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Aerodynamics for Formula SAE: Initial design and performance prediction

Scott Wordley and Jeff Saunders
Monash Wind Tunnel, Mechanical Engineering
Monash University

ABSTRACT

The initial design of an aerodynamics package for a Formula SAE car is described. A review of Formula SAE rules relating to aerodynamics is used to develop realistic parameters for the specification of front and rear inverted airfoils, or ‘wings’. This wing package is designed to produce maximum downforce within the stated acceptable limits of increased drag and reduced top speed. The net effect of these wings on a Formula SAE car’s performance in the Dynamic Events is then predicted. A companion paper [1] describes in detail, the CFD, wind tunnel and on-track testing and development of this aerodynamics package.

INTRODUCTION

Formula SAE is a collegiate design competition where groups of students design, build and race their own open wheel race cars. Since its beginnings in the USA in 1981 [2], this formula has spread to Europe, Asia, South America and Australasia, with several hundred international teams racing every year in a number of competitions held world-wide. Unlike a conventional motorsport race, teams are awarded points for eight different events, and the team with the highest cumulative total wins. There are three ‘static events’ (Cost, Presentation, Design) where teams are judged on their design justification, presentation and costing skills, and five ‘dynamic events’ (Acceleration, Skid Pan, Autocross, Fuel Economy, Endurance) which test the performance of the car and student drivers on-track [3]. This weighted points system dictates that success is a matter of carefully balancing all aspects of the car design and development process.

FORMULA SAE: DESIGN CONVERGENCE?

Unlike other forms of racing with long term rule stability, Formula SAE has yet to converge upon a single, well defined, design paradigm. There are several theories as to why this is:

- Careful weighting of the rules serves to even out performance gains in one aspect of vehicle performance by penalizing competitors in other areas. For instance a turbo charger can be used to increase engine power at the potential expense of fuel economy and cost scoring.
- Poor information management and knowledge retention within teams due to a high turn-over of members can disrupt long term design and validation cycles, resulting in repeated mistakes and frequent returns to ‘square one’.
- The majority of teams only compete in one competition per year, meaning that the actual time spent driving and developing these cars is limited, and of the order of weeks. A lack of regular competitions and comparison with other teams therefore limits the exposure to, and adoption of, best practices.
- The competition is still inherently focused on learning, and as such teams will pursue technologies of interest to them as well as those seen to provide an overall performance advantage.

An analysis of past Formula SAE competition results [4] shows that to date, the simplest approach is often the most successful, with the vast majority of top ten finishing teams running steel space frame cars with naturally aspirated 600cc engines. While it is assumed that this trend will continue for some time to come, four major shifts in design ethos have been seen in recent years.

The use of carbon fibre monocoque chassis is on the increase, as teams try to reduce their chassis weight while maintaining or increasing torsional stiffness. Wide spread interest in turbo-charging has also resurfaced following the continued success of Cornell and Wollongong universities. A new generation of single-cylinder motorbike engines is offering performance gains in the opposite direction, with teams like RMIT and Delft universities using their reduced weight and fuel usage to offset their reduced power. Several teams, including the Universities of Texas at Arlington, Missouri-Rolla, Cal-Poly and Monash have made use of wings and other aerodynamic devices to generate downforce with the main aim of improving cornering speed. Some teams have employed more than one of these approaches.

Of the major design shifts listed above, the performance of aerodynamic devices is probably the most difficult for student teams to predict and to quantify. As such, considerable debate continues in the Formula SAE community as to the benefit (or otherwise) of using inverted aerofoils or 'wings' for this competition.

The Monash University team (from Melbourne, Australia) has used aerodynamic devices on their Formula SAE cars for the past four years running. This team is also in the somewhat unique position of having regular access to a full-scale automotive wind tunnel for aerodynamic testing. This paper, and a second by the same authors [1], summarizes the four-year-long aerodynamic design and development process undertaken by this team, and presents the first data available in the public domain for the aerodynamic performance a Formula SAE car. It is hoped that the information and methodologies contained herein will serves as both a guide and a benchmark for other teams contemplating the use of aerodynamic devices in Formula SAE.

FORMULA SAE RULE CONSIDERATIONS

When compared with most other road racing categories, the current Formula SAE rules [2] offer some unique challenges and opportunities for the use of aerodynamic devices. These rules will be briefly examined here, starting with those that influence general vehicle design and performance, and moving onto those more relevant to the use of aerodynamic aides. The broad repercussions of these rules on the design and performance of a Formula SAE car will also be discussed where appropriate.

Autocross / Endurance Track Design

While the track layouts for the Skid Pan and Acceleration events are of fixed geometry, the Autocross / Endurance track designs are varied each year within the parameters described by the rules and the individual constraints imposed by the different competition venues world-wide. Due to the fact that these two events account for half of the total points on offer in Formula SAE, the design of these tracks have a major influence on the vehicle designs. Competitions run on open lots (for example, the US), therefore see more variation in track design compared to the British and Australian competitions which utilise narrower, go-kart-like tracks. Maximum 'straight' length is fixed by the rules at 77 m, while corner radii range between 9 m and 45 m. Slaloms with a spacing of between 7.62 m and 15 m are also allowed. The target maximum speed (105 km/h) and average speed (50 km/h) is also defined, with organizers tailoring the track to approximate these velocities. These constraints result in the specification of tracks where competitors generally spend a high proportion of time in transient cornering, and less time is steady-state cornering or straight-line acceleration and braking. As a consequence, successful Formula SAE cars are usually light and nimble with excellent cornering, acceleration and braking. Popular wheelbase and track widths are small, around 1.6 m and 1.2 m respectively, with recent trends seeing these numbers further declining.

Available Power / Weight Ratio

Given engine (610 cc) and intake restrictions (20 mm orifice), the popular 600cc naturally aspirated motorbike engines produce around 50-60 kW, and turbo- or super-charged engines up to 65 kW. Total car weights in the region of 210 kg are frequently achieved using these engines. Given freedom of gearing and the low top speeds imposed by the course, a light and powerful Formula SAE car can be traction limited in first and second gears. Logged data from a variety of teams at the 2004 Australian FSAE Endurance Event suggests that a percentage-of-time-at-wide-open-throttle of less than 15% is typical, at least for the Australian event. Anecdotal reports from US competitors suggest that they spend slightly longer at wide open throttle (during Endurance), but still less than 20%. The fact that the driver cannot demand full power from the engine for the vast majority (>80%) of time spent on-track is evidence that Formula SAE cars are generally 'traction limited' as opposed to 'power limited'. This observation would suggest that significant gains in lap time can be made through either increasing the car's traction, or by decreasing engine power (and using more of it) if such a decrease comes with a large enough weight saving.

Specific Rules Relating to Aerodynamics

To use some of the excess power available to most Formula SAE cars to generate increased levels of grip via aerodynamic downforce requires consideration of the rules relating to such devices.

Following Cornell's use of a sucker fan in 1990 to set a record 1.32 g in Skin Pan [2], the use of powered ground effects in Formula SAE was banned. A further rule change stated that only the car's tires are allowed to touch the ground, effectively prohibiting the use of 'sliding skirts' to seal the underbody which limits the pressure differential achievable with traditional underbody diffusers. In response to safety concerns, the rules also state that any 'wings' and their mounts must not interfere with driver egress. The location of aerodynamic 'wings' is also restricted to the vertical envelope defined by the rear of the rear tyres, the outside edge of the tires, and a line 460 mm forward of the front of the front tires (See Fig 1). As there is no rule regarding maximum wing size or plan area, it therefore becomes limited by the chosen wheelbase and track width (and vice versa, potentially). These allowable package space rules only apply to 'wings', meaning that diffusers and other aero devices could potentially be used outside this region, subject to the judgment of the scrutineers. In 2002, the Monash Formula SAE car was permitted to run a diffuser which ended behind the rear of the rear tires.

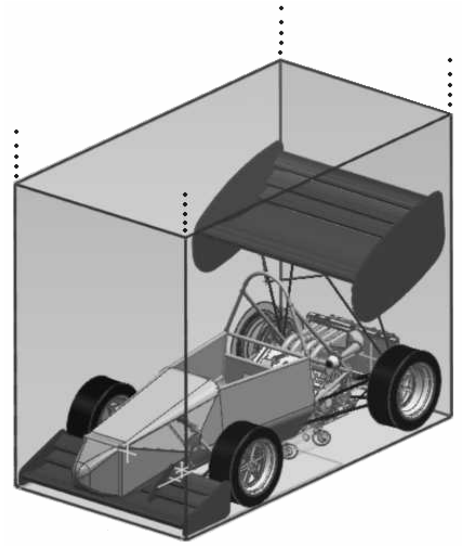

Figure 1: Allowable packaging envelop for 'wings' in Formula SAE.

As there is no stated or practical limitation on the vertical height of the wing, this choice becomes a trade-off between minimization of centre of gravity height (through low mounting) and maximization of downforce (by locating the wing high, in clean airflow). The effect of a given wing's drag force component on the car's aerodynamic balance can also limit the realistic mounting height range. As there is no limitation on minimum wing ride height, a wing can be designed to operate in optimal ground effect at the front of the car, thereby increasing its maximum coefficient of lift, and improving its lift to drag ratio [5,6]. A large, single wing could also be mounted high and centrally, in the style common to Sprint Cars and the A-Modified racing class, provided the driver's egress is not adversely affected.

The rules also dictate that all wing elements have a leading edge radius of at least 12.7 mm (0.5") and a trailing edge radius of 3.0 mm (1/8") for safety reasons. Therefore considerable modification of readily available wing profiles (like those listed in the UIUC on-line data base [7]) is required for compliance with this ruling. An example of this process is described in [1].

One important rule difference between Formula SAE and other formulas, is that movable aerodynamic surfaces are still permitted in this competition. This means that wings and other devices can be mounted 'unsprung' so that downforce can be delivered directly to the wheels rather than via the 'sprung' chassis. In this way the mechanical grip of the car is not compromised by the high spring rates required to prevent the chassis from 'bottoming out' under aero loading. This system has the added advantage of allowing the front wing to track a near constant ground clearance because it is controlled by the outboard assembly which should always be in contact with the ground.

If aerodynamics devices are used in Formula SAE, their settings can be adjusted for the individual events, but wholesale removal or addition of components is not allowed. Some ability to tune the performance of an aerodynamics package is therefore considered advantageous, and might include a low drag setting for Acceleration, a mid to high downforce setting for Autocross and Endurance, and a maximum downforce setting for Skid Pan and any wet weather racing.

DESIGNING FOR DOWNFORCE

A range of resources for the design of race car aerodynamics have been identified below. Drawing from these resources, an example is given for the process of preliminary specification of a wing package for a Formula SAE car. This package is designed for maximum downforce within the stated acceptable limits of increased drag and reduced top speed. As there is no established method for the theoretical prediction of aerodynamic side forces and their associated yawing moments, this aspect of the aerodynamic design will not be considered at this stage. Further discussion and experimental data relating to the measured side forces and yawing moments will be presented in the companion paper [1].

AERODYNAMIC DESIGN RESOURCES

There exists a considerable body of literature relating to the design of aerodynamic devices such as wings, for the generation of lift for airplanes and downforce in race cars. Monographs by Hucho [8], Katz [9] and McBeath [10] provide a good general introduction to vehicle and race car aerodynamics, while the works of Leibek [11], Selig [12], Razenbach and Barlow [13,14], Ross et al [15], Zerihan and Zhang [5,6] describe the optimisation of airfoil performance in more detail. More specific examples of the use of aerodynamic downforce in racing are provided by a wide range of authors [16-22].

PRELIMINARY CALCULATIONS

A few basic assumptions are made in the preliminary calculations described below. Firstly, the use of both a front and rear wing is assumed. A front wing (positioned forward of the wheels) has the potential to operate in 'ground effect', a phenomena which is beneficial to the production of downforce with minimal drag. This fact usually makes the use of a front wing a sensible choice if given the option. If a front wing is used, a rear wing is also needed if aerodynamic balance is to be achieved. For simplicity, the use of diffusers and their consequent effect on the aero balance will be neglected, and the bare vehicle's aerodynamic centre of pressure will be assumed at mid-wheelbase.

The process of wing specification outlined below follows the process described by McBeath [10]. The first step involves determining the amount of brake engine power that can be sacrificed to the aerodynamic drag of a rear wing. This information is used to determine rear wing plan area and C_D, and from that an achievable C_L can be estimated. Balancing aerodynamic moments about the design Centre of Pressure yields the required resolved aerodynamic force vector for the front wing, which is then specified through an iteration of potential wing profiles and plan areas.

Calculating 'Sacrificial' Drag Brake Engine Power

Following the process outlined by McBeath [10], the vehicle's theoretical top speed *without* aerodynamic devices was first calculated using Eq(1), which has been modified for SI units, and using the values given below. This equation assumes ideal gearing and that terminal velocity will coincide with the speed at which the car's maximum brake engine power (kW) is totally absorbed by aerodynamic drag forces. Rolling resistance is neglected. The frontal area (A) and coefficient of drag (C_D) used below relate to the 2003 Monash Formula SAE car with no wings, as tested in the Monash Full Scale Automotive Tunnel. More details on this facility and testing procedure are provided in [1].

$$\text{Brake kW absorbed} = \frac{C_D \times A \times v^3}{1{,}633}$$

$$A_{CAR} = 0.9m^2$$

$$C_D = 0.83$$

$$kW = 45kW$$

…Eq(1)

Rearranging and solving for v yields: v = 46.2 ms^{-1} or 166.2 km/h

This velocity is well above the top speed seen in Formula SAE, so assuming a new 'drag restricted' top speed of 120 km/h it is possible to determine the brake horse power that can theoretically be sacrificed. Recalculation of the power figure for 120 km/h showed that only 17 kW is needed to overcome the base car's aerodynamic drag, meaning that the remaining 28 kW can be made available for the drag of additional wings.

Determination of the Rear Wing C_L and Area

Research reported by McBeath [10] suggests that the drag of open wheel, single-seater cars is only significantly affected by the rear wing, with the front wing contributing little extra drag even at large angles of attack. Wind tunnel testing by these authors on the 2003 Monash FSAE car has confirmed the validity of this assumption. Therefore Eq(1) was used again with the figures of 28 kW and 120 km/h to determine an allowable $C_D.A_{RW}$ of the rear wing of 1.38.

Formula SAE rules state that the rear wing must not protrude behind the rear of the rear tyres, nor beyond the rear outer track width. Practical considerations usually limit the forward most point of the rear wing to the main roll hoop structure unless the wing is to be mounted above this point. For the 2003 Monash vehicle, this described a maximum allowable wing plan area of 1.4 m (span) by 0.65 m (chord), or 0.91 m^2. Solving for C_D yielded 1.5, which can be roughly related via experimental data [7, 9, 10] to an expected wing negative coefficient of lift ($-C_L$) in the order of 3.0 to 4.0. Wing profiles in this performance range are classified as 'high lift' and rely on multi-element designs. Given this plan area, a $-C_L$ of 3.5, and neglecting potential low aspect ratio effects [10], a downforce of 240 N at 40 km/h is predicted for the rear wing.

Front Wing: Designing for Aerodynamic Balance

In specification of the front wing, the most important design consideration was aerodynamic balance rather than outright maximum down force. This means that the net aerodynamic force created by both wings (diffusers will be ignored for the moment) acts near the car's center of gravity. A slight rearward aero bias where the centre of pressure is behind the centre of mass is commonly used to ensure high speed stability. Designing for a good aero balance will ensure that the vehicle exhibits neutral handling characteristics rather than under-steer or over-steer as a result of unevenly distributed aero loads. Balance is determined by the addition of the moments produced due to both down force and drag force over their perpendicular cantilever lengths about the design centre of pressure [22], which in this case, is taken as the ground position directly below the car's center of gravity (mid-wheelbase). Wing positions were first estimated and cantilever lengths determined by measuring the perpendicular distance from the balance point to the estimated centre of pressure for each wing. For a Formula SAE car with a wheelbase of 1650 mm, a 50:50 weight distribution, and the wing positioning shown in Figure 2 below, balancing moments and solving for the required front wing down force (its drag is neglected) gives a value of 165 N at 40 km/h.

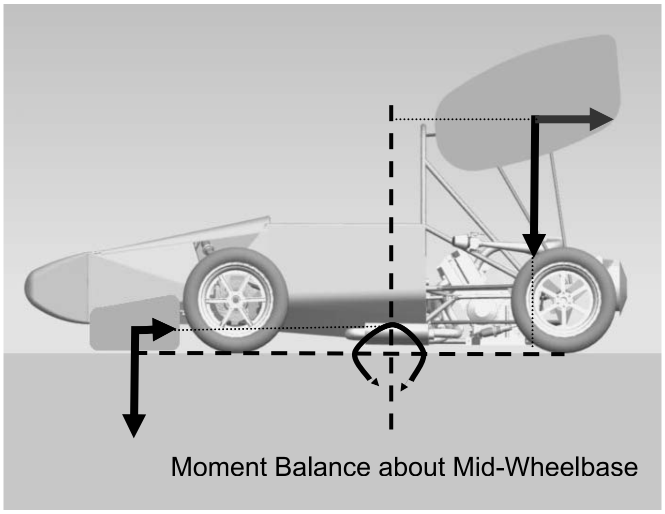

Figure 2: Balancing aerodynamic moments about the CG position as a means of specifying the required front wing performance.

An iterative process was then used to select a front wing profile to produce the required 165 N at 40 km/h within the maximum plan area as defined by the rules and package constraints. The research of Zhang and Zerihan [5,6] which examines the performance of both single elements and dual element wings in ground effect provides a good estimation of the lift and drag coefficients achievable. Depending on the particular car and installation, consideration should also be given to the effects of the car's nose cone [9] and close wheel proximity [21]. Assuming that the front wing operates in clean flow, a negative lift coefficient of 3.4 is required. If the assumption of an ideal flow field is removed, a front wing lift coefficient in excess of 4.0, or the generation of more front wing area is a more realistic requirement for aerodynamic balance. This also implies that the maximum amount of balanced aerodynamic downforce that a Formula SAE car can generate using traditional low mount front, and high mount rear wings will be limited by the front wing, given a 50:50 weight distribution.

If these values of front and rear downforce can be achieved, a total download of 405 N at 40 km/h is generated. Having verified through wind tunnel testing that the wing-less 2003 Monash Formula SAE car generates only a minor (and thus negligible) amount of lift, this additional downforce would result in an overall vehicle coefficient of lift of -4.0, given the total vehicle frontal area (with wings) of 1.35 m^2. It was on this basis that the aerodynamics package for the 2003 car was specified and constructed.

Details of the actual wing profiles are provided in [1].

AERODYNAMIC VALIDATION

The analysis presented above is one process by which an aerodynamics package can be specified for a race car. There is however, no guarantee that the wings will perform as intended within the near flow field of the race car. It is generally safe to assume that their performance will be adversely affected due to their interaction with the vehicle, and even each other. For this reason a wide range of wind tunnel testing and on-track aerodynamic testing was used in the development and tuning of this aerodynamics package, and is described in detail in the companion paper [1].

This work showed the measured downforce values to be significantly lower (by around 35%) than those estimated from free-stream, empirical data. Fortunately, the loss of downforce was reasonably even on both ends of the car, with the front down by 39% and the rear down by 33% on the initial predicted values, meaning that the final aerodynamic balance was still close to neutral. These final measured aerodynamic coefficients are listed in the table below and will be used in the following performance analysis.

PERFORMANCE ANALYSIS

In order to determine if the particular aerodynamic package described would be beneficial for use in Formula SAE an overall performance analysis of the event was conducted, taking into consideration each aspect of the competition. A brief analysis of the four Dynamic Events (Skid Pad, Acceleration, Autocross/Endurance) will be described here.

For the purpose of these performance calculations, the values listed below will be used. It should be noted that all these values have been measured experimentally, and relate to the addition of wings to the 2003 Monash car.

Global Parameters

• Tire Coefficient of Friction	1.6
• Engine Power and Torque vs RPM	See Apdx 1
• Gearbox Ratios	See Apdx 1
• Final Drive Ratio:	3.6

Car and Driver (No Wings)

• Weight: (Car: 225 kg, Driver 80 kg)	305 kg
• Center of Gravity Height:	270 mm
• Polar Moment of Inertia (Yaw):	106 $kg.m^2$

- Car Coefficient of Lift: 0.0
- Car Coefficient of Drag: 0.83
- Frontal Area: 0.9 m^2

Car and Driver (with the Wings described)

- Weight: (Wings and Mounts: +12kg) 317 kg
- Center of Gravity Height: 300 mm
- Polar Moment of Inertia (Yaw): 118 $kg.m^2$
- Car Coefficient of Lift*: 2.57
- Car Coefficient of Drag*: 1.33
- Car Coefficient of Lift* (for Low Drag) 0.44
- Car Coefficient of Drag* (for Low Drag) 0.73
- Frontal Area (For both settings*): 1.35 m^2

* Note: The frontal area of car is reduced in the low drag setting but for convenience the same area has been used, resulting in a low C_D and C_L but correct C_D.A and C_L.A values.

ACCELERATION EVENT ANALYSIS

The Acceleration Event is a timed, 75 meter acceleration from a standing start. To begin with, it is useful to make an estimate of the maximum acceleration performance of the winged car, in its full downforce configuration, versus the same car with no wings.

A modified 'bicycle' model [22] can be developed for predicting acceleration in a straight line using the two sets of vehicle parameters described previously. This model accounts for the effects of longitudinal weight transfer as well as aerodynamic drag and downforce. Rotational inertial has been neglected but is assumed the same for both vehicles. Two maximum potential acceleration curves are generated for each car configuration. The first curve is based on the acceleration power available (brake horse power, gearing and aero drag) and second on available grip (tire friction coefficient and total reaction force as a function of weight transfer and aero download). These curves are shown below (Fig. 3), with the *lower* curve for each car configuration indicating the maximum potential acceleration.

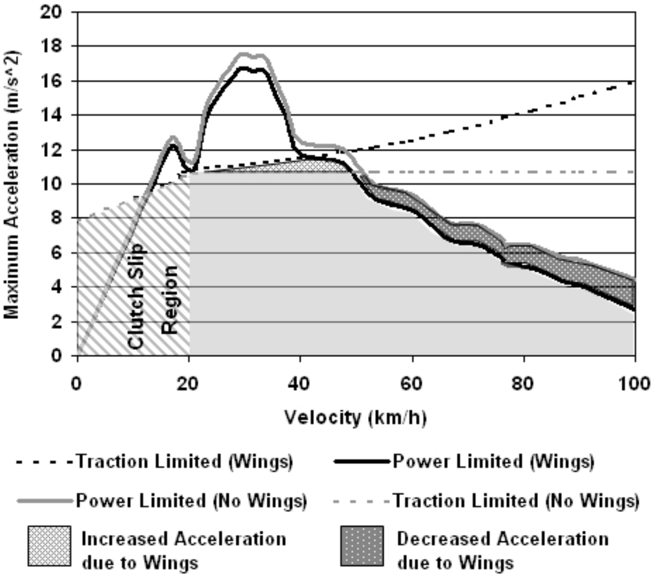

Figure 3: Predicted maximum longitudinal acceleration envelope (shaded grey), with and without wings:

The crosshatched grey shading below 20 km/h indicates the likely clutch slippage region, which results in higher engine speeds and power outputs meaning acceleration is actually limited by the traction curves. Immediately above this speed, the winged car is able to accelerate slightly faster than the same car without wings, mainly due to the increasing aerodynamic download. At 50 km/h the maximum acceleration potential of the two cars is the same, and for speeds above this, both cars become power limited. As the winged car is generating more than twice the aerodynamic drag of the non-winged car, its maximum acceleration decreases more quickly with increasing road speed. While the last point is somewhat obvious, the fact that the winged car should accelerate faster below 50 km/h is an interesting observation, particularly considering that the corner exit speeds for other events like the Autocross and Endurance (where such a wing setting would be used) are typically in the 30 to 60 km/h range.

Using this model, the predicted elapsed times for the Acceleration runs (0-75m) were

- Winged Car 3.89 sec
- Non-Winged Car 3.70 sec

These numbers are low, as they neglect the effects of rotational inertia and assume zero shift times and perfect traction, but provide an indication of the performance difference a high downforce wing setting can make. Ping [23] provides a more detailed analysis of the effect of the number of shifts, shifting times and final drive ratio on the acceleration of a Formula SAE car.

If the same wing package is adjusted for the measured low drag (and low downforce) setting quoted in the vehicle parameters, the predicted time difference for the acceleration event is narrowed considerably.

- Low Drag Setting, Wing Car 3.80 sec

At the low drag setting, the C_D.A value of the winged car is only 32 % greater than the value of the wing-less car, compared to 140 % greater in the high downforce setting. Further analysis shows that predicted time difference (0.10 sec) between the low drag winged car and the wingless car is due, in roughly equal parts, to the wing drag and the weight of the wings themselves.

SKID PAN EVENT ANALYSIS

The Skid Pan event involves the car driving laps around a circular track, 15.25 m in diameter. It can be assumed that the car's centre of gravity tracks a radius of 8.5 m. The course is arranged in a 'figure-8' with the cars entering from the centre and completing 2 consecutive laps on each side of the 'figure-8'. Only the second lap on each side is timed, as a test of the vehicle's maximum steady state cornering speed. To evaluate the effect of wings on skid pan performance, a graph of maximum velocity versus corner radius can be generated using the parameters previously described (Fig. 4).

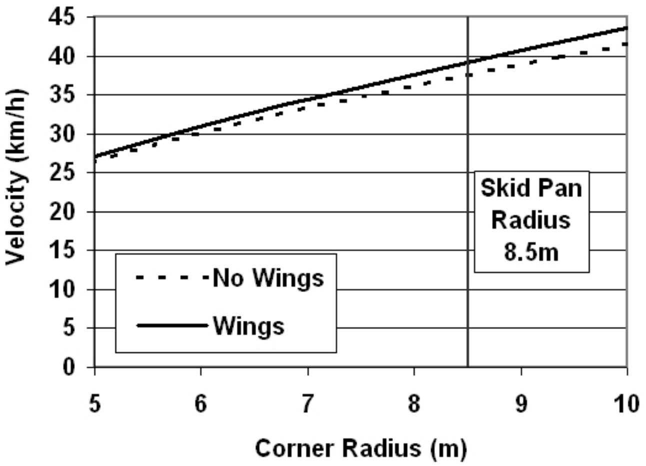

Figure 4: Predicted maximum velocity versus corner radius, for the Monash FSAE car, with and without wings. Skid Pan radius of 8.5m indicated.

This analysis predicts maximum corner speeds of 37 km/h for the non-winged car and 39 km/h for the winged car, corresponding to Skidpan times of:

- Winged Car 4.93 sec
- Non-Winged Car 5.20 sec

It is thought that the time of 4.93 seconds predicted for the wing car is slightly optimistic, given:

- The slight reduction of aerodynamic downforce measured at high yaw angles such as these [1] and;
- The effect of the disproportionately high levels of unsprung weight transfer expected at the rear of the car, due to the high mounted, unsprung rear wing.

Such effects have been quantified but are not taken into account in this simplified model. More complex calculations considering these factors have shown that skid pan performance of the car with and without wings is close to equal.

AUTOCROSS / ENDURANCE EVENT ANALYSIS

The Autocross Event is a single timed lap of a course roughly 800 m long, featuring a variety of straights, turns and slaloms within the parameters described by the rules. The Endurance Event uses a similar course, and two drivers are required to complete a number of laps totaling 22 km, with a driver change in the middle. The Fuel Economy event, which is judged on the basis of the fuel used in the Endurance Event, will not be considered here.

A comprehensive lap-time simulation of the Autocross/Endurance track(s) is required for a thorough analysis of the effect of adding wings to a Formula SAE car, but will not be attempted here. Instead, using the vehicle parameters which have been defined, the cornering and braking performance of the car will be examined. The analysis already presented for the longitudinal acceleration of the car can be considered valid, in unmodified form, for the straight-line acceleration portions of the Endurance and Autocross events. Given all of these performance predictions, and with knowledge of past track designs, the net effect of adding the wings described, to the 2003 Monash Formula SAE car, will be gauged.

Figure 5 below shows another graph of maximum velocity versus corner radius (like Fig 4), but in an expanded domain which encompasses the corner radii allowed within the Autocross / Endurance rules.

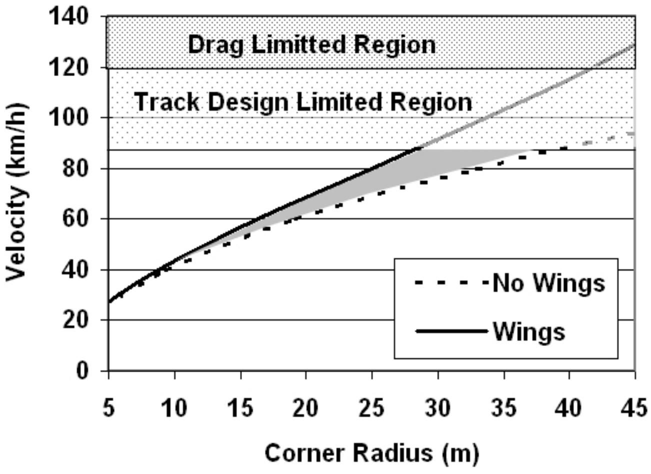

Figure 5: Predicted maximum velocity versus corner radius, for the Monash FSAE Car, with and without wings. Grey shaded region indicates increased cornering speed due to the addition of wings.

These results can also be normalized by the maximum cornering velocity of the wing-less car to give an indication of the difference in relative cornering potential (Fig 6).

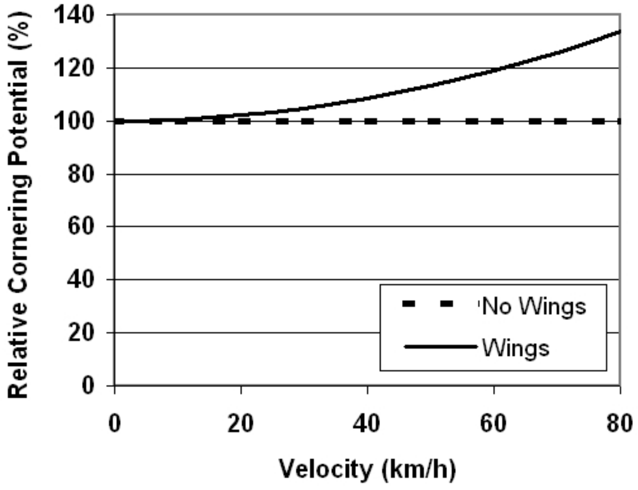

Figure 6: Predicted relative cornering potential versus velocity, for Monash FSAE car, with and without wings.

The graph of relative cornering potential shows that between 30 and 80 km/h (the range of corner speeds measured on track, Australian competition 2004), the winged car provides at least 8% and as much as 30% more cornering potential. The logged track data for previous endurance events shows that corner speeds of 50 km/h and below are more common than those above. This implies that average gains in cornering speeds of between 10% and 15% are realistic depending on the track design.

For best performance through the 'slaloms' frequently used in Autocross and Endurance tracks, a Formula SAE car needs to be capable of high yaw acceleration rates. The addition of wings is both beneficial and detrimental in this respect, depending on the given road speed. At low speeds, the increased polar moment of inertia due the addition of wings will result in lower yaw accelerations compared to the base car. However, above a critical road speed, the increased grip due to the download will result in higher potential yaw acceleration rates for the winged car. If sufficient downforce can be generated for a reasonably small increase in polar moment of inertia, then this critical speed can be lowered. If it can be made lower than the base car's speed through the slaloms, then the winged car will be faster through this section of track, even before its increased cornering potential is considered. A graph showing relative maximum yaw acceleration potential for the Monash FSAE car with and without wings is given below (Fig. 6).

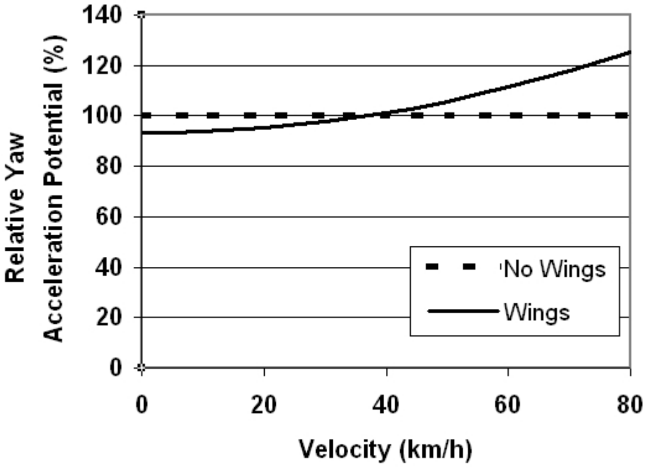

Figure 6: Predicted relative yaw acceleration potential versus velocity, for Monash FSAE car, with and without wings.

From Figure 6, at a road speed of 32 km/h the maximum yaw acceleration of the both cars will be equal. Logged track data shows that the wing-less Monash FSAE car can traverse the minimum allowed slalom spacing (7.62 m) at a road speed of 30 km/h, and the maximum allowed slalom spacing (15 m) at 57 km/h. From this we can predict that the winged car should be faster through any sized slalom, given that it possesses an equal or higher yaw acceleration potential and significantly higher cornering potential at these speeds.

Finally, in terms of braking, it can be shown using that the wing package described is always advantageous compared to the base car. The wings obviously contribute a small amount of weight (12 kg) to the total mass of the vehicle (317 kg) but this is more than compensated for by the increased reaction force and drag forces that they provide. This is illustrated by considering the traction limited curves plotted in Figure 3, where the winged car has access to around 50% more reaction force at a speed of 100 km/h.

SUMMARY OF RESULTS

In summary, with respect to the various Dynamic Events, it has been shown theoretically (using measured values), that the addition of wings to the 2003 Monash FSAE car should result in:

Acceleration Event:

- Similar or marginally slower times

Skid Pad

- Similar or marginally faster times

Autocross and Endurance Events:

- Slightly slower straight-line acceleration
- Significantly higher cornering potential
- Similar to higher yaw acceleration potential
- Higher slalom speeds
- Significantly higher braking potential

In addition, it is assumed that wings will also result in:

- Increased fuel usage

CONCLUSION

The preliminary specification of a high downforce aerodynamics package for a Formula SAE car was described. Using values obtained from experimental measurements described in a companion paper, the net effect of this package on Dynamic Event performance was quantitatively estimated for the 2003 Monash Formula SAE car. This analysis predicted that the 'wing' package described would significantly benefit the car's dynamic event performance.

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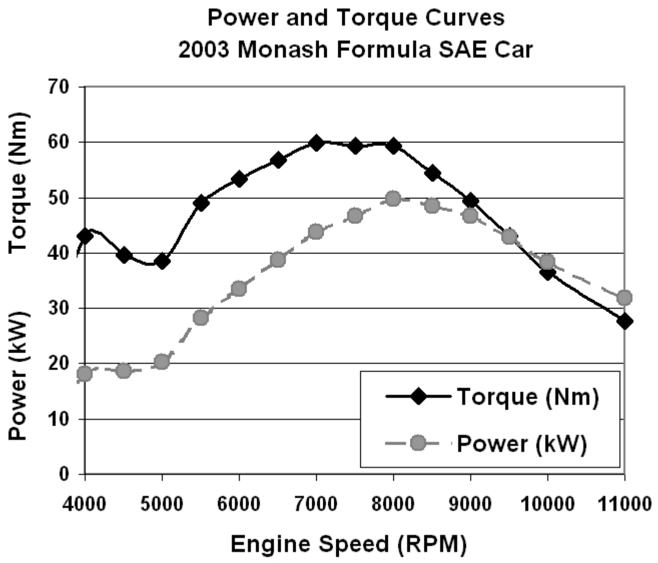
CONTACT

Scott Wordley:

Email: scott.wordley@eng.monash.edu.au

Website: http://www-personal.monash.edu.au/~fsae/

APPENDIX 1:



GEARBOX RATIOS

(All ratios include the Primary Reduction)

Stock Honda CBR 600 cc

1st Gear:	5.45
2nd Gear:	3.84
3rd Gear:	3.07
4th Gear:	2.55
5th Gear:	2.24
6th Gear:	2.03