# 1. Background of VorBlade Development

## 1.1. Where Does Your Money Go?

A trailer is fully loaded and a long route through several states lays ahead. You fill your fuel tank to the top and begin your journey. You stop on red traffic lights, at stop signs, accelerate the truck, slow down from time to time, accelerate again and again, and finally reach the nearest interstate highway. Now you can set up cruise control to an allowed speed, somewhere between 55 mph and 85 mph, and just keep it.

Your speed is almost constant with no significant accelerations or slow downs, the engine runs smoothly and quietly, and it seems that all burned fuel goes into moving tractor and trailer to your destination. But is it really so? Unfortunately, the answer is negative and only a part of the fuel is spent on moving your cargo vehicle while another part is merely lost.

The most significant losses occur in the engine. Although diesel engine is more efficient than other internal combustion engines, it still converts less than half of fuel energy into mechanical energy moving the truck. The rest of fuel energy is released as a heat and is usually referred to as the thermodynamic losses. To put it simply, thermodynamic losses stand for heating your engine and the surrounding air on your expense.

Exact magnitude of thermodynamic losses varies with the type, design, size and mileage of the diesel engine, operational conditions like air temperature and altitude, and many other factors. It is natural that numerous scientific studies of the subject produced slightly different results. The same is true for other fuel expenditures and vehicle characteristics thus averaged values over several representative studies are used throughout this page.

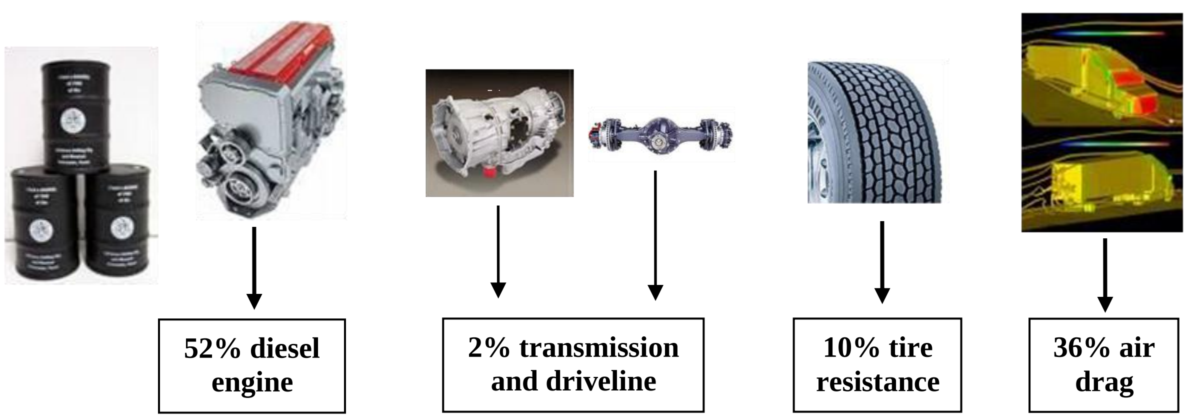



*Figure 1.1-1: Average fuel energy expenditures in a typical class 8 tractor / trailer combination at highway speed. The picture is reproduced from Ogburn et al (2008) where some of the expenditure magnitudes are modified in accordance with results of other studies.*

As illustrated in Figure 1.1-1, such average value for thermodynamic losses in a typical diesel engine of a modern class 8 truck at the highway speed is 52%; DOE (2003) – (2008), 21$^{st}$ CTP (2006), Ogburn and Ramroth (2007), Ogburn et al (2008), van Tooren (2009), Forte (2009) and references therein. The remaining 48% of fuel expenditure is usually referred to as non-engine losses.

About 2% of the fuel energy is further lost in the transmission and driveline. Although scientists and engineers around the world devote huge efforts to further improvement of a diesel engine performance, significant progress is unlikely in the foreseen future therefore 54% losses of fuel energy should be accepted as unavoidable evil.

Only 46% of the fuel energy is spent on moving a tractor / trailer combination against two types of resistance. The first one is a tire rolling resistance which occurs when a round tire rolls on a flat surface. This type of resistance is mainly caused by the tire deformation and depends on a truck speed, tire material, sort of pavement, and few other factors. At typical highway conditions, about 10% of the fuel energy is spent to overcome a tire resistance and to cover vehicle accessories such as lights, air conditioner, heater, etc. This relatively small value is an outstanding achievement of tire manufacturers.

The remaining 36% of the fuel energy is spent on overcoming the second type of resistance, the aerodynamic drag forces acting on tractor / trailer combination. 36% is three-fourth of the non-engine losses and it looks highly upsetting. It means that from each \$100 you pay for a fuel, \$48 is non-engine spending and \$36 from those is literally “gone with the wind”. Fortunately, this dark cloud has its silver linen - the aerodynamic drag could be controlled. Reducing the drag, one can reduce the fuel consumption. For this reason aerodynamic drag is the object of special interest and it is considered in details below. We will illustrate that the drag reduction would result not only in the reduction in fuel consumption but could also improve driving safety and diminish the greenhouse gas (GHG) emission.

## 1.2. What Is Aerodynamic Drag?

We live in the Earth atmosphere which protects us from the deadly solar radiation and supplies the air for breathing. In calm days, the atmospheric air does not slow us down when we walk on city streets, jog in a park or hike picturesque hills but it changes abruptly when we walk against a strong head wind. A force of the fast blowing air pushes us back as heavily as it becomes difficult, sometimes impossible to walk straight ahead. When wind blows, we realize that the air is quite dense and the higher the wind speed is, the stronger the air pushes us back. That oppositely acting air force is called an aerodynamic or air drag and requires a lot of energy to overpower it.

Similarly, air drag for your vehicle is the aerodynamic force acting on a tractor and trailer in the direction opposite to the driving direction. It is generated by the interaction of the vehicle body with the air and depends on the aerodynamics of your vehicle.

### 1.2.1. Vehicle aerodynamics

Motor vehicles travel at high speed and suffer from the dense surrounding air to the full extend, especially on highways. Vehicles go through the atmospheric air which flows fast around the vehicle. You can feel that flow by simply extending your hand out of a cabin window. Aerodynamics of a vehicle is the dynamics of airflow around the vehicle body which defines air forces and moments acting on the vehicle.

When there is no cross wind, two major air forces affecting a vehicle are the air drag and the air lift as illustrated in Figure 1.2-1. The air drag increases fuel consumption and load on tires as well as reduces the vehicle stability and driver comfort. The upward lift force mainly reduces the vehicle stability by decreasing friction between tires and pavement.

Cross wind significantly increases the drag force and it also produces side forces and yawing and rolling moments that could off-track a vehicle, jack-knife tractor / trailer combination, throw a vehicle off the road or roll it over. The impact of cross winds could be highly dangerous as illustrated in Figure 1.2-2.

Aerodynamics of a motor vehicle is mainly defined by the shape and dimensions of its body, speed and direction of its motion, and the speed and direction of the ambient wind. These parameters govern the airflow around a vehicle which in turn defines acting on the vehicle air forces and moments. The air forces and moments impact the fuel consumption, vehicle stability, driver fatigue, visibility and other aspects of driving. In general, aerodynamics of motor vehicles affects operating expenses, driving safety, and environment.

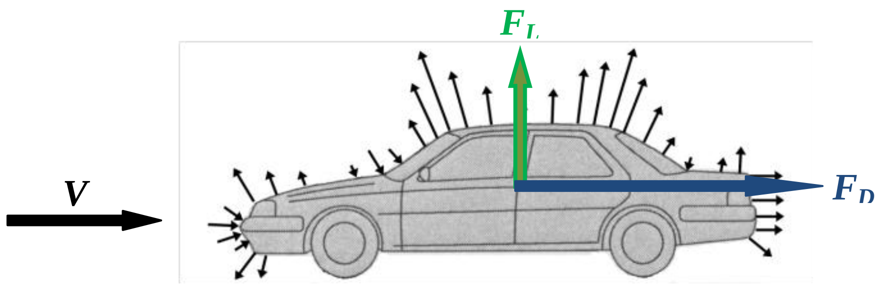



*Figure 1.2-1: Illustration of the aerodynamic drag force $F_D$ and lift force $F_L$ at no cross winds. A car is traveling at a speed V hence the surrounding air moves around the vehicle in the opposite direction at the same speed. Arrows show air pressure-induced forces acting on the vehicle surface. The picture is taken from Buresti (2004).*

It seems that aerodynamics of a vehicle cannot be controlled by the vehicle owner / operator. Winds are obviously uncontrollable and the speed and direction of motion are mainly determined by the speed limits on the chosen route. The most important, the vehicle body is designed by a manufacturer and neither its shape nor size can be modified. However, the situation is not as hopeless as it looks. A diversity of drag reduction devices has been developed that could be mounted on a cargo vehicle without modifications of its construction and affect the airflow around the vehicle; see Sections 1.4 and 2.

*Figure 1.2-2: Illustration of a single truck affected by strong cross wind. The cross wind-generated rolling moment could roll the truck over. The picture is reproduced from NZ Transport Agency (2007).*

The majority of efficient drag reduction devices are practical outcomes of extensive research and development (R&D) efforts of scientists and engineers on the aerodynamics of passenger cars and heavy commercial vehicles. With increasing fuel cost and concerns about environment, reducing the fuel consumption at highway speed by long distance cargo transport and other motor vehicles became an increasingly important task. Immense R&D efforts have been accomplished around the world and literally thousands of scientific papers, presentations, reports and other documents have been published during the last two decades.

The most comprehensive large-scale R&D program has been initiated and sponsored by the US Department of Energy (DOE) during 2003 – 2007; see DOE (2004) – (2008). DOE organized a Consortium for Aerodynamic Drag of Heavy Vehicles which included the leading US national laboratories and universities: Lawrence Livermore National Laboratory, University of California; Argonne National Laboratory, DOE; National Aeronautics & Space Administration; University of Southern California; California Institute of Technology; Georgia Institute of Technology; Sandia National Laboratories, DOE; University of Tennessee, Chattanooga; and Auburn University. The Consortium also involved the National Research Council of Canada.

Multiple research programs have been initiated and sponsored by the US Department of Transportation (DOT) and by DOT of different US states. Large-scale research programs have also been initiated and sponsored by government agencies in Canada, Australia, New Zealand and several European countries. Many commercial truck manufacturers such as Freightliner LLC, International Truck and Engine Corporation, Mack Trucks Inc., Volvo Trucks North America and others have been independently pursuing their own research.

The accomplished R&D efforts have been wide-ranging, thorough and consisting of the state-of-the-art numerical modeling, rigorous experiments in wind tunnels, and multiple track and road tests. The performed research has been well documented and most of the documents are publicly available.

Results of those studies have been invaluable and intensely used for preparing this webpage. On the other hand, we tried to present the material in easily understandable form thus complicated technical details were skipped and some physical concepts were inevitably simplified. Interested readers are highly encouraged to go through the bibliographic documents and numerous references therein.

### 1.2.2. Physics of aerodynamic drag

Aerodynamic drag has been studied for centuries and literally thousands of documents were published ranging from handbooks for specialists like Shapiro (1964) to popular online articles like van Tooren (2009) and Wikipedia (2012a). During the last several decades, special attention has been paid to aerodynamics of heavy vehicles; e.g., DOE (2004) – (2008) and references therein.

Aerodynamic drag is the aerodynamic force acting on a tractor and trailer in the direction opposite to the driving direction which is generated by the interaction of a vehicle body with the surrounding air. There are two types of air drag resulting from the airflow around the vehicle: the pressure drag acting perpendicular to the surface, and the skin friction drag acting tangentially to the surface. At sufficiently high vehicle speed such as the truck speed on highways, the skin friction drag is negligibly small in comparison to the pressure drag thus below we concentrate on the pressure drag.

The physics underneath pressure drag is illustrated by arrows in Figure 1.2-1. One can see that high pressure acts opposite to the direction of car motion, both in the front and in the back of the vehicle, and generates the opposite drag force. That force is the pressure drag which tends to slow down and finally stop the vehicle if it is not compensated by the forward-acting force produced by tires on the road.

At a typical truck speed, the total air drag force $F_D$ acting on a tractor / trailer combination could be expressed by the standard drag equation:

$$F_D = \frac{1}{2} C_D \rho V^2 A \tag{1.1}$$

Hereafter $\rho$ is the air mass density, $V$ is the truck speed, $A$ is the reference area, and $C_D$ is the drag coefficient of the combination. For motor vehicles, the reference area is the projected frontal area of the vehicle. The drag coefficient is a non-dimensional quantity characterizing a vehicle resistance in the surrounding air and depends on the characteristics of the airflow around the vehicle.

Equation (1.1) illustrates the most important feature of the air drag: it increases as a square of the truck speed. Furthermore, the power required to overcome the aerodynamic drag is proportional to the third power of the speed:

$$P_D = F_D V = \frac{1}{2} C_D \rho V^3 A \tag{1.2}$$

If truck increases its speed 2.5 times, for example from 30 mph to 75 mph, the power needed to overcome the air drag increases almost 16 times!

It follows form Equation (1.1) that theoretically one can reduce air drag by decreasing any or all parameters in the right hand side. However practical options are quite limited. The air density depends on the altitude above sea level and atmospheric conditions like temperature and those parameters cannot be controlled. The vehicle projected area is its structural characteristic and cannot be changed. To meet the cargo delivery schedule, the vehicle speed is kept near the speed limit and therefore cannot be varied significantly either.

The only parameter that could be controlled is the drag coefficient $C_D$. Although airflow around a vehicle mainly depends on the vehicle size and shape, it is highly sensitive to the minute details like surface roughness, geometry of edges, and so on. Using appropriate shaping and flow control devices, the airflow could be modified which would affect the vehicle air drag.

Figure 1.2-3 illustrates that the drag coefficient significantly varies with the vehicle shape and size.

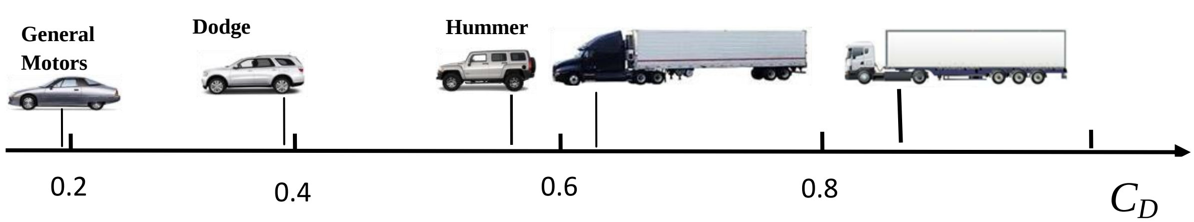



*Figure 1.2-3: Examples of drag coefficients of passenger cars and cargo trucks. The coefficients are taken from Wikipedia (2012b)*

Passenger cars with smooth shape have much smaller drag coefficients than cargo vehicles with trailers of traditional parallelepiped shape and sharp rear edges. In aerodynamics the objects of different shape are typically divided into those with streamlined bodies and smooth airflow around, and those with bluff bodies and flow separation behind as illustrated in Figure 1.2-4.

When a vehicle moves through the air, the air flow closely "hugs" its front surface. The front area of the moving vehicle pushes the air, compressing it, making it thicker, and forcing it to move with the same speed as the vehicle as illustrated in Figure 1.2-5. The force needed to accelerate the air just in front and push away some more air (shown in Figure 1.2-5, left, by red and yellow dots) is the frontal aerodynamic drag. It could be viewed as spring acting against the vehicle driving direction; Figure 1.2-5 right.

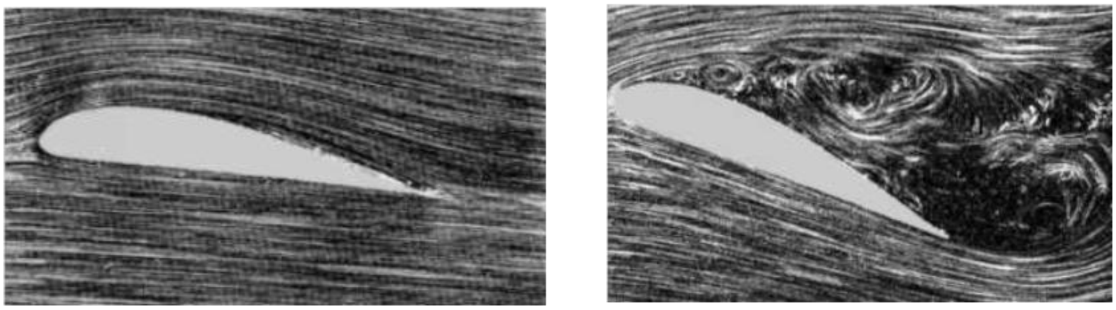


*Figure 1.2-4: Examples of streamlined (left) and bluff (right) bodies: the airfoil at small and large angle of attack. The picture is reproduced from Buresti (2004).*

As the higher air pressure builds in front of the vehicle, it accelerates the downstream flow in close vicinity of a truck, causing the airflow pressure around the truck to drop. This is the well-known Bernoulli law: when the velocity of airflow increases, the pressure consequently decreases. The abrupt change at the base of the trailer leads to a separation of the airflow from the trailer surface. This abrupt change forces the flow to break suddenly free of the surface and create highly-energetic wake of large vortices at the rear side of the trailer. This vortex shedding phenomenon is the source of a low pressure region and consequently the pressure drag in the back. The second contribution, on the other hand, is determined by the mass entrainment by vortices from the region directly behind the back of the trailer (Balkanyi *et al*, 2000; Buresti, 2000). The entrainment effect drops the air pressure behind the trailer back, and determines the value of the suction acting on the base. In terms of pressure coefficient $C_{ps}$ in the separation point, by using Bernoulli's equation one has:

$$C_{ps} = 1 - V_s^2 / V^2 \qquad (1.3)$$

where $V_s$ is the velocity at the separation point. Therefore, the higher is the velocity at the separation point, the lower is the base pressure, and the higher the base drag.

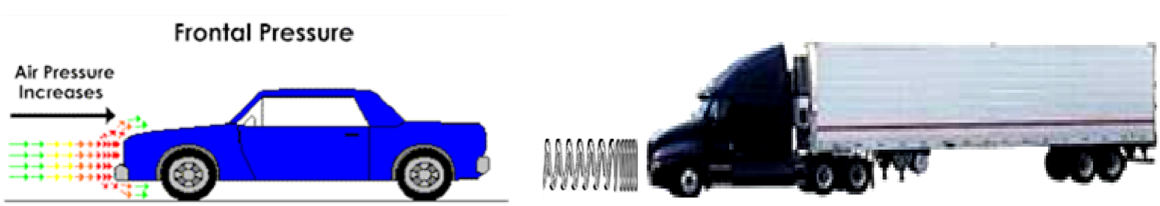
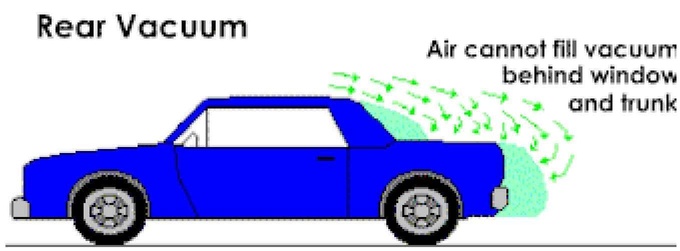



*Figure 1.2-5: (Left) An illustration of the pressure increase in the front of passenger car creating the frontal drag is reproduced from Unlimited Products (2007). The right picture illustrates that drag force could be imagined like a spring.*

When a vehicle moves ahead at significant speed, it leaves "an empty space" behind and this space should be filled by the air; Figure 1.2-6, left. "An empty space" is not very rigorous term but it describes the fact that there is a deficit of air behind which is often referred to as “rear vacuum” – another not-rigorous but useful descriptive term. It means that air pressure behind the bluff rear end of a vehicle, especially of a cargo trailer, is low as described by Equation (1.3). This low-pressure volume behind the bluff body is called separation volume and it is formed by flow separation on the abrupt edges. The air should fill that space which is usually referred to as the mass entrainment. Furthermore, the air behind moving vehicle shall follow the vehicle thus it has to be also accelerated in the driving direction to the vehicle speed. The force needed for the air entrainment and acceleration behind the vehicle is the rear aerodynamic drag.



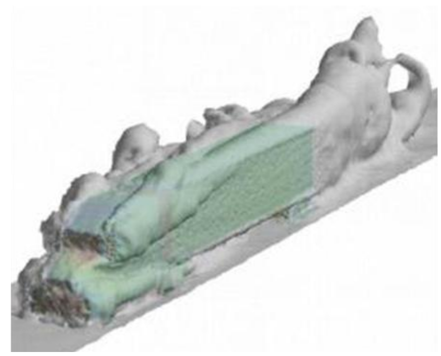



*Figure 1.2-6: (Left) An illustration of the pressure drop in the back of passenger car creating the rear drag is reproduced from Unlimited Products (2007). The right picture is reproduced from Cobalt Solutions (2012) and shows vorticity in the air wake behind the tractor and trailer’s bluff bodies at 10° yaw angle.*

Although it is counterintuitive, the rear drag is much larger than the frontal one. As outlined above, drag is mainly the force needed to accelerate the air to the driving speed, both in front and behind the vehicle. As can be seen in Figures 1.2-5 and 1.2-6, the volume of air to be accelerated is much larger in the rear wake than it is in the front.

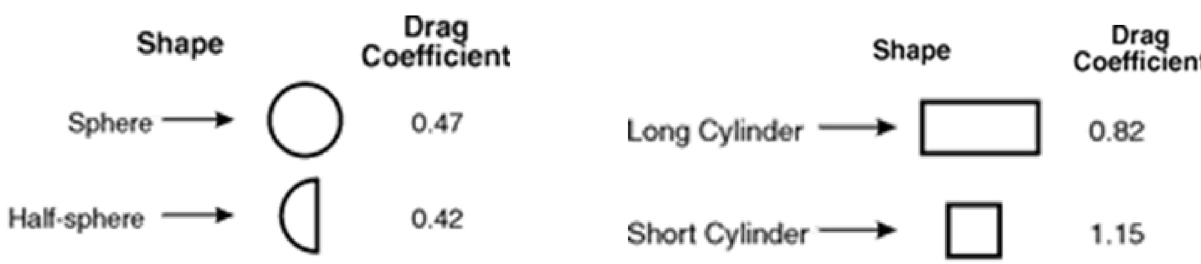



*Figure 1.2-7: Measured values of drag coefficients for several three-dimensional shapes taken from Wikipedia (2012c)*

In general, there are many counterintuitive facts about air drag. As the most known examples, one can mention the drag coefficient of a sphere being larger than that of a half-sphere, and the drag coefficient of a short cylinder being larger than that of a long cylinder; Figure 1.2-7.

Even more counterintuitive experimental fact is illustrated in Figure 1.2-8. It is well known that a teardrop is the Mother Nature’s “perfect” aerodynamic shape with the drag coefficient 0.04 – 0.05 when it is moved in a natural way with the broad end forward. When the same teardrop is moved inversely with the sharp end forward, its drag coefficients jump up almost 7 times!

The physics underneath this “surprising” fact is explained in Figure 1.2-8. When the body moves in a natural way, it is fully streamlined and airflow smoothly merges behind the body. In the inverse case, the rear end is a bluff body, the flow forms a separation zone of the low pressure and generates an energetic wake of large vortices behind the body. Those vortices are the major contributors into the air drag.


*Figure 1.2-8: The measured values 0.05 and 0.34 of drag coefficients are taken from Aqua Phoenix (2011).*

Modern streamlined tractors have side deflectors and roof fairing although still have bluff edges at the rear. Bluff edges on the rear vertical surfaces of tractors and trailers are the major contributors into the total aerodynamic drag of the vehicle. Those edges produce significant separation volumes and generate intensive large-scale vortices which in turn highly increase air drag.

The vortex shedding is also the source of oscillating side forces that may induce significant oscillations (fish-tailing) of tractor and trailer. The main point is that a strict connection exists between the amount of perturbation energy and the organization of the vorticity present in the wake (Buresti, 2000). Therefore, the most effective way of reducing the air drag is to destroy irregular large-scale vortices in the drag-producing volume; the latter are discussed in the next sub-section.

### 1.2.3. Five tractor – trailer air drag problems

As outlined in Section 1.1, about 36% of the fuel energy is spent at the highway speed to overcome the aerodynamic drag of a modern class 8 truck. There are five major drag-producing areas for the tractor / trailer combination: the area in a front of a tractor which contributes about 19% in the total drag, the area behind a trailer (the “trailer base”) contributing 33%, the gap area between tractor and trailer which contributes 14%, the areas along two sides of the trailer roof contributing 6%, and the areas beneath the tractor and trailer bodies (the “underbody”) which contribute about 28% in the total drag of the vehicle. These drag-producing areas are typically referred to as five tractor / trailer drag problems; see DOE (2003) – (2008), 21st CTP (2006), Ihlein *et al* (2007), Ogburn et al (2008), van Tooren (2009), Forte (2009), and references therein.

The five drag-producing areas can be seen clearly in Figure 1.2-6, right. Average distribution of the fuel energy needed for overcoming the air drag forces in those problem areas for a typical modern tractor / trailer combination at highway speed is illustrated in Figure 1.2-9.

VorBlade does not affect the air drag in front of a tractor and that in the truck underbody (shown in green) but those problems may be mitigated by other means; see Section 2. The drag-producing volumes in the tractor / trailer gap, on the edges of the trailer roof and in the trailer base can be affected significantly by the VorBlade vortex generators. Those volumes, shown in pink, are responsible for 53% of the total aerodynamic drag and VorBlade can reduce it more than in half.

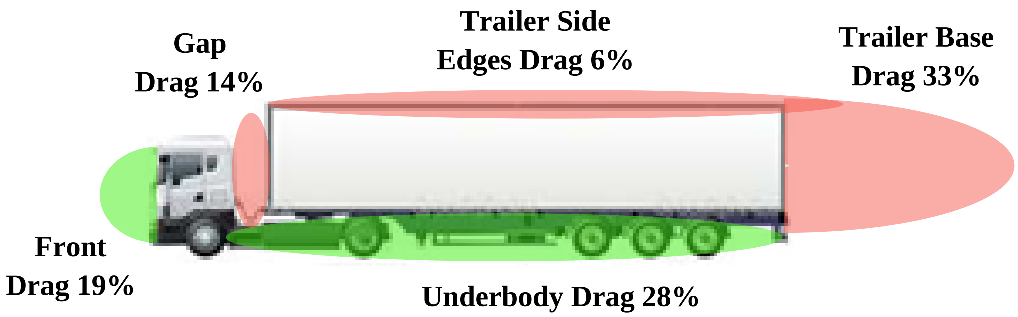



*Figure 1.2-9: Average distribution of fuel expenditure between five drag-producing volumes*

### 1.3. How Does Cross Wind Affect You?

Cross wind is typically defined as a component of an ambient wind that is blowing onto the side of the vehicle. Its basic effects on moving cargo vehicles are outlined in this section and more details are given in Section 2. Rigorous analysis and technical details can be found in Cairns (1994), Balsom *et al* (2006), R&S Consulting (2007), Tremblay *et al* (2009), Billing (2010), Kwon *et al* (2011), and references therein.

Cross winds greatly affect operating expenses and driving safety for motor vehicles especially those with flat sides like semi trailers and single trucks. To understand the physics underneath those detrimental effects of cross winds, let us first look at a parked semi truck illustrated in Figure 1.3-1.

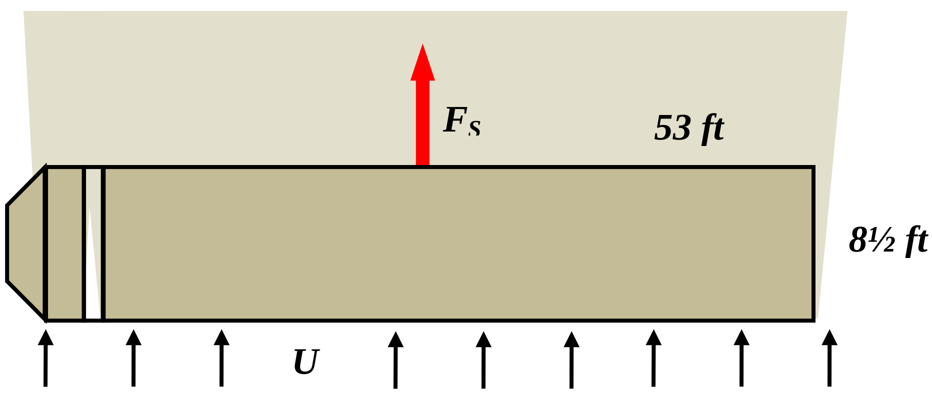



*Figure 1.3-1: Schematic of a parked semi truck in a cross wind of speed U (top view). The wind produces side force $F_S$ acting on the tractor and trailer windward and leeward side surfaces. The shaded grey areas illustrate initial parts of air wakes in the leeward side of a vehicle.*

A truck "feels" cross wind in the same way as a moving vehicle "feels" an incoming airflow at no cross winds; see Figures 1.2-1, 1.2-5 and 1.2-6. The wind increases air pressure on the windward side and creates an air wake with a low pressure on the leeward side of a vehicle. Those effects in turn generate an aerodynamic drag in the lateral direction (perpendicular to the direction of travel) and that drag acts on a vehicle as a side force. Therefore, the side force $F_S$ and drag force $F_D$ are physically alike, both increase as a square of air speed and merely act in the perpendicular directions. Similarly to the drag force in Equation (1.1), the side force is usually expressed through the non-dimensional side force coefficient $C_S$:

$$F_S = \frac{1}{2} C_S \rho U^2 A_S \tag{1.4}$$

Here $U$ is the cross wind speed and $A_S$ is the vehicle projected area in the lateral direction. It is clear that for a simple case in Figure 1.3-1, the side force coefficient $C_S$ is equal to the drag coefficient of a truck in the lateral direction. However the similarity stops here. The longitudinal drag coefficient $C_D$ of a modern tractor – trailer combination is about 0.4 – 0.5; e.g., DOE (2004) – (2008). The lateral drag coefficient $C_S$ of the same tractor is about 0.8 – 0.9 like that of an angled cube, and coefficient $C_S$ of a rectangular trailer is about 2.0 - 2.1 like that of a smooth brick. The vehicle projected area $A_S$ in the lateral direction is about 6 times larger than that in the longitudinal direction (the ratio is mainly defined by the trailer dimension 53 ft / 8½ ft ≈ 6.2). Equations (1.1) and (1.4) show that the drag force $F_D$ and the side force $F_S$ are proportional respectively to the coefficients $C_D$ and $C_S$ and to the projected areas $A$ and $A_S$. Therefore, for a modern class 8 truck, the laterally directed airflow generates about 25 times larger side force than the longitudinally directed airflow with the same speed would generate the drag force. This high vehicle sensitivity to winds from the side dramatically multiplies detrimental effects of cross winds on cargo vehicles. Numerous studies found that cross wind produces significant lateral forces and moments acting on a truck even when the wind speed is not high and is not perceptible to the driver. In strong winds, when a driver can feel the wind blowing against the truck, the effects are much stronger.

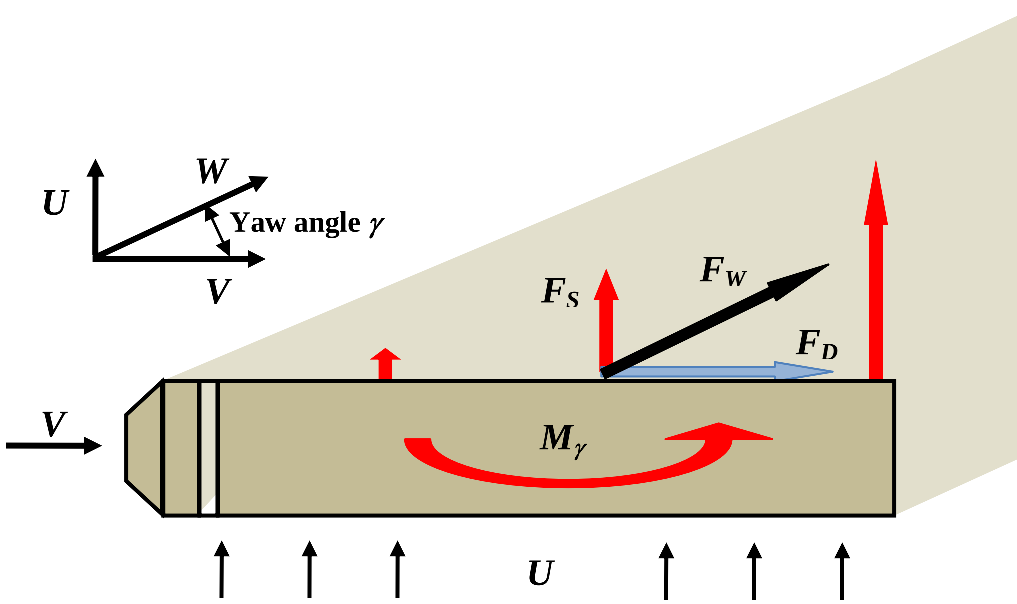



*Figure 1.3-2: Schematic of a semi truck traveling at a speed V in a cross wind of a speed U. The airflow encounters the truck at a speed W under the yaw angle $\gamma$ and acts on the vehicle with a force $F_W$. That force may be decomposed into the drag force $F_D$ (shown in blue) and the side force $F_S$ (shown in red). Inhomogeneous side force along the vehicle produces the yawing moment $M_\gamma$. The shaded grey area illustrates initial part of an air wake in the leeward side of a vehicle.*

Figure 1.3-2 illustrates a semi truck traveling at a speed $V$ in a cross wind of speed $U$. In a truck-related coordinate system (for example, as felt by a truck driver), a surrounding air blows at the truck with a speed $W$ at the yaw angle $\gamma$ such as tan ($\gamma$) = $U$ / $V$. Flowing around the bluff-shaped vehicle, the air generates a wake which is tilted from the travel direction at approximately the same yaw angle $\gamma$.

One can see in Figures 1.3-2 and 1.2-6 (right) that cross wind significantly increases the wake volume. For simplicity of explanation, we will be considering the aerodynamic forces acting on the vehicle and generated by the low pressure in a wake as being roughly proportional to the wake volume. As illustrated in Figure 1.3-2, the major increase in the wake volume is in the leeward side of a trailer.

One can easy obtain that at the highway speed of long-distance cargo transport of 60 mph and average cross wind of about 5.8 mph the yaw angle is about 5.5°. The estimates have shown that it increases the trailer air wake volume and acting on a truck aerodynamic force $F_W$ by about 60% compared to the air drag force at zero cross winds. That angled force creates the air drag $F_W \cdot \cos(5.5°)$ with the magnitude of about 99% of $F_W$ and the side force $F_W \cdot \sin(5.5°)$ with the magnitude of about 1% of $F_W$. Thus the average cross wind increases the truck drag by about 59% (at the base and side roof edges), the total vehicle air drag about 23%, and the total fuel consumption by more than 8%. A strong 30 mph cross wind increases air wake volume about 2.4 times increasing the truck drag by about 2.1 times, the total vehicle air drag by about 82%, and the total fuel consumption by about 30%.

Cross wind creates an asymmetric airflow around the vehicle and generates side forces $F_S$ distributed over the vehicle side surfaces. Those side forces mainly affect a trailer because of its parallelepiped shape and large side area. Side forces create lateral acceleration which has to be compensated by driving a vehicle in a continuous turn. Even at moderate cross winds it significantly increases driver workload and fatigue. Short but strong cross wind gusts of 50 mph which happen in Wyoming, Colorado, Kansas and some other states could off-track a cargo truck from the lane or road. Lateral acceleration also creates side friction on tires which works like tire misalignment and increases further fuel consumption and reduces a tire life. At strong cross winds of 30 mph, the increase in total fuel consumption due to side force-induced tire misalignment could exceed 15%.

*Figure 1.3-3: Left - The trailer is actually being tilted; the right-side wheels are off the ground. The photo is reproduced from R&S Consulting (2007). Right – At cross winds large cargo trucks generate strong turbulent air wakes which could off-track other vehicles to a point that the driver loses control. The picture is reproduced from NZ Transport Agency (2007).*

Figure 1.3-2 illustrates another hazardous cross wind effect: significant yawing moment $M_\gamma$ produced by inhomogeneous distribution of side forces along a trailer. The moment increases the lateral acceleration of a trailer tail and could jack-knife a truck. The side moment further increases side friction on rear tires which results in increased misalignment, tire wear and fuel consumption.

The side forces also produce a rolling moment which tends to roll the vehicle over the leeward tires as schematically illustrated in Figures 1.2-2 and 1.3-3. Studies found that short but strong cross wind gusts of 50 mph, the same winds that could off-track a truck, could also roll it over depending on the vehicle configuration, payload, road conditions and other factors.

Continual compensation of the steering wheel against the crosswind increases driver stress and the risk of accident. Detrimental cross wind effects also include amplified hazardous impact on closely traveling vehicles as illustrated in Figure 1.3-3 and some others considered in Section 2.

### 1.4. How Could Vehicle Aerodynamics Be Improved?

As illustrated in sub-sections 1.2 and 1.3, negative impacts of "imperfect" vehicle aerodynamics are especially pronounced for heavy vehicles like semi tractor / trailer combinations, single cargo trucks, buses and recreational vehicles (RV). Those vehicles typically have aerodynamically bluff bodies with flat vertical surfaces. Large-volume air wakes and intensive large-scale vortices are inevitably formed on such surfaces, especially at cross winds.

One should realize that it is impossible to fully eliminate the aerodynamic drag and other detrimental effects of airflow around bluff edges of tractor / trailer combination. Even a teardrop, the most aerodynamically "perfect" shape, has the non-zero drag coefficient of about 0.04. However, the drag can be greatly reduced and other detrimental effects significantly mitigated by applying different aerodynamic devices. Such devices differ by efficiency, simplicity of installation, convenience of operation and maintenance, and their price.

*Figure 1.4-1: Examples of fuel-efficient tractors. (Left) Kenworth Cascadia; the picture is reproduced from Ogburn et al (2008). (Right) Volvo test truck; the picture is reproduced from DOE (2007).*

Enormous efforts have been put into research and development of aerodynamically effective cargo vehicles during the last decades. The DOE Heavy Vehicle Systems Optimization Program was probably the most comprehensive, five-year long study involving government laboratories, academia and industry. Details of the accomplished studies are presented in comprehensive reports DOE (2004) – (2008). The informative and brief overview may be found in the presentation by McCallen *et al* (2006) where the objectives of the program were formulated as follows: provide guidance to industry in the reduction of aerodynamic drag; shorten and improve design process; establish a database of experimental, computational, and conceptual design information; demonstrate new drag-reduction techniques; and get devices on the road.

The major program accomplishments have been summarized in the presentation as well: concepts developed / tested that exceeded 25% drag reduction goal; insight and guidelines for drag reduction provided to industry through computations and experiments; joined with industry in getting devices on the road and providing design concepts through virtual modeling and testing; and international recognition achieved through open documentation and database

Major focuses of the research efforts, to name a few, included aerodynamically efficient tractors and devices for reducing air drag of a tractor / trailer combination. From the latter, base flaps, trailer skirts, gap splitter plates and side extenders were studied very thoroughly. DOE is continuing intensive work on fuel economy for heavy trucks; e.g., DOE (2009).

Based on government-funded R&D programs and own research, the trucking industry developed and made commercially available new tractors with greatly improved aerodynamics, e.g., Figure 1.4-1. The US Environmental Protection Agency (EPA) organized SmartWay Transport Partnership that has been playing invaluable role in the progress (EPA, 2012). Modern SmartWay eligible tractors offer a full aerodynamic package including integrated roof fairings, fuel tank side fairings, tractor-mounted gap reducers, aerodynamic bumpers and mirrors, idle reduction technology readiness, and low rolling resistance tires; see, for example Kenworth (2008).

Figure 1.2-9 shows that the frontal drag is only 19% of the total drag contrary to about 30% - 40% for old tractors (e.g., Gelzer, 2011). This is an outstanding achievement of tractor manufacturers working continuously on further improvement of tractor aerodynamics.

Situation is quite different with trailers which still have bluff bodies with a traditional parallelepiped shape and sharp rear edges for maximizing a cargo space. To change the trailer’s shape and size, one would need to modify significantly the transportation infrastructure, for example loading docks, and this is unlikely to happen in the foreseen future. In addition, tens millions of conventional trailers are already on the roads and they are supposed to serve for a long time. For this reason, the major efforts of scientists and engineers were focused on relatively compact devices that could streamline airflow around a trailer with no change in its construction, e.g., the devices that could be merely attached to a trailer.

As noted above, the DOE studies were mainly concentrated on the trailer skirts, base flaps and gap splitter plates. DOE continues studying these devices (e.g., Salari, 2010; and Salari and Ortega, 2010), which are also considered in other countries (e.g., Buresti *et al*, 2007). An overview of advanced trailer technologies may be found, for example in Wood (2006) where boat tails, guide vanes, edge rounding, pneumatics and vortex generators are considered in addition to skirts, base flaps and gap splitter plates.

The EPA SmartWay Technology Program maintains a list of verified aerodynamic technologies that could minimize aerodynamic drag and improve airflow over the entire tractor-trailer vehicle (EPA, 2012). As specified in EPA (2012): “Aerodynamic technologies include gap fairings that reduce turbulence between the tractor and trailer, side skirts that minimize wind under the trailer, and rear fairings that reduce turbulence and pressure drop at the rear of the trailer. Using fairings in combination with one another (or, in a few cases, when used alone) have the potential to provide an estimated 5 percent or greater reduction in fuel use relative to the truck's baseline, when used in conjunction with an aerodynamic tractor on long haul Class 8 trucks, in highway type operation.” Several devices from the EPA list are shown in Figure 1.4-2. It should be noted that the devices are picked up from the list randomly and for illustration purpose only as well as the tractors in Figure 1.4-1. We neither advertise the devices or tractors nor accept any responsibility for their performance.

From the devices in the EPA list, the trailer skirts received the most attention during the last decade. They were intensely studied (e.g., van Raemdonck and van Tooren, 2008) and many companies are now manufacturing commercially available skirts. Some of the manufacturers have executed the fuel economy tests, e.g., TRC (2004) and Surcel (2008), and have been verified by the EPA SmartWay program (see EPA, 2012 for a full list). The trailer skirts has shown significant fuel savings, are easy to install, do not require sizable maintenance and are now widely used by transportation industry on heavy cargo vehicle.

**Trailer gap fairing and splitter plate**
**by Laydon Composites**


**Inflatable trailer boat tail**
**by AeroVolution**

**Trailer tail end fairing**
**by ATDynamics**


**AeroFlex trailer skirt**
**by Freight Wing**

*Figure 1.4-2: Examples of drag reduction devices for cargo trailers. Pictures are reproduced from the respective manufacturer websites (http://laydoncomp.com/nose-fairing-vortex-stabilizer.php; http://www.aerovolution.com/information.shtml; http://www.atdynamics.com/trailertail.htm; http://www.freightwing.com/gallery.php)*

The most important drawback of existing drag reduction devices is that they are designed for dealing with airflow along the travel direction and have from low to negative usefulness at cross winds. It is noteworthy that EPA SmartWay tests must be executed at low or no winds and testing at cross winds is not required at all. More specifically, the EPA (2011) testing requirements say that "Wind speed at the test track cannot exceed 12 mph for duration of test".

Comparing Figures 1.3-1, 1.3-2 with 1.4-2, one can expect that hard fairings might amplify detrimental effects of side winds such as side force and yawing and rolling moments because they increase the tractor and trailer projected area in the lateral direction; see Equation (1.4). Scientific studies have shown that it is indeed the case not only for the trailer front and back fairings but also for the tractor side extenders; for example DOE (2006). A few experimental results of the study are reproduced in Figures 1.4-3 and 1.4-4.

Figure 1.4-3 shows base flaps with the flap angle 16° installed at the tractor rear end and the measurement results for the flaps. One can see that the side force coefficient $C_S$ and the rolling moment coefficient $C_{RM}$

are not affected by the base flaps at the studied yaw angle below 15°. It is expected at the yaw angles less than the flap angle. Surprisingly the flaps increase the yawing moment $C_{YM}$ at all yaw angles.

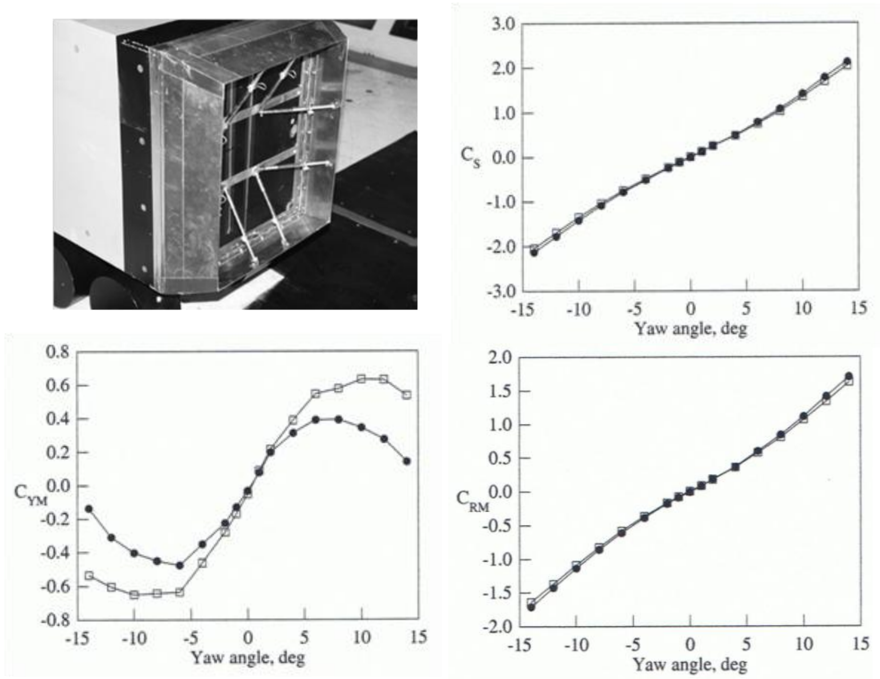



*Figure 1.4-3: Illustration of the effect of base flaps on tractor / trailer combination at cross winds. $C_S$, $C_{YM}$, and $C_{RM}$ are coefficients of the side force, yawning and rolling moments respectively: solid symbols – baseline, open – base flaps. Picture and experimental results are reproduced from DOE (2006).*

Figure 1.4-4 shows the tractor side extenders with the lengths 0.6 and 0.3 of gap width (denoted as 0.3g and 0.6g, respectively). The 0.6g length was considered the baseline because it reduces air drag better than 0.3g. However, the experimental results in Figure 1.4-4 demonstrate that side extenders of larger length generate larger yawing moments. In other words, every device works within specific ranges of operational conditions. Figures 1.4-3 and 1.4-4 illustrate that if the device works well at no cross winds, it may or may not be effective at light or especially strong cross winds.

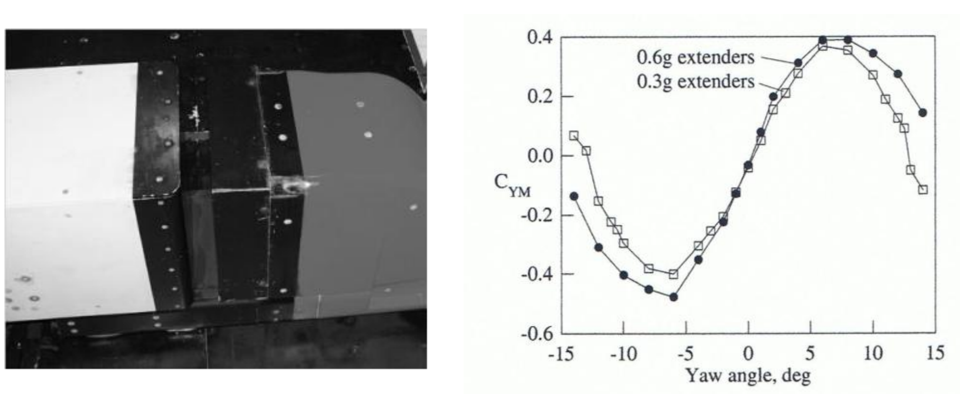



*Figure 1.4-4: Illustration of the effect of tractor side extenders on tractor / trailer combination at cross winds. Picture and experimental results are reproduced from DOE (2006).*

This generic rule is especially true for another type of drag reduction devices, vortex generators. The devices are considered in Section 2 although a brief comment seems appropriate here.


*Figure 1.4-5: Schematics of tested vortex strakes. The left picture is reproduced from Wood (2006) and two on the right are reproduced from Leuschen and Cooper (2006).*

The mostly studied vortex generators for class 8 semi trucks are vortex strakes; Figure 1.4-5. Wood (2006) reported 2% fuel savings by the strakes. Leuschen and Cooper (2006) studied almost the same strakes and found about 2% increase in the drag rather than the drag reduction. Perhaps, there were differences between the vortex strakes and / or measurement procedures in two experiments which led to different results. This example illustrates that aerodynamic devices for active control of turbulent flows such as vortex generators are "highly focused" – the effect strongly depends on their detailed characteristics and operational conditions.

## 2. VorBlade Design and Assessment

As illustrated in Figure 1.2-9, there are five problem drag areas in the tractor / trailer combination: the area in a front of a tractor that contributes 19% in the total drag, the underbody area contributing 28%, the tractor / trailer gap area contributing 14%, the area on the trailer roof edges contributing 6% and the trailer base area contributing 33% in the total vehicle drag. The front drag is taken care of by the tractor manufacturers and the underbody drag could be reduced by the trailer skirts. The remaining three areas, the tractor / trailer gap, the trailer roof edges and the rear base have not been adequately addressed yet although they contribute 53% in the total drag. As outlined in Section 1.4, the majority of proposed and thoroughly studied drag reduction devices like the trailer gap splitters and fairings and the trailer end boat tails and fairings are inconvenient to use and not very efficient. Although the existing vortex generators are simple and convenient to use, they are not very efficient either. The most important drawback of existing devices is that they do not mitigate detrimental effects of cross winds and may even amplify those effects; see Figures 1.4-3 and 1.4-4.

VorBlade is a conceptually new vortex generator designed specifically for heavy motor vehicles. It is simple, convenient to use, inexpensive and extremely efficient. VorBlade reduces fuel consumption for class 8 semi trucks by about 8.3% in addition to savings by the underbody skirts. It is the only commercially available aerodynamic device that addresses detrimental effects of cross winds reducing those by 60%. The process of designing VorBlade vortex generators as well as theoretical analysis and experimental tests of their performance are outlined in this section.

### 2.1. What is VorBlade?

VorBlade is a vortex generator that had been designed specifically for heavy motor vehicles like class 8 semi trucks to reduce aerodynamic drag and mitigate detrimental cross wind effects.

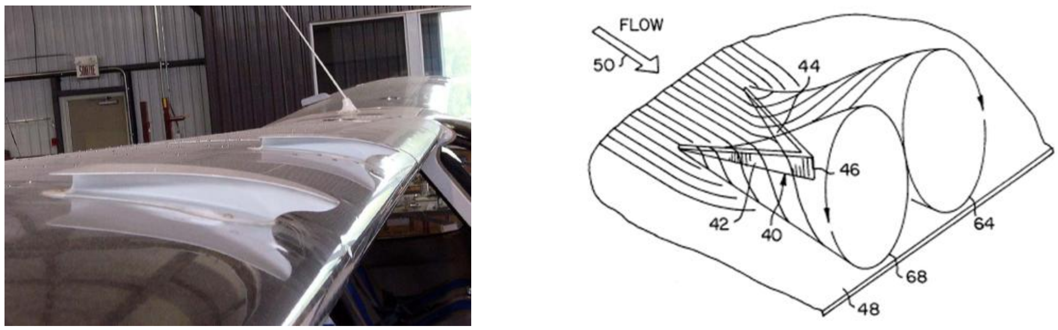



*Figure 2.1-1: (Left) Symphony SA-160 aircraft was designed with two unusual vortex generators on its wing to ensure aileron effectiveness through the stall; the picture is reproduced from Wikipedia (2011). (Right) Schematic of the vortex generator invented for delaying flow separation on aircraft wings, preventing span wise flow and reducing tip vortices; the drawing is reproduced from Wheeler (1991).*

By definition, vortex generator is an aerodynamic device that generates vortices. Vortex generators have been used for decades for controlling airflow and a diverse body of small-scale generators has been developed and widely utilized in different applications. As representative examples, one can mention the use of the generators for intensifying turbulent heat transfer in air and water heaters and coolers, enhancing air and fuel mixing in combustion chambers of jet engines and automotive diesel engines, and preventing flow separation on aircraft wings at high angles of attack.

The latter application is “the preferable area” for small-scale vortex generators and literally hundreds of designs have been described in scientific literature and / or patents. As noted in Wikipedia (2011), vortex generators can be found on many devices, but the term is most often used in aircraft design where the generators delay flow separation and aerodynamic stalling, thereby improving the effectiveness of wings and control surfaces. Two typical examples of the generators on aircraft wings are shown in Figure 2.1-1.

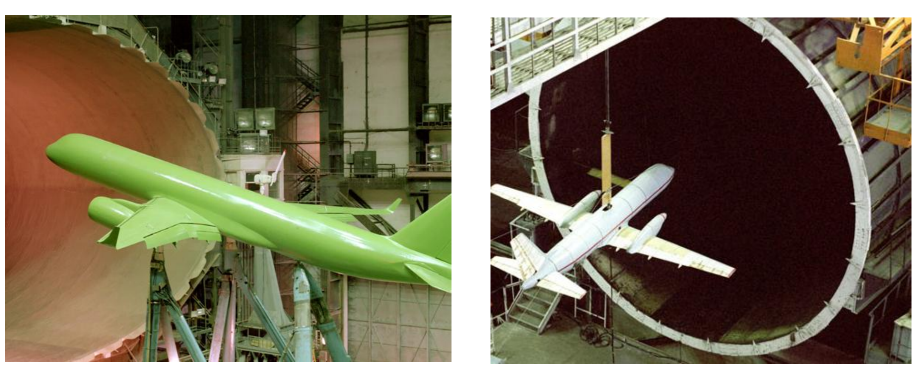


*Figure 2.1-2: The exhaust nozzles of two large wind tunnels in the Central Aero-Hydrodynamic Institute (TsAGI, Moscow, Russia) are equipped with small-scale vortex generators. (Left) T-101 with 24 m x 14 m elliptical cross section has serrated edges and (right) T-104 with circular 7-m cross section has small triangles. The photos are reproduced from the TsAGI website [http://www.tsagi.com/](http://www.tsagi.com/)*

Generators of small-scale turbulent vortices were found extremely effective in destroying large-scale turbulent vortices in wind tunnels with open test section (Figure 2.1-2) and in the aircraft engine inlets where such harmful vortices could cause the compressor stall (e.g., Praskovsky *et al*, 1985). It is noteworthy that the wind tunnels in Figure 2.1-2 were built before the World War II and even so long ago small-scale vortex generators had already been recognized as effective means for destroying large-scale vortices shedding from bluff edges.

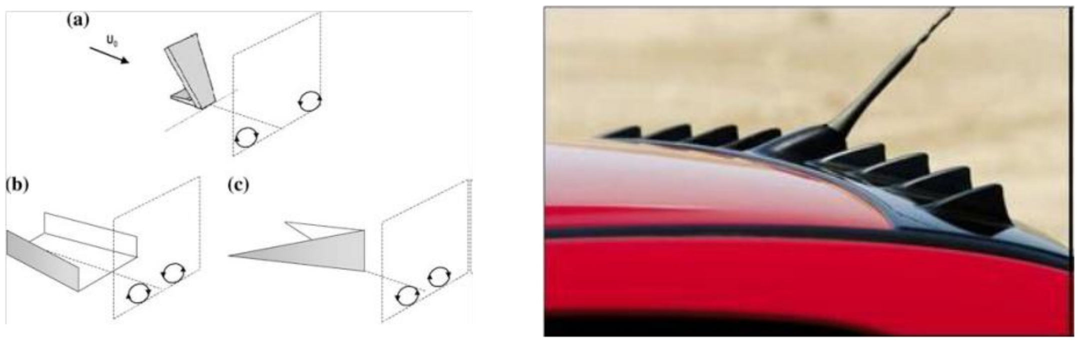



*Figure 2.1-3: (Left) Vortex generators for drag reduction reproduced from Aider et al (2009) and studied by: (a) author (2009); (b) Angele and Grewe (2002); and (c) Betterton et al. (2000). (Right) Vortex generators in the rear of a vehicle reproduced from Ismail (2008).*

It is quite natural that vortex generators have also been applied to motor vehicles, both to passenger cars and cargo trucks where mostly copies or slight modifications of generators for aircraft wings were used; e.g., Koike *et al* (2004), Aider et al (2009), Wood (2006), and Leuschen and Cooper (2006).

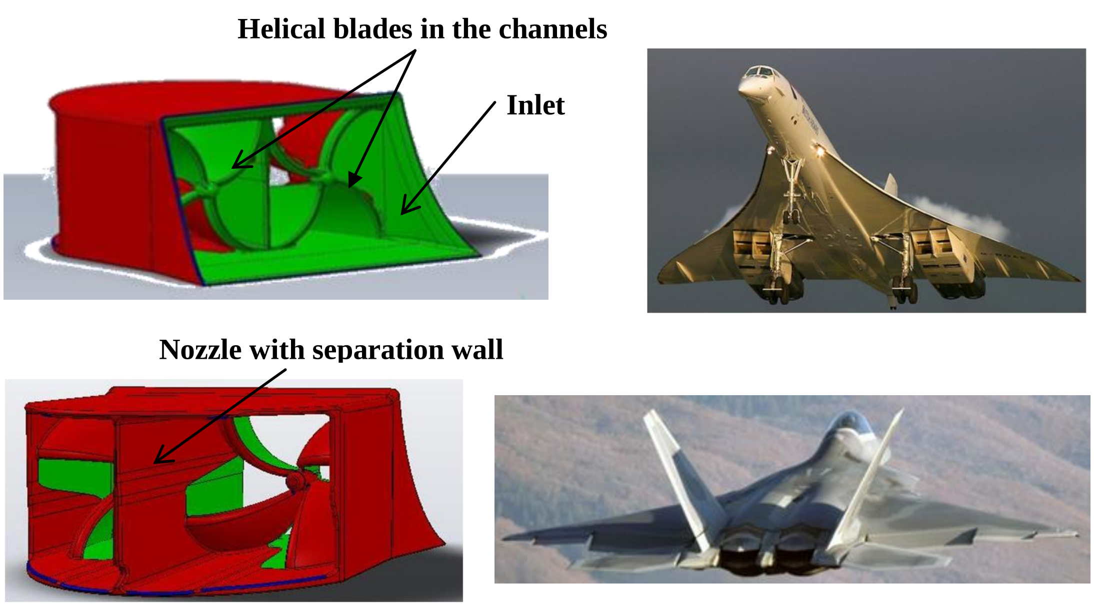



*Figure 2.1-4: VorBlade vortex generator for reducing air drag and mitigating cross wind effect for cargo vehicles. Top: front perspective view of the generator and of Concorde with the engine inlets clearly seen. Bottom: rear prospective view of the generator and of F-18 Hornet with the engine nozzles clearly seen. Aircraft photos are reproduced from the Google images.*

As an illustration, four thoroughly studied generators are shown in Figure 2.1-3. One can see that one of them is similar to the generator by Wheeler (1991) in Figure 2.1-1. The vortex strakes for cargo trailers are also similar devices, merely of a larger size; see Figure 1.4-5.

However, the strategy to control airflow over a cargo vehicle is very different from the one used to control the flow over an airplane wing. One can see in Figures 1.2-4 and 2.1-1 that vortex generators on airplane wings are designed to delay flow separation by enforcing fast transition of boundary layer from laminar to turbulent. It is achieved by generating small-scale vortices with a short lifespan smaller the wing chord, and the latter is comparable with a characteristic size of the generator. To prevent negative effects on the aerodynamics of wings and control surfaces, the generator must have as low own aerodynamic drag as possible. Free airflow tends to avoid any resistant obstacles and tends to run outside open blockages and for this reason vortex generators for aircraft wings are open-type devices. The freeway speed is much smaller than the speed of an aircraft and a self-adaptation of airflow results in a low intensity and lifespan of small-scale vortices generated by vortex strakes and other conventional automotive vortex generators. That in turn results in a low reduction in the vehicle aerodynamic drag and fuel consumption by available devices.

Requirement for cargo vehicle are completely different from those for air wings. It is important to identify the flow structures that contribute the most to the aerodynamics forces, select the right shape and size of the vortex generators and place them properly. To fully destroy large-scale vortices shedding from the cargo vehicle abrupt edges and streamline airflow around the vehicle, the generators must produce highly intensive small-scale vortices with very long lifespan. Being similar to aircraft wing vortex generators, commercially available generators for heavy vehicles have short lifespan and they weaken slightly large-scale vortices but do not destroy them completely.

On the contrary, the VorBlade generators are designed for automotive applications; Figure 2.1-4. The “channel-trapped” airflow ensures generation of highly intensive small-scale vortices. Their longitudinal axes ensure very long lifespan similar to convex vortices on the ends of air wings.

Similar to the twin jet engines, VorBlade has a joint inlet, two chambers with helical blades, and an exhaust nozzle. In the helical design, the blades curve around the axes in such a way that the sum of the lift and drag forces on each blade does not change abruptly with rotation angle. The blades generate smooth torque curve to minimize aerodynamic loads and stress in the structure and materials, and also minimize vibration and noise. Such design generates a pair of highly intensive vortices with the opposite rotational direction and a very long lifespan of about 10ft.

VorBlade incorporates the best finding in generating turbulent vortices for aircraft wings, jet engines, combustion chambers, heat exchangers, paper machines and other applications, and it has been designed specifically for motor vehicles at the highway speeds from about 45 mph to 85 mph. The VorBlade development was greatly based on the accumulated theoretical and experimental knowledge of optimal characteristics of vortex generators and their effects on the airflow; e.g., Wetzel and Simpson (1992), Koike *et al* (2004), Wood (2006), Leuschen and Cooper (2006) and Aider et al (2009). The generators were designed by combining theoretical analysis and available experimental data with the designated wind tunnel tests.

The VorBlade design was started from qualitative analysis of promising configurations to narrow a range of parameters to be studied theoretically and experimentally, and a few major points are outlined below.

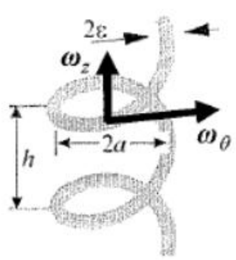
- Accumulated experience in controlling turbulent flows shows that a pair of vortices with an opposite rotational direction is the most stable and long-living structure, e.g., the wingtip vortices. Therefore, VorBlade was designed for generating such an oppositely rotating pair.
- “There’s no such thing as a free lunch”: an efficient vortex generator must have relatively high air drag. It is well-known that the intensity of generated turbulence is proportional to the air drag of the generator (e.g., Hinze, 1959) and this experimental observation is easy to understand. To impose vorticity on the non-rotating fluid, one must apply a proper force and the stronger vorticity is to be imposed, the larger force needs to be applied. The only available energy source for imposing the rotation is the energy of airflow around a vehicle and that energy can be extracted only through the generator air drag. If a generator is of an open-type, airflow avoids it hence the flow shall be “trapped” in a channel before the rotation is imposed. This is similar to trapping airflow in a jet engine and the inlet for a twin jet engine was a natural prototype for VorBlade; Figure 2.1-4, top.
- After the vortices are generated, they should have small time (or distance) to diverge otherwise they may weaken one another. For this reason, an exhaust nozzle with a separation wall and open sides was implemented into VorBlade similar to nozzles of dual jet engines; Figure 2.1-4, bottom.
- The helical blades were chosen as the vorticity-producing elements. The helically twisted fins and blades were found to be the most effective and compact vortex generators for many applications, for example to intensify the mixture of air and fuel in combustion engines (e.g., Lyssy, 1982).

Those considerations have defined the generic VorBlade design shown in Figure 2.1-4. Theoretical analysis of the helically twisted blades was the next step. A one-dimensional model for a helical vortex by Velte (2008) was applied for this task and it is outlined in Figure 2.1-5.

Helical vortex

$a/(a^2 + l^2)$

$l/(a^2 + l^2)$




**CONDITION OF HELICAL SYMMETRY**

$$u_\tau \equiv \text{const} \quad \text{or} \quad u_z + r u_\theta / l = u_0 \equiv \text{const}$$

**It means that the vorticity vector is always directed tangentially to the helical lines** (vortex interpretation of the condition)

$$\omega_r = 0; \quad \omega_\theta / \omega_z = r / l \quad \text{or} \quad \omega_\theta = r\omega_z / l.$$

$$\omega_z = \frac{\Gamma}{\pi \varepsilon^2} \exp\left(-\frac{r^2}{\varepsilon^2}\right)$$

$$u_\theta = \frac{\Gamma}{2\pi r}\left[1 - \exp\left(-\frac{r^2}{\varepsilon^2}\right)\right]$$

$$u_z = u_0 - \frac{\Gamma}{2\pi l}\left[1 - \exp\left(-\frac{r^2}{\varepsilon^2}\right)\right]$$

$$S = F_{mm}/F_m L,$$

$$l = -F_{mm}/(F_m - u_0 G) = -LS/(1 - u_0 G/F_m)$$

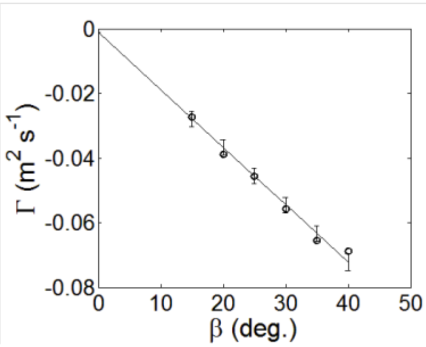



*Figure 2.1-5: Basic equations of the one-dimensional model for a helical vortex from Velte (2008).*

The plot in that figure shows practically linear dependence of the generated vorticity $\Gamma$ on the rotation angle $\beta$ of the individual blade. Similarly, the air drag of the generator increases almost linearly with the angle $\beta$ . Theoretical analysis has shown that the optimum rotation angle of the individual blade is between 10° and 20°, and this range was studied experimentally.

The square channels were chosen to ensure axial symmetry of helical vortices and, at the same time, get the maximum cross section area at given height. The square cross section defined four blades as the optimum number of blades ensuring the maximum imposed vorticity at the minimum channel shadowing and dynamic load on each blade. A choice of the height was based on existing experimental and theoretical studies (e.g., Koike *et al,* 2004; Aider *et al*, 2009, Gustavsson and Melin, 2006), and two considerations. First, it is well-established that shedding of large-scale vortices can be effectively prevented when the size of interfering small-scale vortices is from about 1/40 to about 1/20 of a characteristic size of a bluff edge. The width of a typical 53 ft cargo trailer is 102" hence vortices with a diameter between 2.5" and 5" would be the most effective. A vortex diameter increases with distance from a generator thus the initial diameter between 1" and 2" is the optimum. Another consideration is the US DOT size requirement: no protrusions from the trailer can exceed 3inches; DOT (2002, par. 658.16). To satisfy the requirements, the internal channel height and width of 1.25" were chosen.

The 17° angle of inlet walls was chosen after theoretical analysis to ensure high generator performance at the yaw angle with respect to incoming airflow from zero to 20°. Wind tunnel tests confirmed validity of those theoretical estimates; see Figure 2.1-6 below. Two more parameters to test experimentally were the length of helically twisted blades and the length of a nozzle. Theoretical estimates provided the ranges for these parameters to be tested from 1" to 5" and from zero to 2.5", respectively.

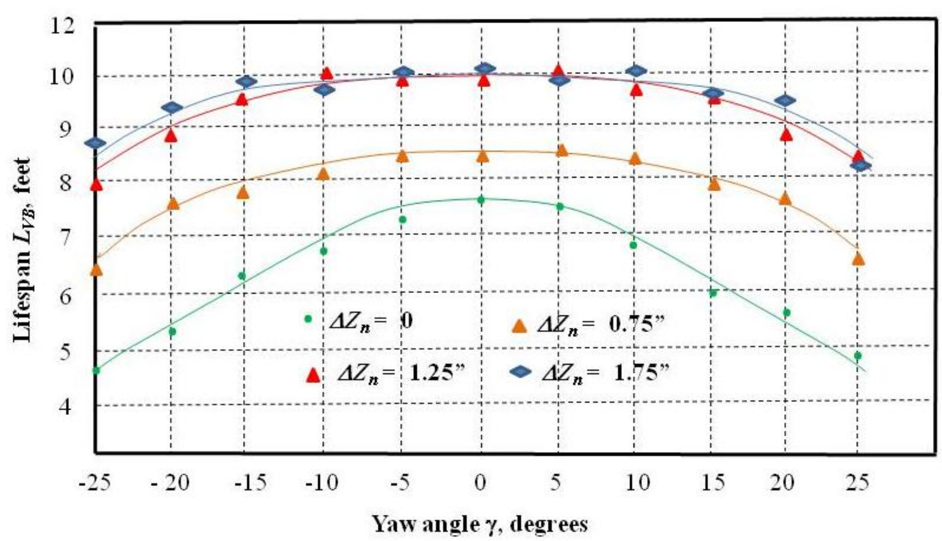



*Figure 2.1-6: Measured values of the lifespan $L_{VB}$ of the VorBlade-generated vortices vs the yaw angle $\gamma$ at varying nozzle length $\Delta Z_n$ and fixed blade length 1.5", blade angle 15° and flow velocity 67 mph.*

The VorBlade design was finalized in the wind tunnel tests where multiple generators similar to that in Figure 2.1-4 but with varying parameters were tested to obtain the largest achievable lifespan of generated vortices. The tests were performed in the wind tunnel with circular open test section like that in Figure 2.1-2 although of smaller diameter of 1.3 m and the length of 3.9 m. The flow velocity varied from 20 m/s to 40 m/s, or from 45 mph to about 90 mph. The Reynolds number $Re = wV/\nu$ based on the channel width $w$ = 2.5" varied from $0.8 \cdot 10^5$ to $1.7 \cdot 10^5$ and was sufficiently high to ensure turbulent nature of the airflow. The cross-wire anemometer was used to measure the profiles of rotational velocity in the generated vortices that were used to calculate the vorticity. The lifespan of the vortices was defined rather conservatively as the distance from the generator where the vorticity dropped to 20% of its initial value.

The experiments have shown that the lifespan $L_{VB}$ of generated vortices was long enough and it varied from about 6 ft to about 10.5 ft over all range of studied parameters. Based on the tests, the VorBlade optimum values were chosen as 1.5" for the blade length, 15° for the rotation angle of the individual blade, and 1.25" for the length of a nozzle. Those parameters ensure lifespan of generated vortices of about 10 ft at yaw angle of airflow with respect to the generator up to 15° with slight decrease of about 15% - 20% at the yaw angle of 25°.

As an illustration, experimental results on the vortices lifespan $L_{VB}$ at the flow velocity of 30 m/s (or 67 mph) for varying nozzle length $\Delta Z_n$ at the optimum values of the blade length of 1.5" and the blade angle of 15° are shown in Figure 2.1-6. One can see that lifespan increases with increasing length of the nozzle to 1.25" and remains almost constant at larger $\Delta Z_n$ . The result is expected because 1.25" is the height / width of the channel and, respectively characteristic lateral vortex size. Based on the tests, the minimum effective value of 1.25" was chosen for the nozzle length in the VorBlade design to ensure the minimum size and weight of the generator. Figure 2.1-4 illustrates the optimized VorBlade vortex generator with the configuration established by theoretical analysis and finalized in the wind tunnel tests; the exact VorBlade dimensions are presented in Section 3.

The experiments have shown that the lifespan of the VorBlade-generated vortices depends weakly on the yaw angle at $\gamma < 20°$; e.g., as seen in Figure 2.1-6. It also depends weakly on other varied parameters. In particular, the lifespan was found to decrease less than 5% and increase less than 7% when the velocity changed from 30 m/s to 20 m/s and 40 m/s, respectively. It proves the reasonable choice of the generator parameters in the *a priori* theoretical analysis. The experimental finding of weak dependence of $L_{VB}$ on $\gamma$ also illustrates the adaptive nature of the VorBlade-generated vortices – they are merely carried out by the airflow in its direction.

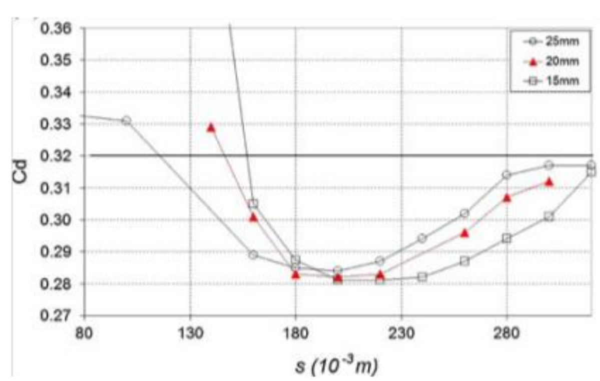



*Figure 2.1-7: Influence of spacing S between vortex generators that are shown in Figure 2.1-3 (a). The picture is reproduced from Aider et al (2009)*

The second experiment was aimed at optimizing separation between the generators as well as testing their performance at variable distance from the abrupt edge, and it was designed as follows. Nine VorBlade generators were mounted near the rear top and side edges of a box of parallelepiped shape; three generators on each edge. The box had a length of 3 ft and a square cross-section with the 20” sides. The drag coefficient of the box with and without the generators was measured by the wind tunnel electro-mechanical balance system.

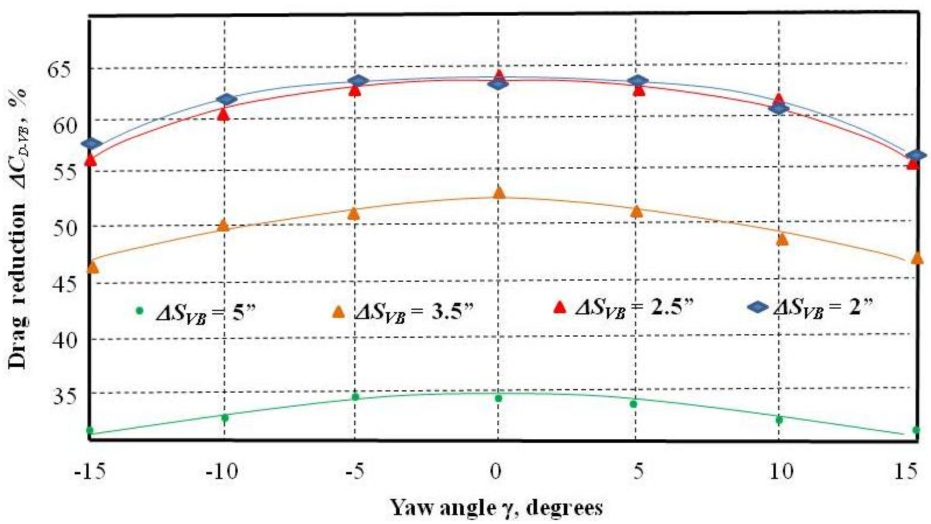



*Figure 2.1-8: Measured values of the normalized drag reduction $\Delta C_{D\text{-}VB}$ by the optimal VorBlade vortex generators for a distance from the edge $\Delta X_e$ = 3 inches and flow velocity 67 mph at the varying separation between the generators $\Delta S_{VB}$.*

It is well established that separation between vortex generators may significantly affect their performance while the distance from the rear edges of tractor and trailer may or may not be significant; e.g., Aider *et al* (2009). Figure 2.1-7 illustrates an intuitive fact that effective drag reduction is achieved when separation between the generators is close to the characteristic size of the generator. Another important feature in Figure 2.1-7 is that the drag reduction is practically independent of the flow velocity at the optimum separation.

Theoretical analysis and experimental data by Koike *et al* (2004), van Raemdonck and van Tooren (2008) and Aider *et al* (2009) were used in planning the experiment. The *a priori* analysis has shown that the optimum separation between VorBlade generators $\Delta S_{VB}$ is between 2.0” and 4” (equal or slightly larger than the two-channel width of 2.5”) and the performance does not depend significantly on the distance from the edge $\Delta X_e$ at $\Delta X_e \ll L_{VB}$. The experiments have confirmed that the drag reduction by the VorBlade generators was practically independent of the distance from the edge at $\Delta X_e$ < 1.3 ft over the whole studied range of flow velocity from 20 m/s to 40 m/s and yaw angles from zero to 15°.

Experimental values of a normalized drag reduction coefficient $\Delta C_{D\text{-}VB}$ by the optimized VorBlade generators are illustrated in Figure 2.1-8 and they were measured in the following way. For each value of flow velocity and yaw angle, the baseline value of the box drag force $F_{D\text{-}0}$ was measured without the generators. During the experiment, the drag force $F_{D\text{-}VB}$ was measured at each combination of the test parameters: flow velocity, yaw angle, separation $\Delta S_{VB}$ and distance $\Delta X_e$ . Taking into account Equation (1.1), corresponding normalized reduction in the drag coefficient for each combination of the test parameters was calculated as follows.

$$\Delta C_{D-VB} = 100\% \cdot \left(F_{D-0} - F_{D-VB}\right) / F_{D-0} \tag{2.1}$$

It is seen in Figure 2.1-8 that the maximum drag reduction is achieved at $\Delta S_{VB}$ from about 2” to about 2.5”. The performance was found degrading at $\Delta S_{VB}$ = 1.5” (not shown) which was expected. Separation $\Delta S_{VB}$ = 2.5” was chosen as the optimum value: it is the larger value with the best performance. The larger value is obviously preferable because it requires the minimum amount of generators to be installed on a vehicle. The generator performance at $\Delta S_{VB}$ = 2.5” was found to be practically independent of the flow speed which agrees well with the results in Figure 2.1-7.

One can see in Figure 2.1-6 that optimized VorBlade generators produce pairs of vortices with the lifespan of about 10 ft over a wide range of flow speed and yaw angle. One can further see in Figure 2.1-8 that at the optimum separation of 2.5” the generators reduce aerodynamic drag of a bluff body up to about 63% over a wide range of flow parameters. Those two features make the VorBlade generators uniquely efficient devices which could significantly reduce aerodynamic drag of motor vehicles and greatly mitigate detrimental effects of cross winds.

### 2.2. How does VorBlade work?

The VorBlade vortex generators produce intensive stream-wise vortices with a large lifespan. How does it help to reduce air drag or mitigate cross wind effects?

To answer that question, one should understand where the drag comes from. Although the physics of air drag was briefly outlined in Sections 1.2.2 and 1.3, it is constructive to look on the bluff bodies from a slightly different point of view. Figure 2.2-1 illustrates the basic feature of the pressure drag of bluff bodies: it is mainly caused by flow separation always accompanied by shedding of large-scale vortices. Those large-scale vortices are major contributors into the drag due to two physical processes: they greatly increase a volume of the separated flow and lower the air pressure in the volume.

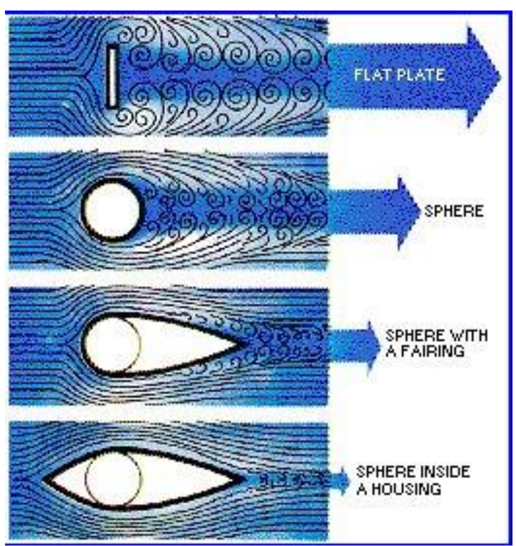



*Figure 2.2-1: An illustration of the pressure drag caused by the separation of air flows; reproduced from The Encyclopedia of Science http://www.daviddarling.info/encyclopedia/D/drag.html#top*

Although those processes are illustrated in Figure 2.2-1, the most destructive feature of large-scale vortices is not seen well enough there: temporal and spatial irregularity. The pictures in Figure 2.2-2 show the mean and instantaneous flow patterns of the same airflow. One can clearly see that the large-scale vortices occupy much larger volume than it seems after temporal averaging. The reason is that such vortices are irregular and asymmetric: they fluctuate in time and space from one side of a bluff body to another as illustrated in Figure 2.2-3. The fluctuating vortices obviously increase a volume and a weight of the air to be accelerated by the vehicle; see Section 1.2.2. The large vortices also decrease the air pressure inside the separation volume by increasing the local air speed (the Bernoulli effect).

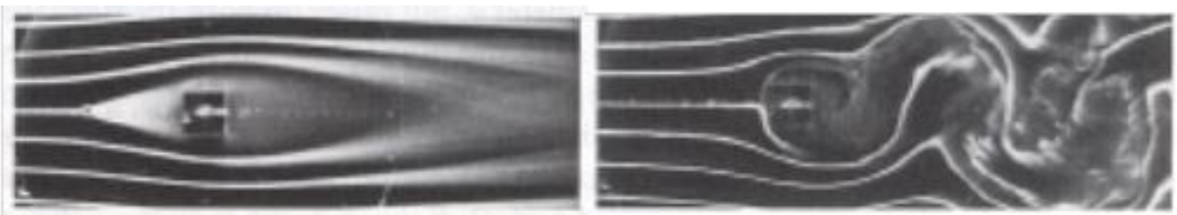


*Figure 2.2-2: The mean (left) and instantaneous (right) flow patterns around a square cylinder; the pictures are reproduced from Buresti (2000).*

Therefore the most effective way for reducing air drag is to destroy those vortices. One can see in Figures 2.2-2 and 2.2-3 that the vortices are highly energetic and there destruction would require a lot of energy. However this is not completely true: the vortices become energetic after gaining their energy from airflow through the air drag, the energy that was supplied by burned fuel. Like a large river begins from a small creek, the vortices are weak when they are just originated which happens very close to the bluff edges. It does not take much energy to destroy such vortices while they are still weak, e.g., how it is done by small-scale vortex generators on the bluff edges of the wind tunnel nozzles in Figure 2.1-2.

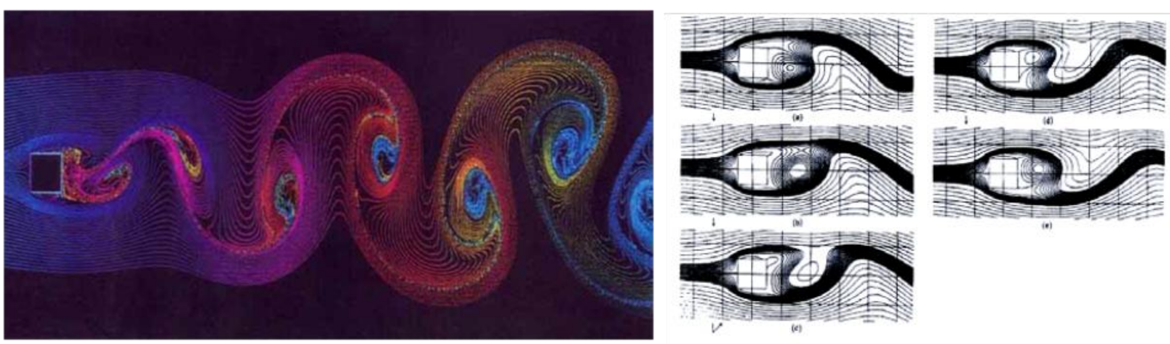


*Figure 2.2-3: Visualization of large-scale vortices shedding from a square prism (left) and (right) temporal variation of flow pattern around the prism; the pictures reproduced from Tamura (2001).*

And this is exactly what VorBlade-generated small-scale vortices do: they destroy harmful large-scale vortices before those gained the force. VorBlade generators are installed near bluff edges that initiate flow separation and large-scale vortices: near the rear edges of the tractor roof and side fairings (or the tractor cabin if there are no fairings), the rear edges of the trailer roof and side walls, and near the side edges of the trailer roof; see Section 3 for more details. VorBlade-generated vigorous small-scale vortices prevent the very origination of the harmful large-scale vortices behind bluff edges and do it in varying operating conditions like variable truck speed, cross winds, etc. By destroying the large vortices, VorBlade vortex generators eliminate the major contributors into the vehicle air drag. The physics behind the adaptive nature of VorBlade small-scale vortices is quite simple: they move into locations with the lowest pressure, and the origins of large-scale vortices are exactly such locations of the lowest pressure.

Second aspect of VorBlade-produced drag reduction is illustrated by the lowest picture in Figure 2.2-1: the generators decrease separation volume by streamlining airflow. VorBlade vortices create smooth "liquid wall" behind the bluff body and this wall shapes itself like a teardrop – the perfect shape with the minimum possible drag coefficient. The along-teardrop path is that of the minimum resistance and small-scale vortices follow it at varying conditions. Such wall works as self-adaptive "invisible fairing": it streamlines the airflow for the lifespan of the vortices which was found to be up to 10 ft.

One more qualitative feature of the generators is noteworthy here. Contrary to sleek, low drag vortex generators for aircraft wings, VorBlade would work even when its channels are almost packed by snow or blocked by ice. The VorBlade generators were designed for such situations as well and still generate small-scale vortices. However, the effectiveness of the generators drops to about 30% of that for unblocked channels.

In general, VorBlade is a conceptually new, extremely efficient close-type generator producing highly vigorous and long-living small-scale turbulent vortices. Such long-living vortices are self-adaptive which results in preventing origination of harmful large-scale turbulent vortices, and creating the "invisible fairing" with the minimum resistance of a streamlined body in varying conditions.

VorBlade small-scale turbulence generators target large-scale turbulent vortices in three major drag-producing areas: the tractor / trailer gap, the trailer roof sides and the trailer base. The generators use airflow around a vehicle to create self-adaptive vortices which choose the path of the minimum resistance and direct themselves into the nearest locations with the lowest pressure. Those are the locations near the bluff edges of a vehicle where the large-scale irregular vortices would be originated otherwise. The VorBlade-generated small-scale vortices prevent the very origination of large-scale vortices thus destroying those vortices before they gained a force. By doing so, VorBlade turbulence generators effectively reduce an aerodynamic drag, mitigate detrimental effects of cross winds, and greatly reduce fuel consumption. The VorBlade invisible fairings significantly increase aerodynamic stability of motor vehicles, and improve a visibility to the vehicle operator by preventing particles like mud, rain and snow from spraying to the mirror height. The invisible fairings also significantly increase visibility to operators of passing vehicles and decrease an "air impact" on the vehicles thus providing more safety and comfort for other drivers.

VorBlade generators are the only commercially available aerodynamic devices that effectively mitigate harmful effects of cross winds.

### 2.3. How could VorBlade reduce operating expenses?

Quantitative estimates of the VorBlade benefits are outlined in this and the following sub-sections. The estimates are based on the comprehensive studies of drag reduction and safety issues for heavy vehicles conducted by scientists and engineers around the world outlined in Section 1.4 and the wind tunnel tests of the VorBlade vortex generators outlined in Section 2.1. Whenever possible, the US DOE and DOT-funded studies were used for the estimates. We prefer our customers to be pleasantly surprised rather than disappointed thus we kept the estimates quite conservative.

From two major wind tunnel test results outlined in Section 2.1, only one can be used directly for the estimates, the 10-ft lifespan of the VorBlade-generated vortices. The second result, up to 63% drag reduction of the bluff body, provides the reliable reference value but cannot be applied directly to heavy cargo vehicles. Therefore, we need some kind of a “bridge” between drug reduction by conventional devices and the VorBlade vortex generators.

The first-order equation for estimating drag coefficient by Mighty Mira (2006) was used for that purpose. The equation was suggested for a simplified teardrop-like construction consisting of two parts: the half-sphere of radius $r_0$ and a cone with the taper angle of approximately 11° which is truncated at the radius $r_f$; Figure 2.3-1. The drag coefficient of such construction can be estimated as:

$$C_D = 0.04 + \Delta C_{D0}\frac{A_f}{A_0}, \quad A_0 = \pi r_0^2, \quad A_f = \pi r_f^2 \tag{2.2}$$

Here $A_0$ and $A_f$ are the front and rear areas of the cone, and $\Delta C_{D0}$ is the difference in drag coefficient of the bluff body from the teardrop. Because $C_D$ for half-sphere is 0.42, $\Delta C_{D0}$ = 0.38 for specific construction in Figure 2.3-1.

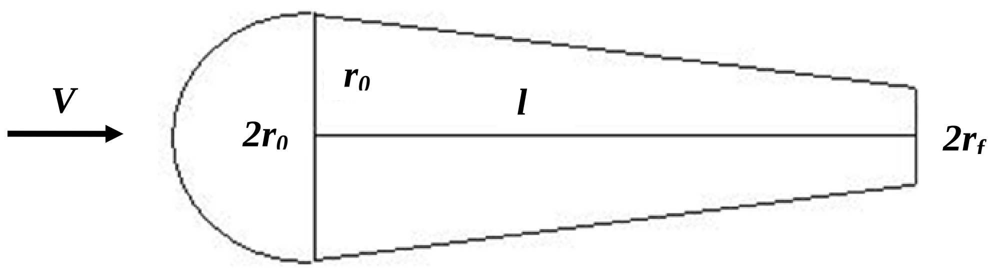



*Figure 2.3-1: Schematic of a truncated teardrop-like construction; reproduced from Mighty Mira (2006).*

As shown in Section 1.2.2, the air drag of heavy trucks depends mainly on airflow behind rear bluff edges. Therefore one can consider partially streamlined trailer with fairings as a truncated teardrop in Figure 2.3-1 and estimate its drag coefficient with Equation (2.2) at properly adjusted $\Delta C_{D0}$. Let us apply this approach to the trailer base flaps from DOE (2006) shown in Figure 1.4-3. The characteristic base area of a typical 53-ft trailer is about $A_0$ = (9 ft)$^2$ and the final area for studied flaps of 63.5 cm full scale in length at the angle of 16° is about $A_f$ = (7.9 ft)$^2$.

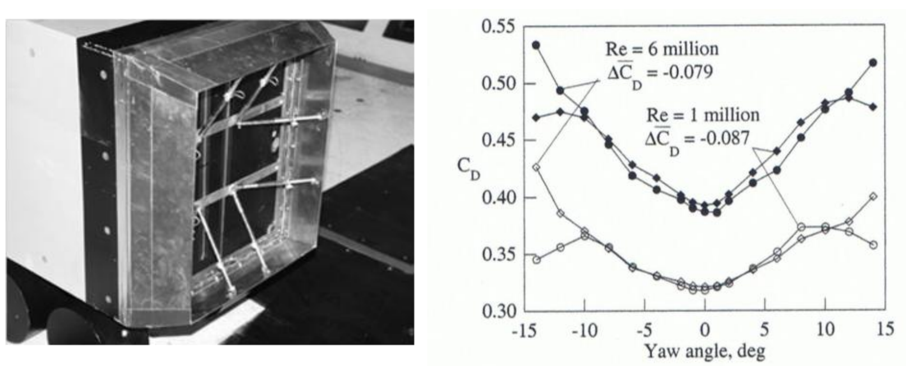



*Figure 2.3-2: Effect of base flaps on the drag coefficient of the general configuration model (GCM) of heavy cargo vehicle. Open symbols – baseline, solid – 16° base flaps. The picture and plot are reproduced from DOE (2006).*

Experimental data in Figure 2.3-2 at no flaps yield the value of $\Delta C_{D0} = 0.35$ at zero yaw angle. According to equation (2.2), the drag coefficient with base flaps at zero yaw angle is about 0.31, or about 22% drag reduction, which is in good agreement with the measured values.

We can now apply the same equation and estimate expected effect of VorBlade generators considering "invisible" liquid flaps of 9.5 ft in length and 11° flap angle. (VorBlade vortex generators are considered to be installed 0.5 ft from the edges hence the 9.5 ft length). In this case $A_f$ = (5.3 ft)$^2$ and the drag coefficient is 0.16, or about 54% drag reduction, which is lower than 63% drag reduction established in the wind tunnel tests. Therefore Equation (2.2) provides reasonable and conservative estimates for a drag reduction and it is used below for assessing the expected VorBlade performance.

A diverse body of simulations and measurements of the airflow patterns around motor vehicles are presented in scientific literature; examples are given in Figures 1.2-6 (right) and 2.3-3. One can see that the flow pattern around a cargo vehicle is highly complicated, especially at cross winds.

For this reason a simplified finite volume technique was developed for estimating drag reduction by VorBlade which incorporated Equation (2.2). The airflow at considered winds was divided into several representative finite volumes and the drag reduction was estimated with Equation (2.2) for each volume separately. $\Delta C_{D0}$ was adjusted for each volume with respect to the shape of the obstacle in the volume and the volumes were then combined together. The calculations are lengthy hence the details are skipped and only the results are presented hereafter.

To further simplify understanding of fuel savings, one can present percentages in Figures 1.1-1 and 1.2-9 in a different way. One can consider 100 gallons of burned fuel from which 36 gallons are used on the air drag. At no cross winds, 5 gallons, 2 gallons and 12 gallons are spent to overcome air drag in the tractor / trailer gap, the trailer roof sides and the trailer base, respectively. It was found with the finite volume technique that VorBlade generators decrease drag and save fuel in those areas by 35%, 45% and 55%, respectively which altogether accounts for 9.3 gallons in saved fuel. It corresponds to the drag-related fuel saving of 9.3 gallons / 36 gallons = 0.26, or 26% at no cross winds.

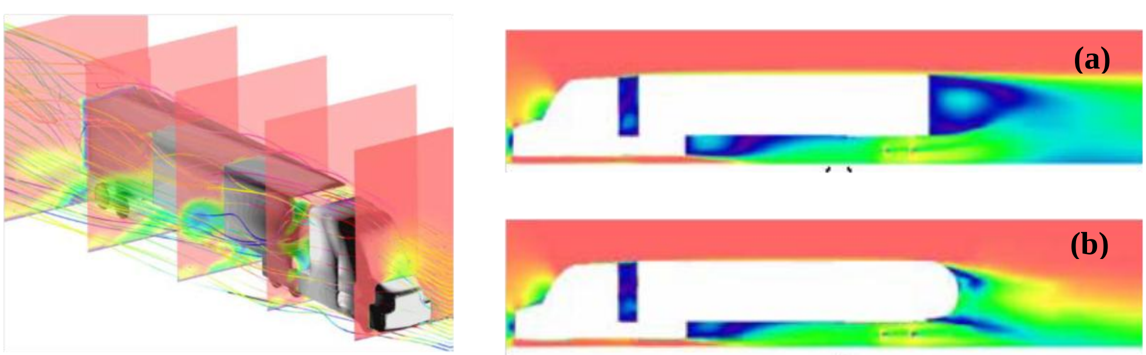



*Figure 2.3-3: (Left) Stream lines showing predicted air flow across the surface of the GCM at a yaw angle of 10°. (Right) Comparison of Velocity Magnitude Predictions without (a) and with (b) the boat tail device installed. The pictures are reproduced from DOE (2006).*

Analysis of climatology data on a wind speed around the US has shown that an average cross wind, either from the left or the right side of a vehicle, can be conservatively estimated as 5.8 mph. Taking an average truck speed on the US highways as 60 mph, one can obtain that the average yaw angle is about 5.5°. At that angle the trailer air wake volume increases about 60% increasing the vehicle fuel consumption from 100 gallons to 108.25 gallons. Another cause of the increase in fuel consumption at cross winds is a tire misalignment; e.g., Good Year (2008), Mu (2011). Light cross wind of 5.8 mph just slightly increases the misalignment as illustrated in Figure 2.4-1. The tire misalignment leads to additional fuel expenditure of about 0.25 gallons hence the total increase in the fuel consumption at the average cross winds is about 8.5 gallons from which VorBlade generators save about 4.5 gallons, or 53%.

The total fuel saving by VorBlade vortex generators is 12.8% which is 13.9 gallons from 108.5 gallons of fuel that would be spent without the generators. The magnitude is estimated for the entire set of the generators on the tractor and trailer rear edges and on the trailer roof side edges; Section 3.

If the VorBlade generators are mounted on the tractor only (see Section 3), they decrease air drag in the tractor / trailer gap, the trailer roof side edges and the trailer base by respectively 35%, 23% and 16% which reduces fuel consumption to about 4.1 gallons at no cross winds. In addition, generators mounted on the tractor decrease the average cross wind-induced fuel consumption by about 1.8 gallons. Altogether it accounts for about 5.9 gallons, or 5.4% from 108.5 gallons in the fuel saving.

The above estimates presume 36% of the fuel spent on the air drag, and that value is based mainly on the results of the DOE 2003 - 2007 studies. As stated by McCallen *et al* (2006), "overcoming air drag represents 65% of energy expenditures at highway speed." Similar high values for the air drag-related fuel expenditure are presented in the overviews by Salari (2010) and 21st CTP (2006) which state that 10% reduction in the drag coefficient leads to 5% - 7% reduction in the fuel consumption. It is so at the highway speed of about 80 mph as illustrated in Figure 2.3-4. However, the partition of the air drag-related fuel spending decreases with decreasing driving speed as is clearly seen in Figure 2.3-4. For example Ogburn and Ramroth (2007) have attributed about 21% - 25% to the air drag at the highway speed of about 60 mph.

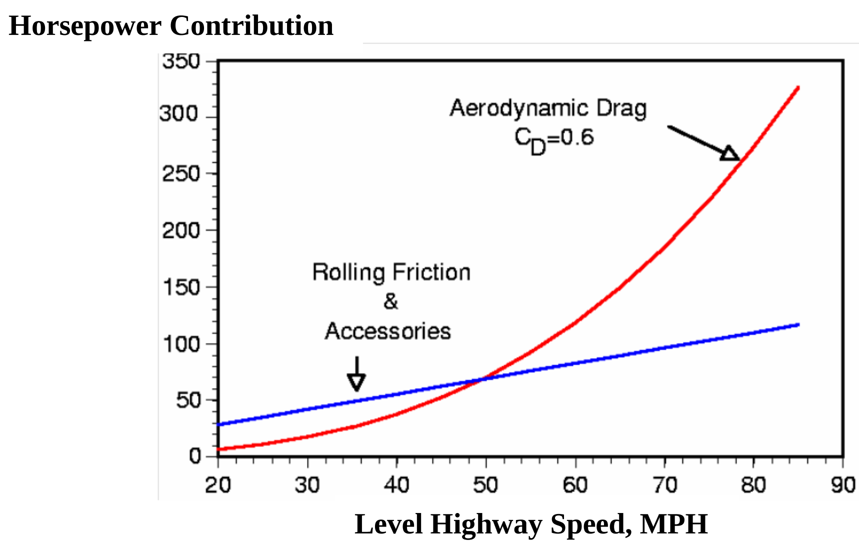



*Figure 2.3-4: Energy expenditure at highway speeds; reproduced from McCallen et al (2006).*

To get the most conservative estimates of the VorBlade efficiency, we adopted the value of 23% for the fuel expenditure on the air drag corresponding to the highway speed of 60 mph. In this case the previously indicated values of 12.8% and 5.4% decrease respectively to 8.3% and 3.5% in the fuel savings by the entire set of VorBlade vortex generators and the generators on the tractor only; those most conservative estimates are used hereafter.

Analysis of statistical information shows that a class 8 semi truck spends in average about 17,000 gallons of diesel fuel per year; e.g., FHA (1997), Kenworth (2008), and DOE (2011). At the current fuel price above $4 per gallon, it accounts for more than $68,000 in annual fuel spending. Thus the VorBlade vortex generators could save more than $5,600 per semi truck per year on the fuel alone.

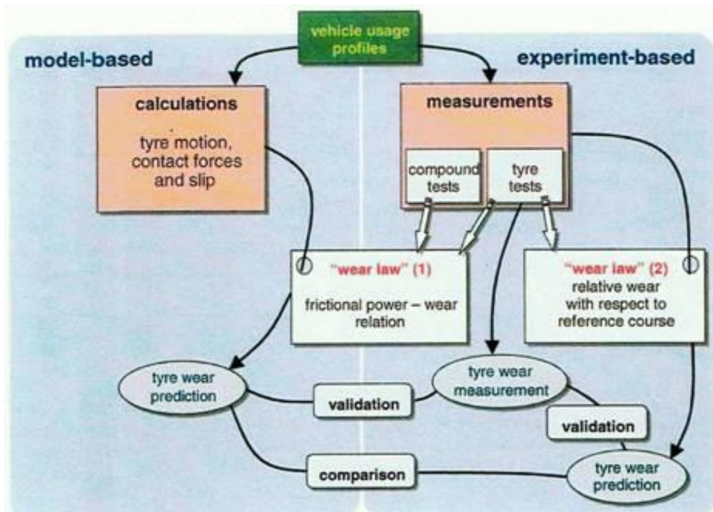



*Figure 2.3-5: Workflow for tire wear assessment, modeling and prediction from Lupker et al (2002).*

Decreasing aerodynamic drag, VorBlade vortex generators also reduce loads on tractor and trailer tires which in turn reduces tire wear. Reduced tire misalignment at cross winds was noted above. Another and the major load on tractor tires is the frictional power over the pavement that moves a vehicle and is directly related to the air drag. One more load on tractor and trailer tires is sideslip which is especially pronounced at cross winds. The tire wear is discussed in scientific literature; e.g., TSG (2011), Good Year (2008), Lupker *et al* (2002). To estimate quantitatively VorBlade-produced reduction in tire wear, a methodology by Lupker *et al* (2002) was used. The work flow of the full methodology is shown in Figure 2.3-5 although it was simplified for the present analysis.

Analysis with the chosen methodology included many empirical parameters to be specified and the most conservative values were always chosen. The analysis has shown that VorBlade vortex generators could extend tire life by at least 6% or more. If one assumes that in average about $4,000 is spent annually on truck tires, 6% stand for about $240 in annual savings.

It is shown in the next subsection that VorBlade reduces spray of dirt on the rear surfaces of tractor and trailer by about 60%. Expert analysis based on interviewing truck drivers has shown that it would result in only 20% savings on truck wash expenses. Most interviewed drivers said that they wash their truck only when it becomes “too damn dirty” which is about once a month. At a typical $80 cost for the truck wash, it means an annual saving of about $190.

The last contributor into the savings is a reduction in the cost of the VorBlade-prevented accidents. It is shown in the next sub-section that VorBlade could prevent annually 46,000 accidents with large trucks involved and that would save about $3.9B nationwide. Researchers found that a semi truck accident is about four times more costly than that of a single truck; e.g., Zaloshnja and Miller (2004, 2006), Truckinfo (2009), IIHS (2011), Dulaney *et a*l (2012). In 2010 there were about 2.7 million semi trucks and 8.6 million single trucks on the US roads; e.g., DOE (2011). It means that in average VorBlade could save more than $800 per semi truck annually by reducing potential expenses on accidents.

Altogether, about $5,600 on fuel, $240 on tires, $800 on prevented accidents, and $190 on truck wash, the VorBlade vortex generators could save annually about $6,800 per semi truck.

### 2.4. How could VorBlade improve driving safety?

Driving safety and motor vehicle accidents are the areas that get considerable attention of government agencies and the transportation industry. The US DOT National Highway Traffic Safety Administration (NHTSA) and Federal Motor Carrier Safety Administration (FMCSA) publish annually hundreds of statistical documents, research reports and notes on the issues with special emphasis on heavy vehicles. Government-funded research has been going in national research laboratories and universities and the trucking industry has been carrying its own research.

This sub-section is focused on two causes of accidents, winds and driver fatigue. Statistics show that annually in average 500,000 accidents in the US involve large trucks. Wind was identified as the major cause in 32% of those or in 160,000 accidents,, and the driver fatigue was the major cause in 18% or in 90,000 accidents; e.g., Zaloshnja and Miller (2004, 2006), Truckinfo (2009), IIHS (2011), Dulaney *et al* (2012), NHTSA (2010), NCSA (2003), Liu and Subramanian (2009), Liu and Ye (2011). Therefore the VorBlade vortex generators could affect 50% of accidents with large trucks involved, or 250,000 accidents annually.

As illustrated qualitatively in Sections 1.2 and 1.3, wind generates aerodynamic forces and moments affecting the vehicle. Although longitudinal forces like the air drag affect fuel consumption, their effect on safety is not significant (an exception is the lack of power on steep hills which is considered below). In addition, the wind speed is typically much smaller than highway speed of a truck. The lift force may decrease driving stability for empty truck / trailer combination but its effect on a safety is not significant either. Really hazardous are side forces and yawing and rolling moments generated by cross winds.

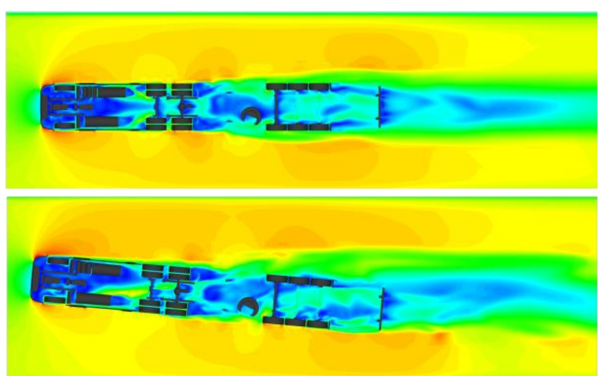


*Figure 2.4-1: Velocity magnitudes around semi truck at the yaw angles of zero (top) and 5 ° (bottom). The pictures are reproduced from Mu (2011).*

Figure 2.4-1 illustrates that, even at no cross winds, the large-scale shedding vortices create irregular side forces that lead to fish-tailing of trailer and tractor. At strong cross winds side forces and moments may lead to several dangerous effects including sideslip (also referred to as off-tracking), load transfer, jack-knifing, and roll over. Some of those instability effects are illustrated in Figures 2.4-2 and 2.4-3, and the effect severity depends on aerodynamic forces and moments acting on the vehicle at cross winds.

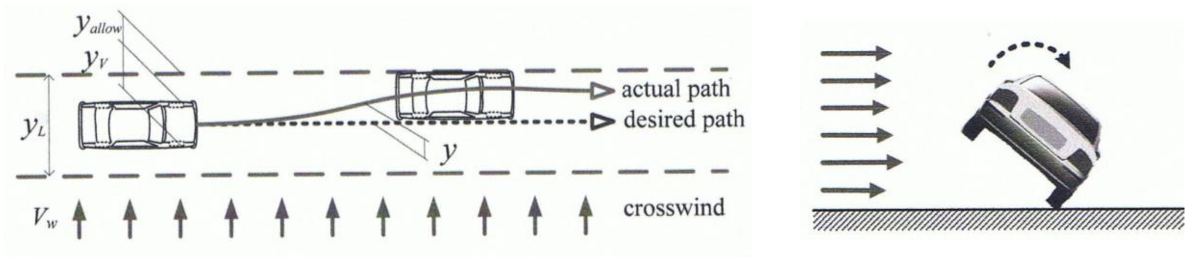



*Figure 2.4-2: Vehicle path and overturning under cross wind; reproduced from Kwon et al (2011).*

As outlined in Section 1.3, side forces are physically identical to a drag force and just act in the lateral direction. Therefore the finite volume technique and Equation (2.2) were applied for estimating the effect of VorBlade vortex generators on the side force and the yawing and rolling moments. It was found that the generators reduce the harmful force and moments in the range of highway speed from 45 mph to 85 mph and cross wind speed from 5 mph to 30 mph in average by about 39%.

This result can be applied to estimating the effect of VorBlade generators on the vehicle aerodynamic stability. Two techniques have been used for this purpose. The first one uses simple algebraic equations. The overturning force was assumed proportional to the square of the overturning wind velocity and the latter is given in Carr *et al* (1993) and Kwon *et al* (2011):

$$F_{over} \propto V_{over}^2 = \frac{2mg}{\rho A\left(C_L + 2R_{RM} l/t\right)} \qquad (2.3)$$

Here $l$ is the wheel base, $t$ is the mean wheel tread, $\rho$ is the air density, $A$ is the frontal projected area, $m$ is vehicle mass, $g$ is the gravity acceleration, $C_L$ is the lift coefficient and $C_{RM}$ is the rolling moment coefficient.

The sideslip was expressed by the following car accident index given in Kwon *et al* (2011) and Emmelman (1981):

$$C_F = \sqrt{\frac{1}{1 - 2y_{t=0.8} / y_{allow}}} - 1 \qquad (2.4)$$

Here $y_{t=0.8}$ is the lateral deviation of the vehicle under a crosswind after a time lapse of 0.8 seconds, $y_{allow}$ = $(y_L - y_V)/2$) is the lane margin, $y_L$ is the width of the traffic lane, $y_V$ is the width of the car; Figure 2.4-2. This equation uses an empirical fact that about 0.8 seconds is required for a vehicle to start recovering its path after wind action because of the dynamics of the steering system; e.g., Emmelman (1981).

The second technique used for the estimates was quite comprehensive although more complicated model for dynamic instability of tractor and trailer due to cross wind speed and gusts; Tremblay *et al* (2009). Decomposition of the trailer motion into translation and rotation and a few equations from the model are illustrated in Figure 2.4-3.

Thorough analysis with those two techniques included many empirical parameters to be specified and the most conservative values were always chosen. The analysis has shown that in average VorBlade vortex generators improve the vehicle aerodynamic stability by more than 50%.

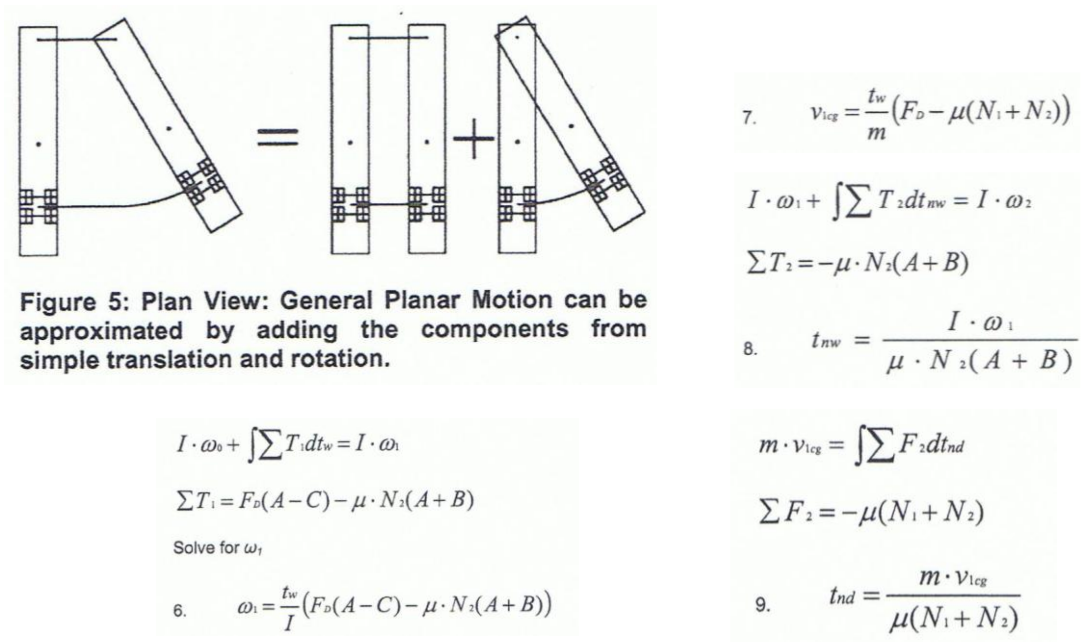



*Figure 2.4-3: The vehicle off-tracking and jack-knifing at cross winds and a few equations from the model. Reproduced from Tremblay et al (2009).*

The improved stability results in the increased driver comfort and reduced fatigue; the latter is considered below. The most important, stability directly affects the wind-related accidents. In particular, Equation (2.4) directly relates deviation of the vehicle to the accident rate. Effect of the improved stability on accident rates was analyzed using results from Kwon *et al* (2011), Tremblay *et al* (2009) and several comprehensive DOT reports; the reports by Winnicki and Eppinger (1998), NHTSA (2011), Sivinski (2011) and Wang (2011) were especially useful. Those reports provide methodological approaches to relating the vehicle stability to preventing accidents, injuries and fatalities.

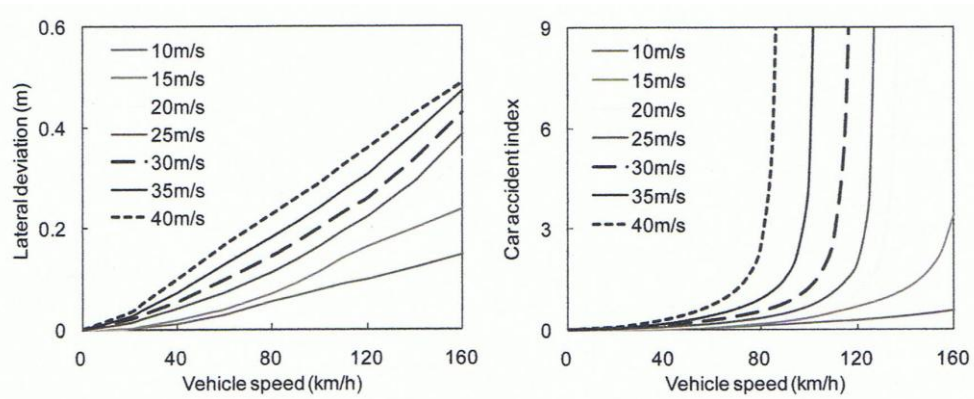



*Figure 2.4-4: Lateral deviations at cross winds varying from 10 m/s to 40 m/s and corresponding accident indices for large trucks at dry conditions; reproduced from Kwon et al (2011).*

Analysis has shown that the VorBlade vortex generators could reduce the rate of wind-related accidents involving heavy trucks by 20%. At 160,000 wind-related accidents annually, it means 32,000 prevented accidents. It is noteworthy that the analysis was executed assuming linear effect of stability on the probability of accidents which makes the 20% value highly conservative. In reality the effects of all hazardous impacts act highly non-linearly: after some threshold, a small increase in the impact dramatically increases the accident probability. The right plot in Figure 2.4-4 clearly illustrates this well-established fact.

Stress and fatigue effects on driving heavy motor vehicles have been intensively studied around the world. The current analysis was mainly based on the US DOT and Australian studies, e.g., FMCSA (2000), Dinges *et al* (2005), Haworth *et al* (1988), Haworth (1998) and references therein.

Haworrth (1998) presented simple and at the same time rigorous illustration of the fatigue accumulation reproduced in Figure 2.4-5. In this figure the fatigue is compared to the level of liquid in a container, and recovery is shown as the outflow from the container. Among fatigue-building factors, the VorBlade generators could reduce intensity of manual and mental work by improving the vehicle aerodynamic stability, especially at cross winds, and improve illumination by improving visibility (considered below).

The conducted theoretical analysis utilized available scientific results and expert analysis with experienced truck drivers as experts. The analysis has shown that the VorBlade vortex generators could reduce the driver fatigue in average by 15%. This conservative estimate was obtained by assuming linear dependence of fatigue on the causes. As shown in Haworth (1998) and references therein, the number of driving hours is the most important fatigue contributor. However, the fatigue is built very non-linearly during those hours. At the standard 10-hour workday, fatigue typically reaches the dangerous level at the last one – two hours. If one looks at Figure 2.4-5, one can imagine those hours as the last portions of a liquid that could overfill the container. When a weak non-linearity was incorporated into the analysis, the average VorBlade-induced reduction in the driver fatigue acceded 25%.

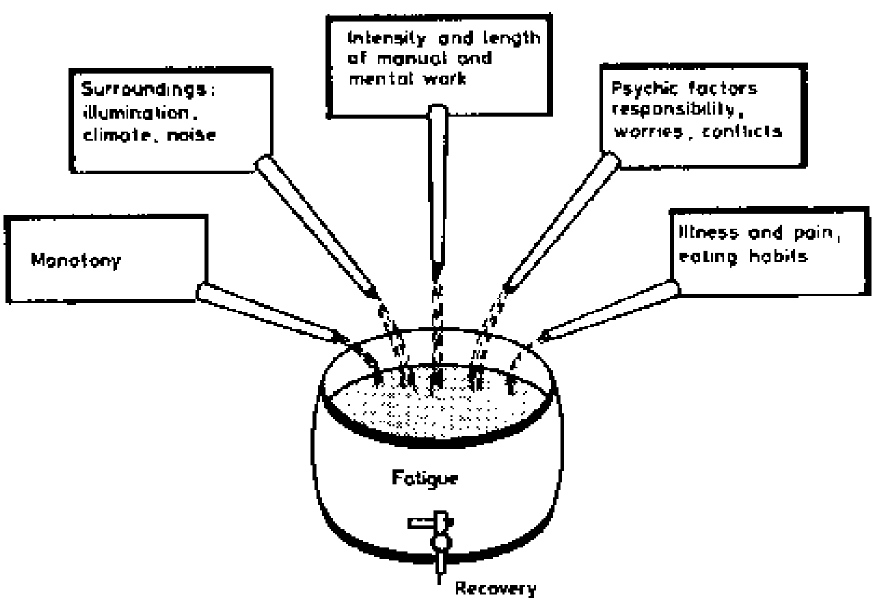



*Figure 2.4-5: Schematic representation of the cumulative effect of daily causes of fatigue; reproduced from Haworth (1998).*

An estimate of the reduction in the probability of fatigue-related accidents was based on the DOT methodologies and on the conservative assumption that VorBlade generators reduce fatigue by 15% at the first 8 hours of driving and by 25% during the last two hours.

The analysis has shown that VorBlade vortex generators could reduce the probability of fatigue-related accidents by 16%. At 90,000 fatigue-related accidents annually, it means more than 14,000 of prevented accidents with large trucks involved.

Therefore the VorBlade vortex generators could prevent annually 46,000 of the wind and fatigue-related accidents. At 500,000 accidents annually with heavy trucks involved, it means the conservatively estimated reduction in the average accident rate of 9.2%.

Statistics show that annually more than 5,500 people are killed and 122,000 are injured in large truck crashes in the United States; e.g., Zaloshnja and Miller (2004, 2006), Truckinfo (2009), IIHS (2011), Dulaney *et al* (2012), NHTSA (2010), NCSA (2003), Liu and Subramanian (2009), Liu and Ye (2011). Therefore, 9.2% reduction in the accident rate by the VorBlade vortex generators could result in preventing annually more than 500 fatalities and 11,000 injuries.

Statistics also show that an average cost of the accident involving large truck is about $84,500; e.g., Zaloshnja and Miller (2004, 2006), Dulaney *et al* (2012), NCSA (2003). Therefore 46,000 VorBlade prevented accidents could save annually about $3.9B nationwide.

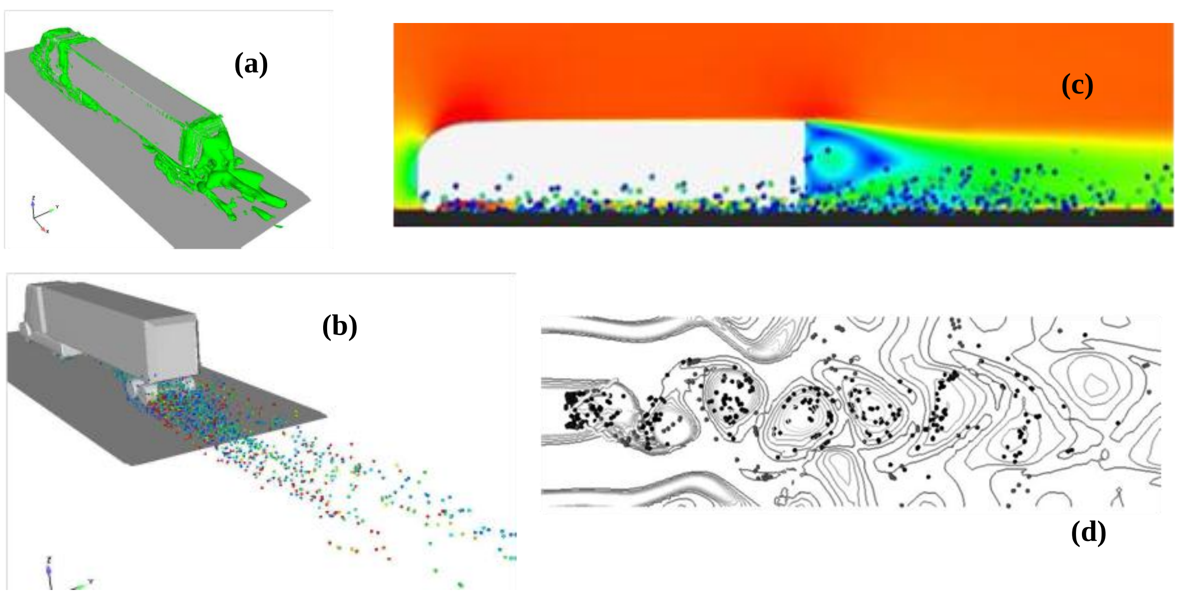



*Figure 2.4-6: Flow visualization of the instantaneous vortex structures (a) and spray (b) in the wake of GCM with base flaps. Flow visualization of the instantaneous velocity magnitude along centerline with spray for GTS (c), and (d) vorticity contours and particle positions. The plots are reproduced from Paschkewitz (2006a, 2006b).*

The effect of drag reduction devices on the mirror visibility and spray of particle by heavy vehicles was studied thoroughly in the DOE program and results are reported in DOE (2004) – (2008). More details on the studies can be found in the reports, e.g., Manser *et al* (2003), McCallen *et al* (2005), and Paschkewitz

(2006a, 2006b). Those reports provide accurate modeling of the dispersion behavior of sprays or particles around heavy vehicles.

In the DOE-funded studies by Paschkewitz (2006a, 2006b), the impact of aerodynamic drag reduction devices, specifically trailer-mounted base flaps, on the transport of spray in the vehicle wake was considered for the Generic Conventional Model (GCM) for the tractor / trailer combination using advanced numerical simulation techniques. Numerical simulations have shown that the maximum visibility reduction by the base flaps could reach 90%, which correlates well with the experimental data by Dumas and Lemay (2004). A few modeling results from the studies are illustrated in Figure 2.4-6.

The results of those and other studies were used for estimating the VorBlade effect on visibility and transport of particles. It was taken into account that the experimentally established lifespan of the VorBlade-induces vortices is about 10 ft and a typical length of the base flaps is about 2 ft.

The analysis has shown that in average VorBlade vortex generators could improve driver visibility by about 60%. This value is much smaller than reported 90% for base flaps although VorBlade provides much longer "fairing" than the flaps. The difference results from the highly conservative approach to estimating VorBlade benefits carried throughout the analysis. The VorBlade-improved visibility by 60% was incorporated into the analysis of the driver fatigue using the results of available studies of the effects of degraded visibility on the driving safety; e.g., Pronk *et al* (2001).

Analysis also shown that in average VorBlade vortex generators could reduce spray of dirt particles on rear surfaces of tractor and trailer by about 60%. The reduction in operating expenses due to VorBlade-reduced spray of dirt was considered in Section 2.3.

The effect of VorBlade generators on blown tires was estimated with the methodology in Figure 2.3-5. Similarly to the analysis in Section 2.3, the considered loads on tractor and trailer tires included reductions in the frictional power, cross wind-forced misalignment and sideslip. The difference from the estimates in the previous section was that the non-linear effects were taken into account. It was assumed that the probability of tire to be blown increases with its wear. When the tire is close to being replaced, even small "jump" in the load could force its blow. As before, the empirical parameters to be specified were chosen in a conservative way.

The analysis has shown that VorBlade vortex generators could reduce the risk of blown tire by about 20%. This VorBlade effect obviously increases the driving safety although it was not included in the safety improvement estimates. The reason is that we were unable to find appropriate methodologies, scientific results, or data for quantitative characterization of the impact of blown tires on driving safety.

The VorBlade-provided air drag reduction increases the effective truck power on steep uphill roadways. This effect was analyzed using a simple mechanical model of a vehicle going at 60 mph on a road with the 6° grade which one can often encounter in Colorado, Wyoming and other mountainous states. It was assumed that an engine is working near its power limit and the drag reduction was related to the reduction in the power required to maintain the speed. The latter was interpreted as the "increase in the effective truck power". All empirical parameters to be specified were chosen in a conservative way.

The analysis has shown that in average VorBlade vortex generators could increase the effective truck power on steep uphill roadways by about 3.5%. This effect certainly increases driver comfort and could also affect the driving safety but it was not included in the safety improvement estimates either. Similar to the case of blown tires, we were unable to find appropriate methodologies, scientific results, or data for quantitative characterization of the impact of increased power on the driving safety.

### 2.5. How could VorBlade fight cross winds?

VorBlade vortex generators are the only commercially available aerodynamic devices which could significantly mitigate detrimental effects of cross winds. Different impacts of the generators on the cross winds effects were considered above separately and they are combined below.

As outlined in Section 1.3, the laterally directed airflow generates about 25 times larger side force on a modern class 8 truck than the longitudinally directed airflow with the same speed would generate the drag force. This high vehicle sensitivity to winds from the side dramatically multiplies detrimental effects of cross winds on heavy trucks. At the highway speed of 60 mph, the average cross wind of 5.8 mph increases the total air drag of class 8 truck by about 23% and the total fuel consumption by about 8.5%.

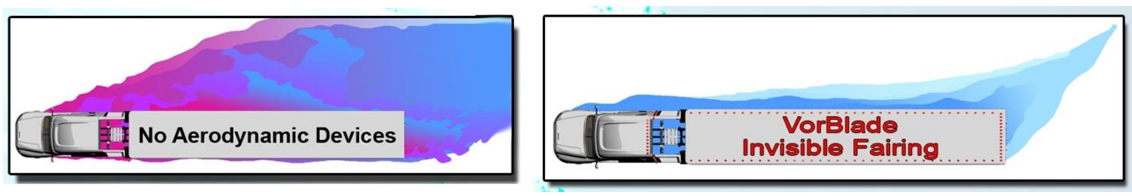



*Figure 2.5-1: Schematic illustration of the VorBlade impact on the air wake in the leeside of heavy vehicle at cross winds.*

There are two major physical reasons for such powerful impact of a cross wind: the increase in the volume of the air wake and intensification of the harmful large-scale turbulent vortices. As explained in Section 2.2, VorBlade vortex generators mitigate effectively both those impacts which is schematically illustrated in Figure 2.5-1. The generators target three problem areas responsible for 53% of the total vehicle air drag: the tractor / trailer gap, the trailer roof edges and the trailer rear end. VorBlade could significantly reduce operational expenses and improve driving safety of heavy vehicles.

An example of the VorBlade effects on the cross wind is noteworthy. As shown in Section 2.3, VorBlade could reduce the cross wind-induced fuel consumption by more than 55%. A strong cross wind of 30 mph happens quite often in Wyoming, Colorado, Kansas and some other states. At a typical highway speed of 60 mph, such wind increases air wake volume about 2.4 times increasing the trailer air drag by about 2.1 times, the air drag-related fuel consumption by about 30%, the fuel consumption due to the tire misalignment by about 15%, and the total fuel consumption by about 45%. If a driver stays on the road for 10 hours per day, he/ she cover about 600 miles. If there were no cross wind, a driver would spend 109 gallons of fuel on those 660 miles at an average fuel consumption of 5.5 mpg. Cross wind would “cost” additional 49 gallons or $196, and from that VorBlade could save $108 just per one windy day.

VorBlade could reduce loads on the tractor and trailer tires at cross winds by reducing the frictional force, misalignment and sideslip and extend tire life by 6% or more.

As shown in Section 2.4, VorBlade vortex generators could improve the vehicle aerodynamic stability more than 50% and reduce the rate of wind-related accidents involving heavy trucks by 20%.

The generators could reduce the driver fatigue in average by 15% and by about 25% after about 8 driving hours, and reduce the probability of fatigue-related accidents by 16%.

VorBlade vortex generators could prevent annually 46,000 of the wind and fatigue-related accidents which could results in preventing annually more than 500 fatalities and 11,000 injuries.

Preventing annually 46,000 of the wind and fatigue-related accidents, VorBlade could reduce the average accident rate by 9.2% and save nationwide about $3.9B in costs of those accidents.

Those are the most important individual impacts of VorBlade vortex generators on harmful effects of cross winds hence the cumulative effect is worth of the analysis.

The analysis was performed using a modification of the standard methodology typically used for estimating weighted effectiveness of a technology; e.g., the NHTSA DOT research note by Wang (2011):

$$E_{VB} = \sum_{i=1}^{n} w_i a_i e_i \Big/ \sum_{i=1}^{n} w_i \tag{2.5}$$

Here $E_{VB}$ is the accumulated VorBlade effectiveness in reducing harmful cross wind effects, $n$ is the number of individual impacts, $e_i$ is the individual effectiveness of the $i$-th impact, $a_i$ is the relative effect of the impact on the vehicle operations, and $w_i$ is the weight of the impact. Wang (2011) applied Equation (2.5) at $a_i = 1$ to describe the weighted average effectiveness. To estimate the accumulated effect, the relative effects $a_i \neq 1$ were applied together with the weights $w_i$ to compile properly the most important impacts like drag reduction and stability improvement with less significant ones like reduced truck wash expenses.

The analysis has shown that in average the VorBlade vortex generators reduce detrimental effects of cross winds on large trucks by more than 60%. The value of 60% is the conservative estimate because all individual effects $e_i$ in Equation (2.5) were estimated quite conservatively.

### 2.6. How could VorBlade help environment?

Analysis of statistical information shows that an average class 8 semi truck spends about 17,000 gallons of diesel fuel per year and an average single truck spends about 2,000 gallon annually; e.g., FHA (1997), Kenworth (2008), and DOE (2011). In 2010 there were about 2.7 million semi trucks and 8.6 million single trucks on the US roads; e.g., DOE (2011). It means that nationwide semi trucks consume annually about 45.9 billion gallons of diesel fuel and single trucks consume about 17.2 billion gallons. Altogether it accounts for about 63.1 billion gallons of annual diesel fuel consumption by heavy trucks nationwide.

The VorBlade vortex generators could save in average 8.3% of that fuel which means that the generators could save nationwide up to 5.2 billion of diesel fuel per year.

It is well known that about 22.4 pounds of carbon dioxide ($CO_2$) is produced when a gallon of diesel fuel is burned; e.g., DSEWPC (2008) and EIA (2011). It might seem peculiar that the weight of emission is almost three times larger than the weight of burned fuel. An explanation is however quite simple: two molecules of oxygen $O_2$ from the atmosphere are added to each molecule C of burned carbon. That explanation is frightening as well. It emphasizes that fuel combustion takes from the atmosphere pure oxygen $O_2$, the “gas of life”, and produces carbon dioxide $CO_2$, the greenhouse gas linked to a global climate change. 63.1 billion gallons of consumed diesel fuel means that 1,706 billion pounds or 706 million tons of $CO_2$ is exhausted annually by heavy trucks nationwide.

The VorBlade vortex generators could reduce this amount by 8.3%, or reduce the annual $CO_2$ emission by about 59 million tons. To get a “feeling” for that number, one may recall that one acre of forest absorbs six tons of carbon dioxide per year according to the U.S. Department of Agriculture; e.g., Shelby Farms Park (2012) and DEP (2011). Therefore, the annual reduction in the $CO_2$ emission of 59 million tons is equivalent to planting about 10 million acres, or about 15,200 sq miles of new forest.

One can have another look at 15,200 sq miles of forest from Table 2.1 that was compiled from statistical data in Netstate (2012) and Wikipedia (2012d).

| State | Total area, sq miles | Forest cover, % | Forest cover, sq miles |
|---|---|---|---|
| Illinois | 57,918 | 11.5 | 6,661 |
| Indiana | 36,420 | 18.9 | 6,883 |
| Maryland | 12,407 | 37.9 | 4,702 |
| Vermont | 9,615 | 75.7 | 7,279 |
| New Hampshire | 9,351 | 78.4 | 7,332 |

*Table 2.1: Forest cover in several states*

The table shows that the annual reduction in $CO_2$ emission by VorBlade vortex generators of 59 million could exceed the amount of $CO_2$ absorbed by forests in several states. Indeed, it is almost as much reduction as is absorbed by the forest cover in Illinois, Indiana and Maryland altogether.

Reduction in spills of hazardous substances is another positive impact of VorBlade generators on the environment. Analysis of statistical data shows that in average about 15 gallons of oil, Freon, and other substances are spilled from a truck and other vehicles in a typical accident involving a heavy truck; e.g., ATSDR (1999) and Etkin (1999). Crashes of oil and gasoline tankers and alike are quite rear and not included in that conservative value.

VorBlade vortex generators could prevent accidental spill of about 690,000 gallons of hazardous substances annually by preventing about 46,000 accidents nationwide.

## 3. VorBlade Road Tests and Technical Specification

The VorBlade road tests report and an overview of the VorBlade technical specifications are presented in this section. Avantechs, Inc. does not endorse, certify or advertise utilized articles; the names of manufacturers and products are presented just for identifying the test items.

### 3.1. How was VorBlade Tested on the Roads?

Theoretical estimate for about 8.3% average fuel saving for class 8 semi trucks by VorBlade vortex generators is a good indicator of their high efficiency, but it is no more than the indicator. Reliable estimate may only be obtained in road tests that are representative of actual vehicle operations. The actual fuel saving by VorBlade vortex generators have been tested on a typical class 8 semi truck and the results are presented below.

The SAE Surface Vehicle Recommended Practice J1321 (SAE, 1986) and the EPA Modifications to SAE J1321 (EPA, 2011) were used as the guidance for the test. TRC (2004) and Surcel (2008) reports were very useful in executing the test and presenting the results.

*Description of the test*

Two similar Freightliner Cascadia tractors were used for the test; the details are given in Table 3.1. The tractors were equipped with modern fuel-saving features including high roof fairing, side cab extender fairings, and aerodynamic profile as seen in Figures 3.1-1 and 3.1-2.


*Figure 3.1-1: The control vehicle on the weigh scales at the Tomahawk Auto & Truck plaza*

Two identical Wabash van trailers with no payload were used for the test; see Table 3.2 for details. Both trailers were equipped with the DuraPlate AeroSkirt fuel saving devices; see Figures 3.1-1 and 3.1-2.


*Figure 3.1-2: The test vehicle with VorBlade vortex generators installed on the rear edges of a tractor and a trailer and on the side edges of a trailer roof*

| | Control Tractor | Test Tractor |
|---|---|---|
| Unit # | Ryder 602838 | Ryder 470651 |
| Make | FREIGHTLINER | FREIGHTLINER |
| Model | PX12564ST CASCADIA | PX12564ST CASCADIA |
| V.I.N. | 1FUJGLDR4CSBE5813 | 1FUJGLBG4CSBV7997 |
| Year | 2012 | 2012 |
| Start odometer | 89678.9 | 2402.1 |
| Engine make and model | Detroit DD15 | Cummins ISX10 |
| Rated power, hp | 488 | 450 |
| Transmission | Fuller PRO-15210C | Fuller PRO-15210C |
| Drive axle ratio | 3.36 | 3.55 |
| Tires | Bridgestone 295/75R22.5 | Bridgestone 295/75R22.5 |
| Tire pressure (cold), psi | 110 | 110 |
| Test weight with trailer, lb | 33820 | 34160 |

*Table 3.1: The tractor data*

The tractors and trailers were randomly paired as the test and control vehicles for the duration of the test referred to as the vehicles "T" and "C", respectively. The only re-pairing was made for the independent last test run as described below.

| | Control Trailer | Test Trailer |
|---|---|---|
| Unit # | Xtra Lease U98013 | Xtra Lease U97857 |
| Make | Wabash | Wabash |
| Model | TRA/REM VAN DVCVHPC | TRA/REM VAN DVCVHPC |
| V.I.N. | 1JJV532D8CL741869 | 1JJV532D7CL738199 |
| Year | 2012 | 2012 |
| Height, ft | 13½ | 13½ |
| Length, ft | 53 | 53 |
| Tires (make/ model/ type/ size) | GoodYear 295/75R22.5 | GoodYear 295/75R22.5 |
| Tire pressure, psi | 100 | 100 |
| Skirts | DuraPlate AeroSkirt | DuraPlate AeroSkirt |
| Gap from the back of cab to front of trailer, inches | 49 | 49 |

*Table 3.2: The trailer data*

Two experienced and unbiased drivers were chosen to operate the vehicles. One driver was randomly prescribed to operate the test vehicle and another one the control vehicle throughout the entire test.

The test consisted of the baseline segment without VorBlade generators and the test segment with the generators mounted on the test tractor and trailer, and each segment consisted of three test runs. One more test run was made with the generators mounted on the test tractor only.

The same circular route with the distance of 114.1 miles was used for all runs. It started at the Tomahawk Auto & Truck plaza in Watkins, Colorado. From that location the test and control vehicles entered highway I-70 at the mile marker 295 and headed east to the I-70 mile marker 352. There the vehicles turned around on the overpass and returned to the starting location; the Google maps of the route are given in Figure 3.1-3.

The tests were performed from March 2 to March 4, 2012. Before the first baseline run on March 2, the vehicles were weighed at the truck weigh station at the Tomahawk plaza and the trailer doors were sealed for the rest of the test. The gross combination weights of tractors with trailers are given in Table 3.1 and the control vehicle on the scales is illustrated in Figure 3.1-1. Each test day, just before the warm-up driving began, all truck tires were set to specified pressures, mirrors were adjusted to a consistent position between the two tractors, headlights were turned on and switched to low beam, heater blowers were set at medium speed, and other switchable electrical loads were turned off. The trucks were warmed up every day by being driving for about one hour at the average speed of about 50 mph.


*Figure 3.1-3: The Google maps of the driving route for the road test runs. The vehicles start in the Tomahawk Auto & Truck plaza in Watkins, CO (location A in the left maps), enter highway I-70, head east to the I-70 mile marker 352, turn around on the overpass (location B in the top maps), and return to the Tomahawk plaza (location C in the right bottom map is the same as location A).*

After the warm-up, the test truck was driven to the starting point at the fuel pump #10 at the Tomahawk Auto & Truck plaza. Its engine was stopped and the fuel tank was filled to the top. The engine of the test tractor was started, the vehicle was moved about 50 yards and stopped there with the idling engine. The control truck was driven to the same pump, its engine stopped and the fuel tank was filled to the top. The odometer readings for both trucks were recorded at the pump during the fueling. The control truck engine was started after the fueling and idled for about 30 sec. After that interval the test truck started the test route and the control truck followed about 30 sec. later; the start times were recorded.

Once on I-70, the cruise control of the leading test vehicle was set to the driving speed of about 60 mph unless road conditions dictated the lower speed. The control vehicle followed the test vehicle on the cruise control at a separation of approximately half-mile which excluded any interference between the vehicles. At the end of each run, the test vehicle returned to the same pump #10 at the Tomahawk plaza, its engine stopped and time and odometer readings recorded. Its fuel tank was filled to the top and the volume of fuel consumed during the run was recorded. After the re-fueling, the test vehicle was moved about 50 yards and its engine was stopped. The control truck was driven to the same pump, its engine stopped, the fuel tank filled to the top and time and odometer readings recorded. It was then moved next to the test truck and its engine was stopped.

After the drivers took a short break, the engine of the test truck was started and idled for about 5 min. corresponding to the time of re-fueling. Then the engine of the control vehicle was started and idled for about 30 sec. After that interval the standard test run routine was repeated: the test truck started the route and the control truck followed it about 30 sec. later; the start times were recorded.

The Shell D2 diesel fuel oil was used during the tests. The fuel meets all applicable ASTM standards for motor fuel and is routinely used by class 8 trucks in actual operations. The fuel pumps at the Tomahawk Auto & Truck plaza are regularly calibrated to maintain the measurement accuracy of ±0.3% specified by the National Institute of Standards and Technology (NIST). The use of the same pump and practically simultaneous fueling of the test and control vehicles eliminate an ambiguity related to variations in the fuel density and air temperature during the runs.

The driving times for the test and control vehicles were the same within one minute accuracy in all test runs. For this reason only one time for the test vehicle is presented in the test schedules; Tables 3.3 and 3.5. There were however small discrepancies in the odometer reading between two vehicles. According to the control vehicle odometer, the test route distance varied from 114.2 miles to 114.6 miles and that of the test vehicle varied from 113.7 miles to 113.9 miles over three baseline and three test runs. To eliminate the errors due to differences in the odometer calibration, the same average route distance of 114.1 miles was used for both vehicles in the analysis of collected data.

| Run | Date | Start time | End time | Average speed, mph | Pavement; weather, temperature and wind |
|---|---|---|---|---|---|
| #1 | 3/2/2012 | 18:03 | 20:07 | 55.2 | Wet; overcast, light snow, 21°F, SW 4.6 mph |
| #2 | 3/2/2012 | 20:41 | 22:48 | 53.9 | Wet; overcast, light snow, 18°F, SW 5.1 mph |
| #3 | 3/3/2012 | 11:09 | 13:02 | 60.6 | Dry; sunny, 40°F, W 15.4 mph, gusts 25 mph |

*Table 3.3: Schedule for the baseline segment*

The road and weather conditions were observed and recorded during the runs. The air temperature, wind speed and direction presented in Tables 3.3 and 3.5 were obtained by averaging observation data from two NOAA weather stations: the Buckley Air Force Base airport station in Aurora that is close to the

Tomahawk Auto & Truck plaza (A and C on the maps in Figure 3.1-3) and the Limon Municipal airport station that is close to the turnaround location B on the maps.

It was intended to maintain the constant highway speed of 60 mph throughout the tests. However the actual speed varied depending on the road and weather conditions which is typical for actual vehicle operations on highways. The average speed for each run is presented in Tables 3.3 and 3.5.

The baseline segment was executed during two days, March 2 and 3, 2012; detailed schedule is given in Table 3.3. The first two runs on March 2 were driven in the dark at the occasional light snow and on a wet pavement. Although the average speed in those runs was below intended 60 mph, it was more appropriate for those driving conditions and better corresponded to actual vehicle operations. The third baseline run was driven on March 3 in better conditions and the average speed was close to 60 mph.

| Run | Consumed fuel (gal): vehicle "C" | Consumed fuel (gal): vehicle "T" | T/C ratio | Fuel efficiency (mpg): vehicle "C" | Fuel efficiency (mpg): vehicle "T" |
|---|---|---|---|---|---|
| #1 | 11.488 | 12.338 | 1.074 | 9.931 | 9.248 |
| #2 | 11.864 | 12.462 | 1.050 | 9.617 | 9.156 |
| #3 | 12.712 | 13.755 | 1.082 | 8.976 | 8.295 |
| Average values over the baseline runs | | | 1.069 | 9.508 | 8.900 |

*Table 3.4: Results for baseline segment – T/C calculation*

Test results for the baseline segment are summarized in Table 3.4. Following the Recommended Practice J1321 (SAE, 1986), the T/C ratio was estimated for each run. It is defined as the ratio of consumed fuel by the test vehicle to that by the control vehicle. The fuel efficiencies in mpg for each vehicle are presented for the completeness.

It shall be emphasized that the tractors and trailers were paired for the entire test although neither was designated as the test or the control ones before the baseline segment was completed. The reason can be seen in the last two columns of Table 3.4: the average fuel efficiencies of two vehicles differed by 6.4%. The vehicle with the worse fuel efficiency of 8.90 mpg was designated as the test one, and the vehicle with the better fuel efficiency of 9.51 mpg was designated as the control one. Such procedure ensured conservative experimental results for the fuel saving by VorBlade.

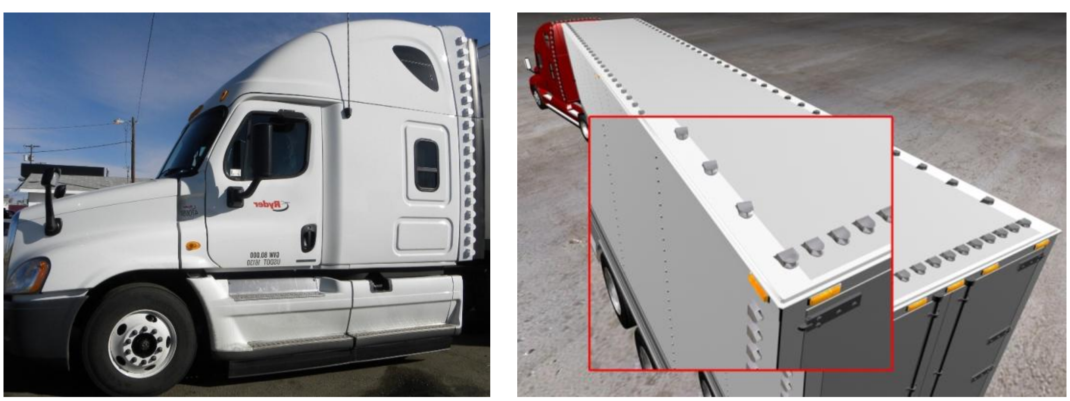


*Figure 3.1-4: Closer look at VorBlade vortex generators on a driver side of the test tractor and on the trailer roof*

After the choice was made, the entire set of VorBlade vortex generators was mounted on the test vehicle as illustrated in Figure 3.1-2 and 3.1-4. 48 units were installed on the tractor rear edges with 2½ inches separation between the units: 12 units on the roof fairing and 18 units on each side fairing. 54 units were installed on the trailer rear edges with separation of 2½ inches between the units: 18 units on the roof and 18 units on each side wall. 84 units were installed on the trailer roof sides, 42 units on each side. Those were installed at the angle of 17° to the vehicle travel direction and separation between the units of 14¾ inches. The generators were glued to the vehicle surfaces by the double-sided adhesive tape at the afternoon of March 3 and the glue was left to harden until the next day.

| Run | Date | Start time | End time | Average speed, mph | Pavement; weather, temperature and wind |
|---|---|---|---|---|---|
| #1 | 3/4/2012 | 10:36 | 12:31 | 59.5 | Dry; sunny, 55°F, NW 14.4 mph, gusts 24 mph |
| #2 | 3/4/2012 | 13:12 | 15:05 | 60.6 | Dry; sunny, 58°F, NW 12.7 mph, gusts 22 mph |
| #3 | 3/4/2012 | 15:44 | 17:38 | 60.1 | Dry; sunny, 51°F, N 5.0 mph |
| #4 | 3/4/2012 | 18:35 | 20:28 | 60.6 | Dry; clear, 43°F, N 5.4 mph |

*Table 3.5: Schedule for the test segment*

The test segment was executed on March 4, 2012; detailed schedule is given in Table 3.5. The segment consisted of runs #1, #2 and #3; an independent run #4 is described below. All runs were driven on dry pavement and good visibility and the average speed was close to intended 60 mph.

Results for the test segment are summarized in Table 3.6. According to the Recommended Practice J1321 (SAE, 1986), the percent of fuel saved was estimated using the average T/C ratios for the baseline and the test segments as follows:

$$Percent\ Fuel\ Saved = \frac{Average\, baseline\, T/C - Average\, test\, T/C}{Average\, baseline\, T/C} \times 100\% \qquad (3.1)$$

Using Equation (3.1) and experimental data for the T/C ratios from Tables 3.4 and 3.6, the percent of fuel saved by VorBlade vortex generators in the road tests was found to be 10.76%.

| Run | Consumed fuel (gal): vehicle "C" | Consumed fuel (gal): vehicle "T" | T/C ratio | Fuel efficiency (mpg): vehicle "C" | Fuel efficiency (mpg): vehicle "T" |
|---|---|---|---|---|---|
| #1 | 12.627 | 11.848 | 0.938 | 9.036 | 9.631 |
| #2 | 12.320 | 11.607 | 0.942 | 9.261 | 9.830 |
| #3 | 11.909 | 11.680 | 0.981 | 9.581 | 9.769 |
| Average values over the test runs #1, #2 and #3 | | | 0.954 | 9.293 | 9.743 |
| #4 | - | 12.159 | - | - | 9.384 |

*Table 3.6: Results for test segment – T/C calculation*

To estimate improvement in the fuel efficiency *IFA*, J1321 Test Procedure (SAE, 1986) recommends the following equation based on the representative efficiency for the control vehicle *Control MPG*:

$$IFA = \frac{Control\,MPG}{Average\,test\,T\,/\,C} - \frac{Control\,MPG}{Average\,baseline\,T\,/\,C} \tag{3.2}$$

The improvement in the fuel efficiency by VorBlade vortex generators of 1.059 mpg was obtained with Equation (3.2). The average fuel efficiency of 9.40 mpg over all runs for the control vehicle was used as the *Control MPG* value together with the T/C ratios from tables 3.4 and 3.6.

The test run #4 was aimed at estimating the fuel saving by VorBlade generators installed on a tractor only. For this purpose the control trailer without the generators was hooked up to the test tractor with the generators and this vehicle combination was driven over the same test route. The measured fuel consumption during the run is presented in Table 3.6. To get the T/C ratio, the fuel consumed by the control vehicle in the test run #3 was chosen as the control data point. One can see in Table 3.5 that the test runs #3 and #4 were executed at similar road and weather conditions which substantiates the choice. In addition, the fuel consumption of 11.909 in the run #3 was the smallest one among all runs of the control vehicle which ensures a conservative estimate of fuel savings. It gives the test T/C ratio of 1.021 which, according to Equations (3.1) and (3.2), corresponds to the fuel saving of 4.49% and the improvement in fuel efficiency of 0.413 mpg by VorBlade vortex generators mounted on the tractor only.

*Analysis of the test results*

The road tests were performed in light and moderate winds which allow estimating the VorBlade efficiency at cross winds. One can see in Table 3.3 that baseline runs #1 and #2 were executed at light winds of about 5 mph. The average fuel consumptions over those runs of 11.676 gal and 12.400 gal (Table 3.4) can be considered as the baseline values at light winds for the control and test vehicles, respectively. The fuel consumptions for run #3 of 12.712 gal and 13.755 gal may be considered as the baseline values at moderate winds of about 15 mph with gusts up to 25 mph for the control and test vehicles, respectively. It gives the respective baseline T/C ratios of 1.062 and 1.082 for light and moderate gusty winds.

The test runs could be similarly separated into #1 and #2 at moderate gusty winds and #3 at light winds (Tables 3.5 and 3.6) and the respective test T/C ratios of 0.940 and 0.981 can be obtained. Using Equation (3.1), one can get the fuel savings by the entire set of VorBlade vortex generators of 7.63% and 13.12% at light and moderate gusty winds, respectively. Those values confirm that VorBlade efficiency increases significantly at stronger winds.

Separating all performed runs into those at light and moderate gusty winds, one can estimate the increase in the vehicle fuel consumption due to increased winds. It can be done using experimental data for all runs without VorBlade generators. The fuel consumption values for the baseline and test runs of the control vehicle and the baseline runs of the test vehicle provided the increase of 10.1%.

Using that value, one can presume that in moderate gusty winds a vehicle spends about 110.1 gallons of fuel instead of 100 gallons that would be spent on the same driving distance at light winds. The VorBlade fuel saving at light winds of 7.63% means that it would save 8.40 gallons from 110.1 gallons and the fuel saving at moderate gusty winds of 13.12% means saving of 14.45 gallons. Those additionally saved 6.05 gallons or 60.0% from the 10.1 gallons represent the pure VorBlade reduction in the wind-increased fuel consumption.

It should also be noted that the driver of the test vehicle detected significant improvement of the vehicle aerodynamic stability by VorBlade generators when compared three runs at moderate gusty winds, the baseline run #3 without VorBlade and the test runs #1 and #2 with the generators.

Therefore the performed road tests have shown the average fuel saving by the entire set of VorBlade vortex generators of about 10.8% and about 4.5% for the generators on the tractor only, and the respective improvements in a fuel efficiency of 1.059 mpg and 0.413 mpg. The tests have also shown that at moderate gusty winds the fuel saving increases to 13.1% and reduction in wind-induced fuel consumption reaches 60%. However those values were obtained for empty trailers and they need to be re-evaluated for the trailer loads typical for actual highway operations.

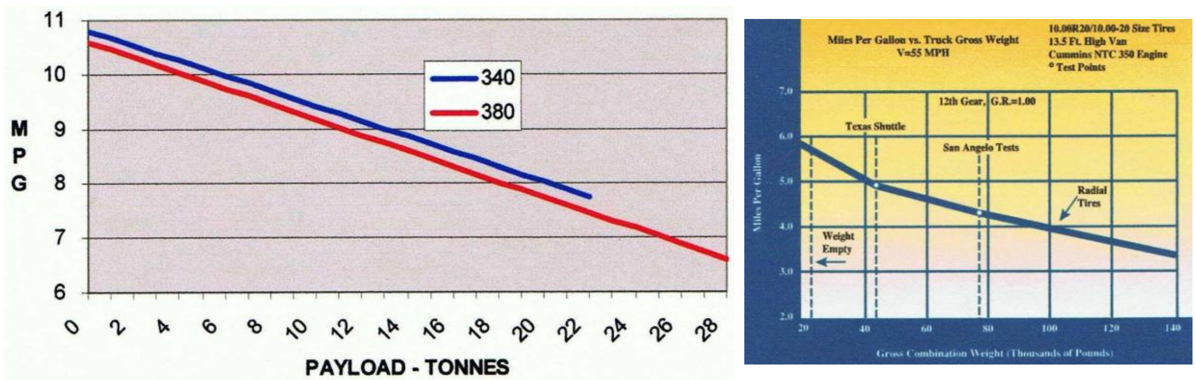



*Figure 3.1-5: Left - Regression lines for 340 and 380 Volvo FM12 tractors with the trailers of variable payload from Coyle (2007); right – Good Year Testing Data reproduced from Good Year (2008)*

Results of the rigorous and comprehensive study of the effect of payload on the fuel consumption for heavy cargo trucks by Coyle (2007) were used for that task. Coyle (2007) has tested the Volvo FM12 aerodynamically enhanced tractors with 340 and 380 horse power engines and standard 53 ft trailers over a broad range of the payload from zero (empty trailers) to 28 tonnes (tonne is the metric ton equal to 2,240 lb). The weights for empty 340 and 380 tractor / trailer combinations were respectively 34,400 lb and 36,400 lb which is close to the empty weight of the vehicles in Table 3.1. The fuel efficiency for empty trucks of about 10.7 mpg was also close to that in Tables 3.4 and 3.6 hence the results by Coyle (2007) can be safely applied for re-evaluating the performed road test.

Summary of the Coyle (2007) results for semi trucks is reproduced in Figure 3.1-5. It was found in the study that the linear regression model has an exceptionally high accuracy which means that the fuel efficiency $E$ in mpg decreases linearly with the payload in tonnes as:

$$E_G = E_0 - \Delta E_G, \quad \Delta E_G = \delta_G G \tag{3.3}$$

Hereafter the subscripts "*0*" and "*G*" denote the empty trailer and that with the payload $G$, and $\delta_G$ is the gradient of the regression curve in mpg/tonne. The percent of fuel saved $\varepsilon_0$ and $\varepsilon_G$ for empty and loaded trailers can be expressed as:

$$\varepsilon_0 = \frac{\Delta C_0}{C_0} \times 100\%, \quad \varepsilon_G = \frac{\Delta C_G}{C_G} \times 100\%, \quad C_0 = \frac{L}{E_0}, \quad C_G = \frac{L}{E_G} \tag{3.4}$$

Here $C_0$ and $C_G$ are the volumes of fuel in gallons that would be spend without fuel-saving devices by the empty and loaded trucks on the same driving distance $L$, and $\Delta C_0$ and $\Delta C_G$ are the fuel volumes in gallons that are saved by the devices on the empty and loaded trucks. To evaluate the percent of fuel saved $\varepsilon_G$ for loaded trailers from the values of $\varepsilon_0$ measured in the road tests for empty trailers, it was assumed that $\Delta C_G = \Delta C_0$. This conservative assumption implies that the air drag does not increase with the payload and neither is the amount of fuel $\Delta C$ saved by VorBlade generators. In this case one can obtain from Equations (3.3) and (3.4) the following expressions:

$$\varepsilon_G = \frac{\Delta C_0}{C_G} 100\% = \varepsilon_0 \frac{C_0}{C_G} = \varepsilon_0 \left(1 - \frac{\Delta E_G}{E_0}\right) = \varepsilon_0 \left(1 - \frac{\delta_G G}{E_0}\right) \tag{3.5}$$

Equation (3.5) relates percent of fuel saved by VorBlade for an empty truck $\varepsilon_0$ to the percent $\varepsilon_G$ for a trailer with a payload $G$. An average payload for class 8 cargo transportation trucks on highways is about 30,000 lb and this value was used as $G$ for evaluating the VorBlade effect on the fuel consumption for loaded trailers. According to Coyle (2007) results, the fuel efficiency $\Delta E_G$ / $E_0$ reduces at $G$ = 30,000 lb by 0.172 and 0.181 (or 17.2% and 18.1%) for 340 and 380 trucks, respectively.

Good Year (2008) presented testing data for a truck with a fuel efficiency of about 5.3 mpg for the gross combination weight (GCW) of about 35,000 lb; Figure 3.1-5. The data also show approximately linear reduction in the fuel efficiency with the payload and provide a value $\Delta E_G / E_0 \approx 0.205$ (or 20.5%) for the payload of about 30,000 lb corresponding to GCW of about 65,000 lb. To get the most conservative estimates, the average reduction value of 18.6% was used for re-evaluating the results.

Using Equation (3.5) at $\Delta E_G / E_0 = 0.186$, one can obtain that the average fuel saving by the entire set of VorBlade vortex generators on the tractor and trailer (Figure 3.1-2) decreases from 10.76% to 8.76% and that for the generators on the tractor only (as in Figure 3.1-2 left) decreases from 4.49% to 3.65% when trucks with empty trailers are loaded to the GCW of about 65,000 lb. The respective improvements in fuel efficiency for the entire set of generators and generators on the tractor only decrease from 1.059 mpg and 0.413 mpg for empty trailers to 0.862 mpg and 0.336 mpg at the payload of 30,000 lb.

Using Equation (3.5) at $\Delta E_G / E_0 = 0.186$, one can further obtain that the 30,000 lb payload decreases the fuel saving by the entire set of VorBlade vortex generators at moderate gusty winds from 13.12% to about 10.68% and a reduction in wind-induced fuel consumption from 60% to 49%.

Results of the performed road tests are in good agreement with theoretical estimates in Section 2.3. The fuel savings for loaded trucks of about 8.8% by the entire set of VorBlade generators and about 3.7% by the generators on the tractor only are slightly higher than 8.3% and 3.5% theoretical estimates based on the most conservative value of 23% for the air drag-related fuel expenditure. At the same time the road test-produced values are lower than theoretical estimates of 12.8% and 5.4% based on 36% value for the expenditure which is reported in many studies. At moderate gusty winds VorBlade generators saved about 49% from the wind-induced increase in the fuel consumption which also agrees well with the theoretical estimates of up to 55% saving at cross winds.

*Conclusions*

The analysis of collected data in the performed road tests allows concluding that VorBlade vortex generators are highly effective aerodynamic devices for reducing fuel consumption for class 8 cargo trucks. The tests were representative of actual operations at the average highway speed of about 60 mph and the presented results correspond to a typical gross combination weight of about 65,000 lb. The tests covered light winds and moderate gusty winds and the produced results for average fuel savings are in good agreement with theoretical estimates.

The tests have shown 8.76% in the average fuel saving by the entire set of VorBlade vortex generators on the tractor and trailer and the improvement in the fuel efficiency by 0.86 mpg. The average fuel saving of 3.65% and the improvement in the fuel efficiency of 0.34 mpg was found for the generators on the tractor only.

It was also found that the fuel consumption raised by 10.1% when light ambient winds of about 5 mph strengthen to about 14 mph with gusts up to 25 mph. VorBlade vortex generators reduced that harmful wind effect by 49% and the fuel saving by the entire set of VorBlade generators at such moderate gusty winds reached 10.7%.

Two features of the performed road tests are to be noted. First, the test vehicle had about 6.4% worse fuel efficiency (mpg) than the control vehicle. Second, the control and test trailers were equipped with the DuraPlate AeroSkirts therefore the observed significant fuel saving by VorBlade vortex generators is additional to that by the skirts.

### 3.2. What are VorBlade Specifications?

*Dimensions*

The VorBlade design incorporates the accumulated theoretical and experimental knowledge of optimal characteristics of vortex generators and their effects on the airflow; e.g., Wetzel and Simpson (1992), Koike *et al* (2004), Wood (2006), Leuschen and Cooper (2006), Gustavsson and Melin (2006) and Aider et al (2009). The generators were designed by combining theoretical analysis and available experimental data with the designated wind tunnel tests.

The design process is described in details in sub-section 2.1 and it was started from a qualitative analysis to narrow a range of parameters to be studied theoretically and experimentally. Based on the analysis results, the closed-type VorBlade vortex generator has two parallel channels and helically twisted blades in each channel to produce a pair of vigorous small-scale vortices rotating in the opposite directions. The generator has the air inlet and the exhaust nozzle similar to those in aircraft twin jet engines. The front and rear prospective views of the generator are shown in Figure 2.1-5 and reproduced in Figure 3.2.1.

Quantitative theoretical analysis has shown that the optimum internal cross-section of the channel is the square with the height and width of 1.25” and four helically twisted blades, and the optimum expansion angle of inlet walls is 17°. The quantitative analysis has also shown that the optimum rotation angle of the individual blade is between 10° and 20°, the length of helically twisted blades is between 1” to 5”, the length of a nozzle is between zero and 2.5”, and those ranges were studied experimentally; section 2.1. Based on the wind tunnel experimental tests, the VorBlade optimum values were finalized as 1.5” for the blade length, 15° for the rotation angle of the individual blade, and 1.25” for the length of a nozzle.

The experiments have shown that the optimized VorBlade generators produce vigorous small-scale vortices with the lifespan of about 10 ft at yaw angle of airflow with respect to the generator up to 15°; section 2.1. It was also found that the lifespan of the VorBlade-generated vortices depends weakly on the yaw angle at $\gamma < 20°$ and on the velocity variation from 20 m/s to 40 m/s. The experiments have also proven the adaptive nature of the VorBlade-generated vortices at varying driving conditions.

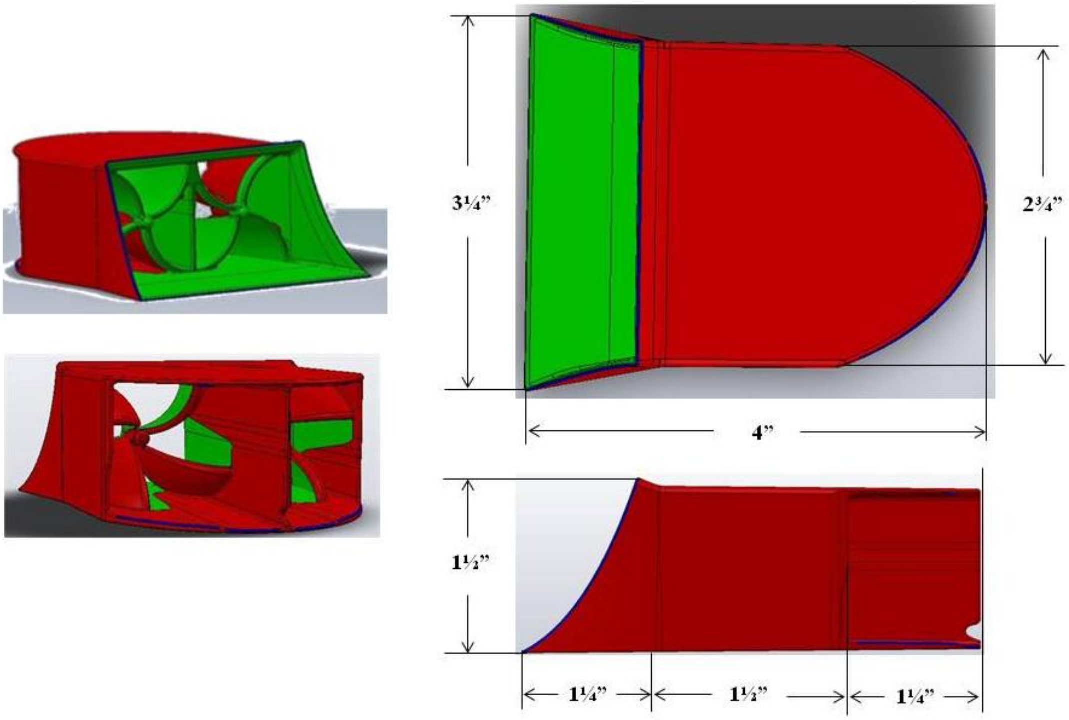



*Figure 3.2-1: Left - Prospective front and rear views of VorBlade as in Figure 2.1-5; and right – external dimensions of the VorBlade vortex generator*

The VorBlade design meets size regulations for the “Truck Length and Width Exclusive Devices”; DOT (2002). The VorBlade length is 4”, width 3¼” and height is 1½“; see Figure 3.2-1 for more details.

*Operating conditions and dynamic loads*

VorBlade vortex generators and attachment means shall operate reliably in the most diverse conditions and withstand any actually possible static and dynamic loads.

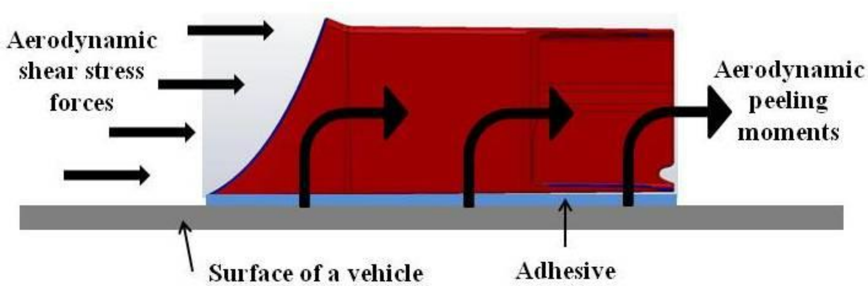



*Figure 3.2-2: Schematic of distributed aerodynamic shear stress forces and peeling moments acting on VorBlade generator and adhesive*

Among the operating conditions, the hardest demands for the VorBlade actual operations are caused by extensive exposure to ultra-violet (UV) radiation, large variations in the ambient temperature and relative humidity. The demands also include heavy rain, snow and icing conditions.

The static loads like the weight of a generator fully packed by snow or ice are negligibly small in comparison with the dynamic loads including vibrations of a vehicle and the loads caused by airflow through the generators. The airflow creates aerodynamic forces and moments that could fracture the generators or torn them away from the vehicle surface. Those aerodynamic forces and moments are estimated below.

It is well known that the operational loads should better be overestimated than underestimated thus the most conservative values of the governing parameters are adopted hereafter. Two aerodynamic loads are of utmost importance to define the requirements for the VorBlade material and attachment means, namely the distributed shear stress forces and peeling moments; Figure 3.2-2. The maximum total shear is equal to the maximum actually possible air drag force $F_{D,\max}$ acting on the generator and it can be estimated using Equation (1.1) reproduced in a slightly modified form as Equation (3.6).

$$F_{D,\max} = \frac{1}{2} C_{D,\max} \rho V^2 A_f \tag{3.6}$$

Hereafter $\rho$ is the air mass density, $V$ is the truck speed, $A_f$ is the generator front area, and $C_{D,\max}$ is the maximum drag coefficient of the generator.

It is obvious that the air drag reaches its maximum value when the generator is fully packed by snow or ice which in unlikely although still possible circumstance. In this case $C_{D,\max} = 2.1$ could be adopted corresponding to that of a smooth brick. Applying Equation (3.6) at the maximum values for the drag coefficient, the truck speed of 100 mph and the front generator area of 1½“ x 3¼“, one can obtain the maximum total shear stress force $F_{D,\max} = 1.81$ lb.

The shear stress force creates the moment tending to peel the generator from the vehicle surface and the maximum value of the total peeling moment $M_{max}$ can be estimated as follows:

$$M_{\max} = F_{D,\max} h_f / 2 \tag{3.7}$$

Here $h_f$ = 1½“ is the front generator height; Figure 3.2-1. Using Equation (3.7) and $F_{D,\max} = 1.81$ lb, one can obtain the maximum value of $M_{max} =$ 0.23 lb·ft. One should keep in mind that the aerodynamic shear stress force and the peeling moment are distributed over the entire VorBlade bottom surface where adhesive means are applied; Figure 3.2-2.

*Material*

VorBlade vortex generators were designed as lightweight as possible and still being able to ensure sufficient durability in actual operating conditions.

| **TYPICAL PROPERTIES** (1) | | | |
|---|---|---|---|
| **MECHANICAL** | **Value** | **Unit** | **Standard** |
| Tensile Stress, yld, Type I, 2.0 in/min | 7600 | psi | ASTM D 638 |
| Tensile Stress, brk, Type I, 2.0 in/min | 7300 | psi | ASTM D 638 |
| Tensile Strain, yld, Type I, 2.0 in/min | 4 | % | ASTM D 638 |
| Tensile Strain, brk, Type I, 2.0 in/min | 120 | % | ASTM D 638 |
| Tensile Modulus, 2.0 in/min | 326000 | psi | ASTM D 638 |

| | | | |
|---|---|---|---|
| Tensile Modulus, 0.2 in/min | 326000 | psi | ASTM D 638 |
| Flexural Stress, yld, 0.05 in/min, 2 in span | 12100 | psi | ASTM D 790 |
| Flexural Modulus, 0.05 in/min, 2 in span | 294000 | psi | ASTM D 790 |
| Tensile Stress, yield, 50 mm/min | 50 | MPa | ISO 527 |
| Tensile Stress, break, 50 mm/min | 50 | MPa | ISO 527 |
| Tensile Strain, yield, 50 mm/min | 4 | % | ISO 527 |
| Tensile Strain, break, 50 mm/min | 120 | % | ISO 527 |
| Tensile Modulus, 1 mm/min | 2050 | MPa | ISO 527 |
| Flexural Stress, yield, 2 mm/min | 80 | MPa | ISO 178 |
| Flexural Modulus, 2 mm/min | 2000 | MPa | ISO 178 |
| **IMPACT** | **Value** | **Unit** | **Standard** |
| Izod Impact, notched, 73°F | 13.3 | ft-lb/in | ASTM D 256 |
| Izod Impact, notched, -22°F | 9.9 | ft-lb/in | ASTM D 256 |
| Izod Impact, notched, -40°F | 5.6 | ft-lb/in | ASTM D 256 |
| Instrumented Impact Total Energy, 73°F | 531 | in-lb | ASTM D 3763 |
| Izod Impact, notched 80*10*4 +23°C | 50 | kJ/m² | ISO 180/1A |
| Izod Impact, notched 80*10*4 -30°C | 30 | kJ/m² | ISO 180/1A |
| Charpy 23°C, V-notch Edgew 80*10*4 sp=62mm | 55 | kJ/m² | ISO 179/1eA |
| **THERMAL** | **Value** | **Unit** | **Standard** |
| Vicat Softening Temp, Rate B/50 | 251 | °F | ASTM D 1525 |
| HDT, 264 psi, 0.125 in, unannealed | 183 | °F | ASTM D 648 |
| HDT, 66 psi, 0.250 in, unannealed | 225 | °F | ASTM D 648 |
| HDT, 264 psi, 0.250 in, unannealed | 210 | °F | ASTM D 648 |
| CTE, flow, -40°F to 100°F | 5.27E-05 | 1/°F | ASTM E 831 |
| CTE, xflow, -40°F to 100°F | 5.E-05 | 1/°F | ASTM E 831 |
| CTE, -40°C to 40°C, flow | 9.5E-05 | 1/°C | ISO 11359-2 |
| CTE, -40°C to 40°C, xflow | 9.E-05 | 1/°C | ISO 11359-2 |
| Vicat Softening Temp, Rate B/50 | 120 | °C | ISO 306 |
| Vicat Softening Temp, Rate B/120 | 125 | °C | ISO 306 |
| HDT/Af, 1.8 MPa Flatw 80*10*4 sp=64mm | 75 | °C | ISO 75/Af |
| Relative Temp Index, Elec | 75 | °C | UL 746B |
| Relative Temp Index, Mech w/impact | 75 | °C | UL 746B |
| Relative Temp Index, Mech w/o impact | 75 | °C | UL 746B |
| **PHYSICAL** | **Value** | **Unit** | **Standard** |
| Specific Gravity | 1.21 | - | ASTM D 792 |
| Specific Volume | 22.97 | in³/lb | ASTM D 792 |
| Mold Shrinkage, flow, 0.125" (5) | 0.8 - 1 | % | SABIC Method |
| Mold Shrinkage, xflow (2) (5) | 0.8 - 1 | % | SABIC Method |
| Density | 0.04 | lb/in³ | ISO 1183 |
| Water Absorption, equilibrium, 73°F | 0.5 | % | ISO 62 |
| Moisture Absorption (23°C / 50% RH) | 0.15 | % | ISO 62 |
| Melt Flow Rate, 250°C/5.0 kg | 16 | g/10 min | ISO 1133 |
| Melt Volume Rate, MVR at 250°C/5.0 kg | 15 | cm³/10 min | ISO 1133 |
| **ELECTRICAL** | **Value** | **Unit** | **Standard** |
| Arc Resistance, Tungsten {PLC} | 5 | PLC Code | ASTM D 495 |
| Hot Wire Ignition {PLC} | 3 | PLC Code | UL 746A |
| High Voltage Arc Track Rate {PLC} | 0 | PLC Code | UL 746A |
| High Ampere Arc Ign, surface {PLC} | 0 | PLC Code | UL 746A |
| Comparative Tracking Index (UL) {PLC} | 1 | PLC Code | UL 746A |
| **FLAME CHARACTERISTICS** | **Value** | **Unit** | **Standard** |
| UL Recognized, 94HB Flame Class Rating (3) | 0.059 | in | UL 94 |
| UV-light, water exposure/immersion | F2 | - | UL 746C |

*Table 3.7: Major properties of the plastic that is used for manufacturing VorBlade vortex generators*

Extensive research has been accomplished and the process of injection molding from a modern plastic was chosen as the best technological procedure. Intensive analysis of a variety of commercially available products was performed for selecting the type of a plastic that can withstand the harsh operating conditions and dynamic loads for 10 years or more.

The analysis resulted in selecting the impact modified PBT+PC Alloy with improved retention of mechanical properties under UV exposure, excellent low temperature impact and chemical resistance. Although this product is relatively expensive, it was chosen as the optimum material to ensure sufficient reliability and durability of VorBlade vortex generators. Detailed specification of the VorBlade material is presented in Table 3.7.

*Attachment options*

Similarly to the VorBlade material, an extensive research was performed to define the best installation options for VorBlade vortex generators on a vehicle that can withstand the harsh operating conditions and dynamic loads for 10 years or more. However the analysis of attachment means was significantly more complicated than that of plastics.

To understand the reasons for the complexity, one should recall that VorBlade vortex generators are to be attached to a cargo vehicle near the rear edges of a tractor, the rear edges of side walls of a trailer and the edges of the roof of a trailer as illustrated in Figures 3.1-2 and 3.1-4. The external surfaces of class 8 trucks in those locations are typically quite different in texture. The tractor surfaces may be two-stage painted with a clear external coating, the trailer side walls may be from aluminum with painted or anodized surfaces, and the trailer roof may be from fiberglass with a smooth or raw surface. It is clear that different means are needed for reliable attachment of plastic generators to such very different surfaces and the unique “best option” merely does not exist.

| Substrates: | 90° Peel Adhesion (oz/in) | |
|---|---|---|
| | Tape 1 | Tape 2 |
| 1. Plastic Part | 145.3 | 180.9 |
| 2. Fiberglass | 42.9 | 55.7 |
| 3. Painted Fiberglass | 135.2 | 196.4 |
| 4. Anodized Alum | 141.6 | 167.2 |
| 5. Painted Alum | 191.9 | 182.7 |

*Table 3.8: Results for the peel adhesion test for the VorBlade generators bonded to typical truck surfaces by two types of adhesive double sided tape*

An extensive research has been performed to define the best installation options of plastic generators for each type of the surface texture. A variety of commercially available products has been analyzed including acrylic adhesive sealants, double sided automotive adhesive foam tapes with high bonding properties, polyurethane adhesive seals specially developed for fiberglass surfaces and specially designed leak-proof automotive rivets.

Commercially available products are tested by the manufacturers and the product specifications were used for preliminary selection of promising products for thorough testing. Adhesives were our prime choice since bonding technology can be used to tie virtually any desired combination of materials with each other, creating long-lasting connections. The adhesives are often lighter in weight, less costly and easier to assemble than mechanical means. The adhesives distribute stresses more uniformly than mechanical fasteners. This feature is important for VorBlade generators subjected to distributed aerodynamic forces and moments. Adhesives are non-flammable, fast and easy to use, and have quick setting. Bonded joints also have high peel strength and toughness.

The suppliers of selected products executed properly designed tests to address our operational requirements. Each chosen adhesive has undergone a thorough evaluation for the static and fatigue strengths which included shear, tack, peel and bend adhesion tests. The environmental testing included heat freeze cycling testing and artificial aging, and flexural strain tests mimicked the vehicle vibrations. An example of the testing results for the peel adhesion test for the VorBlade generators bonded to typical truck surfaces by two types of the adhesive double sided tape is given in Table 3.8.

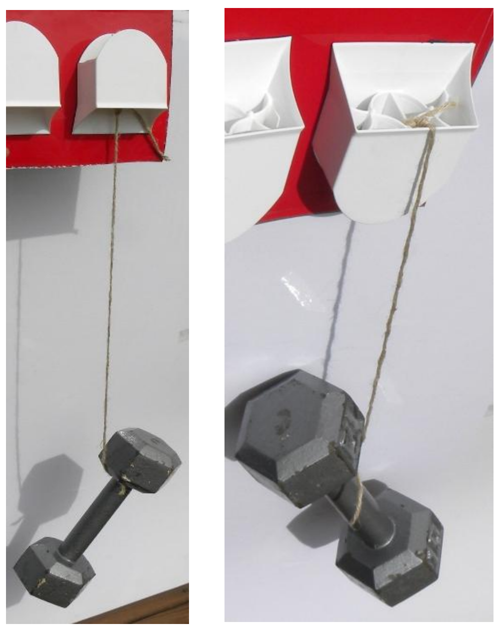


*Figure 3.2-3: Simple shear and peel tests of the two-sided adhesive tapes with 10 lb dumbbells*

In addition to supplier-executed tests utilizing sophisticated specialized equipment like artificial aging cameras, we performed our own tests with the simplest commonly available tools. As noted by Vaca-Cortés *et al* (1998), the simple techniques often give highly reliable and conclusive results comparable with the most sophisticated methods. An example of such test is illustrated in Figure 3.2-3 where VorBlade was attached to painted automotive surface with the two-sided adhesive tape and the 10 lb dumbbell was applied to tear VorBlade from the surface. It is noteworthy that 10 lb weight and 1.25 lb·ft moment in Figure 3.2-3 exceed the maximum actually possible values of the shear stress force $F_{D,\max}$ = 1.81 lb and the peeling moment $M_{max}$ = 0.23 lb·ft by more than 5 times.

The performed tests have shown that the reliability of the VorBlade attachment to the surface depends mainly on the top surface layer rather than the underneath material. For example, in one of the tests

VorBlade was bonded by acrylic adhesive sealant to one-stage painted aluminum plate and was torn from the plate together with the paint layer. Another important result of the tests is that combination of two products can be more reliable and cost-efficient than an individual product. For example, polyurethane adhesive seal can be applied at the edges of two-sided adhesive tape. This is less expensive than using the seal over the entire bottom surface of the generators and at the same time provides extremely reliable and durable bonding. The major result of the tests is that the optimum attachment options shall be customized for specific vehicle or fleet of vehicles, especially when the entire VorBlade Systems are to be installed on the tractors and the trailers.

*Installation recommendations*

Detailed instructions for installing VorBlade vortex generators are presented in the Installation Guides located on the "Cab & Trailer Systems" webpage. Several generic recommendations are provided below.

It is well established that separation between vortex generators may significantly affect their performance while a distance from the edges of tractor and trailer may not be very significant; e.g., Aider *et al* (2009). The optimum separation between VorBlade generators and a distance from the edges were thoroughly studied theoretically and in the wind tunnel experimental tests; details are given in section 2.1.

The *a priori* theoretical analysis utilizing experimental data by Koike *et al* (2004), van Raemdonck and van Tooren (2008) and Aider *et al* (2009) has shown that the optimum separation between VorBlade generators is from 2.0" to 4" which is close to the two-channel width of 2¾" in Figure 3.2-1. The tests have also shown that the performance does not depend significantly on the distance from the edge.

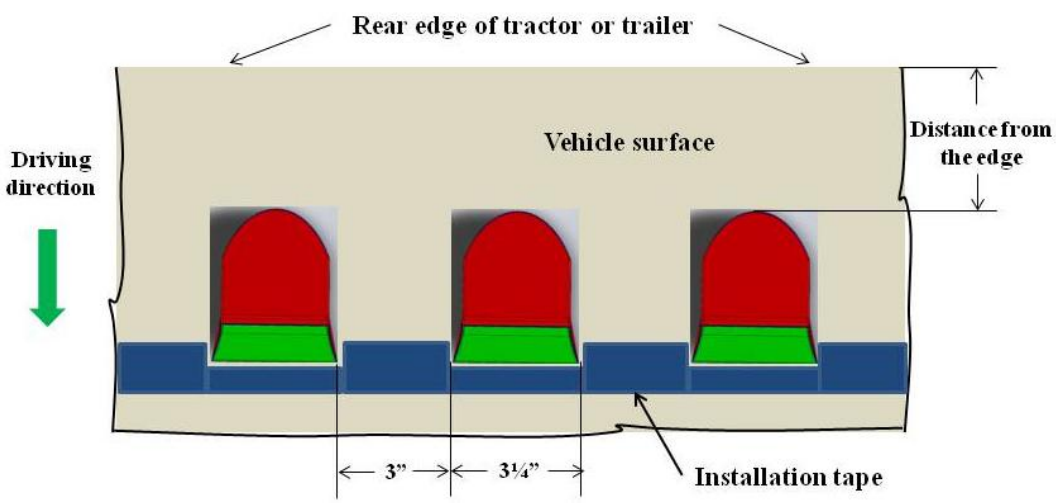



*Figure 3.2-4: Schematic of the installation masking tape with the indentation-marked locations for VorBlade generators on the rear edges of tractors and trailers*

The wind tunnel experiments have confirmed that the drag reduction by the VorBlade generators was practically independent of a distance from the edge up to 1.3 ft at the yaw angles from zero to 15° and flow velocities from 20 m/s to 40 m/s. Based on the experimental data, the optimum separation between the generators is from 2.5" to 3". VorBlade generators reduced aerodynamic drag of a bluff body up to about 63% at such separations over the studied ranges of yaw angle and flow velocity.

The road tests have shown that VorBlade generators at such separation reduce fuel consumption of class 8 truck by about 8.8% in addition to the fuel savings by the trailer skirts.

Installation of VorBlade generators near the rear edges of tractor and trailer is illustrated in Figures 3.1-2 and 3.1-4. Figure 3.2-4 shows a masking tape which greatly simplifies the installation process. The tape has indentations at recommended locations for VorBlade generators and those indentations ensure 3" separations between adjacent generators. The use of such tape is illustrated in Figure 3.2-4: one simply attaches generators in the indicated locations. If for any reason one cannot exactly comply with the indentations on the tape, the nearest available positions will work. The "rule of thumb" for a distance from the rear edges of a vehicle is "as small as practical", say about 1". As was found in the wind tunnel experiments, VorBlade remains effective at the distance up to 1.3 ft hence the distance can be increased to avoid any obstacles near the edges.

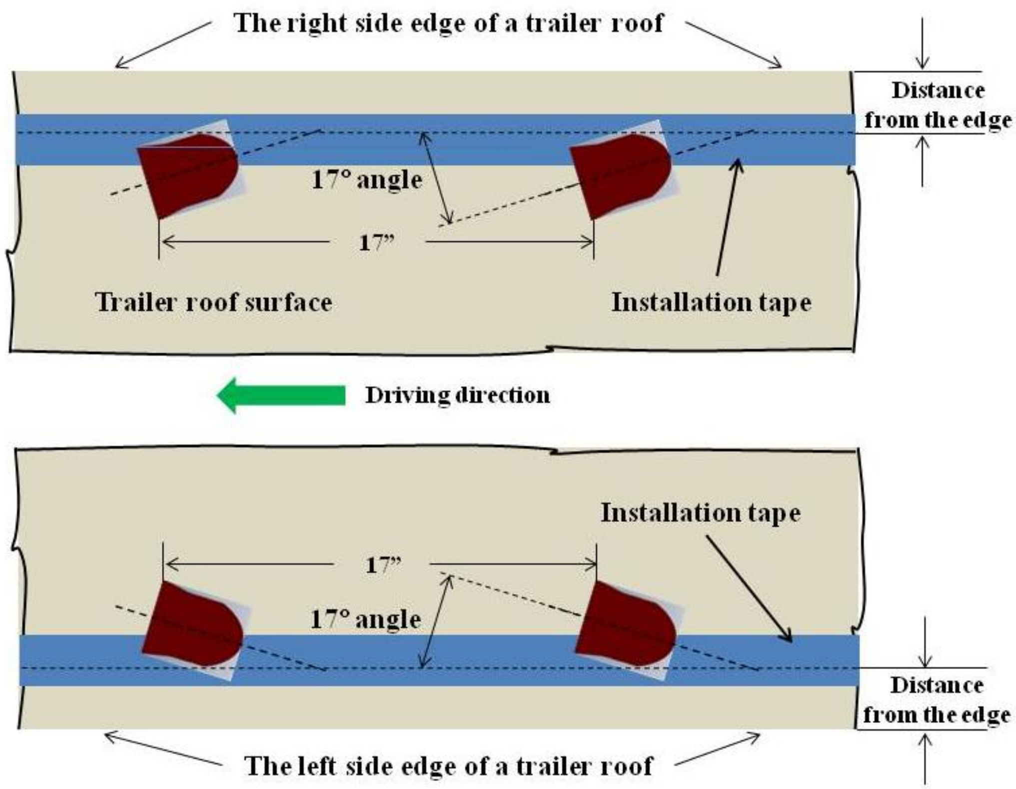



*Figure 3.2-5: Schematic of the installation masking tape with marked locations for VorBlade generators on the side edges of the trailer roof*

Another configuration of masking tape with indentations was developed to simplify installation of VorBlade generators near the side edges of the trailer roof as in Figure 3.1-4. The tapes for two sides of a trailer roof are shown schematically in Figure 3.2-5. Similarly to rear edges, the nearest available positions will work if one cannot exactly comply with the markings on a tape. The same "as small as practical" rule of thumb is applied to the distances from the side edges and the front of the trailer roof; the distances may be increased up to 1.3 ft if needed.

### 3.3. EPA Verified and CARB compliant VorBlade Wing Systems

EPA verified and CARB compliant VorBlade Wing Systems are advanced trailer end fairings designed specifically for heavy motor vehicles to reduce aerodynamic drag and mitigate detrimental impacts of cross winds. A full VorBlade Wing System consists of a VorBlade Wing and a Crosswind Mitigator subsystem; Figure 3.3-1.

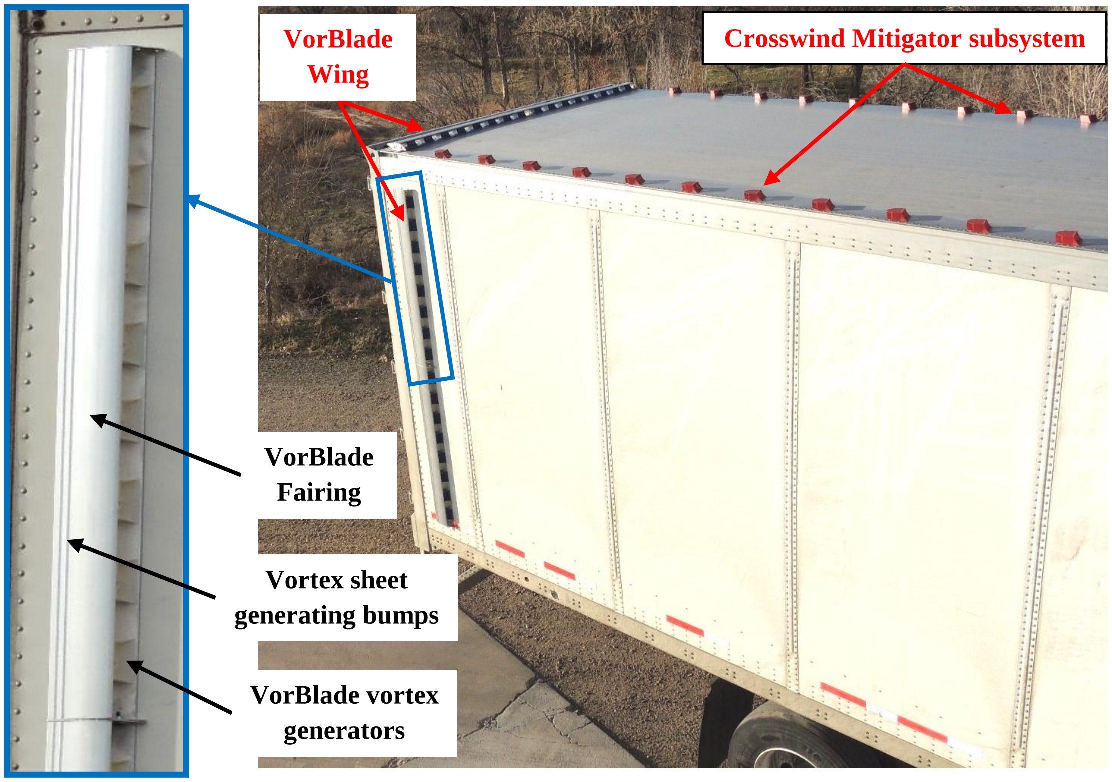



*Figure 3.3-1: VorBlade Wing System with Crosswind Mitigator subsystem on a typical 53-ft cargo trailer. The insert shows an upper part of VorBlade Wing module on the passenger-side wall of a trailer*

As illustrated in Figure 3.3-1, the Crosswind Mitigator subsystem is an assembly of individual VorBlade vortex generators described in Section 2 that are mounted on the sides of a trailer roof as described in Section 3.1. The VorBlade Wing consists of three identical modules mounted closely to the rear edges of the trailer roof and side walls. Each module is a set of VorBlade vortex generators enhanced by the innovative VorBlade trailer end fairing.

VorBlade Fairing is a scientifically modified conventional fairing with significantly enhanced efficiency in reducing air drag and mitigating detrimental impacts of cross winds. The enhancement is achieved by combining in a solitary device two advantageous physical effects: as all conventional fairing, VorBlade Fairing streamlines airflow near bluff trailer edges and, in addition, it generates a protective sheet of intensive small-scale vortices that conventional fairings do not produce.

Physical basis for reducing aerodynamic drag by VorBlade Wing is illustrated schematically in Figures 3.3-2 – 3.3-4. The physics of air drag on a trailer back is illustrated schematically in Figure 3.3-2; more rigorous description is presented in Section 1.2.

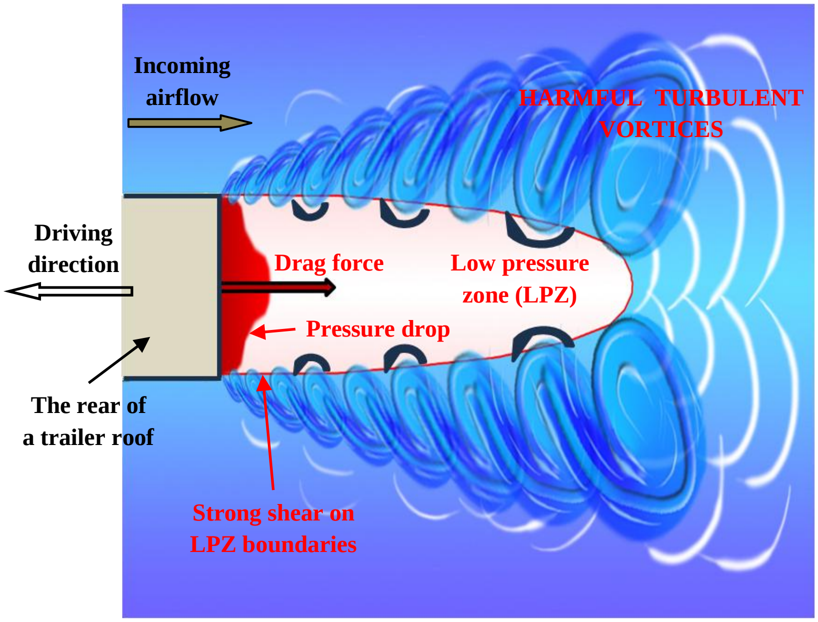



*Figure 3.3-2: Schematic illustration of the physics of air drag on a trailer back without aerodynamic devices (top view)*

As shown in Figure 3.3-2, surrounding air cannot follow a fast moving vehicle and fill a space behind it. The air shortage creates a low pressure zone (LPZ) and pressure drop on a trailer back. The difference in pressure on the front and back vertical walls creates an aerodynamic force opposing the vehicle's motion through surrounding air which is called air drag.

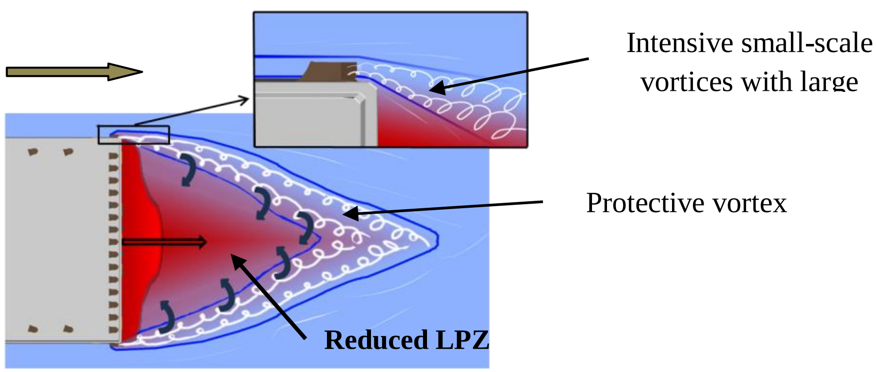



*Figure 3.3-3: Schematic illustration of airflow on a trailer back with installed VorBlade vortex generators (top view). More legends are given in Figure 3.3-2*

If one considers Figure 3.3-2 in the truck-related coordinate system, an incoming airflow cannot make a sharp turn towards a trailer back wall due to the inertia which forms a flow separation zone with low pressure behind a trailer. Strong shear in an air speed on narrow boundaries of LPZ generates harmful large-scale turbulent vortices. These vortices are spatially and temporary unstable and lead to irregular changes in the yaw angle of airflow on the trailer back similar to varying cross winds. It significantly increases the effective size of LPZ and the pressure drop on a trailer rear wall which in turn significantly increases air drag. The vortices also prevent an air from going into LPZ and compensating the low pressure as illustrated by black curved arrows in Figure 3.3-2. Those features make large-scale turbulent vortices the major contributors into air drag near bluff edges.

VorBlade vortex generators in the Crosswind Mitigator and inside VorBlade Wing create strong aerodynamic shield on the boundaries of LPZ; Figure 3.3-3. The generators produce intensive small-scale vortices with large lifespan and direct them towards the shear area. The vortices intensively mix air on the boundaries of LPZ and reduce the shear in an air speed which eliminates the very formation of harmful large-scale turbulent vortices. Small-scale vortices create an "invisible fairing" that streamlines airflow and reduces a size of LPZ. In addition, the vortices inject surrounding air into LPZ which reduces further the zone size and the pressure drop on a trailer back wall. Cumulatively those processes result in significant reduction in air drag of a trailer.

The drag reduction by VorBlade vortex generators is further enhanced by another component of VorBlade Wing, the VorBlade fairing. The Fairing-produced physical processes are illustrated in Figure 3.3-4.

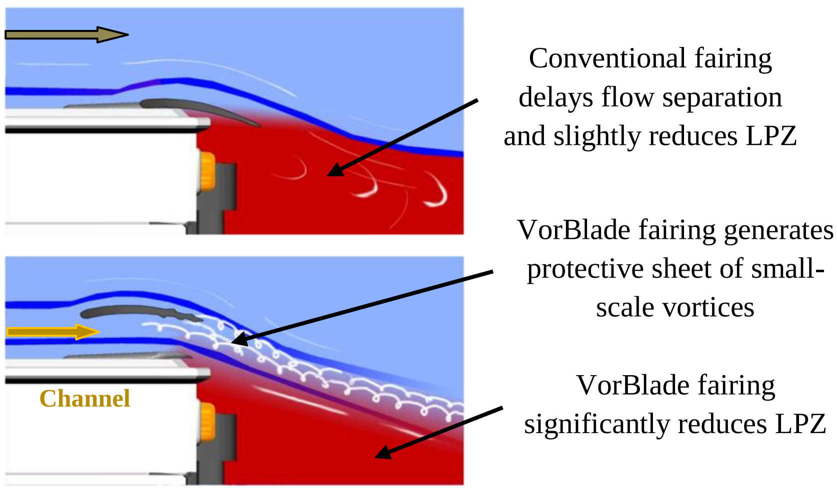



*Figure 3.3-4: Schematic illustration of airflow on a trailer back with conventional fairing (top) and VorBlade Fairing (bottom). The figure shows a side view; more legends are given in Figure 3.3-2*

Conventional trailer end fairings streamline airflow near bluff edges which delays flow separation, decreases a size of LPZ and thus reduces air drag. VorBlade innovative fairing "traps" the incoming air and creates an intensive channel flow. The channel flow increases air rate through VorBlade vortex generators inside VorBlade Wing which intensifies small-scale vortices produced by the generators and increases their lifespan. The fairing efficiently streamlines airflow and injects surrounding air into LPZ which reduces the zone size and pressure drop on a trailer back wall. In addition, scientifically designed profile of the fairing ensures intersection of the channel flow and external flow at the optimum angle to generate a layer of rigorous small-scale vortices which are strengthen further by vortex-generating "bumps" on the fairing surfaces; Figure 3.3-1. This protective vortex sheet is directed towards the boundaries of LPZ where it intensifies turbulent mixing of mass and momentum, reduces the shear in air speed, enhances elimination of harmful large-scale turbulent vortices and significantly reduces air drag.

VorBlade innovative trailer end fairing is the aerodynamically optimum configuration for the rear edges of a trailer. Scientific analysis has shown that VorBlade Fairing reduces air drag by about 25% more efficiently than conventional fairings.

VorBlade Wing System combines unique advantageous physical features of VorBlade vortex generators with those of VorBlade Fairings. The System reduces air drag on a trailer back by about 50% at no cross winds and by more than 60% at strong cross winds.

The efficiency of VorBlade Wing System in reducing air drag on heavy duty cargo trucks has been accurately tested by the independent authority, the EPA-authorized Texas A&M Transportation Institute (TTI). The tests were performed in accordance with the SAE J1321 testing procedures and the EPA SmartWay modifications outlined in the EPA-420-F-09-046 document.

The testing of a full VorBlade Wing System as in Figure 3.3-1 was conducted on August 13$^{th}$ – 14$^{th}$, 2012 at the Pecos Research and Testing Center outside Pecos, Texas at a driving speed 64 mph. The facility includes a 9-mile circular test track where all the driving for the testing was conducted. The Control and Test tractors were identical Freightliner Cascadia Sleepers towing identical Hyundai 53-ft dry van trailers. The gross weight of each vehicle was 68,000 lb.

The tests have shown the Percent Fuel Saved of 9.53% and the Percent Improvement of 10.54% with the accuracy within ±1%. Using this accuracy, it was concluded by the TTI that VorBlade Wing Fairing Trailer End System can be expected to produce a fuel savings of 8.53% – 10.53% and a fuel economy improvement of 9.54% – 11.54%. The TTI technical report “Fuel Economy Testing Results: Heavy Duty Trucks Equipped with VorBlade™ Wing Trailer End Fairings System” is presented on the webpage “Tech Info” in the Section “VorBlade Road Tests and Technical Specification”.

It is constructive to analyze the test data further. According to reported weather information during the testing, the baseline segment was executed at practically calm conditions. During the test segment, the average wind speed was about 7.7 mph. For a circular track, it gives an average cross wind speed of about 4.9 mph which corresponds to the average yaw angle $\gamma$ = 4.4° of incoming airflow with respect to a vehicle at a driving speed of 64 mph. The reported test data allow estimating fuel saving by a full VorBlade Wind System at $\gamma$ = 0, that is at calm conditions.

| | Average Baseline run (measured at $\gamma$ = 0) | Average Test run (measured at $\gamma$ = 4.4°) | Average Test run (estimated at $\gamma$ = 0) |
|---|---|---|---|
| Average fuel consumption by the Control vehicle | 20.00 kg | 21.42 kg | 20.00 kg |
| Average fuel consumption by the Test vehicle | 20.83 kg | 20.18 kg | 19.05 kg |
| Average T/C ratio | 1.0417 | 0.9424 | 0.9525 |

*Table 3.9: Fuel consumption by the Control and Test vehicles at the testing averaged over valid runs*

The measured fuel consumption and T/C ratios averaged over valid runs for the Baseline and Test segments are presented in Table 3.9. Hereafter a weight of fuel corresponds to an average Baseline or Test run.

The test data show that fuel consumption by the Control vehicle rose by 21.42 kg – 20.00 kg = 1.42 kg or by (1.42 kg / 20.00 kg) * 100% = 7.1% when the yaw angle changed from zero to 4.4°. This real-life test value is in a good agreement with an approximate estimate for the increase in a fuel consumption of about 8.25% at $\gamma = 5.5°$ obtained with a simplified finite volume technique; Section 2.3.

It is natural to assume that a fuel consumption by the Control vehicle at an average Test run would remain the same 20.00 kg if the run was executed at calm conditions; Table 3.9. To estimate fuel consumption by the Test vehicle at an average Test run at $\gamma = 0$, one can apply a linear approximation to small variations in fuel consumption at small yaw angles. In this case a fuel consumption by the Test vehicle would be 20.83 kg * 1.071 = 22.31 kg at $\gamma = 4.4°$ if the vehicle was not equipped with VorBlade Wing System. It follows from the testing data in Table 3.9 that the System had saved about 22.31 kg – 20.18 kg = 2.13 kg of fuel at $\gamma = 4.4°$. As shown in Section 2.3, the 7.1% increase in fuel consumption by the Control vehicle corresponds to the increase in the vehicle air drag without aerodynamic devices of about 7.1% / 0.36 = 19.7%. Thus the amount of fuel saved by the Test vehicle equipped by a full VorBlade Wing System would decrease to about 2.13 kg / 1.197 = 1.78 kg if the Test segment was executed at calm conditions. It gives a fuel consumption by the Test vehicle on an average Test run of about 20.83 kg – 1.78 kg = 19.05 kg at $\gamma = 0$; Table 3.9.

Therefore, the average T/C ratio at the Test segment would be about 19.05 kg / 20.00 kg = 0.9525 if the segment was executed at $\gamma = 0$. It corresponds to the Percent Fuel Saved of about [(1.0417 – 0.9525) / 1.0417] * 100% = 8.56% and to the Percent Improvement of about [(1.0417 – 0.9525) / 0.9525] * 100% = 9.36% at calm conditions.

It follows further from the data in Table 3.9 that an actual fuel saved by VorBlade Wing System increases by about 20.18 kg – 19.05 kg = 1.13 kg when the yaw angles changes from 0 to 4.4°. It means that a full VorBlade Wing System reduces the additional fuel consumption induced by crosswinds by approximately (1.13 kg / 2.13 kg) * 100% = 53%.

*EPA verification and CARB approval*

VorBlade Wing System had been verified by the EPA SmartWay Technology program as the 5%+ fuel saving aerodynamic device. Links to the EPA SmartWay Aerodynamic Technologies page, the EPA Verification Letter and the CARB Compliance Confirmation are provided on the “EPA-CARB Wing Systems” page.

The real-life road and track tests have shown that VorBlade™ Wing System with Crosswind Mitigator™ subsystem as in Figure 3.3-1 ensures up to 8% in fuel savings, over 50% of increase in aerodynamic stability and over 60% in compensating detrimental impacts of crosswinds.

VorBlade Wing™ Systems are the lowest cost and the easiest ways to meet the CARB requirements. It ensures the minimum CARB-required 5% fuel savings for both dry van and reefer trailers as a single device - no trailer skirts or any other supplemental devices are necessary.

*Installation recommendations*

Detailed instructions for installing VorBlade Wing Systems are presented in the Installation Guides located on the “EPA-CARB Wing Systems” page. Several generic recommendations are provided below.

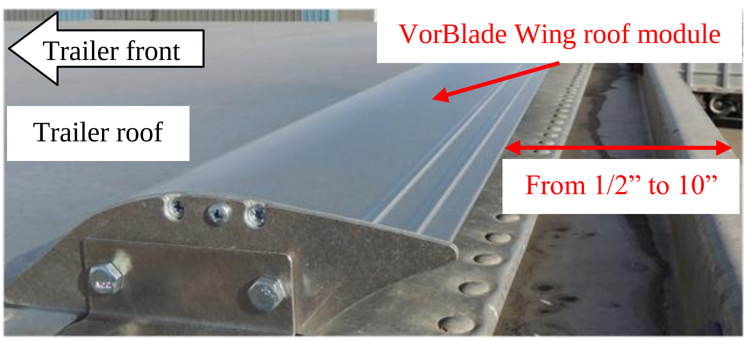
Safety of the personnel performing the installation comes first! Each VorBlade Wing module is about 8 ft long, weighs about 13 lb and has to be mounted on a trailer at a height up to 14 ft above the ground. The

Crosswind Mitigator subsystem has to be mounted on a trailer roof at a height up to 14 ft above the ground. Attaching VorBlade Wing modules and Crosswind Mitigator subsystem to a trailer must be performed from a trailer bay, scaffold, rolling ladder or other appropriate platform providing stable, non-slippery and otherwise safe support to the personnel performing the installation.

Adhesive tapes and pads for attaching VorBlade Systems to a vehicle are specifically developed for automotive industry. Thorough tests have shown that the adhesives withstand a workload of 17 lb per square inch at the most adverse operational conditions such as high or low temperatures, dry air or high humidity and a long-term exposure to ultraviolet radiation. To guarantee the bond strength of adhesive tapes and pads, VorBlade Wing modules and Crosswind Mitigator subsystem should be installed on a trailer in dry environment at temperatures from 50°F to 110°F. The VorBlade and vehicles surfaces should be cleaned and dried carefully – adhesives do not provide strong bond on wet, greasy or otherwise dirty surfaces.

Cargo trailers are different and the "optimum" positions for VorBlade Wing modules depend on a specific trailer configuration. To ensure the best performance of VorBlade Wing systems, it is preferable to attach the modules as close to the rear edge of a trailer as possible. However the performance of the systems does not degrade significantly when the VorBlade Wing modules are positioned up to 10" from the rear edges of a trailer as illustrated in Figures 3.3-5 and 3.3-6.

As illustrated in Figure 3.3-5, a door frame of some trailers may stick up about 1" or more above the roof level which may potentially interfere with the generated vortices. In order to ensure the best performance of the roof module in such cases, the module should be positioned at least 4" ahead from the door frame but not farther than 10" from the rear roof edge.



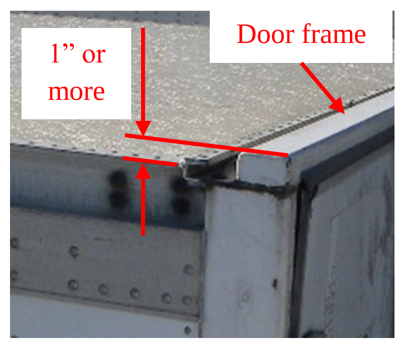




*Figure 3.3-5: (Left) Positioning VorBlade Wing roof module near the rear edge of a trailer roof, and (right) a trailer door frame sticking up above the roof level*

Although it is preferable to position VorBlade Wing modules as close to the rear trailer edge as possible, the wall modules should not prevent opening a trailer door far enough for normal trailer operations. One should choose the closest to the rear edge position where the module does not interfere with door opening as illustrated in Figure 3.3-6.

It is recommended to inspect thoroughly the rear edges of a trailer and find such positions for VorBlade Wing modules that ensure the best fit to the trailer - the "optimum positions" for a specific configuration of a trailer. As illustrated in Figures 3.3-5 and 3.3-6, the "optimum distances" from the back of modules to the rear edges of a trailer are from 1/2" to 10".

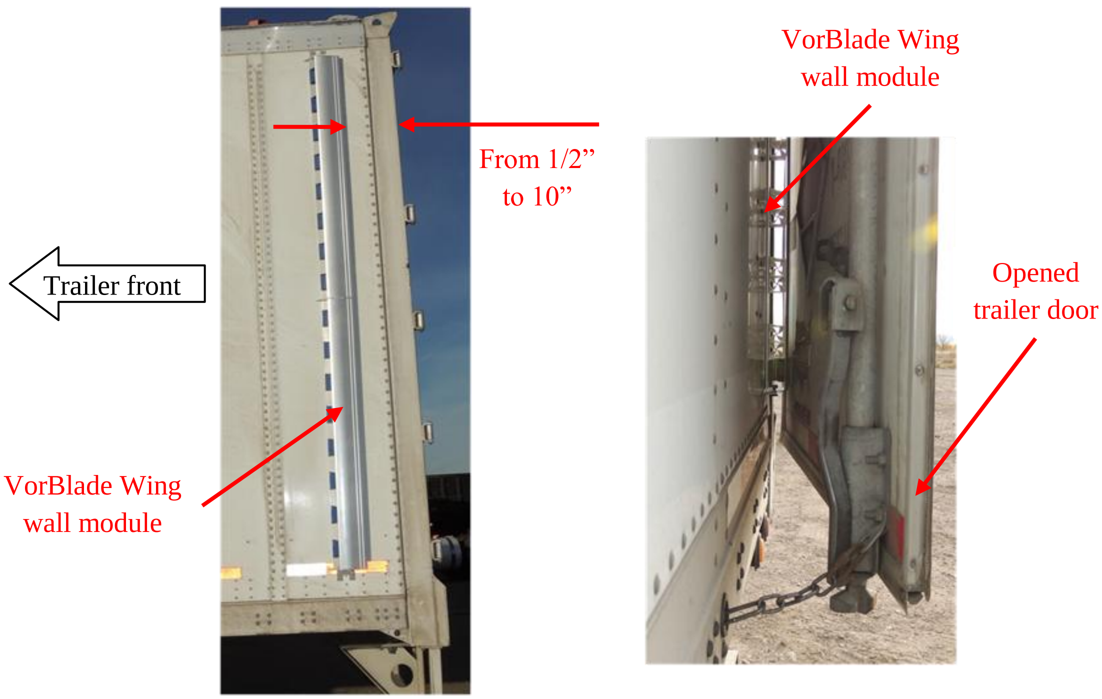



*Figure 3.3-6: (Left) Positioning VorBlade Wing wall module near the rear edge of a trailer wall, and (right) the module should not interfere with opening the trailer door*

## 4. Bibliography

We tried to present technical information in a simple and clear way and sometimes sacrificed physical rigorousness for clarity of explanation. Detailed and thorough scientific analysis of the issues related to aerodynamics of heavy vehicles, reduction in air drag and fuel consumption, driving safety and environmental impacts may be found in the below listed documents, mostly results of the government-funded R&D programs. Each of the cited documents refers to tens or even hundreds of specialized and deep scientific papers. Preparing the page, we had a pleasure to work with the documents and references therein and highly encourage interested readers to do so.

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