Improving Fuel Efficiency of Tractor Trailer Trucks with Deturbulator Aero-Drag Reduction

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ABSTRACT

A new method for streamlining tractor-trailer trucks based on weakening turbulent vortices in regions of separated flow using a flexible surface Deturbulator tape patented by the author. Minimal Deturbulator application on the tractor-cab sides yielded 4% improved fuel mileage by de-energizing recirculating vortices in the tractor-trailer gap. The entire trailer, especially flatbeds with loads can be encapsulated within a quiescent separated bubble by extending Deturbulator application to the tractor. It makes the truck appear more streamlined to the airflow evidenced by 13-30% fuel economy improvement. The Deturbulator configured as a replaceable strip provides a cost effective fuel savings add-on for already streamlined class-8 tractors, which does not impede normal operations.

INTRODUCTION

Diesel fuel prices have been rapidly increasing due to crude oil price increases and added processing required for meeting recently upgraded emission regulations. The latter has also resulted in lowering the fuel economy (mpg or km/liter) of diesel engines. According to the American Trucking Association, fuel costs currently constitute the largest cost for trucking fleets, even exceeding the cost of hiring and retaining truck drivers. Since trucks deliver 64% of the value of goods transported across the U.S., this has contributed to price increases of goods across the economy. It has also put many smaller fleets and owner-operators out of business. As a result all methods for reducing fuel consumption are being considered. Additionally, effective means of truck fuel economy increase are extremely important for reducing climate changing greenhouse gas emissions.

Aerodynamic drag accounts for about 50% of the total energy delivered to the wheels of a vehicle traveling at a constant speed of about 88 km/h (55 mph) on a level road. This increases to about 75% at typical highway speeds of 110 km/h (70 mph) and is 65% even for loaded class-8 tractor trailer trucks. This is because the drag force $F_d$ is proportional to $C_d V^2$, where the coefficient of drag $C_d$ remains approximately constant as the velocity of the air relative to the vehicle ($V$) increases. For vehicles, such as long distance tractor-trailer trucks which spend most time traveling at constant speed on highways, even a modest reduction in $C_d$ can have a measurable impact on fuel consumption. Finally, unlike advertised fuel-saving additives for fuel or oil, add on aero-drag reducing devices are benign in terms of possible adverse effects on engine components.

Starting with cab-top wind-deflectors class-8 tractors have been progressively streamlined by manufacturers. Generally, the trailers have remained unstreamlined for functional reasons. Hence the U.S. Dept of Energy sponsored implementation of several commonly used aerodynamic flow control techniques to reduce flow losses in the gap between the tractor and trailer, under the trailer and in the wake behind the trailer (Clarke, 2006, Wood, 2003). Typically three to four trailers have to be streamlined for each tractor and most flow-control appendages are prone to damage during normal operations. Truck fleets have therefore been extremely slow to adopt these in spite of increasing fuel prices even though many of the methods investigated yielded fuel economy enhancements of 2-7%. Some devices such as boattails are unpopular since modifications to loading docks or operating procedures are called for. The Deturbulator drag reduction concept presented here was developed to address these shortcomings.

Fig 1. Schematic of the Deturbulator
THE DETURBULATOR

The Flexible Composite Surface Deturbulator, or FCSD (Fig 1; Sinha, 2003, Sinha and Sinha, 2006) is a passive multi-layer flexible-skin tape which behaves as a large-eddy breakup device. When applied on the surface of an aerodynamic body, the streamwise (x-direction) flow momentum equation on the flexible skin simplifies to:

\[
v(\partial u/\partial y)_{y=0} = -((1/p)(\partial p/\partial x) + (\mu/p)(\partial^2 u/\partial y^2))_{y=0} \tag{1}
\]

\[
\mathbf{v}_u \mathbf{u} / \mathbf{y} |_{y=0}
\]

is the flow-skin interaction term (v = velocity component of the flow and flexible-skin in the wall-normal direction y, u = streamwise or x-component of velocity, \(\mu\) = viscosity, \(p\) = density and \(p\) = the pressure of the air). Since \(\partial p/\partial y = 0\) for boundary layers, pressure fluctuations pass from the freestream to the flexible skin and induces a velocity \(\mathbf{v}\) on the skin provided \((\partial u/\partial y)_{y=0} \neq 0\). Hence, the flexible skin undergoes traveling wave-like oscillations in response to turbulent fluctuations in the flow.

Longer wavelengths are associated with large vortices responsible for sustaining turbulent fluctuations (i.e., production of turbulent kinetic energy from the mean flow; Tennekes and Lumley, 1989). A series of ridges aligned normal to the flow direction form the substrate of the flexible skin (Figs 1 and 2). Small flexural perturbations of the form \(v(x)\) are introduced into the traveling wave on the flexible skin each time the trough of the aforementioned traveling wave encounters a ridge (Fig 2). These \(v(x)\) perturbations introduce a series of small vortices (vorticity \(\omega = (\partial v/\partial x - \partial u/\partial y)_{y=0}\)) into the flow, which feed upon and eventually drain out the energy in the larger turbulence producing vortices (Fig 2). The periodic generation of small vortices occur at the characteristic frequency \(f = U/s\), (where \(U\) is the freestream velocity outside the boundary layer over the flexible skin and \(s\) is the spacing of ridges on the substrate of the Deturbulator). These vortices are dissipated much faster by viscosity compared to the larger vortices. This bypasses the normal stepwise vortex stretching and breakdown process which defines turbulence, dissipating turbulent producing eddies as soon as they form. This reduces turbulence levels not only in the boundary layer but also in the shear layer when the boundary layer separates. Turbulent entrainment across the separated shear layer is significantly reduced. Vortices in the separated region, driven by turbulent (or Reynolds) shear stresses are also weakened, resulting in transforming separated regions into zones of quiescent air. Weakened turbulent vortices also reduce pressure loss in the separated zone. This lowers pressure or form drag.

The Deturbulator or FCSD was originally developed to eliminate skin-friction drag of streamlined shapes like airfoils and aircraft wings by promoting turbulence-free marginally separated flow. Rather than damp turbulence within its structure like previously investigated “compliant walls”, the Deturbulator reduces drag on airfoils by stabilizing the marginally separated boundary layers (Sinha, 2007). Fig 3 shows surface oil flow visualizations of an untreated and FCSD treated sailplane wing. The normal transition through breakdown of the separation bubble is avoided by the FCSD and almost the entire chord has a thin stagnant separated “slip-layer” with almost zero skin friction. Fig 4 shows the test sailplane with full-span Deturbulator treatment on the upper surface. Fig 5 shows increases in lift-to-drag (L/D) or glide ratios across most of the flyable the airspeed as independently measured through flight performance evaluations by Johnson (2007). The best L/D increases by 18% and this is not possible using more conventional forms of flow control. This validated the FCSD.

Fig 2. Sketch showing Eddy Breakdown by Deturbulator

Fig 3. Oil Flow Visualization on Wing Top Surface
Left: Untreated. Right: Deturbulator Treated
Previous work by Sinha and Sinha (2007) had shown evidence of the Deturbulator’s capability of reducing drag in separated flows on a minivan and pickup truck and presented preliminary evidence of doing the same on class-8 tractor trailers.

For a tractor trailer with a streamlined tractor-cab the flow separates off the cab, bridges across the trailer gap and grazes the front corners of the trailer. For a van trailer, the recirculating vortices in the gap reduce static pressure behind the tractor cab and increase the pressure on the front face of the trailer. Both increase pressure drag. Hence, placing Deturbulators on the sides and top of the tractor as shown in Fig 6 is expected to weaken turbulence-driven recirculating vortices in the tractor-trailer gap and reduce drag. To a lesser extent the same Deturbulators can also reduce turbulence in the wake behind the trailer as depicted in Fig 6. Additional Deturbulators on the trailer can be expected to reduce the trailer wake turbulence further.

RESULTS

Preliminary Wind Tunnel Drag Measurements:

Initial tests were conducted in the Sinhatech low-speed wind tunnel (www.sinhatech.com) on a 1/48th scale Freightliner-Columbia with van trailer (Fig 7). The Eiffel-type Sinhatech wind tunnel has a 12-inches (305-mm) high, 9-inches (229-mm) wide, 14-inches (356-mm) long test section; a 4-ft (1.22-m) high 3-ft (0.91-m) wide exponential profiled bell mouth entrance and a variable speed suction fan. At the nominal 30-m/s test airspeed, turbulence (u-rms/u-mean) in the test section is about 0.8% without screens. The model was placed on free rolling wheels on the test section floor and held against the flow with a cord. The measured tension in the cord provided a direct measure of the drag force and showed the possibility of 25% drag reduction with Deturbulators on the sides and top of the tractor and on top of the trailer. Additional Deturbulators on the trailer either had no influence or in some cases increased the drag. The 25% figure is an underestimate since added rolling resistance due to flattening of the 18 solid rubber tires of the model under predicts reduction in drag force.
Deturbulator Installation on Prototype Tractor Trailers:

Proper placement of the Deturbulator tape so as to maximize coupling of its flexible skin with turbulent fluctuations without increasing device drag is key to the success of this method. Coupling is maximized if the Deturbulator is located where the boundary layer streamwise pressure gradient \( \frac{\partial P}{\partial x} = 0 \) as it passes from favorable to adverse (Sinha, 2001) and \( \left( \frac{\partial u}{\partial y} \right)_{y=0} \) is high as per equation (1). At the same time the edge of the tape constitutes a small but finite step which can impede the near-wall flow and increase drag. A convenient method for determining best locations for attaching the Deturbulator is to visualize the surface flow with oil as the truck is operated at highway speed. Fig 8 shows oil flow visualization on the side of a Freightliner Columbia tractor operated without a trailer (i.e., bobtailing). The longest horizontal streaks indicate the vicinity of maximum \( \left( \frac{\partial u}{\partial y} \right)_{y=0} \). This may or may not coincide with \( \frac{\partial P}{\partial x} = 0 \). To also guarantee \( \frac{\partial P}{\partial x} = 0 \), the Deturbulator needs to mounted on a substrate with a slight hump. The location on the prototype (Fig 9) is very different from the same points on the 1/48th scale model of Fig 7. The difference is on the smaller model laminar separation occurs around the leading edges.

Estimating Fuel Efficiency Changes:

50-mm (2-inch) wide Deturbulator tape with 6-µm (0.00025-inch) thick Mylar® skin and 2-mm (0.08 inch) substrate ridge spacing was applied to the sides of the cab as per the optimum locations estimated through visualizing the flow on the tractor without trailer (Fig 8). However, operating the tractor with a trailer during its normal routes left the fuel economy (km/liter or mpg) unchanged. Oil flow visualization was repeated with the trailer attached. The presence of the trailer was found to change the optimum locations sufficiently to miss the 50-mm wide tape. Also optimum locations were found on top of the cab and trailer as well as the front corners of the trailer.

Preliminary operational fuel efficiency measurements were conducted on a different Freightliner Columbia tractor matched with the same Wabash 53-ft box trailer operating with light loads on the same less than truckload (LTL) route everyday, with the same driver. The driver was instructed to fill the tanks completely during each fill up and note the fill up volumes. Additionally, the fleet operator downloaded data from the truck’s cpu approximately once a month. Baseline data existed for about two months prior to applying the Deturbulator.

Since applying the Deturbulator tape in situ required skill and excessive time, the tape was pre-mounted to 60-mm wide rigid strips. The strips were taped in place on to the sides of the tractor (Fig 9). Deturbulator tape was also directly mounted on top of the cab and trailer. These Deturbulator tapes unfortunately were knocked off by low hanging tree limbs during the very first run; and any improvement in mpg or km/liter was assumed to be due the strips on the cab sides only. Fig 10 shows the baseline and treated fuel mileages deduced from the fill up data recorded by the driver. The maximum speed of the truck was limited to 73 mph (117 km/hr) with 18-22% time spent below 67 mph (107 km/hr).

The data of Fig 10 shows an overall base fuel economy of 6.08 ± 0.14 mpg (2.59 ± 0.06 km/liter) which increases to 6.32 ± 0.16 mpg (2.69 ± 0.07 km/liter) after...
the Deturbulator treatment. This represents a 3.94% increase in fuel economy due to Deturbulators only on the tractor sides with a 97% confidence that the increase is real. From a fleet operation standpoint treating tractors is preferred to treating trailers since two to three trailers are typically associated with each tractor. Trailers are dropped off for loading and unloading while the tractor is hitched to a different trailer. Hence, the cost associated with the treatment has to be multiplied by two or three thereby increasing the payback period. Long payback periods also increase the likelihood of damage to the device and this is especially true for trailers.

The second set of data in Fig 10 represents changes in fuel economy excluding idling fuel consumption. The idling fuel consumption was 2.5% of the total fuel used for the truck. Aero-drag does not influence idling fuel consumption. However, strict regulations on idling time imposed by the State of California in order to control truck emissions hasinitiated the adoption of auxiliary power units for powering cab heaters and air conditioners in a parked truck. These reduce idling fuel consumption by 70% or more. Hence the 4.1% increase in “Highway mpg” depicted in Fig 10 is a realistic estimate.

In order to determine how the treatment could be extended a series of screening tests were run. Fig 11 reflects the average of truck CPU measured trip mpg with zero indicated idling time over 8 to 8.2 mile segments at 65 mph. A brand new Freightliner Columbia tractor, a slightly dented Great Dane 53-ft trailer and a new undamaged trailer were used. The data has not been corrected for accelerating, braking, road slope and changing wind conditions and rain. It however clearly shows a comparison between treatments and also shows that cab-top treatment is undesirable. The Deturbulator on top of a tractor cab can increase drag by causing the airflow to hit the top corner of the trailer. Treating the front vertical corners of the trailer increases fuel economy and overcomes the disadvantages of an old dented trailer.

In view of the trends in Fig 11, the Deturbulator treatment was extended to the corners of the trailer on the original operational LTL truck of Fig 9. Fig 12 shows long term (1.5 to 3 months average) data downloaded from the CPU. It should however be emphasized that the Deturbulator on top of the cab was completely destroyed when the truck was examined. The Deturbulator on the top rear of the trailer was also significantly damaged. A comparison between comparable data and treatments in Figs 11 and 12 show that by installing Deturbulators on the sides of the cab and trailer the fuel mileage increased from 6.0 mpg to about 6.35 mpg or 5.8%. The last treatment in Fig 12 also included a Deturbulator on the bottom rear of the trailer (below the safety bar) that was found undamaged.

Redesigning the Deturbulator:

The Deturbulators tested thus far had the 6-µm Mylar skin that was fairly delicate. For example, after about 15,000 miles (24,000 km) of operation the Deturbulator skins had several tears. Moisture collection in the air gap impedes the motion of the flexible skin and makes the Deturbulator ineffective. Since flexible-skin oscillation amplitudes are very small (less than 1-µm or 0.00004 inch) the thickness of the air gap in the substrate (Fig 1) needs to be controlled in the face of varying static pressures caused by the external flow. This requires venting the air gap to the external flow. To prevent moisture from entering the air gap a system of micro-porous vent inserts were developed. Also a composite skin was developed which had the same mass density and flexibility of the original Mylar but was resistant to stretching and tear. The composite skin is a sandwich of fibers between two polymer sheets. The composite skin was evaluated on existing airfoil models in the Sinhatech wind tunnel and found to be dynamically as responsive as the Mylar it replaced for the range of airspeeds typical for trucks.
Even with the composite skin, Deturbulators can be expected to have longer but finite lives on an operational truck. Hence a method for quick and easy replacement of Deturbulator strips was devised. In this design a receptacle is attached to the body of the tractor or trailer with double stick tape. The Deturbulator strips simply slide into the receptacles and can be replaced as needed.

In addition to withstanding road grime and weather extremes, the Deturbulators also need to survive high pressure washes. Fig 13 shows the first prototype of the aforementioned slide-in Deturbulator on a tractor after a wash. The composite skin did not show any tears even though the glued joint of a receptacle failed. This problem has since been solved.

The removable Deturbulator strips also had a slight curvature, thereby facilitating the \( \frac{\partial P}{\partial x} = 0 \) condition for the cab-side mounting location (Fig 13).

Fig 14 shows screening test data on a Freightliner Columbia tractor with trailer treated with the new slide-in composite surface Deturbulator (Fig 15). The first treatment consisted of 5.5 ft (1.68-m) of Deturbulator strips on each side of the cab and resulted in 4% increase in fuel economy. Adding another 6-ft (1.84-m) of Deturbulator on the front corners of the trailer increases fuel economy by 8% compared to the untreated baseline.

The data was obtained by running the truck 45 miles on the interstate along with other traffic while monitoring the average fuel economy continuously. The miles per gallon depicted in Fig 14 represent values after they stabilized near the end of the 45 mile segment.

The in operation fuel mileage for van trailer hauling (Fig 15) increased from 5.89 mpg to 6.01 mpg or about 2.0%. However, the 6.01 mpg is an average over one month with the Deturbulator installed middle of the month. Hence the extrapolated estimate of “true” increase for is about 4%, which is in line with Fig 14. During the same
time the average mpg of 800 similar untreated 2007 Freightliner Columbia tractors in the fleet increased from 5.72 mpg to 5.79 mpg, or 1.0%.

Deturbulators for Flatbed Hauling: The large separated region behind the tractor cab and wide variations in the shapes and profiles of loads places an enormous challenge in reducing aero-drag for flatbed hauling. Even with a streamlined tractor, the separated shear layer breaks down into turbulent vortices. These vortices impact the load as shown in Fig 16 (top). The resulting increase in drag can be alleviated by Deturbulators on the tractor cab. The Deturbulators can be expected to prevent early breakdown of the separated shear layer, thereby encasing the trailer and load within a quiescent separated bubble (Fig 16). Previous wind tunnel tests on a model tractor cab demonstrated this possibility (Sinha and Hyvärinen, 2008; Sinha and Sinha, 2007).

Fig 17 shows an installation on a Freightliner Columbia flatbed hauling tractor. Table 1 shows the measured fuel consumption and mileage data one-week with Deturbulators and one week without for similar routes and loads with the same driver. Trailers were exchanged.

The 12.7% improvement in mpg resulted from Deturbulator installations on the bumper, mirrors, top lateral wind deflectors as well as on top of the cab (Fig 17) in addition to the two on the cab sides similar to the van-trailer hauling tractor of Fig 15.

The installation of Fig 15 showed that the composite skin of the Deturbulator remained intact after 75,000 miles. However, repeated high pressure washing degraded the substrate ridges and reduced gain in mpg. The Deturbulators in Fig 17 included material substitution to mitigate this problem. They also had a more streamlined shape with a thinner leading edge and a smaller ridge spacing to increase the interaction frequency $f$. Increasing $f$ reduces turbulence even more (Sinha and Hyvärinen, 2008).

Table 2 shows fuel economy increases when a treatment similar to Fig 17 was applied to a 2004 Volvo tractor. Even though the tractor had a streamlined high roofline for van-trailer hauling it was used by the operator for hauling flatbeds. A 29.5% increase in fuel economy was measured after Deturbulator application.

The improvements in Tables 1 and 2 are large enough to extend beyond other factors affecting fuel economy. This is based on data from the fleets with the treated, as well as similar untreated trucks in truck-load operations.

Other Considerations:

The Deturbulator was also found to perceptibly reduce swaying during cross winds. This not only improves safety and driver fatigue but improves life of the steering tires. Thus far, treating the tractor only appears to yield 12-30% increase in fuel economy for flatbed operations. Treating the tractor cab sides only for van-trailer hauling appears to yield 4% improvement. Treating the van-trailer corners increases it to 8%. However, improvements in the latest slide-in Deturbulator as well as additional application positions (Figs 17) are also
CONCLUSIONS

A thin (100µm thick) microstructured flexible surface Deturbulator tape developed for drag reduction on streamlined wings has been successfully adapted for fuel economy enhancement of class-8 tractor trailer trucks.

The Deturbulator weakens vortices in the separated flow between the tractor and van-trailer and behind the trailer. Applying a strip of 50-mm wide, 1.8-m long Deturbulator tape to each side of an already streamlined tractor cab to reduce the strength of vortices in the tractor van-trailer gap resulted in 4% increase in fuel economy. Additional Deturbulators on the front corners of the trailer enhanced the fuel economy by 8%.

The Deturbulator also delays breakup of the separated shear layer coming off the tractor cab, thereby reducing the impingement of the flow on loads carried on a flatbed trailer.

For maximum improvement, the Deturbulator encapsulates the entire trailer behind a streamlined tractor within a separated bubble containing quiescent air. The separated bubble makes the truck appear streamlined to the flow.

For flatbed hauling operations where the aforementioned encapsulation is easier to achieve, close to 30% increase in fuel economy was observed, resulting in savings over two-weeks of 226 gallons of diesel fuel worth $1,041 at $4.61 per gallon. For less than ideal encapsulation, fuel economy increase of about 13% was observed for tractor-only treatment.

The improved composite flexible-skin Deturbulator is embodied as a replaceable slide in strip inserted into a streamlined receptacle attached to the truck body. Attachment locations are dependent on the shape of the tractor and deduced from surface oil flow visualization. In view of large (12-30%) improvements in fuel economy on operational trucks, the aforementioned Deturbulator strip is currently being offered as an aftermarket fuel saving device to truck fleets. The payback period is expected to be short.

Based on $4.70/gallon diesel fuel, a Deturbulator treated tractor is expected to save about 1,900 to 5,800 gallons of fuel costing $9,200 and $27,600 per year, driving 136,000 miles per year. If all 1.1-million long-distance tractor trailers in the U.S. were treated the potential of saving 6.5 billion gallons annually exists. This is about five times greater compared to savings resulting from maximizing the use of corn based ethanol.

REFERENCES


**CONTACT**

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**ADDITIONAL SOURCES**

[www.sinhatech.com](http://www.sinhatech.com): Information regarding further developments and availability of the Deturbulator on Sinhatech’s website.

**DEFINITIONS, ACRONYMS, ABBREVIATIONS**

FCSD: Flexible Composite Surface Deturbulator.

Deturbulator: A device for taking turbulent fluctuations out of a flow. Opposite to a turbulator which enhances turbulent mixing in boundary layers.