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L. RAY BUCKENDALE LECTURE

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Reynolds Number Impact on Commercial Vehicle Aerodynamics and Performance

Richard Wood

SOLUS-Solutions and Technologies LLC

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L. RAY BUCKENDALE LECTURE

This lecture, presented annually at the SAE Commercial Vehicle Engineering Congress, focuses on automotive ground vehicles for either on- or off-road operation in either commercial or military service. The intent is to provide procedures and data useful in formulating solutions in commercial vehicle design, manufacture, operation and maintenance.

Established in 1953, this lecture commemorates the contributions of L. Ray Buckendale, 1946 SAE President. L. Ray Buckendale, by his character and work, endeared himself to all who were associated with him. Foremost among his many interests was the desire to develop the potential abilities in young people. As he was an authority in the theory and practice of gearing, particularly as applied to automotive vehicles, it was in this field that he was best able to accomplish his purpose. To perpetuate his memory, SAE established this lecture to provide practical and useful technical information to young people involved in vehicle engineering.

The individual presenting the Buckendale Lecture will receive an honorarium and a framed certificate. All those attending the lecture receive an electronic copy of the lecture, and are invited to attend a sponsored breakfast with the lecture immediately following.



2015 LECTURER

Richard Wood

Richard Wood is president and owner of SOLUS, a service-disabled veteran-owned aerodynamic technology company. Richard has 35 years of experience in aerodynamic research and product development for various organizations including NASA, DARPA, DOD, DOE, EPA, NASA, Boeing, Lockheed Martin and Northrop Grumman. His extensive ground vehicle experience includes experimental and computational fluid dynamics and fuel economy testing. Richard holds a Bachelor of Science in Mechanical Engineering from Old Dominion University and has authored 120 technical papers with SAE, AIAA, ASME, and NASA and has 17 patents and 7 patents pending. Mr. Wood is a registered Professional Engineer and has received numerous awards including; 2011 Hampton Roads Entrepreneur of the Year Award, NASA 2005 Richard Whitcomb Technology Transfer Award, NASA Engineering and Safety Center X43A Award, and Boeing Hornet Wing Drop Program Award.

Mr. Wood is an active member of SAE International. His support for SAE meetings include; chair of the ComVEC Commercial Vehicle Aerodynamics Committee and past chair of the ComVEC Total Vehicle Committee where he has organized and chaired more than 30 technical sessions and reviewed more than 70 papers. In the area of SAE standards Mr. Wood is vice chair of the Truck and Bus Council, chair of the Total Vehicle Steering Committee, and past chair of the Aerodynamics and Fuel Economy Committee. He currently chairs the J3015 Reynolds Number task force and has chaired J1321 and J2971 task forces. In addition to his leadership roles he is a member of the Aerodynamics and Fuel Economy Committee and Road Vehicle Aerodynamics Forum Committee. Mr. Wood has received SAE International's 2014 James M. Crawford Technical Standards Board Outstanding Achievement Award and SAE International's 2015 Forest R. McFarland Award for his contributions to the SAE Transportation Standards Board and SAE Engineering Meetings Board, respectively.

60TH ANNUAL L. RAY BUCKENDALE LECTURE

Reynolds Number Impact on Commercial Vehicle Aerodynamics and Performance

Richard Wood

2015-01-2859

This SAE technical paper presents the 60th Annual L. Ray Buckendale Lecture, which was presented during the SAE Commercial Vehicle Engineering Congress on October 7, 2015 in Rosemont, Illinois, USA.

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Reynolds Number Impact on Commercial Vehicle Aerodynamics and Performance

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ABSTRACT

The impact of Reynolds number on the aerodynamics and operational performance of commercial vehicles is discussed. All supporting data has been obtained from published experimental and computational studies for complete vehicles and vehicle components.

A review of Reynolds number effects on boundary layer state, unsteady and steady flow, time dependent wake structure, interacting shear layer and separated flows is presented. Reynolds number modeling and simulation criteria that impact aerodynamic characteristics and performance of a commercial vehicle are shown. The concepts of dimensional analysis and flow similarity are employed to show that aerodynamics of commercial ground vehicles is only dependent on Reynolds number. The terminology of Roshko is adopted for discussing the variation in drag with Reynolds number in which the subcritical, transitional and transcritical flow regimes are defined for commercial vehicles. Criteria for aerodynamic simulation as well as testing and design of commercial vehicles are defined and show a minimum transcritical Reynolds number value of 3 million is recommended for simulating the aerodynamics of full-scale commercial vehicles.

Guidance is provided for aerodynamic design and analysis in the framework of Reynolds number and boundary layer flows as they relate to previous designs, current testing and analysis criteria, and the development of future vehicles. A discussion of aerodynamic tools is presented which call for the continued development of aerodynamic test and analysis tools capable of capturing Reynolds number sensitivities. Of particular importance is the maturation of computational simulation tools with improved friction modeling capability specifically developed for commercial ground vehicles.

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CHAPTER 1. INTRODUCTION

1.1. Objectives

The commercial trucking industry is the keystone of our economy but continues to be burdened by the cost of fuel, the most volatile operational expense. Complicating the equation are the growing environmental-based regulatory requirements that are driving up vehicle cost and maintenance requirements. Both the industry and regulators have recognized aerodynamic drag reduction as a viable solution to these challenges. The majority of effort to date has focused on 1950 based aerodynamic fairing concepts where test data suggest reductions in aerodynamic drag up to 40 percent may be possible with corresponding improvements in fuel economy approaching 20 percent. However these projected improvements have not been consistently realized under operational conditions due to the narrow design window of the aerodynamic system and the significant difference between the operational and test environment.

To minimize the uncertainty in operational performance the aerodynamic process must include a broad range of operational conditions and take into account environmental factors, such as wind

disturbances from traffic and weather. Compared to the ideal test case, these factors can dominate the aerodynamic drag of commercial vehicles. In addition the freight industry requires aerodynamic solutions that are operationally practical, aerodynamically robust, and satisfy all safety requirements. It is within this context that Reynolds number and boundary layer sensitivity factors will influence aerodynamic design and vehicle performance.

This 60th L. Ray Buckendale paper will build upon the 33rd lecture by Richard Drollinger entitled "Heavy Duty Truck Aerodynamics" [1]. Drollinger's 1987 paper provides an excellent introduction to heavy truck aerodynamics and review of the available testing and analysis procedures of the time. His insight into the benefit of aerodynamics to improve the performance of commercial vehicles is reflected in the following statements taken from his paper.

"In the early sixties, it was estimated that aerodynamic drag could be reduced by 37 percent,"

“today it is possible to achieve over 9mpg with modern aerodynamic shapes; high torque, low rpm engines; low profile tires and efficient drive trains...”

Unfortunately, after 27 years these statements remain true. An objective of this paper is to provide the industry with actionable aerodynamic information so that in 2040 we are not revisiting the past. However, as also pointed out by Drollinger, aerodynamics is but one of many disciplines that must work together.

“Having good aerodynamics and a general fuel efficient truck can all be made useless with poor driving habits.”

The goal of this paper is to provide a foundation to guide current and future aerodynamic design and analysis efforts. Specifically this paper will focus on Reynolds number and boundary layer flows as they relate to previous designs, current testing and analysis criteria, and the development of a pathway for future design efforts. To address these objectives requires a review of the past to establish the role of fundamental aerodynamic principles on commercial vehicle design and performance. A brief history of Reynolds number and the boundary layer concept are presented in sub-sections 1.3 and 1.4 of this Chapter and a detailed discussion is contained in Chapter 2.

To provide a clear historical record, all information contained in this paper will be based solely on published, peer-reviewed, publically available scientific and engineering documents. Listed at the end of each Chapter are the references supporting the information presented.

Portions of this paper have been willfully plagiarized from the author's 2012 SAE publication “A Review of Reynolds Number Effects on the Aerodynamics of Commercial Ground Vehicles,” *SAE Int. J. Commer. Veh.* 5(2): 2012, doi:10.4271/2012-01-2045. [2]

1.2. Background

“The Reynolds number is physically a measure of the ratio of inertia forces to viscous forces in a flow and is one of the most powerful parameters in fluid dynamics.” John D. Anderson Jr., “Fundamentals of Aerodynamics”, 1991 [3]

There is a growing acceptance of aerodynamic drag reduction as a viable fuel economy improvement technology by all sectors of the commercial vehicle industry [4]. Regulators have established several goals for class 8 trucks that range from a ten to fifteen percent increase in fuel economy associated with drag reduction to a fifty percent increase in freight efficiency by 2015. Analysis of United States energy consumption show a twelve percent reduction in aerodynamic drag will save 3.0 billion gallons of fuel [4] which equates to a reduction in emissions of 28.0 million tons.

Aerodynamic vehicle shaping and aftermarket drag reduction technologies appear regularly on light, medium and heavy trucks and trailers [5]. Supporting this growing interest is the increased use of aerodynamic testing and computational tools. However, anecdotal evidence indicates that the sophistication of the tools and techniques being employed may not be improving at a sufficient rate to deliver the quality of data needed. Typically wind tunnel tests of commercial

vehicles are performed with sub-scale models at test conditions that may fail to satisfy the governing aerodynamic similarity criteria (i.e. Reynolds number) and do not represent the critical fluid dynamic characteristics found on a full-scale vehicle [2]. Computational studies of representative vehicles may also fail to accurately represent the critical fluid dynamic characteristics found on a full-scale vehicle [2]. Additionally full-scale coast down testing used to obtain high-speed aerodynamic data are performed over a broad range of Reynolds numbers without an understanding of the change in the off-body and on-body flow conditions [2]. To quantify these concerns a review was performed of published literature contained in archives of long standing organizations.

Recognizing that the Society of Automotive Engineers (SAE) is a leading source for commercial vehicle information a search of their ground vehicle publication archives was conducted to shed light on the evolution of commercial vehicle aerodynamic information and knowledge. The review begins with the year SAE added aeronautics to its charter. From 1916 to 1960 there were less than 20 publications per year that mention either “aerodynamic” or “wind resistance” or “air resistance” and less than 10 percent of those mention Reynolds number. Unfortunately, the majority of the Reynolds number content was editorial in nature. There was a noticeable increase in aerodynamic technical content after 1960.

During the 30-year period from 1960 to 1990 the society published an average of 70 aerodynamic documents per year. Perhaps initially motivated by the Federal highway act of 1956 [6] and the OPEC oil crisis [7, 8] of the 70s and 80s the publication rate increased significantly in the 1990s and is currently at 400 aerodynamic publications per year. This trend with time is mirrored in SAE aerodynamic publications that discuss both Reynolds number and boundary layer flows. However the archive search shows that aerodynamic publications discussing Reynolds number and those covering both Reynolds number and boundary layer comprise less than 10 percent and 5 percent respectively of all SAE aerodynamic publications.

To provide context to the SAE publications a review of the National Aeronautics and Space Agency (NASA) and American Institute of Aeronautics and Astronautics (AIAA) archives was performed. This search found a significantly greater number of publications but similar trends with time, compared to SAE archives. Analysis of the NASA and AIAA publications showed more than three times the percentage of aerodynamic publications discussing Reynolds number and boundary layer flows compared to SAE publications. Further analysis of selected publications show that the Reynolds number and boundary layer content in SAE papers is less detailed and provides less significant findings compared to that contained in AIAA and NASA publications.

Another observation from the review is the influence of Computational Fluid Dynamics (CFD) in aerodynamic studies. Prior to 1990, aerodynamic papers discussing the combination of Reynolds number and CFD were less than 1 percent of the total published.

Since 1990 CFD content is contained in more than 50 percent of all published aerodynamic papers with Reynolds number content. The results highlight the growing attention paid to aerodynamic studies.

raise concern with the growing dependence on CFD and the lack of detailed investigation of the fundamental aerodynamics of commercial vehicles.

A technical review of a diverse set of relevant commercial vehicle literature [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] suggests that despite the rapid increase in the use of aerodynamic technology the commercial vehicle industry has not fully embraced Reynolds number scaling and boundary layer simulation methods as a critical testing or analysis criteria. Influencing the slow adoption may be the recommended minimum Reynolds number of 700,000 contained in the 1979 and 1981 versions of SAE J1252

Recommended Practice, SAE Wind Tunnel Test Procedure for Trucks and Buses [62]. The subject SAE document does not provide a reference for the recommended Reynolds number. It is assumed that this value is based on legacy data from wind tunnel test of 1960 and 1970 era commercial vehicles which are known to be insensitive to Reynolds number effects due their aerodynamically sharp-edges and surfaces with small radii of curvature, see Anderson [9], Buckley [18, 19, 20, 21], Cooper [23, 24, 25] and Watkins [57, 58, 59, 60]. For flow similarity the Reynolds number of the wind tunnel test shall match of the operational vehicle. That leads to Reynolds numbers of 0.7, 2.2 and 4.4 million for commercial vehicles driving at speeds of 10, 30, and 60 mph, as we will see in [Chapter 2](#).

In 1976 Hucho [40] raised the initial concern that aerodynamic testing of commercial vehicles, with moderate levels of aerodynamic shaping, was being performed at Reynolds numbers below that required obtaining representative data. In 1981 Gilhaus [35] suggested a minimum width based Reynolds number value of 1.6 million. Gilhaus was followed by Cooper's suggestion of 2.0 million in 1985 [26]. Drollinger supported a value of 2 million in 1987 [1], and Olson offered 1.7 million in 1992 [46]. Note, the differences in the recommended minimum Reynolds number values listed above 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. The use of the 0.7 million Reynolds number value well into the 21st century is unfortunate given the guidance provided by the leading ground-vehicle aerodynamicists of the time.

The minimum Reynolds number debate restarted in 2000 with the launch of the Department of Energy (DOE) 21st Century Truck Program [63]. In 2004 Storms [54] published wind tunnel test results for a generic concept vehicle that showed the minimum Reynolds number is greater than 1 million and may exceed 3 million. Again the industry was not swayed and the 0.7 million value remained the standard until 2012 when SAE J1252 [62] was updated. At this time the 0.7 million Reynolds number was removed from the document and replaced with a Reynolds number sensitivity test procedure [64]. Follow on studies employing the Reynolds number sensitivity test by Wood in 2012 [2], Leuschen in 2013 [65] and McArthur in 2013 [66] clearly show that the minimum width-based Reynolds number is greater than 2 million. Unfortunately, the J1252 Reynolds number test procedure has yet to be generally adopted within the industry as indicated by the significant number of current publications that

continue to reference the 0.7 million minimum Reynolds number value and the use of a minimum Reynolds number value of 1.0 million by the California Air Resources Board (CARB) [67].

For commercial vehicle aerodynamic technology to mature it is critical that the use of all tools is based on the governing fundamental aerodynamic and fluid dynamic criteria. For subsonic aerodynamics the most critical criteria are Reynolds number and by association boundary layer flows which taken together guide vehicle design principles and govern the use of testing and analysis tools. An historical review of the development of the Reynolds number and the boundary layer concept will be presented in the following sub-section of this Chapter.

1.3. Developments and Early Use of Reynolds Number

Reynolds number and boundary layer flow effects are intertwined in present day aerodynamic studies. This is especially true for matters related to drag and flow separation, which is synonymous with aerodynamic investigations of commercial vehicles. This section will provide a brief review of the early works of both Reynolds and Prandtl, the founders of Reynolds number and boundary layer concepts, respectively.

The motivation for the section is captured in the following statements taken from Reynolds' 1883 paper [68] and von Kármán's 1954 book [69]. Reynolds' begins his 1883 paper with the following statements;

"The results of this investigation have both a practical and a philosophical aspect."

"In their practical aspect they relate to the law of resistance to the motion of water in pipes..."

"In their philosophical aspect these results relate to the fundamental principles of fluid motion..."

In discussing Reynolds number von Kármán states:

"The Reynolds number is now generally used in hydrodynamics, aerodynamics, hydraulics, and other sciences which have to do with fluid flow. It works in some cases like black magic."

"I said that the Reynolds number works like black magic, because in engineering one can sometimes use a similarity rule and other general methods for the reduction of parameters without much of an understanding of the phenomena."

Clearly, both Reynolds and von Kármán are expressing the importance of understanding the foundational basis behind a finding. Extending this argument further, the foundational basis should be viewed as being inversely proportional to the simplicity and utility of the finding. Dr. von Kármán is also raising concern that a symptom of a useful finding is that it can depress intellectual curiosity that will adversely impact the quality of ones future work.

This following review will make use of the recollections of Theodore von Kármán, as documented in his 1954 book ["Aerodynamics"](#) [69], the historical review of Osborne Reynolds by

Rott in 1990 [70] and by Jackson and Launder in 2007 [71] and the historical review of Ludwig Prandtl by Anderson in 2005 [72] and by Bodenschatz and Eckert in 2011 [73].

Reynolds seminal 1883 paper [68] reported on a series of experiments on the flow in a tube. In Reynolds experiment the tube was connected to a reservoir, as depicted in figure 1.1 taken from Reynolds' paper. The experiment looked at variations in pipe diameter, fluid viscosity while the flow velocity in the tube was increased in small increments. Reynolds' interest was to understand the resistance and motion of fluids in a pipe. He evaluated the resistance through careful measurements and determined the flow characteristics by introducing dye into the flared entrance of the tube.

Reynolds developed this flow-visualization method as outlined in his 1877 publication [74]. The flow visualization studies showed at low velocities the dye formed a thin line that was parallel to the tube centerline, see figure 1.2a image taken from Reynolds' paper. This indicated that the flow was steady and orderly. As the flow velocity was increased the thin line of dye thickened and became random indicating that the flow was transitioning from orderly to random, see lower sketch in figure 1.2b taken from Reynolds' paper. Reynolds also noticed that as he increased the flow velocity the random motion moved closer to the tube entrance.

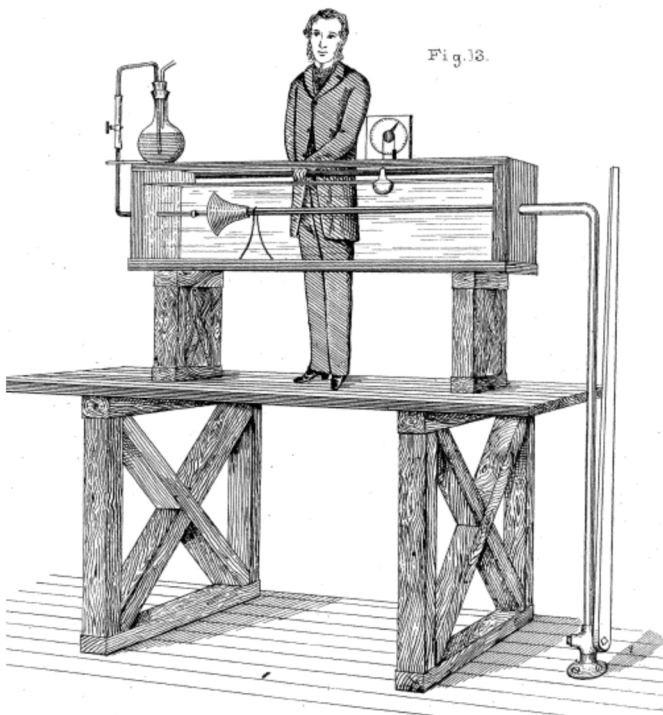
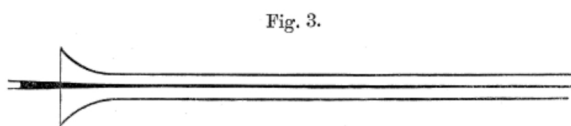
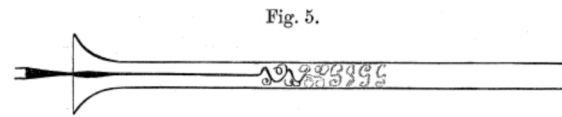


Figure 1.1. Sketch of Osborne Reynolds experimental apparatus [68].



a. Direct (laminar) flow.



b. Sinuous (turbulent) flow.

Figure 1.2. Sketch of observed direct and sinuous flow [68].

However Reynolds did not use the present day terms of laminar and turbulent but referred to the two states as “direct” and “sinuous”. These data were correlated with the resistance data to obtain a correlation parameter, which was not in a form of the dimensionless parameter, Reynolds number, we use today. He calculated a parameter “B” which was the reciprocal of the product of Reynolds number multiplied by a reference value of the kinematic viscosity. He continued his work in this area and published his second paper in 1895 [75] that was directed at calculating the critical Reynolds number that he labeled “K”. In so doing he developed the Reynolds averaged equations of motion.

There is no dispute that Reynolds' 1883 [68] and 1895 [75] publications are a foundational element of aerodynamics.

Regarding Reynolds' contribution, Jackson and Lauder [71] state;

“..it is no exaggeration to assert that his two principal papers on turbulent flow essentially provided a marker for the direction of research in Engineering Fluid Mechanics for the next century.”

However there are differing opinions as to the naming of Reynolds' nondimensional parameter (i.e. Reynolds number). Various historians [70, 71, 72, 73] have indicated that the naming of the parameter may be attributed to Ludwig Prandtl, Heinrich Blasius, and Lord Rayleigh. Rott [70] writes that Lord Rayleigh in 1892 [76] was the first to reference Reynolds' similarity law, however von Kármán [69] states that Sommerfield in 1908 [77] was the person who named the parameter after Reynolds.

Von Kármán writes in 1954 [69];

“...neither Reynolds himself or other British scientists who followed him gave a specific name to the nondimensional parameter UL/ν ; it was Arnold Sommerfield who named the parameter in honor of Reynolds in 1908”

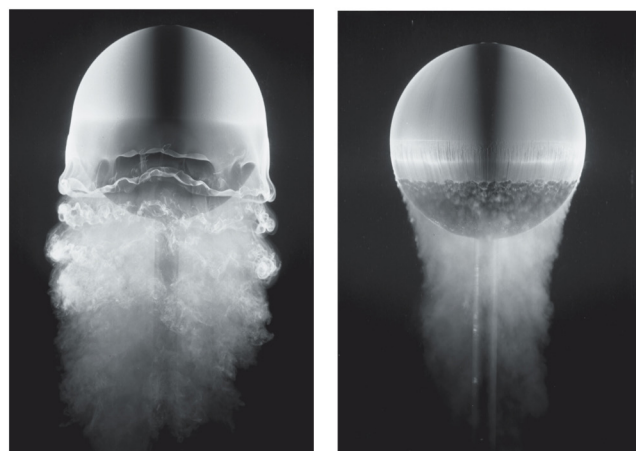
Regardless of who authored the “Reynolds number” label it is clear that Reynolds' work was acknowledge and relied upon by most of those advancing fluid mechanics, the boundary layer concept and aerodynamics in the 20th century. Rott points out that the adoption of Reynolds number by the scientific community is attributed to the writings of Prandtl in 1910 - 1914 [78, 79, 80], von Kármán in 1911 [81], and Blasius in 1912 and 1913 [82, 83]. Most notable among those is Prandtl, the first to introduce the boundary layer concept in 1904 [84].

In reference to Pradt's 1904 paper, Anderson writes in 2007 [72];

“Prandtl boundary-layer idea revolutionized how engineers conceptualized fluid dynamics.”

The linkage between Reynolds number and Prandtl's boundary layer concept was implied in the work of Blasius in 1907 [85] and 1908 [86] with his investigation of boundary layer flow on a flat plate and flow separation from a circular cylinder. However, Prandtl formalized this linkage in 1914 [79] when he correlated the change in drag with Reynolds number in his investigation of Gustav Eiffel's sphere drop tests of 1912 [87].

In 1912 Eiffel's measurements of the drag of spheres came under scrutiny by Prandtl when wind tunnel data obtained in the Göttingen wind tunnel differed with that of Eiffel by a factor of 2 [73]. To address these concerns Eiffel performed additional testing and discovered that his original data was correct. The difference between Eiffel's data and that from the Göttingen wind tunnel was the result of a new phenomenon in which at a critical speed the drag decreased with increasing velocity. Eiffel noted that this velocity is greater than that achievable in the Göttingen wind tunnel. However, Eiffel did not offer an explanation for this effect. In 1914 Prandtl [80] investigated this claim by modifying the Göttingen wind tunnel and was able to reproduce Eiffel's findings. However, unlike Eiffel who correlated the change in drag with velocity, Prandtl correlated the drag data with Reynolds number and showed that the new phenomena occurred at a constant Reynolds number, which can be achieved for different sphere sizes and different wind speeds. Prandtl offered an explanation of this new phenomena in which he stated that the boundary layer flow on the sphere is laminar at low speeds and transitions to turbulent at a higher or critical speed. The drop in drag correlates with the laminar boundary layer transitioning to a turbulent boundary layer and the subsequent delay in boundary layer separation that produces a reduction in the size of the trailing wake. Representative photographs of the phenomena are depicted in Figure 1.3 [88]. Prandtl investigated this effect further by employing a trip wire to force early transition of the boundary layer. This resulted in the drag drop occurring at a lower Reynolds number. Prandtl's correlation of Reynolds number, drag force, boundary layer state, flow separation, and wake flow provides the basis for the critical elements of bluff body aerodynamics [89].



a) Laminar boundary layer.

b) Turbulent boundary layer, wire trip at equator.

Figure 1.3. Flow visualization of boundary layer separation and wake flow about a sphere at low speed [88].

At the time of Prandtl's 1914 findings the world was on the verge of World War I and the scientific community was beginning to direct their efforts towards improving the efficiency of flight. The United States (US) lagged far behind Europe in aerodynamic understanding and in response the National Advisory Committee for Aeronautics (NACA), predecessor to NASA, was formed and SAE evolved from the Society of *Automobile* Engineers to the Society of *Automotive* Engineers, as they included aeronautics into their charter. Both organizations focused on power plant development during the World War I and little effort was directed at aerodynamics of ground vehicles. The next sub-section will highlight the Reynolds number and boundary-layer-based aerodynamic developments between 1920 and 1990 that serve as the foundation of commercial vehicle aerodynamics.

1.4. Review of Reynolds Number Aerodynamic Developments

The fundamental findings of Reynolds and Prandtl lay the foundation for all future developments in aerodynamics. World War I clarified the need for aeronautics research and stimulated a dramatic increase in the number of wind tunnels, experimental testing, and theoretical developments. Ground vehicle related aerodynamic studies of the 1920s and 1930s followed several paths; NACA focused on fundamental aerodynamics, the automotive industry focused on streamlining concepts [90] while the aeronautics industry focused on product development. In the 1940s all aerodynamic efforts were re-directed to support World War II. During the 1950s and 1960s NACA became NASA [91] and the agency split its resources between military support and basic research while the commercial vehicle industry published several significant studies. Driven by the 1973 oil embargo [92] and 1979 energy crisis [93] the two decades from 1970 to 1990 saw an increase in aerodynamic testing, development of new products and the drafting of the first ever engineering test procedure specifically targeted at fuel savings [94]. This sub-section will highlight significant aerodynamic and Reynolds number findings related to commercial vehicle aerodynamics from 1920 to 2015.

The 1920s and 1930s saw a significant growth in aerodynamics as new wind tunnel facilities and the development of foundational principles that guide current aerodynamic studies were pursued in the US and Europe [95]. A significant effort was directed at the development of wind tunnel test and correction methods [91]. Leading European aerodynamicists such as Hoerner, Munk, Prandtl, and von Kármán were encouraged to continue their work in the US at various government facilities and universities. The Daniel Guggenheim Fund [91] provided over \$3 million to eleven US universities to develop aeronautical programs and the construction of wind tunnels at seven of the eleven institutions. At the same time NACA was constructing seven wind tunnels; most notable are the Variable Density Tunnel (VDT) [94] developed by Max Munk, a student of Prandtl, and the Full-Scale facility at the Langley Aeronautical Laboratory [95].

The VDT allowed for testing sub-scale models at full-scale Reynolds numbers while the Full-Scale facility allowed the testing of full size models. This unique combination of facilities generated research findings that defined the effect of scale and flow conditions on test data as well as the relationship between Reynolds number, boundary

layer flows and aerodynamic forces. Most notable are the experimental findings for simple shapes by Dryden [96, 97], Jacobs [98], Hoerner [99] and Lindsey [43] and the results obtained on streamwise bodies by Munk [100, 101], Abbott [102] and Freeman [103]. In 1928 US Navy Captain Walter Diehl captured much of these findings in his book entitled "Engineering Aerodynamics"[104]. Below are several statements from Diehl's book regarding Reynolds number.

"Reynolds Number is of such fundamental importance in aerodynamics that a clear conception of its physical significance is essential. It is one of the most unusual numbers used in scientific work. Itself a pure number or ratio having no dimensions, it combines the effects of the four most important variables affecting air forces."

The following quote from Diehl is equally applicable to the components of a ground vehicle.

*"The actual value of a Reynolds Number has no significance except in comparing a given series of geometrical similar forms.".....
..... "Actually the effect of Reynolds Number is different on each item: wings, fuselage, struts, wires, etc. Furthermore, the effect is not the same on all wings or on all struts, but varies widely in each group."*

Occurring in parallel with the fundamental research were wind tunnel studies directed at streamlining ground vehicles. The "streamlining" design approach was not science based but may be viewed as an observational based concept. Descriptions of the concept can be found in several SAE papers [90, 105] in which Reynolds number and boundary layer criteria are mentioned but discounted. Despite the influence of this concept Pawlowski in 1930 [47] and of Lay in 1933 [106,107] investigated the effect of changes in edge radius for a generic bluff body. Pawlowski's and Lay's papers covered many topics with the edge radius discussion comprising a small portion of their papers. It is unfortunate that neither paper correlated the finding with Reynolds number as suggested by Prandtl in 1914 and restated in his 1923 paper [89], entitled "The New Interpretation of the Laws of Resistance". In Prandtl's 1923 paper he comments on the difference in drag for smooth and sharp edge shapes.

"the drag coefficient is not a constant, but a function of Reynolds number".

"the drag coefficient is constant over quite a long reach, especially for bodies having edges."

The streamlining period may have delayed fundamental aerodynamic studies of ground vehicle. One can imagine the additional progress that may have occurred without the distraction of streamlining.

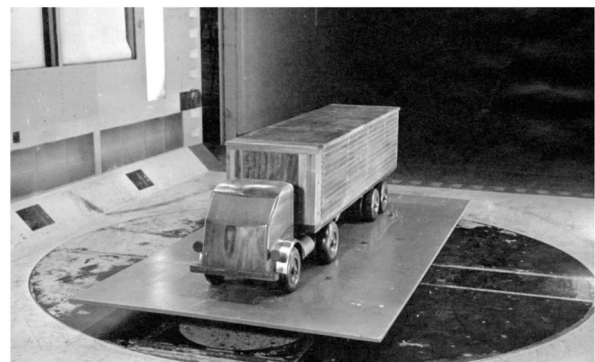
There was minimal progress made in ground vehicle aerodynamics during the 1940's as World War II consumed the world's attention and resources. Europe was once again leading the world in aerodynamic knowledge and technology and in response the US moved to expand its technical capability. Both Europe and the US worked to refine wind tunnel testing capability and the US continued to expand the understating of Reynolds number and boundary layer flows and the influence of pressure gradients, surface curvature and roughness on

transition and separation [108, 109, 110, 111, 112]. These data supported the development of present day computational tools in use within the commercial vehicle industry.

The 1950s and 1960s saw government funded aerodynamic research directed at transonic and supersonic aerodynamics and in 1958 space flight became the focus. There was a continuation of the fundamental study of Reynolds number effects and boundary layer flows and the influence of pressure gradients, surface curvature and roughness on transition and separation [113, 114, 115]. In this area of aerodynamics one of the most important publication from the government labs was NASA report TN D-3579 by Braslow and Hicks [116] that defined the testing standard for using grit to force boundary layer transition. The most notable development in fundamental aerodynamics during this time were the publication of Schlichting's "Boundary Layer Theory" in 1950 [117] and Hoerner's self-published "Aerodynamic Drag" in 1951 [118]. Hoerner re-published his book in 1958 and 1965 re-titled as "Fluid Dynamic Drag" [38].

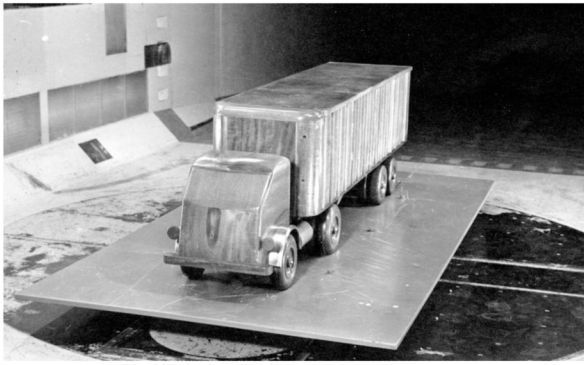
On the application of aerodynamics to commercial vehicles the US and European automotive industry expanded their aerodynamic studies through the construction of new wind tunnels or in partnership with universities and government labs [119, 120, 121, 122] and the development of wind tunnel test methods and technology [121, 123, 124]. Each of these latter studies discusses the importance of model scale and drag sensitivity with increasing Reynolds number. There are several studies worth noting that address commercial vehicle aerodynamics. In the 1950s the University of Maryland worked with Trailmobile to investigate tractor-trailer drag. A significant finding was the drag reduction potential with edge rounding [125, 126], see figure 1.4.

In 1962 General Motors published their wind tunnel test findings [32] on a generic tractor-trailer concept. The data also showed that edge rounding on the trailer front and the tractor provides significant drag reduction. These findings are consistent with those from all previous tests since the 1920s.



a. Trailer with sharp side edges

Figure 1.4. Photographs of tractor-trailer model in the University of Maryland wind tunnel [127].



b. Trailer with rounded side edges

Figure 1.4 (cont). Photographs of tractor-trailer model in the University of Maryland wind tunnel [127].

It should be noted that both the General Motors test at Guggenheim Aeronautical Laboratory at the California Institute of Technology (GALCIT) tunnel and the University of Maryland test had difficulty with the scale of the ground plane boundary layer affecting the force data. In 1967 NASA supported the automotive industry with a study of the ground plane boundary layer in which the newly installed moving-belt ground-plane in the 17 foot test section of the NASA 7 by 10 foot subsonic tunnel was used in the test of a 3/8 scale model of a sedan. The study indicated that eliminating the floor boundary layer was essential for accurate drag measurements and that a moving belt was one such approach that may be used [128].

The 1970s and 1980s brought a dramatic increase in fuel prices resulting from the 1973 oil embargo [92] and the 1979 energy crisis [93]. In response the US established a national speed limit of 55 mph and the Department of Energy (DOE) was established in 1977. From 1974 to 1983 the US Department of Transportation (DOT) and SAE executed the SAE/DOT Truck and Bus Fuel Economy Measurement Program [129] with contributions from the US Environmental Protection Agency (EPA), DOE and the National Research Council (NRC) of Canada. SAE partnered with the American Trucking Association (ATA) Technology and Maintenance Council (TMC) to develop fuel economy test procedures [130]. The SAE also published a recommended practice for wind tunnel testing of trucks and busses [62]. NASA jumped into the heavy truck aerodynamic fray with fundamental shape studies on operational vehicles [131]. The NRC initiated multiple developmental and fundamental wind tunnel investigations led by Kevin Cooper [27] and the University of Maryland continued their aerodynamic studies [21]. General Motors sponsored a Symposium on Aerodynamic Drag Mechanisms of Bluff Bodies and Road Vehicles in 1976 [54] that brought together the foremost aerodynamicist of the time. Drollinger's 33rd Buckendale lecture provides a summary of the notable studies from 1970 to 1987 [1].

From 1990 to 2000 fuel prices remained stable, around \$1.00 a gallon, as did the design of most commercial vehicles. Beginning in 2000 fuel prices rose to a high of nearly \$5.00 a gallon in 2008 and have averaged approximately \$3.00 a gallon since. The DOE launched the 21st Century Truck Partnership in 1998 [63]. The program produced a limited number of fundamental aerodynamic publications addressing Reynolds number effects [10, 27, 52, 55]. The voluntary EPA

Smartway program began in 2004. This effort stimulated significant amount of validation efforts that were redefined as verification testing. The verification testing was based on J1252 [62] and J1321 [94]. These verification efforts grew dramatically with the launch of CARB's mandatory aerodynamic product use in 2010 [67]. The EPA Smartway and CARB verification efforts produced limited data on the fluid dynamic characteristics of the subject products. Also in 2010 DOE launched the SuperTruck demonstration program with industry [131]. At this time, limited data from these efforts have been published. A noted exception is the 2014 publication by Smith, Mihelic, Gifford and Ellis [132]. Perhaps the most significant published contributions that provide an understanding of the fundamentals aerodynamic characteristics of commercial trucks has been the; maturation of CFD tools, publication of SAE CFD guidelines J2966 [133], updates to the SAE recommended practice J1252 [62] for wind tunnel testing and fuel use testing with SAE recommended practices J1321 [134] and J [135].

1.5. Structure of Paper

This document is structured to provide the reader with an understanding of the relationship between Reynolds number and boundary layers and their impact on the aerodynamics and performance of commercial vehicles. Criteria for aerodynamic and performance simulation as well as testing and design of commercial vehicles is presented. Users of this document should have a prior knowledge of aerodynamics and fluid dynamics to the level represented by Anderson [3], Hucho [39] or to have such a reference readily available. Included in the prior knowledge is an understanding of flow similarity. The data and information presented in this document has been obtained from peer-reviewed and published scientific and engineering papers and reports.

Chapter 2 reviews fundamental aerodynamic principles that impact the aerodynamic and thereby the performance of a commercial vehicle. Critical to this discussion are Reynolds number modeling and simulation criteria. Included in the discussion is an overview of flow similarity and boundary layer flows. The reader is provided the necessary insight into the relationships between Reynolds number, boundary layers, flow separation, shear flows and wakes that is required to appreciate the complex aerodynamics of commercial vehicles.

Chapter 3 introduces the aerodynamic bluff body concept, which is a class of aerodynamic shapes that includes all commercial vehicles. Bluff body vehicles have blunt fronts and truncated bases and their aerodynamics is characterized by the presence of significant flow separation and pressure drag which is significantly larger than friction drag. The discussion reviews bluff body aerodynamics and presents to the reader Reynolds number and boundary layer test and analysis criteria. The chapter presents fundamental aerodynamic trends associated with specific geometrical features of commercial vehicles that are dependent on a combination of Reynolds number and boundary layer state.

Chapters 4 and 5 provide the reader with an overview of commercial vehicle Computational Simulations and Experimental Testing capabilities, respectively. Each Chapter presents the computational simulation and testing factors that are influenced by Reynolds number

and boundary layer modeling. Information for proper modeling of the governing physics for all vehicle components are outlined and discussed. The reader should leave these chapters with insight into Reynolds number effects that impact the design and evaluation of commercial vehicles. Furthermore the reader will be able to recognize the limitations and applicability of a facility or method that is critical to establishing credibility of a vehicle evaluation.

Chapter 6 discusses the application of Reynolds number and boundary layer criteria to the design of current and future commercial vehicles such as buses, single unit trucks and combination vehicles. The Chapter provides a brief review of vehicle design trends over the last four decades highlighting the increased use of aerodynamics and aerodynamic shaping to increase vehicle performance. This trend has dramatically increased the importance of Reynolds number, boundary layer management and flow separation control in the design process. The reader should take away from this Chapter that the importance of the Reynolds number and its impact on the design process, aerodynamic testing, viscous-pressure drag ratio, and vehicle performance will continue to increase.

Chapter 7 provides the reader a summary of the document including a detailed list of the critical analysis, testing and design criteria discussed in each Chapter. The reader will also be presented a discussion of future directions and challenges in vehicle design, aerodynamics and Reynolds number effects.1.6.

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CHAPTER 2. AERODYNAMIC FUNDAMENTALS

The aerodynamics of commercial vehicles are extremely complex consisting of varying boundary layer states, unsteady and steady flows, time dependent wake structures, vortices, bubbles, interacting shear layers and separated flows with and without reattachment. Adding to the complexity is the presence of vehicle-based thermal and vibrational effects as well as atmospheric and operational based turbulence. A third level of complexity is the presence of internal flows and rotational systems. All of these fluid dynamic and geometric characteristics are Reynolds number sensitive.

To provide context, this Chapter will review fundamental aerodynamic and fluid dynamic concepts that impact the aerodynamic characteristics and performance of a commercial vehicle. Critical to this discussion are Reynolds number modeling and simulation criteria. Included in the discussion is an overview of flow similarity and boundary layer flows. It is beneficial if the reader has prior knowledge of aerodynamics and fluid dynamics to the level represented by Anderson [3], Hucho [40] or Shames [136].

2.1. Dimensional Analyses and Dynamic (Flow) Similarity

Aerodynamic studies of ground vehicles are interested in pressure and viscous generated forces and moments acting on a vehicle and the flow field in close proximity to the vehicle. The investigations take many forms directed at a comparison of data sets, such as between types of methods for the same test article or various geometric scales of a test article and may employ operational testing (OT), wind tunnel (WT) testing or computational fluid dynamic (CFD) analysis. Regardless of the approach and method the objective is to obtain aerodynamic data that represents a full-scale vehicle in operation. The ability to use one data set to represent another data set requires that the two test articles have dynamic similarity. Dynamic (i.e. Flow) similarity is present when the two test articles have the same length scale ratio, time scale ratio, and force scale (or mass scale) ratio. The first and primary requirement for dynamic similarity is geometric similarity in which all test article dimensions have the same linear scale ratio, including the surface roughness ratio (e/L). In addition, geometric similarity requires surface angles, flow directions, and relationship of each test article to the physical surroundings to be the same. The combination of the same length scale ratio and time scale ratio is the definition of kinematic similarity and dynamic similarity exists when force and pressure coefficients are identical in concert with kinematic similarity.

The most common approach to mathematically express the concept of similarity is through dimensional analysis using some form of the Buckingham Pi theorem [137]. Using a minimum of independent variables uses dimensional analysis to express flow similarity with dimensionless parameters. In aerodynamics the number of independent parameters is obtained based on the requirement of dimensional homogeneity for any equation expressing a valid relationship among physical variables. The fundamental dimensions for aerodynamic studies are; mass (m), length (L), time (t) and temperature (T).

Commercial ground vehicle or test article geometry is typically non-dimensionalized by the vehicle width. The fluid velocity is non-dimensionalized by the ratio of the local fluid velocity to the free stream fluid velocity. Fluid density is non-dimensionalized in terms of the ratio of local fluid density to the free stream fluid density. Local pressure is non-dimensionalized in a pressure coefficient defined as the difference between the local pressure (due to the presence of the body) and the free stream pressure divided by the free stream dynamic pressure. Local temperature will be non-dimensionalized by its ratio to the free stream value. The time will be non-dimensionalized as a ratio to the time for a fluid particle to travel the reference length at the speed of flow far from the body. When time dependence is averaged out or the actual circumstance of having steady boundary conditions yields steady results, the aerodynamic coefficients are functions only of the dimensionless similarity parameters, Reynolds number and Mach number along with the orientation angle of the test article. Each solution of the non-dimensional system for a value of the Reynolds number provides a result that applies equally to different fluids as well as different sizes of bodies at differing speeds and differing coefficients of viscosity as long as the similarity parameters are matched. For subsonic aerodynamic studies of commercial ground vehicles the density may be assumed to be constant, as long as the Mach number is well below a value of 0.3. Hence, and the flow is incompressible resulting in forces and moments to be independent of Mach number and results are only dependent on the Reynolds number similarity parameter. In some cases, local flow phenomena can cause higher flow speeds, and a more detailed analysis is necessary. Therefore, the Mach and Strouhal numbers as well as the Roughness ratio will also be introduced in this chapter.

2.2. Reynolds Number

The significance of Reynolds number differs greatly between an aerodynamically shaped (streamline) body, such as an aircraft, and a bluff body such as a commercial ground vehicle. An aerodynamic body aligned with the flow will have minimal flow-separation and low drag that is primarily a result of skin friction drag. For this class of body the importance of Reynolds number is in defining the boundary layer state and thereby the dominating viscous drag term. For a bluff body, pressure drag dominates and significant levels of flow separation are present where the degree of flow separation is dictated by surface geometry and the state of the boundary layer, both of which are dependent on the Reynolds number.

Reynolds number is the primary similarity parameter of interest for aerodynamic studies of commercial ground vehicles. The parameter is defined as the ratio of the fluid inertia and the shear stress, as a result of viscosity, as expressed in Eq. 2.1 [68, 75].

$$Re = (\text{inertial forces})/(\text{viscous forces}) \quad (2.1)$$

The dimensionless Reynolds number is a combination of physical parameters viscosity (μ), velocity (U), length (L) and density (ρ), which are represented by fundamental dimensions length (L), mass (M) and time (t) as expressed in the following four dimensional relationships.

1. Viscosity (μ) $\sim M/(Lt)$
2. Velocity (U) $\sim L/t$
3. Length (L) $\sim L$
4. Density (ρ) $\sim M/L^3$

These parameters are used to dimensionally define the inertial forces and the viscous forces.

The *inertial forces* per unit area $\sim$ (mass flow rate per unit area) $\times$ (fluid velocity) $= \rho U U = \rho U^2$

The *viscous forces* per unit area $\sim \tau = \mu (du/dy) = \mu U / L$

Taking the ratio of the two forces we can derive the nondimensional expression for Reynolds number, see [Eq. 2.2](#).

$$Re = ((\rho U^2) / (\mu U / L)) = ((\rho U L) / \mu) = UL / \nu \quad (2.2)$$

For commercial vehicles the vehicle width (w) is typically used as the reference length (L) resulting in nominal operational Re_w values of 0.8, 2.4 and 4.8 million for vehicle speeds of 10, 30, and 60mph, respectively. However the geometric complexity of this class of vehicle results in significant local Reynolds number effects that are better represented by a component based reference length. Typical examples are the trailer front side edge radius, diameter of tire/wheel assembly and chord length of the cab visor.

Vehicle Reynolds number is typically calculated based on a fundamental geometric length such as width (w) of the vehicle. An equivalent reference length is the square root of the reference vehicle area (A). Component Reynolds number values shall be calculated based on the linear dimension of the component in the streamwise direction. Local Reynolds number values shall be based on the local radius of curvature (r) or the linear dimension of the region in the streamwise direction (l). All Reynolds number values shall be based on the operating conditions of the reference vehicle and the test/analysis conditions of the model/geometry under investigation.

Calculation of Reynolds number based on model/vehicle width (w) is shown in [Eq. 2.3](#).

$$Re_w = U w / \nu \quad (2.3)$$

Calculation of Reynolds number based on square root of the model/vehicle reference area (A) is shown in [Eq. 2.4](#).

$$Re_A = U (A^{0.5}) / \nu \quad (2.4)$$

Calculation of Reynolds number based on model/vehicle local radii of curvature (r) of interest is shown in [Eq. 2.5](#).

$$Re_r = U r / \nu \quad (2.5)$$

Aerodynamic similarity is a foundation of sub-scale studies and requires the matching of Reynolds number, boundary layer, on and off-body flow and geometric details for the test article compared to the operational conditions for the full-scale vehicle. In practice this is extremely difficult for computational studies as well as experimental testing, see [Chapters 4 and 5](#) respectively. Although the Reynolds number value can be matched in computational studies an accurate simulation of the relevant boundary layer and flow features can only be obtained if the Reynolds number dependent boundary layer characteristics and flow separation features on the full-scale reference vehicle at operational conditions are implemented in the computational model. Coastdown testing has a different challenge in which the width based Reynolds number will typically vary from greater than 5 million to less than 1 million during a test run. The large variation in Reynolds number may generate significant changes in separation characteristics and drag values resulting in an increase in data uncertainty. An overarching challenge in defining the Reynolds number sensitivity of a complete vehicle is accounting for the differences in Reynolds number sensitivity for the various components of the vehicle. In addition to the variation in Reynolds number sensitivity for each vehicle component, bluff body vehicles have a significant Reynolds number sensitivity with changes in yaw angle. See [Chapters 3, 4, 5 and 6](#) for additional information.

2.3. Principal Elements of Aerodynamics

The fundamental principles from which the equations used to model low speed aerodynamic flows are;

1. Conservation of mass;
2. Newton's second law (Force = mass $\times$ acceleration);
3. Energy is conserved.

The equations expressing these three principles provide the relationships among various quantities (such as density, velocity, pressure, rate of strain, internal energy, and viscosity) as they vary in space and time. Additional discussion on this topic can be found in references [3, 14, 15, 38, 40, 84, 136, 138, 139, and 140].

In considering low speed flows it is common to adopt the assumption that the density is constant. In cases in which density is nearly constant, there are many situations in which the temperature variation is negligible. Such problems are entirely mechanical without any thermodynamic phenomena. The force and moment coefficients in such cases will, of course, not be dependent on Mach number.

However, in pursuit of flow similarity local compressibility effects can occur for configurations with small edge radii, when testing at incompressible speeds. In such cases, both compressibility and Reynolds number can influence flow separation onset and effects, and at times one effect can mask the other. Experimental Reynolds number effects can also be determined when the free stream velocity is held constant and the geometry or fluid density is varied [3].

In addition to Reynolds number there are three other non-dimensional parameters that are considered in subsonic aerodynamic studies. These parameters are; Mach number (Ma), Strouhal number (St) and Roughness ratio (Rr). Mach number is defined as the ratio of the freestream velocity (U) to the speed of sound (c).

flow, see [Eq. 2.6](#). For Mach number values less than 0.3 the flow is incompressible and the density is constant. [Equation 2.7](#) is the definition of the Strouhal number (St) that is used to characterize flow oscillations. The Strouhal number is defined as the ratio of the product of the flow oscillation frequency (ω) and reference length (L) to the freestream velocity (U). Additional discussion is presented in sub-section 2.5. The final parameter is the Roughness Ratio (Rr) defined in [Eq. 2.8](#). This parameter is used to guide the modeling of the surface roughness height (ϵ) for a sub-scale model compared to that for a full-scale vehicle.

$$\text{Mach Number, } Ma = U/c \quad (2.6)$$

$$\text{Strouhal Number, } St = \omega L/U \quad (2.7)$$

$$\text{Roughness Ratio, } Rr = \epsilon/L \quad (2.8)$$

2.4. Aerodynamic Loads

Although the primary focus of aerodynamics is to understand the forces and moments, these values are built upon more fundamental elements such as dynamic pressure (Q) defined in [Eq. 2.9](#). Dynamic pressure is used to obtain the non-dimensional pressure coefficient, skin friction coefficient, force coefficients and moment coefficients defined in [equations 2.10](#), [2.11](#), [2.12](#), and [2.13](#) respectively. For incompressible flow the dynamic pressure is exactly the difference between total and static pressure.

$$\text{Dynamic Pressure, } Q = 0.5\rho U^2 \quad (2.9)$$

The loads acting on a body immersed in a flow are produced by pressure forces acting normal to the surface and tangential stress (skin friction) over the surface, see [equations 2.10](#) and [2.11](#) respectively.

$$\text{Pressure Coefficient, } C_p = (p - p_\infty)/(0.5\rho U^2) = (p - p_{\text{tot}})/Q \quad (2.10)$$

$$\text{Skin Friction Coefficient, } C_f = \tau/(0.5\rho U^2) = \tau/Q \quad (2.11)$$

When integrated, these stresses give rise to the resultant force and moment load components, which are expressed in non-dimensional form by means of force and moment coefficients, defined as follows:

$$\text{Force Coefficient, } C_F = F/(0.5\rho U^2 A) = F/QA \quad (2.12)$$

$$\text{Moment Coefficient, } C_M = M/(0.5\rho U^2 AL) = M/QAL \quad (2.13)$$

where F and M are the components in the direction of the resultant force and moment, respectively, acting on the body, U is the undisturbed upstream flow velocity, A is the reference area typically defined as the projected frontal area, ρ is the density of the flow stream and L a reference length.

To relate the importance of Reynolds number to the aerodynamic loads Anderson [3] presents a dimensional analysis using the Buckingham Pi (P) theorem [135] that shows force and moment coefficients are only a function of Reynolds number and Mach number for a given orientation of the test article relative to the flow direction. A brief summary of this analysis follows;

The aerodynamic force on a body can be expressed as a function of physical variables; force (F), density (ρ), velocity (U), length (L), viscosity (μ), and speed of sound (c) as shown in [equation 2.14](#).

$$g(F, \rho, U, L, \mu, c) \quad (2.14)$$

Following the Buckingham theorem, the number of dimensionless quantities needed to fully describe a physical system is the difference of the number of independent variables with dimension, here the six present in [equation 2.14](#), and the number of physical dimensions involved, here three (length L, mass M, time t). Hence, [equation 2.14](#) is re-expressed using $6-3=3$ nondimensional Π relationships in [equation 2.15](#). The three Π relationships are defined in [equations 2.16](#), [2.17](#) and [2.18](#) in which the right side of each equation is dimensionless. Solving for the coefficient of each physical variable in [equations 2.15](#), [2.16](#) and [2.17](#) allows further development of the equations.

$$f_1(\Pi_1, \Pi_2, \Pi_3) = 0 \quad (2.15)$$

$$\Pi_1 = f_2(\rho, U, L, F) = F/(\rho U^2 L^2) = (2F)/(\rho U^2 A) = C_F \quad (2.16)$$

$$\Pi_2 = f_3(\rho, U, L, \mu) = (\rho UL)/\mu = Re_L \quad (2.17)$$

$$\Pi_3 = f_4(\rho, U, L, c) = U/c = Ma \quad (2.18)$$

Substituting [equations 2.16](#), [2.17](#) and [2.18](#) into [equation 2.15](#) and reorganizing results in [equation 2.19](#).

$$C_F = f_5(Re, Ma) \quad (2.19)$$

For the subsonic operational conditions of commercial vehicles we know that Mach number effects are not present resulting in the aerodynamic forces and moments on a commercial vehicle are only a function of Reynolds number. This fact magnifies the importance of flow similarity in the aerodynamic study of commercial vehicles.

2.5. Time Dependence

Aerodynamic loads have, in general, mean and time-varying components. The fluctuating loads may be significant not only when the upstream flow is time-dependent but also when the wake produced by the body itself has more or less regular fluctuations. For steady upstream flow an aerodynamic body is characterized by a steady wake and load, whereas for bluff body commercial vehicles



the opposite is true [141]. Specific examples related to commercial vehicles involve trailing wakes, rotating systems, and multiple bodies such as towed components.

When the boundary layer separates prematurely on a bluff body, the phenomenon of separation is associated with the formation of vortices and a large energy loss in the wide wake. At moderate Reynolds numbers the wake is dominated by a periodic train of alternating vortices (see Figure 2.1), known as the von Kármán vortex street [142], at moderate Reynolds numbers.

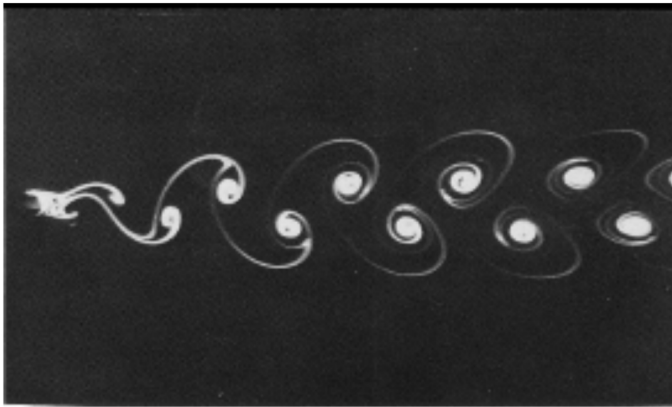


Figure 2.1. von Kármán vortex street from a circular cylinder (flow is left to right) [142].

A vortex street is present when boundary layers separate from the opposing sides of a body roll up in the wake region producing large vortices that separate from the body and move downstream as free vortices. The mechanism of shedding is found to be the interaction between the boundary layers from either side of the body. The predominant frequency of shedding is a narrow band of values such that when it is presented in a non-dimensional form, is called the Strouhal number. The presence of oscillatory vortex shedding will impact the aerodynamic forces on the body. In certain regions of Reynolds number, this shedding process is inhibited and a coherent set of vortices is not produced although a random shedding process of smaller scale still occurs.

2.6. Boundary Layer Flows

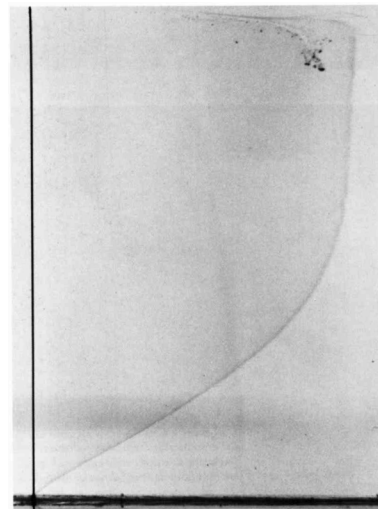
In 1904 Prandtl [83] introduced the concept of a boundary layer, as a thin region close to the solid surface where the effects of viscosity are felt, and a large velocity gradient exists normal to the surface.

The boundary layer is often referred to as a shear flow. A boundary layer begins to form at the stagnation point on a body and increases in thickness with distance along the surface, except in regions of high acceleration where its thickness can be reduced.

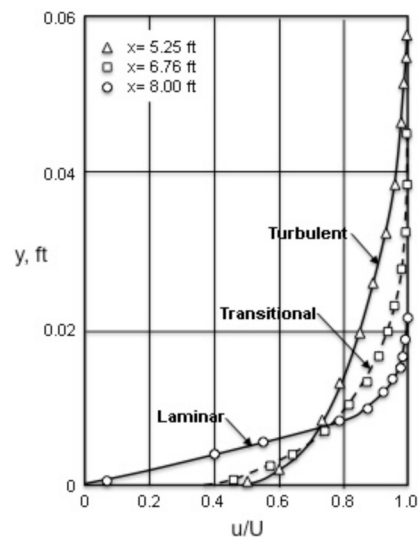
Shown in figure 2.2a is a photographic image taken by Wortman [142] of the velocity profile in a laminar boundary layer and depicted in figure 2.2b are measured velocity profiles for laminar, transitional and turbulent boundary layers. The thickness of the velocity boundary layer is defined as the distance from the solid body at which the viscous flow velocity (u) is 99 percent of the freestream velocity (U). Note the difference in boundary layer profile, thickness and the

relative growth in boundary layer thickness as it transitions from laminar to turbulent. The boundary layer state and the transitioning of the boundary layer between states is a function of Reynolds number.

For the case of a specific surface geometry, such as a flat plate, Reynolds number may be used to infer the boundary layer state as either laminar or turbulent, referenced to the stagnation point. Flat plate transition from laminar to turbulent flow typically occurs for Reynolds number values based on local length between 1 and 2 million but may be as low as 0.5 million [117]. A sketch comparing the features of a flat plate boundary layer with increasing Reynolds number are depicted in figure 2.3. The sketch indicates the forward movement of the transition region with increasing Reynolds number. Photographs of streamwise sectional cuts of laminar, transitional and turbulent boundary layers are shown in figure 2.4 which highlight the increased mixing as the boundary layer transitions to turbulent flow.



a. Tangential velocity in laminar boundary layer made visible by tellurium seeding [142].



b. Velocity distribution

Figure 2.2. Boundary layer velocity profile over a flat plate (flow is from left to right).

Transition of the boundary layer from laminar to turbulent depends on Reynolds number and is influenced by parameters such as wall surface roughness, surface curvature, freestream turbulence, and the pressure gradient along the surface. These features may promote or inhibit boundary layer transition. Additionally, the specific flow features within a boundary layer will vary with Re , surface roughness, crosswind, temperature, freestream turbulence as well as other factors. Turbulent boundary layers are characterized by an increased value of the tangential stresses at the surface producing larger friction forces on the bodies.

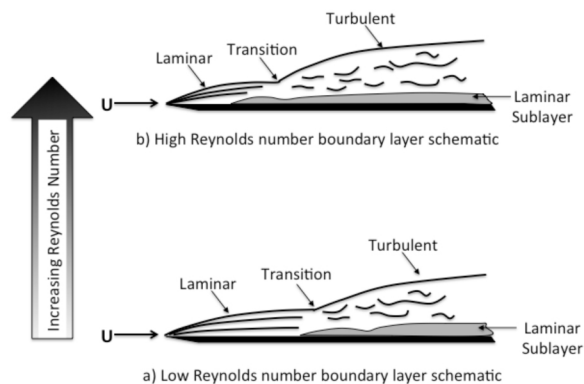


Figure 2.3. Effect of Reynolds number on boundary layer flow.

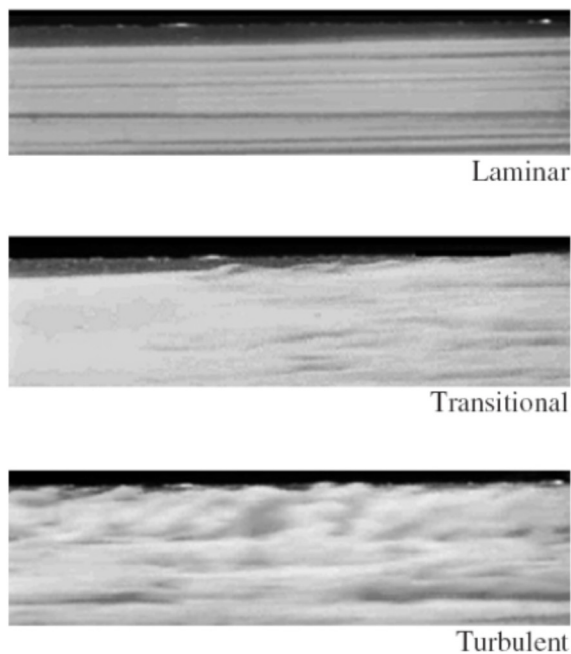


Figure 2.4. Flat plate boundary layer flow structure [142].

As with all boundary layers those found on operating commercial road vehicles or their components begin as laminar and transition to turbulent as the flow moves aft along the surface of the vehicle. At width-based Reynolds number for a commercial vehicle at highway speeds the boundary layer on the forward portion of the vehicle or vehicle component, such as the tractor of a tractor-trailer, will have small but measurable percentages of both laminar and turbulent boundary layers, however, the boundary layer on the trailer of a combination vehicle will be predominately turbulent. The extent of laminar flow and the thickness of the boundary layer will increase

with decreasing Reynolds number. For example, a flat plate analysis indicates that at 1.0 million, representing a full scale vehicle operating at low speed or testing a sub-scale model, laminar boundary layer flows may be present over a significant portion of the front of the vehicle and the development of a fully turbulent boundary layer will occur significantly downstream compared to the full-scale vehicle operating at highway speeds. The result is a change in separation characteristics and vehicle drag. Additional details can be found in Schlichting [117].

2.6.1. Laminar Boundary Layer

All boundary layers begin as laminar (see figures 2.2, 2.3 and 2.4) in which the streamwise velocity changes uniformly as one moves away from the body and all exchange of mass or momentum takes place only between adjacent layers within the boundary layer. Laminar boundary layers will always be present but the ability to persist along a body require; that external disturbances do not excite resonances within the layer, a favorable external pressure gradient as well as a sufficiently smooth body surface.

Approximations of the laminar boundary layer thickness, displacement thickness, skin friction coefficient and integrated average skin friction drag coefficient for a flat plate of length l are provided in equations 2.20, 2.21, 2.22 and 2.23, respectively. The variation of these parameters with Reynolds number will be discussed in sub-section 2.6.3.

$$\delta_{lam} = 5.0 \times (Re_x)^{-0.5} \quad (2.20)$$

$$\delta_{lam}^* = 1.727 \times (Re_x)^{-0.5} \quad (2.21)$$

$$C_{f,x,lam} = 0.664 (Re_x)^{-0.5} \quad (2.22)$$

$$C_{f,l,lam} = 1.330 (Re_l)^{-0.5} \quad (2.23)$$

2.6.2. Turbulent Boundary Layer

A turbulent boundary (see figure 2.3 and 2.4) layer exist downstream of the laminar to turbulent transition region and is characterized by rapid fluctuations in velocity and pressure due to the eddying motion with mixing across several layers resulting in an exchange of mass, momentum and energy on a much larger scale compared to a laminar boundary layer.

Approximations of the turbulent boundary layer thickness, displacement thickness, skin friction coefficient and integrated average skin friction coefficient for a flat plate are provided in equations 2.24, 2.25, 2.26 and 2.27, respectively. The variation of these parameters with Reynolds number and surface roughness effects will be discussed in sub-section 2.6.3.

$$\delta_{turb} = 0.37 \times (Re_x)^{1/4} \quad (2.24)$$

$$\delta_{\text{turb}}^* = (1/8) d_{\text{turb}} \quad (2.25)$$

$$C_{f,x,\text{turb}} = 0.059 (\text{Re}_x)^{-0.2} \quad (2.26)$$

$$C_{f,l,\text{turb}} = 0.074 (\text{Re}_l)^{-0.2} \quad (2.27)$$

2.6.3. Natural Laminar-Turbulent Transition

Boundary layer transition takes place over a range of critical Reynolds numbers where the characteristic length in the definition of Reynolds number is the distance along the surface from the stagnation point. The transition Reynolds number is affected by many factors; most important are surface pressure distribution, the surface roughness and the intensity of free stream turbulence.

The start of transition is characterized by short turbulent bursts with rapid velocity and pressure fluctuations; see [figure 2.5](#). Further downstream the duration and frequency of the turbulent signals increase until the boundary layer is fully turbulent. A boundary layer can transition to turbulent through a number of paths depending on the conditions such as initial disturbance amplitude and/or surface roughness. The first stage of the natural transition process consists of the transformation of environmental disturbances into small perturbations within the boundary layer. The next stage of the transition process is that of primary mode growth in which the initial disturbances grow or decay. The specific instabilities that are exhibited depend on the body geometry and the nature and amplitude of initial disturbances.



Figure 2.5. Photograph of turbulent spot in a transitional boundary layer, flow left to right [142].

A graph of the variation in friction drag for laminar, transitional and turbulent boundary layer flows as a function of Reynolds number is presented in [Figure 2.6](#). The figure shows flat-plate friction drag coefficients for laminar and turbulent boundary layer smooth-wall relations as well as the effect of surface roughness. In the fully rough regime, which is plotted to the right of the dashed line in [Fig. 2.6](#), C_f is independent of the Reynolds number, so that the drag varies as U^2 is based on Schlichting [117]. The figure also shows the behavior of the drag coefficient in the transition region $5 \times 10^5 < \text{Re}_t < 8 \times 10^7$, where the laminar drag at the leading edge is an appreciable fraction of the total drag.

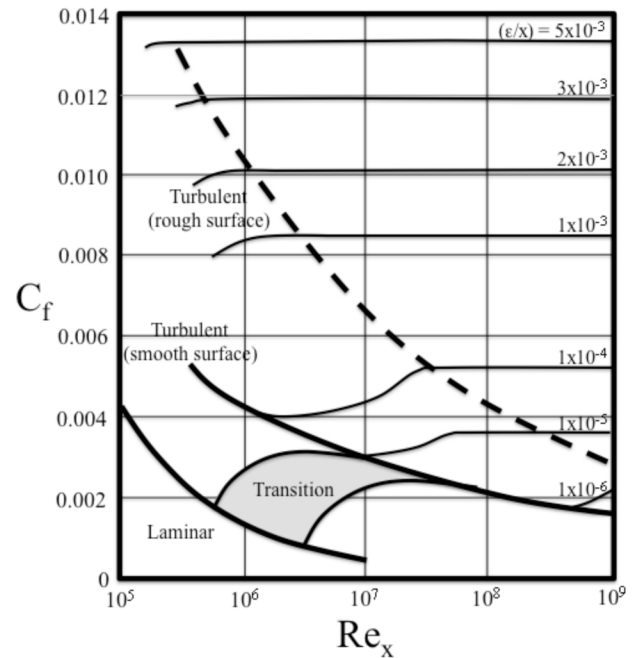


Figure 2.6. Drag coefficient of laminar, turbulent and transitional boundary layer on flat plate [143].

The impact of boundary layer state, boundary layer thickness, boundary layer displacement thickness, friction drag and transition Reynolds number on the aerodynamic performance of commercial vehicles will change with each design cycle of the vehicle. Vehicles designed prior to 1990 have limited aerodynamic contouring. As a result pressure drag dominated despite the fact that the friction drag was also maximized due to a combination of transitional Reynolds numbers below 10^6 and the presence of a rough surface covering large areas of the vehicle. Vehicles from the 1990 to 2000 era have increased aerodynamic shaping and routinely employ aerodynamic fairings on the tractor to reduce the pressure drag. These vehicles have reduced surface roughness as a result the transition Reynolds number is increased however the fairings increase the wetted area resulting in friction drag that is equivalent to pre-1990 vehicles. Recent design studies indicate that the next generation of vehicles will have significant reductions in pressure drag that will effectively increase the percent contribution of friction drag to the total drag. These vehicles will have further increase in the transition Reynolds number, more extensive presence of laminar flows and thinner boundary layers. This combination will combine to increase the sensitivity of the vehicle to local flow separations and roughness induced drag. Additional discussion of these design trends will be presented in [Chapters 5](#) and [6](#).

2.6.4. Forced Laminar-Turbulent Transition

At Reynolds number values below the operational Reynolds number of a vehicle, a laminar boundary layer flow is present over a greater surface area of the vehicle (or model) compared to that at operational conditions. Relative to a turbulent boundary layer a laminar boundary layer is more susceptible to flow separation, when subjected to an adverse pressure gradient, resulting in flow features and aerodynamic loadings that are not representative of the vehicle in operation. In contrast a turbulent boundary layer is able to withstand a more

intensive adverse pressure gradient without separating. Matching full-scale boundary layer features such as the location of boundary layer transition, boundary layer thickness and location of separation requires a detailed understanding of boundary layer, flow control concepts as well as the boundary layer characteristics at full scale Reynolds number. Successful use of forced transition to mimic high Reynolds number boundary layer flow requires an understanding of the desired boundary layer conditions as well as the expected aerodynamic characteristics at higher Reynolds number conditions.

The aerodynamics of a vehicle can change significantly with changes in Reynolds number and/or changes in boundary layer state. It is known that the critical and transcritical Reynolds number can occur at lower values by introducing turbulence structures into the boundary layer to promote early laminar to turbulent transition. Methods used to force transition include roughness elements, vortex generators and trip wires placed on the surface of the body, heating of the surface and oscillatory blowing of the boundary layer.

As shown in [figure 2.6](#) surface roughness will cause the boundary layer to transition from laminar to turbulent at a lower Reynolds number compared to a smooth surface. The result is an increase in friction and total drag, compared with the smooth surface value, but under certain conditions the reverse happens as illustrated in [Figure 1.3](#). At certain Reynolds numbers the laminar boundary layer separates upstream resulting in a wide wake and a large pressure drag. However, if the boundary layer transitions to a turbulent state before separation occurs then it is less susceptible to separation and remains attached further round the body surface compared to the laminar boundary layer. This results in a reduction in wake width, pressure drag and total drag, relative to the smooth surface values.

In use since 1940, surface roughness is a generally accepted approach where roughness elements take many forms from individual grit elements, shaped and positioned 2D structures, tape strips, vortex generators, and sandpaper, see Barlow [14], Metz [44], Loftin [144], Dryden [145], Klebanoff [146], Braslow [147], [117], and Von Doenhoff [148]. Most surface roughness techniques have been developed to support aircraft related subscale wind tunnel testing in which the work of Von Doenhoff [148] and Braslow [116] are most significant, see [figure 2.7](#). The objective is to force transition with roughness elements such that the drag of the roughness elements produces a negligible amount of roughness drag (i.e. roughness drag is the pressure drag of the roughness elements). For the study of low drag aerodynamic shapes roughness drag can be a significant portion of the drag, however for ground vehicles roughness drag is not a significant portion of the vehicle drag. For subsonic boundary layers the roughness size requirements are reasonably similar for 2D and 3D flows.

Forced transition should be used to simulate full-scale Reynolds number flows, match boundary layer thickness, and inhibit separation of the boundary layer. See [Chapter 5](#) for additional guidelines. The general roughness application criteria are;

1. Boundary layer transition roughness elements shall have a height that is less than the thickness of the laminar boundary layer at the location applied.

2. Boundary layer transition roughness elements should be randomly distributed or have an irregular shape.
3. The roughness should be a minimum width strip that is aligned perpendicular to the surface streamlines.
4. Boundary layer transition roughness shall have a minimum roughness Reynolds number (Re_k) of 600.
5. Forced transition application should vary with vehicle shape, vehicle type, operational conditions, and test objectives.
6. Forced transition effectiveness shall be verified experimentally.

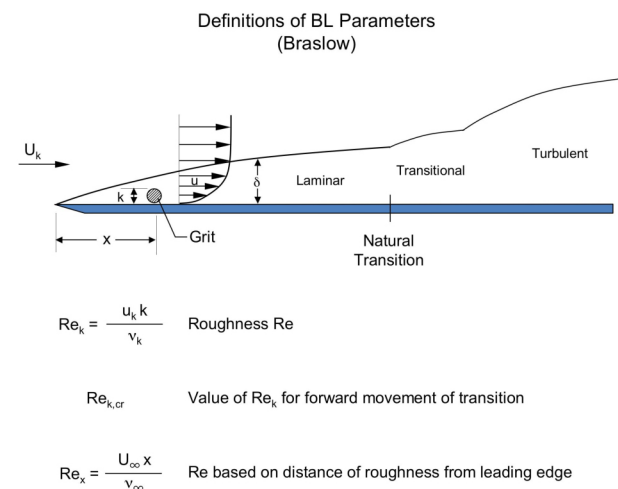


Figure 2.7. Details of distributed roughness criteria for forced boundary layer transition [117].

2.6.5. Boundary Layer State Assessment

To understand the effect of Reynolds number on the aerodynamics of a vehicle/model requires an understanding of the boundary layer characteristics over the complete vehicle/model, [44, 118, 136, 139, 142, 145, 149, and 150]. Of particular importance is the location of transition. There are numerous intrusive and nonintrusive techniques that may be used. These methods vary from a boundary layer survey rake/probe to optical techniques such as a laser Doppler velocimetry (LDV) to determine the velocity profile in the boundary layer. Hot films or floating element balances may be placed on the model surface, or pressure sensors may be placed flush with the surface or behind a surface pressure tap, in order to measure the fluctuations due to turbulence. These three methods have the advantage that they are essentially non-intrusive and allow simultaneous measurements. A disadvantage is that they do not give useful information in regions of separated flow. Each measurement point requires its own transducer and signal conditioning equipment. Oil film interferometry and a hot wire may be placed on the surface of the body. Stanton gauge, Preston tubes and survey rake probes may be traversed along the surface. These techniques allow for a high density of measurement points. However there are errors associated with the intrusive nature of a physical probe.

When evaluating a complex vehicle/model consisting of multiple components the location of transition and the boundary layer state should be determined at various locations on the vehicle/model as well as on each component. When comparing test data for different Reynolds number that have been obtained from the same or different test methods the location of transition and the boundary layer state at

various locations should be determined for each data set. For example, for wind tunnel tests of a vehicle/model a boundary layer survey should be used to obtain the location of transition and the boundary layer profile immediately upstream of the trailing edge of each vehicle/model component.

2.6.6. Boundary Layer (Flow) Separation

Experimental methods used to evaluate vehicle aerodynamic performance routinely involve test conditions at Reynolds number significantly less than that seen by the operational vehicle. Understanding and controlling boundary layer separation for Reynolds number at and below the operational Reynolds number is critical to testing, analysis and vehicle design efforts. The tendency of a boundary layer to separate is dependent not only the Reynolds number and boundary layer state but also the surface pressure gradient which is dictated by the shape of the vehicle. The influence of a pressure gradient on the boundary layer profile is shown in [figure 2.8a](#), [2.8b](#) and [2.8c](#) respectively. As shown in [figure 2.8b](#) a negative static pressure gradient ($dp/dx < 0$) is described as favorable because the boundary layer is stabilized by the increase in freestream velocity. This type of gradient would be observed in a region of smooth convex curvature. In contrast a positive static pressure gradient ($dp/dx > 0$) is unfavorable as it produces a deficit in the boundary layer velocity profile eventually leading to reverse flow and separation as depicted in [figure 2.8d](#). Possible locations on a body where an unfavorable static pressure gradient would occur are the transition region from a convex curvature region to a flat surface or within a region of concave curvature.

A schematic depicting the change in boundary layer flow during the separation process is shown in [figure 2.9](#). Note that the flow in the figure is from left to right. Boundary layer separation, and thus flow separation, occurs when the portion of the boundary layer closest to the wall reverses in flow direction as shown in the third from left boundary layer profile in [figure 2.9](#). The separation point is located between the forward and backward flow, where the shear stress is zero. The overall boundary layer initially thickens at the separation point and is then forced off the surface by the reversed flow at the surface. Flow separation often results in increased pressure drag.

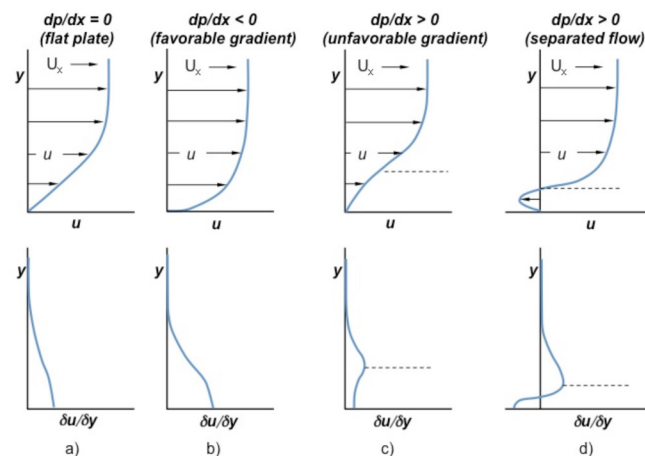


Figure 2.8. Representative flat plate boundary layer velocity profiles.

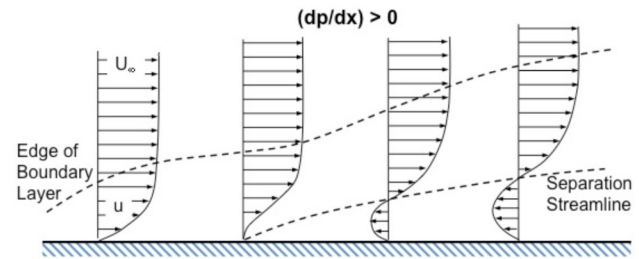
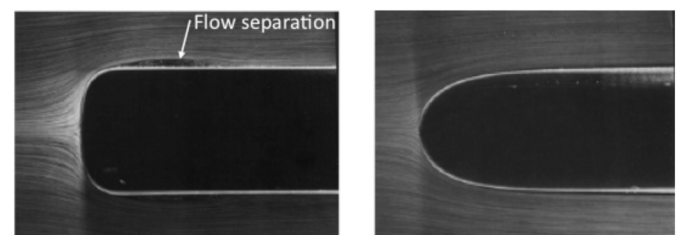


Figure 2.9. Representative change in boundary layer profile for the onset of separation.

Flow visualization images showing the impact of favorable and unfavorable static pressure gradients on an axisymmetric body with a laminar boundary layer are presented in [figure 2.10](#). [Figure 2.10a](#) show flow visualization for a bluff face body with moderate curvature at the shoulder and [figure 2.10b](#) show a body with increased nose curvature. The static pressure distribution on bluff body of [figure 2.10a](#) would have a pronounced negative gradient followed by a severe positive gradient as the flow transitions from the front face and around the curved shoulder of the body. The severe positive gradient (i.e. unfavorable) is the mechanism for the observed separation. In contrast the static pressure distribution on the body shown in [figure 2.10b](#) would have a gradual positive gradient (i.e. favorable) as the flow moves aft from the stagnation point at the forward most point on the body.

The mixing process in a turbulent boundary layer causes an effective shear stress which allows a turbulent boundary layer to progress further against an adverse/unfavorable pressure gradient and separates at a point further along a surface, compared to a laminar boundary layer under the same conditions. A comparison of laminar and turbulent flow separation over the same geometry is depicted in [figure 2.11](#). The photographs depict the flow over a curved surface with an adverse pressure gradient resulting in a high momentum deficit. In the case where the boundary layer is laminar, insufficient momentum exchange occurs, the flow is unable to adjust to the increasing pressure and separates from the surface. In the case of turbulent flow, the increased transport of momentum from the free-stream to the wall increases the streamwise momentum in the boundary layer. This allows the flow to overcome the adverse pressure gradient and will delay separation to a point further downstream.



a) Bluff nose, laminar separation

b) Rounded nose, no separation

Figure 2.10. Laminar boundary layer flow over two bluff face body of revolution [142].

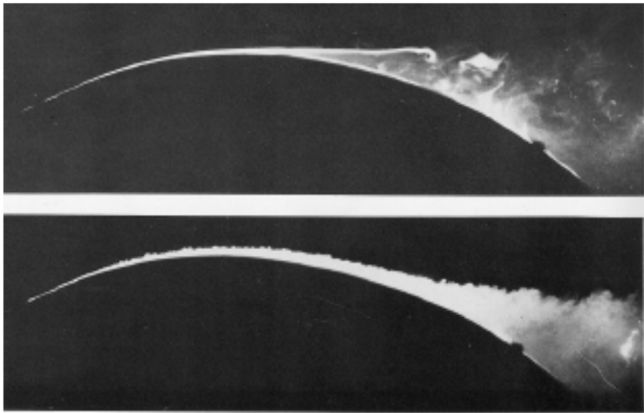


Figure 2.11. Example of laminar (upper photo) and turbulent (lower photo) separation over a curved surface [142].

The presence of a body in relative motion to a fluid will cause the flow passing over the body to accelerate and decelerate resulting in favorable and unfavorable pressure gradients. When the body is thin, the pressure gradients are weak and the flow remains attached. For a thicker and less aerodynamic shaped body, adverse pressure gradients cause strong flow decelerations resulting in flow separation, circulation, and vortex shedding. For a commercial vehicle the rate of change in body thickness is exaggerated resulting in large pressure gradients and susceptibility to flow separation and a drag level that is sensitive to Reynolds number. For the range of operational conditions of a commercial vehicle flow separations that occur at the front of the vehicle in close proximity to a stagnation point or from interactions with a sharp edge or corner will typically not be sensitive to Reynolds number. If the geometry at the front of the vehicles is void of sharp edges and abrupt geometry changes then flow separations may be sensitive to Reynolds number. However flow separation at the trailing edge of the vehicle will be sensitive to Reynolds number.

2.7. Free Stream Turbulence Effects

Commercial vehicles in operation on the open road experience turbulence [151] from a variety of sources with average levels between two percent and five percent and turbulent length scales that exceed the width of a typical vehicle [151, 152]. In contrast the free stream turbulence intensity and length scale in a typical wind tunnel are one to two orders of magnitude smaller [31, 50, 54, 58, 60, 96, 104]. The effect of turbulence can be best demonstrated with a wind tunnel test of a smooth shaped aerodynamic body in which both laminar and turbulent boundary layers are present. Figure 2.12 from Diehl [104] show the effect of free stream turbulence on a smooth sphere is to promote boundary layer transition resulting in drag reduction to occur at a lower Reynolds number. Diehl states that these results are not exact but are representative in that similar test have shown that sphere size and turbulence length scale will alter these results. This and other similar data have provided the motivation to minimize the turbulence in all current wind tunnels.

However the desire to minimize turbulence intensity and scale is at odds with the ability to model the flow experienced by a commercial vehicle in operation [152].

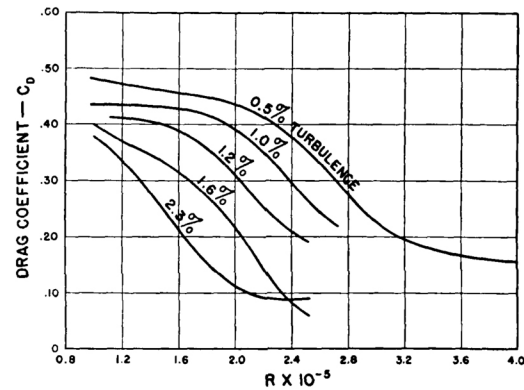


Figure 2.12. Effect of free stream turbulence and Reynolds number on the drag of a sphere [104].

The aerodynamics and performance of a commercial vehicle can be affected in various ways by freestream turbulence in both the wind tunnel testing as well as for a full-scale vehicle in service or subjected to on-road or on-track testing [54, 153, 154, 155]. The impact of turbulence on the aerodynamics of a vehicle or model is a function of turbulence intensity and length scale and will vary with test speed, yaw angle, vehicle shape, transition Reynolds number and boundary layer state. The interaction between turbulence and a body is unique and does not lend itself to general trends in aerodynamic forces and moments [54, 154, 155].

Operational vehicles will experience large variations in turbulence that can generate a broad range of effects [152, 153]. Turbulence scales that exceed the size of a vehicle typically have a negligible effect on vehicle loading other than changing flow direction. When turbulence size is equivalent to vehicle size it can interact with vehicle local surface loadings that may impact flow separation and total drag. Small-scale turbulence levels have the ability to alter local boundary layer characteristics that will impact flow separation, reattachment and wake flows [135].

2.8. Summary Findings

A discussion of Reynolds number modeling and simulation criteria for fundamental aerodynamic and fluid dynamic concepts that impact the aerodynamic characteristics and performance of a commercial vehicle are presented. The concepts of dimensional analysis and flow similarity are presented for various fluid dynamic topic areas. These concepts are applied to show that the aerodynamics of commercial ground vehicles is only dependent on the Reynolds number similarity parameter. The critical subsonic non-dimensional parameters as well as the non-dimensional aerodynamic load parameters are developed using the dimensional analysis process.

A significant portion of the Chapter focused on boundary layer flows, specifically the impact of boundary layer state, boundary layer thickness, boundary layer displacement thickness, friction drag and transition Reynolds number on the aerodynamic performance of commercial vehicles. The boundary layer discussion reviewed the scaling and simulation challenges related to sub-scale wind tunnel testing and correlating wind tunnel and full-scale fuel economy or road load tests. A discussion of transition reviewed both free and

forced transition effects and methods. The influence of free stream turbulence on transition and drag was also reviewed and highlighted the challenge facing sub scale aerodynamic testing of current and future vehicle designs.2.9.

2.9. References

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CHAPTER 3. BLUFF BODY AERODYNAMICS

A bluff body is a class of aerodynamic shapes that includes all commercial vehicles. Bluff body vehicles have blunt fronts with truncated bases and their aerodynamics are characterized by appreciable levels of flow separation and pressure drag levels that are significantly larger than friction drag. Reynolds number is used in bluff body aerodynamic studies to characterize 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 features plays an important role in guiding experimental as well as computational studies of the drag force acting on a commercial vehicle. Specific aerodynamic design and analysis areas of interest for commercial vehicles are wind tunnel testing, coastdown testing, computational design, advanced surface shaping, flow control technology and time dependent atmospheric effects. The Reynolds number and boundary layer dependent aerodynamic trends associated with specific bluff body geometrical features found on commercial vehicles will be discussed in this Chapter. The supporting bluff body aerodynamic data and information can be found in references 1, 5, 10, 12, 13, 14, 17, 18, 20, 21, 23, 24, 25, 26, 27, 28, 30, 36, 37, 38, 39, 40, 42, 43, 45, 46, 48, 49, 51, 52, 53, 54, 56, 57, 60, 65, 68, and 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230.

3.1. Terminology/State Conditions

The first step in understanding the impact of Reynolds number on the aerodynamics and specifically the drag of a vehicle is to define the range of Reynolds numbers and the corresponding variation in drag that reflects the operational as well as test/analysis conditions of these vehicles. This information establishes the boundaries for aerodynamic study of commercial vehicles. A graphical representation of the variation in drag with Reynolds number for current-model commercial vehicles and a sphere is presented in figure 3.1. The sphere is presented as a reference and is selected because it is the most fundamental of three-dimensional bluff body shapes, as discussed previously in Chapters 1 and 2. The variation in drag, depicted in each curve, is a result of changes in the boundary-layer state, flow separation and wake flow. To guide the remainder of the discussion each curve is classified into five regions where each region represents a change in the fundamental flow characteristics as defined by Roshko [49]. A description of each Reynolds number region is defined below.

1. Subcritical Reynolds number Range represents the condition in which the boundary layer and all separations are laminar.
2. Critical Reynolds number (Re_{cr}) represents the start of boundary layer transition from laminar to turbulent.
3. Transitional Reynolds number Range is where large variations in drag are present indicating the progression in the extent of the boundary layer transition from laminar to turbulent.
4. Transcritical Reynolds number (Re_{tr}) represent the point at which a majority of the boundary layer has transitioned to

turbulent flow and the drag level becomes invariant with further increase in Reynolds number.

5. Transcritical Reynolds number Range may exhibit small variations in drag due to local changes in boundary layer state, flow separations, and flow reattachment resulting in changes in the ratio of viscous to pressure drag.

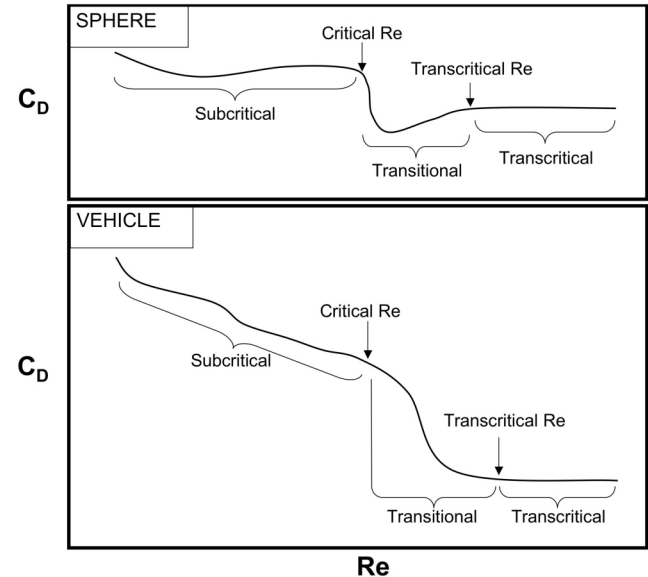


Figure 3.1. Representation of the variation in C_D with Reynolds number for a sphere and a typical bluff vehicle.

Both curves reflect the variation in drag with increasing Reynolds number starting from a condition in which the boundary layer is fully laminar to the condition where the boundary layer is fully turbulent. The curves represent the variation in drag over a Reynolds number range of 10^5 to 10^7 which includes the operational range of Reynolds numbers for medium and heavy commercial vehicles of 0.5 to 6.0 million. However the vertical scales for the two curves are not equivalent, as the sphere will experience a drag reduction of 70 to 80 percent while the bluff body curve reflects a drag reduction on the order of 10 to 20 percent. Experimental tests by Dryden [31], Jacobs [98], Hoerner [38, 99], Diehl [104] and Platt [201] serve as the basis for the sphere curve. The bluff-body vehicle curve is a composite of wind tunnel data for generic shapes and representative vehicles from Wood [2], Cooper [26], Flynn [32], Sovran [54], Storms [55], Leuschen [65], McArthur [66], Gross [124], Turner [128], White [143], Kirsch [174], Ortega [181], Kettinger [193], Van Raemdonck [194], Littlewood [195], Hjelm [196], Newnham [197], Heft [198], and Storms [199].

3.2. Fundamental Aerodynamics

While the curves in figure 3.1 represent the drag variation for two shapes that differ greatly in geometric complexity they also reflect the characteristic trends with Reynolds number that would be observed for current vehicles as well as vehicle components. This observation is not unique to bluff bodies as noted by Diehl in 1928 [104] in his comments related to Reynolds effects for aircraft.

“Actually the effect of Reynolds Number is different on each item: wings, fuselage, struts, wires, etc. Furthermore, the effect is not the same on all wings or on all struts, but varies widely in each group.”

Diehl's observation highlights the importance and complexity of Reynolds number effects and the need to understand these effects for both the complete vehicle as well as each component.

The drag of a bluff body is driven by the flow separation characteristics, which are a function of the boundary layer state that in turn is dictated by Reynolds number and the geometrical features of the body. The front face and bluff base as well as the length of the body of a streamwise continuous bluff body will determine the drag, flow separation and the cross flow sensitivities. Of equal importance are the detailed geometric features such as edge shape. Shown in figures 3.2 are plots of drag against Reynolds number for simple 2D and 3D bluff body shapes with various levels of streamwise curvature. The data contained in figure 3.2 has been taken from Hoerner [38], Hucho [40], and White [143] where the drag coefficient for each curve is based on the body maximum cross sectional area. The data show that bodies with sharp corners or small radii of curvature, as depicted in the top two curves, exhibit negligible change in the flow separation characteristics and drag over a broad Reynolds number range. In contrast the drag of three-dimensional and two-dimensional bodies with significant curvature in the streamwise direction, as shown in the lower five curves, varies significantly with increasing Reynolds number.

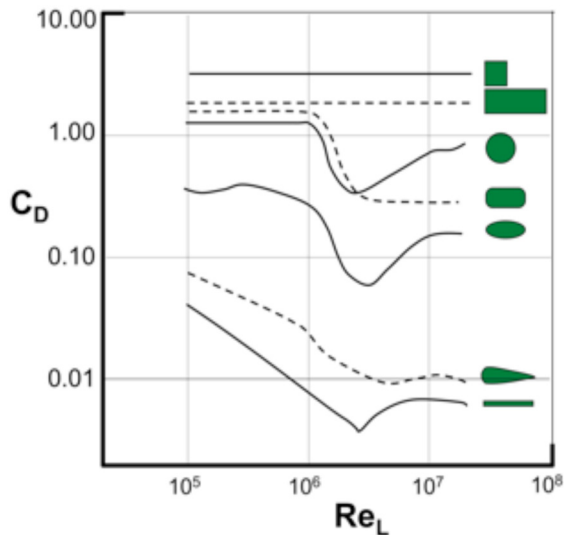


Figure 3.2. Drag coefficients of various cylindrical shapes as a function of Re .

The characteristic trends exhibited by all seven shapes provide insight into the drag levels and Reynolds number sensitivity for various types of vehicles and their components. The upper four curves are bluff body shapes and the two lower curves represent aerodynamic (streamlined) bodies. The oval shaped body located between these two groups has aerodynamics characteristics of both. For example, the trend for the sharp edge rectangle (second from top) is representative of an early model heavy truck with poor aerodynamic styling while the curved edge rectangle (fourth from top) reflects a trend we would expect to see for current model commercial vehicles. From these data we can infer that the lower drag limit for a bluff body vehicle is a

value between that for the curved edge rectangle and the oval shaped body. Additionally, we see that the use of airfoil shaped section (second from bottom) is far superior to a simple oval for components such as a visor, vertical exhaust, mirror, and landing gear.

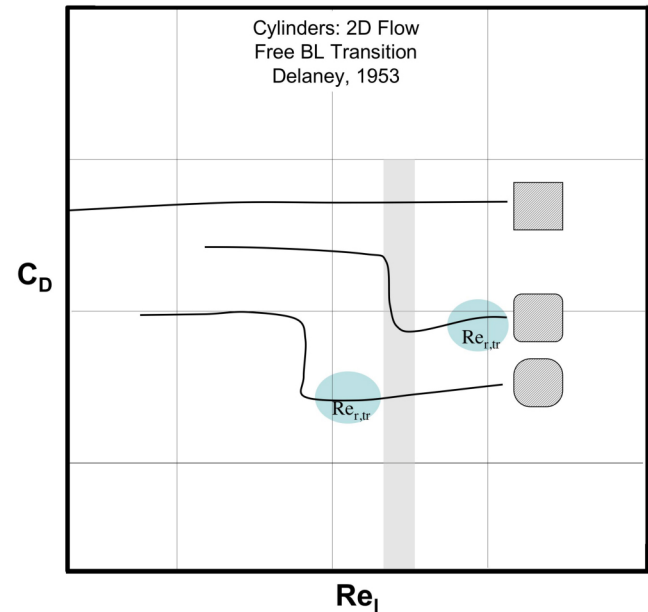


Figure 3.3. Variation in C_D with Re_i due to edge radius for 2D cylinders. Delaney [30].

Presented in figure 3.3 is data obtained by Delaney [30] that show variations in C_D with Reynolds number for two-dimensional cylinders with different edge radii. These data are similar as that of Lindsey [43] and Roshko [49] and may be used to represent the flow about a trailer or freight box front side and top edges or a region of local curvature on a tractor. The upper curve in figure 3.3 is for a square cylinder with sharp edges. For the Reynolds number range shown the flow on the up-stream facing surface is unable to follow around the sharp corner and separates resulting in a wake that extends downstream and engulfs the complete body resulting in a constant drag coefficient value. The transcritical Reynolds number for this body would occur at a Reynolds number value that is greater than the range shown on the figure. The transcritical condition indicates that the flow separation from the up-stream corners has reattached to the upper and lower surfaces of the body. The two lower curves represent bodies with increasing edge radii and the data show that the transcritical Reynolds number is reduced with increasing edge radii. The presence of a curved up-stream corner allows the flow to partially follow around the corner, leading to a smaller separation bubble, which can reattach to the upper and lower surfaces of the body, for the range of Reynolds numbers shown. Depending on the speed of a full-scale vehicle (as represented by the shaded vertical bar) the local edge-based Reynolds number value may be either in the subcritical range (sharp edge, upper curve), transitional range (small edge radius, middle curve) or transcritical range (large edge radius, lower curve). These data show that the transcritical Reynolds number can vary over a broad Reynolds number range for small changes to a vehicle component. These data further strengthens the importance of modeling the full-scale aerodynamics as well as on-body and off-body flow conditions when conducting experimental and computational studies at sub-scale off-design condition. See Chapter 5 and 6 for additional guidelines.