Estimation of aerodynamic performance from constant speed and coast down testing

Introduction

This report will focus on the aerodynamic performance of the vehicle using data collected from a combination of constant speed and coast down runs.

Test Summary

Three constant speed runs were performed at 100, 150 and 200km/h. These were then repeated in the opposite direction on the track for a total of 6 constant speed runs.

Several low speed coast down tests were performed to calculate rolling resistance and a high speed coast down test to measure aerodynamic drag.

The tests were performed with Kistler Roadyn S625 wheel force transducers on the four wheels of the vehicle and Raetech coil over load cells. Track speed and position was measured by a GeneSys ADMA inertial measurement unit with differential GPS. Air speed is measured by a Texys pitot tube mounted to the hood of the car. Ride height was measured with three HF-500C laser sensors by Corrsys Datron.

Math Channels and Constants

The following constants should be measured before testing the car. The wheel inertia in this case includes the rotational inertia of the brake rotors.

$$A = 2.04\ m^2$$

$$Weight\_Distribution = 0.581$$

$$Wheel\_Inertia = 1.740\ kgm^2$$

$$Wheelbase = 2.6\text{m}$$

$$Air\_Density = 1.2\ kg/m^3$$

The air speed is measured using a pitot tube. The pitot tube measures the difference between the stagnation pressure and static pressure. This difference is known as the dynamic pressure.

$$Pitot\_Speed = \sqrt{\frac{Dynamic\_Pressure}{Air\_Density}}$$

Constant Speed Downforce Math Channels

The vertical load on the front wheels is measured via wheel force transducers. The front downforce is therefore the sum of the front wheel force transducer measurements minus the static vehicle corner weights. There is an additional offset due to the weight of the tyre and rim which is measured on the corner scales but not by the wheel force transducers. Note this is not a true downforce value as it includes the vertical load due to the pitching moment caused by the drag force.

$$\begin{aligned} Front\_Downforce = {} & (WFT\_FL\_Fz + WFT\_FR\_Fz) \\ & + WFT\_Offset \\ & - Initial\_Fz\_FR \\ & - Initial\_Fz\_FL \end{aligned}$$

The vertical load on the rear wheels is measured via coil over spring load cells. The force at the wheel is equal to the force seen by the spring multiplied by the motion ratio. This assumes that there is no force reaction from the dampers so is only a valid assumption during steady state conditions. The rear downforce can then be calculated by summing the vertical load on the rear wheels and subtracting the static corner weight. Again this force is not true downforce but includes the pitching moment due to drag.

$$CO\_ForceAtWheel = CO\_Force * MR$$

$$\begin{aligned} Rear\_Downforce = {} & CO\_ForceAtWheel\_RR \\ & + CO\_ForceAtWheel\_RL \\ & - CO\_Offset\_RR \\ & - CO\_Offset\_RL \end{aligned}$$

$$Total\_Downforce = Front\_Downforce + Rear\_Downforce$$

Typical practice is to express aerodynamic forces as dimensionless coefficients. The lift coefficients are calculated by the lift force divided by the product of the dynamic pressure and the frontal area of the vehicle.

$$Rear\_CL = \frac{Rear\_Downforce}{Dynamic\_Pressure \times A}$$

$$Front\_CL = \frac{Front\_Downforce}{Dynamic\_Pressure \times A}$$

$$Total\_CL = \frac{Total\_Downforce}{Dynamic\ Pressure \times A}$$

The aerodynamic balance is defined as the fraction of the aerodynamic load on the front wheels.

$$Aerodynamic\_Balance = \frac{Front\_Downforce}{Front\_Downforce + Rear\_Downforce}$$

Coast Down Drag Math Channels

Determining the drag forces on the vehicle is more complex. One method is to perform coast down testing. This testing involved disengaging the drive train of the vehicle at speed and allowing the vehicle to roll to a stop. The total force acting on the car can be determined from Newton's second law (F=ma) so the aerodynamic drag is equal to the total force minus the rolling resistance.

Note that when decelerating the car we are also decelerating the rotating components of the brake assembly and wheels. Therefore we must take the rotational inertia of these components into account. The inertia of the wheels and brake rotors is measured and converted to an equivalent mass using the loaded radius of the wheel.

$$Wheel\_Loaded\_Radius = Wheel\_Static\_Loaded\_Radius + Tire\_Deflection$$

$$Mass\_Plus\_Wheel\_Inertia = Mass + 4 \times (Wheel\_Inertia \,/\, Wheel\_Loaded\_Radius^2)$$

The deceleration of the car is logged by the ADMA inertial measurement unit so applying F=ma to the vehicle the force on the car is equal to the deceleration measured by the ADMA multiplied by the mass of the car including the equivalent mass of the rotating components.

$$Coastdown\_Drag\_Force = ADMA\_Accel\_Hor\_x \times Mass\_Plus\_Wheel\_Inertia$$

The aerodynamic drag is then the total force minus the rolling resistance. The estimation of the rolling resistance is covered in a later section of this report.

$$Aerodynamic\_Drag\_Force = Coastdown\_Drag\_Force - Rolling\_Resistance$$

Once again this force is commonly expressed as a dimensionless coefficient

$$Drag\_Coefficient = \frac{Aerodynamic\_Drag\_Force}{Dynamic\_Pressure \times A}$$

Constant Speed Drag Math Channels

An alternative method for measuring drag is to measure the force applied to the drive wheels of the vehicle while travelling at constant speed. The drive force can be calculated by the sum of the Fx values measured by the wheel force transducers on the drive wheels. The wheel force transducer value will already include the rolling resistance of the driveline and front wheels.

$$WFT\_Total\_Drive\_Force = WFT\_FL\_Fx + WFT\_FR\ Fx$$

The rear wheel force transducers measure the rolling resistance of the rear wheels.

$$Rear\_Rolling\_Resistance = WFT\_RL\_Fx + WFT\_RR\_Fx$$

The aerodynamic drag is therefore the drive force minus the rolling resistance of the rear wheels.

$$Constant\_Speed\_Aerodynamic\_Drag = WFT\_Total\_Drive\_Force - Rear\_Rolling\_Resistance$$

Additional Math Channels

Several other channels may also be created to measure the ride height and body pitch angle. In this case the car was not tested at a range of ride height settings so these channels are included for reference for future tests. Note the positions of the laser ride height sensors are adjusted to give the "aerodynamic ride height" which is the ride height measured at the front and rear axles.

$$X\_RH\_Front\_BehindFrontAxle = 1015\ mm$$

$$X\_RH\_Rear\_BehindRearAxle = 785\ mm$$

$$Front\_Ride\_Height = ((HF\_Left\_Height + HF\_Right\_Height) \,/\, 2) + Front\_Ride\_Height\_Offset$$

$$Body\_Pitch\_Angle = ATan * ((HF\_Rear\_Height + Rear\_Ride\_Height\_Offset - Front\_Ride\_Height) \,/\, (WheelBase + X\_RH\_Rear\_BehindRearAxle - X\_RH\_Front\_BehindFrontAxle))$$

$$Front\_Aero\_Ride\_Height = Front\_Ride\_Height - X\_RH\_Front\_BehindFrontAxle * Sin(Body\_Pitch\_Angle)$$

$$Rear\_Ride\_Height = HR\_Rear\_Height + Rear\_Ride\_Height\_Offest$$

$$\mathit{Rear\_Aero\_Ride\_Height} = \mathit{Rear\_Ride\_Height} + \mathit{X\_RH\_Rear\_BehindRearAxle} * \mathit{Sin}(\mathit{Body\_Pitch\_Angle})$$

Frontal Area

The first step in the analysis of the data was to determine the frontal area of the vehicle. The front area of the vehicle provides a reference for expressing the aerodynamic loads as dimensionless coefficients. A frontal area of 2.04 m2 was calculated using the simple approximation shown in Figure 1. The RV4 wheel position sensors were not included in the aerodynamic testing due to the additional drag they would generate.

Constant speed testing

Constant speed runs were made at 3 different speeds, 100, 150 and 200 Km/h. The tests were performed in both directions to assess the effects of any wind at the track.

Figure 2 shows the track speed measured by the ADMA and the air speed measured by the pitot tube down the straight. The coloured trace shows the car travelling in one direction the black trace is the car travellling in the opposite direction. We can see the track speed shows a difference of around 0.2m/s between the two traces indicating the track speed is very similar. There is however a difference of around 3 m/s between the two pitot tube measurements. This indicates that there is a small amount of wind at the track. We can also see an offset between the track speed and the airspeed. This is most likely because the pitot tube is not perfectly aligned with the local flow.

Figure 3 shows total downforce vs track speed. We can see that there is a difference between the two runs made in each direction. This error is due to the wind speed seen in Figure 2. It should be noted that these results are not pure downforce figures but are the vertical load measured at the wheel therefore they include the contribution of the pitching moment created by the drag.

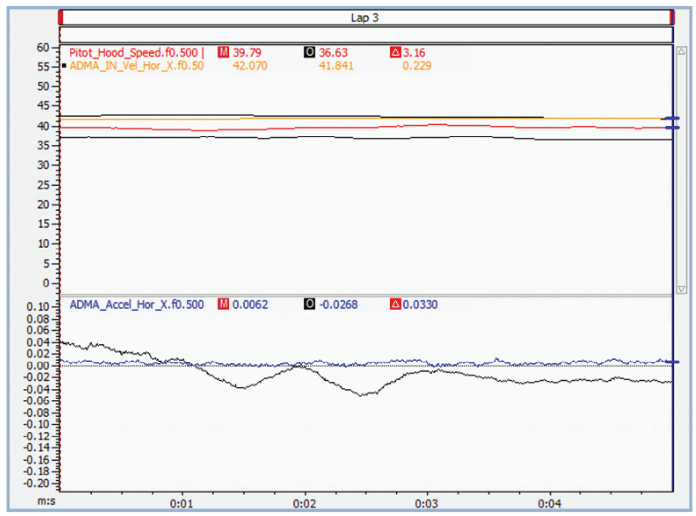

Figure 2: Pitot Tube Airspeed & ADMA Track Speed on Straight

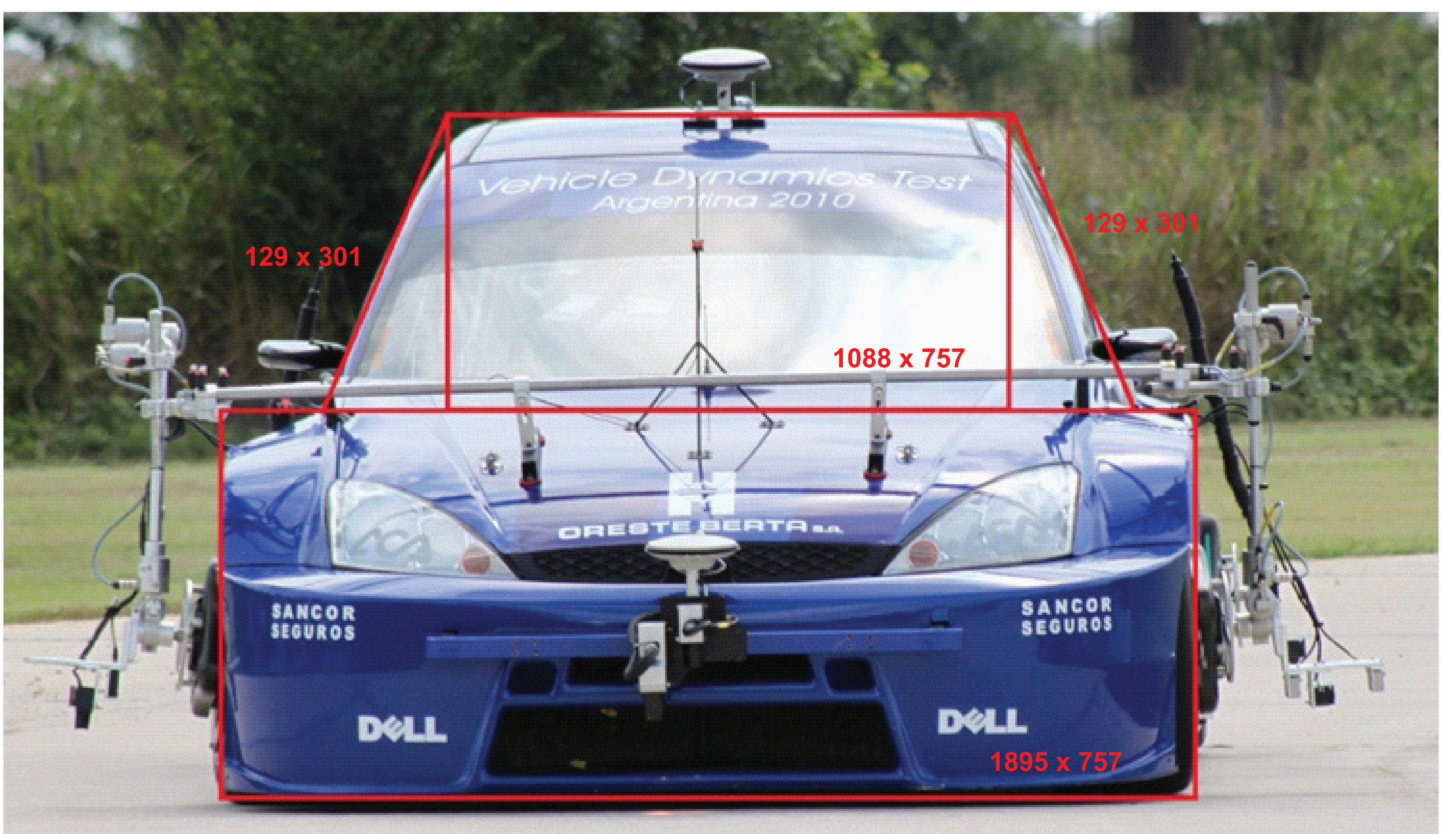

Figure 1: Frontal Area Calculation

When we plot the results against the air speed measured by the pitot tube we can remove the error due to any headwind. Figure 4 shows the total downforce plotted against the dynamic pressure to give a linear trend. This shows the importance of using a pitot tube to measure airspeed when aerodynamic testing as using track speed can produce misleading results. The results are fairly linear as we would expect indicating that there is little variation in the coefficient of lift over the range of speeds tested. The coefficient of lift is fairly constant at around -1.09.

We can analyse the vertical load front and rear to assess the aerodynamic balance of the vehicle. Figure 5 shows the majority of the load is on the front track of the vehicle. An interesting feature of the plot is the drop in downforce at the rear of the vehicle at speeds above 200km/h. There is also a corresponding increase in downforce at the front indicating that the centre of pressure has shifted towards the front of the car. This could be an indication that the rear wing is beginning to stall. More data would be required to verify if this is the case but with a high angle of incidence (12 degrees) combined with the local flow vector due to the curvature of the rear windscreen of the vehicle it is a possibility. It may also be that the increase in total aerodynamic load has lowered the front splitter height thus increasing the efficiency of the splitter and moving the centre of pressure towards the front of the car.

The aerodynamic balance of the car can be calculated from the front and rear vertical loads. The trace on the left in Figure 6 indicates the aerodynamic balance of the vehicle along the straight. The plot on the right shows the percentage of aerodynamic load on the front plotted against dynamic pressure and coloured by speed. The data shows a large amount of variation within each run however the balance stays fairly constant at around 75% over the range of speeds tested.

By measuring the torque applied to the front wheels with the wheel force transducers we can also make an estimation of the drag on the car. An estimation of the rolling resistance is required to get realistic drag figures. This was determined using coast down testing as described in the next section of this report. The force measured at the front wheels already takes the rolling resistance of the front wheels into account. Thus the rolling resistance of the rear wheels was calculated from the rear wheel force transducer data and subtracted from the driving force. Once again the drag vs dynamic pressure plot as illustrated in Figure 7 is close to linear indicating that the coefficient of drag is varying little with speed. The drag coefficient is near constant at 0.546.

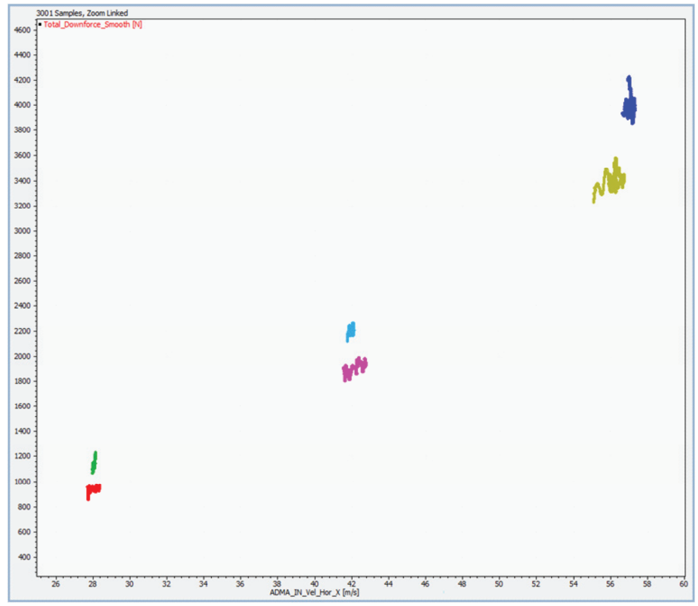

Figure 3: Total Downforce vs Track Speed

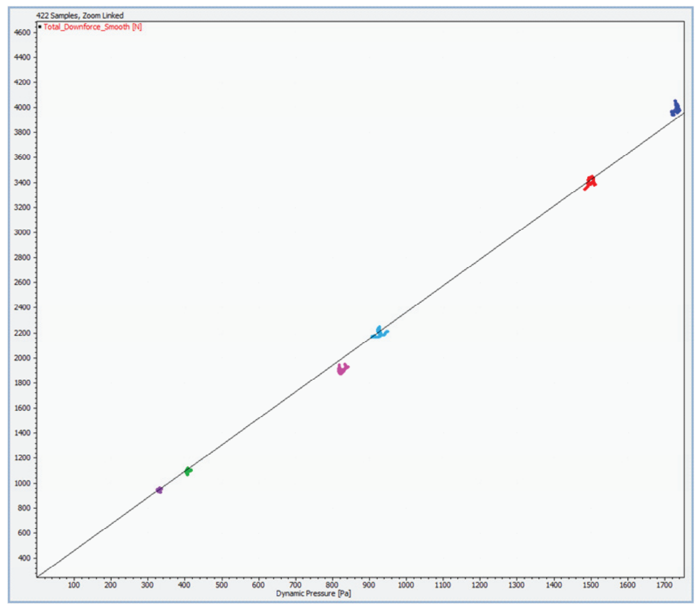

Figure 4: Total Downforce vs Dynamic Pressure

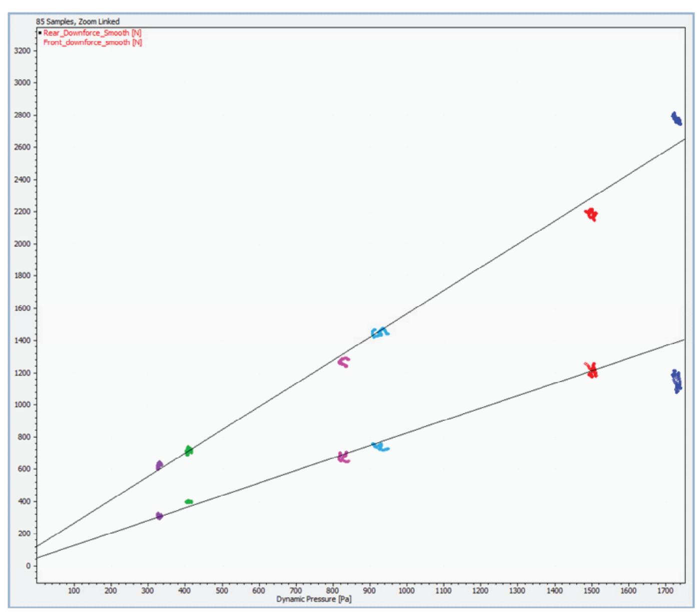

Figure 5: Front & Rear Downforce vs Dynamic Pressure

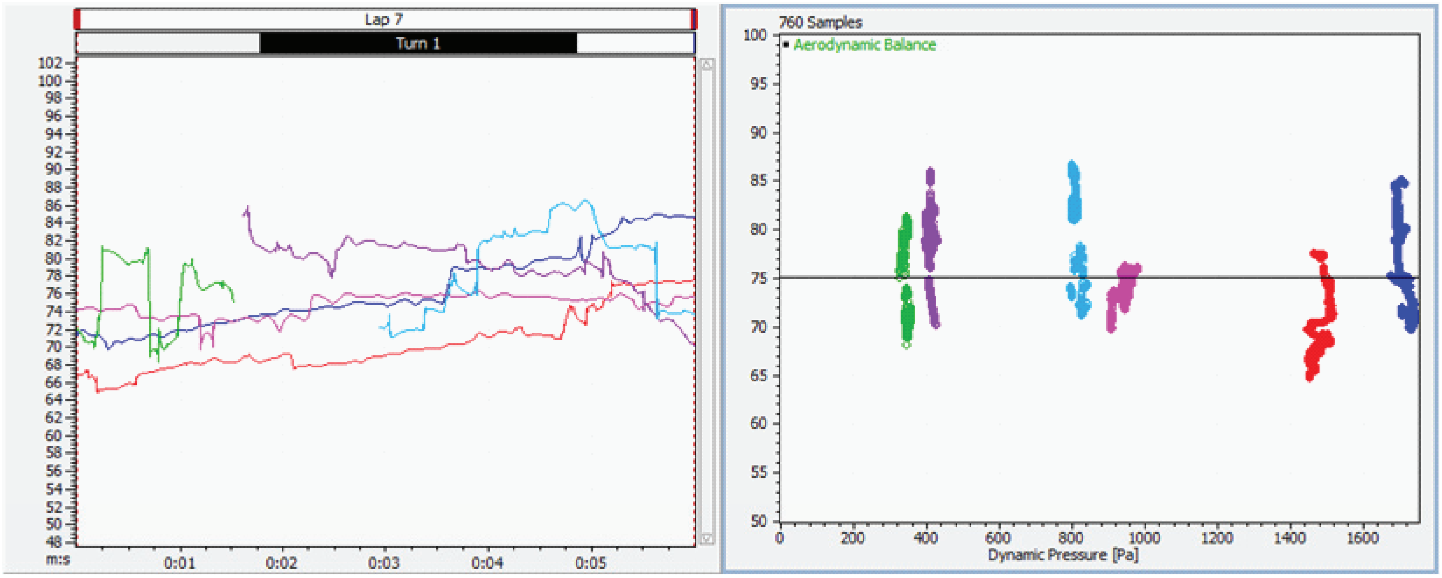

Figure 6: Aerodynamic Balance

Coast down testing

The first step in the coast down testing was to estimate the rolling resistance of the vehicle. To do this a series of low speed coast down tests were performed. The estimation of rolling resistance is based on the assumption that the aerodynamic forces on the car are negligible below 40km/h.

The speed was measured using the ADMA longitudinal speed for the low speed tests as the pitot tube was not accurate below 40km/h. Ideally we should do multiple tests to verify the accuracy of these results however the brake pedal was being dragged in the other low speed coast down tests so only two low speed coast down tests provided reliable data.

Two methods were used to approximate the rolling resistance. The first method shown in Figure 8 estimates the rolling resistance based on the vehicle deceleration as logged by the ADMA inertial measurement unit. The second method shown in Figure 9 calculates the rolling resistance from the longitudinal force logged by the wheel force transducers.

There was not sufficient data to fit a more sophisticated model for rolling resistance to the data, therefore a simple constant approximation for the rolling resistance was used. The rolling resistance was found to be 156N based on the ADMA data and 122N based on the wheel force transducer data.

Figure 8: Fx vs Speed (Coast Down)

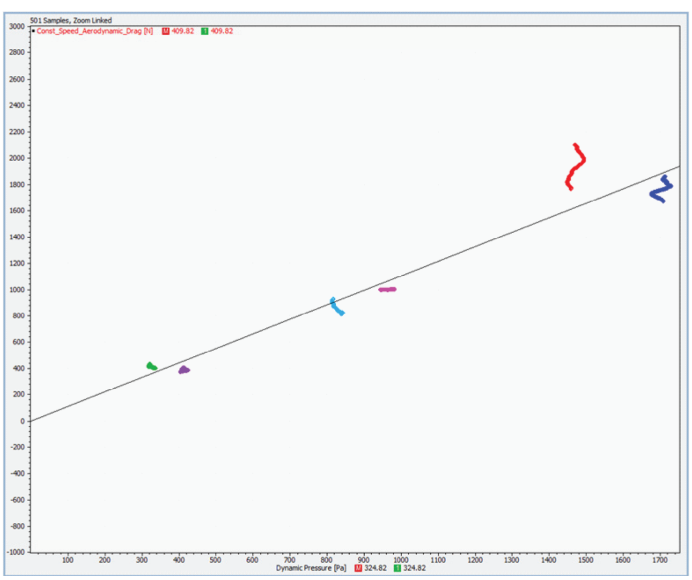

Figure 7: Aerodynamic Drag vs Dynamic Pressure

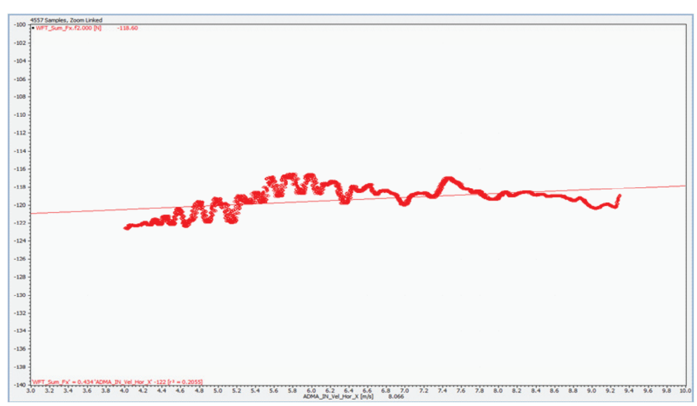

Figure 9: Wheel Force Transducer Fx vs Speed (Coast Down)

Figure 10 and Figure 11 show the total drag force minus the inertial force of the rotating components and vehicle mass in purple. The rolling resistance estimate is shown in orange. Subtracting the rolling resistance from the total drag force gives the aerodynamic drag shown in green. The coast down drag indicates a drag coefficient around 0.468 using the ADMA estimate of rolling resistance and 0.569 using the WFT estimate.

The effect of approximating the rolling resistance as a constant is to shift the drag curve vertically so the gradient remains the same. If we assume that the drag coefficient does not vary significantly with speed the theoretical drag vs dynamic pressure line should pass through zero. This suggests that the WFTs provided a closer approximation of the rolling resistance.

Figure 10: Coast Down Drag vs Dynamic Pressure (ADMA Rolling Resistance Estimate)

Figure 11: Coast Down Drag vs Dynamic Pressure (WFT Rolling Resistance Estimate)

Conclusion

Using data from wheel force transducers an ADMA inertial measurement unit and pitot tube we were able to quantify the on track aerodynamic performance of the vehicle.

The coefficient of lift was determined from constant speed testing. Drag figures were determined from both constant speed and coast down testing. The aerodynamic balance was found to be approximately 75% of the aerodynamic load on the front track.

Suggestions for further tests

The approximation of rolling resistance as constant is not an accurate approximation. A greater number of coast down tests need to be performed to get a larger number of samples to fit a rolling resistance curve.

It would also be useful to repeat the constant speed tests at a range of ride heights to assess the effects of ride height and pitch on the vehicle aerodynamics.

The results of this test would provide a useful comparison to future CFD or wind tunnel tests.

	CL	CD	-L/D	% Front
Constant Speed	-1.09	0.546	2.00	75%
Coast Down (WFT Rolling Resistance)		0.569	1.92	
Coast Down (ADMA Rolling Resistance)		0.468	2.33	