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Biomimicry as a tool for the Aerodynamic Drag Reduction of Class 8 Heavy Vehicle Trailers: A Computational Analysis and Wind Tunnel Study.

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Abstract

In August 2021, the Environmental Protection Agency (EPA), through its Clean Truck Plan, proposed new standards to promote clean air and reduce pollution from heavy-duty vehicles starting in model year 2027. One of the recommended approaches is for heavy-duty vehicles to improve fuel economy by 40% by the year 2027.

Class 8 trucks achieve fuel economy in the range of 6-8 miles per gallon of diesel. At speeds of 70 mph, 65% of the energy is spent in overcoming aerodynamic drag (McCallen et al., 1999), making aero-drag the largest opportunity for improving efficiency. A truck consists of a cab in front and a trailer in the back. Cab aerodynamics is well understood and modeled as is evident with the near-airplane-looking cabs on the roads with aero hoods, aerodynamic bumpers, streamlined mirrors, and roof extenders. The trailer has remained as cubical containers that are designed more for stacking and storage than being aerodynamic.

Inspired by the Boxfish hydrodynamics, different add-on shapes were used in CFD simulations to provide a streamlined shape to the trailer and its corresponding drag measured. A 3D-printed model of the cab and trailer with add-on attachments was tested in a wind tunnel to validate the simulation. When comparing the bio-inspired to a standard trailer, a drag reduction of 13.8% in computational and 16.7% in the wind tunnel experiments was achieved. These results translate to 14%-16% efficiency gains of Class-8 trailers by bio-mimicking the Boxfish.

Introduction

About 4.06 million Class 8 trucks are in operation in 2021, up 2.3% from 2020 in the USA. These categories of trucks have a load capacity of over 33,000 pounds (14,969 kg) known as their gross vehicle weight rating or GVWR. The category primarily consists of all tractor trailers. Heavy trucks and buses (primarily cuboidal containers on wheels) accounted for 18% of U.S. transportation energy use in 2019. Over 300 billion miles were traveled and 44.8 billion gallons of fuel were consumed by all registered trucks in 2020 (Davis & Boundy, 2022). Diesel fuel emits 22.44 pounds (10,180 grams) of carbon dioxide per gallon when combusted. This makes the trucks in the USA alone responsible for 1 trillion pounds of carbon every year. That much carbon is enough to cover the state of Massachusetts completely to a height of 50 ft (*How Much Is a Ton of Carbon Dioxide?*, 2020).

Current state of the art trucks deal with a speed averaged drag coefficient of 0.6 while they can broadly range from 0.6 to 1.0. Reducing the drag coefficient from 0.6 to 0.3 for a typical Class 8 tractor-trailer would result in a mileage improvement from 6.1 miles per gallon to 8.7 miles per gallon—a 43% savings (McCallen et al., 1999).

To reduce aerodynamic drag, the resistive force produced when the vehicle is traveling at high speeds through the medium of air needs to be minimized. There are two components of the resistive force that contribute to drag—pressure force and shear force. Shear force is the component of drag associated with friction. This relates to the material used for the truck which is difficult to change and manufacture on a large scale since truck and container manufacturing processes are already efficient and cost effective.

The other component of drag is the pressure force. This is governed by the separation of flow and has a direct impact on slowing down the vehicle. As the flow comes in from the front, it separates around the truck, forming a wake region of lower pressure behind the vehicle (Lo & Kontis, 2017). This wake can be considered as a vacuum pulling the truck backwards. With more air pushing the front of the truck than air receding from the back, a backward (vacuum) force is created. This force that gets created due to a pressure differential induced by flow separation is the pressure drag. The force of drag on an object moving through any fluid medium, is calculated as per the aerodynamic drag equation below.

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

EQUATION 1.

There are four variables directly proportional to the drag force, the density of air (ρ), the relative velocity of the air traveling against the direction of movement of the truck (v), the drag coefficient (C_D), and the frontal cross sectional area (A) perpendicular to the direction of relative airflow. The density of air, velocity of the air against the truck and the frontal area (defined by the cab) are all variables that cannot be changed. This leaves the drag coefficient as the variable that can be optimized to reduce the aerodynamic drag force on the object.

Biomimicry is the study of nature's models and using them as an inspiration for solving human problems; leaning on millions of years of evolution to supplement technological research. In the case of aerodynamic drag reduction, nature has several examples of species such as birds and fish that move through fluids as primary modality of transport. These species have evolved to adopt streamline shapes, appendages, propulsion techniques and surface materials to minimize energy required for their movement. Although dolphins and swifts are known for their hydrodynamic and aerodynamic shapes, one of the most impressive species when it comes to efficient hydrodynamics is the Boxfish.

In spite of its non-streamlined (box-like) appearance, the drag coefficient of the boxfish is just 0.2 (Summers, n.d.), which is comparable to some efficiently designed aerofoils used for airplanes, and is much lower compared to 1.5, the drag coefficient of a cuboid as is the case of our trailers (Kozlov et.al, 2015) or current tractor trailer trucks at 0.6 (McCallen et al., 1999). Comparing the flow pattern between the b=Boxfish (Summer, n.d.) and Cube (Fig 1) it is interesting to note how the Boxfish has eliminated the area of low pressure (flow reversal) around the back edges. Another interesting aspect of the Boxfish evolution is its low drag in the presence of large payload capacity. This maximizing of payload carrying capability while keeping the inefficiency of drag minimal is the optimization that is required for a trailer. The Boxfish has two aspects of hydrodynamics that can be applied to the trailer design. Streamlining the side horizontal profile of the container and streamlining the top down profile of the container. These design elements of the Boxfish, if replicated onto the trailer container, can be an effective way to reduce trailer drag.

Currently, there is an elaborate amount of research and advancements being made in the side and frontal profile of tractor/cab making them more aerodynamic using techniques such as vortex generators (Lav, 2013) and parametric modeling (Peng et al., 2018). Similar to the Boxfish, the cabs are more sharp nosed and have mimicked streamlined airplane noses. Building on top of this drag reduction of the cab by modifying the trailer is the objective of this research. The goal is to make the trailer more aerodynamic in the side as well as top down profile by replicating the

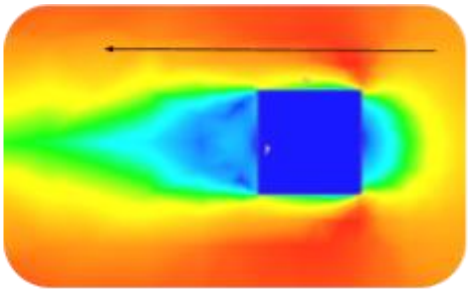

FIGURE 1. Flow around a cube.

design elements of the Boxfish body as closely as possible. In addition, adding a trailing tail would reduce the flow reversal and reduce pressure drag.

Constraints

The most ideal shape for a tractor-trailer would be an airplane wing on its side where its top down view is that of a symmetric aerofoil. This is not practical due to the fact that the containers are required to carry solid geometric shaped payload as opposed to airplane wings that only carry liquid fuel which can conform to any shape. In addition, requirements such as storability and manufacturability of trailer containers force us to solve a multi-faceted optimization problem. Due to these requirements, there were constraints in modifying the container since real world applicability of the design needed to be preserved. The curve of the body in any dimension could not be so extreme as to significantly increase the truck's cross sectional area—which would increase drag force (Eq. 1)—and also result in obstructing the view of the truck's side view mirrors. Secondly, the design should not reduce the inner volume of the trailer as that impacts capacity and any efficiency gains by compromising on internal volume would be offset by reduced payload carrying capacity.

Materials and Methods

The overall approach can be broadly broken down into three sections. First is the modeling of the geometry of the truck with inspiration from the body of a Boxfish. Next is to test it through computational simulations in the Autodesk CFD software. The third step is to validate these results by printing a scaled down 3D model of the truck and testing it in a wind tunnel setup. With simulation results and scaled down wind tunnel data, a strong conclusion can be made about the efficacy of the bio-inspired model's drag reduction compared to standard trailers.

3D Modeling

The body of the Boxfish derives its low drag characteristics from four main features. The snout which is sharp and reduces the direct impact area against oncoming air. The aerodynamic sharp nosed cab designs provide the same benefit and are not in the scope of this research. The second feature is that its two vertical sides are curved outward to form a simple aerofoil shape. The third feature is that the top and bottom of the Boxfish are also convex and allow for reattachment of flow. In this case since the bottom of the cab which is closer to the ground has wheels and axles populating the space the potential only exists to streamline the top of the container. Finally, the tail end of the Boxfish has a tapered design so as to minimize the flow separation around the edges of the back. The same can be modeled by using a rounded back tail as in Fig 2. Autodesk Fusion360 was used to design the 3D models. The models were built to be a 1:120 scaled down version of a standard semi (sized 48 ft in length, 8 ft width and 14 ft high).

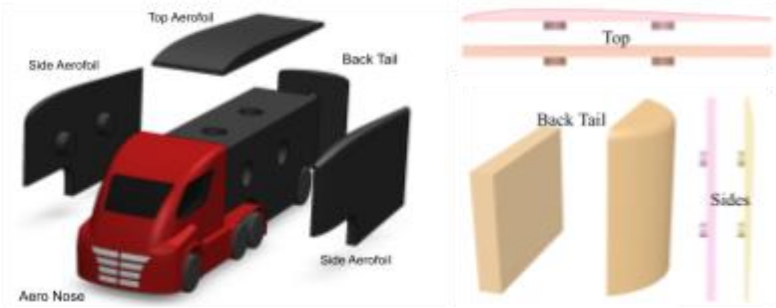

FIGURE 2. Assembly of bio-inspired add-ons of the trailer.

CFD Simulation

The computational simulations were conducted with the Autodesk CFD software with incompressible, laminar equivalent air flow at speeds of 20-70 mph in 5 mph increments. The truck's material was simulated to be Stainless-Steel 304. A virtual wind tunnel was built around the truck using the surface wrap feature of the CFD software. The virtual wind-tunnel was made significantly larger in both cross section and length relative to the truck so that the boundaries of the wind-tunnel don't interfere with the air flow around the truck. The two boundary conditions applied for the simulation were inlet velocity of the air (wind speed) and an atmospheric pressure of one atmosphere at the exit plane. The simulations were run through for 200 iterations to allow time for stabilized flow around the truck model. For most of the runs the flow stabilized at around 160 iterations.

Wind Tunnel Experiment

Based on the CFD analysis, the next step was to conduct experimental validation in a Wind Tunnel. In order to have the ability to perform a large volume of experiments a table top high precision wind tunnel was used. The experiment was run on a 120x scaled model of the real truck. The schematic of the table top wind tunnel is presented in Fig 3. The airflow was driven by a VIVOSUN T6 6 Inch 390 CFM Inline Duct Fan which supports variable airspeed through a regulator. 3D printed honeycombs were built into the inlet and exhaust to channel a laminar flow to the model in the flow chamber. This wind tunnel model was a suction type design. Inside of the tunnel a vertically oriented beam type, aluminum, one kilogram load cell with HX711 analog to digital weight amplifier module with a least count of 0.01 grams was used. This setup allowed the measurement of drag force created by the air pushing the truck with high precision. Since the two trailer models (bio-inspired and standard) have nearly identical cross sections, the frontal cross section area doesn’t change significantly and the velocity and density of the air is constant, so the forces induced by each truck model on the load cells is a direct function of the drag. The fully assembled 3D printed wind tunnel is presented in Fig 4. This model is built of 16 component pieces assembled together and held in place through tape and resin glue. The inner chamber was sanded down and coated with a layer of resin to eliminate any corrugations leading to potential flow interference. Experiments were performed in a suction type open wind tunnel. The suction tunnels have the fan placed after the test section as opposed to the blowing ones which have it before the test section. In the blowing type turbulence is created by the wake of the fan driving the air. This translates to longer honeycomb structures and meshes for the blowing type to straighten out the flow and therefore more energy to operate. The suction type has the advantage of a very low turbulence as compared to a blowing type and hence was ideal for this research.

FIGURE 3. Schematic of wind tunnel design.

FIGURE 4. 3D Printed and assembled wind tunnel (left) and Pedestal Load Cell Arrangement (right).

After observing multiple load cell configurations to measure drag, the pedestal configuration was the one which was able to successfully isolate the drag force (Fig. 4, right). Other configurations ended up generating torque around the load cell's pivot point due to the lift force in addition to the drag. This contaminated the readings of the load cell. In the pedestal configuration, the load cell was placed at the bottom of the truck and the truck transferred the drag force to the pedestal through friction on the resting surface. To accommodate for errors in setting up the tests, such as minor changes in positioning of different parts, 10 trials of the experiment were performed at each tested speed for each model of the truck. For every instance, it took about 30 seconds for the flow to stabilize around the vehicle. Allowing the flow to settle led to a stable drag force reading from the load cells.

Results

Computational Fluid Dynamics Analysis

The CFD visualization of air speed at 70 mph is presented in Fig 5. On the left is the top down view of the trucks and on the right the side on view. Blue and green colors represent low air speed.

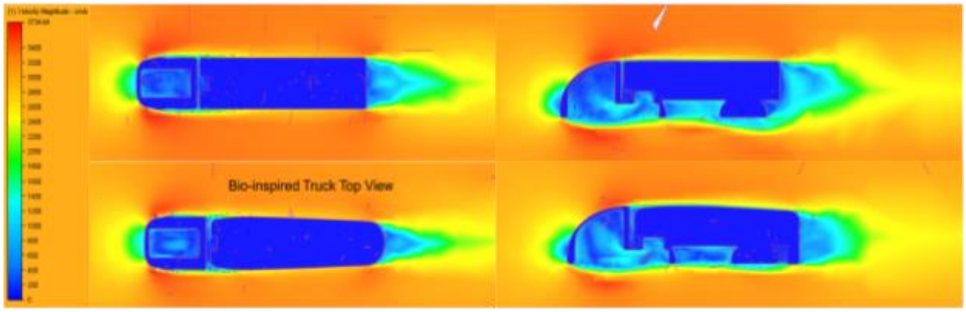

FIGURE 5. Air speed around the base truck (top) and bio-inspired truck (bottom) in the CFD simulation at 70 mph.

Any trailing blue-green behind the truck (in the wake) is indicative of lower air speeds and this translates to a pseudo-vacuum that pulls the truck back. Roughly this volume can be considered to be proportional to the air drag on the tractor trailer. The wake region is a region that contains lower velocities than the surrounding area, which leads to a vacuum, causing the backward force on the truck which is the drag force. As seen in the top views in Fig 5, the wake region is significantly smaller for the bio-inspired model (bottom frames) than the base model (top frames), meaning a much lower drag force. Merging together the side and top views, it is evident that the total volume of the wake region is smaller for the biomimicry truck. One more thing to observe is that when modeling a bio-inspired trailer, the vacuum along the bottom of the truck and wheels decreases as well. By modifying the exteriors to be close to the shape of a Boxfish there is a substantial decrease in wake region. This is supported in the data in Fig 6 as well, with the standard truck producing a higher drag force for the entire air speed spectrum. As seen in the graph, the force of drag increases exponentially in relation to the wind velocity, which is backed up by the (Eq 1) drag force formula. The standard tractor trailer’s drag coefficient was measured to be 0.65, compared to the bio-inspired version having a drag coefficient of approximately 0.56. In the simulations, there was a speed averaged reduction of 13.8% in drag force when comparing the standard trailer to the bio-inspired trailer design.

Experimental Analysis

The wind tunnel experiments were conducted at 5 different air speeds and the drag force for each speed measured on both the base truck model and the bio-inspired model across 10 trials for each wind speed. The drag force saw a reduction of 20.5% for the bio-inspired model at the highest speed and 12.7% at the lowest wind speed with a speed averaged reduction of 16.7%. Once again the quadratic nature of the graph correlates with Eq 1.

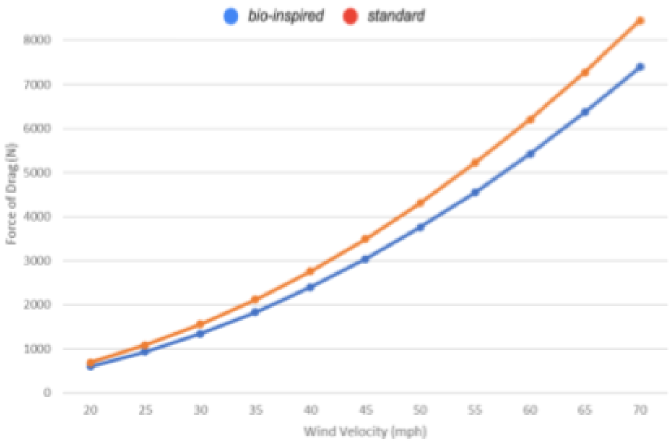

FIGURE 6. Bio-inspired vs standard truck computational drag force.

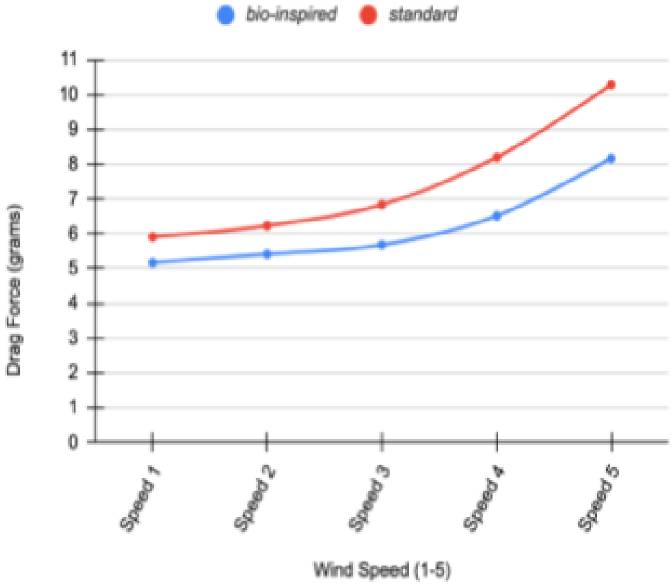

FIGURE 7. Bio-inspired vs standard truck experimental drag force.

Discussion

Both the computational simulation and experimental wind tunnel analysis show comparable results with a 13.8% (computational) and 16.7% (experimental) reduction in speed averaged drag force when the trailer model is adapted to the bio-inspired design of the Boxfish. These results are comparable to the reduction in drag force achieved by using other add-ons such as, 19.1% with cab fairings (Markina et al., 2020), 15% by using a base flap device and 10% by using side skirts for the trailer (McCallen et al., 2004).

The drag reduction in experimentation is higher compared to the simulation (16.7% compared to 13.8%). The experimental models were 3D printed at the highest resolution supported by the printer leading to smooth surfaces and rounded edges. In the simulations the number of triangles in the mesh had to be reduced in order to have the CFD software run efficiently in a reasonable amount of time. This meant that the structure was coarse-grained in its geometry compared to the 3D printed model, leaving some surfaces that were not entirely smooth or as aerodynamic as they were in the experimental model. This accounts for the difference in measurements.

In the wind tunnel set up, walls have an impact on the individual results due to streamline compression and frictional wall forces. These values, although impacting the actual raw numbers of the drag force, will remain similar for either truck model at the same wind speed. This allows for a valid comparison between the induced drag of both the models to still be made. However, in the future this can be addressed by applying friction reducing paint to the insides of the wind tunnel as well as material of the truck and by increasing the size of the flow chamber to minimize streamline compression.

Limitations & Future Work

There are two variants of class 8 trucks. One of them are the unibody trucks where the container is completely attached to the chassis. Some examples of these trucks include mail trucks, moving and delivery vehicles. The concept presented in this paper can be directly applied to these types of trucks as the containers do not need to be detached after manufacturing. The other category is where the container is rectangular in shape and is detachable from the truck. This is a limitation of the proposed solution as these containers need to be maintained as lego blocks for packing, stacking and storage at scale. Modification to their structure can have unintended consequences with respect to other arms of logistics like cargo and freight. Additionally there are millions of these containers currently in circulation that make the possibility of complete swap out almost impossible and economically intensive. In this scenario add-on shapes (Fig 2) can be used that could be attached during transport and detached post transport. This mechanism of adaptation during movement would allow for scalability of this solution across a wider fleet of vehicles.

Conclusion

Biomimicking a Boxfish for a trailer of a Class 8 truck can have a drastic impact on aerodynamic drag. Modifying the sides, top, and back of the trailer to resemble the Boxfish significantly diminished the wake region and flow reversal at the end of the trailer. Furthermore, when testing the bio-inspired model the drag reduction was found to be 13.8% with a drag coefficient reduction from 0.65 (standard trailer) to 0.56. To validate this data, wind tunnel experimentations were conducted where speed-averaged drag force reduction was 16.7%. This translates to 60-85 million tons of carbon emissions reduction when applied to all Class 8 trucks across the US alone. To put this number into perspective, the countries of Norway and Sweden together emitted 55 million tons of carbon in 2019 (Ritchie et al., 2020).

Streamlining the trailer in addition to the cab and reducing the wake region by adding a tail are novel ways of applying bio-inspired engineering to vehicle design and can be a major contributor to reduction of carbon emissions.

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