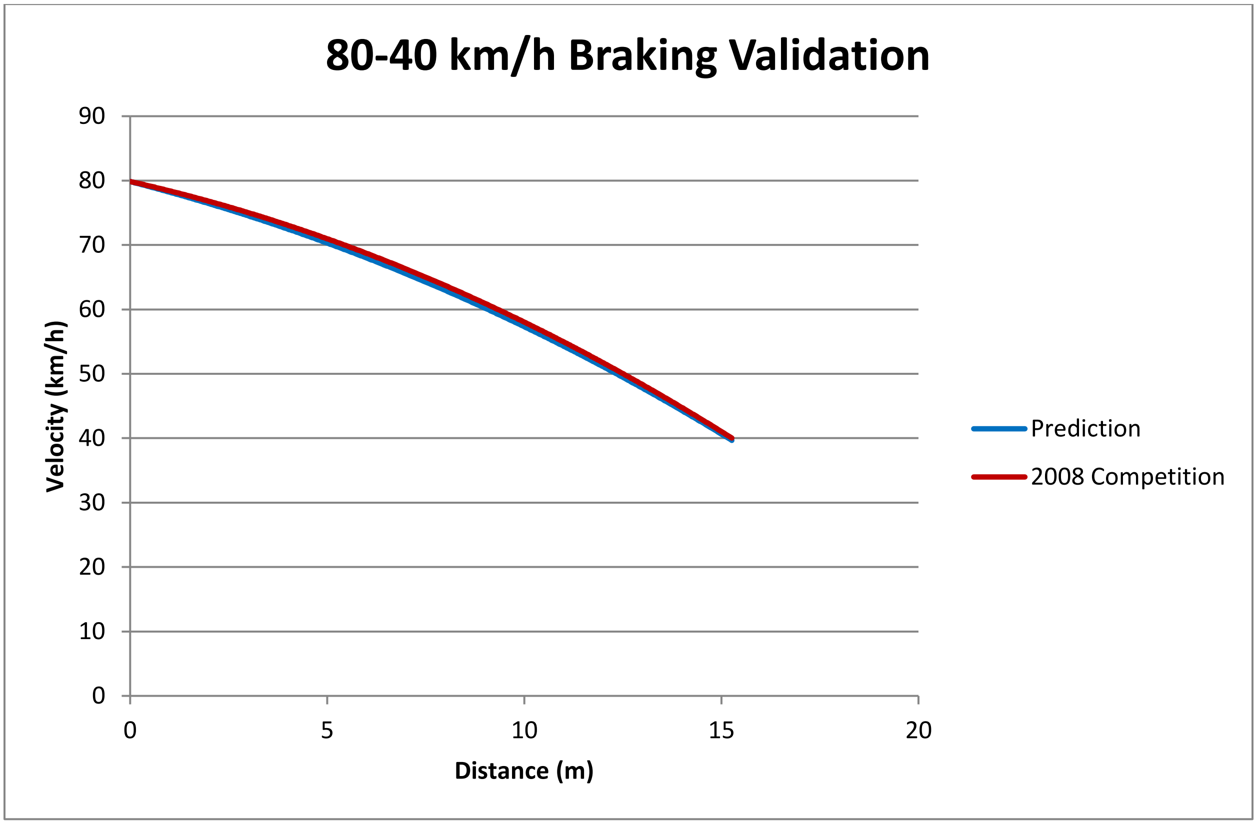


Figure ..3.6 - ChassisSim correlation with 2008 competition braking data

The close correlation of braking performance seen in Figure ..3.6 was achieved by varying front to rear brake bias - the prediction achieved in Figure ..3.6 used 56% front and 44% rear. ChassisSim accurately predicted braking distance from 80km/h to 40 km/h to within 0.5 m of logged 2008 Competition data.

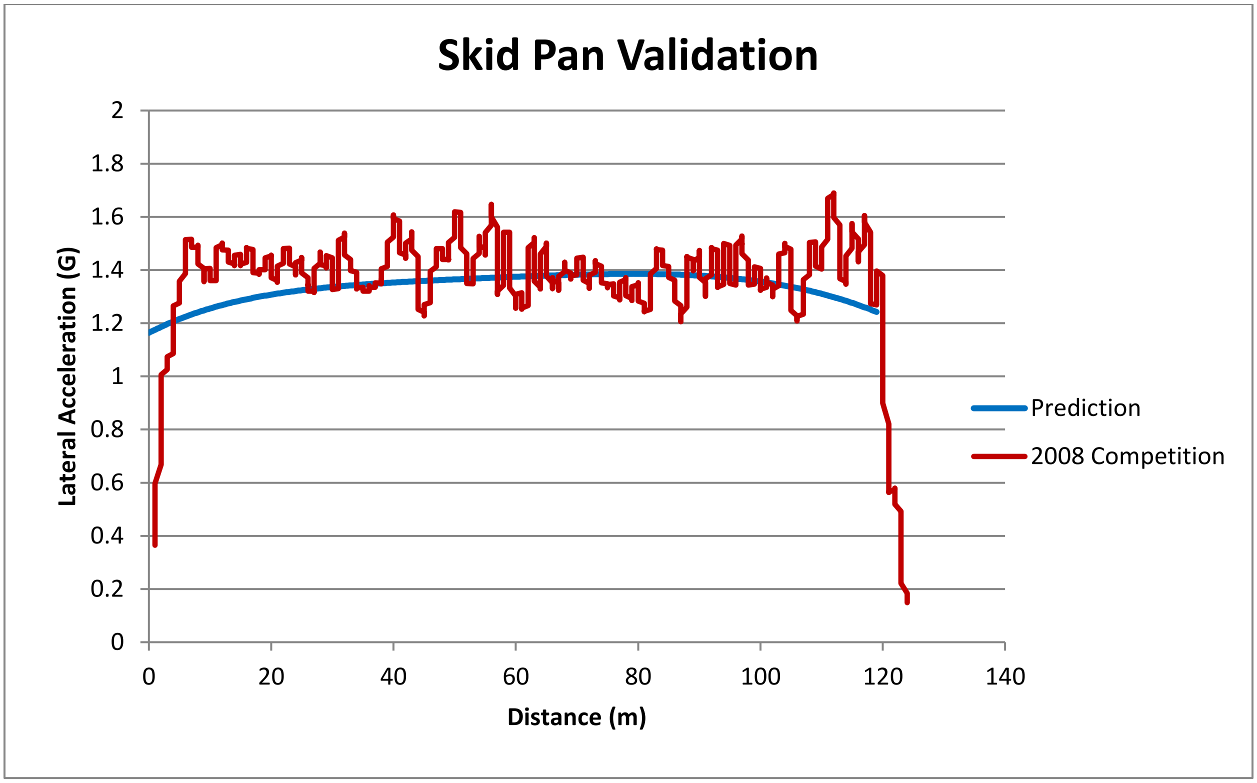


Figure ..3.7 - ChassisSim correlation with 2008 Skid Pan data

Logged data in Figure ..3.7 from the 2008 Competition oscillates considerably, this is characteristic of a vehicle operating close to the grip limit – periodically breaking and regaining traction (Smith, 1978). The ChassisSim simulation does not exhibit this characteristic as the driver model never passes over the grip limit, however despite this the average error for lateral acceleration is less than 0.06 G (5%) and less than 0.01 seconds to complete the full event.

Driver skill was the only parameter varied to achieve this simulation correlation, with the optimal found at 95% use of total lateral grip limit. The relative 'ease' of driving the vehicle in the skid pan event allowed the driver to operate much closer to the grip limit of the tyres than would normally be possible on a typical circuit.

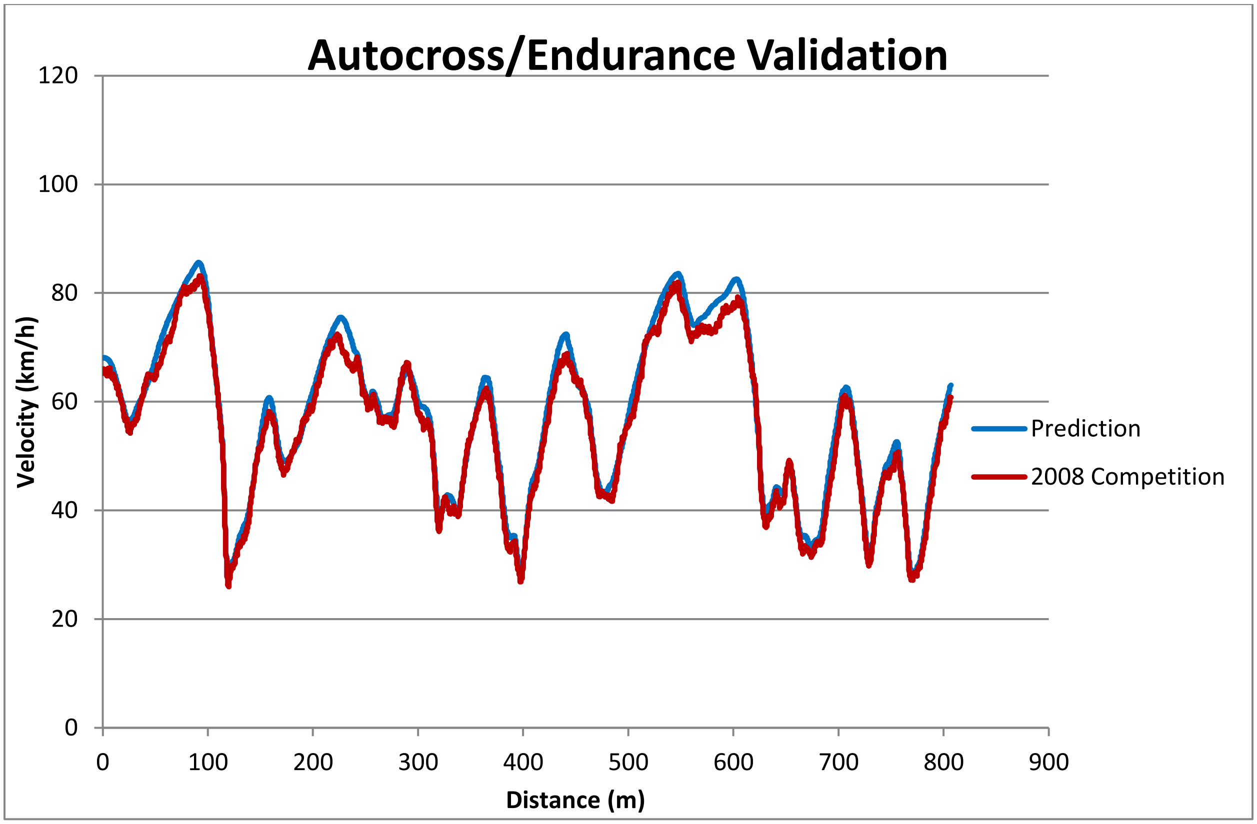


Figure ..3.8 - ChassisSim correlation with 2008 Autocross lap

The blue curve in Figure ..3.8 is the wheel speed prediction produced by ChassisSim for a single flying Autocross lap, while the red curve is the logged wheel speed from the 2008 competition. ChassisSim closely matches the logged wheel speeds of the 2008 Autocross with total lap time variation of only 0.2 s in a 54.32 s lap compared to logged results, giving confidence in ChassisSim's ability to accurately model a vehicles dynamic performance.

Driver skill from the previous validation (Skid Pan) required detuning to utilise only 88% of ultimate lateral grip limit (from 95%), this is due to the autocross track being much more complicated than the quasi-steady state cornering seen in skid pan.

..3.2.2 Acceleration Performance Prediction

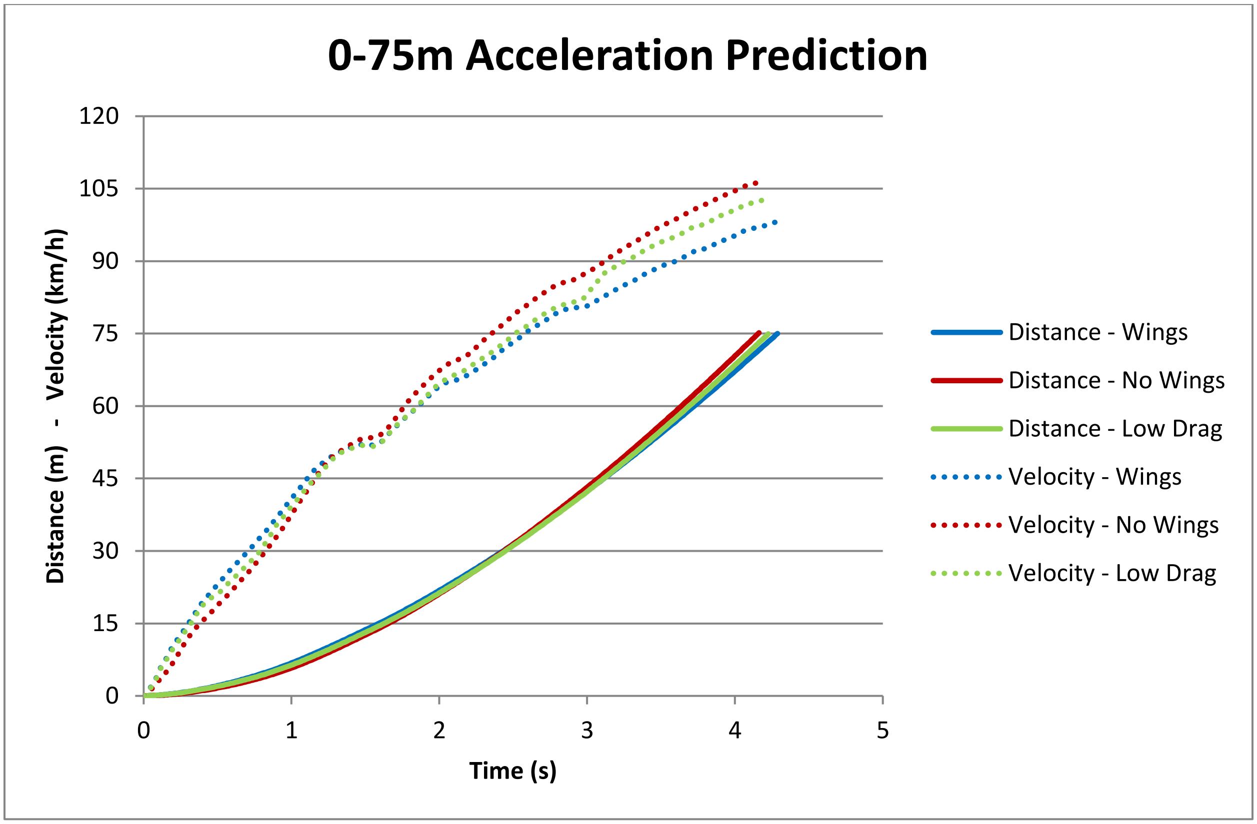


Figure ..3.9 - Acceleration Performance Comparison

Acceleration event times are predicted to increase by 0.13 seconds (3.1%) with the addition of wings - this is credited to the substantial reduction in top end velocity, as substantial engine power is used to overcome the increased aerodynamic drag. Interestingly, the initial acceleration (0-1.2 s) is increased with the addition of wings, aerodynamic drag contributes less at these lower velocities and traction is more the limiting factor rather than engine power. The increased CG height due to the addition of wings facilitates more weight transfer to the rear wheels (the driven wheels) under longitudinal acceleration, and thus improves initial tractive capacity.

Corner exit speeds on a Formula SAE track typically range between 30-40 km/h so this increased acceleration potential with wings could be quite beneficially, however quantification of this benefit is outside the scope of this project.

Using the low drag setting on the rear wing (flaps at 0 degree angle of attack), the acceleration time was only 0.07 seconds (1.7%) slower than the car without wings. Acceleration between 0 and 0.5 seconds is similar to the full wing configuration as the car still has an increased CG height over the bare vehicle, however between 0.5 and 1 seconds the reduced rear wing drag and downforce (as well as front downforce unloading the rear) provides less rear wheel normal load, thus traction reduces resulting in a decrease in vehicle velocity. At higher speeds, the low drag configuration accelerates harder than the full wing configuration due to the reduction in aerodynamic drag, though it is still slower than the car with no wings, this is due to the increase in inertia from wing mass as well as a higher drag coefficient.

..3.2.3 Braking Performance Prediction

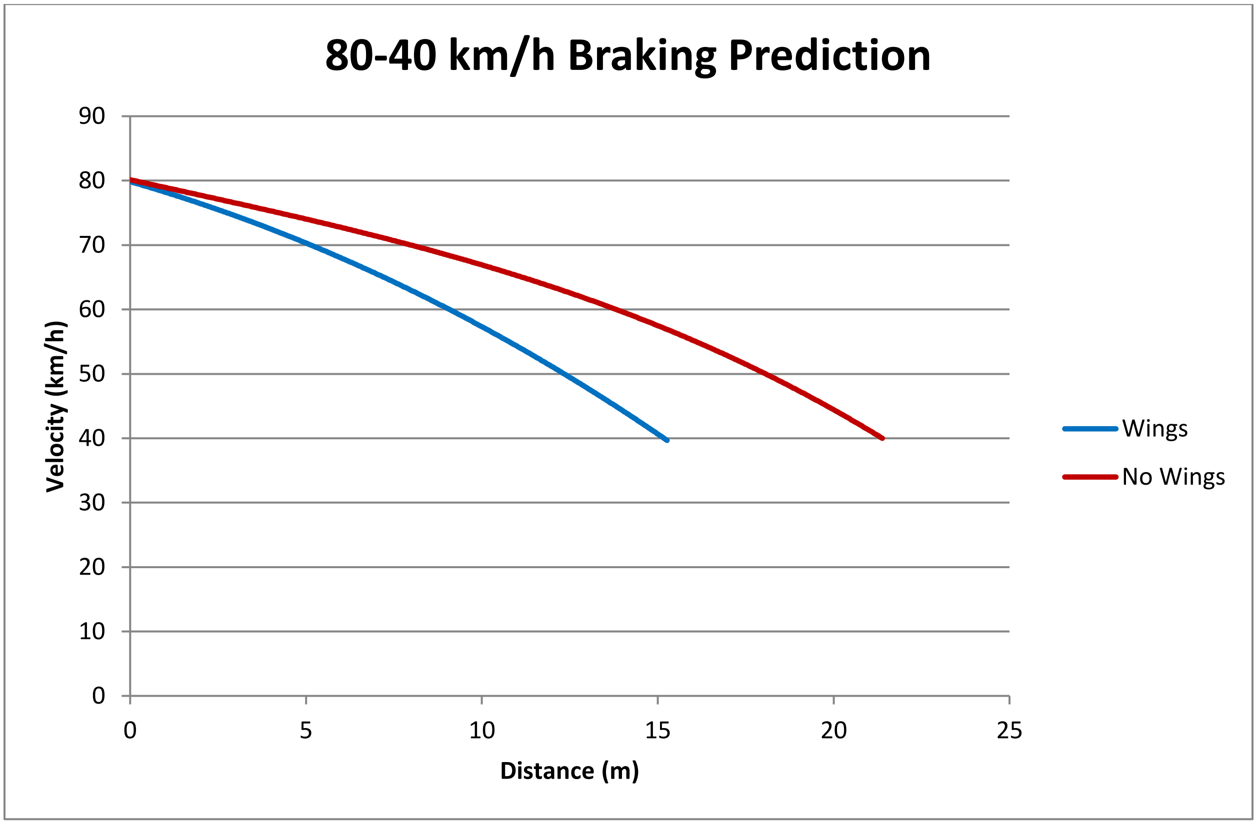


Figure ..3.10 - ChassisSim braking comparison

Predicted braking performance with wings is greatly increased over the bare vehicle, decelerating from 80km/h to 40 km/h in only 15 m compared to 21 m without wings. An average increase in deceleration of 0.3 G (34%) is achieved as the increase in downforce and drag both contribute to slowing the vehicle.

..3.2.4 Skid Pan Performance Prediction

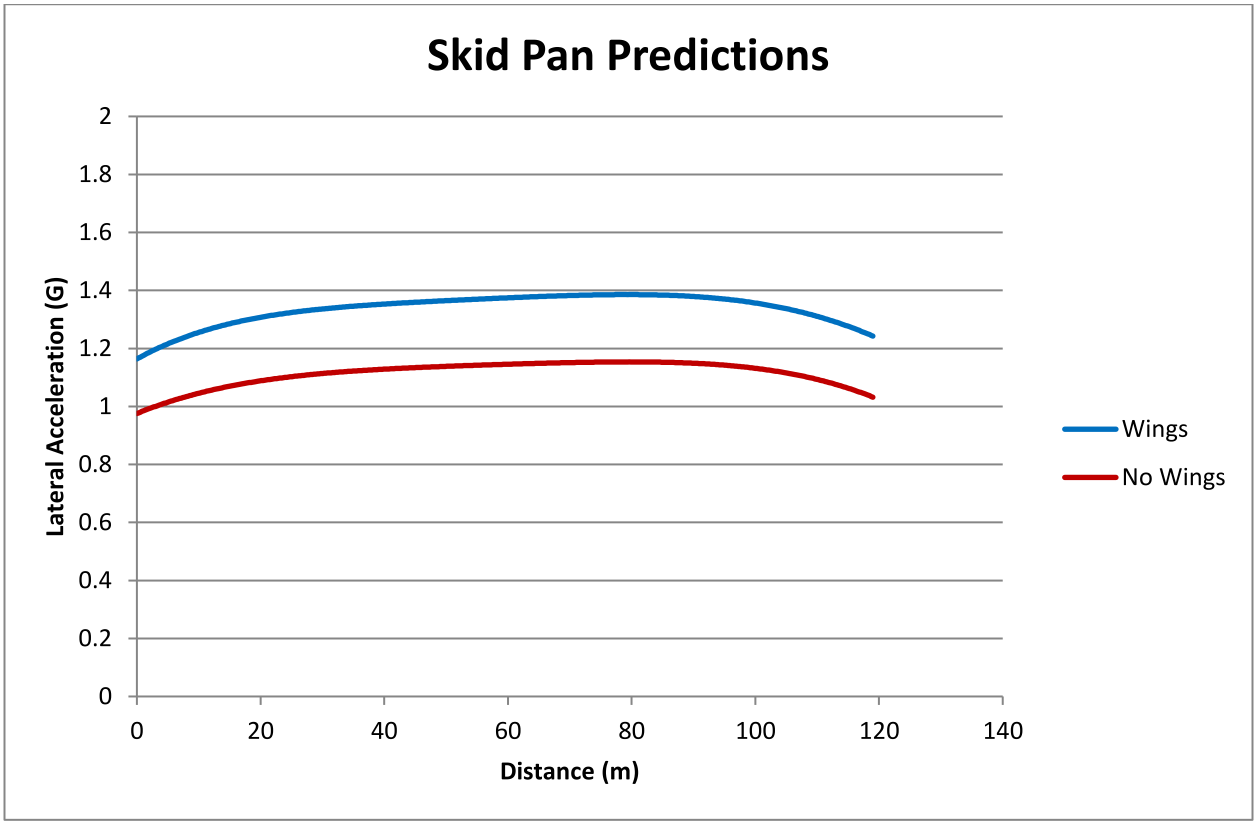


Figure ..3.11 - ChassisSim skid pan comparison

A time reduction of 0.22 seconds (4.3%) to complete the skid pan event is predicted with the addition of wings - this corresponds to an average increase in lateral acceleration of around 0.2 G. As the skid pan event involves quasi-steady state cornering the increased inertia seen with the addition of wings does not contribute to any performance reduction, however the increased downforce provides the majority of the increased lateral grip. To a lesser extent, the increased vehicle mass due to the wings allows the tyres to approach operating temperature quicker, providing an increase in coefficient of friction.

..3.2.5 Autocross/Endurance Performance Prediction

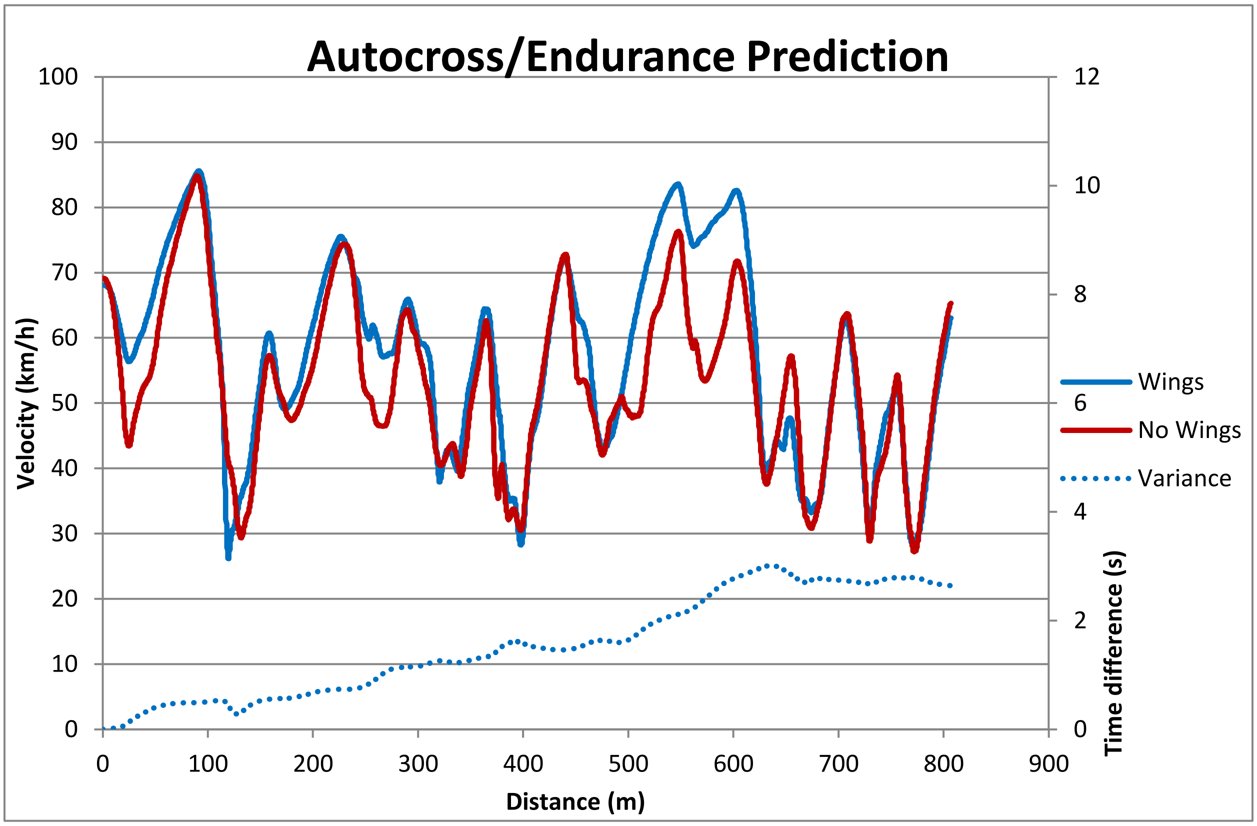


Figure ..3.12 - ChassisSim Autocross/Endurance comparison

Figure ..3.8 shows the predicted wheel speed trace around the 2008 Autocross circuit for the winged configuration (Blue curve) and the vehicle without wings (Red curve), as well as the time difference between each configuration as a function of distance around the circuit (Blue dotted).

An accumulated time saving per lap of 2.5 seconds is seen with the addition of wings, with most gains occurring during the high speed slalom and lane change sections (0-100m & 450-650m respectively) where downforce contributes more to tyre normal load (V^2 relationship). Reduced acceleration due to wings can be seen throughout the lap, particularly at higher velocities (first 100m), however these losses are insignificant in contrast to the time saved during all cornering situations. Due to the increased cornering speeds seen with wings, the car leaves corners at a higher velocity than the bare vehicle is capable of, thus even with reduced acceleration potential, the winged car can still reach the top speeds achieved by the bare vehicle.

The endurance event is typically around 22 laps of the autocross circuit, this would be a total time reduction of 55 seconds – over the course of an endurance the car with wings would lap the car without.

..3.2.6 Performance Prediction Summary

In summary the following changes in performance are predicted with the addition of wings on the 2008 Monash Formula SAE car:

	No Wings	Wings	Δ	Effect?
0-75m Acceleration	4.16 s	4.29 s	+0.13 s (3.1%)	Bad
0-75m Acceleration (low drag)	4.16 s	4.23 s	+0.07 s (1.7%)	Bad
80-40km/h Braking	0.91 G	1.21 G	+0.3 G (34%)	Good
Skid Pan	5.12 s	4.9 s	-0.22 s (4.3%)	Good
Autocross/Endurance	57.5 s	55 s	-2.5 s (4.4%)	Good

..3.3 Conclusion

Confidence has been found in the accuracy of ChassisSim through correlations of predictions with logged track data performed in Section ..3.2.1. Predictions of the changes in performance in a number of dynamic scenarios, with the addition of wings on the 2008 Formula SAE car, have been performed using ChasissSim, with the outcome that wings can be used to significantly increase vehicle performance in all situations excluding a small reduction in straight line acceleration potential. The increases seen in all other areas validate the continued use of a similar aerodynamic package on the 2009 Formula SAE car.

..4 MANUFACTURE

This section gives a brief overview of the revised construction technique used on the 2009 aerodynamic package and subsequent weight improvements.

Figure ..4.1 - Flap profile being prepared for vac bag

..4.1 Previous Methods

Before developing a new manufacturing method, a brief review of previous methods is presented, discussing strengths and weaknesses encountered with each.

..4.1.1 2002

Wing elements were made using 2D wire cut foam profiles, with 1 layer of coarse 400 gsm carbon fibre twill weaves laid over the profile and vac-bagged in place. Due to the vacuum, the foam crushed in places leaving visible indentations which had to be filled afterwards with body filler.
A major problems encountered was the carbon bunching up at the leading and trailing edges, requiring extensive sanding and carbon bandaging. As a result of these imperfections and the coarse carbon cloth, surface finish was poor. In an attempt to improve surface finish, the profiles were coated with a number of layers of resin, however this wasn't particularly successful which resulted in further sanding.
Rear wing mounts were simply bonded to the bottom surface of the mainplane using Araldite. As a consequence of poor surface preparation the rear wing blew off the mounts during a heavy side gust in on-track testing.

..4.1.2 2003

In an effort to improve surface finish and to reduce construction time, the 2003 profiles were manufactured using two-piece moulds. Foam plugs (with flanges) were first CNC wire cut, a fine layer of fibreglass was then layed up onto the foam and vac-bagged to seal the surface. After curing the surface was sanded and filled to improve finish.
These plugs (8 of them in total) were coated in Frekote release agent, before a number of layers of thick fibreglass was layed up on them to produce the moulds. The moulds were utilised to produce a variety of test parts, both in fibreglass and carbon. Quarter portions were used to experiment with a variety of internal structures, including aluminium C-section and fibreglass/foam board ribs. A Divinicell core was added to the skins to improve their localized stiffness - a choice which necessitated 2 separate vac bag procedures for each skin. Ribs and spars were fabricated from fibreglass/ foam core panel, these ribs were hand fitted and bonded to the skins using an epoxy-Q cell mix. Internal lugs for mounting were made from aluminium and strapped in position within the ribs using wet carbon strands. Leading and trailing edges were hand finished using body filler and painted black. When finished each element was given a clear coat of 2-pack paint.

Figure ..4.2 - 2003 wing construction

The end result had a very good surface finish, however manufacturing time remained similar to the 2002 method. Weight was slightly reduced from the 2002 method, but still much higher than initially thought.

..4.1.3 2004-2005

These wings used the moulds made in 2003 to produce 2 layer carbon skins which were then bonded onto wire cut foam profiles. A carbon bandage was used at the leading edge to help join the two separate skins. The main planes used an internal structure from composite board (fibreglass faces with Divinicell core) with bonded inserts, similar to 2003. When bonding the skins to the foam, the entire element was vac bagged, resulting in unwanted compression of the foam due to excessive vacuum. The indentations created around the internal structure consequently resulted in early flow separation in subsequent wind tunnel analysis.

..4.1.4 2006-2008

A 'taco' method was utilised to manufacture these wing profiles – this entailed forming a thin sheet of aluminium (1mm) around a CNC wire cut foam core. Once the desired shape had been formed the aluminium was coated in Frekote release agent and 2 layers of 200 gsm twill weave carbon was layed up on the inside of the aluminium 'taco', then vac bagged down. After curing the carbon sheets were released from the aluminium taco, and then bonded onto the foam profile which the aluminium taco was formed around.

The resulting wings had the best surface finish yet, however the carbon skins did not conform well to the foam profiles, resulting in inaccurate aerofoils, particularly the leading edges. This was attributed to the aluminium taco being bent around during the layup and vag bag processes. The aluminium was also prone to indentations due to its thickness.

..4.2 Technique Developed

The manufacture technique used to manufacture the 2009 wing profiles is similar to the original 2002 method, utilising a CNC wire-cut EPS (expanded polystyrene) foam core. However a two-part female mould is also used to prevent the foam profile from losing camber when subject to vacuum (Figure ..4.3 - Male profile inside female foam mould.

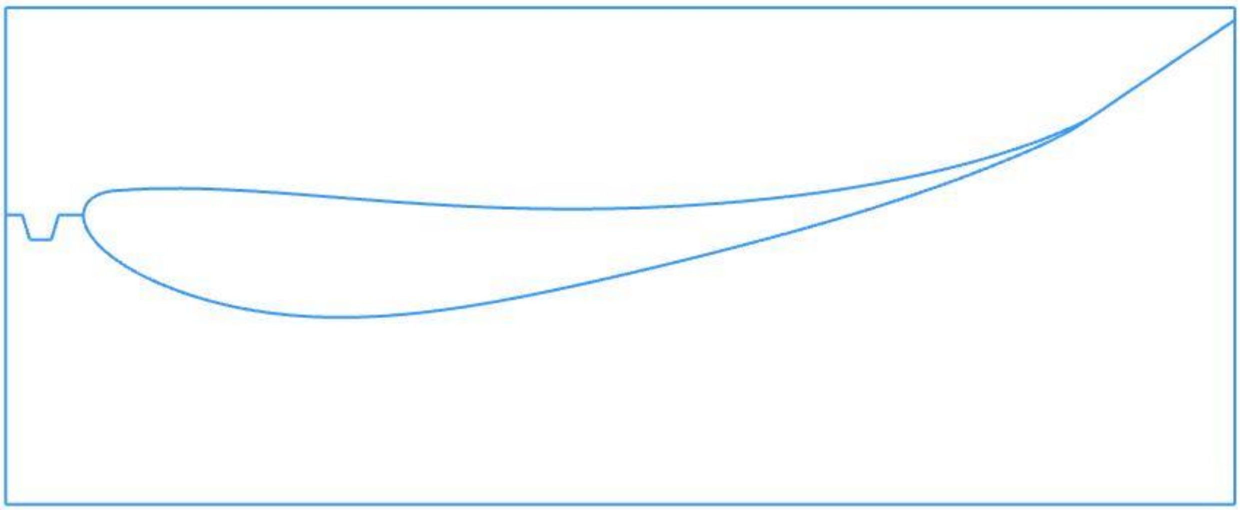


Figure ..4.3 - Male profile inside female foam mould

..4.2.1 Layup Process

1. Cut a sheet of 0.5mm thick PVC plastic so it wraps around foam profile and extends approximately 50mm from the trailing edge, trim width to allow 10mm overhang either side of the profile. This PVC sheet peals off the carbon, providing a smooth surface finish after cure.
2. Cut 2 layers of 200gsm Carbon Fibre plain weave to fit 20mm inside all edges of the vac bag cut in the previous step. This will not completely cover the foam profiles width, however the foam profile is oversized for this purpose as achieving a good finish on an edge is difficult. Care must be taken to ensure the fibre is square relative to the fibres when cut, as dry fibres have a tendency to 'warp' when handled; a common practice is to physically pull out a fibre along the desired cut path and cut along the remaining void.
3. Mix an amount of epoxy resin equal to the combined weight of the two carbon sheets, place the first layer of carbon cloth centrally on the PVC plastic then proceed to gently wet out with resin using bog scrapers. Once the first layer is sufficiently impregnated with resin, carefully lower the second layer down, starting from one end and gradually working it down with your fingers. Remove any air bubbles or folds present in the second layer before you begin applying more resin, as once fully wet out it is much more difficult.
4. Once both layers are fully impregnated, place the foam profile centrally on the wet out carbon, carefully lifting the PVC sheet underneath, wrapping the carbon around the foam profiles leading edge. Gently work out any air bubbles using a cloth on the dry side of the PVC (to prevent your fingers leaving indentations).

5. Place the pressed down side of the profile into the matching female mould so you may gently work down the other side, making sure to press down the trailing edges last.
6. Once the carbon and PVC has been evenly worked down onto the foam profile, wrap the profile in a large vac bag and place back inside the female mould (both profile and vac bag inside mould). Under a vacuum the foam profile alone tends to return to its lowest energy state (zero camber), the female mould prevents this.
7. Slowly increase vacuum on profile, being careful not to let the vacuum reach more than 5 PSI which can crush the foam. Work out any creases in the vac bag before placing the other side of the female mould on the profile.
8. Put a small amount of weight on top of the female mould to ensure it stays in place (10kg evenly distributed)
9. After leaving for sufficient time to cure, remove profile from female mould and vac bag, peel off the PVC layer, then post-cure the profile at around 50°C for 12 hours to improve the mechanical properties. This can be achieved either using a heater in a reasonably sealed box, or wrapping the profile in a conventional electric blanket.
10. After the post-cure is complete, sand back profile to remove any excess resin, then apply an epoxy Q-cell mix to fill any low points on the profile, sanding back after curing.

..4.3 Detailed Design Overview

The detailed design of the mounting and auxiliary components is beyond the scope of this report; however a brief overview of the major changes is given below.

Both front and rear wing mounts used plexus bonded aluminium clevii for positive location; a number of physical tests were performed to assess the bond strength of the plexus, giving satisfactory results. This removed the need for any internal structure, greatly reducing manufacture time and complexity.

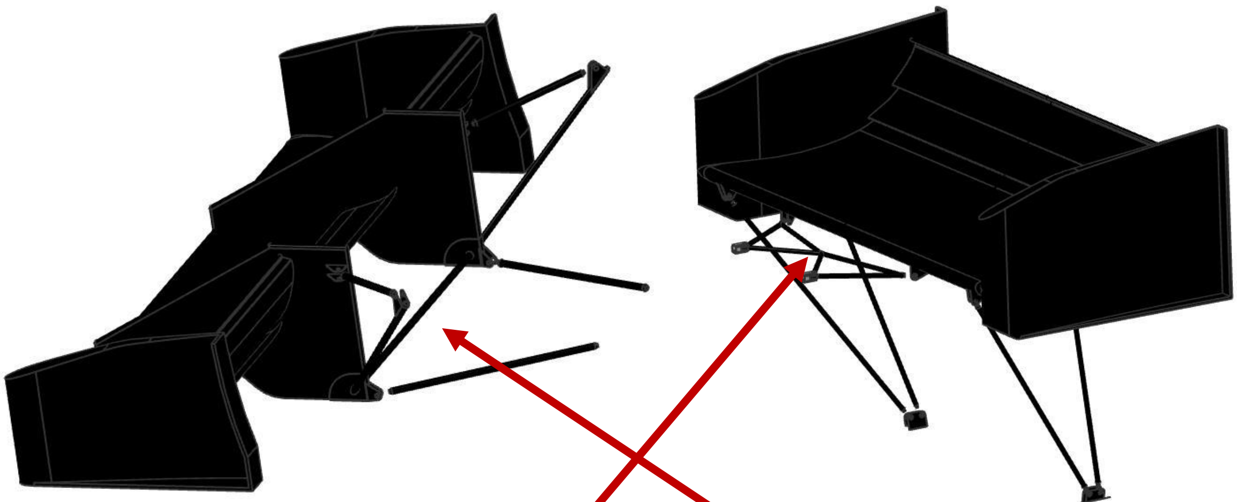


Figure ..4.4 - Front and rear wing assembly

All wing struts excluding the rear wing drag link and front wing lateral stabilising bar were manufactured using 5/8" x 1.2mm carbon tubing with bonded aluminium lugs to receive 1/4" rod ends.

This material change from ½" x 1.2 mm mild steel tubing resulted in a significant weight saving over last years mounting assembly.

..4.4 Weight Comparison

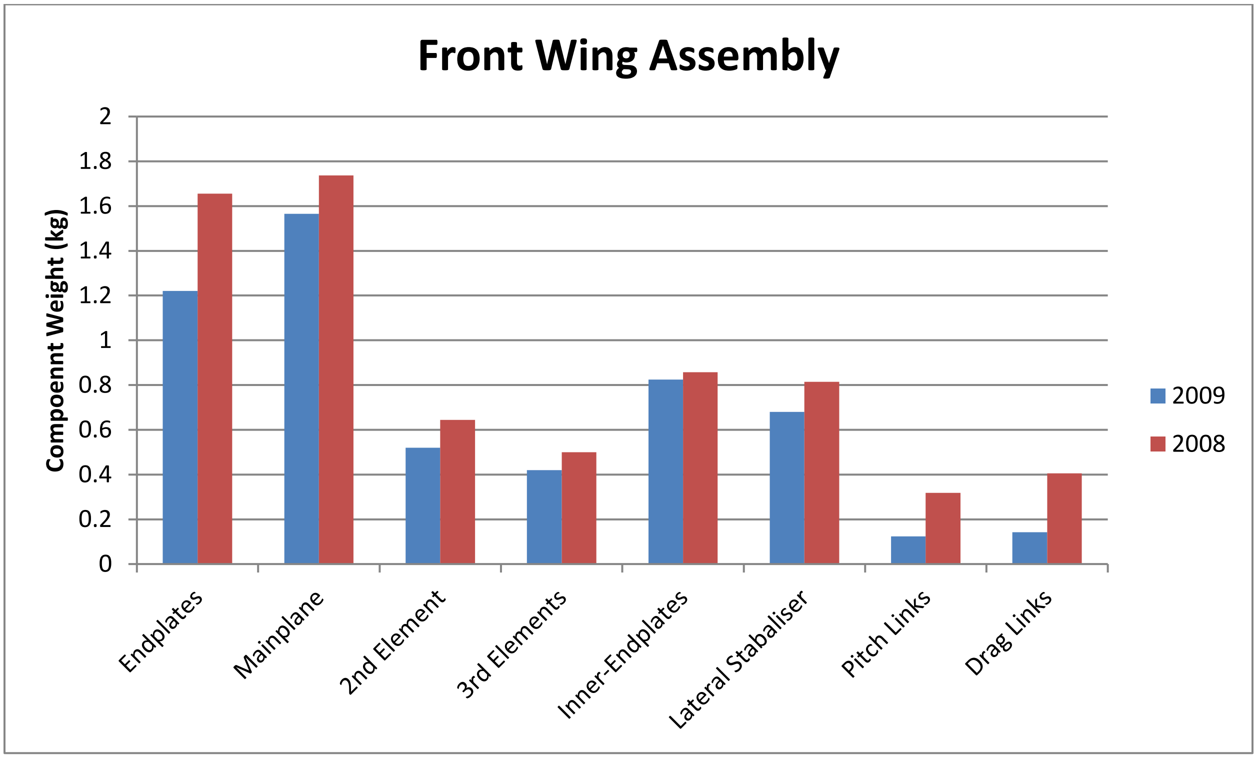


Figure ..4.5 - Front wing weight breakdown comparison

Using the improved manufacturing techniques the entire front wing assembly was 20% lighter (5.5 kg) than the previous year (6.9 kg). Most of this weight saving came from the endplates which used one layer of carbon weave and one layer of carbon/Kevlar weave in place of three layers of fibreglass in 2008. All wing elements were at least 10-20% lighter due to improved surface finish from layup, requiring less body filler than previous years.

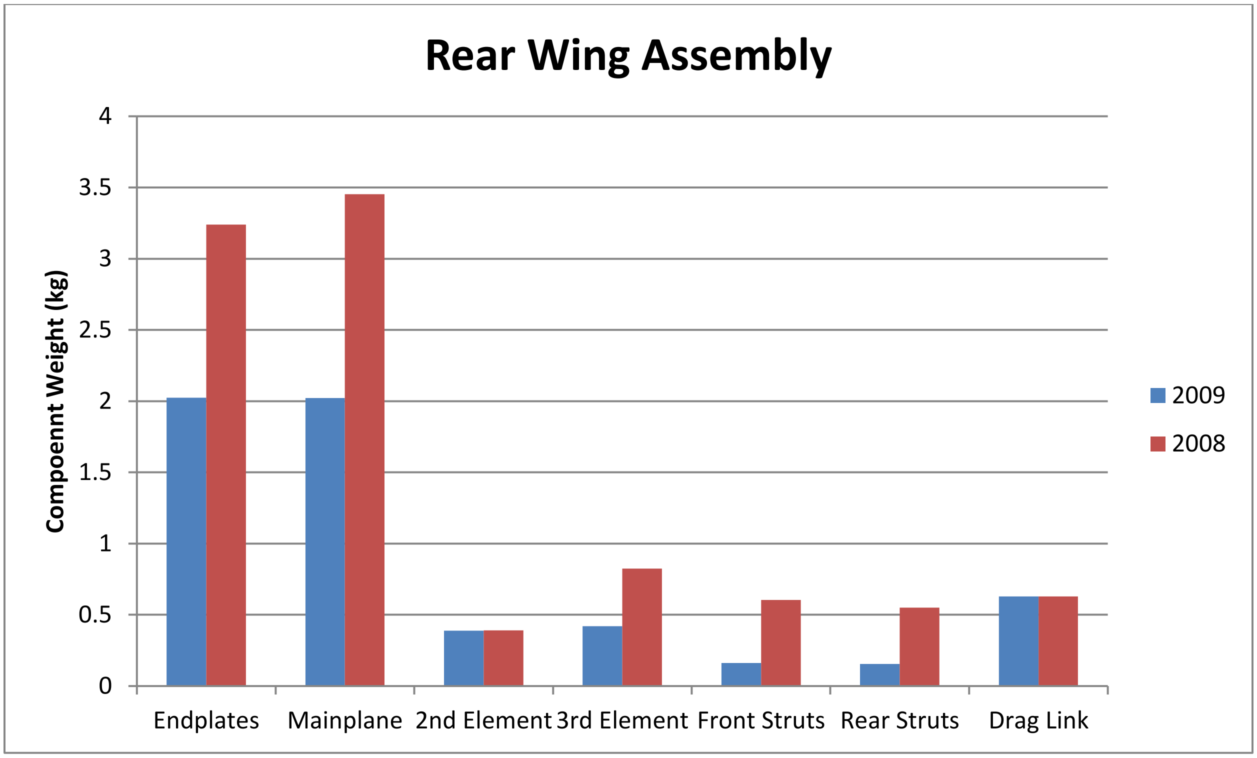


Figure ..4.6 - Rear wing weight breakdown comparison

The majority of the weight saving of the aerodynamic package occurred on the rear wing, with an impressive 40% weight saving over the 2008 aerodynamic package (5.8 kg down from 9.7 kg). The rear endplates utilised a single carbon layer over foam rather than the excessive 3 layers of fibreglass used in 2008.

Weight of the rear wing assembly is particularly important, due to the large height it is placed above the bare vehicles CG.

..4.5 Summary

In summary, the 2009 aerodynamic package has been successfully manufactured in record time, with a total weight saving over the previous year of 5.3 kg (32%), and also exceptional dimensional accuracy to the original CAD profile model. This reduction in weight will carry on to a reduction in vehicle polar moment of inertia and CG height.

Figure ..4.7 - Fully manufactured 2009 aerodynamic package on the 2009 vehicle

..5 NUMERICAL AND WIND TUNNEL ANALYSIS

This section presents the comprehensive full car wind tunnel analysis of the 2008 Monash Formula SAE vehicle. Tests have been performed to quantify the aerodynamic properties of the vehicle as it was setup for the 2008 Formula SAE competition, providing data both with and without wings to be used in modelling section (Section 0). Additionally, the development of new profiled endplates to improve the vehicles performance when subject to yaw conditions will briefly be discussed.

Testing of the newly constructed 2009 aerodynamic package in both free stream and on car is also conducted to validate re-designed flap profiles, slot gap geometry and construction technique, and to provide lift and drag polars for any further analysis.

..5.1 Experimental Method

The Monash full scale wind tunnel is a closed return, open jet wind tunnel with flow properties described in detail by Gilhome(2001). Blockage effects can be ignored as the vehicle to test-section frontal-area ratio is much less than the 7.5% quoted by Pope (1984) and Katz (1995), required to avoid errors of up to several percent. Furthermore, the tunnel is regularly used for the testing of commercial vehicles with substantially greater frontal area.

A purpose built testing apparatus (Figure ..5.2**)** has been manufactured to address inconsistencies between the conditions seen on-track and what occurs in the wind tunnel. As there is no rolling road in the test section, the tunnel floor is a stationary object relative to the airflow, thus a boundary layer develops along the floor interfering with the velocity profile under the vehicles front wing (Figure ..5.1). Raising the vehicle approximately 0.2 m off the floor and placing an artificial ground plane under the vehicle, just ahead of the front wing, attempts to simulate a moving ground plane (minimizing the ground boundary layer).

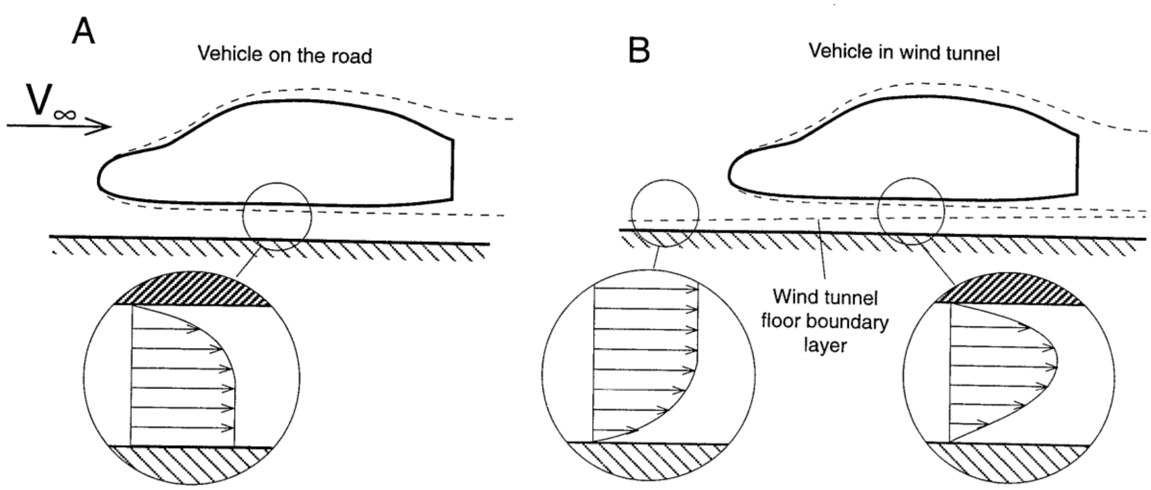


Figure ..5.1 - (Left) Boundary layer and velocity profile with car on-track. (Right) Boundary layer interaction occurring in wind tunnel due to stationary ground place (Katz, 1995).

This testing rig was also designed to allow wings to be held and tested with endplates in free-stream without the car in place; this allows greater resolution between tests as the car can cloud variations in results due to the substantial contribution to aerodynamic force it provides. All results have had the drag and lift produced by the rig subtracted from them for clarity.

Figure ..5.2 - 2008 car setup with artificial ground plane under front wing

Aerodynamic forces were recorded using four multi-axis kistler load cells located under each corner of the test rig (Figure ..5.2). All data was taken at 60 km/h, the average track speed seen at competition, unless otherwise stated. Force coefficients are not expected to substantially vary with vehicle speed as flow regimes appear to be well developed, Section ..5.2.1 discusses in more detail.

The testing procedure for each run is listed below.

Table ..5.1 - Wind Tunnel Data Recording Process

Procedure	Details
1st Zero	10 seconds
Tunnel ramp up	20 seconds
Test	45 seconds @ 500 samples/sec
Tunnel Ramp down	35 seconds
2nd Zero	10 seconds

..5.2 2008 Aerodynamic Package

The following section covers the analysis of the 2008 vehicle and its aerodynamic package, setup in competition trim (wing ride height, angle of attack (AoA), etc.).

..5.2.1 Reynolds Number Effects

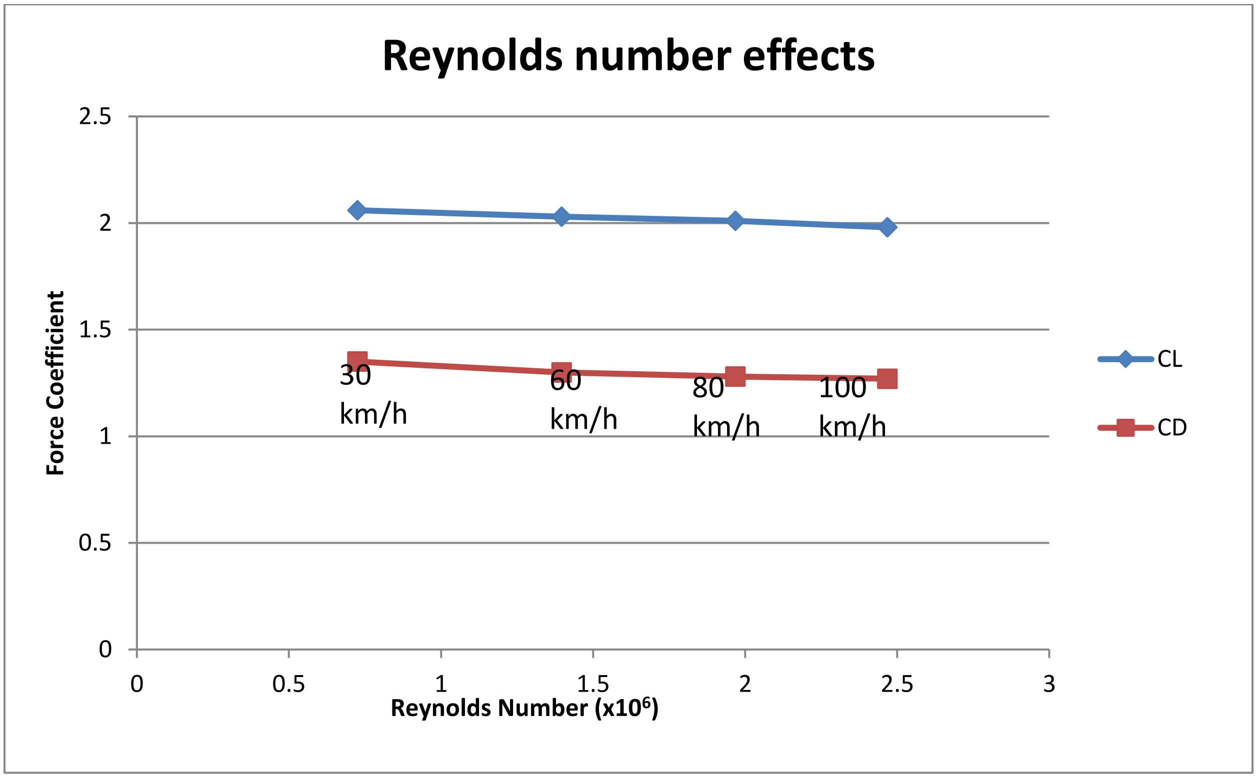


Figure ..5.3 - Force coefficient variation of full vehicle with Reynolds number

The initial test performed on the vehicle was to assess the affect Reynolds number had on vehicle force coefficients; this was to determine if subsequent tests could simply be performed at a single velocity. Figure ..5.3 shows both coefficients of lift (CL) and drag (CD) through the typical velocities seen at competition, little variation was seen between speeds (maximum 3%) indicating flow regimes are already well developed. These results gave confidence in using 60 km/h for the remaining tests.

..5.2.2 Yaw Sweep

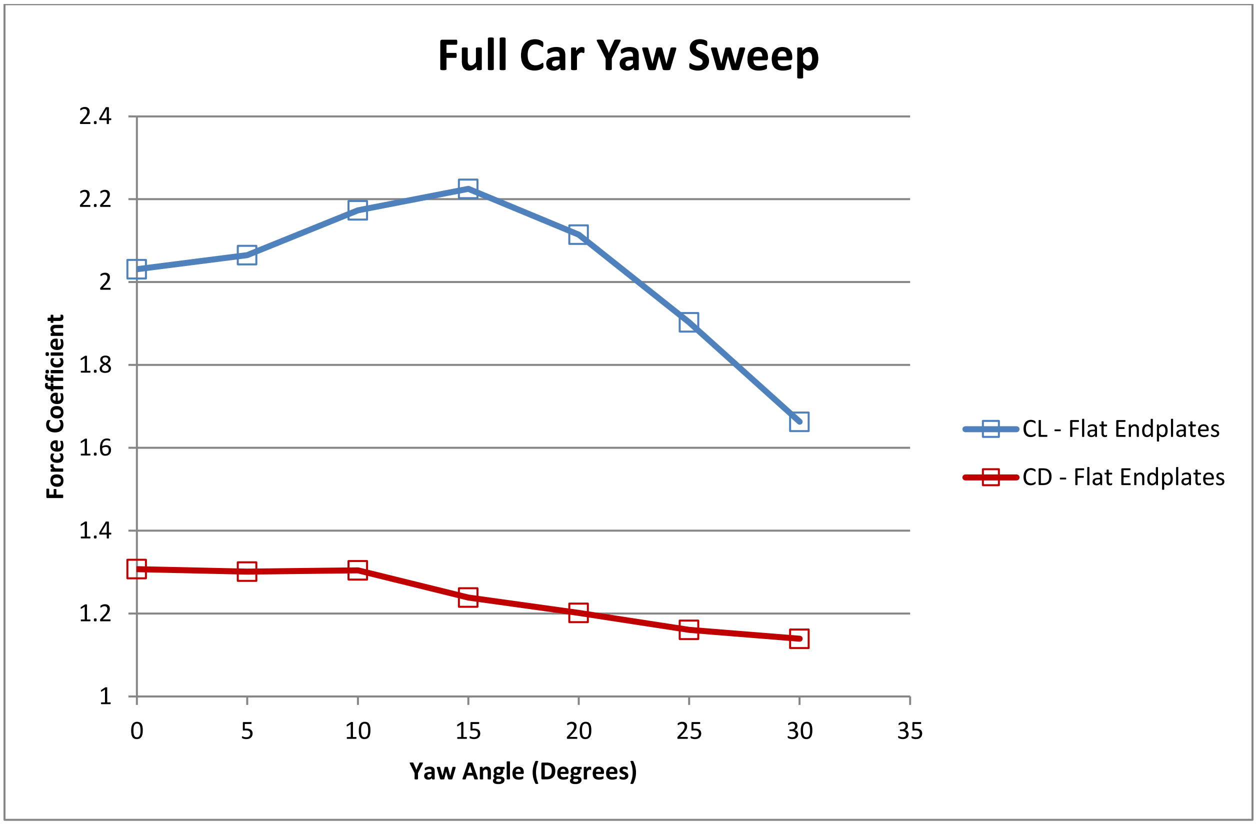


Figure ..5.4 - Yaw sweep of 2008 car with flat endplates

As downforce is predominately utilised during cornering situations, the wings are usually subject to yawed flow conditions rather than purely axial flow, thus information is required on how the force coefficients vary with yaw angle. Figure ..5.4 shows how both lift and drag coefficients vary as the vehicle is yawed between 0 to +30 degrees on the wind tunnel turntable; tests were also performed from 0 to -30 degrees to assess the symmetry of the vehicle, with variance less than 2% allowing the remaining tests to be conducted with confidence to the one side.

Contrary to expectation, Figure ..5.4 shows that the flat endplates do not lose any significant downforce until after 15° of yaw, this indicates that they do not experience leading edge (of the endplate) separation (we are only concerned with the endplate furthest upstream of the flow), this has been confirmed through flow visualisations in the wind tunnel. This is contrary to what was expected (Discussed in more detail in section ..5.3), which was that a flat plate would experience significant separation effects when yawed to even small angles relative to the free-stream flow. The above reasoning is correct for a simple isolated plate, however the 3D interactions with the wing main plane produce a high pressure zone on the inside of the endplate (due to the top surface of the wing being inherently high pressure), this acts to reduce the adverse pressure gradient and thus delays separation (See Figure ..5.5).

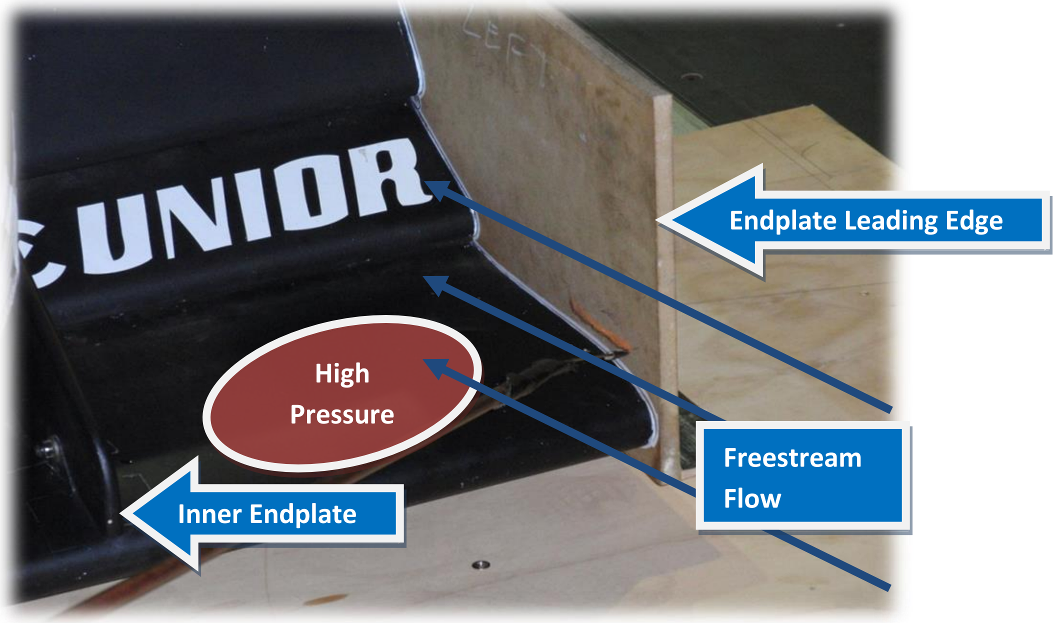


Figure ..5.5 - Flat endplate subject to 10 degree yaw with no endplate separation

Interestingly downforce was seen to actually increase up to 10% when yawed to an angle of 15 degrees, in an effort to isolate this phenomenon tests were performed with only the front wing, and then with only the rear wing.

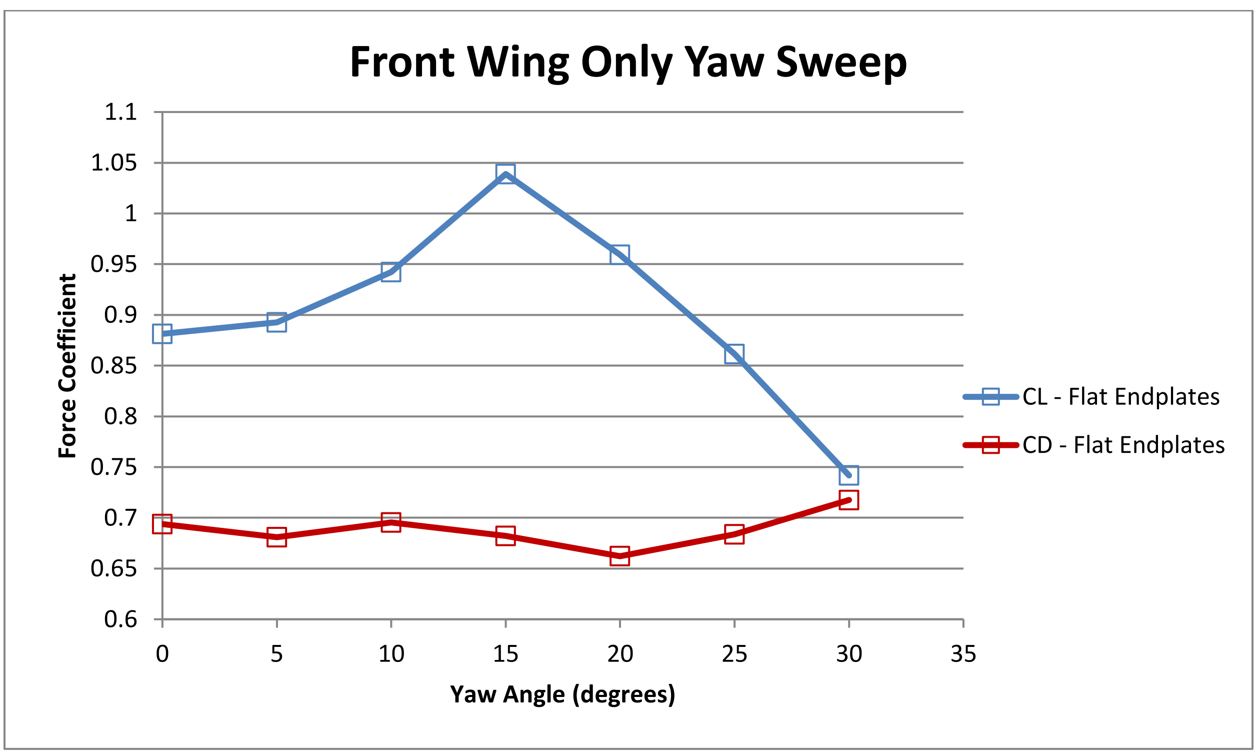


Figure ..5.6 - Front wing only yaw sweep

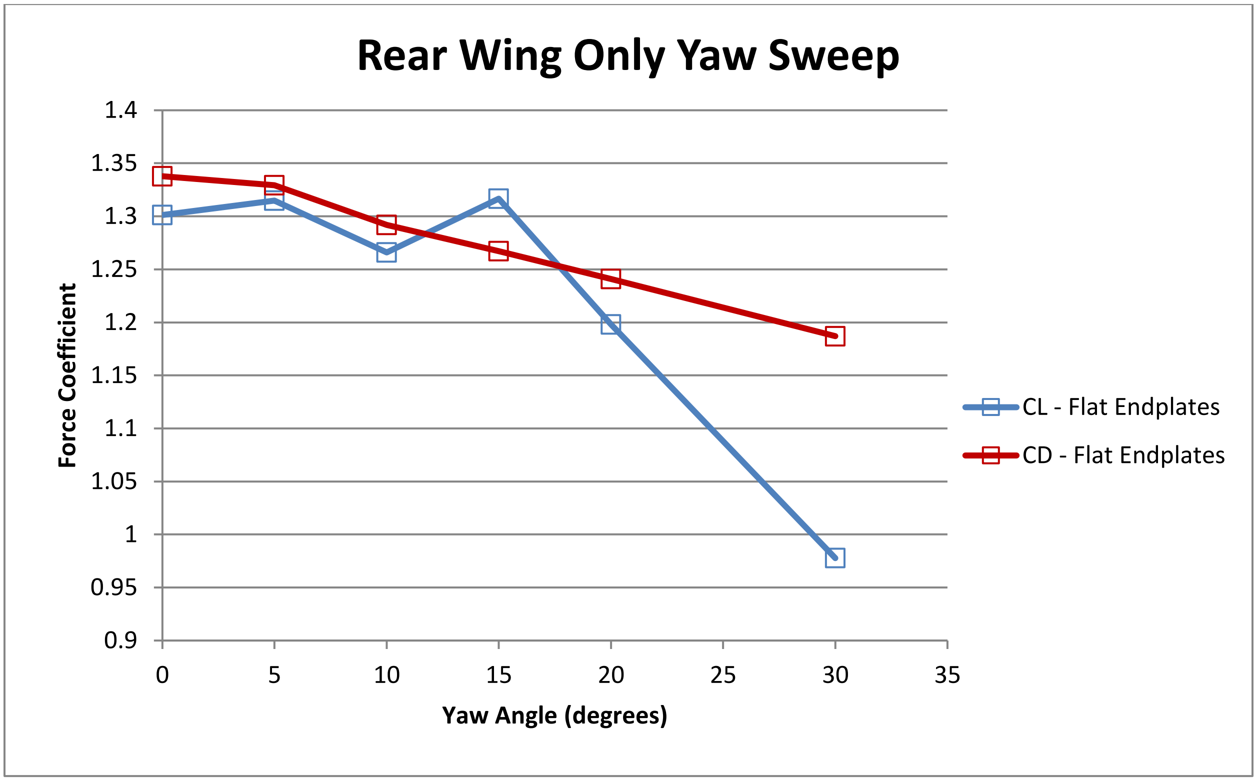


Figure ..5.7 - Rear wing only yaw sweep

Evidently from Figure ..5.6 and Figure ..5.7, the increased downforce with yaw angle is exclusively a front wing phenomenon, with downforce roughly constant until approximately 15° on the rear wing. Further testing involved removal of the nosecone, however this had little impact on the trend. At this time the cause remains unknown, however interactions between the inner endplates (wing mounts) and the forward chassis members are suspected.

..5.2.3 Summary of Aerodynamic Parameters

A number of required aerodynamic parameters for the modelling section have been measured in the wind tunnel, these are presented below:

..5.2 - Aerodynamic Coefficients for 2008 Car

Configuration	CD	CL	Reference Area*
Wings	1.30	2.03	1.10 m^2
No Wings	0.675	-0.23**	0.75 m^2

* - All reference areas for the full car refer to frontal area (Katz, 1995)
** - The negative coefficient refers to lift, rather than downforce for convenience

..5.3 Endplate Development

During on-track use a wing is commonly subject to yawed flow conditions, due to both an inherent vehicle slip angle generated through tyre tread deformation (Trevorrow, 2006) and any cross-winds present. Endplates are used to artificially increase the wings aspect ratios by separating the high and low pressure regions either side of the wing (Katz, 1995), however due to the geometry of conventional endplates (Figure ..5.10, left) they may act as a bluff body to any flow other than axial, causing turbulent flow downstream. If the flow should separate from the leading edge of the upstream endplate, a large portion of the working section of the wing can be removed, resulting in a large loss of downforce.

By introducing a profiled leading edge to the endplate, separation can be delayed to larger yaw angles, increasing the effective operating range of the wings.

..5.3.1 Yaw Angle Quantification

Before initial design could begin for the profiled endplates, it was necessary to quantify the typical yaw angles seen on-track to be used as a design point. Trevorrow (2006) instrumented the 2003 Formula SAE vehicle with a correvit optical sensor (Figure ..9.5) which functions in a similar manner to an optical mouse, logging chassis yaw angle relative to vehicle velocity around three corners of differing radii (Figure ..5.8).

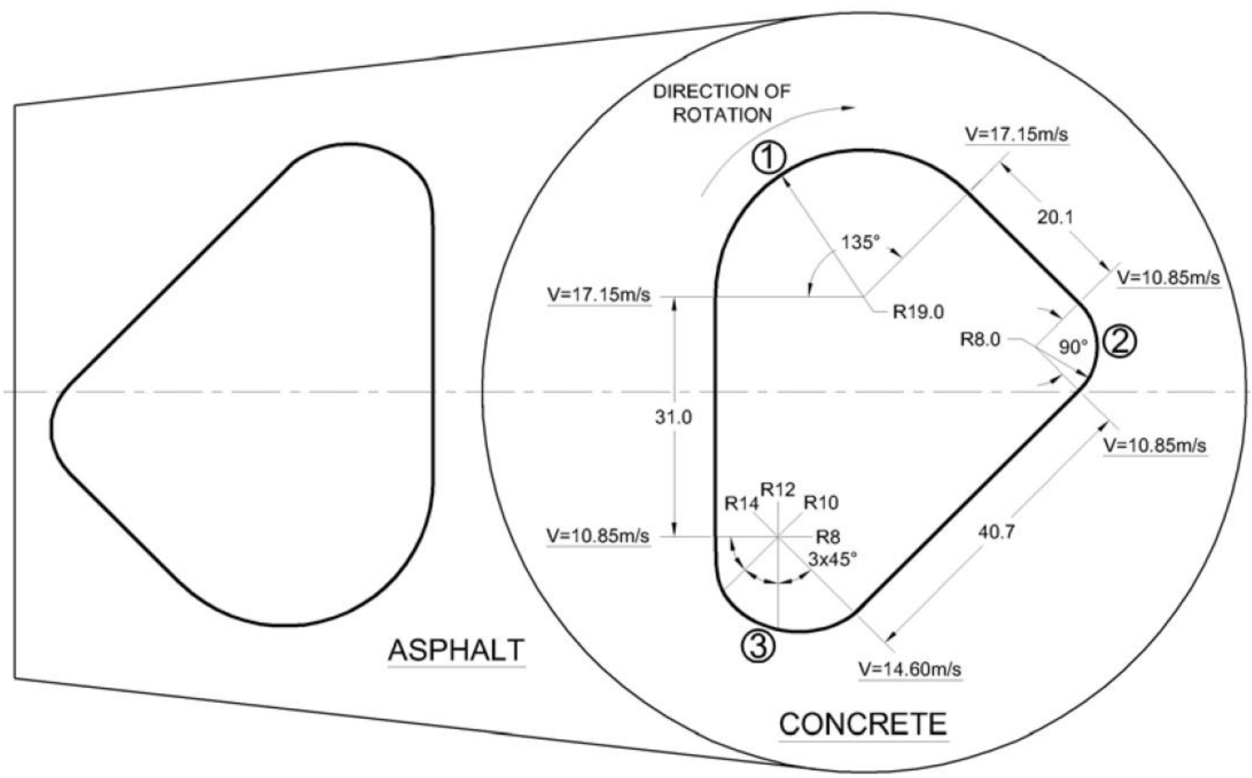


Figure ..5.8 - Track Layout for tyre modelling (Trevorrow, 2006)

Maximum sustained chassis slip angle was recorded to be 7°, however yaw angles of up to 25° were seen when the vehicle encountered oversteer.

The other contributing factor towards the yaw angle is wind speed. Wind speed and direction data for the previous 5 years between November 1st to December 31st (the usual time of year for the competition), was retrieved from the nearby RAAF base in Williamstown. Average wind speed between the times 9am to 5pm for this period was found to be 25 km/h, with the probability of wind speed exceeding 30 km/h less than 20% (Figure ..5.9). A 90° cross wind of 25 km/h at the average track speed results in a relative yaw angle of 22° seen at the wings, thus a design goal of delaying endplate separation to past 25° was set to account for any combined chassis slip angles.

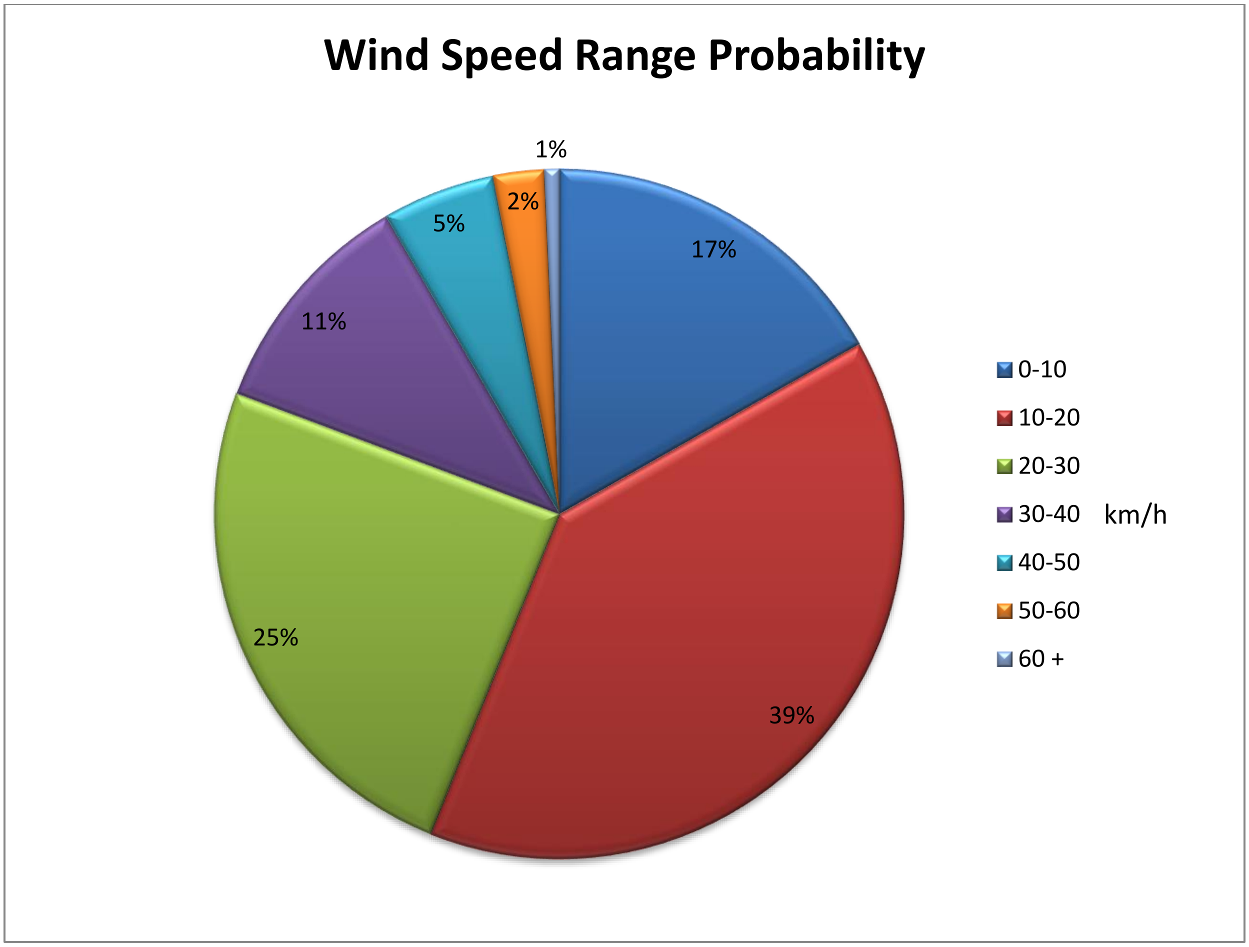


Figure ..5.9 - Wind speed probability at Werribee

..5.3.2 Initial Endplate Design

Unfortunately there is little literature on endplate profiles, as they only become useful on low speed vehicles. Most formulas operate at significantly higher average vehicle velocities, reducing the effect any cross winds have on yaw angle the faster they go. Similarly, aircraft have little need to delay endplate separation due to their high velocities minimising any yaw angles seen.

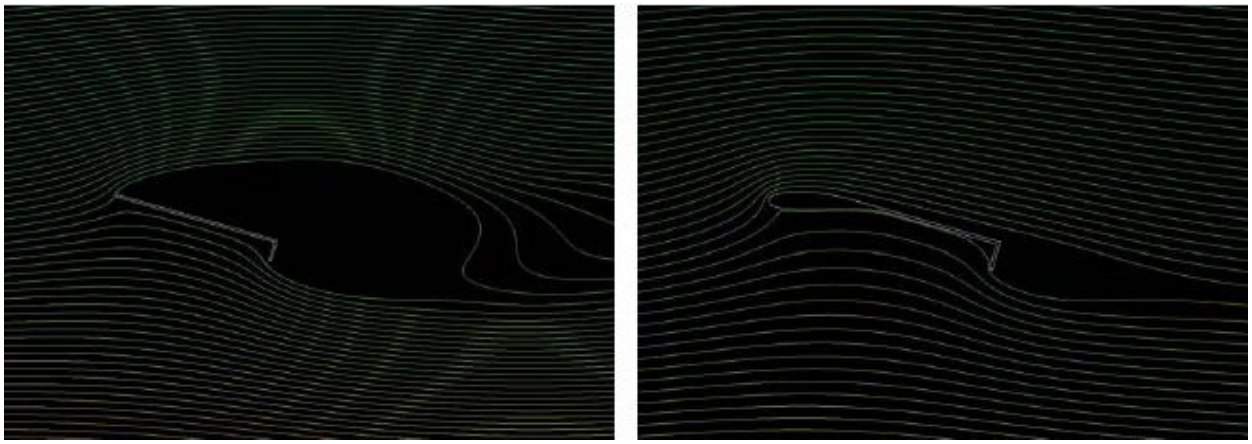


Figure ..5.10 - CFD streamlines of flat endplate (Left) and initial profiled design (Right) subject to 15° yaw

Initial endplate profile design relied on 2D CFD simulations and an iterative process to develop a profile which would resist separation up to yaw angles of 25° relative to free-stream (See Figure ..5.10). Once the final profile had been refined to achieve the 25° target, a prototype was constructed from a CNC wire cut foam core and fibre glass. This profile was tested back-to-back with the original flat endplates on both front and rear wings of the 2008 vehicle in the wind tunnel.

Figure ..5.11 - Initial endplate design after manufacture

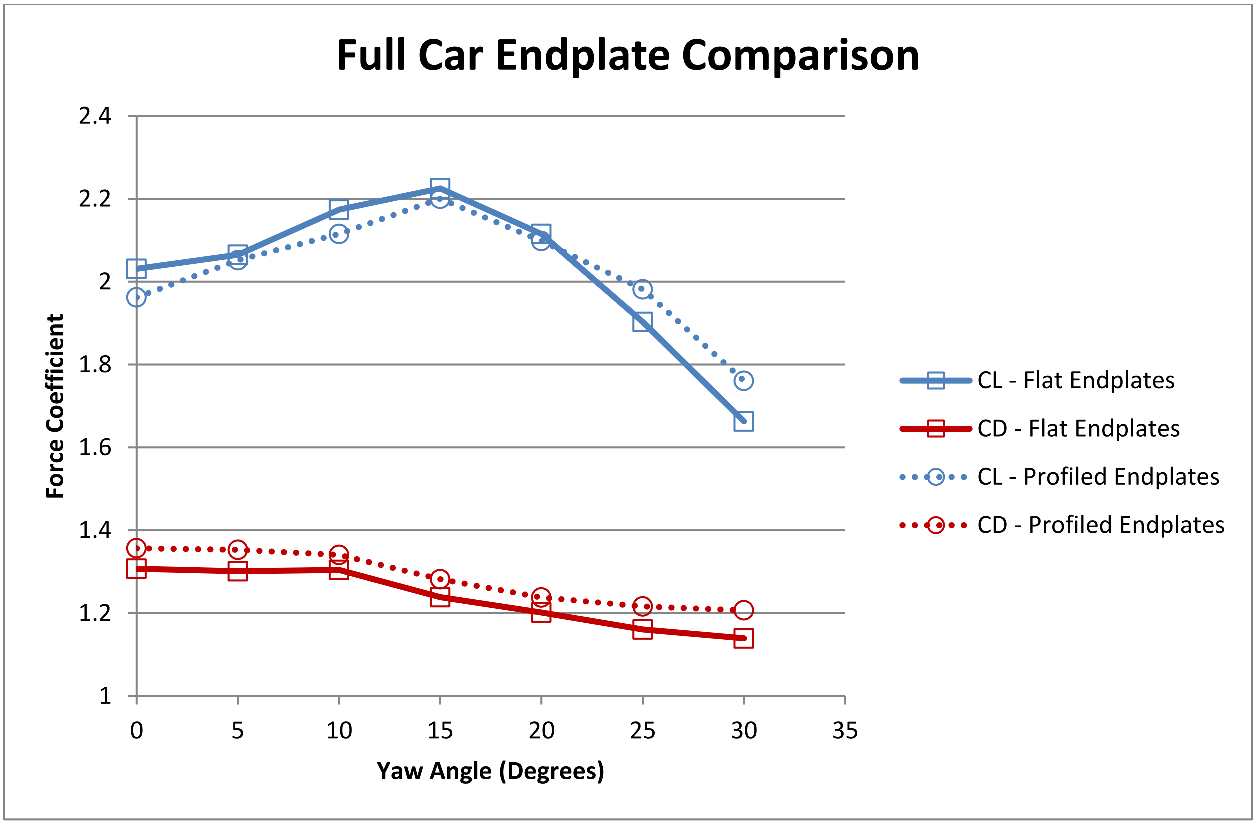


Figure ..5.12 - Full car endplate comparison

Both endplate configurations followed almost identical trends; however the flat endplates performed slightly better with regards to downforce and drag until just after 15° when downforce began dropping off. The profiled endplates appeared to lose downforce more gradually past 15°, which can be attributed to their profiled shape, delaying leading edge (of the endplate) separation.

As discussed in section ..5.2.2, the flat endplates were expected to experience significant separation when yawed to only small angles relative to free-stream flow, however due to 3D effects which cannot be modelled in simple 2D CFD, they remain attached until around 15 degrees. The characteristic high pressure zone on top of the wing delays the expected separation by reducing the adverse pressure gradient on the inside of the endplate (Figure ..5.5).

Through flow visualisations it also became apparent that separation was occurring on the outside surface of the profiled endplates at zero yaw angle. Although this does not affect downforce, unnecessary drag was induced.

From the results of Figure ..5.12 and flow visualisations carried out during wind tunnel testing, it is obvious that 2D CFD cannot be used with any accuracy to design endplates, due to the predominance of 3D effects governing performance.

..5.3.3 Revised Endplate Design

A refined design for the endplate profiles were developed using only observations noted during the initial wind tunnel testing of the previous design, as the 3D CFD model discussed in section ..5.6 had not been developed. Figure ..5.13 shows an overlay of both designs, with the red curve the initial design and blue the revised design.

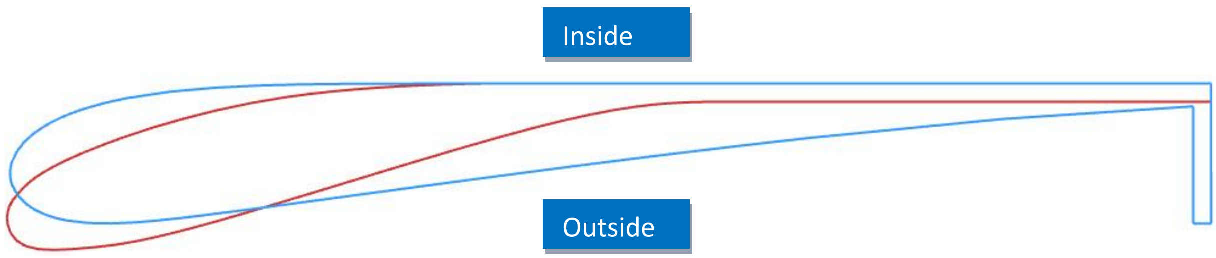


Figure ..5.13 - Initial endplate design (Red) overlayed with revised design (Blue)

The revised profile (blue) utilises the full length of the endplate on the outer side to reduce the adverse pressure gradient, which led to the straight line separation seen on the first design (red). Furthermore, the revised design possess much less outward camber, this stems from the realisation that the high pressure zone of the top surface of the wing directly contributes towards delaying separation, as can be seen with the flat plate remaining attached until 15 degrees of yaw (Figure ..5.5).

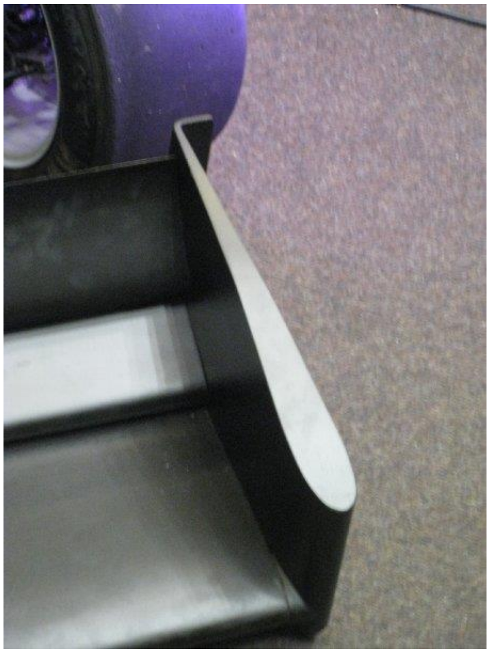


Figure ..5.14 - Revised endplate design after manufacture

Unfortunately the revised endplate design has not been tested in the wind tunnel at this time, however another back-to-back comparison will be performed to assess their performance when testing time becomes available.

..5.4 2009 Aerodynamic Package

The newly manufactured 2009 aerodynamic package is an evolution of the 2008 wings, with slightly modified front flaps to take advantage of the improved manufacturing technique, allowing more cambered profiles to be constructed with sharper trailing edges.

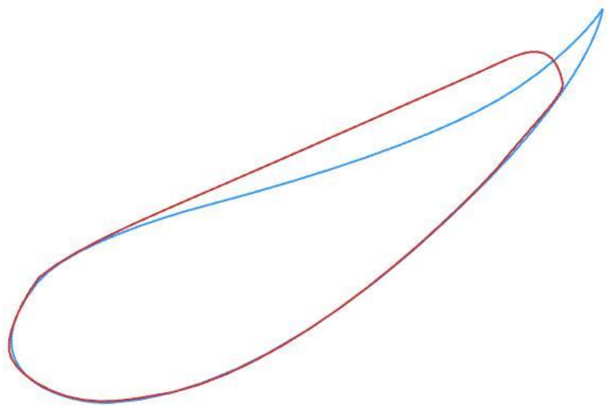


Figure ..5.15 - Modified front flap profiles, new profile (Blue) overlayed with old profile (Red)

The sharper trailing edges allow the slot gaps to function more efficiently (Katz, 1995), however due to these changes the slot gap geometry required changing from 2008 to accommodate the slightly longer profiles. McBeath (2000) recommends between 1-2% mainplane chord for slot gap size and between 1-4% for overlap, however he concedes these are only rough guidelines, recommending extensive wind tunnel testing to find optimal geometry. Figure ..5.16 below shows the initial slot gap geometry that was tested, care was taken to ensure the slot gaps were converging (approximately 4:1 area ratio) as flow leaves the lower element, this was found to be optimal in slot gap testing performed in previous years.

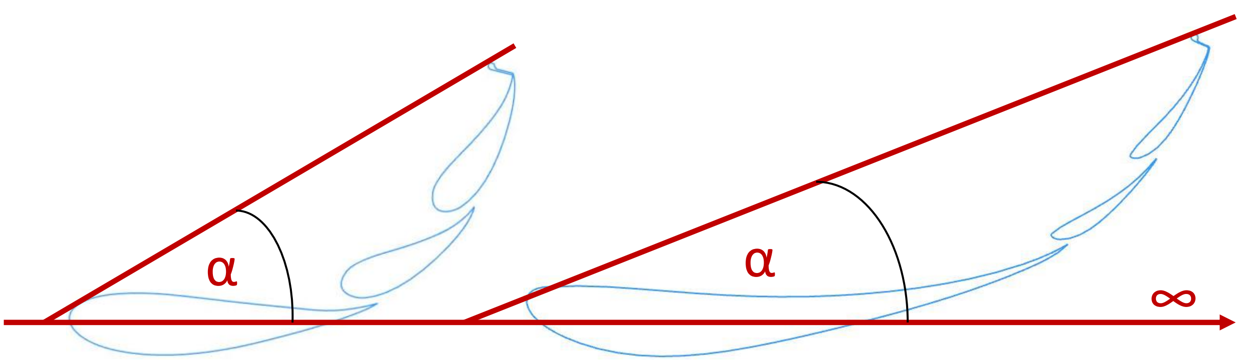


Figure ..5.16 - Front (left) and rear (right) wing geometry

..5.4.1 *Front Wing Free-stream Results*

The 2009 front wing was initially tested in free-stream to assess how the chosen slot gap geometry performed.

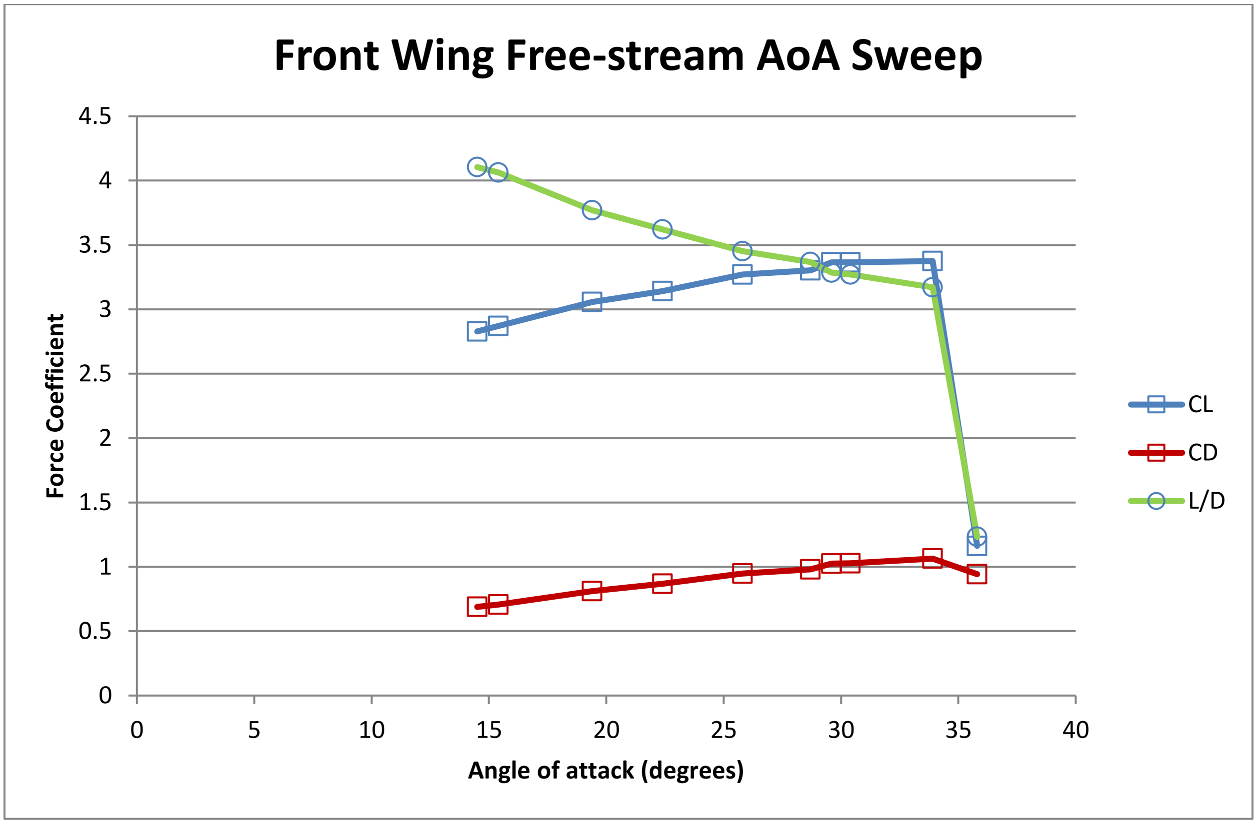
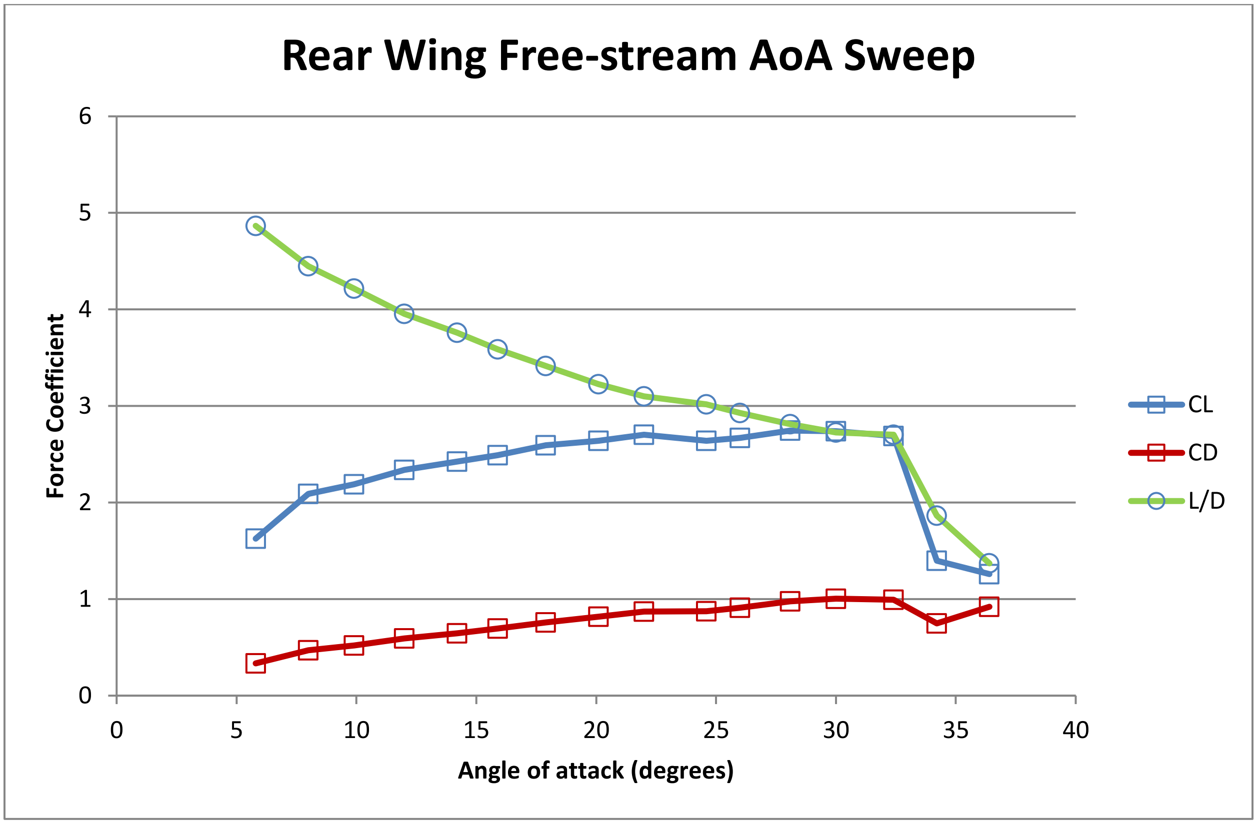


Figure ..5.17 - Front wing free-stream results

Design angle of attack is around 29 degrees, giving a CL of 3.3, or 370 N at 60 km/h. This is a substantial increase over previous free-stream tests of the 2008 front wing, with an increase in CL of 25% from 2.25, however drag has remained similar to previous years with a CD of 1. The wing stalls around 5 degrees past design point at 34 degrees, giving a useful safety margin should the front wing pitch on-track. It should be mentioned the front wings performance will further enhance on-track where it operates in ground effect. A study performed by Wordley and Saunders (2005) using strain gauged wing mounts measured a 30% increase in downforce on-track compared to free-stream results.

..5.4.2 Rear Wing Freestream Results



Design angle of attack for the rear wing is 22 degrees to maintain aerodynamic balance on the vehicle. The 2009 rear wing gives very similar performance to previous free-stream tests on the 2008 rear wing, with a CL at design point of 2.7 and a CD of 0.87. Stall is over 10 degrees away from design point, occurring at 33 degrees, making it extremely unlikely that wings will stall on-track due to vehicle pitching, which is typically only of the order of 1-2 degrees due to suspension movement.

..5.4.3 Full Car Results

The recently manufactured 2009 vehicle was positioned on the testing rig with the front wing attached to the chassis using temporary inner-endplates, to facilitate angle of attack adjustment, which is difficult to achieve with the normal mounting mechanism. The rear wing was positioned on the free-stream rig at the correct height and longitudinal position as design (Figure ..5.18). Unfortunately the 2009 nosecone had not been manufactured in time for wind tunnel testing, thus the 2008 nosecone was modified to fit the 2009 chassis.

Figure ..5.18 - Full car testing of 2009 aerodynamic package with artificial ground plane

Tests were then performed for a small range of angles of attack both for front and rear wings, however design angle of attacks of 29 degrees and 22 degrees for the front and rear wings respectively were found to achieve the optimum downforce with a static margin of 100mm, an acceptable aerodynamic balance. Table ..5.3 summarises the results measured for the vehicle with wings and without.

Table ..5.3 - Aerodynamic characteristics of 2009 vehicle with and without wings

Configuration	CD	CL	Reference Area
Wings	1.26	2.4	1.10 m^2
No Wings	0.67	-0.22	0.75 m^2

Downforce increased by 20% over the 2008 aerodynamic package, with a CL of 2.4, drag was reduced slightly with a CD of 1.26. Aerodynamic properties of the bare vehicle remained almost identical to the 2008 bare vehicle, which was suspected due to the similar design.

..5.5 Repeatability

Where possible, the accuracy and repeatability of the results was tested. Runs with identical configurations were run at the beginning and end of each test session. Additionally, a number of runs were performed at negative yaw angles to assess the symmetry of the vehicle..

Table ..5.4 shows the standard deviation as well as the coefficient of variation (Standard deviation divided by mean) for a number of runs at different yaw conditions. The maximum variation only results in an error of 5 Newtons, and thus is deemed acceptable.

Table ..5.4 - Standard Deviation and Coefficient of Variation for 4 runs each at 0° yaw and 20° yaw

Configuration	Standard Deviation		Coefficient of Variation	
	CD	**CL**	**CD**	**CL**
0° Yaw	0.00823	0.022683	0.61%	1.16%
20° Yaw	0.009188	0.030231	0.74%	1.44%

..5.6 3D CFD Model Development

From section ..5.3 it is evident the applicability of 2D CFD to model aerodynamic components in extremely limited on the vehicle due to a predominance of 3D effects, thus a 3D CFD model has been pursued to provide quick design justification and holistic flow visualisations of the entire car to aid development.

Initially Fluent and Gambit were used to develop the 3D front wing model shown in Figure ..5.19, however Gambit struggled with meshing complex surfaces due to a large number of high aspect ratio faces.

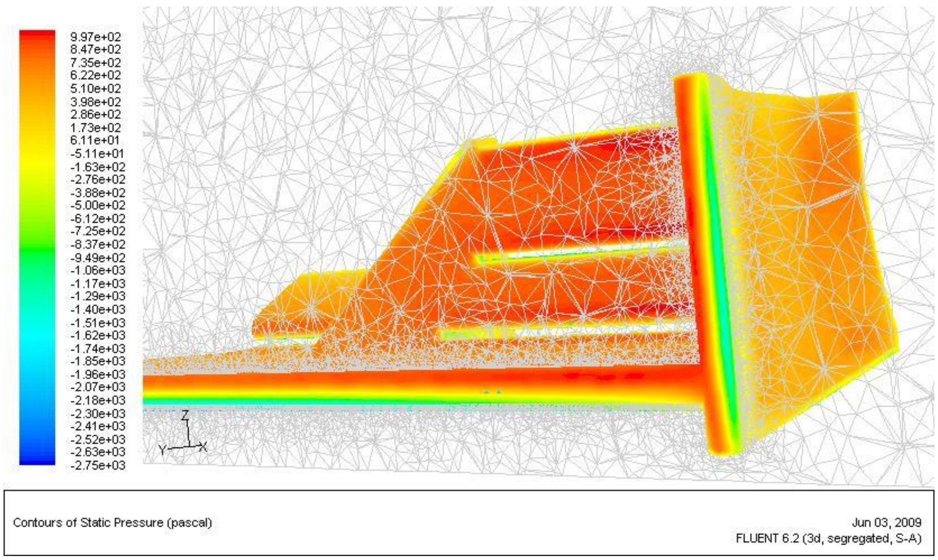


Figure ..5.19 – Pressure contours of the front wing from the 2008 car, a visible mesh plane is also displayed. This preliminary mesh is very coarse.

From the difficulty encountered simply meshing the front wing, it was concluded that pursuing a full car 3D CFD mesh in Gambit would not be an efficient use of resources.

Cradle-CFD, a Japanese based software manufacturer offered the use of their simulation package as well as advice. Cradle has become the leading CFD solution for the automotive industry in Japan, with a powerful pre-processor to simplify complex geometry before meshing, allowing much simpler meshing process than Gambit can provide.

A complete CAD model of the 2009 vehicle was imported into the pre-processor to remove any complex geometry as well as making the model 'water tight' (Figure ..9.8, Appended).

A domain one vehicle length ahead, 4 vehicle lengths behind, and 3 vehicle widths wide was meshed using 11 million triangular elements (See Figure ..5.21). The model was solved using Cradle with a velocity inlet of 60 km/h, a moving ground plane and rotating wheels. After 1000 iterations the solution had converged sufficiently for this preliminary model, giving the following pressure contours.

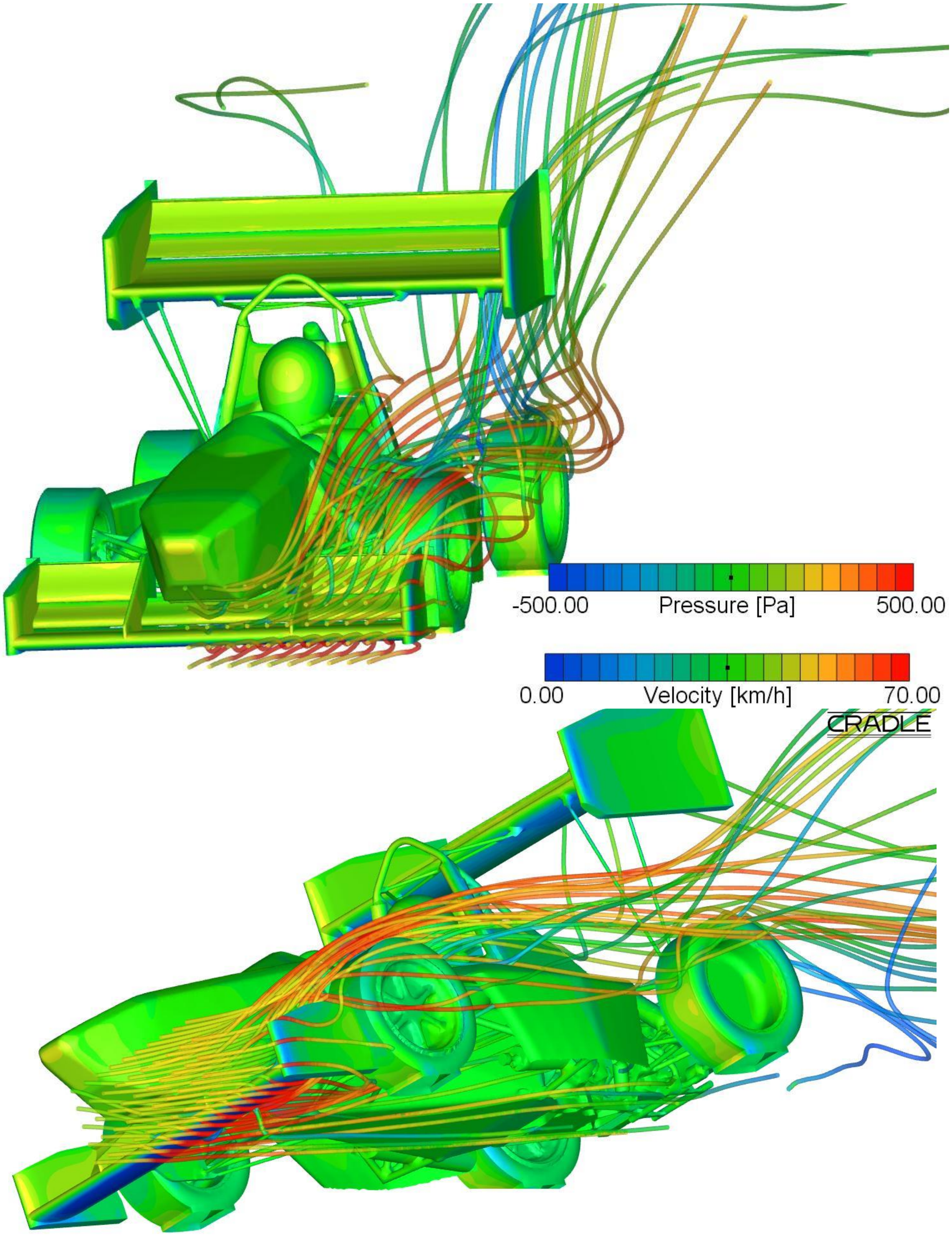


Figure ..5.20 - Full car 3D CFD model pressure contour, streak lines shaded for velocity

The simulation predicts a CL of 1.9, 20% lower than measured in the wind tunnel as well as a CD of 1.3, which closely matches the drag measured in the wind tunnel. Inconsistencies with the wind tunnel measured downforce could be due to a number of reasons, particularly the inherent difficulty any CFD program has solving a complex 3D model with large amounts of turbulent flow (requiring time-averaged

Navier Stokes equations, ignoring higher order components), other factors could be attributed to the rotating wheels and moving ground plane, however the latter should increase downforce.

Regardless of current accuracy, this model has set the foundations for further development towards correlations with over 500 hours of wind tunnel testing.

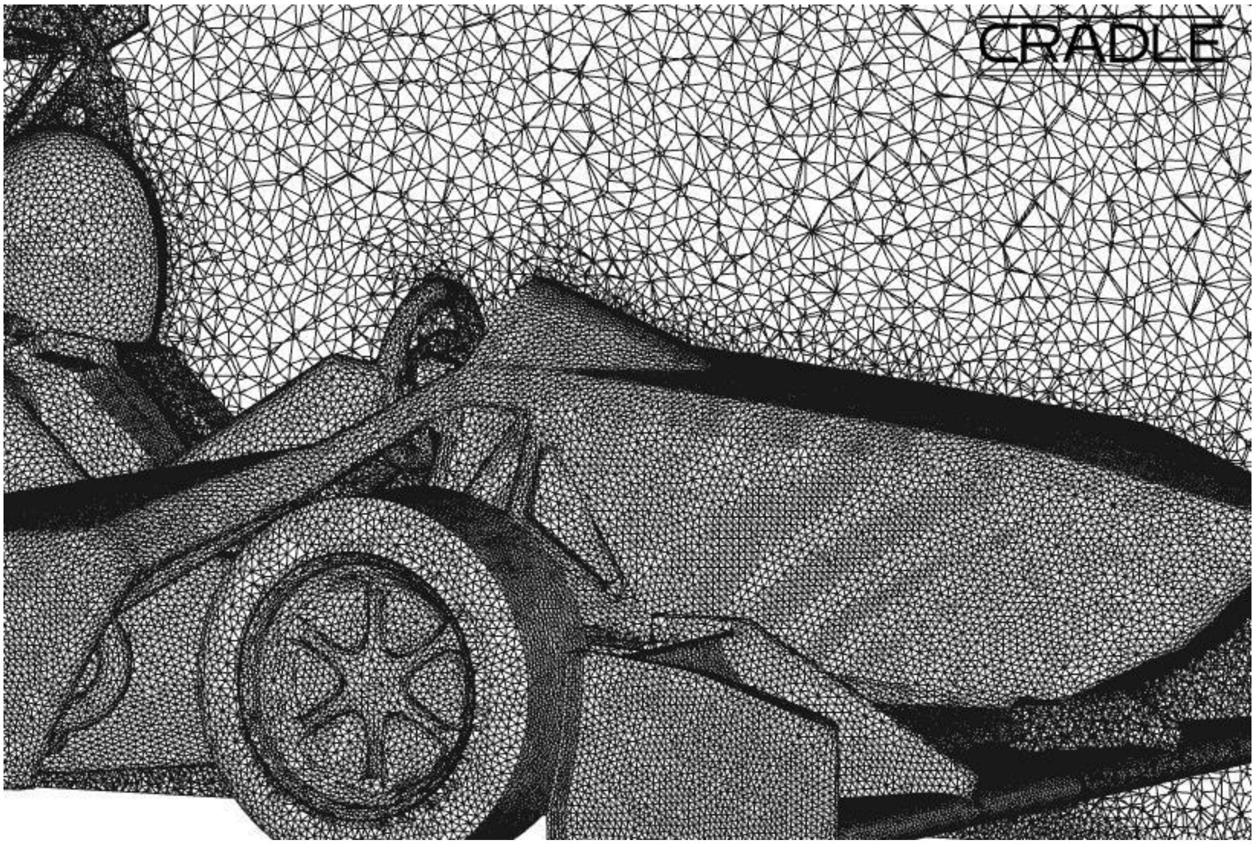


Figure ..5.21 - 3D CFD mesh

..6 PRELIMINARY 2010 ANALYSIS

For the 2010 vehicle, the Monash Motorsport team are moving away from the current design paradigm which has followed for the previous few years, driven from a continually slowing track layout and an increased weighting of fuel efficiency in the endurance event. The four cylinder CBR600 RR engine will be replaced with the lighter single cylinder Husqvarna 450TE, the current 13” wheels will be replaced with 10” wheels, track width and wheelbase are also predicted to decrease. These design changes are aiming to produce a lighter, smaller, more fuel efficient vehicle that will score more overall points in competition than a slightly heavier, more powerful four cylinder vehicle. As such, the applicability of an aerodynamics package needs to be re-assessed; this section describes the preliminary study.

..6.1 Methodology

Initially, a suitable aerodynamic package must be sized for the vehicle, a process outlined by McBeath (2000) will be used.

To begin with, the amount of engine power that can be sacrificed to the aerodynamic drag of the rear wing is determined, as it is assumed that the front wing does not contribute to overall drag - supported by the wind tunnel testing performed in section ..5.2 (with the addition of a front wing only increasing bare vehicle drag by 300g).

This 'excess power' is then used to determine a coefficient of drag for a set plan area (dictated by packaging constraints, see Figure ..10.7), the coefficient of drag is then roughly related to experimental data in Katz(1995) and McBeath(2000) to give an expected negative lift coefficient (-CL). The expected coefficient of lift dictates what type of wing configuration used, single, dual or multi-element designs.

The front wing is designed around aerodynamic balance, with a required coefficient of lift calculated by a moment balance around the cars mid-wheelbase (Figure ..6.1), as plan area is once again dictated by packaging constraints.

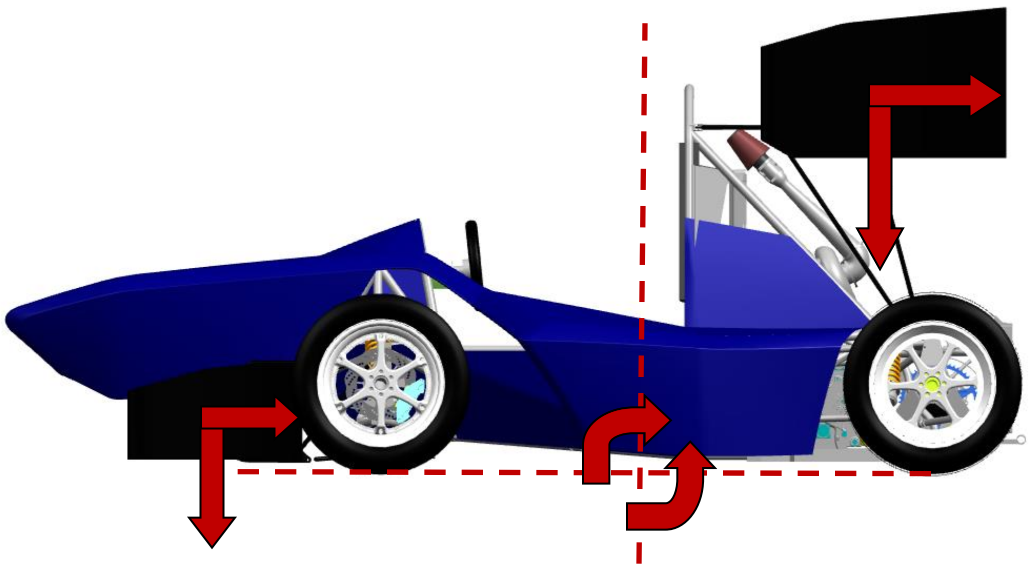


Figure ..6.1 - Moment balance around mid-wheelbase

Vehicle dynamic models will be constructed using simple applications of newtons second law to quantify the gains under cornering situations from the addition of aerodynamic devices (too little physical data to use ChassisSim). These can then be applied to the skid pan event, which tests steady-state cornering potential, as well as the acceleration event which was the only event found to be negatively effected by an aerodynamic package in section 0.

From these vehicle dynamic models an informed decision can be made about the continued design of an aerodynamic package for the 2010 vehicle.

..6.2 Aerodynamic Package Sizing

An equation is presented by McBeath (2000) which allows a vehicles theoretical top speed without aerodynamic devices to be calculated:

$$Brake\ kW\ absorbed = \frac{C_D . A_{car} . v^3}{1633} \qquad 3.3$$

Where:

A_{car} = 0.73m^2 (Scaled from 2009 vehicle)

C_D = 0.67

Brake kW absorbed = 37.3 kW

Frontal area was scaled off the 2009 car master model in Unigraphics NX 5, taking into considerations tyre and track width changes. Chassis frontal area is expected to remain unchanged due to driver egress rules specified for the competition, mandating the size of the front structure (SAE-A, 2009). The coefficient of drag for the bare vehicle was assumed similar to the 2009 vehicle tested in section 0. A conservative estimate of 37.3 kW (50 HP) peak power for the Husqvarna TE450 has been made, supported by Figure ..9.6, showing a physically measured power and torque curve for a similar sized engine (Yamaha WR450) in a Formula SAE application.

Rearranging equation 3.3 and solving for v gives a drag limited top speed of 180 km/h, which is well above the top speed likely to be reached in competition, typically around 90-100 km/h (Juric, 2009). A new drag restricted top speed of 110 km/h is selected for the vehicle, giving a safety margin in case of any head winds, and inputted back into equation 3.3. Only 8.5 kW is required to overcome the bare car's aerodynamic drag, the remaining 28.8 kW can be utilised to overcome the aerodynamic drag of any aerodynamic devices.

Assuming the front wing contributes little drag, equation 3.3 was used once again to determine an allowable rear wing $C_D.A_{RW}$ at 110 km/h, this comes to 1.65. Due to packaging constraints specified in the competition rules, a maximum available rear wing span comes to 1.3 m, with a maximum chord of 0.6m, this results in an allowable rear wing drag coefficient of 2.1. Against initial expectations, this C_D is significantly higher than the current rear wing on the 2009 vehicle is, suggesting that the current aerodynamic package could be applicable for the 2010 vehicle. Rather than developing an entirely new aerodynamic package, a decision was made to continue using the 2009 wings which have had 8 years of development already invested in them to produce maximum downforce for the plan area available.

Henceforth the aerodynamic properties of the 2009 vehicle, physically measured in previous sections, will be used for the preliminary performance analysis.

..6.3 Summary of identified parameters for the 2010 vehicle

For further analysis of the effect of an aerodynamic package on the 2010 car, a number of initial parameters are required.

Table ..6.1 - Summary of identified parameters for 2010 vehicle

Parameter	Value	Details
Target Weight	180 kg	Team decision
Target Weight distribution	50:50	Suspension design
Centre of Gravity Height	0.31 m	Assumed similar to 2008 vehicle
Wheelbase	1.525 m	Suspension design
Tyre rolling Diameter	0.4572 m (18”)	Diameter of typical tyres for 10” Rim
Tyre Coefficient of Friction	1.6	Experimentally measured (Trevorrow, 2006)
Gearbox Ratios	See Table ..9.3	Manufacturer Specifications
Final Drive Ratio	3.5-4.5	Calculated to give desired top speed (Flynn, 2009)
Frontal Area: Bare Car	0.73 m^2	Scaled off 2008 vehicle
Frontal Area: Wings	1.07 m^2	Scaled off 2008 vehicle
Coefficient of Lift: Bare Car	-0.23	Assumed similar to 2009 vehicle
Coefficient of Lift: Wings	2.4	Assumed similar to 2009 vehicle
Coefficient of Drag: Bare Car	0.675	Assumed similar to 2009 vehicle
Coefficient of Drag: Wings	1.26	Assumed similar to 2009 vehicle
Peak power	37.3 kW (50 HP)	Conservative estimate of chosen engine

The power and torque curves from the dynamometer tested 2008 Car have been scaled appropriately to achieve a peak power of 50 HP, this data was used in the initial acceleration model (Section ..6.4). It should be noted, it is not representative to simply take manufacturer supplied data on power and torque characteristics, as the custom intake and exhaust system developed by the team significantly alters both the magnitude and shape of the power curve (Phivopoulos, 2008).

..6.4 Performance Analysis

..6.4.1 Acceleration Potential

To assess the initial feasibility of the 2009 aerodynamic package on the 2010 vehicle, a simple acceleration model has been developed. This model has been constructed from a modified 'bicycle' model (Milliken & Milliken, 1995), which includes the effects of longitudinal weight transfer in addition to aerodynamic drag and downforce. The effect of aerodynamic drag and increased mass due to the addition of wings on longitudinal acceleration is one of the key arguing points against their inclusion on most Formula SAE cars, and the only dynamic situation seen in the previous modelling section where wings were a hindrance to performance.

The maximum potential acceleration curve for each car configuration (Wings and Bare car) has been plotted below (Figure ..6.2). The blue and red solid curves represent the acceleration power available (engine power minus aerodynamic drag) for each configuration, whereas the dashed blue and red lines represent the available longitudinal grip (tyre friction coefficient and normal force as a function of weight transfer and aerodynamic drag) for the car with wings and the bare car, respectively. The lower of these lines for each configuration is what limits the maximum potential acceleration.

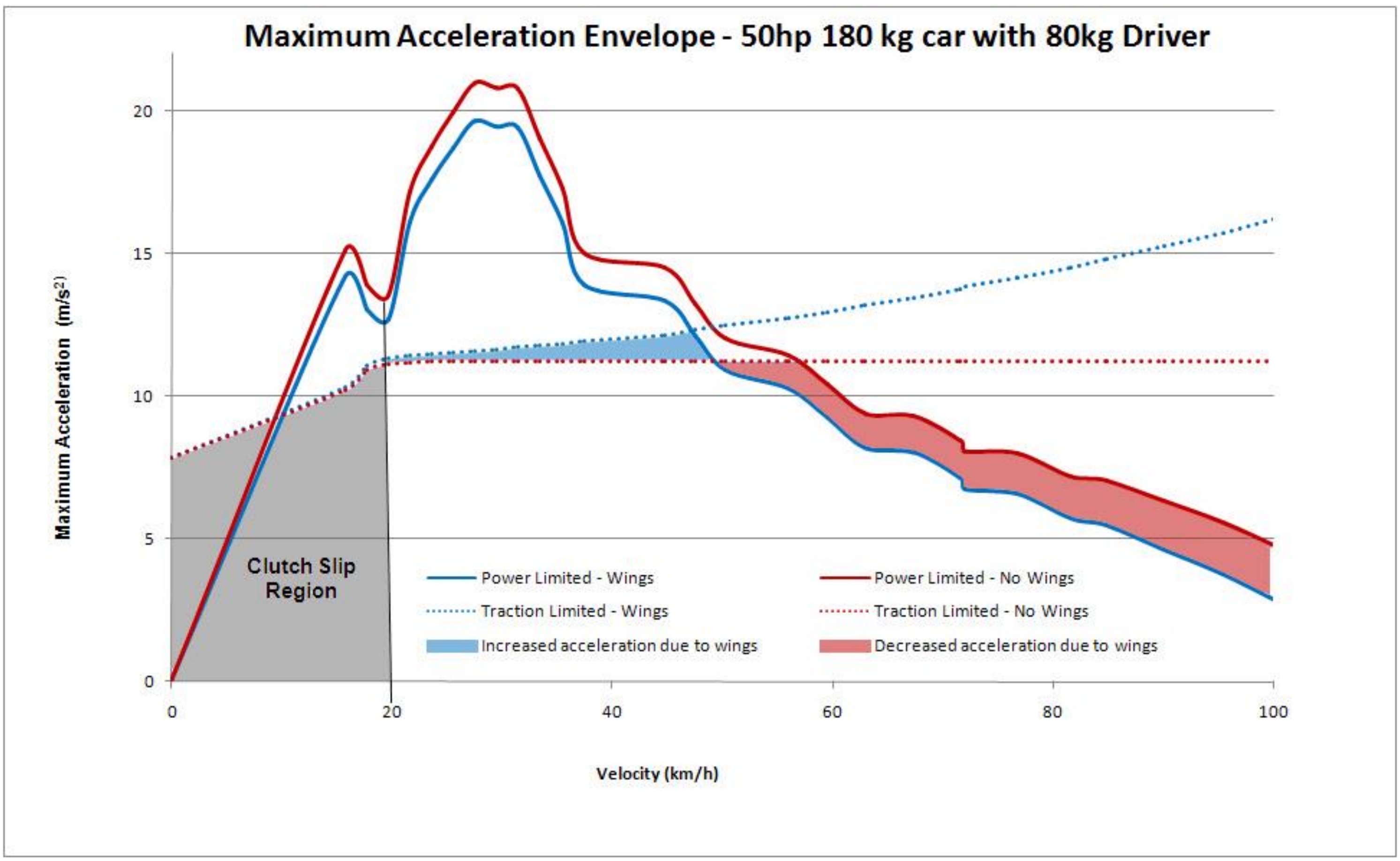


Figure ..6.2 - Acceleration Envelope for 2010 vehicle with (Blue) and without wings (Red)

From the analysis of logged data from the 2008 car (RPM and wheel speed comparison), it is evident that the clutch slips until approximately 20 km/h, this results in higher engine speeds and power output. This is represented by the grey shaded area below 20 km/h, implying that acceleration is actually limited by the traction curves.

From Just prior to 20 km/h to approximately 50 km/h the winged car actually accelerates harder than the same car without wings (shaded blue) – this is attributed to the increased normal force, and thus traction, from aerodynamic downforce. Additionally, extra tractive capacity is achieved from the increase in CG height which facilitates more weight transfer to the rear wheels (the driven wheels) under longitudinal acceleration. This is an interesting observation, as corner exit speeds on a Formula SAE track typically range between 30-40 km/h (Juric, 2009).

After 50 km/h, the car without wings accelerates faster than the car with wings at an increasing rate (shaded red), this is evidently due to the engine power required to overcome the greater aerodynamic drag of the winged car.

Using the theoretical maximum acceleration potential displayed in **Error! Reference source not found.**, times for the acceleration event in the competition can be predicted. The acceleration event is timed over a 75 m distance from a standing start.

Table ..6.2 - Predicated acceleration times (0 - 75 m)

	Wings	No Wings	Δ
Time	4.17 sec	3.90 sec	0.27 sec (6.9%)

At present, this model neglects the effects of rotational inertia, assumes zero shift times, a constant coefficient of friction, and perfect traction.

..6.4.2 Skid Pan

The skid pan event was assumed to be steady-state cornering, allowing a simple model to be developed in excel. A constant coefficient of friction of 1.6 was also assumed for both car configurations, the results are displayed below:

	Wings	No Wings	Δ
Time	4.58 sec	4.80 sec	0.22 sec (6%)

As expected, the winged car was superior due to the extra lateral grip generated by the downforce.

..6.5 Recommendation

These models shows the loss of performance in acceleration event is moderate, thus suggesting the current aerodynamic package utilised on the 2009 car is potentially usable on the lighter and less powerful 2010 car. This result is against initial expectations; it was initially thought the current aerodynamic package would incur far too much drag for the single cylinder engine.

The wings continue to greatly assist in cornering situations, as shown in the skid pan model. This was to be expected, as the downforce being produced by the wings is now a greater proportion of the total vehicle mass compared to the 2008/2009 vehicles, thus it should produce a greater performance benefit.

From this preliminary study, it is recommended the current aerodynamic package used on the 2009 Formula SAE vehicle be utilised on the 2010 vehicle.

..7 CONCLUSION

A number of physical attributes governing vehicle dynamics with the addition of an aerodynamic package has been physically measured, and subsequently analysed using ChassisSim to quantify their effect on vehicle performance at the Formula SAE competition. Wings were found to be advantageous in all scenarios with the exception of the acceleration event, where they were marginally worse, however due to the gains in other events; an informed decision has been made to retain an aerodynamic package for the 2009 vehicle. ChassisSim has also correlated well with logged competition data, giving confidence to its ability to accurately predict vehicle performance, this is an important tool to quantify design changes.

The 2008 aerodynamic package has been extensively tested in the Monash full-scale wind tunnel to provide aerodynamic properties used in the performance modelling section. Furthermore, the 2008 wings were further developed in the form of the 2009 aerodynamic package, giving significant gains in downforce of up to 20%.

A preliminary 3D CFD model of the entire 2009 car has been developed, setting a basis for any further CFD work.

Manufacturing improvements have resulted in more consistent profiles for the 2009 aerodynamic package as well as a 32% reduction in weight.

A preliminary study of the applicability of an aerodynamic package on the 2010 vehicle has been completed, with the finding that the current aerodynamic package on the 2009 vehicle is still a performance advantage.

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..9 APPENDICES

Appendix A: Event scoring formulae

Table ..9.1 - Event scoring formulae

Year	2008	2009	2010
Acceleration		$71.5\times\frac{\left(5.8/T_{your}\right)-1}{\left(5.8/T_{min}\right)-1}+3.5$	
Skidpan		$47.5\times\frac{\left(6.184/T_{your}\right)^2-1}{\left(6.184/T_{min}\right)^2-1}+2.5$	
Autocross		$142.5\times\frac{\left(T_{max}/T_{your}\right)-1}{\left(T_{max}/T_{min}\right)-1}+7.5$ *	
Economy	$50\times\frac{\left(V_{max}/V_{your}\right)-1}{\left(V_{max}/V_{min}\right)-1}$	$100\times\frac{\left(V_{max}/V_{your}\right)-1}{\left(V_{max}/V_{min}\right)-1}$	$100\times\frac{\left(V_{max}/V_{your}\right)}{\left(V_{max}/V_{min}\right)}$
Endurance	$300\times\frac{\left(T_{max}/T_{your}\right)-1}{\left(T_{max}/T_{min}\right)-1}+50$ **	$250\times\frac{\left(T_{max}/T_{your}\right)-1}{\left(T_{max}/T_{min}\right)-1}+50$ **	$250\times\frac{\left(T_{max}/T_{your}\right)-1}{\left(T_{max}/T_{min}\right)-1}+50$ ***

Where V_{max} = Maximum allowed volume of fuel corresponding to 26L/100km over 22 kms (5.72 L)

V_{min} = Minimum amount of fuel used by anyone in the endurance event

V_{your} = The amount of fuel used by the team whose score is being calculated

T_{min} = Minimum time taken for any team to complete their heat

T_{your} = Time taken to complete the heat for the team whose score is being calculated

* $T_{max} = 1.25 \times T_{min}$ (Autocross Event)

** $T_{max} = 1.333 \times T_{min}$ (2008-9 Rules, Endurance Event)

*** $T_{max} = 1.45 \times T_{min}$ (2010 Rules, Endurance Event)

Appendix B: ChassisSim input parameters

Table ..9.2 - Additional ChassisSim parameters

Dimension	Front	Rear
Overall Length, Width, Height	2851mm, 1450mm, 1300mm	
Wheelbase	1550mm	
Track Width	1200mm	
Weight with 80kg driver	165 kg	165kg
Suspension Parameters		
CG height	306 mm	
Suspension travel	30 mm jounce / 25 mm rebound	
Wheel rate	34 N/mm	41 N/mm
Roll rate	0.8 degree/G – adjustable	
Sprung mass natural freq.	3.4 Hz	3.27 Hz
Jounce Damping	70% of crit. damping at 25 mm/s	
Rebound Damping	30% of crit. damping at 25 mm/s	40% of crit. damping at 25 mm/s
Motion ratio	0.7, 0.688, 0.677 – adjustable	0.677
Camber coefficient in bump	0.05 deg/mm	0.06 deg/mm
Camber coefficient in roll	0.46 deg/deg	0.5 deg/deg
Static Toe	0.5 deg toe out	0.1 deg toe in
Static Camber	-1.5 deg	-0.5 deg
Caster	4 deg	
KPI	6 deg	
Kingpin offset	45 mm	
Static roll centre	25 mm	50 mm
Static Ackerman	130%	

Engine Parameters & Drivetrain	
Power & Torque	Figure ..9.1
Differential Type	Spool
Final Drive	4.231

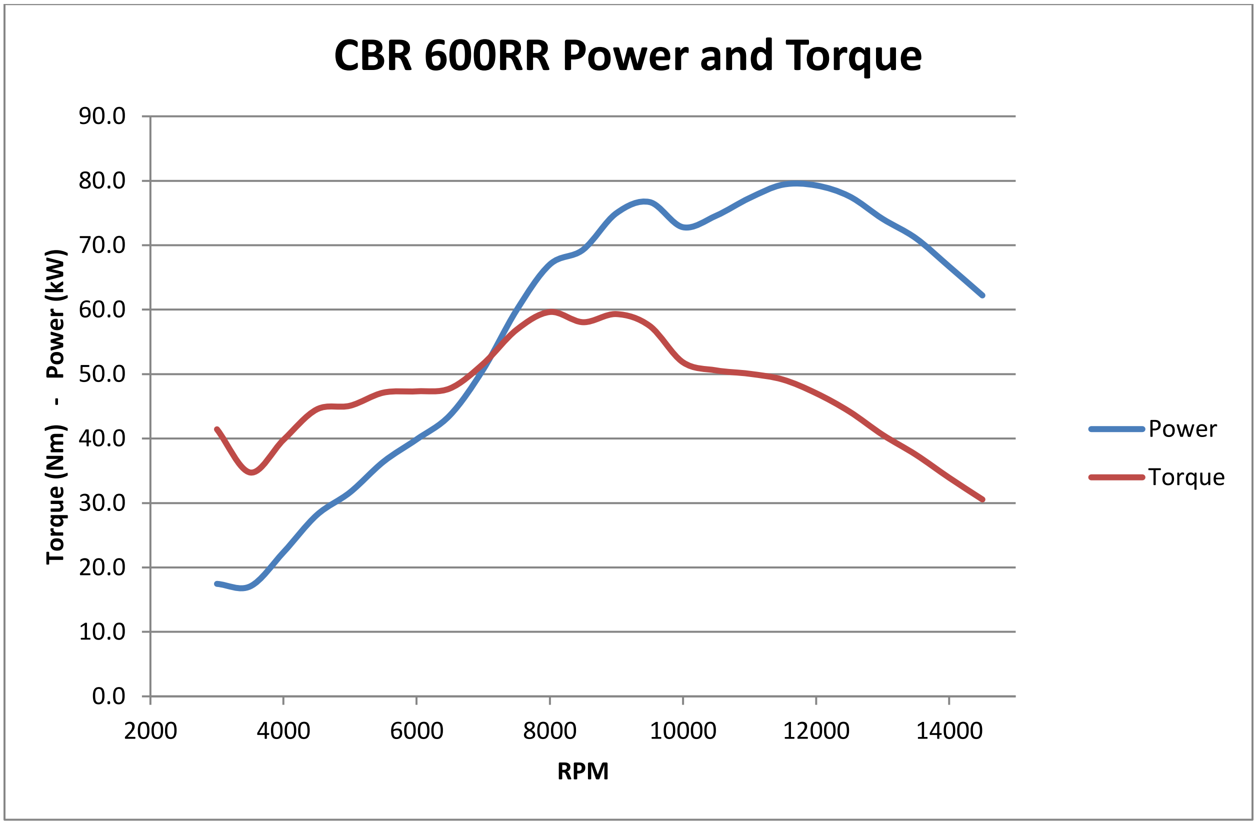


Figure ..9.1 - 2008 Dyno measured Torque and Power for CBR 600RR

Appendix C: Wind tunnel testing

Figure ..9.2 - Front wing endplate flow visualisation, at 25° yaw. Flow visibly separates from the leading edge of the endplate causing turbulent flow over mainplan e in its wake.

Figure ..9.3 - Front wing at 0° yaw, vortex clearly visible from smoke visualisation

Figure ..9.5 - Correvit attached to 2003 Monash Formula SAE car

Appendix D: 2010 Vehicle Data

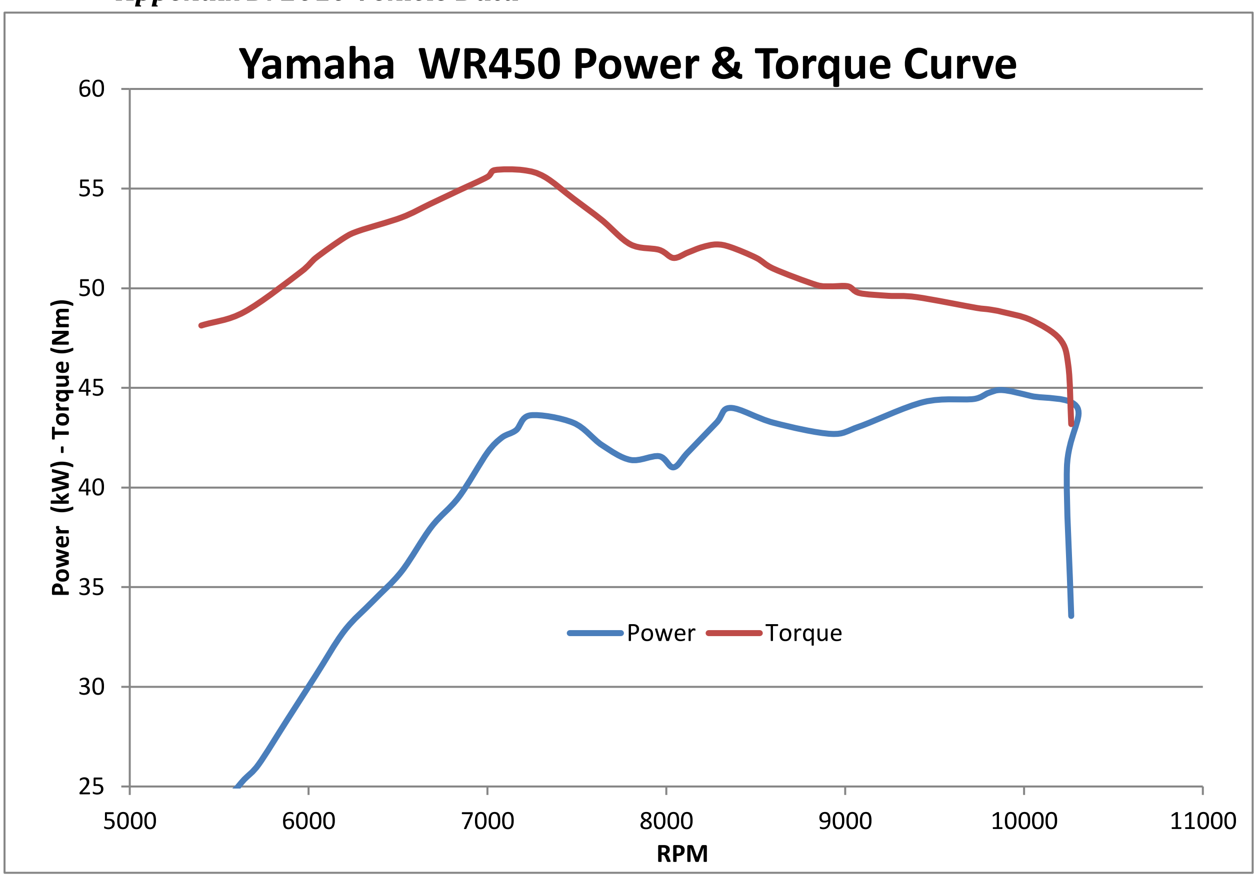


Figure ..9.6 – Formula SAE car Yamaha WR450 Power Curve physically measured on chassis dynamometer

Table ..9.3 - TE450 gear ratios

TE450 Gear Ratios	
Gear	**Ratio**
1st =	2
2nd =	1.611
3rd =	1.333
4th =	1.086
5th =	0.92
6th =	0.814
Primary =	2.739

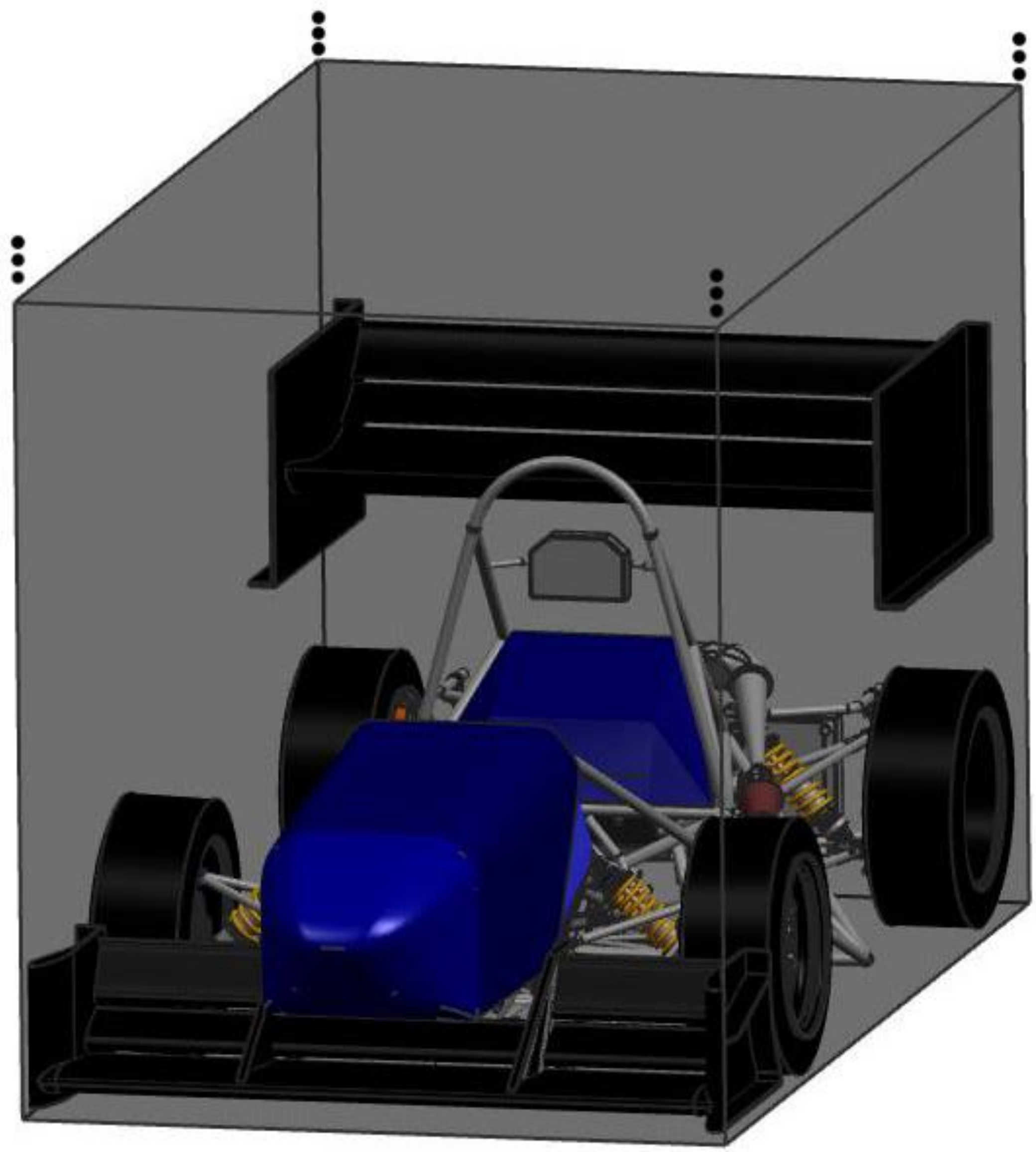


Figure ..9.7 - Aerodynamic packaging constraints

Appendix E: Preliminary 3D CFD model

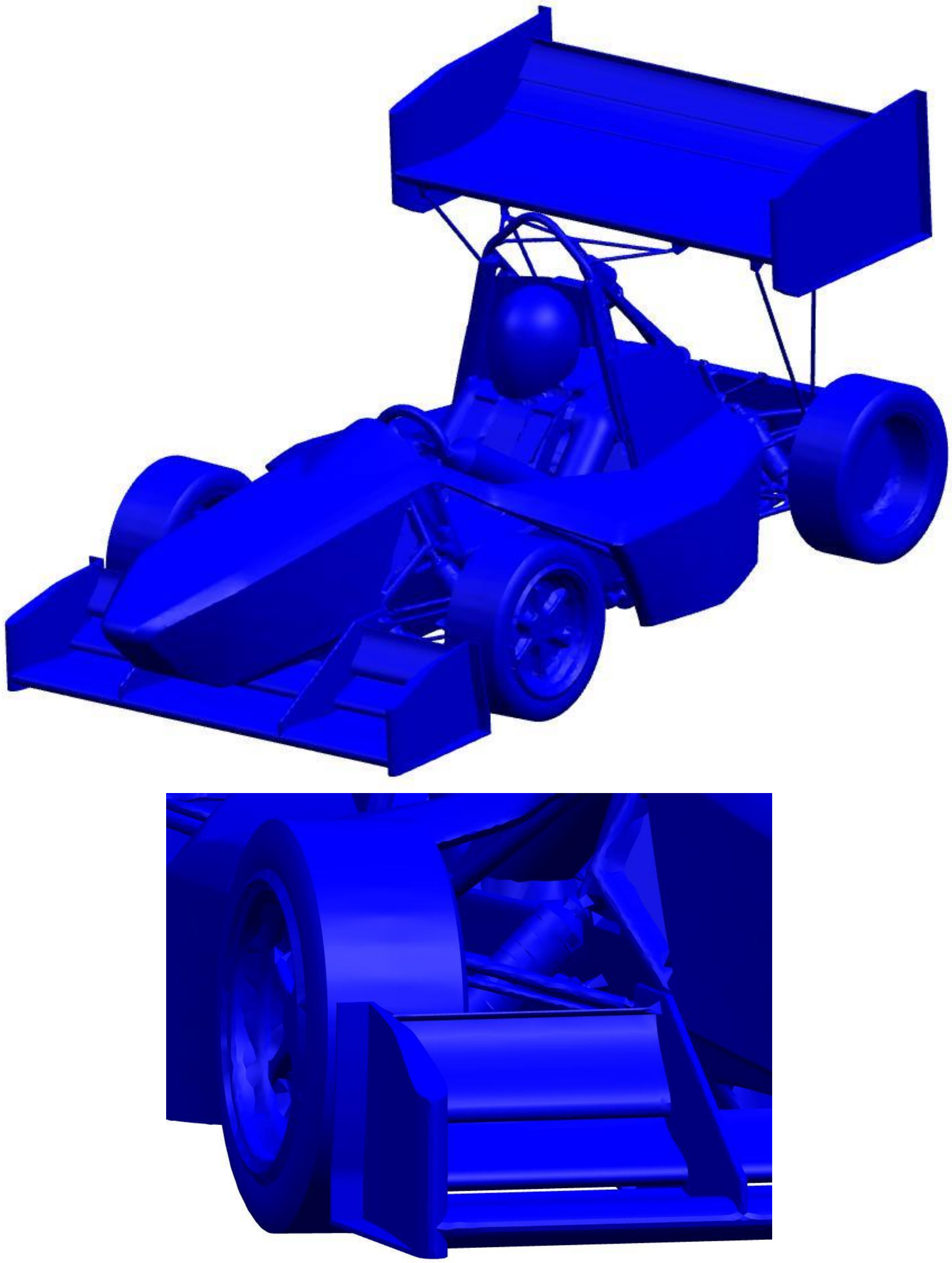
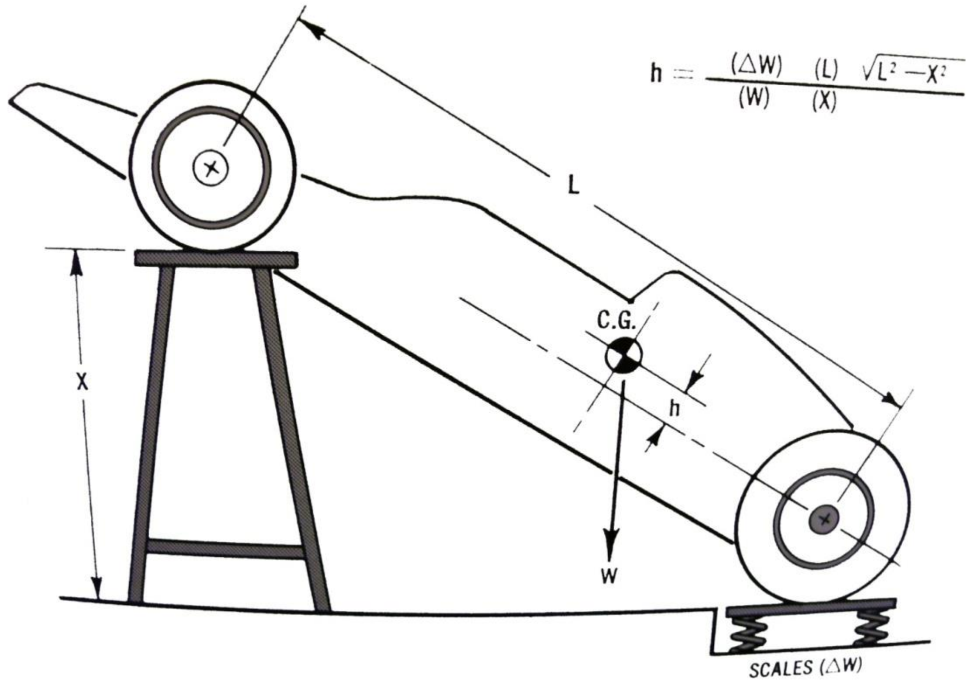
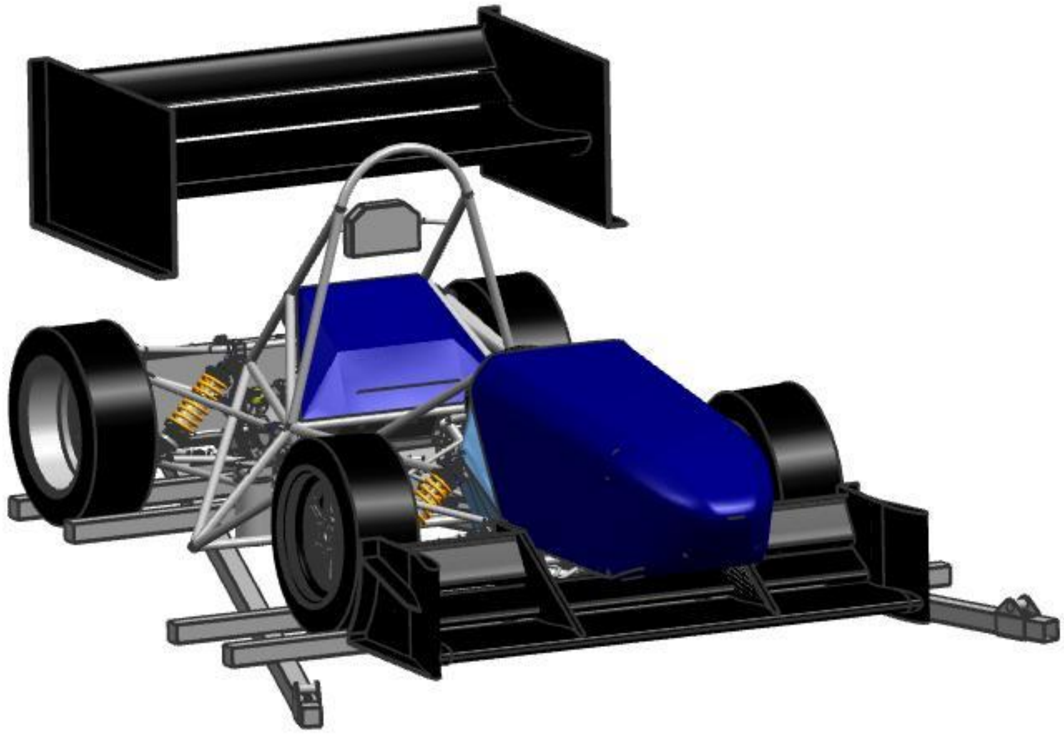


Figure ..9.8 - 3D model with simplified geometry

Appendix F: Additional Figures



..9.9 - Locating Centre of Gravity (Valkenburgh, 2000)



..9.10 - Triangular platform to measure rotational inertia