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**Experimental Investigation of Slotted Wall Wind Tunnel
Test Sections for Low Interference Road Vehicle Testing**

by

Cabot A. Broughton

B.Eng., Carleton University, 1987

**A thesis submitted to the faculty of Graduate
Studies and Research in partial fulfillment
of the requirements for the degree of**

Master of Engineering

**Department of
Mechanical and Aerospace Engineering
Carleton University
Ottawa, Ontario
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Acceptance Sheet

The undersigned recommends to the Faculty of Graduate Studies and Research, acceptance of the thesis: *Experimental Investigation of Slotted Wall Wind Tunnel Test Sections for Low Interference Road Vehicle Testing*, submitted by Cabot Broughton, in partial fulfillment of the Degree of Master of Engineering

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Abstract

Low cost high quality full scale aerodynamic data for typical present day road vehicles is not available from conventional wind tunnels using solid wall test sections.

An experimental investigation of the wall interference levels of a slotted wall wind tunnel test section using three different shaped models which produced flow fields similar to those of typical road vehicles was undertaken. Wall blockage interference was determined by measuring and comparing the drag coefficients, base pressure coefficients and the groundplane pressure signatures of the five model scales for each model shape. Influence of the wall OAR on the data is also presented and demonstrates that for a properly configured test section virtually interference free measurements can be achieved passively for even models of extreme area blockage.

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List of Symbols

A	Area
C_D	Drag Coefficient Based on S
C_p	Pressure Coefficient
d_h	Hydraulic Diameter
H, h	Height
K_1	Dynamic Pressure Calibration Factor
K_2	Static Pressure Calibration Factor
L, l	Length
OAR	Open Area Ratio
P	Pressure Reading
q	Dynamic Pressure
r	Model Front Edge Radius
Re	Reynolds Number
S	Reference Area
w	Width
W	Measurement Uncertainty
X	Axial Distance
z	Axial Distance on the Groundplane from Front Face of the Model (Positive Upstream)
δ	Groundplane Boundary Layer Displacement Thickness

Subscripts:

∞	Free Stream Conditions
o	Stagnation Conditions
b	Base
$c1$	Upstream Contraction Pressure Tap
$c2$	Downstream Contraction Pressure Tap
f	Front Face
gc	Ground Clearance
m	Model
mmp	Model Midpoint
p	Flat Plate
ref	Reference
ts	Test section

Chapter 1

Introduction

The need for accurate aerodynamic data for ground vehicles is a relatively recent development. This aerodynamic data is required to enable vehicle designers to assess the effect of major and minor changes to existing and proposed vehicle shapes. Drag data has generally been the principal aerodynamic parameter investigated as this parameter dictates the high speed power requirement and fuel consumption rate. For example, a typical 2000 lb sedan with a C_D of 0.43 expends approximately 64% of the total power required to maintain 60 mph overcoming aerodynamic drag. Knowledge of other aerodynamic quantities such as lift, pitching moment, side force, and rolling moment are needed to improve vehicle handling and safety levels, particularly under side wind conditions at freeway speeds.

To obtain this much needed data in a cost effective way the ground vehicle design engineers turned to the wind tunnel facilities previously used for aircraft testing. Although by the time vehicle designers became interested in aerodynamics, wind tunnel testing of aircraft models had been brought to a level of accuracy of about 0.1% (W.H. Rae and A. Pope (1984)) on all aerodynamic coefficients, existing wind tunnels and test procedures could not provide the road vehicle design engineers with nearly as reliable data. Evidence of the above is found in

wind tunnel studies by K.R. Cooper (1982), R. Bucheim et al (1983), A. Cogotti et al (1980), and others where aerodynamic data for a given vehicle model from different wind tunnel facilities are compared.

There are several reasons why existing wind tunnels could not deliver better accuracy. If one compares the simulation requirement differences between aircraft and road vehicle testing one can understand why this significant deterioration in accuracy occurred. Ground vehicle testing unlike most aircraft testing requires the simulation of a groundplane which is in contact with the vehicle. For no-wind driving conditions this groundplane has no relative motion between it and the free stream air. Thus the use of the wind tunnel floor or of a groundplane as the boundary is necessary but an imperfect simulation of the real ground. Use of moving belt groundplanes is generally impractical for full scale road vehicle testing where aerodynamic loads are transmitted to the balance through the road wheels. The imperfect ground simulation produces additional data shifts in wind tunnel comparative studies due to differences in groundplane boundary layer thicknesses. The corrections required to account for this effect are difficult to quantify. Furthermore mean pitch angles of the flow referenced to the floor pose no particular problem for aircraft testing but cause problems with ground vehicle testing where pitching of the model to compensate for flow angularity produces non-equivalent underbody to ground simulation.

Additional deterioration in accuracy over that found in aircraft testing occurs in ground vehicle testing due to the differences between the typical types of shapes being tested.

The ground vehicle models tested are usually "bluff body" shapes representative of typical present day vehicles which exhibit large areas of separated flow and

hence relatively large wakes. This is in direct contrast to the necessarily streamlined aircraft shapes being tested. This change in body type introduces additional uncertainty to the measured and "corrected" data due to the poor reliability of the "bluff body" blockage correction methods used for such shapes.

Blockage corrections are corrections which have to be applied to measured wind tunnel data where the test section lateral boundaries are not equivalent to that of free air and account for the squeezing (or expansion) of the streamlines associated with the improper boundary condition around the model (solid blockage) and around the wake (wake blockage). The use of solid wall test sections tends to produce a squeezing of the streamlines while the open jet boundary produces excessive divergence. For typical aircraft tests where the models are usually sized according to the ratio of their wing span to the tunnel test section width, the ratio of the models' frontal area to tunnel area is generally quite low and the solid blockage corrections are small. Accurate estimates of these blockage correction can be made using potential flow analysis. The wake size for most aircraft is also relatively small resulting in very small to negligible wake blockage corrections.

Blockage corrections for "bluff body" shapes are much more difficult to obtain as the near field streamlines will not match the vehicle shape due to the separated regions. Wake blockage is also inherently much larger for "bluff body" shapes and is no longer negligible. Thus even at equivalent geometric blockage levels the correction factors are larger and more susceptible to errors for "bluff body" shapes as compared to streamlined shapes.

The above difficulties have resulted in several courses of action.

One method is the use of larger solid wall test sections to reduce the solid

blockage ratio to that found in aircraft testing (e.g. General Motors' 56m² solid wall test section facility) to minimize uncertainty of both solid and wake blockage correction factors. This greatly increases the initial and operating costs of an automotive wind tunnel facility as extremely large test section sizes are required if full scale road vehicle testing is desired. The initial cost and power costs (fan and cooling) of a wind tunnel vary approximately directly as the test section area (W.H. Rae and A. Pope (1984)).

Figure 1 Typical 3/4 Open Test Section

Use of 3/4 open jet wind tunnel test sections similar to Figure 1 for road vehicle testing in Europe was initiated to reduce blockage effects and enable the use of smaller wind tunnels. Test results have shown that 3/4 open jet test sections do provide less lateral boundary interference. In fact the measured data requires a correction of opposite sign to that of data obtained in solid wall test sections. Unfortunately this benefit of decreased lateral boundary interference comes at a significant cost. With the typical 3/4 open jet wind tunnel configurations used, the test sections are much too short and have diffuser collectors of too great an area as indicated by P.M. Waudby-Smith and W.J. Rainbird (1985), F.K. von Schulz-Hausmann and J.D. Vagt (1988). This results in large axial static pressure gradients, often coupled with poor flow quality, free-jet instability, and model locations which are under the strong influence of this downstream interference. Thus reduction of lateral boundary interference has been obtained with an increase of other interference effects and the overall aerodynamic accuracy is not improved as found by R. Buchheim et al (1983). The use of longer test sections with more appropriate collector sizes has been found by von Schulz-Hausmann and J.D. Vagt (1988) to greatly reduce the downstream interference but this usually results in increased free-jet instability and wind tunnel power losses.

Two new technologies being developed to reduce lateral boundary interference while maintaining other forms of interference at low levels are the adaptive wall and slotted wall test sections. Both types of test section attempt to provide a close approximation to the true free air lateral boundary condition to obtain solid and wake blockage-free data.

The adaptive wall test section uses active control of the elements of the lateral boundaries which through an iterative process are deformed until the shape and axial static pressure distributions along the walls match those of streamlines in the

free air condition. Although this strategy promises to provide very good quality data from small wind tunnels, the deformable wall system and software required to implement the system (especially for 3-D models) are very complex and expensive. At this point in time no full scale wind tunnels incorporating this principle have been built.

The slotted wall test section concept shown in Figure 2 was based on the obser-

Figure 2 Slotted Wall Type Test Section.

vation that blockage correction factors for open jet and solid wall test sections are of opposite sign. Thus it was thought that a boundary made up of a combination of open and solid wall boundary conditions would provide, on average, the same overall boundary condition as free air. This concept would then enable a wide

range of vehicle shapes to be tested at low blockage interference levels using a passive system. The difficulties associated with many of the 3/4 open jet test sections are avoided due to the stabilizing effect of the solid portions of the wall which permit longer test section lengths while maintaining flow quality similar to that of the best solid wall test sections. A number of full scale automotive wind tunnels incorporating slotted walls have, (in recent years) been built (see L.U Nilsson and A. Berndtsson (1987) and J.D. Vagt and B. Wolff (1987)).

1.1 Present Experimental Program

This thesis investigates blockage effects in road vehicle aerodynamic testing and reports on the experimental findings obtained from an existing small closed circuit wind tunnel which was modified to accept a slotted wall type test section. The test section was designed to be an approximate 1/9th scale version of the full scale Porsche wind tunnel test section. With this design of test section one is able to alter the slotted wall "openness" or open area ratio (OAR) and the collector flap setting. Three models of simple geometric shape were chosen for the study. The shapes chosen have drag coefficients which span the probable range anticipated for road vehicles. Each model shape was produced at five different scales to achieve a wide range of solid blockage levels in the slotted wall test section.

The present test program was undertaken to gain additional understanding of the slotted wall boundary condition and the effect of varying model size and shape on the level of blockage interference.

Several tests were made with different slotted wall boundary conditions. This was done to determine whether a more open boundary condition would produce

closer to free air conditions for the larger models.

The test section itself was designed to minimize other boundary interference effects so that the lateral boundary interference would be the primary cause of any measured changes. The parameters used to assess the degree of blockage effect were the measured drag coefficient, the model base pressure coefficient, the groundplane and ceiling slat pressure distributions, and the model vehicle surface pressures.

Chapter 2

Previous Work

Over the history of wind tunnel testing lateral blockage effects have been the subject of much discussion. The poor agreement found between comparative automotive studies intensified the arguments over acceptable levels of blockage and correction methods. This was despite the fact that P.M. Waudby-Smith and W.J. Rainbird (1985) and others have identified as many as 16 possible sources of error in automotive wind tunnel testing. In fact in some of the automotive tunnels other sources of error, have been found to be a greater problem than the lateral boundary interference for example, the previously discussed 3/4 open jet wind tunnels. For wind tunnels having solid-wall test sections the emphasis on lateral interference effects continues because the correction methods proposed by E.C. Maskell (1965), R.W.F. Gould (1969) and others, for separated flow blockage have not been found universally applicable and/or easily applied. The methods of J.E. Hackett et al (1982) show greater promise. Even with better correction methods the solid wall wind tunnel test sections will still require the use of low area blockage ratios to avoid major alterations of the flow patterns (e.g. shifts in separation points) under constraint.

Slotted wall test sections for automotive testing purposes had received little attention before DSMA International Inc. of Toronto, Canada (DSMA) began

their investigations in 1979. Very little information was available on the geometry and interference levels one might expect for road vehicle testing with this boundary condition. The possible benefits of such a test section and the lack of information led DSMA to undertake a very intensive R&D program concerning these test sections. This has resulted in DSMA becoming the principal source of information on these test sections.

The first paper published in the open literature from DSMA¹ by S. Raimondo and P.J.F. Clark (1982) concerning this program covers the results from their first 1/5th scale slotted wall test section design (similar to Figure 2 but without the adjustable collector flaps). With so little prior information existing this investigation was of rather broad scope, covering OAR, model location, area blockage ratio, and amount of plenum flow allowed to directly enter the diffuser. In this investigation (as in later investigations) the test section interference was determined by comparing the surface static pressure distributions of a model in the proposed test section with a reference pressure distribution. In this case the reference pressure distribution was obtained from tests in a solid wall test section with very low area blockage. The comparison of the distributions was made by a least square linear regression analysis of the normalized local velocities. The slope of the correlating line (ideally unity) was used to indicate the correction required to the free stream velocity and free stream dynamic pressure (q_{∞}). This is thus a measure of the overall blockage interference. A measure of how well the corrected data fits the reference data was obtained by taking the standard deviation of the tap by tap differences between the two sets. The main conclusions from the experiments were as follows:

- 1) The size of a slotted wall test section can be much smaller (for a given vehicle

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¹DSMA also undertook many investigations of slotted wall test sections where the results were client, and/or company confidential.

size) than that of solid wall test section without reducing the quality of simulation.

2) Excellent model surface pressure distributions were obtained even at a 21.4% area blockage ratio.

3) A test section of twice the model's length, width and height (l_m, w_m, h_m) should be satisfactory for good simulation at zero yaw conditions.

Unfortunately the optimum pressure distributions were obtained only at certain OARs and model axial positions. These testing conditions did not appear to be predictable before testing a particular vehicle in a given test section. For unknown reasons it was found that the larger area test section resulting in a 16.4% area blockage ratio with the given model was more sensitive to OAR and model position than the smaller cross section test section. The results of F.K. von Schultz-Hausmann and J.D. Vagt (1988) could provide a possible explanation for the above peculiarity. The two test sections were not geometrically similar; the test section remained the same length while the height and width were altered proportionately. This results in different test section length (L_{ts}) to hydraulic diameter (d_n) ratios. F.K. von Schultz-Hausmann and J.D. Vagt (1988) indicate (although for 3/4 open jet test sections) that with L_{ts}/d_n ratios of less than 3 as in the larger test section case, incorrect collector areas produce large downstream interference errors. Additional support is found in the empty test section ground-plane pressure distribution which has a zero gradient for a greater length for the small area test section than that of the large test section even though the collector area is the same for both.

Connected with the above findings it was decided that adjustable collector flaps would be necessary on following designs. The promising results led DSMA

to further investigations of the slotted wall type test sections. Papers by R.G.J. Flay, G.M. Elfstrom and P.J.F Clark (1983) cover results from a 1/5 th scale test section. The primary objectives of these test programs were to investigate the interference levels produced under yaw conditions of an automobile or truck model at 14-15% area blockage ratios (S_m/A_t). An OAR of 30% was used for most of the tests although some tests with 20 and 40% OAR were made. Again effect of model axial position was investigated. Adjustable collector flaps were used. Adjustment of the flaps was carried out by assuming that by the end of the test section the mean wake static pressure coefficient should have the free stream static value.

The main additional conclusions from these two papers were:

- 1) Accurate surface pressure distributions were obtainable even at large yaw angles for models with zero-yaw area blockage ratios of 14-15%.
- 2) The deduced interference correction factor was independent of yaw angle, moderate model configuration alterations and only a weak function of OAR. Model position still influenced the interference levels but influence was much weaker due to the use of the adjustable flaps.
- 3) In order to obtain low interference levels the distance from the upstream end of the test section to the model is fairly critical.

The effect of vehicle position on interference level might have been better established if the mean wake pressures were set differently than the method used. One possible improved method would be to adjust the collector flaps to produce a mean wake static pressure equal to free stream static for the model in its most upstream position. When this condition is achieved the groundplane and ceiling slat pres-

sure distributions are measured. When relocating the model further downstream in the test section the previously measured pressure distributions will indicate the pressure that the collector flaps should be adjusted to to obtain equivalent downstream conditions. Little information was published from the 1/10th scale truck tests (S_m/A_{ts} of 15%) except that their corrected pressure distributions were quite good though the q_∞ correction required for the truck model in one particular test was on the order of 14% suggesting that the correct lateral wall boundary is a function of model configuration and/or C_D level.

The latest information covering the DSMA slotted wall R&D program is found in a paper by J.T. Templin and S. Raimondo (1986). Further studies of test section boundary influences are presented with reference to 1/5th scale results. This test section was altered slightly in view of the previous results (greater area, width to height ratio, and length (though L_{ts}/d_n was reduced to 2.95)). Most testing was carried out using a 30% OAR although 0 and 12% runs were also made. The method of adjusting the collector flaps was altered. For these tests the flaps were opened until further opening was ineffective in influencing the mean wake pressure. When yawing a model the zero-yaw flap setting was used. Models used for this program were three scale versions of the MIRA reference automobile model (a simplified automobile model developed by MIRA as a standard test model for wind tunnel comparative studies) giving S_m/A_{ts} levels of 8.3, 13.0, and 18.7%. Ten flat plates normal to the flow producing S_p/A_{ts} levels from 1.6 to 20% were also tested. For the MIRA models the reference surface pressure distribution was obtained from the results of three tests made on the full scale MIRA model at low S_m/A_{ts} levels in solid wall test sections at DNW in the Netherlands, (6 x 6m, 8 x 6m and 9.5 x 9.5m). These data were linearly extrapolated to obtain the zero-blockage condition. Interference levels for the normal flat plate tests were estimated by shifts in the measured base pressure coefficient. Potential flow

modelling of the models and the test section was also carried out. Two methods were used: M. Lenz (1982) ovoid matching technique and a source panel code developed by M. Mokry (1985). These programs were used to determine the interference velocities at the model due to the presence of the test section walls for both the solid and slotted wall test sections. The main additional conclusions drawn in this paper were that:

1) Flat plates are a suitable test model when investigating road vehicle bluff body blockage interference at zero yaw (when allowances have been made for the effective solid body volume).

2) From the base pressure measurements of the flat plates (effective ovoid body area of approximately 2.2 times the plate area) it was found that practically interference free data was obtained in the 30% OAR test section with plates of S_p/A_{ts} levels of up to 15%.

3) The MIRA model tests found that negligible q_∞ corrections were required for the 8.3% S_m/A_{ts} version but q_∞ corrections of 2.9% were required for the 18.7% S_m/A_{ts} scale. It was felt that an adjustment to the test section length and OAR could reduce the interference level of the larger model.

Chapter 3

Experimental Apparatus

3.1 Overview of Present Experimental Study

Three different body shapes were tested in a slotted wall test section. Each body shape was tested at 5 different scales. The slotted wall test section was incorporated in the circuit of the Carleton University 20" x 30" wind tunnel.

The 20" x 30" closed circuit wind tunnel at Carleton University with its roll-in, roll-out style test section and 3-component external balance provides an excellent facility to make test section design studies. A slotted wall test section used in an earlier Carleton University study (approximately 1/9th scale of the Porsche tunnel designed by DSMA) was modified (longer test section and redesigned collector flap section) to meet the needs of the present study. This small scale test section permits ease of test section modifications (e.g. OAR, slat width and length etc.) and results in high area blockage models which are physically small, reducing costs and set up time. The existing balance permitted direct measurement of the drag forces, reducing the amount of model surface pressure tapping usually used when making flow simulation quality experiments when a suitable balance is not available. With the above equipment it was envisioned that further investigations

into slotted wall type test sections could be undertaken. Of particular interest were the lateral interference levels for the extreme size and shape models which had been found to be significant in previous studies by G.M. Elfstrom, R.G.J. Flay and P.J.F. Clark (1983). Methods of reducing these interference effects were investigated to establish suitable test section geometries for testing at high S_m/A_t conditions.

3.2 Philosophy of Three Body Shapes

The use of three model body shapes for this study was to enable the examination of the slotted wall test section under the extreme cases likely to be seen in an automotive wind tunnel. These extreme cases were envisioned to be tests of large-volume models at quite large area blockage ratios having drag coefficients which span the anticipated range for road vehicles. It was estimated that drag coefficients of about 0.3, 0.8, and 1.2 would adequately cover this range. To keep costs reasonable, simple model shapes were chosen.

The first two drag coefficient levels (0.3 and 0.8) were obtained with block like shapes having overall dimensions (w:h:l 1:1:2.5) representative of a van or short straight truck. The differences in drag coefficient were obtained by front end rounding. The drag coefficients obtained are representative of the best and worst that would be achieved for road vehicles of this volume. Flat plate models mounted normal to the flow and close to the groundplane were used to obtain drag coefficients of about 1.2. These models were chosen because the far field pressure distribution produced by a plate is quite similar to that of typical road vehicles J.T. Templin and S. Raimondo (1986). Flat plates have frequently been used in solid wall blockage studies (E.C. Maskell (1963) and R.W.F. Gould (1969)), and well documented free air results are available.

3.3 Equipment

3.3.1 Block Models

The shapes for the block models were arrived at after consulting K.R. Cooper (1985) and a private conversation with K.R. Cooper (1988). The paper by K.R. Cooper (1985) investigates front and rear end shaping of bluff bodies in ground proximity and the effect of test Reynolds number on the results. Many of the experiments of this paper were carried out using a simple block model of width of 1:1:3. Zero-yaw test results for a range of front edge rounding radii indicated that a drag coefficient of about 0.3 and 0.87 would be obtained with a normalized front edge radius of 0.25 and 0.00 respectively. The results also indicated that a minimum test Reynolds number of about 0.6×10^6 was needed to obtain these C_D levels and to reduce the influence of Reynolds number on the C_D measurement. The minimum Reynolds number requirement meant that the smallest model that could be accurately tested in the Carleton University wind tunnel would be 5.25" in width (the maximum available wind speed for this test section and model being 230 ft/sec). This was judged to be a satisfactory size of model to give low interference results in the slotted tunnel based on DSMA results. The minimum Reynolds number and approximate C_D values were also used to check whether the balance would be capable of measuring the loads. Allowances were made for interference-induced increases in C_D and the possible use of higher Reynolds numbers to improve the pressure measurements on the larger models. To reduce model groundplane boundary interaction with the 0.3 C_D model the front edge radius treatment was also included on the lower front edge, unlike the models of K.R. Cooper (1985). The final design of the van-like models and support system is

shown in Figure 3 and Plate 1. Additional characteristics for these models in this test section are given in Table 1 and 2. The models were constructed of laminated birch hardwood. The two-piece body permitted the use of interchangeable front faces to obtain the two different configurations with the same "main body". The nine surface pressure taps (locations given in Table 3) were made of small diameter brass tubing pressed into the body (4 beltline portside, 4 roof centerline, 1 base). Small diameter flexible plastic tubing was used to bring pressures out of the model via the hollow support strut. The single steel cylindrical support strut is scaled for each model to obtain a 12% ground clearance when referenced to the square root of the model's frontal area ($\sqrt{S_m}$). This is typical of most road vehicles. The diameter of the strut was equal to 1/8th of the model's width. The support was located at the model's midpoint along the centerline of the model's lower surface. Thus all model midpoints were at the same axial location in the wind tunnel test section. The interior of each model was hollowed out to permit access to the surface pressure taps, the front-face attaching bolts, and to reduce model weight. Access to the hollowed out section is through an aluminium cover plate on the starboard side of the model. The models when initially machined conformed to the specified dimensions within $\pm 0.01"$. Although sealed with varnish, the models distorted, presumably due to moisture-content variations. In some instances steps of about 0.05" occurred between the front face and main body at the joint. These steps were faired with automotive spot putty. These models were produced at five different scales (see Plate 2) corresponding to area blockage ratios of 8.16, 12.5, 16.7, 20.2, and 24.0 percent.

Balance Attachment Point

Groundplane

Block Model No. 1

SCALE 1: 4

Right Side Elevation

Viewed from Upstream

Figure 3 Block Model and Balance Mounting Strut Assembly

Plate 1 Block Model Assembly

Plate 2 Block Model Family

	Sharp Edged	Rounded
$l:w:h$	$2\frac{1}{2}:1:1$	
Front Radius $r/\sqrt{S_m}$	0.00	0.25
Ground Clearance (h_{gc})	$0.125\sqrt{S_m}$	
Support Strut Diameter	$1/12w$	

Table 1. Block Model Dimensions

MODEL	L x W x H	S_m	$\sqrt{S_m}$	S_m/A_{ts}	$L_{ts}/\sqrt{S_m}$	$L_{ts}/\sqrt{S_m} - 2.5$
	in.	in. ²	in.	%		
1	13.125 x 5.25 x 5.25	27.6	5.25	8.16	11.9	9.4
2	16.25 x 6.50 x 6.50	42.3	6.50	12.5	9.6	7.1
3	18.75 x 7.50 x 7.50	56.3	7.50	16.7	8.3	5.8
4	20.625 x 8.25 x 8.25	68.1	8.25	20.2	7.6	5.1
5	22.50 x 9.00 x 9.00	81.0	9.00	24.0	6.9	4.4

Table 2. Block Model/Test Section Characteristics

Pressure Tap	1	2	3	4	Base
Axial Position From Nose (x/l)	0.13	0.27	0.40	0.53	1.0
Height Above GP	0.625h				

Table 3. Block Model Pressure Tap Locations

3.3.2 Flat Plate Models

The flat plate models of 1.45:1 width to height ratio were made of 3/4" thick plywood. Sharp edges were produced by means of 45 degree bevels on the downstream surfaces of the plates. A 2 mm gap between the groundplane and the lower edge was used to prevent grounding of the balance. The plates were supported on their downstream surface by two steel struts, as shown in Figure 4. A single flexible plastic tube was attached to the trailing edge of one of the support struts to measure the base pressure. Base pressures were initially measured by simply taping the open end of the tube to the middle of the rear face of the plate. Problems arising with this arrangement (see Appendix A) were circumvented by using a conventional surface pressure tap. The tap was embedded to leave both the upstream and downstream surfaces of the plate smooth. The tap was located at an approximately scaled location for all the plates (see Figure 4). The constant thickness and the use of the same support struts for all of the plates produced dissimilar rear face-geometries. The plates were mounted normal to the flow at a test section axial location of $X_p/L_t = 0.288$. The five scales of the flat plates (shown in Plate 3) used for the study produced area blockage ratios of 6.7, 13.0, 19.7, 25.7 and 35.7 percent. Additional Flat plate/test section characteristics are given in Table 4.

MODEL	W x H	S_p	$\sqrt{S_p}$	S_p/A_{t0}	$L_{t0}/\sqrt{S_p}$
	in.	in. ²	in.	%	
1	5.71 x 3.94	22.5	4.74	6.7	13.2
2	7.87 x 5.51	43.4	6.59	13.0	9.5
3	9.84 x 6.69	65.9	8.11	19.7	7.7
4	11.22 x 7.68	86.1	9.28	25.7	6.7
5	13.19 x 9.06	119.4	10.93	35.7	5.7

Table 4. Flat Plate Model/Test Section Characteristics

All plates were mounted in the tunnel with a 2 mm h_p .

Figure 4 Flat Plate Model and Balance Mounting Assembly,

Plate 3 Flat Plate Family

3.3.3 Balance

The TEM model 528 external three component parallel motion balance is located above the roll-in, roll-out test section as shown in Plate 4. It is for this reason that the test section was designed with the groundplane on the upper surface to facilitate the attachment of the model to the balance. The balance has the factory ranges and accuracies as listed in Table 5 when the balance is operated in the electrical-readout mode. The factory drag range was insufficient for the proposed

	RANGE (lb),(in-lb)	ACCURACY (lb),(in-lb)
LIFT	0 - 20	± 0.05
DRAG	0 - 8	± 0.02
PITCH	0 - 15	± 0.05

Table 5. T.E.M. Model 528 Balance Factory Specifications

tests. Calibration tests were performed and a linear calibration range of 0 - 16 lbs drag was obtained (see Figure 5). Simple checks for possible interaction between lift force and drag force readouts showed no significant interaction. When the heavier models were mounted on the balance the lift counter weights were adjusted to ensure that the lift tare was in a suitable range. For the block models a drag load equivalent to the measured drag loads was applied and axial displacements and pitch rotations of about 1/8th inch and 1/2 degree respectively were measured. These displacements are due primarily to the low stiffness of this balance when operated in the electrical readout mode. No similar test was performed for the flat plate models though it is estimated that the displacements would be larger given the larger loads and the lower stiffness of its mounting system. A significant amount of noise was observed on the drag output signal when the wind tunnel drive motor was running (no aerodynamic loads present). It was found that the frequency of vibration of the drive motor was close to the resonant frequency of the balance drag system. This noise was reduced by the installation of a high quality

capacitor across the drag-signal output terminals. The addition of the capacitor was found not to alter the balance static calibration.

Figure 5 Balance Error vs Applied Load

3.3.4 The Wind Tunnel

The Carleton University 20" x 30" closed circuit wind tunnel was used for this investigation. Its basic specifications are listed in Table 6. Use of the slotted wall test section with its additional contraction of the flow and high blockage models required a reduction of the fan blade angles to prevent their stalling. To reduce losses in the diffusion process downstream of the adjustable flap section a relatively wide angle diffuser insert was made to smoothly join with the existing diffuser; see Figure 6. Small vortex generators were mounted at the upstream end of this diffuser to improve its performance.

Diffuser Insert Cross Section
Viewed from Upstream/Downstream

Sectional View from Above

Sectional Side Elevation of Diffuser/Diffuser Insert

Figure 6 Diffuser Insert

Cross Sectional Area	337.5 in. ²
Slotted Wall Section (l h w)	62.5 x 15 x 22.5 in.
Interchangeable Slat Length	56.5 in.
Plenum (l h w)	69 x 27 x 48 in.
Collector Area	337.5 - 600 in. ²
Contraction Ratio	
Wind Tunnel	12.0
Test Section	1.78
Overall	21.3
Maximum Wind Speed	235 (ft/sec)
Turbulence Intensity	0.25% [†]
Vertical Traverse Flow Uniformity $\sigma(q/q_{ref})$	0.34%

Table 6. Wind Tunnel Characteristics

† Measured in standard 20 x 30 in. test section

3.3.5 Experimental Test Section

The slotted wall roll-in, roll-out test section insert (shown in Figures 7 to 9 and Plates 4 to 7) has 3 major components, the contraction, test section, and the plenum. The other major component of this test section is the adjustable collector flaps which were located in the wind tunnel diffuser and will also be discussed here.

The contraction section was necessary to reduce the wind tunnel's 20" x 30" contraction outlet area down to the desired slotted wall cross-section area of 15" x 22.5" to obtain the desired L_t/d_n ratio. Three contraction pieces constructed of thin plywood shaped over circular arc formers guide the flow to the test section walls and ceiling. These three contraction pieces are attached to the upstream end of the plenum. The contraction surface leading into the test section groundplane is flat and aligned with the top of the existing wind tunnel contraction and wind tunnel diffuser exit (see Figure 7, and Plate 7). The reference contraction pressure taps (P_{c1} , P_{c2}) were located on the ceiling contraction piece.

Figure 7 Sectional Side Elevation of Test Section Assembly 20

Figure 8 Sectional View from Above of Test Section Assembly 31

Figure 9
Cross Section of Test Section Viewed Upstream

Plate 4 Test Section and Test Equipment

Plate 5 View of the upstream end of
the Test Section/Plenum

Plate 6 View of the downstream end of
the Test Section/Plenum

Plate 7 View of the Collector Flaps and
Diffuser/Diffuser Insert from the
upstream end of the Plenum

Plate 8 View of the 30% OAR Test Section
and the Test Section Contraction

The 15" x 22.5" x 62.5" slotted wall test section starts at the slot lead-in fingers located at the end of the contraction and ends just ahead of the adjustable collector flaps. The groundplane of the test section is formed by the plywood top of the test section insert. The test section wall and ceiling boundaries are made of 21 longitudinal slats. The spacing and mounting of these slats is shown in Figure 9. To alter the OAR, designated slats were changed (for solid wall testing plywood sheets replaced the designated slats). The slats forming corners and the pressure tapped ceiling centerline slat were the same for all OARs. Each slat was mounted on two posts 1 11/16 in long. The posts were attached to a steel frame suspended from the groundplane (plenum side)(see Figure 7 and Plate 7). The centreline of the groundplane and the ceiling were pressure tapped with a total of 36 taps located at the axial positions as indicated in Table 7. Groundplane tap number 7

TAP No.	X/L_{10}	TAP No.	X/L_{10}
1	0.120	10	0.576
2	0.168	11	0.624
3	0.216	12	0.672
4	0.264	13	0.720
5	0.312	14	0.768
6	0.360	15	0.816
7	0.424	16	0.864
8	0.480	17	0.916
9	0.528	18	0.960

Table 7. Axial Locations of Slotted Wall Groundplane and Ceiling Slat Pressure Taps. (X measured from start of slot lead in openings)

had to be removed to provide a clearance hole for the block model support strut.

The plenum surrounding the test section extended from the start of the test-section-insert contraction to the end of the slats. The walls of the plenum are formed by hinged Lexan doors which permit access to the test section area. The ceiling of the plenum is also used to mount a pitot static tube and a streamlined strut used to shield the centerline slat pressure lines being brought out of the test section insert.

The three adjustable collector flaps are shown in Figures 6, 7, 8 and Plate 7. The location of these flaps in the diffuser was necessary to achieve the longest possible test-section length. The manually actuated flaps are made of plastic and are hinged at their downstream ends. The circular arc section of the leading edge is short as the space available within the existing 20" x 30" diffuser was limited. The telescopic style struts connecting the flaps to the diffuser support frame allow the flaps to be adjusted to any angle within their range. Grub screws on the telescopic struts are accessed through slots machined in the flaps. Adjustment of the flaps is best made with the test section insert rolled out. The flap hinge area was initially set to provide a symmetrical 5% area increase over the slotted wall area. This was the estimated area increase required to accommodate boundary layer and mixing layer growth. Initial testing indicated that this area was not sufficient and the hinge area was increased (not symmetrically) to 16%, this also reduced the diffuser insert diffusion angle particularly on the ceiling diffuser panel and produced a significant improvement in the wind tunnel's performance.

3.3.6 Instrumentation

All model and test section pressures were measured using a SCANIVALVE model 48CMK3 and two SETRA SYSTEMS ± 0.5 psi (nominal sensitivity 5V/psi) differential pressure transducers model 239 located outside the test section insert. Since differential pressures were expected to exceed the nominal range the transducers were calibrated over a range of +18 to -13 inches H_2O differential. Calibrating pressures were applied to both transducers and one column of a 50 tube multi-manometer. Manometer levels were read to 0.01 of an inch ± 0.02 inch while the transducer outputs were measured using a data acquisition system. A least squares linear fit to the calibration data was found satisfactory for each transducer.

Figure 10 Plot of Transducer Error vs Applied Pressure

This resulted in a standard deviation of less than 0.01 inches H_2O between measured and transducer determined values. Figure 10 is a plot of transducer error versus applied pressure for both transducers.

One of the pressure transducers was dedicated to measure the contraction differential $P_{c1} - P_{c2}$ as the tunnel runs were relatively long and a q_∞ controller was not used. The other transducer measured the SCANIVALVE selected pressure differential referenced to the contraction pressure P_{c2} . A type J thermocouple located in the wind tunnel contraction was used to obtain the air flow temperature used in calculations of density and viscosity. The mercury column barometer in room 130 ME was used for calculations of density. The drag, pressure transducers and thermocouple signals were processed through a SCIOMETRICS LABMATE data acquisition system operated by an EAGLE PC. The inputs and outputs of the system were controlled with SCIOMETRICS MAXIMUM PLUS software. A special version of this software was used which was compatible with experiments using multiplexers. The system sampled all channels at an approximate 1 Hz rate thus samples of a particular channel were taken once every second. Each sample is formed by taking the average the channel input over 1/30th of a second to remove possible mains noise.

3.4 Experimental Procedure

3.4.1 Test Section Calibration

As with all new or modified wind tunnel test sections some initial basic calibrations and flow quality measurements were required. After preliminary adjustments and modifications to the collector flap section were complete, a pitot static probe was positioned into the test section at mid-length, mid-height, aligned with the walls and floor. Runs were then made at various contraction pressure differentials ($P_{c1} - P_{c2}$) where the test section dynamic pressure ($P_o - P_\infty$) and static pressure differential ($P_{c2} - P_\infty$) were measured. The ratios of $(P_o - P_\infty)/(P_{c1} - P_{c2})$ and $(P_{c2} - P_\infty)/(P_{c1} - P_{c2})$ designated as K1 and K2 respectively, were thus determined as functions of $(P_{c1} - P_{c2})$. These enable the freestream reference pressures to be determined when a model is in the test section, precluding the use of a pitot-static tube. This approach is of course, only valid if the pressure taps measuring P_{c1} and P_{c2} are not significantly influenced by the model's flow field. Over the useable wind tunnel speed range these calibration factors were found to vary somewhat, but the values and the variation were the same for both the 30 and 45% OAR test sections and were not influenced by any of the collector flap settings used. With the pitot-static tube removed, empty-test-section centerline groundplane and ceiling-slat axial static pressure distributions were measured for various symmetrical collector flap settings (see Figure 11). A similar measurement was made for a case where the existing wind tunnel diffuser was used as the collector. The flap setting giving the lowest axial static pressure gradient was used for most of the experimental testing.

A single vertical traverse of the pitot-static tube in the same axial location as used for the calibration runs was made to determine the flow uniformity in this region. The results of this traverse indicated a standard deviation of 0.34% for the normalized dynamic pressure.

Figure 11 Test Section Wall Axial C_p Distributions

A Preston tube measurement was made in the empty test section on the centerline of the groundplane at an axial position of approximately $X/L_{ts} = 0.288$ to obtain an indirect measurement of the turbulent boundary layer skin friction coefficient, C_f . Using appropriate correlations by M.R. Head and V. Vasanta Ram (1971) a C_f of 0.0029 was determined. Using this C_f value and J.C. Rotta (1962) turbulent boundary layer relationships for flat plates with zero axial static pressure gradients a displacement thickness of 0.073" was deduced. The 1/7th power law for flat plate turbulent boundary layers was used to determine the empty test section displacement thickness at axial locations corresponding to the nose positions of the largest and smallest block models. Estimated ground clearance ratios (δ^*/h_{gc}) of 6.0 and 11.6% were found for these models respectively.

3.4.2 Data Handling

The following procedures were used to obtain data judged to be of acceptable quality for this study. All drag and base pressure measurements were formed by sampling over a 110 second period (approximately 110 samples). To account for temporal shifts, the $(P_{c1} - P_{c2})$ differential pressure was also sampled and averaged over this time period for use in reducing measurements to coefficient form. The sampling time was determined by trial and error, increasing the time until the standard deviation of ten consecutive measurements was sufficiently small, about 0.002 on both C_D and C_{pb} . All drag and base pressure coefficients presented in this paper, excluding the C_D vs $Re_{\sqrt{A}}$ plot, are the mean values from typically 10 consecutive measurements. The standard deviation of the measurement is also presented on the plots. All other pressure measurements were obtained from a single reading sampled over a 60 second time period. This length of sampling time was determined by calculating the static pressure coefficient of a pressure

tap every 10 sec using its present cumulative average and comparing these values with a value calculated using the very long term average. The agreement found between repeated runs indicated that the sampling time chosen was satisfactory. Pneumatic delays were accounted for by starting the sampling approximately 10 seconds after the scanivalve stepped to a new port. Zero shifts of the pressure transducers and the balance were accounted for by averaging the before and after run wind off drive motor on zeros. Typical shifts over a 20 min run time was 1mv on pressure transducers (0.04% nominal full scale) and 10mv on the drag output (0.14% full range). All data reduction into engineering units and coefficient form was done using several FORTRAN programs after the run was completed.

Since the wind tunnel does not have a heat exchanger and close to maximum power was used for most runs, air temperatures of 105 degrees F were reached after about 20 minutes of running time. Thus single runs measuring all 36 test section pressure taps could not be made because of temperature considerations.

3.5 Testing Procedure

The typical test program for a given model would proceed as follows:

- 1) The model was mounted and aligned geometrically to within 0.5 degrees in yaw.
- 2) Model pressure tapping lines were connected and checked for leaks and plugs.
- 3) A run measuring C_D and C_{p_i} vs $Re_{\sqrt{A}}$ would be made using about 10 different wind speeds within the calibrated range of the test section (see Figure 12). The maximum Reynolds number tested was limited by the wind tunnel speed or

by the balance drag capacity.

4) A run of 10 readings of C_D and C_{p_i} at a "fixed" Reynolds number. No q_∞ or speed controller was used and shifts in Reynolds number due to V_∞ and temperature shifts are also shown in Figure 12.

5) A single run of model surfaces pressures (block models only) at the same Reynolds number as in step 4.

6) Four runs each measuring about nine taps to obtain groundplane and ceiling slat static pressure distributions at the same Reynolds number as in step 4.

Several models were subjected to more extensive programs where all or some of the above tests were repeated with different test section OARs and collector flap settings.

Figure 12 Variation of Drag Coefficient
with Reynolds Number

Chapter 4

Results and Discussion

4.1 Flat Plates

Flat plates have been used extensively in blockage determination studies of solid wall test sections and have proven to be very useful in comparing the test section interference levels for modified test section designs (J.T. Templin and S. Raimondo (1986)). Thus the flat plate tests provide bench mark results which can readily identify a test section's blockage performance. The flat plate found favour for zero yaw road vehicle test section interference studies due to its simplicity and the fact that it provides a far field flow field not unlike that of a typical automobile. The effective body volume that these flat plates produce has been determined by DSMA using a Rankine ovoid matching technique. The results of this study indicate that the maximum axial cross section of the effective body was found to be about 2.2 times the actual plate area and an ovoid length of about 4.5 times $\sqrt{S_p}$. The wake cross sectional area was found to be about 1.2 times the plate area or roughly $C_D \times S_p$. The effective body and wake shapes must be properly reproduced in the test section to produce interference free model forces and pressures.

The above flow field characteristics indicate that the flat plate models are in most respects representative of typical road vehicles, yet are a test case which is much more sensitive to lateral wall and wake blockage interference than other models when compared on a model frontal area basis.

The flat plate testing program undertaken in this work vastly extended the S_p/A_t levels previously tested in a slotted wall test section, as the largest plate tested produced an effective body cross section of about 80% of the test section cross sectional area.

4.1.1 Flat Plate C_D and C_{p_b}

The measured base pressure and drag coefficients obtained in the 30 and 45% OAR slotted test section are plotted as a function of area blockage ratio in Figures 13 and 14, and are listed in Table 9. The free air values $C_D = 1.16$, $C_{p_b} = -0.42$ and average front face pressure coefficient (C_{p_f}) of 0.74 for ground mounted plates of this geometry were determined by DSMA. Base pressure measurements obtained by DSMA in a solid wall test section using plates of the same geometry have been added to Figure 14. The drag coefficient variation estimated to occur in a solid wall test section was plotted in Figure 13 using the solid wall base pressure measurements and Maskell's relationship for blockage. Comparing values measured in the 30% OAR test section with the solid wall results one finds that all the plates tested in the slotted wall section have lower "error" than that obtained with a 5% S_p/A_t plate in a solid wall test section, thus illustrating the large reduction in lateral wall interference. By limiting the plate size to a 20% S_p/A_t level in the 30% OAR slotted section the errors on the measured coefficients are no larger than those obtained with a 1.5% S_p/A_t plate in a solid wall test section. The (C_{p_f}) values plotted in Figure 15 were deduced by adding the base pressure coefficient

to the overall drag coefficient. Using the free-air coefficients given by DSMA the interference error of the coefficients referenced to the overall drag coefficient are tabulated in Table 8. Some interesting trends are revealed by Figures 13, 14 and 15 and Table 8. It appears that up to an S_p/A_{ts} of 20% the base pressure is more or less constant, equal to the correct free air value. As a result the drag coefficient is also very close to the interference free value for these plate sizes. The slight increase in plate drag coefficient for the smallest plate is typical of such plate tests and is thought to be caused by groundplane boundary layer/plate fore body flow field interactions. It is also possible that the 30% OAR slotted wall is a too open boundary when the distance from the start of the slots to the plate is long (relative to plate size) but is appropriate as the plates become larger.

From base pressure measurements the test section interference appears to increase dramatically at a S_p/A_{ts} level of about 22%. This change could be due to a change in the behaviour of the slotted walls and or a much larger downstream interference effect (clearly evident for the 35.7 % S_p/A_{ts} plate in Figure 17). The low interference indicated by the drag measurement for the 25.7% plate appears to be somewhat fortuitous and must have been due to a redistribution of the front face pressures of a similar magnitude to the base pressure shifts. Beyond an S_p/A_{ts} of 25.7% the drag coefficient increases quite rapidly as a result of the rapidly decreasing base pressure. The 35.7% S_p/A_{ts} plate is an extreme blockage case and most likely represents the largest sized plate that could be tested without the effective body exceeding the slotted wall boundaries.

Tests were made to determine the effect of adjustment of the collector area on the base pressure and drag of two of the plates. A plate with a small base pressure "error" (Plate No. 3) and a plate with a large base pressure "error" (Plate No. 4) were selected. Two larger collector area settings were tested with both plates; and

resulted in no measurable differences in either C_{p_b} or C_D within the accuracy of the experiments. This result confirms the findings of F.K. von Schultz-Hausmann and J.D. Vagt (1988) (for 3/4 open test sections) who found for test sections of this geometry that wake blockage interference caused by the diffuser collector will be sufficiently far downstream so as to not propagate upstream significantly close to the model. Thus it is felt that the majority of the base pressure interference is caused by the lateral walls. Due to these findings all other models were only tested using the collector area giving the best empty test section conditions (smallest axial pressure gradient).

The results of tests of the two largest plates in the 45% OAR test section are also presented in Figures 13, 14 and 15 and Table 8. It can be seen that there is a significant reduction in both the base pressure and drag coefficients. In fact both the C_D and base pressure measurements are significantly below the free air values. Thus it is clear that for these very large plates a parallel slotted wall of about 40% OAR would result in interference free conditions.

From the above observations it would appear that a test section boundary giving very low interference for a wide range of plate sizes would require an OAR of about 40% to provide essentially the correct base pressure for all plates up to an S_p/A_{te} level of 35%. Possible benefits from tapered slots or optimum slotted wall length and OAR upstream of the plate would require further tests using a test section with a longer slotted wall length upstream of the plates.

Figure 13 C_o vs Area Blockage Ratio
Normal Flat Plates

Figure 14 C_p vs Area Blockage Ratio
Normal Flat Plates

Figure 15 C_p , vs Area Blockage Ratio
Normal Flat Plates

CAR	MODEL	$\frac{C_D - C_{Dref}}{C_{Dref}}$ %	$\frac{C_{Phref} - C_{Ph}}{C_{Dref}}$ %	$\frac{C_{Pf} - C_{Pfref}}{C_{Dref}}$ %
30%	1	1.9	-0.3	-2.2
	2	0.2	0.5	-0.3
	3	-0.5	0.9	-1.4
	4	0.6	6.6	-6.0
	5	11.6	15.9	-4.2
45%	4	-6.5	-5.2	-1.4
	5	-5.4	-3.7	-1.7

Table 8. Flat Plate Coefficient "Errors"
Reference values C_D , C_{Ph} and C_{Pf} of 1.16, -0.42 and 0.74
from DSMA (1986)

OAR	MODEL	C_D	$-C_{Ph}$
30%	1	1.182	0.416
	2	1.162	0.426
	3	1.154	0.431
	4	1.167	0.497
	5	1.295	0.607
45%	4	1.084	0.360
	5	1.096	0.382

Table 9. Measured Flat Plate Coefficients

4.1.2 Test Section Pressure Distributions

The flat plate groundplane and ceiling slat distributions are found in Figures 16 to 20. Note that all wall pressure distributions are perturbation coefficients i.e. the empty test section pressure distributions have been subtracted from the model in distributions.

The groundplane pressure distributions are on a plane of symmetry and have been made non-dimensional to form easily comparable signatures. This was done by dividing all axial distances from the plate (z origin, positive upstream) by $\sqrt{S_p}$. Ideally if the flow fields are uninfluenced by the lateral walls of the test section the signatures from all the plates should collapse upon a single trace; shifts between signatures indicate that boundary interference effects are present. Assuming the groundplane signature of the 6.7% S_p/A_t plate of Figure 16 to be essentially interference free, one can identify distinct elements of the flat plate signature. At about $3\sqrt{S_p}$ upstream of the plate the static pressures begin to rise smoothly to a peak value, close to stagnation, just in front of the plate.

The "discontinuity" in the pressure distribution at about $0.5\sqrt{S_p}$ is due to the groundplane horse-shoe vortex from the primary separation front about one plate width upstream. From the base of the plate to $-1\sqrt{S_p}$ there is a region of essentially constant static pressure equal to the base pressure; this is associated with the equivalent "solid body" or "bubble" portion of the wake. Due to mixing effects the bubble closes some distance downstream of the plate and there is an attendant increase of the static pressures. The location of the maximum static pressure in the wake is generally associated with the closure of the bubble portion of the wake. The closure of the bubble occurs at about $4\sqrt{S_p}$ downstream of the plate where the static pressure coefficient rises to about 0.1. Final mixing out of the wake resulting in a return to free stream static pressures occurs at about $7\sqrt{S_p}$ down stream of the plate. Shifts from the small-blockage level signatures indicate

regions affected by interference. Comparing the signatures of the five plates in Figure 16 it is found that on the groundplane the distributions downstream of the plate are the most sensitive to the area blockage level and relative length of the test section. All plates but the smallest show signs of wake blockage interference i.e. low static pressures at the end of the test section due to the fixed collector area. Table 10 compares the average downstream groundplane and ceiling pressures with the wake blockage (or relative wake size) factor $-C_D S_p/A_{ts}$. For all the

OAR	Model	$-C_D S/A$ (measured)	Mean Downstream Wake C_p
30%	1	-0.079	-0.03
	2	-0.151	-0.083
	3	-0.227	-0.223
	4	-0.300	-0.328
	5	-0.462	-0.514
45%	4	-0.279	-0.292

Table 10. Comparison of End of Test Section Wake Pressures with Wake Blockage Factor

plates tested, collector area wake blockage interference appears to be limited to the final 25% of the test section length. For the 25.7 and 35.7% S_p/A_{ts} plates in addition to the collector wake blockage all the floor pressures behind the plate are reduced. To determine if the collector wake blockage was influencing the pressures further upstream closer to the base of the plate, the groundplane signatures for the 19.7% S_p/A_{ts} plate with the two larger collector areas are plotted in Figure 18. The result from a similar experiment with the 25.7% plate was virtually identical. The results indicate that while the pressure coefficients at the end of the test section could be brought closer to the correct values, correction of these pressures by collector flap adjustment does not result in a correction of the pressures further upstream. Thus the errors upstream of 80% of the test section are believed to be almost entirely due to lateral boundary interference.

The pressure distributions measured in the 45% OAR test section for the 25.7%

S_p/A_{t0} plate are shown in Figures 19 and 20. It is seen that the larger OAR has a significant effect on the groundplane pressure signature within the wake bubble zone and on the base pressure. In fact the pressures in this zone have been increased to values above those found for the 6.7% S_p/A_{t0} plate while the other groundplane pressures were virtually unchanged by the larger OAR. Thus it appears that the correct local OAR is very important in obtaining proper flow simulation about an object at these high area blockage ratios. The ceiling slat pressure distribution shows a more uniform reduction in the magnitude of the pressures as one would expect from the more open wall condition.

The ceiling-slat pressure distributions are not readily comparable since they are not on the same relative lateral distance for each plate. The wake blockage at the end of the test section is apparent though. The slight dip in the ceiling pressure distribution at approximately $X/L_{t0} = 0.75$ was caused by the disturbance of the plenum flow going around the slat mounting frame.

An important point to note, illustrated by the pressure distributions, is that while the plate disturbance pressure field appears to propagate $3\sqrt{S_p}$ ahead of the plate on the groundplane, at the ceiling height the disturbances would appear to be negligible at the upstream end of the test section. Thus it seems reasonable to expect that negligible errors have been introduced to the contraction pressure measurements (used to determine free stream dynamic pressure in the test section) since these taps were located well off centerline on the ceiling portion of the contraction (see Figures 7 and 8).

Figure 16 Groundplane ϕ Pressure Signatures:
Flat plate Models

Figure 17 Ceiling Slat Perturbation Pressure Distributions:
Flat Plate Models

Figure 18 Effect of Collector Flap Setting on the Flat Plate Groundplane Pressure Signature

Figure 19 Effect of OAR on the Flat Plate Groundplane ϕ Pressure Signature

Figure 20 Effect of OAR on Flat Plate Ceiling Slat Perturbation Pressure Distributions

4.2 Sharp Edged Block Models

4.2.1 C_D, C_{p_b}

The results from the drag and base pressure measurements on the sharp edged blocks are plotted in Figures 21 and 22. The deduced average front face pressure coefficient is also plotted in Figure 23. A C_D value of about 0.84 can be found by extrapolating to the 0% S_p/A_{ts} condition. For comparison, K.R. Cooper (1985) obtained a blockage corrected C_D value of 0.872 for a similarly shaped model (longer and mounted closer to the groundplane). The shifts in the drag coefficient and base pressure for this model (see Table 11) were not straightforward. The drag coefficient is seen to rise quite rapidly as the S_m/A_{ts} is increased in the 30% OAR test section the total increase is however only about 15% (at $S_m/A_{ts} = 0.24$), much less than the increase of about 70% that would be found in a solid walled test section. The base pressure, however, actually increases slightly as S_m/A_{ts} is increased to 16.7%. The decreases in C_{p_b} for models larger than 16.7% result in the higher slope of the C_D versus S_m/A_{ts} curve. Use of the 45% OAR test section reduces significantly the wall interference and provides close to correct base pressure values for the small and large models; however, it is clear that a more open and longer test section would be required to remove all wall interference effects, particularly for the highest blockage model.

4.2.2 Test Section Pressure Distributions

Ceiling slat pressure distributions and groundplane pressure signatures (the groundplane distributions have been formed into a signature by dividing axial distances from the model front face (z origin, positive upstream) by $\sqrt{S_m}$) are plotted in Figures 24 to 31. Both pressure distributions (Figures 24 and 28) indicate downstream wake blockage interference is present for all but the 8.16% S_p/A_{ts} model, for which interference was only mild (Figure 21).

Figure 21 C_g vs Blockage Area Ratio:
Sharp Edged Block Models

Figure 22 C_p vs Area Blockage Ratio
Sharp Edged Block Models

Figure 23 Deduced C_p vs Area Blockage Ratio
Sharp Edged Block Models

OAR	MODEL	$\frac{C_D - C_{Dref}}{C_{Dref}}$	$\frac{C_{Pbase} - C_{Pb}}{C_{Dref}}$	$\frac{C_{Pf} - C_{Pref}}{C_{Dref}}$
		%	%	%
30%	1	3.5	1.0	2.4
	2	6.6	0.7	5.9
	3	9.1	0.4	8.7
	4	12.2	6.3	5.9
	5	16.8	10.0	6.8
45%	1	2.5	-0.9	3.4
	4	8.0	1.7	6.3
	5	7.9	2.0	5.9

Table 11. Sharp Edged Block Model Coefficient "Errors"

Reference values obtained by extrapolating to $S_m/A_{ts} = 0$ condition

$C_{Dref} = 0.83(7)$, $C_{Pb} = -0.17(5)$, $C_{Pref} = 0.66(2)$

OAR	MODEL	C_D	$-C_{Pb}$
30%	1	0.866	0.184
	2	0.892	0.181
	3	0.913	0.179
	4	0.939	0.228
	5	0.978	0.259
45%	1	0.858	0.168
45%	4	0.904	0.190
	5	0.903	0.192

Table 12. Measured Sharp Edged Block Model Coefficients

Again it is the final 20% of the test section where the wake interference errors (caused by the fixed collector area) are largest. From the magnitude of the shifts in the pressures on the groundplane at the end of the test section it appears that the collector areas available with this particular test section would only be able to fully correct this error for models up to an S_m/A_{ts} of about 17%. Upstream of $z/\sqrt{S_m} = -1.0$ the groundplane signatures (on Figure 24) collapse upon one another. Shifts to lower pressures in the $z/\sqrt{S_m}$ equal to -1.0 to -3.5 appear to be ordered by S_m/A_{ts} . It is interesting that the groundplane pressures at the rear of the model are indicating progressively lower pressures while the base pressure itself does not shift in this direction until an S_m/A_{ts} of 16.7% is reached (Figure 22). The effects of the 45% OAR test section on the groundplane and ceiling slat pressure distributions are shown for three models in Figures 25 to 27 and 29 to 31 respectively. The results indicate little influence with the smallest model while progressively greater changes occurred for the larger models. With the 20.2% S_m/A_{ts} model, the groundplane pressures under the base of the model to $z/\sqrt{S_m} = -3.25$ (i.e. the near-wake, bubble area) were increased along with a slight increase of the end-of-test-section pressures. The ceiling slat pressure perturbation for this model (see Figure 30) were decreased at the upstream end with little alteration of the rest of the distribution. The largest 24% S_m/A_{ts} model underwent similar changes due to the "softer" 45% OAR test section but the magnitudes of the shifts were of course greater. It is interesting that the greater OAR causes an increase in the suction pressures measured on the ceiling at $X/L_{ts} = 0.35$ to 0.45 axial distances corresponding to an area centred about the midpoint of the model. This could be due to the separation bubble, which exists downstream of the sharp front edges of the model being too constrained by the 30% OAR boundaries for the larger models, causing smaller separation bubble sizes and forced reattachment much sooner than for interference free flow. A smaller separation bubble would increase the flow area between the model and the ceiling/walls, increasing the static pressures in this area.

Figure 24 Groundplane Pressure Signatures:
Sharp Edged Models

Figure 25 Effect of OAR on the Sharp Edged Model Groundplane p/p_0 Pressure Signatures:

Figure 26 Effect of OAR on the Sharp Edged Model Groundplane Pressure Signatures:

Figure 27 Effect of OAR on the Sharp Edged Model Groundplane C_p Pressure Signatures:

Figure 28 Ceiling Slot Perturbation Pressure Distributions:
Sharp Edged Models

Figure 29 Effect of OAR on the Sharp Edged Model Ceiling Slat Perturbation Pressure Distributions

Figure 30 Effect of OAR on the Sharp Edged Model Ceiling Slat Perturbation Pressure Distributions

Figure 31 Effect of OAR on the Sharp Edged Model Ceiling Slat Perturbation Pressure Distributions

Figure 32 Sharp Edged Model Surface Pressures
Roof Centerline

Figure 33 Effect of OAR on the Sharp Edged Model
Roof Centerline Surface Pressures

Figure 34 Sharp Edged Model Surface Pressures
Left Side Beltline

Figure 35 Effect of OAR on the Sharp Edged Model
Left Side Beltline Surface Pressures

4.2.3 Model Surface Pressures

The sharp edged model's roof centerline and left side beltline surface pressures are presented in Figures 32 to 35 for the test case of zero yaw angle simulating no wind conditions. These pressure coefficients are not as reliable as others presented elsewhere in this paper because of additional uncertainties due to model misalignment, tap location accuracy (in pressure gradients), unsteady pressures due to separation bubbles and static pressure hole errors that could not be removed. The pressure coefficients plotted at $X_m/L_m = 1.0$ are actually the base pressure measurement. Significant S_m/A_{ts} related shifts occurred, unlike the results found for the rounded block model (Section 4.3) and the MIRA model tests by DSMA. Pressures at X_m/L_m equal to 0.4 and 0.53 (associated with the re-attachment of the separated bubble regions) appear to be the most influenced by the boundary interference. The pressures here (interestingly) increase with increasing S_m/A_{ts} and, reduce to practically the $8.16\% S_m/A_{ts}$ values when the OAR is increased to 45% (see above possible explanation). It also appears that the roof pressures are more sensitive to the S_m/A_{ts} level than the model belt line pressures. This is likely due to the test section width to height ratio which is closer to that of automobiles than the one-to-one block models.

4.3 Rounded Block Models

4.3.1 $C_D C_{pb}$

The drag and base pressure coefficients verses S_m/A_{ts} are plotted in Figures 36 and 37 for the 30% OAR test section. Also included are several results from the solid wall and 45% OAR test section. Unlike the flat plate results both the base pressure and drag increase with S_m/A_{ts} indicating a strong solid wall type inter-

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ference. Extrapolating the drag and base pressure coefficients to the zero area blockage case results in free air values of about 0.24 and -0.19 respectively. The lower base pressure for this model as compared to the sharp edged block model is in agreement with S.F. Hoerner (1965), who suggests that the base pressure is a function of the separating shear layers and that the thin shear layers produced by good forebody shaping will create lower base pressures than the thick shear layers from bluff forebodies. No accurate comparable reference drag value was found for this model, as the model used by K.R. Cooper (1985) did not have the lower front edge radius and was mounted closer to the groundplane. Comparisons of the changes in drag, base and deduced mean front face pressures (Figure 38) versus area blockage ratio are made in Table 13. The C_D and C_{p_b} numerical data is found in Table 12. Note that for this body shape a change in C_{p_b} of 0.003 will result in a shift in C_D of about 1%. Thus this model shape is quite sensitive to static pressure gradients. From Table 13 it is seen that almost all C_D errors were produced by a base drag increase with generally only a small increase coming from increased frontal pressure. The results from the 45% OAR test section indicate that the base pressure and drag coefficient are substantially corrected for the largest S_m/A_t model, but significant interference still exists. Note that all of the testing for these models was done with the one collector area. Due to the fact that these models are very sensitive to base pressure errors and that the model's bases are much further downstream, particularly for the large area blockage models, as compared to the flat plate models it is likely that some downstream wake blockage interference is propagating upstream to the models. Adjustment of the collector area and lengthening the test section may reduce or remove this interference, permitting a low interference OAR to be determined.

Figure 36 C_p vs Blockage Area Ratio:
Rounded Block Models

Figure 37 C_p vs Area Blockage Ratio
Rounded Blockage Models

Figure 38 Deduced C_p , vs Area Blockage Ratio
Rounded Block Models

OAR	MODEL	$\frac{C_D - C_{Dref}}{C_{Dref}}$ %	$\frac{C_{P_{ref}} - C_{P_b}}{C_{Dref}}$ %	$\frac{C_{P_f} - C_{P_{ref}}}{C_{Dref}}$ %
30%	1	13.5	2.5	11.0
	2	21.5	4.2	17.3
	3	25.3	10.5	14.8
	4	31.2	14.8	16.4
	5	38.8	26.2	12.6
45%	1	10.5	-1.3	11.8
	5	21.1	13.1	8.0

Table 13. Rounded Block Model Coefficient "Errors"
Reference values obtained by extrapolating to $S_m/A_{te} = 0$ condition
 $C_{Dref} = 0.23(7)$, $C_{P_b} = -0.18(7)$, $C_{P_f} = 0.05(0)$

OAR	MODEL	C_D	$-C_{P_b}$
30%	1	0.269	0.193
	2	0.288	0.197
	3	0.297	0.212
	4	0.311	0.222
	5	0.329	0.249
45%	1	0.262	0.184
	5	0.287	0.218

Table 14. Measured Rounded Block Model Coefficients

4.3.2 Test Section Pressure Distributions

The ceiling slat and groundplane pressure distributions for the rounded block models are plotted in Figures 39 to 42. The groundplane distributions have been formed into a signature as per the sharp edged block models. Collapse of the groundplane signatures onto a single trace is quite good for all models indicating similar flow fields. Note the lower approach pressures and the shorter higher pressure wake of this model compared to the flat plate model. Also note the underbody suction peak located where the front edge rounding becomes a tangent with the main body. A small amount of downstream wake blockage interference is the only clearly detectable alteration of the signatures as the S_p/A_{ts} is increased and this clearly results in a lower base pressure, see Figure 37, and consequently a higher C_D . It should be possible to remove this wake interference by use of a longer test section (say $3.5\sqrt{S_m}$ longer behind the model base) or with larger collector areas. The ceiling slat pressure distributions (Figure 41) are as one would expect, substantially reduced in magnitude from those of the flat plate models and sharp edged block models when compared on a S_m/A_{ts} basis. Again it appears that the pressure fields of these models do not influence pressures significantly far upstream of the test section at the ceiling level. Although the 45% OAR test section produced a significant change in the base pressure and drag coefficients, thus reducing the wall interference effects the effect on the groundplane and ceiling slat pressure distributions appears to be quite small. The distributions for the largest (24% S_m/A_{ts}) model in both the 30 and 45% OAR test section are plotted in Figures 40 and 42. The groundplane signature is virtually unchanged (within the experimental accuracy) except near the downstream end of the test section where the wake blockage is slightly reduced and the model base pressure increased (see Figure 37). The 45% OAR slotted walls causes a small reduction of the ceiling slat pressures upstream of the models front face and an increase in pressures between $X/L_{ts} = 0.35$ to 0.65, essentially opposite the model as expected from the "softer"

Figure 39 Groundplane & Pressure Signatures:
Rounded Block Models

Figure 40 Effect of OAR on the Rounded Model Groundplane Pressure Signature

Figure 41 Ceiling Slat Perturbation Pressure Distributions: Rounded Block Models 2

Figure 42 Effect of OAR on the Rounded Model Ceiling Slat Perturbation Pressure Distributions:

boundary.

4.3.3 Model Surface Pressures

The model's roof centerline and the left side beltline static pressures have been plotted in Figures 43 to 48. Except for the previously discussed base pressure no correlated shifts in the model surface pressure are produced (within the experimental accuracy) with either increasing S_m/A_t levels or altering the OAR from 30 to 45%. The effect of the solid wall test section on the model surface pressures is much more dramatic (see Figures 45 and 46), implying large wall interference with much increased "effective" free stream dynamic pressure; as can also be seen on Figures 36 and 37 for C_D and C_p , respectively.

4.4 Groundplane boundary layer

The groundplane boundary layer and its interaction with the vehicle flow field result in it being another form of boundary interference (P.M. Waudby-Smith, W.J. Rainbird (1985)). The determination of groundplane boundary layer interference effects was not a goal of this work but due to the nature of the experimental methods used, changing groundplane boundary layer interference levels has unfortunately formed a portion of the overall measured interference. In order to eliminate the shifts of groundplane boundary layer interference requires that the boundary layer be properly scaled for each model. This was not possible to do in this test program though other actions were implemented to minimize this improper scaling effect.

Figure 43 Rounded Model Surface Pressures
Roof Centerline

Figure 44 Rounded Model Surface Pressures
Left Side Beltline

Figure 45 Effect of OAR on the Rounded Model Roof Centerline Surface Pressures

Figure 46 Effect of OAR on the Rounded Model Left Side Beltline Surface Pressures

Figure 47 Effect of OAR on the Rounded Model
Roof Centerline Surface Pressures

Figure 48 Effect of OAR on the Rounded Model
Left Side Beltline Surface Pressures

The flat plate upstream centerline groundplane non-dimensional pressure field (see Figure 16) clearly indicates that a massive separation of the groundplane boundary layer will occur at about $1\sqrt{S_p}$ ahead of the plate. This results in the horse-shoe vortex. This phenomenon will be common for all the plates tested and it seems reasonable that changes in interference due to groundplane boundary layer/plate scaling error will be small so long as either the resulting horse-shoe vortex flow field has a small influence on the overall flow field or that the vortex flow field is only mildly influenced by scaling errors for the range of plates tested. It would appear that the above does not hold for the smallest (6.7% S_m/A_{ts}) plate. The sharp edged block model is most likely the most effected by improper scaling of the ground plane boundary layer. The upstream pressure field (Figure 24) suggests a groundplane boundary layer separation (less severe than the flat plate model). Interactions between the separated flow field and the under model flow are not likely to be similar for all models though the fairly high ground clearance and clean underbody should minimize the differences. Since the increases in interference levels were relatively large for this model the portion of the interference due to the groundplane boundary layer have probably not altered the results significantly. The rounded block model produces an upstream groundplane pressure field (Figure 39) which would probably not cause the groundplane boundary layer to separate. This favourable pressure field was likely the result of the radius on the lower front edge and high ground clearance (unlike the model tested by K.R. Cooper (1985)). Thus for this case the empty test section boundary layer measurements could be used to estimate the interference level shifts caused by dissimilar boundary layer/model sizing. The ratio of empty test section groundplane boundary layer displacement thickness to block model ground clearance, δ^*/h_{gc} , varies from about 6.5% for the 24% S_m/A_{ts} model to 11% for the 8.16% S_m/A_{ts} model. It is felt that the rounded block models, with an overall height to h_{gc} of 11%, smooth underbody and single support strut would have a groundplane boundary layer sensitivity equal

to or less than the MIRA automobile models which have been tested under varied groundplane boundary layer conditions by Bendtsson et al (1988). Using the same slope of $\Delta C_D / \Delta \dot{\delta}$ from this paper for the MIRA model it was determined that there could be a increase in the rounded block model drag coefficient of about 0.006 as the size of the model was increased from the smallest to largest due to the dissimilar groundplane boundary layers/model, scales. This shift is fairly small compared to the changes in C_D measured between the extreme models.

Chapter 5

Conclusions and Recommendations for Further Study

1. The slotted wall test section was found to provide substantially improved uncorrected model force and pressure data for zero yaw conditions compared to a similarly sized solid wall test section.
2. The area blockage levels presented vastly extends the levels previously tested in a slotted wall type test section.
  - The flat plate test results indicate that all plates (mounted at about $1/3 L_{ts}$ from the upstream end) up to an area blockage ratio of 35.7% (effective body cross sectional area of about $0.80 A_{ts}$) could be tested interference free using a parallel slotted wall test section having an OAR of about 40% and a length of at least $5.7\sqrt{S_p}$
  - For the longer block models it was found that blockage interference effects are not completely removed when using parallel slotted walls of either 30 or 45% OAR with a fixed collector area. For the larger models the test section length becomes relatively too short. Since the near wake

development (base bubble flow, closure and initial non-recirculating wake development) is strongly influenced by downstream conditions the collector area and diffuser must be producing the correct flow field (similar to an adaptive wall) or be sufficiently far downstream of the model base region. In order to perform tests free of the downstream interference "passively" the test section needs to provide a length of about $5\sqrt{S_m}$ between the model base and the downstream end of the test section (for wakes sizes similar to those tested) and employ adjustable collector flaps.

3. Optimum OAR is likely influenced by the slotted wall length ahead of the model. In order to remove this as a variable, tests should be made such that the forebody pressure field is contained within the test section. For the models tested here a length of about $3\sqrt{S_m}$ is required. Typical road vehicles may not require such a large distance.
4. From the test results it is clear that performing lateral wall interference studies with models that have substantial bubble type separations like the sharp edged block models are one of the more difficult test cases since very minor changes in the far field flow conditions can cause significant changes to the near flow field. Flow visualization can be used to assist in determining the interference effects by comparing separation bubble size.
5. The use of bluff models which produce an unfavourable upstream ground-plane pressure field (e.g. flat plate and sharp edged block model) introduce additional interference effects which are probably not present with typical road vehicles and are difficult to separate from the lateral wall interference effects.

Further study into the use of slotted wall test sections for high blockage testing is required. Areas which should be studied include:

Continued scaled tests with simple models (yawed and unyawed) which do not produce an upstream groundplane boundary layer separation to determine best wall OAR (constant or varying between upstream and downstream ends) carried out in a test section with a width to height ratio roughly equal to that of the model and length as given above.

Employ an analytical model based on M. Mokry and J.T. Templin (1986) to predict the freestream and slotted wall flow patterns for the above model and compare. Utilize the program to obtain optimum OAR distribution. Test this optimised slotted wall boundary with the model in the small scale test section.

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Appendix A

Flat Plate Base Flow

As part of the flat plate testing program certain runs were repeated to determine the repeatability of the measurements. It was found in several of these runs where C_{p_b} measurements were remeasured (after the plate had been removed and re-installed in the test section) that a significant change of the base pressure had occurred (on the order of 5%). The drag coefficient also measured during the same run was unchanged. The only known difference between the repeated runs was the orientation and location of the opening of the flexible tube taped to the rear face of the plate. A simple investigation of the effect of orientation of the tube opening on the base pressure measurement was made. The open end of the tube was centrally located on the rear face of the plate and runs were made with the open end facing the groundplane, away from the groundplane and parallel to the groundplane facing either the right or left side. Equal measurements obtained when the tube faced either right or left indicated the base flow was essentially symmetric about the vertical centerline. When the tube end was faced away from the ground the base pressure coefficient increased by about 0.02 from the value obtained with the tube end facing the groundplane. Flow visualization using tufts attached to the rear face of the plate and a streamer confirmed the indications given by the pressure measurements that a significant recirculating mean flow ex-

isted on the base of the plate. This flow on the base of the plate travelled from near the top edge of the plate towards the groundplane where it separated and became entrained in the jet flow passing through the groundplane/plate gap. The streamer measurements indicated a recirculating flow pattern as sketched in Figure A1. To avoid measuring components of the plate base flow standard style surface pressure taps were installed into the plates. The pressure tap was located on the vertical centerline of the plate at an approximately scaled height from the groundplane (geometric dissimilarity of the rear faces of the plates precluded perfect scaling).

Figure A.1 Sketch of Flat Plate Flow Field

Appendix B

Error Analysis

The following is an estimate of the uncertainty of the force and pressure coefficients presented in this work. Standard deviations of repeated measurements were presented along with the measurements on the plots.

B.1 C_D

(For measurement of drag forces greater than 5 lbs)

$$\begin{aligned}C_D &= \frac{D}{q_\infty S} \\ \frac{W_{C_D}}{C_D} &= \left[\left(\frac{W_D}{D} \right)^2 + \left(\frac{W_{q_\infty}}{q_\infty} \right)^2 + \left(\frac{W_S}{S} \right)^2 \right]^{\frac{1}{2}} \\ \frac{W_D}{D} &= 0.002 \\ \frac{W_{\Delta P}}{\Delta P} &= 0.002 \\ q_\infty &= \frac{P_{c1} - P_{c2}}{K1} \\ K1 &= \frac{P_{c1} - P_{c2}}{P_o - P_\infty}\end{aligned}$$

$$\begin{aligned}
\frac{W_{q_{\infty}}}{q_{\infty}} &= \left[2 \left(\frac{W_{(P_{c1}-P_{c2})}}{P_{c1}-P_{c2}} \right)^2 + \left(\frac{W_{(P_o-P_{\infty})}}{P_o-P_{\infty}} \right)^2 \right]^{\frac{1}{2}} \\
\frac{W_{q_{\infty}}}{q_{\infty}} &= 0.0035 \\
S &= h w \\
\frac{W_s}{S} &= \left[2 \left(\frac{W_h}{h} \right)^2 \right]^{\frac{1}{2}} \\
\frac{W_s}{S} &= 0.0067 \\
\frac{W_{C_D}}{C_D} &= 0.0078 \\
&\approx 0.8\%
\end{aligned}$$

B.2 Cp

$$\begin{aligned}
C_{p_{\beta}} &= \frac{P_{\beta} - P_{\infty}}{q_{\infty}} \\
&= \frac{(P_{\beta} - P_{c2}) + K2(P_{c1} - P_{c2})}{q_{\infty}} \\
K2 &= \frac{P_{c2} - P_{\infty}}{P_{c1} - P_{c2}} \\
\frac{W_{C_{p_{\beta}}}}{C_{p_{\beta}}} &= \left[\left(\frac{W_{(P_{\beta}-P_{c2})}}{P_{\beta}-P_{c2}} \right)^2 + \left(\frac{W_{(P_{c2}-P_{\infty})}}{P_{c2}-P_{\infty}} \right)^2 + 2 \left(\frac{W_{(P_{c1}-P_{c2})}}{P_{c1}-P_{c2}} \right)^2 + \left(\frac{W_{q_{\infty}}}{q_{\infty}} \right)^2 \right]^{\frac{1}{2}} \\
\frac{W_{C_{p_{\beta}}}}{C_{p_{\beta}}} &= 0.0053 \\
&\approx .5\%
\end{aligned}$$

From the balance and pressure transducer error plots it can be seen that the errors will be smaller than listed here when tests were made at higher dynamic pressures, maximum drag capability and the larger models.

END

1 9|0 2|9 1

FIN