

A Review of Reynolds Number Effects on the Aerodynamics of Commercial Ground Vehicles

Richard Wood
SOLUS-Solutions and Technologies LLC

ABSTRACT

A review of Reynolds number scaling and high Reynolds number simulation for commercial ground vehicles is presented. The supporting data was extracted from published wind tunnel tests, coastdown tests and computational studies for complete vehicles and vehicle components. For complex vehicles the data suggest that the use of forced transition for higher Reynolds number simulation is a viable test technique however various component specific schemes may be required to replicate the aerodynamics of a full-scale vehicle. The Reynolds number sensitivity of; boundary layer transition control, surface curvature effects, bluff base flows, wheel/tire aerodynamics, and complete vehicle aerodynamics is presented. The data show that the width-based transcritical Reynolds number for commercial vehicles is between 1 and 3 million with the averaged values for edge radius, wheels and full vehicle data sets between 1.6 and 1.8 million. A minimum width-based transcritical Reynolds number value of 3 million is recommended for simulating the aerodynamics of full-scale commercial vehicles operating at a width-based Reynolds number greater than 3 million. If the dominant aerodynamic and fluid dynamic features of the vehicle are well established the minimum width-based transcritical Reynolds number value that may be used is 2 million. To ensure an accurate simulation of full-scale vehicles operating below the 3 million transcritical value future studies should be performed at the vehicle full-scale Reynolds number.

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INTRODUCTION

Over the past decade there has been a growing acceptance of aerodynamic drag reduction as a viable fuel economy improvement technology for commercial vehicle. Aerodynamic vehicle shaping and aftermarket drag reduction technologies appear regularly on light, medium and heavy trucks and trailers. Supporting this growing interest is the increased use of aerodynamic testing and computational tools by all sectors of the industry. Typically commercial vehicle wind tunnel test use scale models with vehicle boundary layers that fail to represent the critical characteristics found on a full-scale vehicle. Computational studies of representative vehicles may also fail to accurately represent the critical boundary layer characteristics found on a full-scale vehicle. Additionally full-scale coast down testing used to obtain high-speed aerodynamic data are performed over a broad range of test speeds without an understanding of the change in the off-body and on-body flow conditions.

For aerodynamic technology to mature it is critical that the use of all tools is based on the governing fundamental aerodynamic and fluid dynamic criteria. In aerodynamics the most critical criteria is Reynolds number which guides

vehicle design principles and governs the use of testing and analysis tools. A review of the literature [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107] indicates that despite the rapid increase in the use of aerodynamic technology the industry has not fully embraced Reynolds number scaling and simulation methods as a critical testing or analysis criteria. A factor affecting the slow adoption may be the 0.7×10^6 minimum Reynolds number claimed in SAE J1252 Recommended Practice [105]. Though SAE J1252 does not provide a reference for the minimum Reynolds number value it is most likely based on legacy data sets from the 1960s and 1970s. These data sets are for aerodynamically sharp-edged (i.e. small edge radii) bluff body vehicles that are known to have aerodynamic forces and moments that vary little with Reynolds number, see Anderson [2], Buckley [13, 15], Cooper [20, 23] and Watkins [92, 93, 94, 95, 96, 97].



The continued acceptance of the 0.7×10^6 minimum Reynolds number value is surprising given that the validity of this value has been challenged by leading ground-vehicle aerodynamicists beginning in 1978. In 1978 Hucho [50] raised the initial concern, in 1981 Gilhaus [42] suggested a minimum width based Reynolds number value of 1.6 million, Cooper suggest 1.0 million in 1982 [20] and then 2.0 million in 1985 [25], Drollinger supported a value between 1 and 2 million in 1987 [33], and Olson offered 1.7 in 1992 [64]. Storms in 2004 [84] executed a sub-scale model study in a NASA pressure wind tunnel that was able to obtain full scale Reynolds number data on a 0.125 scale model. Storms test data clearly suggest that the minimum width-based Reynolds number is greater than 1 million and may be as large as 3 million. These differences in the recommended minimum Reynolds number may be attributed to differences in the test facility, the characteristics of the specific vehicle in question or may be dictated by a specific component on the vehicle. To address each of these possible factors the current study used a large data sample for the full vehicle as well as several vehicle components that have the potential to impact the behavior of the total vehicle. The study reviewed the available literature to develop an understanding of Reynolds number scaling and simulation methods on the aerodynamics of the total vehicle, leading edge radius, bluff base and tires/wheels. The information presented in this paper has been extracted from published works and where available accepted correlation parameters and summary data plots are presented. The evaluation of complete vehicles made use of references 6, 8, 9, 11, 13, 15, 16, 18, 20, 21, 22, 23, 24, 26, 27, 29, 33, 36, 37, 44, 45, 48, 49, 50, 51, 52, 56, 64, 70, 73, 74, 77, 80, 81, 82, 83, 84, 85, 86, 87, 91, 93, 94, 95, 96, 97, 100. Edge shaping analysis is based on the work of Copper [25] in addition to references 1, 3, 7, 16, 32, 42, 50, 54, 55, 63, 64, 65, 66, 72, 76, 78, 90, 101, 103. Bluff base evaluations focused on boattail effects as documented in references 11, 12, 17, 25, 35, 36, 39, 47, 61, 62, 67, 68, 84, 90. The investigation of wheel aerodynamics is based on references 4, 5, 19, 31, 38, 46, 53, 57, 58, 59, 71, 80, 88, 92, 98, 102. In support each of these vehicle and component studies a review of boundary layer forced transition effects made use of references 2, 8, 10, 14, 25, 26, 28, 34, 37, 40, 41, 43, 47, 60, 75, 89, 93, 94, 95, 96, 97, and 99.

DISCUSSION

Reynolds number (Re) is the most critical parameter for the aerodynamic study and design of commercial vehicles [8, 9, 49]. However the supporting data and information guiding the application of Reynolds number scaling criteria for ground vehicles is limited compared to that available to the aircraft and watercraft communities. The Reynolds number data used in this study was extracted from a published wind tunnel tests, coastdown tests, and computational studies for complete vehicles and vehicle components. To provide context, the data analysis presented is compared to relevant

SAE Recommended Practices [104, 105, 106, 107]. The remaining sections of the paper will discuss the Reynolds sensitivity of boundary layer transition control, curvature effects, bluff base flows, wheels and complete vehicle. The final section of this paper summarizes the Reynolds number data into a single chart to define a width based transcritical Re value for commercial vehicles.

Background

Reynolds number is used in aerodynamic studies to characterize critical on-body and off-body flow features such as the vehicle boundary layer state, boundary layer thickness, flow separation, flow expansion, shear layer stability and flow reattachment. Each of these fluid dynamic characteristics plays an important role in guiding both experimental as well as computational studies. Specific aerodynamic design and analysis areas of interest are wind tunnel testing, coast down testing [107], computational design, advanced surface shaping, flow control technology and time dependent atmospheric effects.

The first step in understanding the impact of Reynolds number in vehicle design is the determination of the minimum test Reynolds number for wind tunnel testing [20, 42, 50], also known as the transcritical Reynolds number [69], see figure 1. The terminology of Roshko [69] is used to describe the relevant Re regions. Figure 1 shows representative variations in C_D with Re for a simple bluff body (sphere), see upper graph, and a typical bluff body vehicle, see lower graph. The variation in C_D with Re for a bluff body has the following characteristics; 1) the highest drag occurs at subcritical Re values where the boundary layer and all separations are laminar, 2) the start of the abrupt drag reduction is noted as the critical Re (Re_{cr}) and coincides with the start of boundary layer transition from laminar to turbulent, 3) the transitional range of Re covering the large variations in drag reflects the progression in the extent of the boundary layer transition from laminar to turbulent, and 4) transcritical Re (Re_{tr}) is the point at which a majority of the boundary layer has transitioned to turbulent flow on the body and the drag level becomes invariant with further increase in Re. It is important to note that the drag level in the transcritical range may exhibit small variations, with increasing Re, due to changes in boundary layer state, flow separations, and flow reattachment.

Vehicle aerodynamic design and/or analysis studies should be performed at Re values in which the vehicle aerodynamics as well as on-body and off-body flow conditions match those of the full-scale vehicle under operational conditions. This may require the representative Re to be greater or less than the transcritical Re value, this point is graphically depicted in figure 2 [32]. Presented in figure 2 is a portion of the data obtained by Delaney [32] which show variations in C_D with Re for two-dimensional cylinders of different edge radii. Depending on the operational speed of a full-scale vehicle (see shaded vertical

bar) the representative Re value may be either in the subcritical range (sharp edge bluff body upper curve), transitional range (middle curve) or transcritical range (smooth bluff body lower curve). Note the transcritical Re for the sharp edge bluff body (upper curve) would occur at a Re value that is greater than shown on the figure. These data show that the transcritical Re may vary over a broad Re range for small changes to these simple shapes.

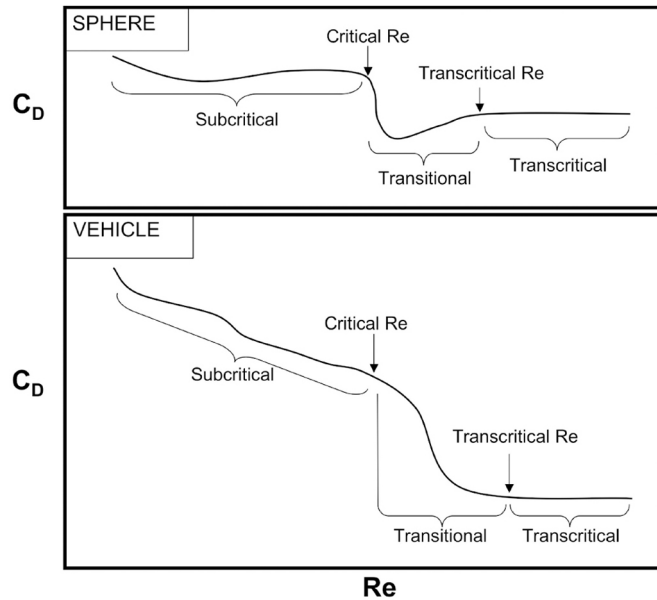


Figure 1. Representation of the variation in C_D with Re for a sphere and a typical bluff vehicle.

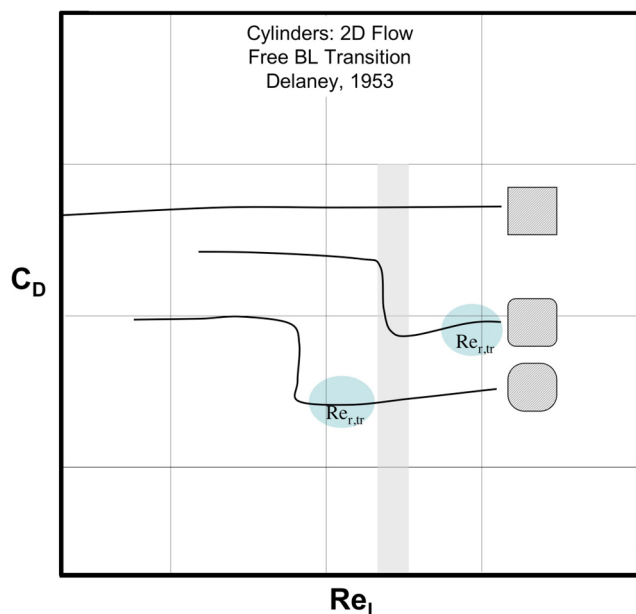


Figure 2. Variation in C_D with Re_l due to edge radius for 2D cylinders.

Forced Transition

The on-body flow, off-body flow and the aerodynamics of a vehicle can change significantly with changes in Re . The Re for a specific vehicle will vary with a change in the velocity of the air stream (or vehicle speed) and/or by a change the density of the air (fluid) passing over the vehicle surface. It is known that the critical and transcritical Re can occur at lower values by forcing boundary layer (BL) transition with the use of either roughness elements placed on the surface of the body [8, 10, 25, 26, 37, 40, 41, 43, 47, 60, 89] or by introducing turbulence into the air-flow upstream of the body [2, 14, 28, 34, 75, 93, 94, 95, 96, 97, 99]. Representative forced boundary layer transition test results, showing the impact of forced transition on the C_D , are shown in figures 3 and 4 for generic vehicle components and in figure 5 for a combination vehicle.

The chart shown in figure 3 is from a report by Cooper [25]. The test program investigated leading edge radius effects on generic bluff body models over a broad Re range for both free BL transition and the use of grit roughness elements to force BL transition. Test data is for non-dimensional radius values ($\eta=r/A^{.5}$) of 0.025, 0.050 and 0.063. The data for $\eta=0.063$ show that the use of grit reduces the critical and transcritical Re values by 50%. In contrast, the forced transition data for the relative sharp edge body ($\eta=0.025$) varies little from the free transition data indicating that the sharp edge body is insensitive to Re over the test range.

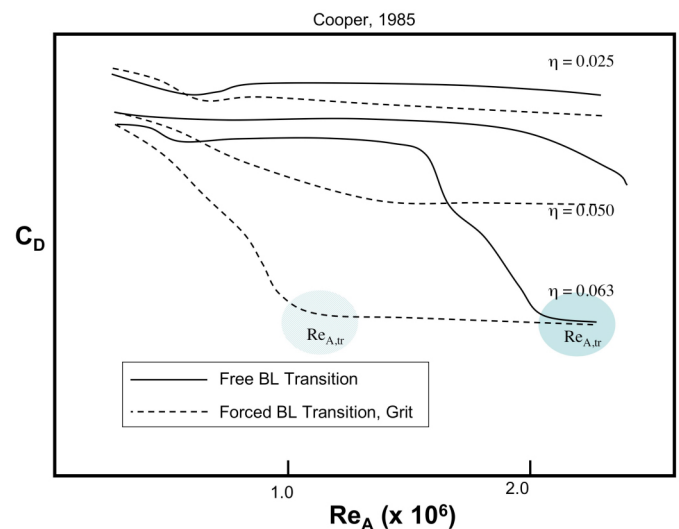


Figure 3. Effect of boundary layer transition on Re_A dependent C_D for 3D cylinders.

An alternate approach to surface roughness is to increase the free stream turbulence. The increased free stream turbulence structures interact with the BL flow to promote early transition. Shown in figure 4 is a plot from a boattail study by Morel [61] in which free stream turbulence was used to successfully force early BL transition. The data show that

the change in BL transition location impacts both the drag levels and the slant angle at which the base flow separation occurs.

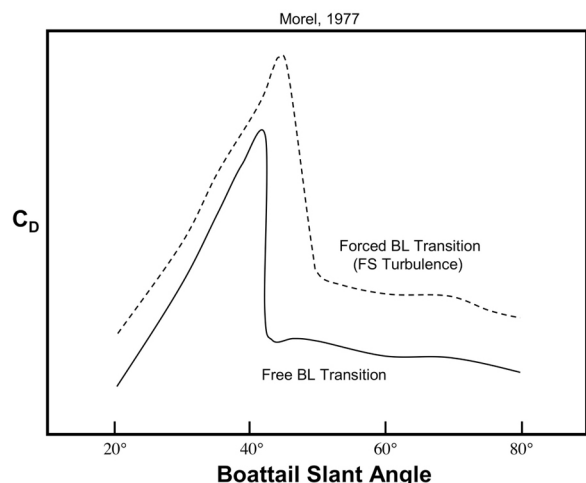


Figure 4. Effect of boundary layer transition on Boattail angle dependent C_D for a simple bluff body.

The two previous examples of forced BL transition were for simple bluff body shapes at zero yaw angle. Shown in [figure 5](#) is a data plot by Cooper [29] for two combination vehicles over a range of yaw angles. Results are presented for free transition and three levels of free stream turbulence. Compared to the free transition data the forced transition data show significant changes in the C_D level and the variation in C_D with yaw angle for each free stream turbulence level for the two combination vehicles.

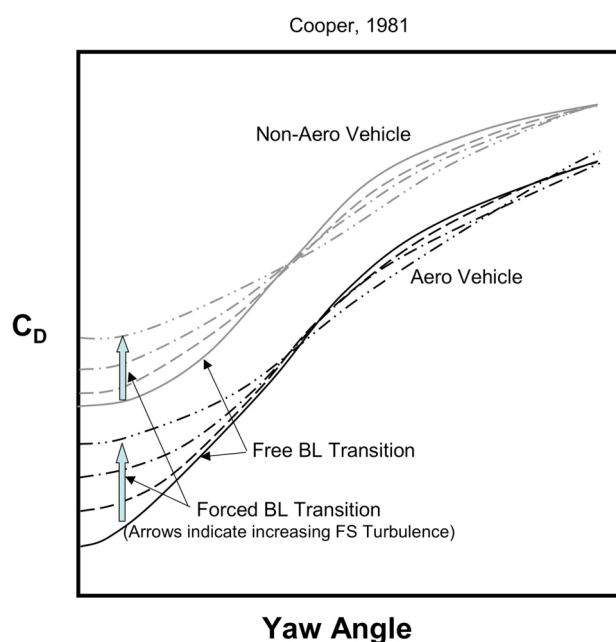


Figure 5. Effect of boundary layer transition on Yaw angle dependent C_D for two combination vehicles.

The data presented in [figures 3, 4 and 5](#) highlights the benefit and complexity of using forced transition techniques to simulate higher Reynolds number flow conditions. Successful use of forced transition requires an understanding of the desired boundary layer conditions as well as the expected aerodynamic characteristics at higher Reynolds number conditions. The data also suggest that the use of forced transition [\[10, 45\]](#) on complex vehicle shapes with multiple components may require the use of multiple forced transition treatment scheme on a subscale vehicle in order to obtain results that are consistent with full scale Reynolds number conditions. Although the commercial vehicle industry does not routinely use forced boundary layer transition to replicate higher Reynolds number flows it is suggested that future test programs develop and implement these methods in order to correct current limitation of existing facilities.

Radius of Curvature

Aircraft design technology and edge shaping techniques found their way into ground vehicle design beginning in the 1930s [\[65\]](#). However associated with any edge shaping there is an increase in the complexity of the aerodynamics of the vehicle resulting in greater sensitivity of the drag force to both the Re and the direction of the onset flow (yaw angle). Edge shaping on commercial ground vehicles has historically used fixed radius shaping on the side edge of the tractor, trailer, and freight box. Recent design trends show an increase in the use of complex three-dimensional shaping where changes in the local radii of curvature will become the figure of merit in the evaluation BL transition and Re sensitivity. The importance of this parameter will continue to increase as the front of trucks and trailers adopt more complex shaping strategies in the design process.

The work by Cooper [\[25\]](#) serves as the basis for this portion of the paper. A number of additional papers [\[1, 3, 7, 16, 25, 32, 42, 50, 54, 55, 63, 64, 65, 66, 72, 76, 78, 90, 101, 103\]](#) were reviewed and their findings were evaluated in the context of the Cooper summary charts [\[25\]](#). Of note is the work by Buckley [\[16\]](#), Delaney [\[32\]](#), Gilhaus [\[42\]](#), Hucho [\[50\]](#), Lindsey [\[55\]](#), Pawlowski [\[65\]](#) and Polhamus [\[66\]](#).

One of the earliest data sets and one that is often cited is the 1930 paper by Pawlowski [\[65\]](#), based on the thesis by Frank Wyszynski, see [figure 6](#). The plot of [figure 6](#) is constructed by plotting the Pawlowski data as a function of Re based on the edge radius. The plot indicates that the critical Re ($Re_{cr,r}$) value for the bodies with an edge radius is less 0.05×10^6 while the $Re_{cr,r}$ value for the sharp edge body is greater than $.25 \times 10^6$. The C_D data for bodies with radius values 0.167, 0.250, and 0.333 is in the transcritical Re range. In contrast the data for the 0.083 radius body indicate it is in the transitional Re range. A review of the full data set suggest that the transcritical Re ($Re_{tr,r}$) value would occur above