Experimental Investigation of the Ground Transportation Systems (GTS) Project for Heavy Vehicle Drag Reduction*

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ABSTRACT

A wind tunnel experimental research program was conducted on a heavily instrumented Ground Transportation System (GTS) vehicle. The GTS baseline model represented a generic 1:8 scale Class-8 van-type tractor trailer geometry. Five base drag reduction add-on devices, instrumented with surface pressure ports, were also tested. These add-on devices included two ogive boattail shapes and three slant geometry devices.

Six component force and moment data, surface pressure contours, and wake velocity surveys are presented for each configuration along with qualitative insights gained from flow visualization.

This wind tunnel program was designed to complement a parallel research effort in computational fluid dynamics (CFD) which modeled many of these same vehicle geometries. The wind tunnel data are documented and archived in ASCII format on floppy discs and available to researchers interested in further analysis or comparison to other CFD solutions.

NOMENCLATURE

a	Speed of sound
S	Reference area, $S = hw = 10.66 \text{ m}^2$ (114.75 ft ²) full scale
A	Body axis axial force (positive in the positive x_{axis} direction, Figure 5)
C_A	Axial force coefficient; $C_A = A/q_{\infty}S$
C_D	Drag force coefficient; $C_D = D/q_{\infty}S$
C_l	Rolling moment coefficient; $C_l = l/q_{\infty}Sw$
C_m	Pitching moment coefficient; $C_m = m/q_{\infty}Sw$
C_n	Yawing moment coefficient; $C_n = n/q_{\infty}Sw$
C_N	Normal force coefficient; $C_N = N/q_{\infty}S$
C_P	Static pressure coefficient; $C_P = (P - P_{\infty})/q_{\infty}$
C_Y	Side force coefficient; $C_Y = Y/q_{\infty}S$
D	Drag force
h	Trailer height (measured to bottom of tires), $h = 4.11 \text{ m}$ (13.50 ft) full scale
l	Body axis rolling moment (positive clockwise about MRP, driver's view looking forward)

m	Body axis pitching moment (positive nose up about MRP, driver's view looking forward)
M	Mach number, $M = V/a$
MRP	Body axis moment reference point, center of the rear axles of the tractor at ground level ($x/w = 2.451$, $y/w = -0.196$, $z/w = 0.0$)
n	Body axis yawing moment (positive nose right about MRP, driver's view looking forward)
N	Body axis normal force (positive in positive y_{axis} direction, Figure 5)
P	Static pressure
q	Dynamic pressure; $q = 0.5\rho V^2$
Re_w	Reynolds number, $Re_w = \rho V w / \mu$
V	Velocity
w	Trailer width, 2.59 m (8.50 ft) full scale
x, y, z	Body axis cartesian coordinates, often non-dimensionalized by trailer width, w (e.g., x/w)
x'/w	Body axis distance behind trailer (non-dimensionalized, as measured in positive x_{axis} direction, Figure 5)
Y	Body axis side force (positive in negative z_{axis} direction, Figure 5)
ρ	Density
μ	Viscosity
Ψ	Yaw angle
$B_N W_A$	GTS Baseline, with No add-on, Wheels Attached
$B_N W_R$	GTS Baseline, with No add-on, Wheels Removed
$B_{O5} W_A$	GTS Baseline, with 5 ft Ogive, Wheels Attached
$B_{O5} W_R$	GTS Baseline, with 5 ft Ogive, Wheels Removed
$B_{O8} W_A$	GTS Baseline, with 8 ft Ogive, Wheels Attached
$B_{O8} W_R$	GTS Baseline, with 8 ft Ogive, Wheels Removed
$B_{S5} W_A$	GTS Baseline, with 5° Slant, Wheels Attached
$B_{S5} W_R$	GTS Baseline, with 5° Slant, Wheels Removed
$B_{S12.5} W_A$	GTS Baseline, with 12.5° Slant, Wheels Attached
$B_{S12.5} W_R$	GTS Baseline, with 12.5° Slant, Wheels Removed
$B_{S30} W_A$	GTS Baseline, with 30° Slant, Wheels Attached
$B_{S30} W_R$	GTS Baseline, with 30° Slant, Wheels Removed

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MASTER
Subscripts
∞ freestream value
w denotes based on width

INTRODUCTION

Sandia National Laboratories has undertaken a research project to investigate the aerodynamics of a general class of Ground Transportation Systems (GTS)¹. The project goal was to investigate the base flow of a generic Class-8 van-type tractor trailer and gain information useful for base drag reduction. This project had complementary programs in computational fluid dynamics (CFD)² and in experimental wind tunnel testing.

The baseline GTS model shape was chosen to represent the geometry of a family of heavy ground transportation vehicles but without the added complexity of tractor-trailer gap, wheel wells, and rough under belly which vary amongst trucks, buses, and trains and would complicate the CFD grid generation.

Five add-on base drag reduction devices were investigated. Two of these were ogival boattails and three were designs similar to the Ahmed et al.³ add-on slants.

The experimental program described in this paper was conducted in a 2.13 m x 3.05 m (7 ft x 10 ft) wind tunnel at a model width based Reynolds number of 1.6 million for the 1:8 scale model. This represents the highest Reynolds number achievable in the wind tunnel without exceeding the maximum load on the external balance-side force gage. At 29 m/s (60 m.p.h.), the full scale GTS vehicle Reynolds number is 4.8×10^6 . The baseline GTS vehicle model and the five add-on base drag reduction devices were instrumented with internally mounted pressure scanners to obtain 109 surface pressure measurements. Six component force and moment data were obtained on all test configurations at yaw angles to ± 14 degrees. The body surface flow was investigated with oil flow and tufts. The body external flow field was visualized using smoke and a rectangular tufted grid. The model base region wake flow was extensively mapped with a computer driven 7-hole wake pressure probe for the GTS baseline configuration and each of the five add-on drag reduction devices.

Data comparing the baseline GTS geometry and the add-on drag reduction devices, surface pressure contours and wake velocity profiles are presented for each configuration. The effectiveness of these devices, analysis of the test results and the qualitative insights gained from flow visualization are also presented.

WIND TUNNEL DESCRIPTION

The Texas A&M University Low Speed Wind Tunnel⁴ is a closed circuit single return type facility shown in Figure 1. The total circuit length at the center line is 121.3 m (398 ft). The rectangular test section is 2.13 m (7 ft) high, 3.05 m (10 ft) wide, and 3.66 m (12 ft) long. Cross sectional area of the test section is 6.3 m^2 (68 ft^2). The corners have 0.305 m (1 ft) fillets which house fluorescent lamps to provide photographic lighting. Vertical venting slots in the side walls at the test section exit maintain near atmospheric static pressure in the test section. The test section side walls diverge about 0.4 degrees to account for boundary layer growth. A 3.81 m (12.5 ft) diameter, four blade propeller operating at 900 RPM provides the air flow in the wind tunnel. The test section dynamic pressure between zero and 4.79 kPa (100 psf) can be obtained by proper propeller blade pitch angle positioning.

The measured tunnel flow angularity is less than $\pm 0.25 \text{ deg}$ ⁴. Boundary layer thickness⁵ at the test section entrance is 3.8 cm (1.5 in) and at the exit is 8.9 cm (3.5 in). The tunnel turbulence factor⁶ is less than 1.1. The wind tunnel balance is a six-component pyramidal balance that resolves the aerodynamic loads into three orthogonal forces and their associated moments. The forces and moments are accurate to $\pm 0.1\%$ of the measurement or $\pm 0.1 \text{ lbs}$ or ft-lbs , whichever is greater⁴.

A turntable 2.13 m (7 ft) in diameter built into the test section floor rotates with the external balance system to provide remote model positioning. The GTS model was mounted in the test section using the external balance's two base mount support struts as shown in Figure 2. All testing was performed with the wheels located 1.27 cm (0.5 in) above the test section floor. This wheel clearance corresponds to the CFD modeling and keeps the model from grounding on the tunnel floor, based on TAMU operating experience. Because of the greater interest in the base drag reduction the model was positioned forward in the test section as depicted in Figure 3. A view looking upstream of the GTS Baseline model in the test section is shown in Figure 4.

MODEL DESCRIPTION

The GTS baseline model configuration represents a generic 1:8 scale Class-8 van-type tractor trailer geometry. The model structure was built around a 15.25 cm (6 in) aluminum I beam running approximately 85% of the model length. All flat surfaces were produced from aluminum sheet goods. All curved surfaces were machined from Ren Shape 450. The wheel assemblies were machined from aluminum bar stock. The wheels were easily removed for comparative testing. Figure 5 shows the GTS baseline dimensions non-dimensionalized by the model trailer width which was 32.385 cm (12.75 in).

Five base drag reduction add-on devices were also fabricated for attachment to the upper rear of the GTS baseline configuration. Two of these were ogival shapes defined in Figure 6 and Figure 7, designated as the 5 ft and 8 ft Ogive Boattail geometries. The 5 ft and 8 ft correspond to the overall length of the full size add-on device. The ogive surfaces are tangent at the top of the trailer and on the sides. The boattail is square at the base of the trailer and linearly transitions to a circle at the boattail base. Computational fluid dynamics simulations of these ogive boattails are presented in Ref. 2. The remaining three add-on devices were 5, 12.5, and 30 degree slants fabricated from aluminum sheet and described in Figure 8. These slant designs are of similar geometry to the Ahmed et al.³ add-on slants. Reference 1 provides a detailed discussion of the reasons for selecting these particular add-on devices.

INSTRUMENTATION

All of the above model configurations were instrumented with internally mounted pressure scanners to obtain surface pressure measurements. The distribution of pressure port locations is indicated by the small circles on the model drawings (Figure 5 through Figure 8) and the coordinates of the pressure port locations are documented in Appendix A. Note that the majority of pressure ports are located on the model symmetry plane and the base region. Figure 9 shows a portion of the sur-

face pressure instrumentation installed in the GTS baseline configuration.

A 7-hole pressure probe was used to obtain three orthogonal velocity components at discrete points in the wake region behind all the GTS configurations at several axial stations and model yaw angles. This probe was mounted to and remotely positioned by the computer controlled traversing mechanism. Figure 10 shows the pressure probe performing a survey behind the 5° slant. The seven hole probe measures flow angles to $\pm 1.5^\circ$ and velocities to $\pm 1.0\%$. The traversing mechanism positioned the probe at a given Y,Z coordinate location to within ± 0.0127 cm (± 0.005 in). The X or longitudinal position of the probe is manually set with an accuracy of ± 0.0127 cm (± 0.005 in)⁸. Wake velocity surveys were conducted at four longitudinal stations as referenced to the base surface of the GTS baseline model configuration. They were: Station 1 = 11.43 cm (4.5 in); Station 2 = 22.86 cm (9.0 in); Station 3 = 34.29 cm (13.5 in); and Station 4 = 45.72 cm (18.0 in). All velocities were non-dimensionalized by the freestream velocity.

Four methods of flow visualization were used during this test program. General flow over the model was investigated using the wind tunnel's smoke wand. Figure 11 shows the shear layer rolling into a longitudinal vortex for the baseline model at -10° yaw. Surface flow on the body was visualized using either yarn tufts taped to the body or by oil flow using a mixture of tempera paint and diesel fuel painted on the model surface. Yarn tufts as shown in Figure 12 for the 5 ft boattail have the advantage of continually tracking changing tunnel conditions, thus allowing an entire yaw angle sweep to be performed. The oil flow mixture defines the streamlines directly on the surface by leaving the tempera paint on the surface when the diesel fuel evaporates due to the air flow as illustrated in Figure 13. However, the oil flow technique required a separate repainting for each yaw angle. The wake flows were visualized by attaching a 61X61 cm (24X24 in) yarn tuft grid (Figure 14) to the tunnel traversing mechanism. The tuft grid had 5 cm (2 in) streamers at every 2.54 cm (1 in) grid point. The tuft grid essentially provided a visual representation of the seven hole pressure probe wake survey data. A 35 mm still camera and three VHS video cameras were used to document the test, including all the flow visualization.

DATA REDUCTION

All force and moment data were corrected for static tare values and then reduced to coefficient form based upon the frontal area of the model (S) and the model width (w). The data were then transferred from wind axis balance center coordinates to the body axis model center coordinate system. The center of the model was defined as the center of the rear wheels of the tractor at ground level. The wind axis coordinates are aligned with the relative wind and do not rotate with the model, whereas the body axis coordinates are fixed to the model and remain aligned with it through yaw angle changes so that axial force is always along the longitudinal axis of the model and side force is always perpendicular to the side of the vehicle. All data in this paper are presented in body axis coordinates.

The wind-averaged drag coefficient values presented in Figure 15 and Figure 16 are based on the SAE Recommended Practice⁷ which assumes that the mean wind speed in the Unit-

ed States of 7 mph has an equal probability of approaching the vehicle from any direction. This mean wind speed and forward truck velocities of 30 and 55 mph are then used to obtain a weighted average of the drag coefficient at various yaw angles.

An uncertainty analysis documented in Reference 8 shows an uncertainty in force and moment coefficients of approximately $\pm 0.25\%$. Uncertainty estimates for pressure coefficients vary from $\pm 1.0\%$ to $\pm 1.5\%$ depending on the full scale range of the pressure transducer.

EXPERIMENTAL PROCEDURE

The Run Schedule of all the quantitative data presented in this paper is summarized in Appendix B. This schedule provides the actual test run number, the configuration type, the measurement type, and the applicable model fixed yaw angle or yaw angle sweep range. There were three quantitative measurement types: Wake Pressure Surveys, Force and Moment, and Surface Pressure. The Force/Moment and the Surface Pressure measurements were always taken simultaneously on the same wind tunnel run and over a yaw sweep range of $\pm 14^\circ$. The Wake Pressure Survey data were acquired on separate tunnel runs at fixed model yaw angles and with the probe tip located at one or more of the four previously defined longitudinal Stations (1-4). Appendix C defines the content, format, and nomenclature of the 3.5" DOS ASCII floppy disk, and the information on requesting this disk which contains the reduced coefficient data of the Run Schedule listed in Appendix B. Runs not listed in Appendix B were primarily for static tare data and flow visualization. The full Run Schedule is documented in Reference 8.

Table 1 describes the nominal wind tunnel test conditions employed for each type of measurement condition. The yaw angle increment for the yaw sweeps (ψ) was 2.5 degrees up to angles of 12.5 degrees, (with a maximum yaw angle of 14 degrees to avoid exceeding yawing moment gage limits), for all force & moment and surface pressure measurements.

Table 1 Wind Tunnel Test Conditions

Measurement	Velocity KPH (FPS)	Re _w x10 ⁻⁶	ψ degrees
Force & Moment	285 (260)	1.6	Sweep ± 14
Surface Pressure	285 (260)	1.6	Sweep ± 14
Wake Pressure	285 (260)	1.6	0, -10
Oil Flow	285 (260)	1.6	0, -5, -10
Body Tufts	216 (197)	1.2	0, ± 5 , ± 10
Wake Tufts	216 (197)	1.2	0, ± 5 , ± 10
Smoke	33 (30)	0.2	0, ± 5 , ± 10

RESULTS

The wind tunnel measurements are presented as reduced data coefficients in the form of plots comparing and contrasting the GTS baseline vehicle (with and without wheels) and the five add-on drag reduction devices. The results are organized into the following six areas:

1. Axial Force ("Drag") Coefficient Comparison
2. Six Component Force & Moment
3. Vehicle Horizontal Plane Static Pressure
4. Vehicle Symmetry Plane Static Pressure
5. Vehicle Base Surface Static Pressure Contours
6. Wake Velocity Vector Surveys

1. DRAG - Figure 15 presents a comparison of the Axial Force ("Drag") Coefficient for the Baseline model with wheels and the five add-on devices. The 12.5° Slant is seen to have minimum drag at 0° yaw, with a 7.6% reduction compared to the Baseline vehicle, but the 8 ft Ogive is more effective overall. The performance of the 5 ft Ogive was below expectation based on CFD predictions¹. The drag data for the three slants mirror the performance documented by Ahmed et al.³ Figure 16 provides the same comparison but with the wheels removed and again the 8 ft Ogive provides the best overall drag reduction.

2. SIX COMPONENT FORCE & MOMENT - Figure 17 through Figure 22 show the effects of the Ogives on the six component Force and Moment Coefficients. The data for the Baseline with attached Ogives are contrasted with the Baseline (B_{NWA}), and the Baseline without wheels (B_{NWR}). The 5 ft Ogive does not significantly affect Axial Force except at higher yaw angles than would occur at highway conditions. Likewise the Yawing Moment indicates less stability, but is not a problem under normal conditions. Yawing Moment for the 8 ft Ogive drops abruptly for yaw angles greater than 7.5 possibly due to flow separation over the base region. Figure 23 through Figure 28 show the effects of the Slants on the six component Force & Moment Coefficients. The Axial Force Coefficient for the 30° Slant increases rapidly with yaw. Because all of the Slants have the same length, their respective Side Force and Rolling Moments are similar when contrasted with the Baseline vehicle. Likewise the Yawing Moments for the three Slants track each other closely.

3. HORIZONTAL PLANE STATIC PRESSURE - Figure 29 through Figure 34 are a family of plots which examine the effect which the five add-on devices have on the Horizontal Plane Static Pressure Coefficient, C_p , as a function of the non-dimensional body axial station, x/w . The Horizontal Plane is parallel to the X-Z plane of Figure 5 at the midpoint between the top of the trailer and the underbelly, station $y/w=0.7$, and includes the pressure ports on the front of the cab to the rear of the trailer in addition to the mid-height pressure ports on each of the add-on devices. Data are presented for all configurations at 0° yaw, and at 10° yaw with separate symbols to indicate the windward and leeward side of the model.

For all of these configurations, on the front of the vehicle ($x/w=0$) the stagnation pressure is high, the pressure drops as the flow expands and accelerates around the front corners of the

cab, the static pressure then remains relatively constant along the sides of the vehicle to the base region ($x/w=7.3$). The pressure curves in the base region ($x/w>7.3$) indicate the effect of the add-on devices. For the Ogives of Figure 30 and Figure 31, there is again a static pressure drop (greater for 5 ft Ogive) as the flow expands around the curved surface until the pressure abruptly recovers at the corner of the flat rear base. For the Slants, the Horizontal C_p shows little differentiation as was anticipated since the geometries look identical in this plane.

4. SYMMETRY PLANE STATIC PRESSURE - Figure 35 through Figure 40 are another family of plots which map the Static Pressure Coefficient in the Symmetry Plane for the Baseline model and the add-on devices. The Symmetry Plane is parallel to the X-Y plane of Figure 5, at the $z/w=0$ vertical symmetry plane and includes the surface pressure ports intersected by this plane. Data are presented at 0° and 10° yaw for all configurations. The portion of the curve on the left for all plots defines the C_p on the front (cab) of each vehicle and is seen to be virtually identical for all configurations. The nearly vertical portion of curves in the center of the plots indicate the C_p on the back (base) of the vehicle. Thus the difference between these front and back C_p curves can be viewed as a measure of the vehicle drag. The 8 ft Ogive base region C_p curve is larger than for the 5 ft Ogive indicating more pressure recovery and less drag. The 12.5° Slant base region C_p curve is more positive than the 5° Slant, implying less drag, but comparable to the 30°. The 30° Slant C_p however has significant area on its upper surface at a lower pressure, as seen by the upper spike in the plot, which increases its overall drag.

5. BASE SURFACE STATIC PRESSURE - Figure 41 through Figure 46 show the Base Static Pressure Coefficient as a contour plot mapped on the model base, viewed from behind the trailer, looking forward. These plots are for all configurations at 0° yaw. Figure 47 through Figure 52 show the same family of plots for -10° yaw. The small open circles on these plots represent the location of the surface pressure ports which are shown mirrored about the vertical symmetry plane. Figure 5 through Figure 8 show the actual distribution of ports and their locations are defined in Appendix A. The 0° yaw surface pressure data are mirrored and interpolated to present these contour plots. Figure 47 through Figure 52 include the interpolated data from both the +10° and -10° yaw runs which are plotted on the same figure. The light areas indicate regions of higher surface pressure.

6. WAKE VELOCITY - Figure 53 through Figure 69 show the wake velocity projected in the Y-Z plane of Figure 5, non-dimensionalized by the free stream velocity. Wake surveys were obtained in four planes aft of the base of the trailer at Stations 1-4, and at 0° and -10° yaw, for selected configurations. The 7-hole pressure probe used for these surveys provided valid data if the angle of attack of the probe relative to the local flow direction was less than 70°. Regions of the flow where this condition is exceeded are indicated by disproportionately large arrows or deviation from a pattern or trend. Although more sophisticated probes and correction techniques are available to measure these recirculating flows it was not possible for this test due to cost and time limitations. Note that the projected profile of the trailer base has been overlaid on the plane of these plots for reference.

Figure 53, Figure 54, Figure 56, and Figure 57 illustrate the Wake Velocity Vectors at Stations 1-4 behind the Baseline model at 0° yaw. Uniform convergence of the wake behind the trailer is noted for increasing distance downstream. Figure 55 and Figure 58 show the wake structure at Stations 2 & 4 for the Baseline model with no wheels for comparison.

Figure 59 through Figure 63 show the Wake Velocity Vectors behind the Ogives and Slants, at 0° yaw, and at the closest survey station to each add-on device. The Ogives display a similar uniform flow pattern over their upper surface and indication of recirculating flow behind the rear flat face. The 5° and 12.5° Slants show similar flow patterns with the 12.5° Slant starting to develop a vortex pattern on the upper corners which becomes more pronounced on the 30° Slant.

Figure 64 through Figure 69 compare the Wake Velocity Vectors at Stations 2 & 4 and -10° yaw for the Baseline, 5 ft Ogive, and 12.5° Slant. In all cases the vortex structure becomes more defined and distinct as it moves downstream from Station 2 to 4. Because these are time averaged surveys it can be inferred that these vortex structures are very stable.

SUMMARY

This wind tunnel test program was conducted on a generic Ground Transportation Systems (GTS) Baseline vehicle and five add-on drag reduction devices. The Baseline GTS configuration represents the generic features of a 1:8 scale Class-8 van-type tractor trailer geometry. The test focus was to investigate the trailer base region flow and evaluate the effectiveness of two ogive boattails and three Ahmed et al.³ slant-style add-on devices to manage this base flow to reduce base drag. The force and moment, wind-averaged drag, surface pressure, and wake pressure survey experimental database obtained are available to other researchers (see Appendix C) and has been used for comparison to analytical and CFD results¹.

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REFERENCES

- ¹ Gutierrez, W. T., Hassan, B., Croll, R.H., Rutledge, W.H., "Aerodynamics Overview of the Ground Transportation Systems (GTS) Project for Heavy Vehicle Drag Reduction", SAE Publication 960906 SP-1145, 1996 SAE International Congress and Exposition, February, 1996.
- ² Hassan, B., Gutierrez, W. T., Wolfe, W. P., Walker, M. A., Ruefer, B. G., and Hurt, J. W., "Numerical Prediction of Aerodynamic Drag for Heavy Ground Transportation Vehicles," AIAA 95-1913, 13th AIAA Applied Aerodynamics Conference, June 19-22, 1995.
- ³ Ahmed, S. R., Ramm, G., and Faltin, G., "Some Salient Features of the Time-Averaged Ground Vehicle Wake," SAE Paper No. 840300, 1984.

⁴ *Low Speed Wind Tunnel Facility Handbook*, Aerospace Engineering Division, Texas Engineering Experimental Station, The Texas A&M University System, College Station, TX, 1985.

⁵ Nicks, O. W., and Ferrell, W., "Boundary Layer Profile Measurements On The Floor Of The 7' X 10' Low Speed Wind Tunnel," TEES Report No. TR-8130, Texas A&M University, College Station, TX, January, 1982.

⁶ Hafermalz, S., and Steen, G., "Freestream Turbulence Intensity Measurements In The Texas A&M University Low Speed Wind Tunnel" TEES Report No. TR-9211, Texas A&M University, College Station, TX, July, 1992.

⁷ "SAE Wind Tunnel Test Procedure for Trucks and Buses," SAE J1252 JUL81, SAE Recommended Practice, July 1981.

⁸ Steen, G., "Subsonic Wind Tunnel Test of the Sandia National Laboratories Ground Transportation Vehicle," TEES Report No. TR-9514, Texas A&M University, College Station, TX, July, 1995.

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Figure 1. Texas A&M University Low Speed Wind Tunnel facility diagram (dimensions in feet).

Figure 2. GTS Model installation side view (dimensions in inches).

Figure 3. GTS Model installation top view (dimensions in inches).

Figure 4. View Looking Upstream of the GTS Baseline Model in the Test Section

Figure 5. Dimensioned GTS Baseline Geometry including pressure tap locations.

Non-dimensionalized with
base trailer width, w

Figure 6. 5 ft Ogive Boattail including pressure tap locations.

Non-dimensionalized with
base trailer width, w

Figure 7. 8 ft Ogive Boattail including pressure tap locations.

Non-dimensionalized with
base trailer width, w

Figure 8. Slants 5° , 12.5° , 30° including pressure tap locations.

Figure 9. Surface pressure instrumentation.

Figure 12. Surface tufts on 5 ft Boattail.

Figure 10. Wake pressure survey probe behind 5° Slant.

Figure 13. Oil flow on 5 ft Boattail at $\Psi = -5^\circ$.

Figure 11. Smoke flow visualization.

Figure 14. Wake tuft grid.

Figure 15. Axial Force ("Drag") Coefficient Comparison with Wheels.

Figure 16. Axial Force ("Drag") Coefficient Comparison without Wheels.

Figure 17. Effect of Ogives on Normal Force.

Figure 20. Effect of Ogives on Pitching Moment.

Figure 18. Effect of Ogives on Side Force.

Figure 21. Effect of Ogives on Yawing Moment.

Figure 19. Effect of Ogives on Axial Force.

Figure 22. Effect of Ogives on Rolling Moment.

Figure 23. Effect of Slants on Normal Force.

Figure 26. Effect of Slants on Pitching Moment.

Figure 24. Effect of Slants on Side Force.

Figure 27. Effect of Slants on Yawing Moment.

Figure 25. Effect of Slants on Axial Force.

Figure 28. Effect of Slants on Rolling Moment.

Figure 29. GTS Baseline, Horizontal Plane Static Pressure Coefficient.

Figure 32. GTS Baseline with 5° Slant, Horizontal Plane Static Pressure Coefficient.

Figure 30. GTS Baseline with 5 ft Ogive, Horizontal Plane Static Pressure Coefficient.

Figure 33. GTS Baseline with 12.5° Slant, Horizontal Plane Static Pressure Coefficient.

Figure 31. GTS Baseline with 8 ft Ogive, Horizontal Plane Static Pressure Coefficient.

Figure 34. GTS Baseline with 30° Slant, Horizontal Plane Static Pressure Coefficient.

Figure 35. GTS Baseline, Symmetry Plane Static Pressure Coefficient.

Figure 38. GTS Baseline with 5° Slant, Symmetry Plane Static Pressure Coefficient.

Figure 36. GTS Baseline with 5 ft Ogive, Symmetry Plane Static Pressure Coefficient.

Figure 39. GTS Baseline with 12.5° Slant, Symmetry Plane Static Pressure Coefficient.

Figure 37. GTS Baseline with 8 ft Ogive, Symmetry Plane Static Pressure Coefficient.

Figure 40. GTS Baseline with 30° Slant, Symmetry Plane Static Pressure Coefficient.

Figure 41. GTS Baseline, 0° Yaw, Base Static Pressure Coefficient.

Figure 44. GTS Baseline with 5° Slant, 0° Yaw, Base Static Pressure Coefficient.

Figure 42. GTS Baseline with 5 ft Ogive, 0° Yaw, Base Static Pressure Coefficient.

Figure 45. GTS Baseline with 12.5° Slant, 0° Yaw, Base Static Pressure Coefficient.

Figure 43. GTS Baseline with 8 ft Ogive, 0° Yaw, Base Static Pressure Coefficient.

Figure 46. GTS Baseline with 30° Slant, 0° Yaw, Base Static Pressure Coefficient.

Figure 47. GTS Baseline, -10° Yaw, Base Static Pressure Coefficient.

Figure 50. GTS Baseline with 5° Slant, -10° Yaw, Base Static Pressure Coefficient.

Figure 48. GTS Baseline with 5 ft Ogive, -10° Yaw, Base Static Pressure Coefficient.

Figure 51. GTS Baseline with 12.5° Slant, -10° Yaw, Base Static Pressure Coefficient.

Figure 49. GTS Baseline with 8 ft Ogive, -10° Yaw, Base Static Pressure Coefficient.

Figure 52. GTS Baseline with 30° Slant, -10° Yaw, Base Static Pressure Coefficient.

Figure 53. GTS Baseline, 0° Yaw, Wake Velocity Vectors at Station 1.

Figure 54. GTS Baseline, 0° Yaw, Wake Velocity Vectors at Station 2.

Figure 55. GTS Baseline, 0° Yaw, (No Wheels), Wake Velocity Vectors at Station 2.

Figure 56. GTS Baseline, 0° Yaw, Wake Velocity Vectors at Station 3.

Figure 57. GTS Baseline, 0° Yaw, Wake Velocity Vectors at Station 4.

Figure 58. GTS Baseline, 0° Yaw, (No Wheels), Wake Velocity Vectors at Station 4.

Figure 59. GTS Baseline with 5 ft Ogive, 0° Yaw, Wake Velocity Vectors at Station 2.

Figure 62. GTS Baseline with 12.5° Slant, 0° Yaw, Wake Velocity Vectors at Station 2.

Figure 60. GTS Baseline with 8 ft Ogive, 0° Yaw, Wake Velocity Vectors at Station 3.

Figure 63. GTS Baseline with 30° Slant, 0° Yaw, Wake Velocity Vectors at Station 2.

Figure 61. GTS Baseline with 5° Slant, 0° Yaw, Wake Velocity Vectors at Station 2.

Figure 64. GTS Baseline, -10° Yaw, Wake Velocity Vectors at Station 2.

Figure 65. GTS Baseline with 5 ft Ogive, -10° Yaw, Wake Velocity Vectors at Station 2.

Figure 66. GTS Baseline with 12.5° Slant, -10° Yaw, Wake Velocity Vectors at Station 2.

Figure 67. GTS Baseline, -10° Yaw, Wake Velocity Vectors at Station 4.

Figure 68. GTS Baseline with 5 ft Ogive, -10° Yaw, Wake Velocity Vectors at Station 4.

Figure 69. GTS Baseline with 12.5° Slant, -10° Yaw, Wake Velocity Vectors at Station 4.

Appendix A. Surface Pressure Port Locations

Table A.1. GTS Baseline

Port No.	x/w	y/w	z/w
1	.0000	.3529	.0000
2	.0000	.7059	.0000
3	.4521	1.2467	.0000
4	1.1765	1.3922	.0000
5	1.5882	1.3922	.0000
6	2.0000	1.3922	.0000
7	3.1765	1.3922	.0000
8	4.3529	1.3922	.0000
9	5.5294	1.3922	.0000
10	6.7059	1.3922	.0000
11	7.1176	1.3922	.0000
12	7.2353	1.3922	.0000
13	7.3529	1.3922	.0000
14	7.4706	1.3922	.0000
15	7.5882	1.3922	.0000
16	7.3529	1.3922	-.4412
17	7.1176	1.3922	.4412
18	7.2353	1.3922	.4412
19	7.3529	1.3922	.4412
20	7.4706	1.3922	.4412
21	7.5882	1.3922	.4412
22	7.3529	1.3922	.2206
23	.2353	.6961	.5000
24	.8235	.6961	.5000
25	1.4118	.6961	.5000
26	2.0000	.6961	.5000
27	3.1765	.6961	.5000
28	4.3529	.6961	.5000
29	5.5294	.6961	.5000
30	6.7059	.6961	.5000
31	7.1176	.6961	.5000
32	7.2353	.6961	.5000
33	7.3529	.6961	.5000
34	7.4706	.6961	.5000
35	7.5882	.6961	.5000
36	7.3529	1.0147	.5000
37	7.3529	.3775	.5000
38	7.1176	1.3333	.5000
39	7.2353	1.3333	.5000
40	7.3529	1.3333	.5000
41	7.4706	1.3333	.5000
42	7.5882	1.3333	.5000
43	7.1176	.0588	.5000
44	7.2353	.0588	.5000
45	7.3529	.0588	.5000
46	7.4706	.0588	.5000

Table A.1. GTS Baseline

Port No.	x/w	y/w	z/w
47	7.5882	.0588	.5000
48	.0344	.0344	.0000
49	.6896	.0000	.0000
50	1.3448	.0000	.0000
51	2.0000	.0000	.0000
52	3.1765	.0000	.0000
53	4.3529	.0000	.0000
54	5.5294	.0000	.0000
55	6.7059	.0000	.0000
56	7.1176	.0000	.0000
57	7.2353	.0000	.0000
58	7.3529	.0000	.0000
59	7.4706	.0000	.0000
60	7.5882	.0000	.0000
61	.8235	.6961	-.5000
62	4.3529	.6961	-.5000
63	7.3529	.6961	-.5000
64	7.6471	1.3333	.4412
65	7.6471	1.0147	.4412
66	7.6471	.6961	.4412
67	7.6471	.3775	.4412
68	7.6471	.0588	.4412
69	7.6471	1.3333	.2206
70	7.6471	1.0147	.2206
71	7.6471	.6961	.2206
72	7.6471	.3775	.2206
73	7.6471	.0588	.2206
74	7.6471	1.3333	.0000
75	7.6471	1.0147	.0000
76	7.6471	.6961	.0000
77	7.6471	.3775	.0000
78	7.6471	.0588	.0000
79	7.6471	.6961	-.4412

Table A.2. 5 ft Ogive Boattail

Port No.	x/w	y/w	z/w
110	7.9882	1.3460	.0000
111	8.0824	1.3150	.0000
112	8.1765	1.2751	.0000
113	7.7059	1.3824	.4902
114	7.8000	1.3581	.4660
115	7.8941	1.3268	.4347
116	7.9882	1.2887	.3965
117	8.0824	1.2435	.3513
118	8.1765	1.1907	.2986
119	7.7059	.8922	.4990
120	7.8000	.8922	.4915
121	7.8941	.8922	.4765
122	7.9882	.8922	.4538
123	8.0824	.8922	.4228
124	8.1765	.8922	.3829
125	7.7059	.4020	.4902
126	7.8000	.4262	.4660
127	7.8941	.4575	.4347
128	7.9882	.4956	.3965
129	8.0824	.5409	.3513
130	8.1765	.5936	.2986
131	7.7059	.3932	.0000
132	7.8000	.4006	.0000
133	7.8941	.4156	.0000
134	7.9882	.4384	.0000
135	8.0824	.4693	.0000
136	8.1765	.5093	.0000
137	7.9882	.4956	-.3965
138	7.9882	.8922	-.4538
139	7.9882	1.2887	-.3965

Table A.2. 5 ft Ogive Boattail

Port No.	x/w	y/w	z/w
100	8.2353	.8922	.0000
101	8.2353	1.1863	.0000
102	8.2353	1.1002	.2080
103	8.2353	.8922	.2941
104	8.2353	.6842	.2080
105	8.2353	.5980	.0000
106	8.2353	.8922	-.2941
107	7.7059	1.3911	.0000
108	7.8000	1.3837	.0000
109	7.8941	1.3687	.0000

Table A.3. 8 ft Ogive Boattail

Port No.	x/w	y/w	z/w
200	8.5882	.8922	.0000
201	8.5882	1.1275	.0000
202	8.5882	1.0585	.1664
203	8.5882	.8922	.2353
204	8.5882	.7258	.1664
205	8.5882	.6569	.0000
206	8.5882	.8922	-.2353
207	7.7059	1.3916	.0000
208	7.8706	1.3818	.0000
209	8.0353	1.3595	.0000
210	8.2000	1.3244	.0000
211	8.3647	1.2129	.0000
212	8.5294	1.2125	.0000

Table A.3. 8 ft Ogive Boattail

Port No.	x/w	y/w	z/w
213	7.7059	1.3871	.4949
214	7.8706	1.3620	.4699
215	8.0353	1.3248	.4326
216	8.2000	1.2752	.3831
217	8.3647	1.2125	.3203
218	8.5294	1.1371	.2449
219	7.7059	.8922	.4995
220	7.8706	.8922	.4896
221	8.0353	.8922	.4674
222	8.2000	.8922	.4322
223	8.3647	.8922	.3207
224	8.5294	.8922	.3204
225	7.7059	.3973	.4949
226	7.8706	.4223	.4699
227	8.0353	.4595	.4326
228	8.2000	.5091	.3831
229	8.3647	.5718	.3203
230	8.5294	.6472	.2449
231	7.7059	.3927	.0000
232	7.8706	.4022	.0000
233	8.0353	.4248	.0000
234	8.2000	.4599	.0000
235	8.3647	.5715	.0000
236	8.5294	.5718	.0000
237	8.2000	.5091	-.3831
238	8.2000	.8922	-.4322
239	8.2000	1.2752	-.3831

Table A.4. 5 deg Slant

Port No.	x/w	y/w	z/w
300	7.7080	1.2836	.5000
301	7.9335	1.2836	.5000
302	8.1589	1.2836	.5000
303	7.7080	.6712	.5000
304	7.9335	.6712	.5000
305	8.1589	.6712	.5000
306	7.7080	.0588	.5000
307	7.9335	.0588	.5000
308	8.1589	.0588	.5000
309	7.9335	1.3673	-.4412
310	7.7080	1.3870	.0000
311	7.9335	1.3673	.0000
312	8.1589	1.3475	.0000
313	7.7080	1.3870	.2206
314	7.9335	1.3673	.2206
315	8.1589	1.3475	.2206
316	7.7080	1.3870	.4412
317	7.9335	1.3673	.4412

Table A.4. 5 deg Slant

Port No.	x/w	y/w	z/w
318	8.1589	1.3475	.4412
319	8.2177	1.2836	.4412
320	8.2177	1.2836	.2206
321	8.2177	1.2836	.0000
322	8.2177	.6712	.4412
323	8.2177	.6712	.2206
324	8.2177	.6712	.0000
325	8.2177	.6712	-.4412
326	8.2177	.0588	.4412
327	8.2177	.0588	.2206
328	8.2177	.0588	.0000
329	7.9335	.0000	.4412
330	7.7080	.0000	.0000
331	7.9335	.0000	.0000
332	8.1589	.0000	.0000
333	7.9335	.0000	-.4412
334	7.9335	.6712	-.5000

Table A.5. 12.5 deg Slant

Port No.	x/w	y/w	z/w
400	7.7195	1.2099	.5000
401	7.9392	1.2099	.5000
402	8.1589	1.2099	.5000
403	7.7195	.6344	.5000
404	7.9392	.6344	.5000
405	8.1589	.6344	.5000
406	7.7195	.0588	.5000
407	7.9392	.0588	.5000
408	8.1589	.0588	.5000
409	7.9392	1.3304	-.4412
410	7.7195	1.3791	.0000
411	7.9392	1.3304	.0000
412	8.1589	1.2816	.0000
413	7.7195	1.3791	.2206
414	7.9392	1.3304	.2206
415	8.1589	1.2816	.2206
416	7.7195	1.3791	.4412
417	7.9392	1.3304	.4412
418	8.1589	1.2816	.4412
419	8.2177	1.2099	.4412
420	8.2177	1.2099	.2206
421	8.2177	1.2099	.0000
422	8.2177	.6344	.4412
423	8.2177	.6344	.2206
424	8.2177	.6344	.0000
425	8.2177	.6344	-.4412
426	8.2177	.0588	.4412
427	8.2177	.0588	.2206

Table A.5. 12.5 deg Slant

Port No.	x/w	y/w	z/w
428	8.2177	.0588	.0000
429	7.9392	.0000	.4412
430	7.7195	.0000	.0000
431	7.9392	.0000	.0000
432	8.1589	.0000	.0000
433	7.9392	.0000	-.4412
434	7.9391	.6344	-.5000

Table A.6. 30 deg Slant

Port No.	x/w	y/w	z/w
500	7.7824	1.0480	.5000
501	7.9707	1.0480	.5000
502	8.1589	1.0480	.5000
503	7.7824	.5534	.5000
504	7.9707	.5534	.5000
505	8.1589	.5534	.5000
506	7.7824	.0588	.5000
507	7.9707	.0588	.5000
508	8.1589	.0588	.5000
509	7.9707	1.2495	-.4412
510	7.7824	1.3582	.0000
511	7.9707	1.2495	.0000
512	8.1589	1.1408	.0000
513	7.7824	1.3582	.2206
514	7.9707	1.2495	.2206
515	8.1589	1.1408	.2206
516	7.7824	1.3582	.4412
517	7.9707	1.2495	.4412
518	8.1589	1.1408	.4412
519	8.2177	1.0480	.4412
520	8.2177	1.0480	.2206
521	8.2177	1.0480	.0000
522	8.2177	.5534	.4412
523	8.2177	.5534	.2206
524	8.2177	.5534	.0000
525	8.2177	.5534	-.4412
526	8.2177	.0588	.4412
527	8.2177	.0588	.2206
528	8.2177	.0588	.0000
529	7.9707	.0000	.4412
530	7.7824	.0000	.0000
531	7.9707	.0000	.0000
532	8.1589	.0000	.0000
533	7.9707	.0000	-.4412
534	7.9707	.5534	-.5000

Appendix B. Run Schedule

Run	Configuration	Measurement Type	Yaw Angle (deg)
12	B _N W _A	Wake Pressure Survey (Station 1)	0
13	B _N W _A	Wake Pressure Survey (Station 2)	0
14	B _N W _A	Wake Pressure Survey (Station 3)	0
15	B _N W _A	Wake Pressure Survey (Station 4)	0
16	B _N W _A	Wake Pressure Survey (Station 2)	-10
17	B _N W _A	Wake Pressure Survey (Station 4)	-10
18	B _{O5} W _A	Wake Pressure Survey (Station 2)	0
19	B _{O5} W _A	Wake Pressure Survey (Station 2)	-10
24	B _{O5} W _A	Force and Moment, Surface Pressure	Sweep ±14
26	B _{O5} W _R	Force and Moment, Surface Pressure	Sweep ±14
29	B _N W _A	Force and Moment, Surface Pressure	Sweep ±14
31	B _N W _R	Force and Moment, Surface Pressure	Sweep ±14
33	B _{S12.5} W _R	Force and Moment, Surface Pressure	Sweep ±14
35	B _{S12.5} W _A	Force and Moment, Surface Pressure	Sweep ±14
36	B _{S12.5} W _A	Wake Pressure Survey (Station 2)	0
37	B _{S12.5} W _A	Wake Pressure Survey (Station 2)	-10
38	B _N W _R	Wake Pressure Survey (Station 2)	0
40	B _{S30} W _R	Force and Moment, Surface Pressure	Sweep ±14
42	B _{S30} W _A	Force and Moment, Surface Pressure	Sweep ±14
43	B _{S30} W _A	Wake Pressure Survey	0
44	B _{S5} W _A	Wake Pressure Survey	0
46	B _{S5} W _A	Force and Moment, Surface Pressure	Sweep ±14
48	B _{S5} W _R	Force and Moment, Surface Pressure	Sweep ±14
50	B _{O8} W _R	Force and Moment, Surface Pressure	Sweep ±14
52	B _{O8} W _A	Force and Moment, Surface Pressure	Sweep ±14
53	B _{O8} W _A	Wake Pressure Survey (Station 3)	0
54	B _{O8} W _A	Wake Pressure Survey (Station 4)	0
55	B _{O5} W _A	Wake Pressure Survey (Station 4)	0
56	B _{O5} W _A	Wake Pressure Survey (Station 4)	-10
57	B _N W _R	Wake Pressure Survey (Station 4)	0
58	B _{S12.5} W _A	Wake Pressure Survey (Station 4)	0
59	B _{S12.5} W _A	Wake Pressure Survey (Station 4)	-10
60	B _{S5} W _A	Wake Pressure Survey (Station 4)	0

Appendix C. Data File Formats

File 1 - Force and Moment Data, Surface Pressure Data (Column Format)

Filename: TAMUCxxx.DAT (where xxx is the run number)

```
Line 1:  WRITE (*,100) Test#, Run#, BARO, MO, DAY, YR, HR, MIN, SEC, CD(0), CD7&30, CD7&55, S, W, UMC, VMC,
        HPC
Line 2:  WRITE (*,110) CONFIGURATION
Line 3:  WRITE (*,120) PT#,  $\alpha$ ,  $\psi$ ,  $CL_w$ ,  $CY_w$ ,  $CD_w$ ,  $Cm_w$ ,  $Cn_w$ ,  $Cl_w$ , CN, CY, CA, Cm, Cn, Cl,  $Q_\infty$ , TEMP, VEL, Re, Re/ft,  $\rho$ ,
         $\mu$ ,  $MACH_\infty$ ,  $PT_\infty$ ,  $PS_\infty$ , PS1, PS2, PS3, PORT 1, Cp 1, PORT 2, Cp 2,....., PORT END, Cp END

        100  FORMAT (A4, 5X, I3, F10.2, 6I4, 8F10.4)
        110  FORMAT (A72)
        120  FORMAT(I3, 5X, 19F10.4, 2E12.5, 6F10.4, 109(I4, F10.4))
```

File 2 - Surface Pressure Data (Row Format)

Filename: TAMURxxx.DAT (where xxx is the run number)

```
Line 1:  WRITE (*,200) Test#, Run#, BARO, MO, DAY, YR, HR, MIN, SEC
Line 2:  WRITE (*,210) CONFIGURATION

        DO 1000 IPT = 1, # OF POINTS
Line 3:  WRITE (*,220) PT#,  $\alpha$ ,  $\psi$ , TEMP, VEL, Re, Re/ft,  $\rho$ ,  $\mu$ ,  $MACH_\infty$ ,  $PS_\infty$ , PS1, PS2, PS3

        DO 1000 I = 1, # of PORTS
Line 4:  WRITE (*,230) PORT I, X(I)/W, Y(I)/W, Z(I)/W, Cp(I), P(I),  $PS_\infty$ ,  $Q_\infty$ 
        1000 CONTINUE

        200  FORMAT (A4, 5X, I3, F10.2, 6I4)
        210  FORMAT (A72)
        220  FORMAT (I3, 5X, 6F10.4, 2E12.5, 5F10.4)
        230  FORMAT (I3, 5X, 7F10.4)
```

File 3 - Wake Survey Data

Filename: TAMUWxxx.DAT (where xxx is the run number)

```
Line 1:  WRITE (*,300) Test#, Run#, BARO
Line 2:  WRITE (*,310) CONFIGURATION
Line 3:  WRITE (*,320) PT#,  $\alpha$ ,  $\psi$ , X/W, Y/W, Z/W,  $\alpha_{probe}$ ,  $\psi_{probe}$ ,  $VT/V_\infty$ ,  $u/V_\infty$ ,  $v/V_\infty$ ,  $w/V_\infty$ ,  $V_{yz}/V_\infty$ ,  $\phi$ ,  $PT_\infty$ ,  $PS_\infty$ ,  $V_\infty$ ,
         $Q_\infty$ , TEMP,  $PT_{loc}$ ,  $PS_{loc}$ ,  $PT_{loc}-PS_{loc}$ ,  $Cp_{wake}$ 

        300  FORMAT (A4, 5X, I3, F10.2)
        310  FORMAT (A72)
        320  FORMAT (I3, 5X, 22F10.4)
```

Floppy disk with data may be obtained by contacting:

Robert H. Croll
Sandia National Laboratories
Mail Stop 0825
P. O. Box 5800
Albuquerque, NM 87185-0825
Phone: (505) 844-5359
FAX: (505) 844-4523
E-mail: rhcroll@sandia.gov