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Rolling Road versus Non-Rolling Road Effects on Air Flow Quality

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ABSTRACT

As the world becomes more and more interested in automotive efficiencies, fuel efficiency becomes a priority and has now been established as a key governmentally regulated parameter for vehicles being sold in different countries. At highway speeds (ie 50mph – 70mph), vehicle aerodynamic drag plays a much more significant role than vehicle mechanical drag when it comes to improving fuel efficiency. Therefore, reducing a vehicle's aerodynamic drag will directly correlate to improving the vehicle's fuel economy. This makes improving a vehicle's aerodynamic drag increasingly important for future automotive sales.

Automotive aerodynamic development began with testing on a track and developing on the road. This presented an issue with not being able to control many variables that affect this type of testing (ambient conditions, cross winds, drivers, tire degradation etc.). For more precise automotive aerodynamic development, fixed floor wind tunnels were used. These types of tunnels allowed designers to limit most of the variables that were uncontrollable with real world testing, however, the wheels did not rotate and the floor remained stationary under the vehicle. The next step in physical aerodynamic testing of automobiles is the "Rolling Road" wind tunnel. A "Rolling Road" wind tunnel allows the designer the ability to control all variables and mimic real world conditions.

The need for further understanding of the benefits of using a Rolling Road wind tunnel for the development of automotive aerodynamics has led to a series of three technical papers: "Rolling Road Versus Non-Rolling Road Effects on Air Flow Quality;" "Rotating Wheel and Moving Ground Effects on A Sedan Type Vehicle;" "Upper Body and Internal Air Flow Effects on a Sedan Type Vehicle With Rotating Wheels and Moving Ground." The intent of these papers is to show the reasoning behind the need for using Rolling Road wind tunnels to develop vehicle aerodynamics.

To achieve the best results with wind tunnel testing, the air flow quality in the working section of a wind tunnel must be optimal. Moving ground plane or 'Rolling Road' tunnels are fast becoming the standard tool for automotive wind tunnel testing because the rotation of the wheels coupled with the road moving beneath the vehicle offers a much more realistic modeling of the real world and accounts for the proper drag over a vehicle compared with a fixed floor wind tunnel and non-rotating vehicle wheels. A key component in all vehicle wind tunnel testing is the elimination or control of the boundary layer.

In this study pressure data was measured using a pitot tube above a moving ground plane and a stationary ground plane with both boundary layer suction on and off at varying air velocities. A four stage boundary layer suction system was utilized for all of this testing. The boundary layer profiles for each case were measured, and the displacement thicknesses calculated, to illustrate the effects on air flow quality.

SUMMARY

The data taken during this test shows that a moving ground plane gives a more accurate representation of the true interactions between the air and ground. The best results in terms of both boundary layer profile and displacement thickness are seen with the use of boundary layer suction and a moving ground plane. These are shown clearly in *figures 1 & 9*. It is also seen that flow quality is maintained throughout the 'test section' of the tunnel (*figure 8*), a key factor in ensuring repeatability in testing.

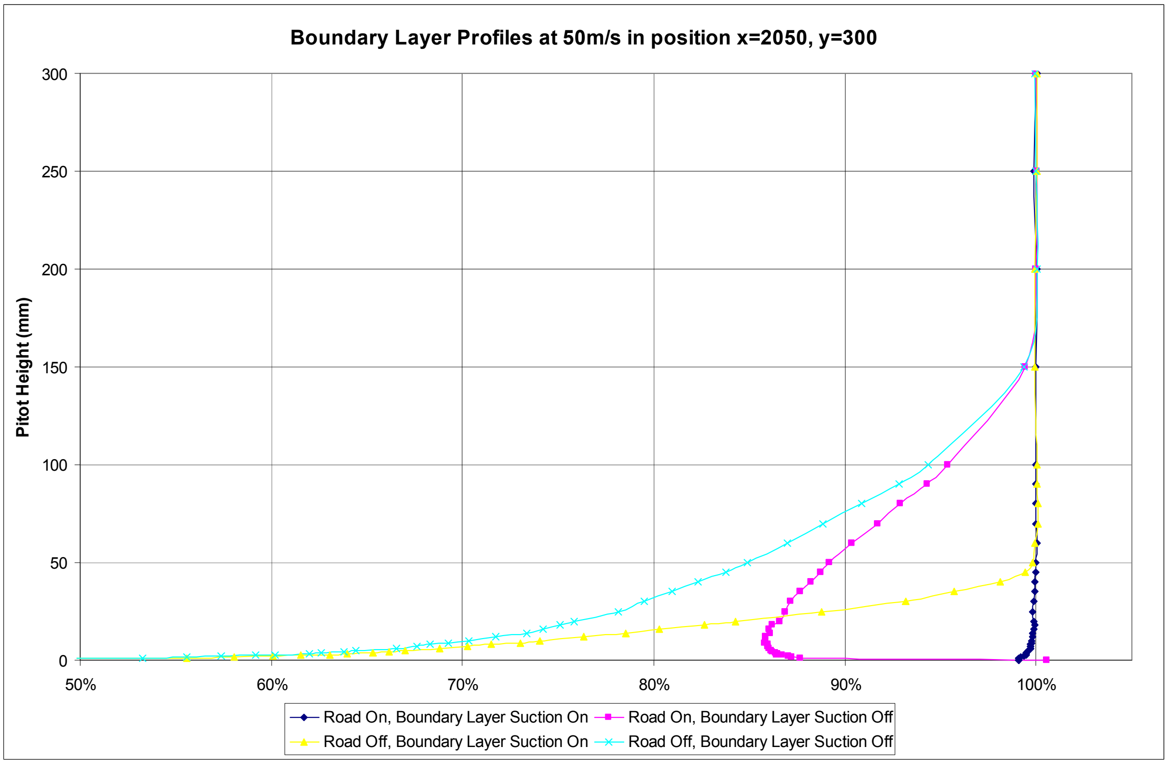

Figure 1: Boundary layer profiles measured at position x=2050, y=300 for each case at 50m/s.

INTRODUCTION

The interactions between vehicle and ground plane in wind tunnel testing have become increasingly important with the aerodynamic demands forced upon the automotive industry through regulation and rising fuel prices. However, much automotive development has been based upon misleading results provided by the use of stationary ground plane wind tunnels. There is a large body of research showing advances in wind tunnel technology and the associated effects on results. For example, Elofsson et al [5] noted differences in drag at the wheel housings and the rear of the car, pointing out that stationary ground plane and wheels do not correctly simulate the rear wheel and wheel housing interference with the base wake.

There are two basic types of wind tunnels, open and closed circuit. The test section of the tunnel can be of varying design with the three types being open jet, closed jet and slotted wall. The wind tunnel at the Auto Research Center incorporates a closed circuit, single return design with a ¾ open jet and moving ground plane working section with boundary layer suction, as shown in *figure 3*. A scale vehicle model is mounted on a force balance which is in turn mounted under a sting.

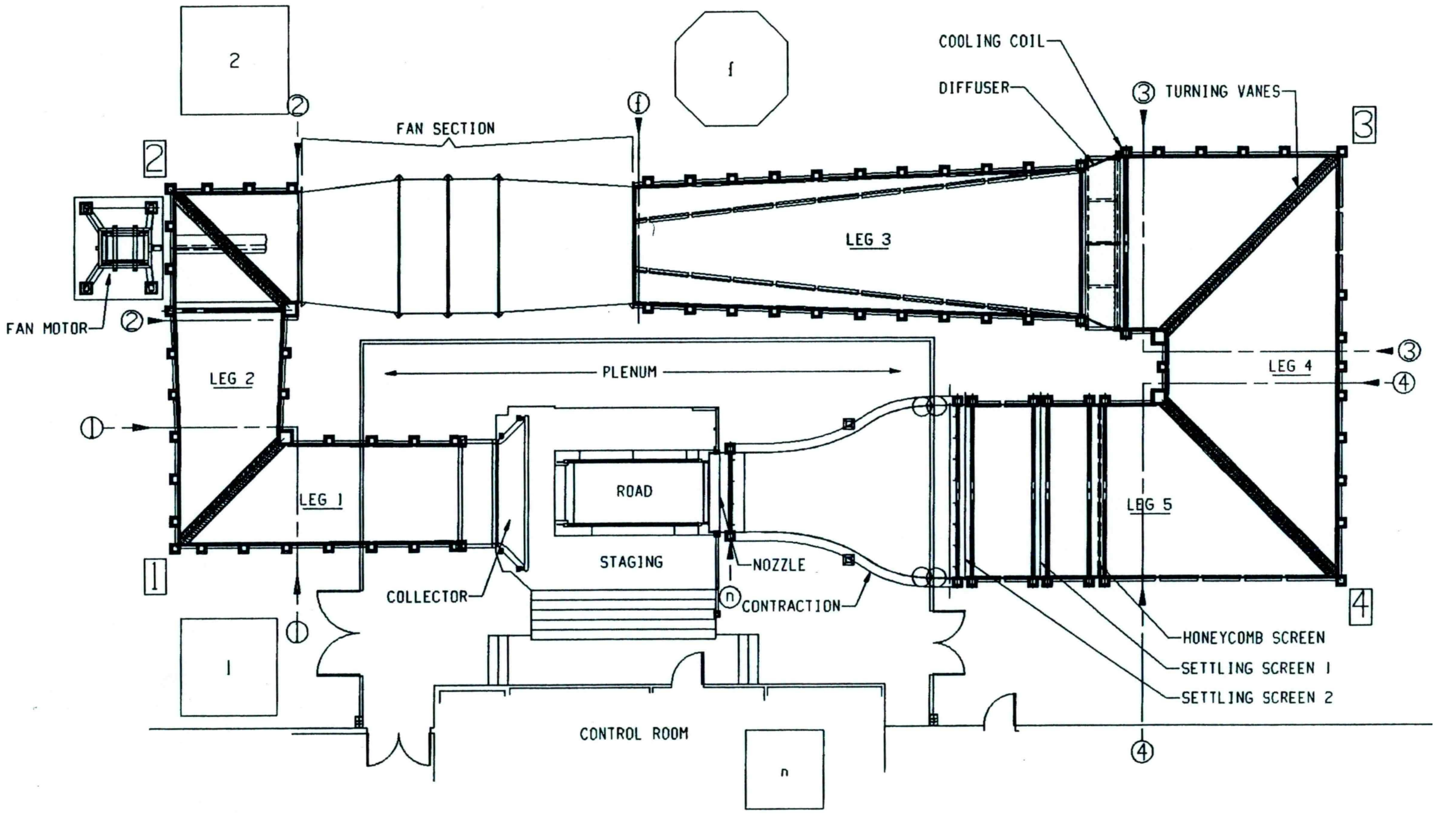

Figure 3: Schematic diagram of the ARC wind tunnel. *Source ARC*

The working section of a traditional stationary wind tunnel is structured around a fixed floor design, with force measurements being taken through a floor balance. Flow along any stationary surface will result in a diminishing flow velocity near the surface called a boundary layer. Boundary layer suction is one development that can be applied to reduce this effect, but it cannot completely eliminate it. Using a rolling road combined with boundary layer suction gives the best possible flow quality in terms of boundary layer profile (shown in *figure 4c*) since the road is moving at the same velocity as the free stream air. The change in velocity near the road surface is minimal, which also results in a reduced displacement thickness and reduced momentum loss.

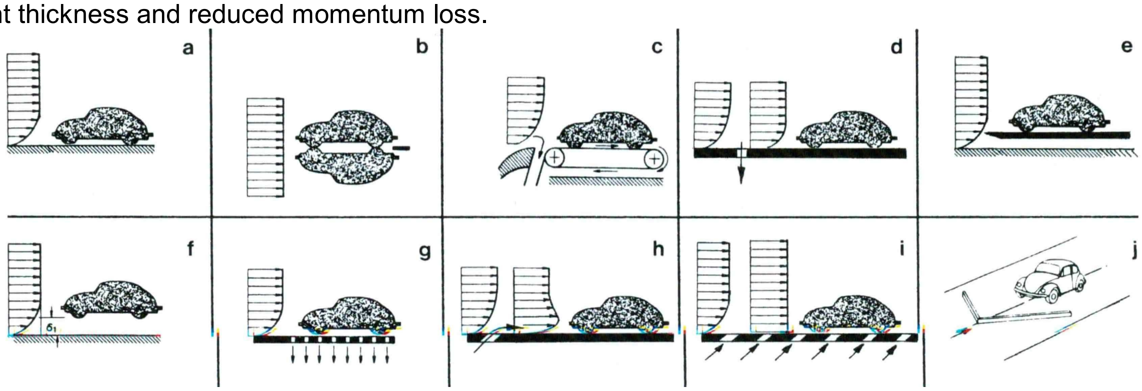

Figure 4, a-j: Varying forms of boundary layer control. *Source* [1]

A minimized boundary layer profile is always important; not only for low ride height cars or small scale models, but because the wheel contact with the road surface has an effect on the aerodynamics. This will be looked into in more detail in the following technical papers.

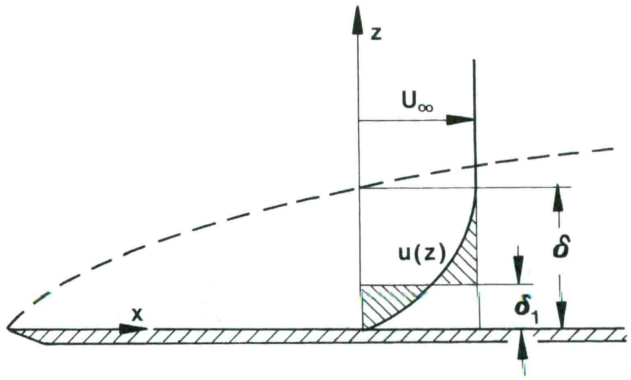

Figure 5: The boundary layer profile. *Source* [1]

The definition of the boundary layer thickness is the height at which the velocity is found to be 99% of the free stream velocity shown as δ in *figure 5*: [1]

$$\delta = u(y) = 0.99U_{\infty}$$

The boundary layer displacement thickness is the distance the surface is offset in order to maintain the same mass flow as seen between the surface and a reference plane, shown as δ_1 in *figure 5*. This is mathematically defined as: [1]

$$\delta_1 = \int_0^{\infty} \left(1 - \frac{u}{U_{\infty}}\right) dz$$

In this study the trapezoidal numerical method was used to calculate δ_1 : [8]

$$\int_{z1}^{z2} f(z)dz = dz\left[\frac{1}{2}f_1 + \frac{1}{2}f_2\right]$$

$$\therefore \delta_1 = \sum\left(dz\left[\frac{1}{2}f_n + \frac{1}{2}f_{n+1}\right]\right)$$

EXPERIMENTAL SETUP

This test was undertaken by the Auto Research Center at their wind tunnel facility in Indianapolis, Indiana USA. The ARC wind tunnel utilizes a contraction ratio of 4.8 to 1, rolling road matching air test speeds to +/- 0.1 m/s in a temperature controlled environment of +/- 0.2 degrees Celsius. Tests were conducted at varying wind and road speed of between 20 and 50m/s (constant dynamic pressure). The turbulence intensity is 0.11% and flow angularity is within 0.2°. The moving ground plane size is 3.4m long by 1.66m wide. The testing apparatus constituted a single pitot tube suspended via an overhead support strut in the test section. Previous wind tunnel calibration data has shown the calibration boundary layer rake repeats closely to the single pitot tube used in this study.

In addition to the pressure measurements recorded, dynamic pressure was calculated / recorded via a pitot static tube located just forward of the strut at constant height. Ambient pressures were recorded outside the working section, along with a series of reference pressures, or static rings, located in the nozzle (used to control the air velocity). Ambient temperature is controlled inside the circuit and was recorded forward of the strut.

TEST PROCEDURE

Appendix I shows the matrix of the test procedure (*figure 11*) and the pressure measurement heights above the road surface for each run (*figure 12*). Measurements were recorded and processed to determine the boundary layer profile and displacement thickness. At each location in the working section, pressures were recorded at 10 hertz for one second then averaged for each measurement height at zero degrees yaw. The process was repeated once per run with the increase in wind speed and road speed where applicable, by 10m/s. Runs were then duplicated with the removal of boundary layer suction, and compared between road on and road off conditions.

Figure 6 shows the test fixture mounted on the sting. The horizontal bar has 4 possible y positions for the pitot tube, 300mm being the furthest. The entire sting is moved on the supporting gantry in order to adjust the x direction. The z direction is varied during the runs by the sting itself. *Figure 7* shows the coordinate system of the working section, 0 being the knife edge above the road belt and centerline.

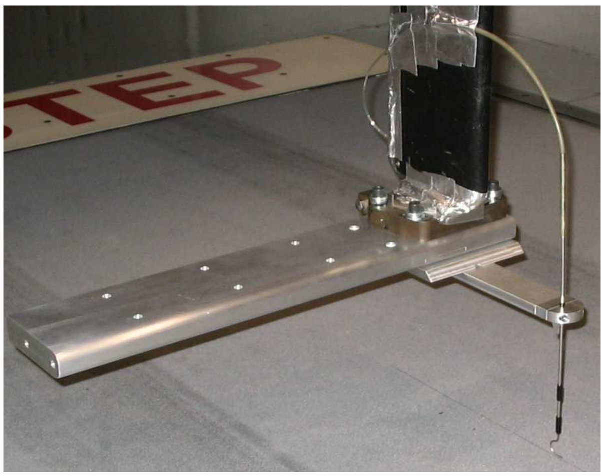

Figure 6: Pitot tube mounted on sting at position x=2050, y=0

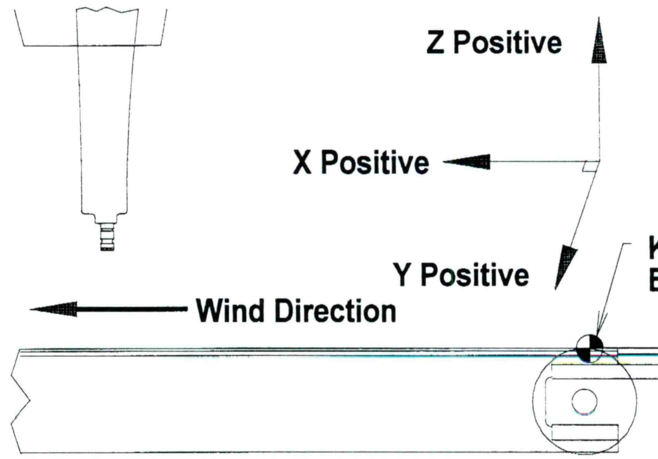

Figure 7: Working section coordinate system

RESULTS AND DISCUSSION

Shown in *figure 8* are the boundary layer profiles measured at 4 different locations in the tunnel. Only runs at 50m/s with both the road and the boundary layer suction on are compared in this graph and each shows good correlation to the others.

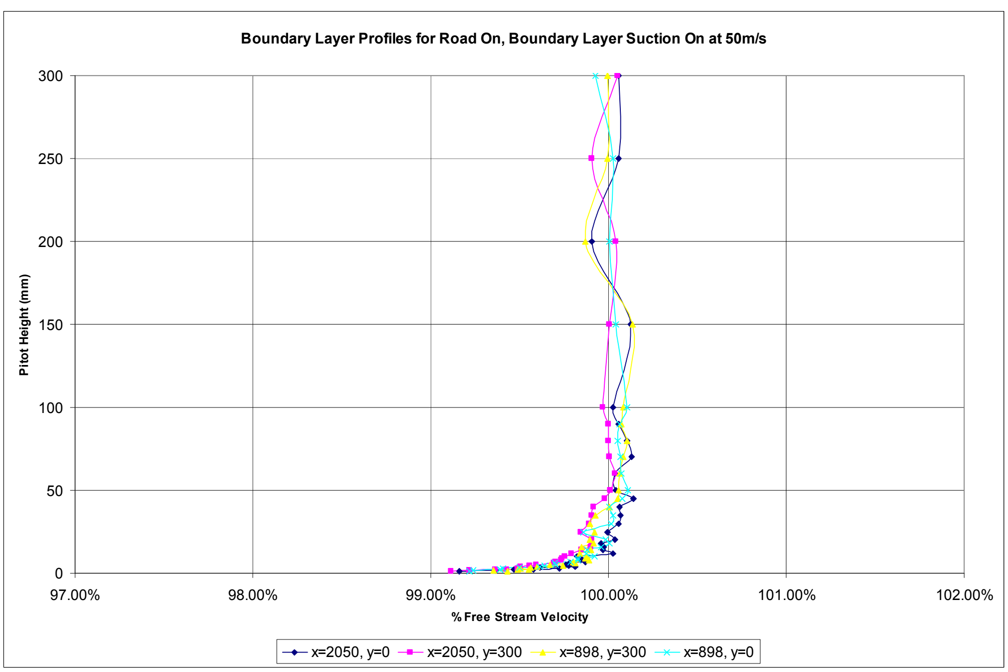

Figure 8: Boundary layer profiles at 50m/s for road on and boundary layer suction on

At 50m/s in the position x=2050, y=300 the boundary layer profiles were measured as seen in *figure 1*. The boundary layer thicknesses are shown in *figure 9* and are also tabulated in appendix II. Note that the boundary layer thickness for the case of road on and boundary layer suction on is below the lowest measurement point. The limits of the measurement equipment available for this test meant that below 1mm there was a risk of the rotating belt damaging the pitot tube. This presents a challenge when looking at the results for the road on and boundary layer suction on case since the boundary layer profile is extremely small.

The percentage of free stream velocity measured at 1mm above the road surface was 99.11%; therefore, the value of 1mm is used as δ for these cases. Although this introduces a deliberate error it avoids an unquantifiable error through extrapolating the value since:

- It would assume the trend of reduction in velocity nearer the road surface will continue. This is a fundamentally incorrect assumption since the case of 'road on and boundary layer suction off' shows an increase in air velocity nearer the moving road surface; we would expect the same trend in this unmeasured region.
- It would assume the previous two data points at 1mm and 1.5mm are accurate measurements and not subject to error themselves. Although it should be noted these two data points correlate well with the same data points for similar runs.

For the other cases a linear interpolation was used to obtain the boundary layer thicknesses at 99% free stream velocity. This is also subject to an error but since we know both data points surrounding the value this error would be negligible.

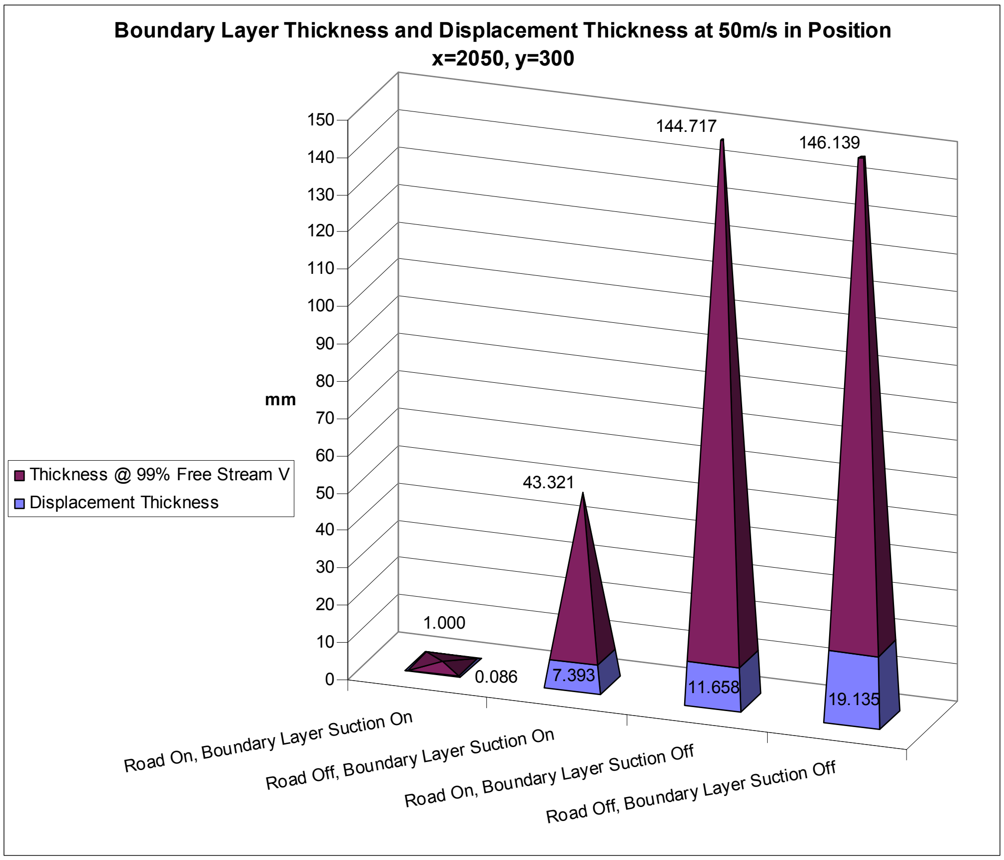

Figure 9: Boundary layer thicknesses and displacement thicknesses, x=2050, y=300

The boundary layer displacement thickness for the road on and boundary layer suction on cases are also subject to a similar error. In this case in order to calculate the displacement between 0 and ∞ we have to assume a velocity for the 0mm pitot height. We know that the value will be equal to that of the road surface velocity; however, the scale of the profile curve in these cases is small so a straight line drawn between 1mm and 0mm will cause a large error in comparison with the rest of the curve. To avoid this, the last measured velocity at 1mm is assumed the same as the 0mm velocity.

With both road off cases the 0mm pitot height air velocity can be assumed to be 0m/s and, since the profile curves are large, there is little error in drawing a straight line between the 1mm point and the 0 point. The road on, boundary layer off cases also have a sufficiently large boundary layer profile that a straight line can be drawn between the 1mm point and the road surface velocity at the 0mm pitot height without a significant loss of accuracy.

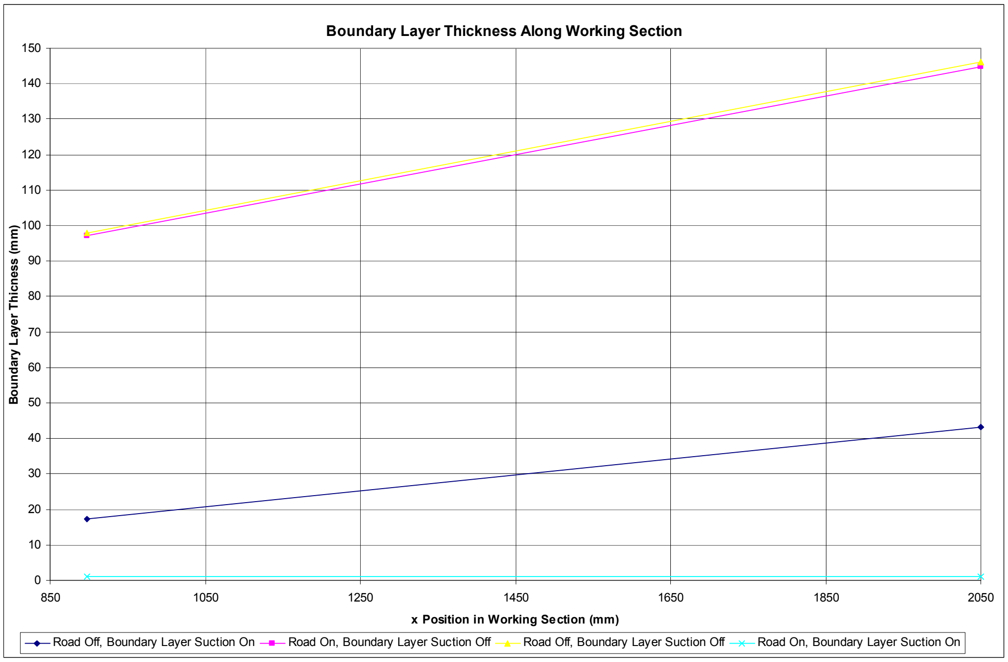

Figure 10: Boundary layer thicknesses at y=300 and varying x

Throughout the length of the working section the boundary layer can be expected to grow. *Figure 10* shows this with lower values for boundary layer height at 99% free stream velocity. The only exception to this is the road on and boundary layer suction case where the 99% free stream velocity value is also below the lowest measurement point. In this case at 1mm above the road surface the percentage of free stream velocity was 99.43% which suggests the 99% free stream velocity value will be lower than that of the previous case. Plots of the boundary layer profiles for each case at the different x positions can be seen in Appendix II.

CONCLUSIONS

A fixed floor tunnel without a boundary layer control system has the largest boundary layer in the test section. The addition of a boundary layer suction system to the fixed floor tunnel reduced the boundary layer thickness by 70.4%. Adding the boundary layer suction system to the rolling road tunnel reduced the boundary layer thickness by 99.0%. Comparing the road on with boundary layer suction to the road off with boundary layer suction showed that the road on with boundary layer suction had a reduced boundary layer thickness by 97.7%.

Adding boundary layer suction to the road off tunnel reduced the displacement thickness by 61.4%. Adding the boundary layer suction system to the road on tunnel reduced the displacement thickness by 99.3%. Comparing the road on with boundary layer suction to the road off with boundary layer suction showed that the road on with boundary layer suction had a reduced displacement thickness by 98.8%.

The addition of a rolling road surface and boundary layer suction significantly improves the boundary layer profile and displacement thickness in the working section of a wind tunnel.

This allows vehicles to be tested with confidence in the results obtained. In all of the cases with road on and boundary layer suction on, the height of the boundary layer at 99% free stream velocity was found to be less than 1mm. With this the boundary layer displacement thickness was found to be less than 0.1mm.

These results clearly show that the optimal method for removing or reducing the boundary layer is through a combination of boundary layer suction and rolling road. Based on this, a rolling road wind tunnel is much more accurate than a fixed floor tunnel for the purposes of evaluating vehicle aerodynamics.

APPENDIX I

Test matrix:

RUN #	X POSITION mm	Y POSITION mm	ROAD on/off	B/L SUCTION on/off	FLOW VELOCITY A m/s	FLOW VELOCITY B m/s
1	2050	0	ON	ON	20	30
2	2050	0	ON	ON	40	50
3	2050	0	ON	OFF	20	30
4	2050	0	ON	OFF	40	50
5	2050	0	OFF	ON	20	30
6	2050	0	OFF	ON	40	50
7	2050	0	OFF	OFF	20	30
8	2050	0	OFF	OFF	40	50
9	2050	300	ON	ON	20	30
10	2050	300	ON	ON	40	50
11	2050	300	ON	OFF	20	30
12	2050	300	ON	OFF	40	50
13	2050	300	OFF	ON	20	30
14	2050	300	OFF	ON	40	50
15	2050	300	OFF	OFF	20	30
16	2050	300	OFF	OFF	40	50
17	898	300	ON	ON	20	30
18	898	300	ON	ON	40	50
19	898	300	ON	OFF	20	30
20	898	300	ON	OFF	40	50
21	898	300	OFF	ON	20	30
22	898	300	OFF	ON	40	50
23	898	300	OFF	OFF	20	30
24	898	300	OFF	OFF	40	50
25	898	0	ON	ON	20	30
26	898	0	ON	ON	40	50
27	898	0	ON	OFF	20	30
28	898	0	ON	OFF	40	50
29	898	0	OFF	ON	20	30
30	898	0	OFF	ON	40	50
31	898	0	OFF	OFF	20	30
32	898	0	OFF	OFF	40	50

Figure 11: Test Matrix

Pressure measurement heights above road surface (in mm) for each run:

300	16
250	14
200	12
150	10
100	9
90	8
80	7
70	6
60	5
50	4.5
45	4
40	3.5
35	3
30	2.5
25	2
20	1.5
18	1

Figure 12: Pressure measurement heights

APPENDIX II

50m/s Position x=2050, y=300	δ @ $0.99U_{\infty}$	δ_1
Road On, Boundary Layer Suction On	1.00 (99.11)*	0.086
Road Off, Boundary Layer Suction On	43.321	7.393
Road On, Boundary Layer Suction Off	144.717	11.658
Road Off, Boundary Layer Suction Off	146.139	19.135

Figure13: Results for 50m/s at position x=2050, y=300

50m/s Position x=898, y=300	δ @ $0.99U_{\infty}$	δ_1
Road On, Boundary Layer Suction On	1.00 (99.43)*	0.0597
Road Off, Boundary Layer Suction On	17.254	3.314
Road On, Boundary Layer Suction Off	97.128	11.717
Road Off, Boundary Layer Suction Off	97.975	14.808

Figure 14: Results for 50m/s at position x=898, y=300

Note*: δ @ $0.99U_{\infty}$ below measured values, percentage of free stream velocity (in brackets) at 1mm shown instead.

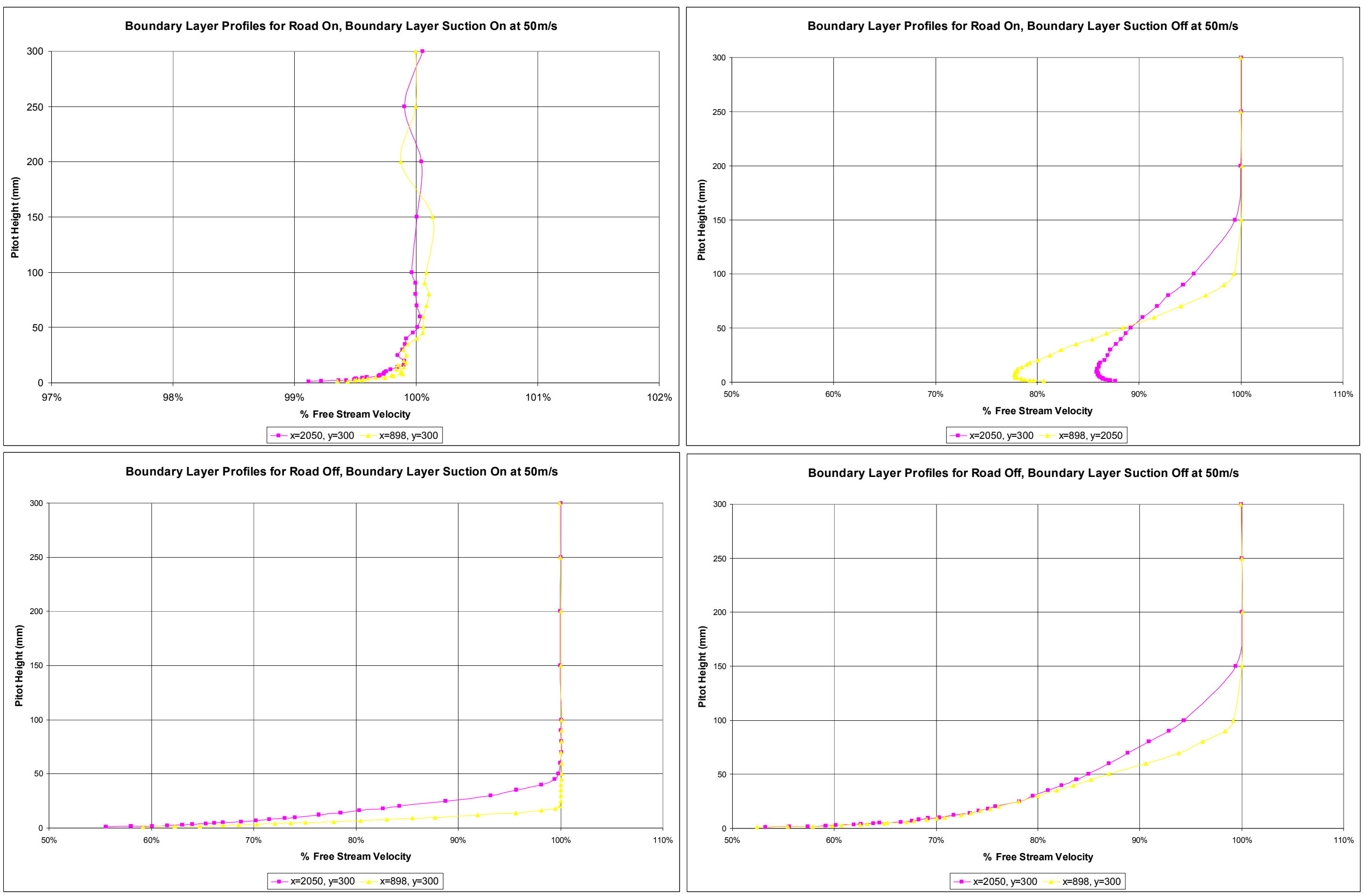

Figure 15 a-d: Boundary Layer Profile variance between x=2050 and x=898.

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