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Institutionen för Energivetenskaper

MMVN01

Aerodynamics and compressible flow

Group assignment

The impact of advanced aerodynamic modification on heavy duty truck

Authors:

Tanuj Nagentra Ramachandran

Reco Rambang Putra Negsagis

Victor Soomus

Advisor:

Pierre Vauquelin

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Table of Contents

1 Introduction

As the world moves towards a greener future the need for sustainable ways of transporting goods is greater than ever. The emissions caused by transportation are, according to Statista [1], 21% of the total worldwide carbon dioxide emissions. Out of these 21%, almost 30% are caused by truck freight. Therefore reducing the amount of carbon dioxide emitted by trucks is a vital part of our possibly green future.

A part of reducing these emissions is reducing the amount of fuel used when driving. A lot of work is put down into making the combustion engines more effective or switching to an electrical motor but one thing that is often disregarded is the aerodynamic properties of the truck. Streamlining the shape of the truck makes it more aerodynamically efficient which reduces the amount of force dragging it backwards when driving. Trucks today are not very effective in this aspect and contain big gaps and big flat areas where the incoming air creates high pressure-areas in the front and low pressure-areas in the back.

In this paper six different modifications to effectivize the aerodynamic properties of a truck are evaluated. Five of them are physical modifications mounted on the truck while one of them is an active system which responds to the temporary conditions of the truck and adjusts to make it as effective as possible.

Reviewing the aerodynamic properties of a truck and effectivizing these reduces the drag coefficient (eq. 1) of the truck which directly affects the amount of fuel used which in turn, reduces the amount of carbon dioxide released from the truck.

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 A} \qquad \text{(Equation 1)}$$

2 Literature review

The information presented in this report was obtained from Google Scholar, ResearchGate, and internet-based resources to review methods of aerodynamic drag reduction for heavy-duty trucks. Different passive and active aerodynamic modifications such as sloped nose, boat-tail, wheel deflector, vortex generator, and side skirt were studied using pertinent papers and publications.

3 Theory

3.1 Sloped Nose (BET):

Aerodynamic drag acts as one of the deciding factors, as it has a direct impact on fuel efficiency and the performance of the heavy-duty truck. It has been said that the aerodynamic drag constitutes 65 percent of the total resistive force that the truck has to overcome, particularly on the highway. The frontal geometry of the truck plays an important role in this phenomenon. In figure 1 it's visible that the conventional truck design has abrupt changes in the surface geometry, sharp edges, and a flat frontal face, which leads to increased stagnation pressure as air completely stops and creates high drag and affects streamwise flow continuity. In the Generic conventional model, a large recirculating wake region is formed at the rear of the truck due to the flow detachment that happens at every sharp abrupt region like windshield and vertical front surface junction. This phenomenon also contributes to turbulent kinetic energy dissipation, which ultimately corresponds to the reduction in fuel efficiency and the vehicle performance. The aerodynamic performance of the Generic Conventional Model truck was analysed through computational fluid dynamics (CFD). The results illustrate that flow separation at the front part of the cabin creates vortex shedding and high-pressure differentials, which are responsible for the increased aerodynamic drag forces.

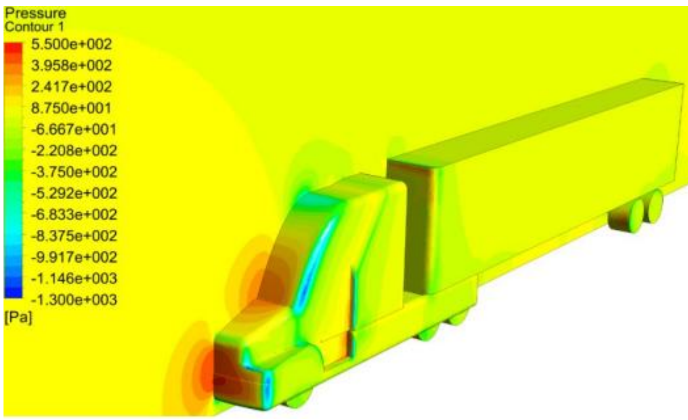

Figure 1: Pressure distribution over GCM [7]

The sloped nose design acts as the advanced aerodynamic technique to overcome these problems by enabling smooth airflow along the vehicle's surface. CFD simulation utilizing Reynolds Averaged Navier-Stokes (RANS) equations with a realizable k- ε turbulence model under highway rolling conditions was used. By adopting the curved and sloped nose profile, the following observations were noted.

First, reduced stagnation pressure as the rounded nose decelerates the airflow at the front grille and minimises pressure-induced drag as shown in the figure 2. Secondly, it delays the flow separation with the help of gradual slope transition, which ensures the flow is attached over the windshield, thereby reducing the flow detachment and forming a shear layer. Thirdly, it mitigates the interaction of the turbulent boundary layer, which leads to laminar airflow structure; therefore it reduces the intensity of the vortex. Wake energy reduction was also noted due to the streamlined frontal profile that helps to maintain the flow stability. The CFD confirms that these techniques help to reduce the overall aerodynamic drag coefficient by 35.5% without compromising cargo volume.

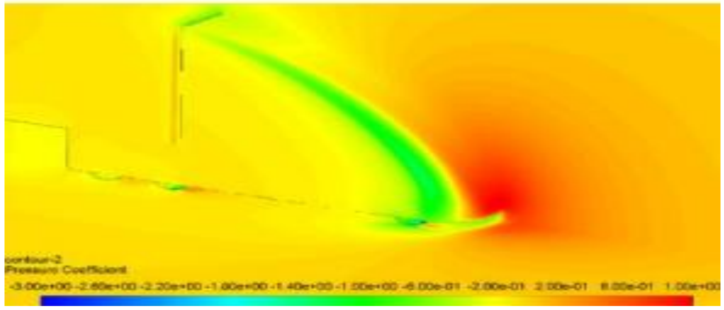

Figure 2: Pressuredistribution over sloped nose design [7]

The Implementation of these techniques can be seen in modern day trucks, such as the Tesla Semi, Volvo Super Truck which ensures that the aerodynamic efficiency of the truck increases and enhances the fuel efficiency.

Conclusion: As the freight industry is transitioning towards the sustainable path, these techniques help to achieve them by increasing fuel efficiency, thereby resulting in the decrease in emissions [7].

3.2 Boat-Tail Extensions:

A Boat-Tail extension is a construction mounted on the back of the truck to reduce drag. They reduce drag by smoothing out airflow and decreasing turbulence around and behind the truck. As the truck moves forward a vacuum is created behind it which creates drag which slows the truck down. This is caused by the fact that the shape is not streamlined in any way as it is an abrupt end to the shape. Using a boat-tail extension the shape is instead tapered at the end which allows the air to flow more smoothly as the airflow is attached longer. By using this extension the entire end-shape is also narrowed which makes the wake narrower and thus reduces the suction effect created by the vacuum.

The efficiency of these extensions are affected by the length as well as the angle. Because of limiting legislation you cannot make the extensions too big as there is a limitation of length of vehicles.

Below you can see an example of how a boat-tail extension affects the airflow.

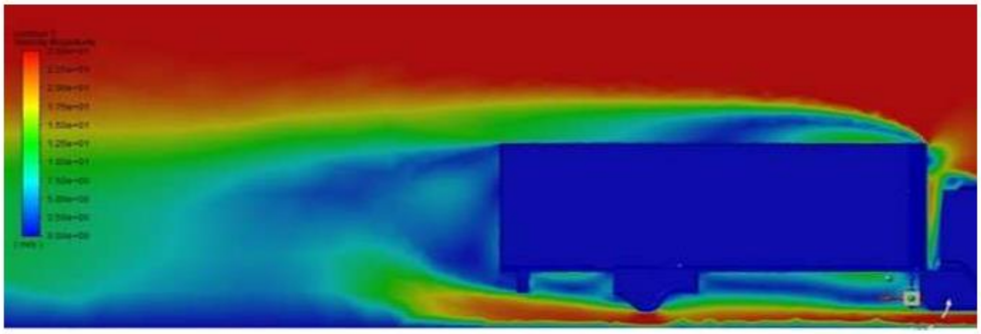

Figure 3: Side view of velocity for baseline truck [2]

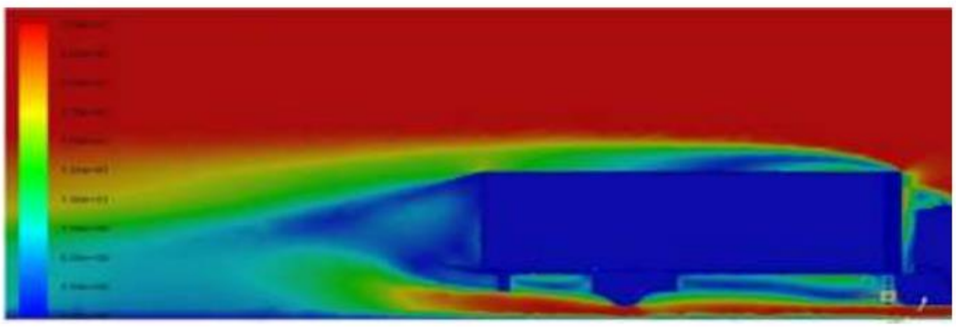

Figure 4: Side view of velocity for flat tail boat at 20 degrees [2]

As you can see the boat-tail increases the likeness of a streamlined body and reduces the vacuum created behind the truck.

Using these kinds of instalments can reduce the drag coefficient up to 9% according to Lee et al. [3].

3.3 Wheel Covers and Deflectors:

Wheel turbulence is a significant contributor to aerodynamic drag in vehicles, reducing efficiency and increasing energy consumption. Wheel covers and deflectors are two key solutions used to mitigate this issue.

Wheel covers smooth airflow by enclosing the wheel's surface, preventing air from getting trapped between spokes and reducing vortex formation. This leads to lower drag and improved efficiency. An experimental study demonstrated that combining wheel covers with full underbody coverage resulted in an 18.1% reduction in drag, compared to a 17.8% reduction with only underbody coverage [4].

Final Drag Comparisons			
Test Number	Features	Drag Coefficient, C_d	Drag Reduction, %
1	Car Only	0.6890	-
2	Wheel Covers Only	0.6566	4.70%
3	Fairings Only	0.6732	2.29%
4	Wheel Covers & Fairings	0.6583	4.45%
5	Back Air Dam Only	0.6822	0.99%
6	Side Air Dams Only	0.6594	4.30%
7	Front Air Dam Only	0.5889	14.53%
8	Front & Side Air Dams	0.5567	19.21%
9	All Air Dams	0.5561	19.29%
10	Wheel Covers & Air Dams	0.5779	16.12%
11	Fairings & Air Dams	0.5790	15.96%
12	Full Underbody Coverage	0.5666	17.77%
13	Wheel Covers & Underbody	0.5645	18.07%
14	Fairings & Underbody	0.5865	14.88%
15	All Features	0.6100	11.46%
16	All Features & No Windows	0.6533	5.19%
17	No Windows	0.7233	-4.97%

Figure 5: Feature combinations with their corresponding drag coefficients and drag reductions [6]

Wheel deflectors, small aerodynamic components placed in front of the wheels, help redirect airflow around the tires rather than letting it hit them directly. This minimizes turbulence, reduces drag, and enhances vehicle stability at higher speeds. Automakers integrate these features into modern fuel-efficient cars to meet stringent efficiency regulations [5]. Conventional Deflectors, while intended to divert airflow from the wheels, some studies have found that conventional deflectors can inadvertently reduce overall drag by up to 10% [6].

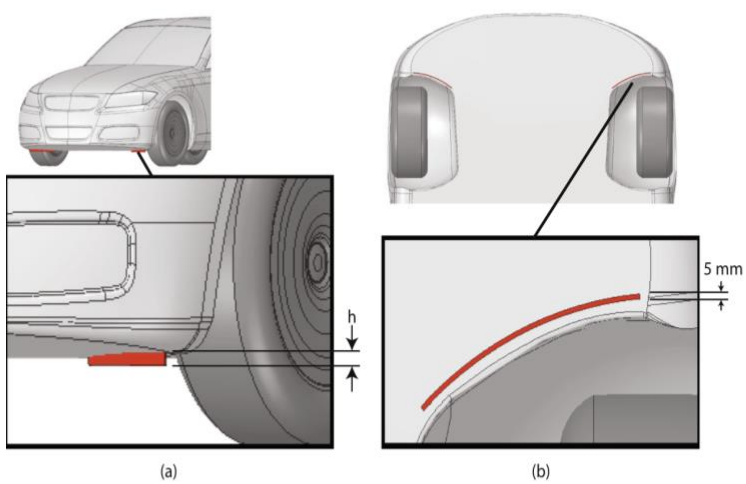

Figure 6: Notchback DrivAer model with a conventional wheel deflector (**a**) front view and (**b**) bottom view [6]

In summary, the application of wheel covers and deflector designs can lead to reductions in the drag coefficient, ranging from modest decreases with wheel covers to more substantial improvements with optimized deflectors.

3.4 Side Skirts:

Skirt panels, or side skirts, are aerodynamic components installed along the lower edges of trailers to improve airflow and reduce drag. These panels work by preventing air from flowing underneath the trailer, thereby minimizing turbulence and lowering aerodynamic resistance. Studies have shown that side skirts can reduce overall drag by 4% to 7%, leading to fuel savings of 5% to 7% in highway conditions [8].

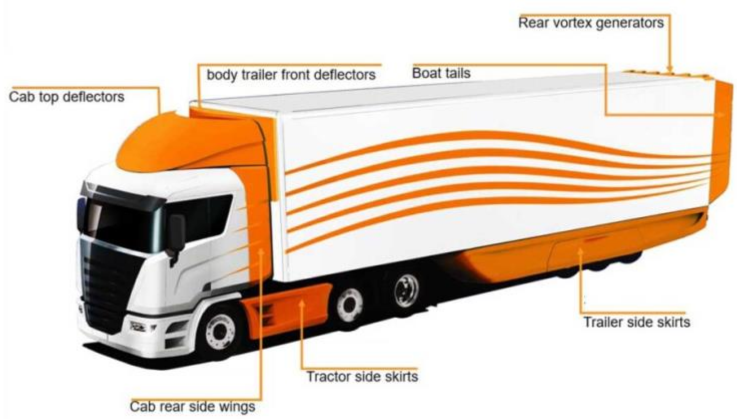

Figure 7: Side skirts on truck [8]

The effectiveness of skirt panels depends on their design and placement. Research indicates that full-length skirts covering the entire trailer bottom yield the greatest aerodynamic benefits. Computational Fluid Dynamics (CFD) simulations confirm that side skirts improve pressure distribution along the trailer body, reducing the formation of wake turbulence [9].

Many fleet operators have adopted skirt panels to comply with fuel efficiency regulations and reduce operational costs. As sustainable transportation becomes a priority, advanced skirt panel designs continue to evolve, offering greater performance and aerodynamic efficiency.

3.5 Vortex generators:

Vortex Generators: The boundary layer slows down as it moves along the vehicle's surface due to friction and pressure gradient. VGs introduce small swirling air patterns called vortices. These vortices mix with fast moving outer airflow with the slower moving boundary layer air, resulting in momentum increase of the boundary layer. This phenomenon results in reduced wake size and thereby decreasing the pressure drag.

A case study was conducted on Vortex Generators by the green truck partnership, which aimed at calculating fuel efficiency, greenhouse gas (GHG) emissions, and economic benefits by comparing the baseline model without VGs to the trial model with VGs. The study was conducted after achieving a comparable duty cycle by achieving a similar engine load and speed profile.

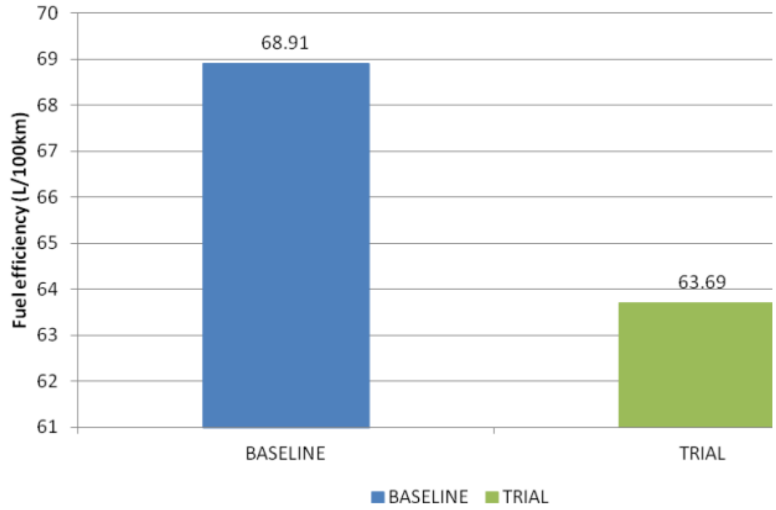

Figure 8:Comparison of vehicles fuel consumption across baseline and trial model [10]

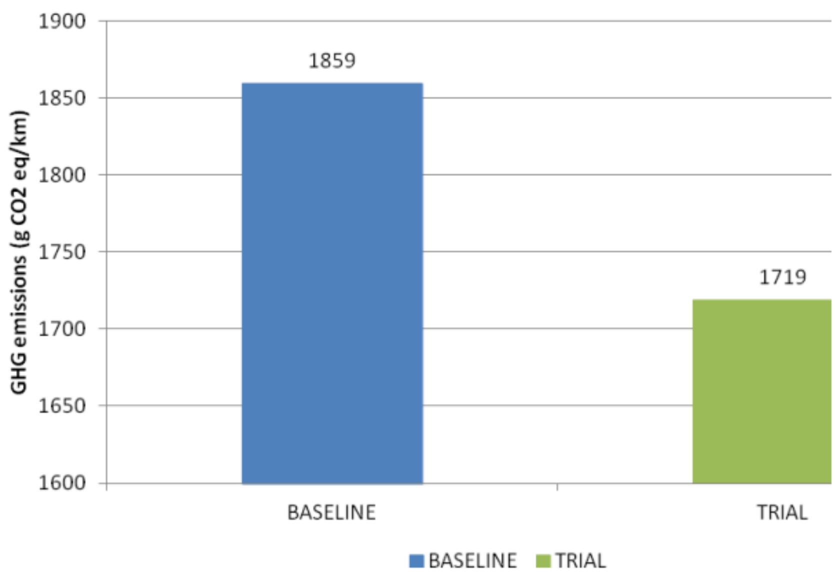

Figure 9:Comparison vehicles GHG emissions across baseline and trial model [10]

From figure 8 and 9 it is evident that 5 to 8 percent improvement was seen in fuel efficiency, with corresponding decrease in the emissions up to 140 g CO_2-e/km thereby leading to annual cost saving of $10,900 per truck based on an operational distance of 150,000 km per year [10].

4 Emerging technologies

4.1 Shape memory alloys:

SMA are called morphing materials as they are capable of undergoing reversible thermoelastic phase transformation from martensite to austenite phase. SMA can be used to manufacture the side skirts, as these are widely accessible for application in active aerodynamics systems. The trucks installed with SMA-made side skirts have enhanced aerodynamics. At low speeds, the side skirts remain in the martensitic phase and have a highly twinned microstructure, enabling them to stay in the retracted position and minimizing unwanted aerodynamic drag. As the speed of the truck increases, the surrounding airflow cause an increase in temperature. This thermally induced phase transforms the phase from martensite to austenite and leads to the deployment of the side skirts. In this deployed state, the side skirts help to reduce the flow separation and wake turbulence, increasing the fuel efficiency. The main advantage of this way is that the aerodynamic efficiency is increased without any mechanical actuation thereby eliminating the energy need [11].

5 Challenges and Limitations

Using these aerodynamic modifications are not a given and there are multiple limitations to these technologies. A large part of this is because the trucking industry has been a big part of society for a long time and is not prone to change. There is a different standard in different parts of the world which also makes it more difficult to create a modification that works everywhere.

If you want to have a rounded or sloped nose you have to redesign the entire chassis of the truck which is expensive for automobile manufacturers which makes it more expensive for the trucking companies. It is also difficult to refit already existing trucks with this technology since the chassis has to be rebuilt.

All countries, though varying, have a maximum length of which a truck can be. Often trucks are at this max length to maximize the amount of space in the trailer. This can make it so you can’t mount a boat tail on the truck since that would mean that the length of the truck exceeds that of which is legal. Even if a country makes a length-exception for these kinds of aerodynamic installments, since a lot of trucks trek entire continents there is not a guarantee that these modifications will be legal everywhere.

6 Conclusion

The study on truck aerodynamics highlights the significant role of aerodynamic modifications in reducing drag and improving fuel efficiency in heavy-duty trucks. Given that truck freight is responsible for a substantial share of global carbon emissions, enhancing aerodynamic efficiency is crucial for sustainability.

Several aerodynamics modifications were analyzed, including sloped noses, boat-tail extensions, wheel covers, deflector, side skirts, and vortex generators. Each of these modifications demonstrated measurable reductions in drag, with sloped noses achieving up to a 35.5% reduction in drag coefficient,wheel covers with full underbody coverage resulted in an 18.1% reduction in drag, boat-tail extensions reducing drag by 9%, and vortex generators improving fuel efficiency by 5–8%. These reductions directly contribute to lower fuel consumption and reduced carbon dioxide emissions.

Furthermore, emerging technologies like shape memory alloys (SMA) offer new possibilities for active aerodynamic systems that adapt to changing driving conditions without requiring mechanical actuation. Despite these advancements, challenges remain, such as regulatory constraints on vehicle length, high retrofitting costs, and regional differences in standards. Addressing these barriers will require collaboration between governments, manufacturers, and logistics operators.

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