

Methodology for the Design of an Aerodynamic Package for a Formula SAE Vehicle

Christopher Craig and Martin A. Passmore
Loughborough Univ.

ABSTRACT

Recent changes to the rules regarding aerodynamics within Formula SAE, combined with faster circuits at the European FSAE events, have made the implementation of aerodynamic devices, to add down-force, a more relevant topic. As with any race series it is essential that a detailed analysis is completed to establish the costs and benefits of including an aerodynamic package on the vehicle. The aim of the work reported here was to create a methodology that would fully evaluate all aspects of the package and conclude with an estimate of the likely gain in points at a typical FSAE event. The paper limits the analysis to a front and rear wing combination, but the approach taken can be applied to more complex aerodynamic packages.

An initial wind tunnel investigation of the potential flow interactions between the driver's helmet and rear wing using a multi-hole pressure probe is reported and the data used in a two-dimensional CFD calculation to provide an accurate prediction of the likely down-force from the wing package. The chosen configurations are tested in a comprehensive wind tunnel program and a map of potential setups generated. The potential aerodynamic configurations are assessed in both quasi-static and dynamic handling analysis to demonstrate the effects of aerodynamic lift, lift distribution, aerodynamic drag, and the effect of additional weight, weight distribution and height of the center of gravity. The paper includes a description of the wind tunnel model and scaling considerations and a description of the handling model and the lap simulation methods.

The results shows that a simple front and rear wing combination, providing relative low down-force (1000N at 110kph on a vehicle of 280kg, including driver), gives an improvement in performance equating to a gain of approximately 40 points during the event. The largest improvements are seen during the autocross and endurance events. This gain is considered sufficient to justify the inclusion of the package on the vehicle.

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INTRODUCTION

Aerodynamics within motorsport is an ever evolving area. Aerodynamic devices to generate down-force as a route to faster cornering speeds have been employed in mainstream racing series since the 1960's, for example in Can-Am and Formula 1. The success of the approach has subsequently filtered down into other series where competitors and designers have exploited the considerable advantages that they offer in improving lap times.

In practice, with the evolution of the sport, most race series have introduced restrictions on the use of aerodynamic devices, or have tightly controlled their application via the series regulations. For example this may include restrictions regarding position, shape and size of allowable devices and the complete banning of others.

Formula SAE (FSAE) is an exception to this as the rules are essentially free in terms of positioning and design of aerodynamic devices. This freedom is possible because in FSAE the average speed of the vehicle has typically been quite low making the exploitation of aerodynamics more difficult and the potential gains relatively small. In recent years, however, a change in style of FSAE circuits to more gradual changes of curvature, instead of the sharp changes of direction associated with previous competitions has made higher speeds possible and has resulted in an increase in average speed of around 10 km/h.

This change in track style has led to an increase in numbers of vehicles utilizing aerodynamic aids ([Figure 1](#)). In the 2012 UK event these ranged from small single element wings and flat floors, to large quadruple element wings and fully shaped under bodies. In 2012 at Formula Student Germany, 17 cars

had an aerodynamic device, either wings or shaped under-floors. Ten of these vehicles finished in the top 20 and the top five cars all employed such devices.



Figure 1. Karlsruhe Institute of Technology and Melbourne Monash 2012 FSAE Vehicles.

There are a number of publications exploring FSAE performance, including some that refer to how an aerodynamic package improves performance (Monash [1][2]), how to use CFD to design a large wing (Chalmers[3]) and both sources cover the broad performance benefits. They do not however provide any in depth analysis or description of specific techniques, methodologies and geometries, or a detailed evaluation of the benefits of implementing particular devices.

This paper addresses this gap and provides a starting point for any team wishing to implement an aerodynamic package on a FSAE vehicle. The aim is to describe a methodology that fully evaluates all aspects of the aerodynamic package. This includes the design of the wing sections, experimental and computational methods, evaluation of the dynamic performance and finally an estimate of the likely gain in points at a typical FSAE event. The paper limits the analysis to a front and rear wing combination, but the approach taken can be applied to any combination of aerodynamic devices or an integrated complex aerodynamic package.

EXPERIMENTAL METHODOLOGY

The design methodology employed here combines experimental work carried out in the Loughborough University model scale Wind Tunnel with a number of simulation techniques. CFD modeling was conducted using a commercial code on quad core processors with 16GB RAM, and all dynamic simulation was completed using a purpose written program in MATLAB and Simulink running on the same computer hardware.

It is recognized that many teams may not have access to comparable experimental facilities but by validating the computational methodology used here the intention is that any team can use the simulation methods to implement a basic aerodynamic package into their design.

Wind Tunnel

The Loughborough Large Wind Tunnel (figure 2) is a novel open circuit horseshoe design allowing for a relative large working section of 1.92m × 1.32m (width × height) within the constraints of the total floor space. Normal working section

velocity is 40m/s with a turbulence intensity of 0.2% and spatial uniformity is +/-0.4%. Full details can be found in Johl [4].

Force and moment measurements are made via a 6 component under-floor balance with an integrated yaw drive. When testing a 1/4 scale automotive model; a repeatability of +/- 2 drag counts is typical when fully removing and reinstalling the model. All force and moment data reported in this paper is averaged over a 30 second sampling period.

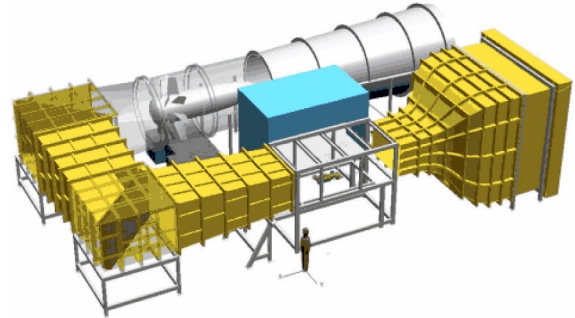


Figure 2. CAD Model of Loughborough Large Wind Tunnel.

The tunnel uses a fixed floor that gives a boundary layer thickness (δ^{99}) of approximately 50mm at the front of the model location in normal operation. As this model requires a relatively low ground clearance, particularly the front wing, a reduction in boundary layer thickness was essential. A common approach is to introduce a separate suspended ground plane. While this is an effective method for reducing boundary layer thickness it adds complexity to the model mounting and measurement method when an underfloor balance is employed, as in this case. It was therefore decided to install a 25mm high, v-shaped boundary layer trip upstream of the model and measure the reduction in the boundary layer thickness. The arrangement is shown in figure 3.

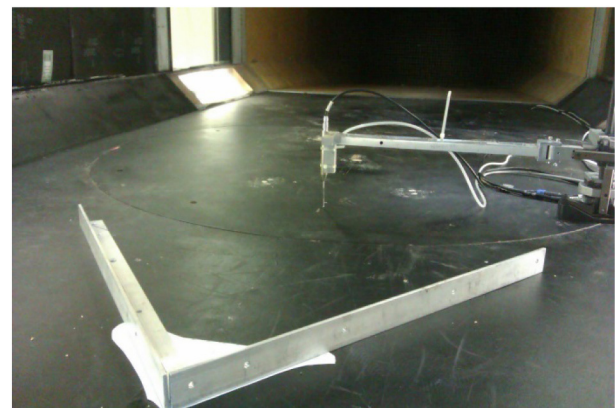


Figure 3. Boundary layer trip installed in the wind tunnel. Also showing instrumentation for measuring the boundary layer thickness.

By conducting a sweep of the internal angle for the trip and its location upstream, the optimum configuration of an 80 deg angle located 1000mm upstream of the model front impingement was identified. This results in a boundary layer thickness (δ^{99}) of approximately 14mm. The comparison of with and without the trip is illustrated in Figure 4 and includes a

measurement on the model centerline and displaced 100mm laterally. The boundary layer measurements were taken using a 4-hole TSI Cobra probe providing flow velocity and an estimate of turbulence intensity.

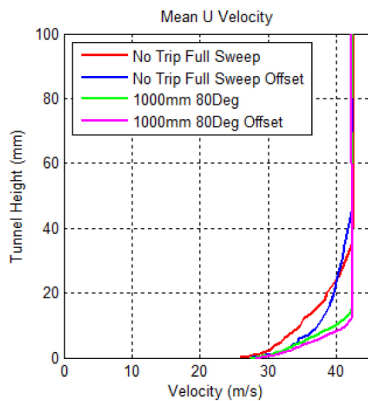


Figure 4. Effects of Boundary Trip Installation on U-Velocity on the tunnel centerline and 100mm laterally from the centerline.

Model Design

The model is based on the 2012/2013 Loughborough University Formula Student Vehicle. To reduce Reynolds sensitivity, small features such as the engine detail, engine intake and roll hoops have been removed. Newnham [5] has shown that drag of a simplified model is affected by model leading radii, leading to post or pre critical flow. On the real FSAE vehicle the nose radius must be a minimum of 75mm. Based on an average speed of 25m/s and using the minimum edge radius, a real car Reynolds number of 1.20×10^5 based on edge radius is obtained; Newnham's work shows this value to be located in the region between trans and post critical. Therefore all nose radii on the model must have a Reynolds number greater than 1.20×10^5 to ensure similar flow behavior, resulting in a minimum model scale radius of 45mm.

Other components have been omitted for experimental simplicity; the side-pods have been removed as the fixed ground plane makes wheel flows inaccurate which are the primary contributors to flow condition in this region (they also will have little effect on the flow conditions that are in the wing positions). These may be added in future if required. A 3D CAD image of the model is shown in figure 5.

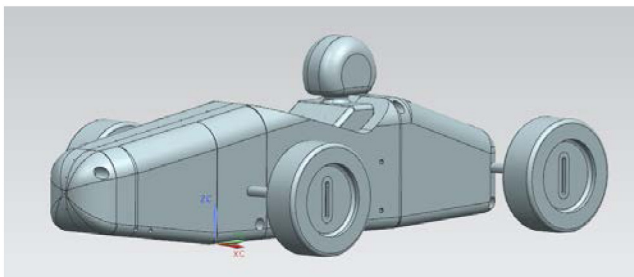


Figure 5. 5/18th Scale Windtunnel Model.

A model scale of 5/18th was chosen to allow for a wide range of aerodynamic components to be tested in future work without overloading the force balance.

Ride height adjustments are made at the wheel hubs, with both positive (3 fixed adjustments) and sliding adjustments possible. An hatch located in front of the driver gives access to pressure tappings and pressure scanners although results from these are not included in this paper. The driver shoulders and helmet are removable and can therefore be replaced if required.

The model body is CNC manufactured in two halves from medium density machinable polyurethane model board. It is then held together with dowel pins and 4 M6 bolts. Axles are produced from mild steel and press fit into one side of the model body. The wheels are made from high density model board with acrylic inserts for the ride height adjustment.

During initial testing a Reynolds sweep confirmed the model to be insensitive to Reynolds numbers above $Re = 6 \times 10^5$ (based on wheelbase) corresponding to a full scale vehicle speed of 5m/s, demonstrating the applicability of the results to full scale. All subsequent wind tunnel testing was conducted at a Reynolds number of 1.0×10^6 . The initial testing was also used to verify that the setup procedure produced repeatable results.

PERFORMANCE ANALYSIS

Before designing the aerodynamic package a lap simulation tool was developed to determine the value of any aerodynamic down-force and compared with changes in vehicle mass and weight distribution. Two approaches are taken. A lap simulation is used to broadly quantify the gains and a dynamic model is used to assess the effect on the handling limits.

Lap simulation tools are now widely used across motorsport as a method of predicting the vehicle performance and making informed setup changes.

The Milliken Moment Method [6] allows a calculation of vehicle stability in a quasi-static scenario. Tire slip ratios and steered angles are input into the model and the tire forces balanced by modifying the body slip angle. The balancing is calculated using a non-linear least squares optimization, implemented in Matlab, with the weight transfer allowed to settle until differences between two iterations are less than 0.01N. This produces a hemispherical plot of lateral and longitudinal accelerations, with the limits of this hemisphere providing the limit of the vehicle.

These performance envelopes are constructed in 5m/s increments; interpolation between the 5m/s intervals then creates a full vehicle performance envelope. Example plots at 10 and 20m/s are illustrated in figure 6. The performance envelope is then used in conjunction with the racing line to simulate a lap.

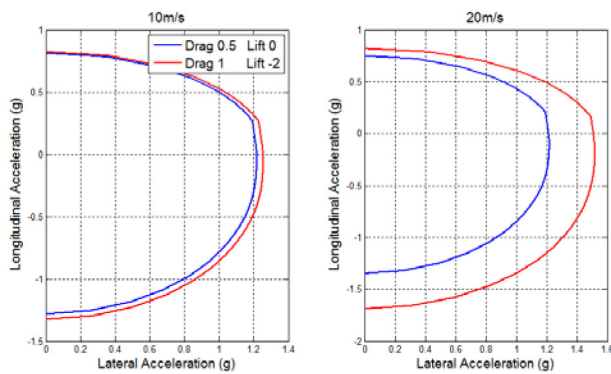


Figure 6. Performance Envelope with Two Aerodynamic Configurations.

Because the track varies at each FSAE event a bespoke test circuit was devised to capture all of the important features of a typical circuit. This is illustrated in [figure 7](#).

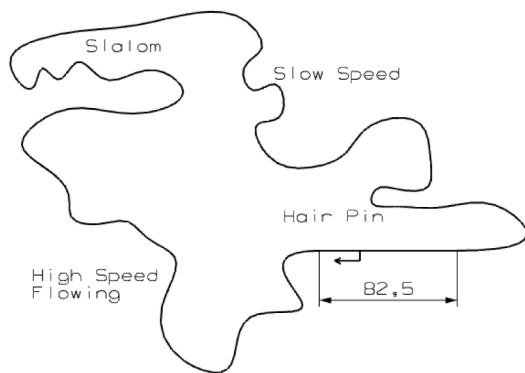


Figure 7. Bespoke Design FSAE Track, Dimension in meters.

The lap simulation was applied, using the methodology shown in [figure 8](#), to the endurance and autocross events to determine the sensitivity of the vehicle to a number of design parameters. This was assessed in terms of the potential improvement in the points awarded at the event. A summary of the points system is given in [appendix one](#).

[Table 1](#) shows the sensitivities to Mass and CoG height for the Loughborough FSAE vehicle. It can be seen that although the mass and CoG do need to be considered, they do not have a large impact on the maximum performance of the vehicle.

[Table 2](#) shows the impact of drag and total down-force on the points awarded. As expected an increase in drag causes a loss of points in all events but increasing down-force offers significant improvements in both the endurance and autocross events accompanied by a small penalty in efficiency (fuel consumption). This small reduction in points in efficiency is due to the greater grip capacity during traction and higher cornering speeds. The value of using a lap simulation becomes particularly clear from this data because typically increases in down-force are accompanied by increases in drag and the net gain is the important criteria for judging the package. It also illustrates the need to ensure that any aerodynamic package is aerodynamically efficient, i.e. that it has a good lift to drag ratio.

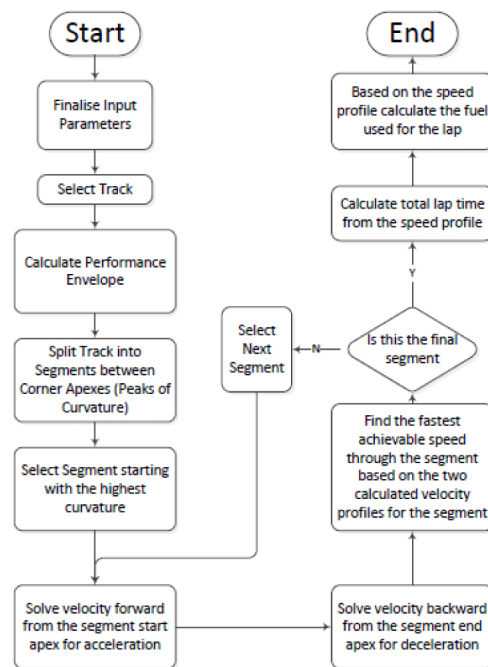


Figure 8. Lap Simulation Methodology.

Table 1. Mass and CoG Height Sensitivity.

Event	Mass Points Sensitivity	CoG Height Points Sensitivity
Autocross	-0.11 Points per kg	-0.0118 Points per mm
Endurance	-0.19 Points per kg	-0.0315 Points per mm
Efficiency	-0.25 Points per kg	-0.051 Points per mm

Table 2. Drag and Downforce Sensitivity.

Event	Drag Points Sensitivity	Downforce Points Sensitivity
Autocross	-2.27 Points per 1000 counts	6.05 Points per 1000 counts
Endurance	-3.99 Points per 1000 counts	10.62 Points per 1000 counts
Efficiency	-6.65 Points per 1000 counts	-0.43 Points per 1000 counts

The handling effects of an aerodynamic package, including the effects of aerodynamic yaw moment, were evaluated using a six degree of freedom dynamic handling model. The model has an input interface of steer angle, throttle position and brake force, along with a braking control and speed control module, and allows a variety of set maneuvers to be completed. The model allows more sophisticated aerodynamic packages to be analyzed than outlined here, for example the trade-off between total lift and yaw moment associated with end plate geometry. In this paper its use is limited to analysis of the lift distribution