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

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

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.

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.

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.

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.

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 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.

	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

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.

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.

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 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.

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.

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

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.

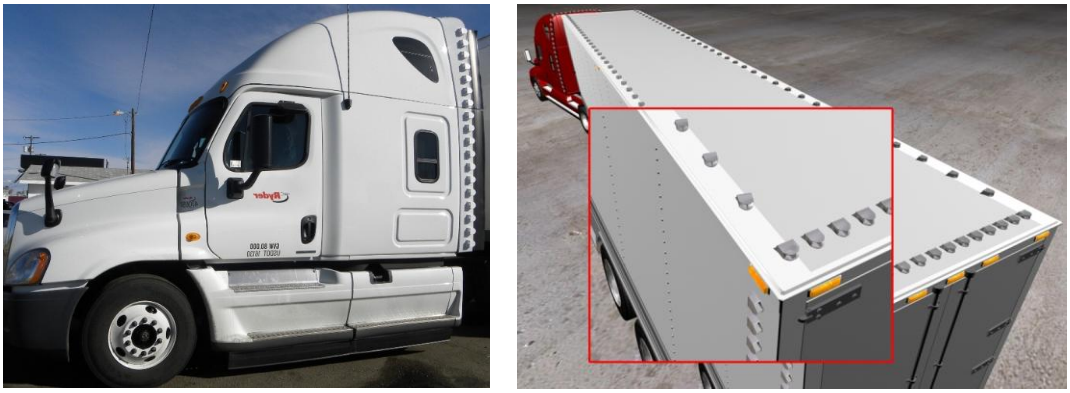

Figure 3.1-4: Closer look at VorBlade vortex generators on a driver side of the test tractor and on the trailer roof

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*:

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

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.

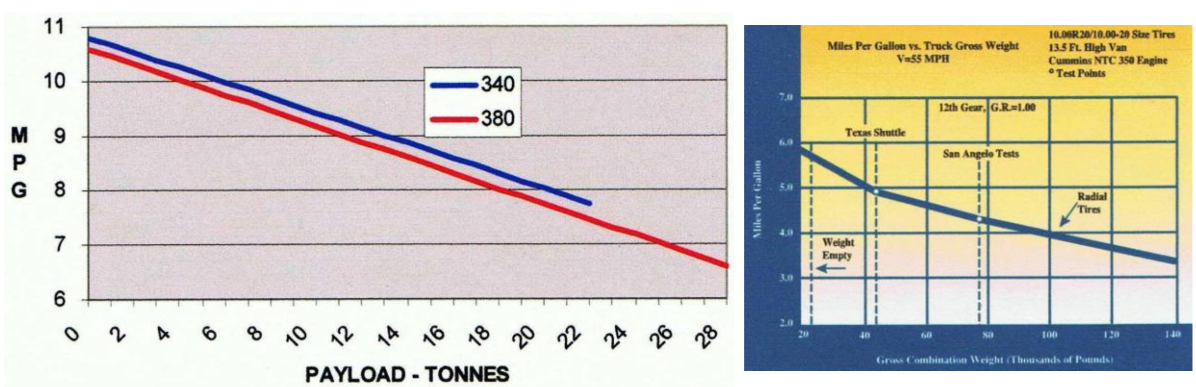

Figure 3.1-5: Left - Regression lines for 340 and 380 Volvo FM12 tractors with the trailers of variable payload from Coyle (2007); right – Good Year Testing Data reproduced from Good Year (2008)

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 δ_G is the gradient of the regression curve in mpg/tonne. The percent of fuel saved ε_0 and ε_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 ΔC_0 and ΔC_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 ε_G for loaded trailers from the values of ε_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 ΔC 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 ε_0 to the percent ε_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.

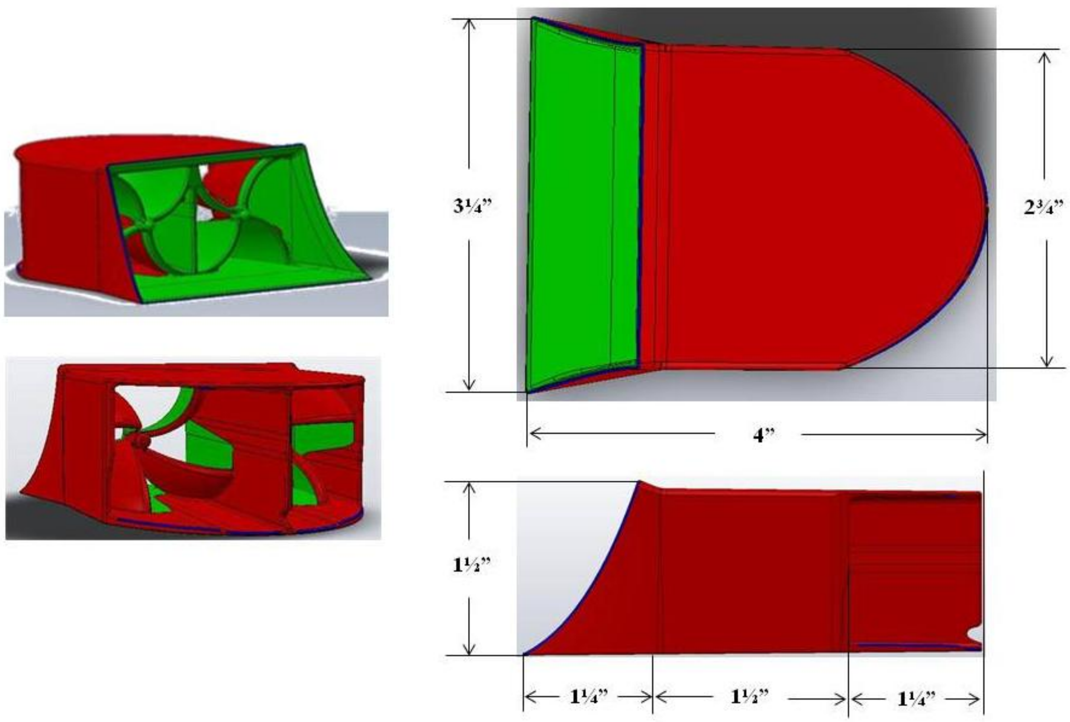

Figure 3.2-1: Left - Prospective front and rear views of VorBlade as in Figure 2.1-5; and right – external dimensions of the VorBlade vortex generator

The 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.

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.

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.

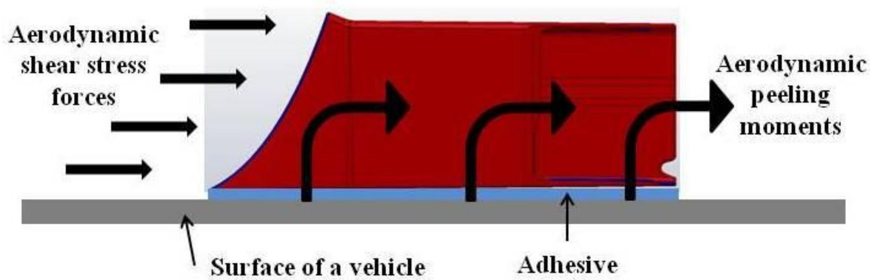

Figure 3.2-2: Schematic of distributed aerodynamic shear stress forces and peeling moments acting on VorBlade generator and adhesive

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).

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

Hereafter ρ 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:

$$M_{\max} = F_{D,\max} h_f / 2 \qquad (3.7)$$

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. 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.

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

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.

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.

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

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.

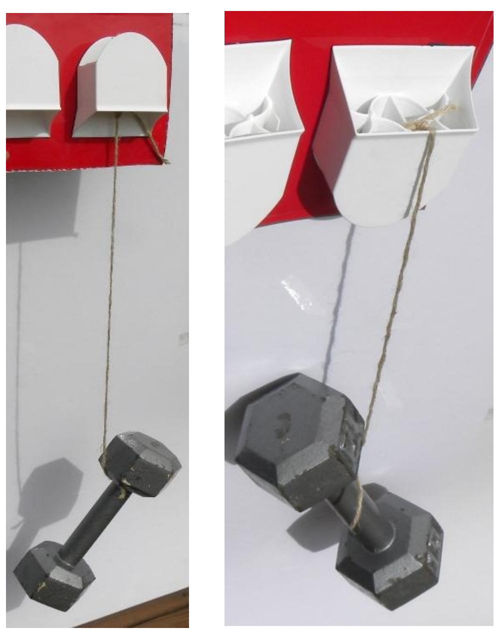

Figure 3.2-3: Simple shear and peel tests of the two-sided adhesive tapes with 10 lb dumbbells

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

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.

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, a separation between the generators of 2½" was chosen as the optimum value. VorBlade generators reduced aerodynamic drag of a bluff body up to about 63% at that separation 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 2½" 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.

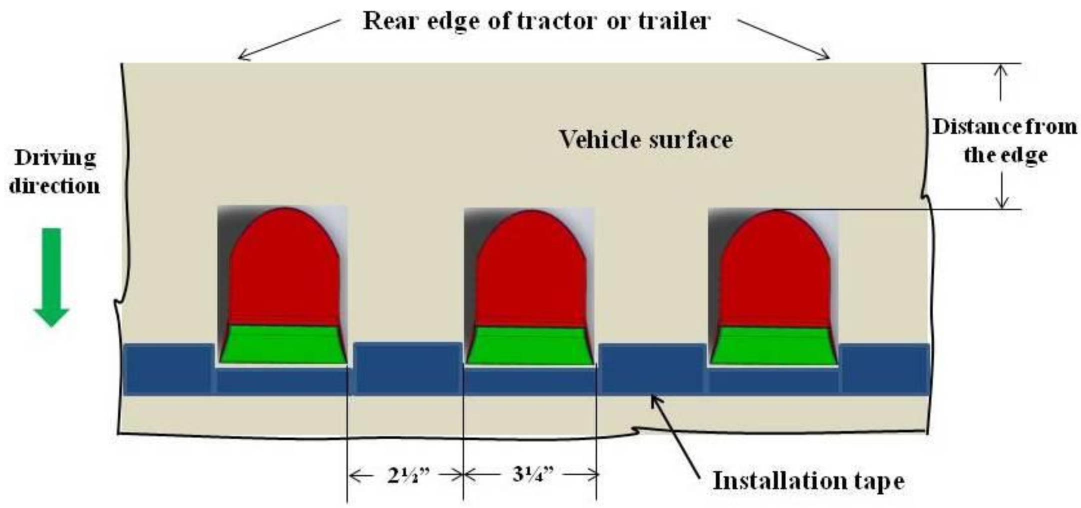

Figure 3.2-4: Schematic of the installation masking tape with the indentation-marked locations for VorBlade generators on the rear edges of tractors and trailers

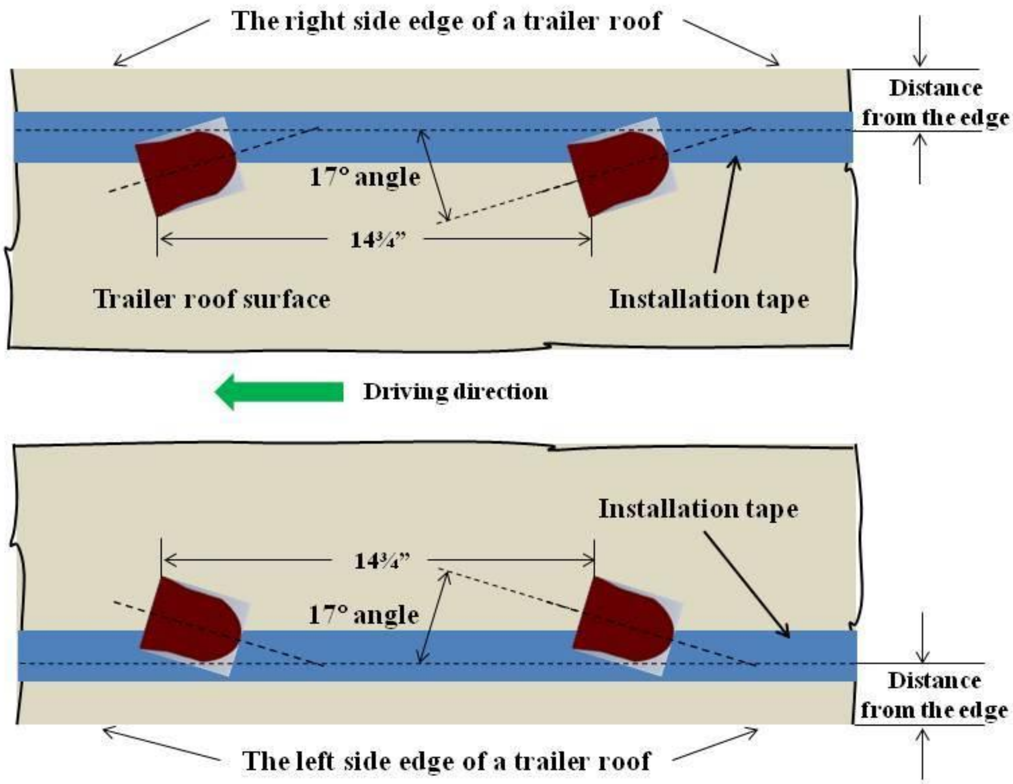

Figure 3.2-5: Schematic of the installation masking tape with marked locations for VorBlade generators on the side edges of the trailer roof

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.