(R) SAE Wind Tunnel Test Procedure for Trucks and Buses

RATIONALE

Wind tunnel testing of heavy vehicles has evolved in the past thirty years with new facility types, new ground simulation techniques, and more robust methods for estimating aerodynamic force and moment coefficients. References have been added for support of the narrative and emphasize the common elements between automotive and heavy vehicle testing, and thus avoid duplication of material. The origin of the US average annual wind speed was not disclosed in the original document and is now supported by references and calculations performed by the revision task force. The derivation of the wind averaged drag coefficient and a sample calculation have been added for completeness. Uncertainty bounds are a required element for any contemporary wind tunnel test report and a suggested uncertainty analysis method has been added for the first time with an included sample calculation.

1. SCOPE

The scope of this SAE Recommended Practice is sufficiently broad that it encompasses the full range of full-scale medium and heavy duty vehicles represented as either full-scale or reduced-scale wind tunnel models. The document provides guidance for wind tunnel testing to support current vehicle characterization, vehicle development, vehicle concept development, and vehicle component development.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

i.)   Aerodynamic Testing of Road Vehicles – Testing Methods and Procedures, SAE J2084,1993.

ii.)   Aerodynamic Testing of Road Vehicles - Open Throat Wind Tunnel Adjustment Interference, SAE J2071, 1994.

iii.) Closed Test Section Wind Tunnel Blockage Corrections for Road Vehicles, SP-1176, SAE International, 1996.

iv)   Cooling Flow Measurement Techniques, SAE J2082, 1992.

v.)   Barlow, Rae, and Pope, Low-Speed Wind Tunnel Testing, 3rd ed., Wiley, 1999.

vi.)   Hucho, W.H., Aerodynamics of Road Vehicles, 4th ed., SAE 1998.

vii.) Test Uncertainty, ASME PTC 19.1-2005.

viii.) Recommended Best Practice for Climatic Wind Tunnel Correlation, SAE J2777, 2007.

ix)   Vehicle Aerodynamics Terminology, SAE J1594, 2010.

x)   Wind Energy Resource Atlas of America, DOE/CH 10093-4, Oct. 1986, DE86004442

xi)   Barnard, R. H., Road Vehicle Aerodynamic Design, 3rd ed., Mech Aero, 2010.

xii) Sumantran, V., Sovran, G., "Vehicle Aerodynamics", PT-49, SAE International, 1996

xiii) Carr, G.W., "Wind Tunnel Blockage Corrections for Road Vehicle", MIRA, 1971/4.

xiv) Carr G. W. and Stapleford W. R., "Blockage Effects in Automotive Wind-Tunnel Testing, SAE 8600093,1986.

xv)   Broughton C. A., Rainbird W. J. and Kind R. K., "An experimental investigation of interference effects for high blockage bluff bodies in a slotted-wall wind tunnel test section;" Wind Engineering , Vol. 56, No 1, pp.23, Apr 1995.

xvi) Lombardi G., and Carmassi S., "Wall Interference Effects: Analysis and Correction for Automotive Wind Tunnels", MIRA Vehicle Aerodynamics, pp 1,vol. 1, 2002

xvii) Cooper K. R., Gerhardt H.J., Whitbread R., Garry K.P., Carr G.W., "A comparison of aerodynamic drag measurements on model trucks in closed-jet and open-jet wind tunnels". J. of Wind Engineering and Industrial Aerodynamics, Vol 22, Issue 2-3 June 1986, Page 299- 316.

xviii) Storms B.L., Satran D. R., Heineck J. T.and Walker, S. M., "Detailed Experimental Results of Drag-Reduction Concepts on a Generic Tractor-Trailer". SAE 2005-01-3525, 2005.

xix) "Blockage corrections for bluff bodies in confined flows" Engineering Sciences Data Unit (ESDU) article 80024 November 1980

xx)   Wind Tunnel Wall Corrections, AGARD-AG-336, Oct. 1998,

xxi) Al Garni A.M., Bernal L. P. and Khalighi B., "Experimental Investigation of the Near Wake of a Pick-up Truck", SAE 2003-01-0651, 2003.

xxii) Storms B, Satran D., Heineck J. and Walker S., "A Study of Reynolds Number Effects and Drag-Reduction Concepts on a Generic Tractor-Trailer". AIAA 2004-2251, 2004.

3. OBJECTIVE

The objective of this document is to provide recommended practices for wind tunnel testing of medium and heavy duty trucks and buses represented as either full-scale or reduced-scale wind tunnel models. This document will help guide the wind tunnel user towards making the best choices for achieving specific testing objectives and help to insure good data quality through best practices. The primary focus of this document is in establishing good practices for characterizing medium and heavy vehicle aerodynamic behavior when operating in the natural environment. Medium and heavy truck and bus testing requirements are similar to automotive testing requirements; however, there are some distinct differences between truck and bus testing as compared to automotive testing. Principal ones are due to differences in typical dimensions. In general, trucks and buses are taller relative to their width than automobiles. Trucks and buses are also generally longer relative to their width than automobiles. Trucks, but not buses, generally have higher average ground clearance than automobiles. Trucks and buses generally have blunter rear ends than automobiles and therefore have longer wakes relative to their widths. All of these characteristic differences lead to some effects on wind tunnel practices for these classes of vehicles. Vans included in the category of light trucks and often tested by the same groups who carry out automobile development have been recognized as having requirements somewhat different from automobiles generally. For brevity, this document highlights the requirements that differ from automotive practice and cites the references for detailed coverage of common requirements.

4. MODEL DEFINITIONS

The aerodynamic characteristics of a model/test article must accurately represent the full scale operational aerodynamics of the vehicle or class of vehicles under investigation. It is recognized that the model type and the associated geometric details will vary based upon the wind tunnel capability, costs and test program objectives.

4.1   Full Scale Models

Full scale models include actual vehicles and models of concept, development and production vehicles produced at a full scale when compared to the as-manufactured size of a representative operational vehicle.

4.2   Reduced Scale Models

All models of concept, development and production vehicles produced at a reduced scale when compared to the full scale of a representative operational vehicle.

4.3   Concept Vehicle

A concept vehicle model is any model at either full or reduced scale that contains all of the aerodynamically relevant features that are required to evaluate the overall characteristics of a vehicle and/or the detailed characteristics of a component. The concept vehicle may lack the complete geometric representation required of a production vehicle. As an example, consider a model lacking an inlet for the engine cooling system, with wheels, but no axles or drive train.

4.4   Production Vehicle

A production vehicle model is any model at either full or reduced scale that accurately represents a production vehicle with high fidelity as specified in section 9.1.5.

5. NOMENCLATURE

5.1   Aerodynamic Parameters

A   Projected frontal area of the model. Projected frontal area is defined as that area described by the silhouette (shadow) of a vehicle on a plane behind and normal to the longitudinal axis if it were lit from the front using a collimated light source.   This area includes tires, wheels, suspension, and driveline components which extend below the body or front bumper. Alternatively, maximum width times height of the vehicle or model may be used. The area and method used must be stated in the report. The width and height measurements should exclude mirrors and safety protuberances.

C_D Drag force coefficient = $D/(\tfrac{1}{2}\rho\ V^2 A)$.

C_L Lift force coefficient = $L/(\tfrac{1}{2}\rho\ V^2 A)$.

C_S Side force coefficient = $S/(\tfrac{1}{2}\rho\ V^2 A)$.

C_{RM} Rolling moment coefficient = $RM/(\tfrac{1}{2}\rho\ V^2 Aw)$.

C_{YM} Yawing moment coefficient = $YM/(\frac{1}{2}\rho\, V^2 Aw)$.

C_{PM} Pitching moment coefficient = $PM/(\frac{1}{2}\rho\, V^2 Aw)$.

$\overline{C}_D$ Wind averaged drag coefficient.

d   Component reference dimension.

D   Aerodynamic drag force acting parallel to the longitudinal axis of the vehicle, or model, and positive aft.

$\overline{D}$ Wind average drag force with same axis and sense as D.

L   Aerodynamic lift force acting normal to the ground and positive upward.

PM   Aerodynamically induced pitching moment. Moment about a horizontal axis which is normal to the vertical centerplane of the vehicle, or model, and positive when it tends to raise the vehicle's nose.

Rew   Overall Vehicle Reynolds number = $\rho Vw/\mu$.

Re_d Component Reynolds number = $\rho Vd/\mu$.

RM   Aerodynamically induced rolling moment. Moment about a horizontal axis located in the vertical centerplane of the vehicle, or model, and positive when it tends to lower the right side of the vehicle.

S   Aerodynamic side force acting normal to the vertical centerplane of the vehicle, or model, and positive to the right.

V   Velocity relative to the vehicle or model (See Figure 2).

V_T Vehicle velocity relative to the roadway (See Figure 2).

V_W Mean wind velocity (See Figure 2).

w   Maximum width (excluding mirror and safety protuberances) of vehicle or model.

wb   Wheel base.

YM   Aerodynamically induced yawing moment. Moment about a vertical axis fixed into the vertical centerplane of the vehicle, or model, and positive when it tends to rotate the vehicle nose to the right.

μ   Absolute viscosity of air.

ρ   Mass density of air.

φ   Angle of the mean wind relative to the vertical centerplane of the vehicle (See Figure 2).

ψ   Angle of yaw of the vehicle or model relative to the equivalent free airstream. (See Figure 2).

5.2   Force and Moment Sign Convention

The recommended sign convention is illustrated in Figure 1. It is recommended that the moment reference center be placed along the intersection of the vehicle vertical plane of symmetry and the ground. The longitudinal location for straight trucks and buses should be at the wheel base mid-point, and for tractor trailers should be at the center line of the tractor rear axle(s) as shown in Figure 3.
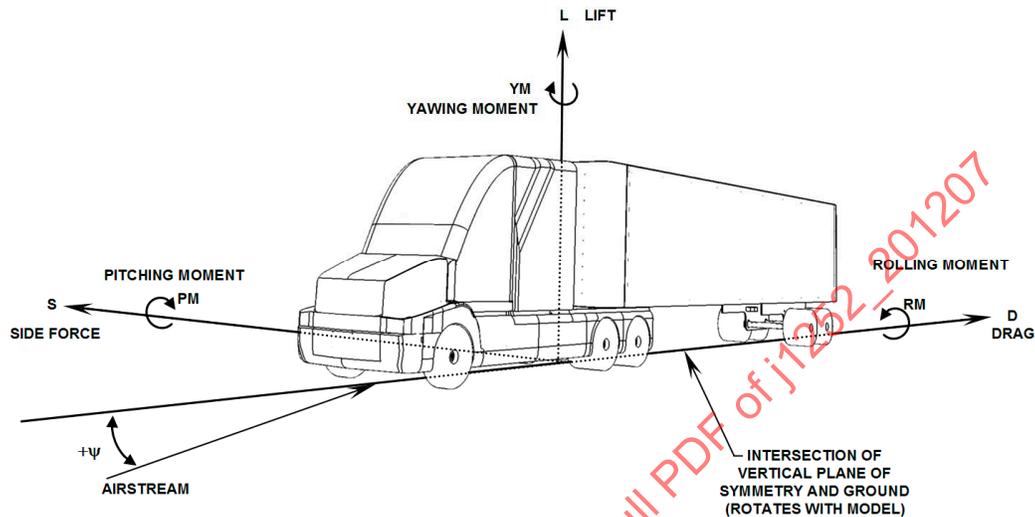
FIGURE 1 - DEFINITION OF FORCES, MOMENTS,
AND THE STABILITY AXES COORDINATE SYSTEM

5.3   Relative Airspeed and Yaw Angle

A road vehicle traveling at velocity V_T subject to natural wind velocity V_w will experience relative airspeed V at yaw angle ψ.
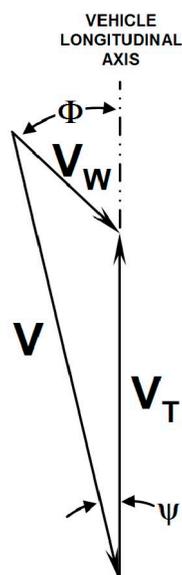
FIGURE 2 - RELATIVE AIRSPEED VECTOR DIAGRAM

5.4   Truck and Bus Dimensions

It should be noted that dimensions may vary from the left to the right side of the vehicle. It is recommended, that in the case of dimensions that could be measured on either side, both sides be recorded.

1   Overall Length
2   Overall Width
3   Overall Front Height
4   Cab/Sleeper Length
5   Gap Length
6   Trailer/Box Length
7   Rear Body Height
8   Rear Ground Clearance
9   Roof Height Differential
10 Front Ground Clearance
11 Minimum Ground Clearance
12 Front Overhang
13 Rear Overhang
14 Front Track Width
15 Front Bumper Width
16 Roof Width
17 Front Wheel Air Gap (obsolete)
18 Rear Wheel Air Gap (obsolete)
19 Typical Tire Size and Diameter
20 Leading Edge Geometry
21 Front Side Edge Geometry
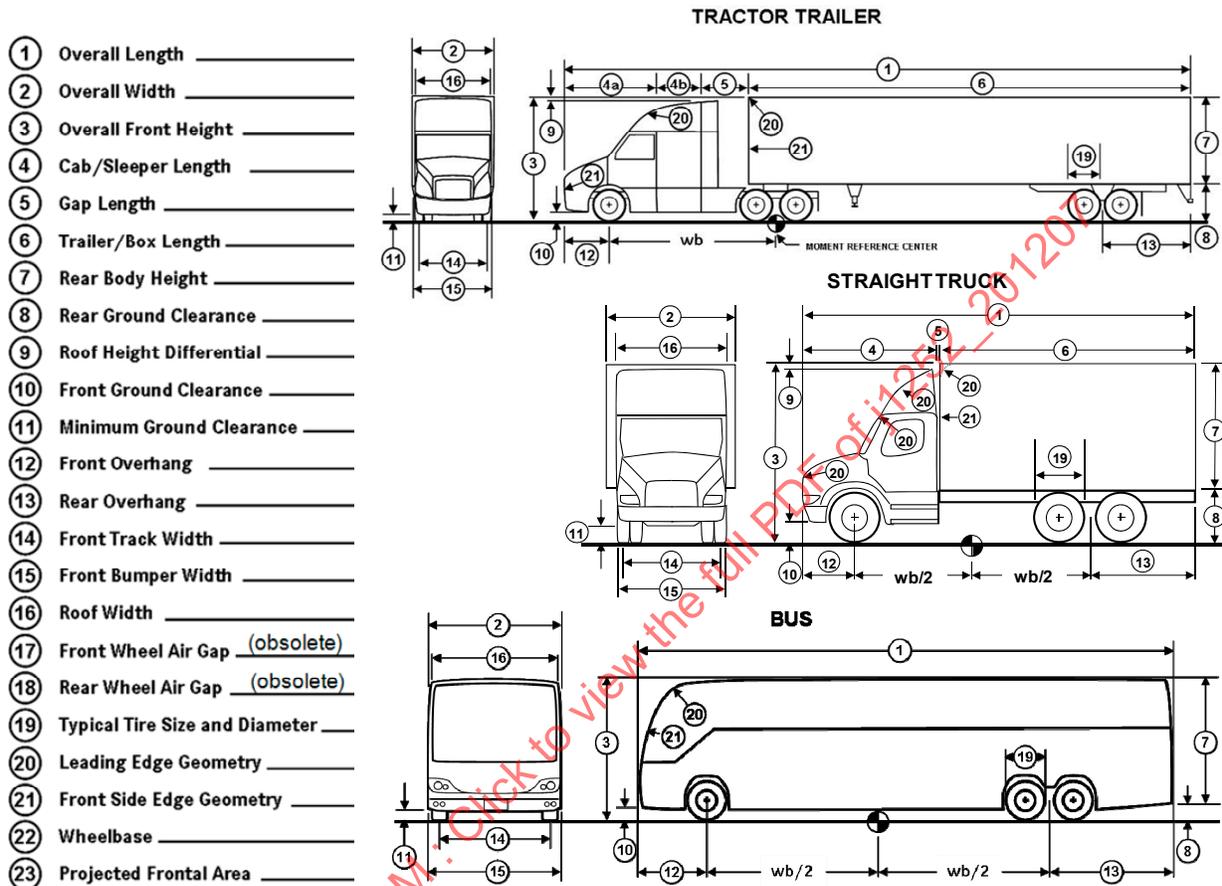22 Wheelbase
23 Projected Frontal Area

FIGURE 3 - TRUCK AND BUS DIMENSIONS

6.   OBJECTIVES OF WIND TUNNEL TESTING

There are two primary objectives for wind tunnel testing of trucks and buses, aerodynamic development of a new vehicle and improvement of existing vehicles through modifications to the basic vehicle or through add-on devices. The achievement of vehicle performance as measured by end users through fuel economy dictates the requirement for aerodynamic drag measurement as the primary objective of testing. It should be noted that a production vehicle drag coefficient obtained through wind tunnel measurements will inherently vary with choice of facility.

6.1   Production and Concept Vehicle Aerodynamic Characterization

The main objective of production and concept vehicle aerodynamic characterization tests is the determination of the vehicle's mean (time-averaged) aerodynamic drag along its longitudinal axis as a function of yaw angle for the purpose of performance prediction. Comparative studies of add-on devices are conducted by referencing measurements from a baseline (reference) geometry over a range of yaw angles.

6.1.1   Yaw Polar Requirements and Relevance to On-Road Operations

A vehicle operating in the natural environment will experience a relative airspeed acting at a yaw angle as depicted in Figure 2. When characterizing a vehicle for use in a specific geographic region, it is recommended that an average wind speed be estimated for the intended area of operation. The average value for the continental US is the recommended default choice for vehicles intended to operate everywhere in this region. Medium and heavy trucks and buses differ from automobiles in that the rate of change of drag with yaw angle is greatly increased (approximately 10 times). Figure 4 shows comparative drag coefficient versus yaw response for various vehicle types. A wind averaged drag coefficient is the recommended metric to incorporate the integrated effect of the relative wind contribution to drag. Computation of the wind averaged drag coefficient at the vehicle highway operating speed (V_T) for the average wind speed (V_w) is recommended for use in vehicle comparative testing, and vehicle performance prediction and simulation. For instance, it is possible that an aerodynamic device may reduce drag at low yaw angles and increase drag at higher yaw angles. A complete evaluation of an aerodynamic device for use on a medium or heavy truck or bus will include wind averaged drag coefficients.
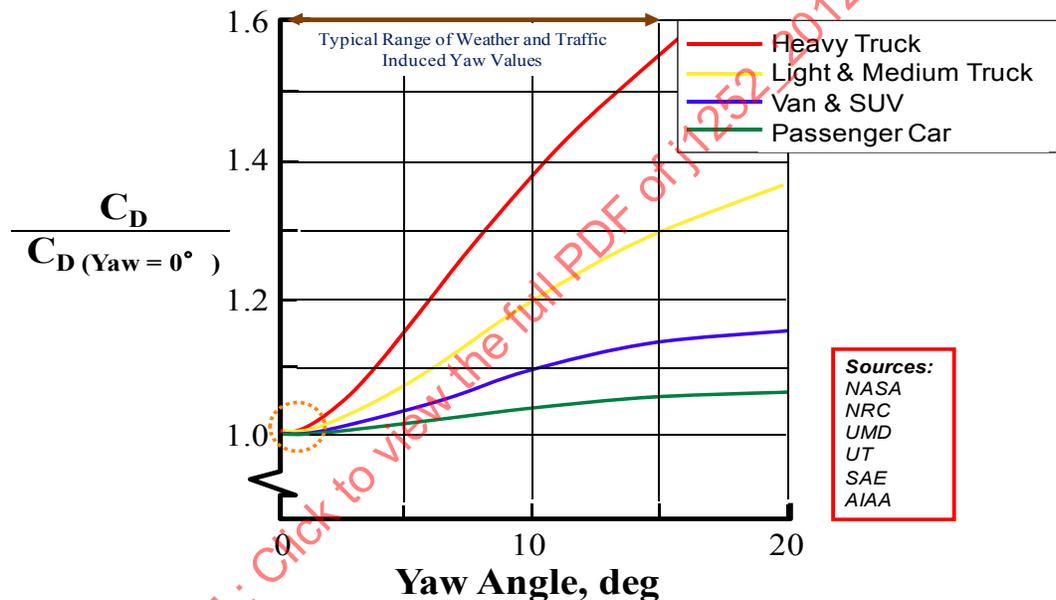

FIGURE 4 - YAW EFFECT ON DRAG COEFFICIENT FOR FAMILIES OF VEHICLES

6.1.2   Relation to Fuel Consumption Testing

The use of the wind averaged drag coefficient is recommended to correctly characterize the aerodynamic drag force acting on a medium and heavy truck or bus. When investigating the relative merit of devices that alter the vehicle drag and hence the fuel economy, it is important to include the integrated effect of the relative wind direction as described in 6.1.1. On-road and on-track fuel consumption testing in accordance with SAE and TMC fuel consumption recommended test procedures is subject to random wind conditions and is by nature an ineffective method for a production or concept vehicle characterization. Fuel consumption performance prediction is best based on a combination of a no-wind fuel consumption test coupled with a wind tunnel measured yaw dependent drag model.

6.2   Specialized Testing Objectives

6.2.1   Underbody Aerodynamics

Trucks have higher average ground clearance than automobiles. As the ground clearance of a model is reduced, the effect of the ground boundary simulation including wheel rotation becomes increasingly more important. For vehicles with very low ground clearance, a moving ground plane and rotating model wheels will provide the best simulation of the underbody aerodynamics around zero yaw. Whether fixed floor or moving ground plane simulations are used it should be noted that increased yaw typically degrades the simulation.

6.2.2   Internal Flow

The effect of the internal airflow rate on drag (such as engine cooling flow) can be investigated by conducting tests where inlets are blocked versus unblocked. Tests should be made over the entire range of yaw angles necessary for calculation of the wind averaged drag coefficient if the objective is production or concept vehicle aerodynamic characterization.

6.2.3   Detailed Tractor/ Component testing

Specialized full-scale tractor wind tunnel facilities that feature the use of a commercial tractor with a fixed facility simulation of a trailer or partial trailer may be used for aerodynamic evaluation of the tractor and tractor components. Comparative incremental force measurements and internal flow evaluations may be obtained on components at full fidelity. It should be noted that in facilities where yaw is not simulated, the wind averaged drag coefficient may not be computed.

6.2.4   Aero-Thermal Characterization

It is recommended that the aero-thermal characterization of a heavy truck or bus be conducted in a specialized test facility known as a Climatic Wind Tunnel. Typical testing includes evaluation of engine cooling systems and heating and air conditioning system performance while under load and subject to a range of ambient conditions.   For more information the reader is directed to references i, iv, viii.

6.2.5   Research

Research objectives lead to testing of a basic or fundamental nature. These tests typically use small scale concept models where detail geometric fidelity requirements are often relaxed in order to control costs.   The focus may be on preliminary evaluation of specific aerodynamic devices (or combinations thereof) or evaluations of vehicle designs with significant departures from current production vehicles. Note, although the model geometric fidelity requirement is not rigorous, the accurate modeling of full scale on-road global and local aerodynamic and flow field features is required. Research testing may be performed over a limited yaw range and may focus on flow visualization studies and surface pressure measurements. Most testing is done using reduced scale models in relatively small test facilities.

7.   AERODYNAMIC REQUIREMENTS

The following section describes the fundamental aerodynamic criteria that should be addressed to achieve the best aerodynamic simulation.

7.1   Reynolds Number

7.1.1   Overall Vehicle

Tests should be performed to determine the effect of vehicle Reynolds number (Re_w) on the measured forces and moments over the range of yaw angles dictated by the test requirements. When the Reynolds number effects have been determined, the remainder of the test program should be performed at a Reynolds number above which the force and moment coefficients are essentially invariant for the yaw angles investigated. Reynolds effects can be determined using a velocity sweep.   In tests where results require the best estimate of the overall absolute force and moment coefficients, particular attention should be paid to the Reynolds number scaling effects. A sampling of Reynolds number effects on truck and bus geometries is provided in section 4.4 of reference i. Compressibility is an additional consideration in developing a working Reynolds number and will need to be considered anytime the freestream Mach number exceeds 0.25. When operating near Mach 0.25, careful scrutiny of local conditions in the vicinity of model contour changes such as corners and rounds is required.

7.1.2   Component

Aerodynamic characterization of vehicle components may be performed at component Reynold's numbers (Re_d) below that required for true dynamic similitude. Tests should be performed to determine the effect of Reynolds number on the measured forces and moments over the range of yaw angles dictated by the test requirements. When the component Reynolds number effects have been determined, the remainder of the test program should be performed at an overall component Reynolds number above which the incremental component force and moment coefficients are essentially invariant for the yaw angles investigated. The influence of local corner radii (and hence component Reynolds number) on truck and bus model measured drag coefficients is illustrated well by section 4.4 of reference i.

7.2   Boundary Corrections

From reference xx, "In general, the aim of wind-tunnel tests is to make measurements of aerodynamic quantities under strictly controlled and defined conditions in such a way that, despite the presence of the tunnel walls, the data can be applied to unconstrained flow. The existence of a free-air flow which is "equivalent" to that in the tunnel is the fundamental assumption underlying the entire framework of the theory and practice of wind tunnel wall constraint."   The full implications of the above statement requires a considerable explication that is beyond the scope of this document. Those who wish more details should consult reference xx and the other references of section 2.0. Some basic implications are viewed as essential to point out for present purposes.

a. Boundary corrections are by no means the only or often the primary adjustments to wind tunnel measurements required to predict full scale loads from the wind tunnel measurements. In order that boundary corrections be the only adjustments required, the test article must be geometrically and kinematically scaled to a very high degree of detail. Common examples where this is an issue for truck testing are lack of scaled simulation of the flows through the engine compartment, non-rotating wheel-tire components, and a stationary ground boundary. Adjustments of data for these types of effects are not covered by "boundary correction" methods. They require separate and customized treatment although boundary corrections will still be needed after effects such as these are evaluated.

b. If the only correction considered is a "blockage" factor that consists only of computing a "corrected" dynamic pressure, this carries an implied assumption that the distribution of the surface pressure and shear stress on the test article is the same as it would be in the target operating environment.   It implies that the locations of transition of boundary layers from laminar to turbulent take place at the same location on the test article as on the full scale device, and even more important that loci of separation are the same for the test article as for the full scale device.

c. The presence of boundaries of wind tunnel flows at finite distances from the test article lead to changes in the distribution of surface pressures and shear stresses as compared to typical full scale operating environments. The "fundamental assumption" is met only to some approximation. The distances from the test article to all boundaries are important. So the distances from the test article to the test section upstream entrance, to the diffuser or collector entry, to the side walls or jet boundaries, and to the upper wall or jet boundary are all significant dimensions to be considered. Correction methods are available which provide guidance on these issues. They are labeled as "measured variable" methods. The ones for which the most details have been published are the "pressure signature" method, and the "2 variable" method. Both of these methods are discussed in reference xx and others of section 2.0 including guidance on correcting dynamic pressure.

d. Adaptive wall wind tunnels address the issue of boundary corrections by attempting to eliminate the need for them. This is to be accomplished by creating a test section boundary surface that is the same shape as a stream surface for the full scale test article.   This can be accomplished only to some approximation. The degree of approximation required and the algorithms by which the wall positions are adjusted are topics for which there is only limited treatment in open literature. There are obvious potential benefits of adaptive walls for a special purpose wind tunnel such as one devoted to commercial trucks since the range of wall positions needed would be reduced and perhaps made manageable and at the same time the overall facility size would be reduced. At the present time there is insufficient data available in the open literature to provide specific guidance on the practice of wind tunnel testing in an adaptive (or adapted) wall facility.

e. When compared to automotive testing, truck and bus tests differ in that the larger vehicle overall length to width ratio results in a comparatively larger wake at yaw. Area blockage should be calculated based on the projected frontal area of the vehicle at the maximum tested yaw angle. This is the projected area on a plane perpendicular to the longitudinal centerline of the tunnel while the vehicle is at its maximum yaw angle. In addition, vehicle length and proximity to the beginning and end of the test section are important considerations. In general, it is desirable to minimize corrections when the test objective is to determine the absolute performance measurement versus identifying incremental changes for the purpose of comparisons. Current theories and correction methodologies are complicated and approximate and often rely on the assumption that pressure distributions around the model in the test section are relatively unchanged by the presence of the tunnel boundaries when compared to operating in free air. High blockage testing may be justified for incremental comparison testing when a legacy correction database exists. Correction methods for heavy trucks and busses are still an area of research and the reader is directed to the references.

7.2.1   Closed Wall Test Section

When production and concept vehicle performance characterization is the test objective, it is recommended (but not required) that the test blockage ratio be limited to 5% at the maximum yaw angle used, and that the magnitude of the corrections be limited to a 10% change from the overall measured drag coefficient. Correction methods are detailed in reference iii. Comparative characterizations between production or concept vehicles can be made successfully with higher blockage ratios if a vehicle specific legacy correction database is available for support. Blockage ratios up to 15% may be considered provided suitable corrections are limited to a 30% change in the overall vehicle measured drag coefficient.

7.2.2   Open Jet Test Section

When production or concept vehicle performance characterization is the test objective, it is recommended (but not required) that the test blockage ratio be limited to 10% at the maximum yaw angle used and that corrections be limited to a 10% change in the overall measured drag coefficient. Correction methods are detailed in reference ii. Comparative characterizations between production or concept vehicles can be made successfully with higher blockage ratios if a legacy correction database is available for support. Blockage ratios up to 15% may be considered provided suitable corrections are limited to a 30% change in the overall vehicle measured drag coefficient.

7.2.3   Adaptive Wall Test Section

An adaptive wall, adapted wall, or streamlined test section refers to a test section that has been contoured to accommodate a particular test object, specifically by causing the tunnel wall boundaries to form a streamtube at the walls that has a similar shape as would occur in free air. This shape may be determined experimentally or computationally. A blockage ratio should be selected so that it is large enough to accommodate the necessary range of vehicles at the necessary yaw angles. At the time of this writing this technology is new to truck and bus testing and the details of boundary corrections have not been published in the open literature.

7.3   Boundary Layer Development on the Model

In the case where the overall Reynold's number of the model may not match the on-road vehicle, boundary layer characteristics measured on the model should match the boundary layer characteristics at the same locations on the full-scale vehicle. The criteria may be satisfied with or without boundary layer roughness elements on the model. As a minimum the turbulent boundary layer profiles of the tested model should match the road vehicle. This is especially important at free edges.

7.4   Road Simulation Boundary Layer

An acceptable ground-boundary simulation should be one which minimizes the height of the boundary layer displacement thickness relative to the underbody ground clearance at the vehicle's leading edge. As a guideline, a maximum empty test section displacement thickness of 10% the height of the minimum ground clearance is recommended for automobile testing (reference i section 4.3.6). The large yaw sweeps and non-constant ground clearance of a truck or bus makes this recommendation conservative. An extensive discussion of road simulation choices is provided in references i and vi.

8.   FACILITY

8.1   Test Section Size

Wind tunnel testing may be performed in open jet, closed jet, or adaptive wall facilities.   To meet aerodynamic requirements, wind tunnel facilities suitable for medium and heavy truck and bus testing will be those that address the following constraints:

a.   Limits to area blockage ratios based on the projected area of the vehicle at maximum yaw as described in section 7.2.

b.   Vehicle length and proximity to the beginning and end of the test section.

c.   Test velocity, including local velocities around the model should remain below compressibility limits.

8.2   Model Support

The method of model support is dictated by the facility, ground simulation technique and force balance. Common to all installations is the desire to eliminate the air gap between the tires and the ground plane. Ideally no gap should exist as the gap will allow flow to accelerate between the tire and floor causing increased suction on the tire. It is noted that in the case of a tractor trailer model, separate supports for the tractor and trailer that allow separate measurement of loads for each will allow evaluation of tractor/trailer interference.   All configurations that use strut mounting should evaluate the tare and interference loads associated with use of the strut.   Additional details common to automotive testing may be found in section 5 of reference i.

8.2.1   Static Ground Plane Tire Pad Mounting

For external balances with static ground plane simulations, models are typically supported through tire contact pads flush to, but isolated from the floor of the wind tunnel.   Since the exposed pad surfaces experience model induced pressures, it is desirable to minimize the area of the pads.   Vehicles that are free to roll should be fixed in place by wheel chocks and/or the vehicle brakes.   Vehicles with live suspension systems and or pneumatic tires should first experience the maximum desired test dynamic pressure to allow settling before test data is recorded.

8.2.2   Static Ground Plane Through-Floor Strut Mounting

When testing reduced scale models with an external balance and static ground plane, the model may be supported by strut(s) from below the floor. If this configuration is chosen, and the struts transfer loads through the fixed tires, it is recommended that the model tire contact a pad flush with the floor surrounded by an annular gap.

8.2.3   Static Ground Plane Internal Balance with Strut

For static ground plane installations with use of an internal balance it is often difficult to avoid tire/floor air gaps. The method of using pads detailed in the previous section is recommended. The support strut will cause interference with model flow and of course if not shielded will add additional tare loads. If the strut is mounted horizontally behind the model (a sting) it will influence the wake. If the underbody flow is not of great interest, a short strut with a circular cross section that penetrates the floor from below may have minimum changes in interference as the model is yawed.

8.2.4   Moving-Belt Ground Plane

A strut for use with an internal balance or connected to an externally mounted balance can be employed to support a model over a moving belt. The strut will cause aerodynamic interference with the model and wake and this should be measured. A strut support should be configured to minimize strut to model and model to strut interference.   For models with rotating wheels, wind-off rolling resistances will need to be evaluated and subtracted from the total wind-on balance measurements. It is also noted that the rolling resistance is a function of the vertical load on the wheels. Entrainment of air during wind–off tare measurements is a further consideration. It should be noted that if a strut is mounted axially behind the model (a sting) it will influence the model wake directly.

8.3   Ground Simulation

With the exception of tests that focus on underbody aerodynamics with models of low ground clearance, the recommended ground simulation method is to use a static ground plane with a boundary layer removal system. There are several methods commonly in use which include suction and blowing techniques. Their relative merits are discussed in detail in reference i, section 4 as well as reference vi section 13.3.2. An alternative is the use of a raised ground plane which is offset from the tunnel boundaries so that a fresh boundary layer may develop just ahead of the vehicle model.

The wind averaged yaw requirements for a production or concept vehicle characterization make a method of yawing the vehicle (such as a turntable) a necessity.   A yaw capability of +/- 15 degrees will in most cases be adequate for simulating highway speeds of 30 mph and above (See Table A1.)

8.4   Flow Quality and Instrumentation

Wind tunnel freestream flow quality considerations are in keeping with automotive testing practices. Detailed discussions may be found in references i,v and vi.

9.   TEST METHODS AND PROCEDURES

This section describes the test procedures to meet the test objective, based upon test type, aerodynamic requirements, facility considerations, and model/vehicle choice.

9.1   Production and Concept Vehicle Aerodynamic Characterization

9.1.1   Preparation

Before the model/vehicle is installed in the test section, the projected frontal area should be determined. It is recommended that the baseline configuration be used for this measurement and that this value remain constant throughout the testing despite changes in area due to test article changes. The wheelbase and track, overall width, and ideally all key vehicle dimensions (as noted in Figure 3) should be recorded. The location of the test article with respect to the test section should be measured for use in potential boundary or interference corrections. It is recommended to record photographs of the model from all sides throughout the installation and test program.   When testing models or vehicles supported by pneumatic systems, check regularly to insure constant pressures are maintained.

9.1.2   Test Section Flow Calibration

A series of measurements should be made above the ground plane with the test article absent to define the characteristics of the flow in which the model is placed. The turbulence level, flow angularity, uniformity of the velocity field over the test cross-section, and longitudinal static pressure gradient should be measured above the ground plane. In addition, the ground plane boundary layer thickness should be measured at the location of the model leading edge. The wind tunnel dynamic pressure measuring system should be calibrated against an accurate pitot-static tube mounted at the location of the model mid-length and mid-height point.   Flow quality metrics are discussed in detail in references i,v and vi.

9.1.3   Force and Moment Requirements

The primary requirement of the majority of wind tunnel tests is the determination of a model vehicle's mean (time-average) aerodynamic drag along its longitudinal axis as a function of yaw angle. It is recommended that the remaining five components be determined as well, particularly if stability is of interest. The forces and moments should be reduced to coefficient form using the stability axes coordinate system. This coordinate system consists of a set of orthogonal axes fixed in the vehicle and yawing with it as shown in Figure 1. It is recommended that the moment reference center be placed along the intersection of the vehicle vertical plane of symmetry and at the ground. The longitudinal location for straight trucks and buses should be at the wheel base mid-point, and for tractor trailers should be at the center line of the tractor rear axle(s) as shown in Figure 3.

9.1.4   Yaw Angle Sweep Recommendations

It is recommended that the yaw angle maximum and minimum limits be defined by the wind averaged drag coefficient requirements. It is desirable to include both positive and negative yaw values to identify potential asymmetry in the model, model mounting or flow. Experience shows asymmetry around zero-yaw is best captured with small increments. A suggested minimum yaw schedule is -3,-1,0,1, and 3 degrees followed by an increment of 3 degrees beyond -3 and 3. As a measure of within-run precision, it is recommended that as a minimum the zero yaw point be repeated during each configuration yaw sweep.

When characterizing a vehicle for use in the continental US, the use of an average wind speed of 7 mph is recommended based on the survey data of Appendix A. The wind averaged drag coefficient computation incorporates the integrated effect of the relative wind contribution to drag through a weighting algorithm as detailed in Appendix A.   Computation of the wind averaged drag coefficient at the vehicle highway operating speed (V_T) for the average wind speed (V_w) of 7 mph is recommended for use in vehicle comparative testing, and vehicle performance prediction and simulation.   The method for estimation of the average wind value is shown in appendix A.

9.1.5   Model Design and Fidelity

Models must be accurately and rigidly constructed, geometrically scaled, and possess sufficient detail to accurately reproduce all aerodynamically significant full-scale on- and off-body operational flow features. First and foremost, the model size should be selected to simultaneously satisfy the overall vehicle Reynolds number, blockage, ground plane, and interference requirements. The wind tunnel model's construction should be sufficiently rigid that static or dynamic deflections of the vehicle or its components will not affect the model's flow field or the balance output.

For assessment of on-road performance through drag measurements, all criteria listed above must be satisfied in addition to the following; attention should be paid to model details such as horns, lights, mirrors, intake and exhaust stacks, roof air conditioners, hood and door discontinuities, etc. Underbody structural details and the major driveline components should be reproduced. The engine cooling air flow path including engine block, engine compartment, and radiator porosity should be simulated.

For assessment of incremental changes in aerodynamic forces and moments and/or flow field characteristics due to changes in surface shape, components included, or free stream flow conditions, all criteria listed above should be satisfied. When performing reduced fidelity concept model studies to evaluate effects of major shape changes, or effects of inclusions of components, details of secondary importance may be neglected as outlined in section 4. For studies seeking actual incremental changes in a vehicle to use for comparisons of two or more production vehicles, and design decisions, all details such as boundary layer scale protuberances and discontinuities as well as underbody and engine compartment details should be included.

Portions of the model that are removable, or variable, such as corner blocks, front or rear-end shapes, add-on members as well as variable clearances and gaps should be designed for accurate positioning using pins or reference marks.

9.1.6   Model Mounting and Interference Considerations

The mechanical support system that rigidly positions the model in the wind tunnel and connects the model to the balance system will influence the measured aerodynamic forces and moments. To improve data quality it is therefore desirable to minimize the model support aerodynamic interference.

The model support system alters the measured aerodynamic forces and moments in three ways; 1) additional aerodynamic forces and moments exist from the exposed portion of the support system, 2) the support system alters the flow over the model and 3) the model alters the flow over the model support system. Items 2 and 3 above are combined and termed "model support aerodynamic interference".   Aerodynamic interference assessment studies have shown that the effects may be significant and should be minimized and/or corrected. However, the complexity of the aerodynamic interference effects and their variability with changes in vehicle geometry, Reynolds number, and yaw conditions makes it highly unlikely that a simple correction can be derived to account for all test conditions and test models. The problem is further compounded if the desired measurement resolution is extremely small or the geometric variation is in close proximity to the model support structure.

There are several criteria to follow in order to minimize the aerodynamic interference of the support system. The first is to minimize the surface area of the support system exposed to the high velocity free stream air-flow. The second is to minimize the axial projected area of the support system. And the third and fourth criteria are to eliminate the Reynolds number and yaw aerodynamic sensitivity of the support system.

Suggested model support design criteria to minimize aerodynamic interference are:

a. surface area exposed to high-velocity/free-stream flow < 10% of model cross section

b. axial projected area < 1% of model cross section

c. Reynolds number sensitivity = constant

d. Yaw sensitivity = constant

If the above criteria are not satisfied then it is recommended that the test program determine the aerodynamic interference correction through the use of a dummy sting system as part of a model support buildup study.   This step is critical if the desired vehicle measurement resolution is extremely small or the geometric variation is either in close proximity to or down stream of the model support structure. Reference v, section 7.5 describes corrections of this type.

9.1.7   Reynolds Number Effects

Production or concept aerodynamic evaluations require overall vehicle Reynolds numbers be established as described in section 7.1.1.

9.1.8   Considerations for Internal Flow

The effect of engine-cooling airflow on drag can be measured by conducting a comparison test between two model configurations. The difference in drag between a fully sealed (blocked) inlet configuration and a completely open inlet configuration will define the cooling drag. The model's engine should remain in place for all tests. Tests should be made over the entire range of yaw angles. If extensive model modifications are made, it is recommended that the effect of engine-cooling airflow rate be reinvestigated.   Other aerodynamic losses due to internal flow may be evaluated in a similar manner. Where passive means cannot be used to simulate the cooling airflow (as with some buses) consideration should be given to the use of active means. When the test objective is primarily thermal characterization of the engine and cooling system versus measuring drag, studies are best conducted in a climatic wind tunnel as described in reference iv and viii.

9.1.9   Flow Visualization

Off-body and surface flow fields may be visualized with indicators such as fluid vapors (often called Smoke) and tufts. Light sheets are useful for illuminating smoke in off body flows. Colored oil flow or sublimating chemicals may be used to investigate mean surface flows and boundary layer character. These techniques have been well documented and help permit rough correlations with known full scale flow details. The user is directed to references i,v and vi for details.

9.1.10   Surface Pressure Measurements

Surface pressure measurements may assist in determining the local effects of vehicle modifications and in assessing the contribution of certain parts of a vehicle to total drag.   The time varying nature of the flowfields around bluff bodies requires that pressure measurements be averaged over a sufficient period of time to assure data quality.   Surface pressures are best obtained using flush orifices as described in reference i section 7.2. Pressure data is best reported using the nomenclature outlined in reference ix.

9.1.11   Data Corrections

It is recommended that corrections to the drag coefficient for the longitudinal pressure gradient (horizontal buoyancy) be applied if the correction exceeds 1% of the measured drag coefficient. The application of corrections to account for the effects of the model solid and wake blockage are recommended. Open jet correction techniques are detailed in reference ii. Correction techniques for closed jet facilities may be found in reference iii.

9.1.12   Uncertainty Estimates for Individual Drag Coefficients on the Polar

Drag coefficient uncertainty estimates should be computed and reported using a 95% confidence interval. An uncertainty estimate is obtained by combining random and systematic errors as described in reference vii. A random error causes scatter in the test data whereas a systematic error remains constant over the duration of a test.   The random error component is best obtained by replication of measurements. An estimate of the random error may be found using at least two true replicate yaw sweeps (a total of 4 runs). A true replicate requires that a given configuration yaw sweep is conducted, subsequent runs involving model changes are performed, and then the original model configuration yaw sweep is repeated later in the test program. This helps ensure that the random error estimate includes error associated with model changes and test duration. A simplified uncertainty estimation procedure for an individual drag coefficient is provided in Appendix B. It should be noted that the procedure does not include the error associated with model installation and removal, such as alignment with the tunnel centerline.   The method estimates a bound on an individual drag coefficient for a single model installation and test.

9.1.13   Data Reporting

Sufficient background data should be presented to completely define the wind tunnel and ground simulation, test section flow field, and the model's geometry. The following minimum data are required:

Facility

a.   Test section dimensions

b.   Ground simulation type (e.g., fixed/moving)

c.   Ground simulation location and dimensions (e.g., belt size or ground plane dimensions)

d.   Empty facility boundary layer velocity profile at model front bumper or center.

e.   Model location on ground plane/belt

f.   Distance of model from collector

g.   Distance of model from nozzle

h.   Model dimensions as shown in Figure 3 (include true projected frontal area if available)

i.   Type of test section (e.g., ¾ open jet, closed jet)

j.   Type of support

k.   Blockage: frontal area/test section cross sectional area

l.   Facility instrument source bias values

Model

m.   Photographs of all tested model configurations

n.   Photographs of model installed in wind tunnel

o.   Description of baseline model and modifications

p.   Description of engine cooling flow simulation

q.   Description of blockage correction used (if any)

r.   Scale of model

Data Acquisition

s. Results of Reynolds number test (velocity sweep)

t. Results of cooling drag increment (if test is conducted)

u. Force measurement system specification

v. Signal conditioning and data acquisition system specification

w. Sample rate/duration/filtering

x. Wind averaged drag coefficients for each configuration tested should be presented in tabular form. The road vehicle average wind speed (V_w) chosen and the chosen road vehicle speed (V_T) should be reported.

y. Yaw-drag coefficient polar plots should be presented for each tested configuration. A discussion of corrections applied should list all assumptions and relevant parameters.

z. Uncertainty estimates should be reported using a 95% confidence interval (as outlined in Appendix B). The report should specify the mean value of a measured response (e.g., C_D) +/- the uncertainty U. The method and configurations used for uncertainty calculations should be documented.

9.2   Rotating Wheels

The use of rotating wheels and a moving ground plane with truck and bus testing is a relatively new practice. The methods and procedures of section 9.1 apply.

A recommended practice for testing on a moving-belt ground is to suspend the model at the proper attitude over the belt so that the forces on the body may be determined. The wheels should be free to spin on individual axles which are completely free to move vertically from the model. The wheels will rest on the moving belt and spin at belt speed. Drag and side forces can be measured as part of the body forces, minus the wind-off rolling resistance at each belt speed. There does not appear to be a practical way to determine the aerodynamic lift on the wheels with this arrangement and it is understood that the windage of the rotating wheel is included in the wind-off tare and is speed dependent.

An alternative way to mount the model wheels, which can eliminate the vibration of the belt-induced motion being fed into the body force measurements, is to remove the wheels from the body and mount them separately on cantilevered struts from the wind-tunnel side walls or ground plane. The wheels are mounted in the proper relative position to the body but not in contact at the inboard side of the axles. Each of the struts needs to be instrumented to measure drag as the wheels roll on the moving belt.

With either mounting system, it is very important that the wheels spin freely without wobble or bounce. They must be free to move vertically if a bump in the belt hits the wheel but remain in contact with the belt at all times. Good dynamic balance is required to minimize vibration. The wheels must roll true so that they do not create a side force or yawing moment on the model. Consideration should be given to avoid excessive pressure which can overheat and ultimately destroy some belt designs due to the friction between the belt and backing plate. Special consideration should be given to safety when working with a high speed moving belt and spinning wheels. Users should constantly monitor suspension wear, wheel bearing wear, belt wear and the potential for a frozen suspension component which could fix the position of the wheel.

9.3   Detailed Tractor/Component

The use of a full scale production tractor and partial integrated trailer in a specialized wind tunnel for heavy truck testing is a new practice with one facility operational as of the time of this writing. There has been no definitive technical data published on these types of facilities. The methods and procedures of section 9.1 will apply wherever practical. The following specific sections will not apply:

a.) 9.1.2   A classic calibration of the empty test section will not be possible

b.) 9.1.4   The yaw requirements for a wind average drag coefficient calculation can not be met.

c.) 9.1.5   The tractor is ideal in that it is an actual production model; the trailer is not a full trailer nor does it model the undercarriage.

d) 9.1.11   Forces are not measured on a complete tractor trailer nor is the tunnel configuration one that has been studied in the open literature.

10. NOTES

10.1   Marginal Indicia

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY THE SAE TRUCK AND BUS AERODYNAMICS AND FUEL ECONOMY COMMITTEE

APPENDIX A - WIND AVERAGED DRAG COEFFICIENT

A.1   UNITED STATES AVERAGE WIND SPEED

The average wind speed for the continental US was calculated from NOAA weather station data in each state and weighted by the annual truck miles traveled in each state.

A given state's average wind speed was calculated from representative town and city annual wind data available in the state. This data is available from:

http://www.ncdc.noaa.gov/oa/climate/online/ccd/wndspd.txt

The raw data is reported at a height of 32 feet above the ground. Wind speed was scaled to a height of 10 feet using a 1/7 power law.   Vehicle miles traveled (VMT) by trucks in each state is reported in the following reference:

http://www.fhwa.dot.gov/policy/ohim/hs06/htm/ps1.htm

The overall US average was calculated by weighting a state's average by the state's truck VMT.

It should be noted that the actual value found was 7.45 mph and that 7 mph was retained from the previous version of this recommended practice for consistency in reported results.

A.2   WIND-AVERAGED DRAG COEFFICIENT COMPUTATION

A vehicle's wind-averaged drag coefficient can be evaluated using the annual mean wind speed in the United States, assuming that the wind will approach the vehicle with equal probability from any direction. The wind-averaged drag coefficient is defined by:

$$\overline{C}_D(V_T) = \frac{D(V_T)}{1/2 \rho V_T^2 A}$$

(Eq. A1)

The value of $\overline{C}_D(V_T)$ can be approximated as follows:

$$\overline{C}_D(V_T) = \frac{1}{6} \sum_{j=1}^{6} M(j) C_D(j)$$

(Eq. A2)

Where:

$$M(I) = 1 + \left(\frac{V_W}{V_T}\right)^2 + 2\left(\frac{V_W}{V_T}\right) \cos \phi(j)$$

(Eq. A3)

$$\phi(j) = (j \times 30 \text{ deg}) - 15 \text{ deg}$$

(Eq. A4)

$$C_D(j) = C_D \psi(j)$$

(Eq. A5)

$$\psi(j) = \tan^{-1}\left[\frac{(V_W/V_T)\sin \phi j}{1 + (V_W/V_T)\cos \phi j}\right]$$

(Eq. A6)

where ψ is defined in Figure 1.

If this technique is used, the value of V_W recommended for use in computing the wind-averaged drag coefficient and representative of the average winds for trucks and buses is 7 mph. Using this mean wind speed value, the following table is provided to facilitate a computation of $\overline{C}_D(V_T)$ at vehicle speeds of 30 mph (48.3 km/h) and 55 mph (88.5 km/h).

TABLE A1 - WIND-AVERAGED DRAG COEFFICIENT COMPUTATION CHART

i	V_T = 30 mph (48.3 km/h)		V_T = 55 mph (88.5 km/h)	
	$\psi(j)$(deg)	M(j)	$\psi(j)$(deg)	M(j)
1	2.8	1.505	1.7	1.262
2	8.1	1.384	4.7	1.196
3	12.0	1.175	6.8	1.082
4	13.5	0.934	7.2	0.950
5	11.2	0.724	5.6	0.836
6	4.5	0.604	2.2	0.770

The values of $\psi(j)$ given in the table above are all positive. If the $C_D(\psi)$ characteristic is not symmetrical about ψ = 0 deg, the value of $\overline{C}_D(j)$ to be used in the computation of $\overline{C}_D(V_T)$ is the average of the C_D values at plus and minus $\psi(j)$. If the value of $C_D(V_T)$ is reported, the value of the mean wind speed and the vehicle speed used in its computation must be stated.

The following are sample calculations using discrete wind tunnel test points to obtain wind averaged drag coefficients for two vehicle road speeds. It should be noted that this legacy test data does not include the recommended ψ = +/- 1 degree. If the test data does not include the exact required yaw angles (e.g., Table a1) as in the case shown here, then curve fitting techniques may be used to interpolate. B-spline and linear interpolation may be used. The chosen method must be stated and used consistently for all of the compared configurations.

TABLE A2 - WIND-AVERAGED DRAG COEFFICIENT COMPUTATION SAMPLE FOR V_W=7 MPH AND V_T=30 MPH

Wind Tunnel Test Data		$\overline{C}_D$ Computation (V_W = 7 mph and V_T = 30 mph)					
ψ (deg)	C_D	I	ϕ	M	ψ	C_D	MC_D
-15	0.8681	1	-165	0.604	-4.5	0.6067	0.3663
-12	0.8295	2	-135	0.724	-11.2	0.8098	0.5867
-9	0.7576	3	-105	0.934	-13.5	0.8487	0.7924
-6	0.6623	4	-75	1.175	-12.0	0.8294	0.9748
-3	0.5542	5	-45	1.384	-8.1	0.7279	1.0076
0	0.5164	6	-15	1.505	-2.8	0.5519	0.8307
3	0.5604	7	15	1.505	2.8	0.5577	0.8395
6	0.6723	8	45	1.384	8.1	0.7438	1.0297
9	0.7767	9	75	1.175	12.0	0.8374	0.9841
12	0.8374	10	105	0.934	13.5	0.8492	0.7929
15	0.8612	11	135	0.724	11.2	0.8207	0.5946
		12	165	0.604	4.5	0.6146	0.3711
						$\overline{C}_D$ =	0.764

TABLE A3 - WIND-AVERAGED DRAG COEFFICIENT COMPUTATION SAMPLE FOR V_W=7 MPH AND V_T=55 MPH

Wind Tunnel Test Data		$\overline{C}_D$ Computation (V_W = 7 mph and V_T = 55 mph)					
ψ (deg)	C_D	I	φ	M	ψ	C_D	MC_D
-15	0.8681	1	-165	0.770	-2.2	0.5435	0.4186
-12	0.8295	2	-135	0.836	-5.6	0.6497	0.5433
-9	0.7576	3	-105	0.950	-7.2	0.7020	0.6671
-6	0.6623	4	-75	1.082	-6.8	0.6874	0.7439
-3	0.5542	5	-45	1.196	-4.7	0.6162	0.7371
0	0.5164	6	-15	1.262	-1.7	0.5376	0.6785
3	0.5604	7	15	1.262	1.7	0.5410	0.6828
6	0.6723	8	45	1.196	4.7	0.6244	0.7470
9	0.7767	9	75	1.082	6.8	0.6996	0.7570
12	0.8374	10	105	0.950	7.2	0.7155	0.6800
15	0.8612	11	135	0.836	5.6	0.6591	0.5511
		12	165	0.77	2.2	0.5479	0.4220
						$\overline{C}_D$ =	0.636

A.3   A CAUTION ON THE USE OF WIND AVERAGED DRAG COEFFICIENT DATA

Wind tunnel data is typically obtained at an equivalent vehicle speed based upon the minimum test velocity determined from a Reynolds Number sweep.   This minimum wind tunnel test velocity correlates to a minimum vehicle speed on the road at full scale Reynolds number. In calculating wind averaged drag the wind tunnel data cannot be extrapolated to a vehicle speed below the minimum vehicle speed defined above, but may be extrapolated to a higher vehicle speed.   For example, a 1/4 scale model tested at 120 mph has an equivalent minimum road speed of 30 mph. In this case the drag coefficients obtained in the wind tunnel at a speed above the point where there is no further change in coefficient are taken to apply to all road speeds from 30 mph and above.