MTF236 - Road Vehicle Aerodynamics
Department - Mechanics and Maritime Sciences
Mobility Engineering, Master of Science Programme

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Contents

1 Introduction

The aim of this report is to identify potential aerodynamic improvements for a truck as a group, with the aim of reducing its drag, and to test them in a wind tunnel. Initially, the Computational Fluid Dynamics (CFD) model of the truck was examined during the post-processing workshop to identify potential areas of improvement and to familiarize with the aerodynamic conditions. Subsequently, several areas were identified and implemented on a actual scale model during a separate building session. Various materials were used in this process, which will be discussed later. The developed enhancements were then tested in the wind tunnel, and the measurement results were recorded. During this process, the task was to measure the forces acting on the truck, and subsequently calculate the aerodynamic lift and drag coefficients. This was carried out for various velocities, employing a technique known as Reynolds sweep. Additionally, visual methods such as smoke and tufts were utilized to render the aerodynamic behaviour of the truck visible. Specifically for the truck, the objective was to investigate the extent to which the aerodynamic optimizations affect forces at yaw angles. This report will provide a theoretical background and explain the method described in detail. The collected results will then be compiled and evaluated. Finally, the findings will be categorized, in particular to what extent some of the measurements could be implemented in reality.

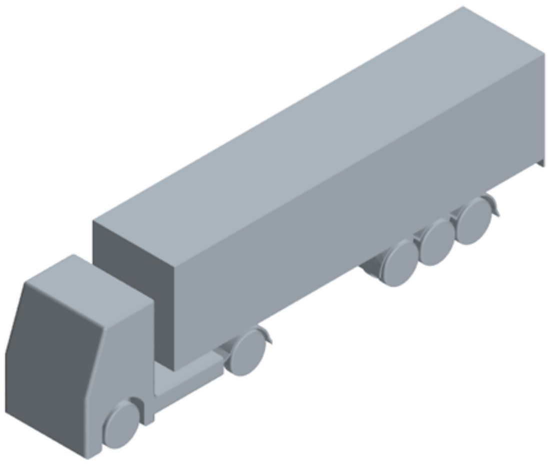


Figure 1: Original truck model

2 Theoretical Background

Aerodynamics of trucks is an important field of research, as it has a direct influence on the fuel consumption, stability and safety of these vehicles. In simple scientific terms, a truck can generally be divided into a tractor and a trailer. The tractor is the main vehicle with the engine, while the trailer is unpowered and responsible for carrying the load. Vehicle aerodynamics, which focuses on how air moves around vehicles, are particularly important at high speeds. When it comes to optimizing aerodynamics, the focus is primarily on vehicle types used in intercity and long-distance transport, where higher speeds are driven. These trucks have long lifespans and a high number of registrations, so optimizing their aerodynamics to save energy and money is significant. In addition, the aerodynamic development of these vehicles has an enormous influence on the reduction of CO2 emissions. **[Schütz 2023]**

The primary source of aerodynamic resistance is pressure resistance, which accounts for over 92% of the total, while friction resistance has less influence. Pressure resistance arises from the significant pressure difference between the front of the truck, where high pressure develops, and the back of the trailer, where a low-pressure, so called wake, forms. The gap between the trailer and the tractor also significantly affects aerodynamic resistance.

The impact of drag reduction for a typical $40t$ standard truck in terms of energy consumption depends on the road profile and driving speeds. Reducing drag by 10% can save up to 3.5% of fuel in a flat driving condition. In the case of an electric truck, this corresponds to an increase in range of 4.5%. Air resistance is the second largest driving resistance in normal driving mode. 30% of the energy provided by fuel is to overcome driving resistance. 40% oft this 30% is to overcome the air resistance. Hence, 12% of total fuel consumption is used to overcome air resistance. **[Schütz 2023]**

Due to their large surfaces, height and shape, high center of gravity, aerodynamic properties and driving at low speeds, crosswinds have a significant impact on trucks. These factors make them susceptible to lateral forces and lift forces, which can lead to instability and hazards on the road. Therefore, aerodynamic improvements and safety measures are crucial to minimize the influence of crosswinds on trucks and ensure road safety for the truck and other road users. These include aerodynamic improvements such as side panels and spoilers, which can direct the airflow around the vehicle and reduce lift. **[Schütz 2023]**

The development and improvement of the aerodynamics of commercial vehicles is subject to strict regulations. The specified length and height measurements play a particularly important role here, as these are generally fully utilized to achieve maximum loading space. The EU Directives 96/53/EC and 97/27/EC are the relevant documents that contain the applicable laws for trucks. This leaves little scope for optimizing the aerodynamics of the vehicle. **[Schütz 2023]**

In addition to the legal regulations and economic aspects, analyzing the vehicle aerodynamics is another challenge. For a wind tunnel test on a 1:1 scale, a very large wind tunnel is required and there are only 3 available full scale wind tunnels all over the world. Moreover larger vehicles cause too much obstruction in the measurement section, both transversely and longitudinally. They must therefore be examined on a smaller scale, also to avoid high costs and enormous effort. This aspects are exacerbated by the fact that crosswind influences also need to be investigated, this is why the vehicle was tested at different yaw angles, rotating it up to 10° during wind tunnel testing, using the model shown in Fig. 2. It should be noted that, as with all model measurements, the Reynolds number dependency must be taken into consideration. With a scale of 1:4, the inflow velocity must be increased by a factor of four. For this reason, models with a scale smaller than 1:4 are avoided for such measurements, because flow effects and model inaccuracies can have an unpredictable influence on the measurement. In addition to the wind tunnel tests, it is also possible to investigate the aerodynamics using CFD simulation or driving tests. Through the huge effort for wind tunnel testing, the simulation of the aerodynamic of a truck is becoming more and more important. **[Schütz 2023]**

Figure 2: Truck original configuration with tufts

3 Methodology

This section presents the methodology used to develop a truck model with lower drag than the baseline model, at different yaw angles. The methodology includes three stages: identification of problem areas, design and fabrication of modifications and finally wind tunnel testing.

3.1 Identification of problematic areas

In order to identify the aerodynamically critical areas of the truck, at first the model was examined using a CFD simulation. To do this, a CAD file of the model was uploaded to the simulation software STARCCM+ and the conditions for the simulation were defined. For the CFD simulation, the model is placed in a virtual wind tunnel and is subjected to a frontal air flow at a speed of $v = 35\,m/s$. As in the wind tunnel, the air moves around the truck, which instead is fixed. The most important key figures where the drag and lift coefficient. The drag coefficient has a value of $C_d = 0.572$ while the lift coefficient of the truck has a value of $C_l = -0.153$. After calculating the coefficients the visual analysis of different figures was carried out.

At first, we plotted the dimensionless pressure coefficient C_p of the truck. The coefficient is the ratio of the relative static pressure divided by the dynamic pressure. Because the value is dimensionless, the result of different aerodynamic configurations of a model can be easily compared with each other. The result of the simulation can be seen in the Fig. 3.

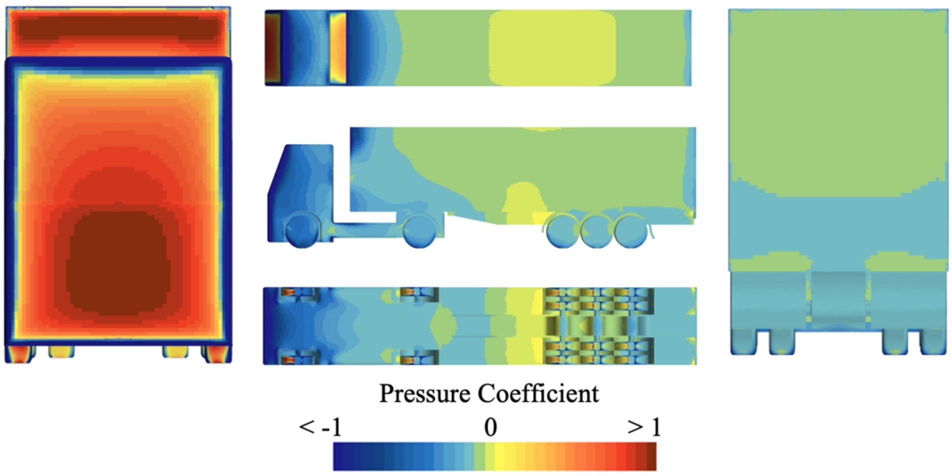


Figure 3: Pressure Coefficient

As seen in Fig. 3 the pressure coefficient is very high in the projected frontal view. This indicates that these surfaces experience high pressure and therefore create drag due to the pressure difference with the back of the truck. In the side view areas a low pressure coefficient at the front of the truck can be observed. This indicates that the flow is accelerated due to the low pressure. The same phenomena is seen on the top view and the bottom view. The rear has a pressure coefficient of roughly zero.

In the next step, we simulated and analyzed the air speed around the truck. For an incompressible and stationary flow in a gravitational field, the energy, which is composed of the potential energy, the kinetic energy and the pressure energy, is always constant along a flow line. This means that areas with a low pressure have a high velocity and at high pressures the velocity is low. By looking at the results in Fig. 4, three red areas with a very high flow velocity can be observed, together with the pronounced dark blue areas, indicating low flow velocity.

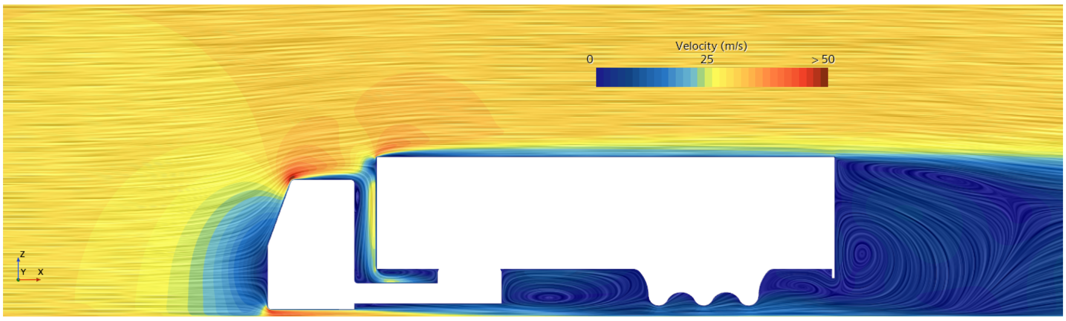


Figure 4: Velocity over the truck

The stagnation area with the dynamic pressure is located in front of the vehicle. At this point, the speed is zero and the pressure is very high. The truck pushes the air in front of it. The size of the stagnation area depends on the area and shape of the cab. The same effect can be seen on the trailer front area above the cab. There, a smaller stagnation area is present because the air is not directed over the trailer, it instead hits the vertical trailer front. In the gap between the cab and trailer, the speed directly behind the cab is close to zero. This is because the air is directed through the cabin around the area directly behind the cab when the airflow is frontal (yaw angle $= 0°$). The closer to the trailer, the greater the speed. This shows that there is flow re-circulation and turbulence in the rear part of the gap. This effect is related to the fact that the flow is separated after it has passed the outside of the cabin and creates turbulence. Also, there are no body elements that guide the flow to the outside of the trailer.

The speed under the trailer is low. The stream lines show that the flow under the trailer swirls strongly both in front of and behind the tires. Behind the trailer is the wake zone, where the air speed is slow, which indicates a negative pressure. In addition, the flow lines again show strong re-circulation.

The first high speed area (red color) is located at the highest point of the cabins roof. There, a sharp edge is present at the transition from the vertical front of the vehicle to the roof, which causes the flow to detach from the surface and the speed to increase. A second critical red area can be found at the front end of the trailer roof. There, another a sharp edge is present, which causes the flow to detach. However, this area is not quite as pronounced as the first area on the roof of the cabin. The third area where the fluid velocity increases significantly is on the underside of the truck. The air flows from the stagnation area in front of the vehicle under the truck, but the available cross-sectional area is limited, this is the reason why the speed of the fluid flowing through increases.

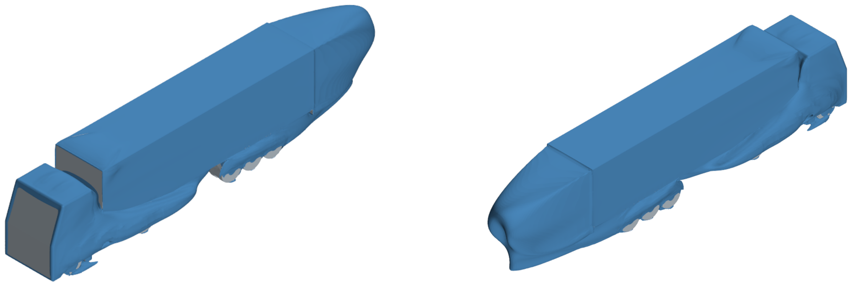


Figure 5: Isosurface of the truck

In Fig. 5 the wake of the truck is visualized with an isosurface. The surface shows where $C_{p,tot} = 0$. This gives an idea of the wake size and shape around the truck. Because of the sharp side edges of the truck the flow separates and creates wake zones at the sides of the cabin. This flow reattaches again because the truck is sufficiently long. The created turbulence at the tires elongate the detached flow. After the last axle of the tractor the wake gets suck into the space under the trailer before the axles and tires of the trailer create a wake again. The biggest wake is at the rear of the trailer. This is mostly because the trailer is shaped like a bluff body and ends sharply, without guiding the flow.

Observing the accumulated drag coefficient plot in Fig. 6, two main areas creating drag can be once again identified. As already described, the stagnation pressure in the front of the cab and in the upper part of the trailer create drag the most drag, consequently they need to be addressed.

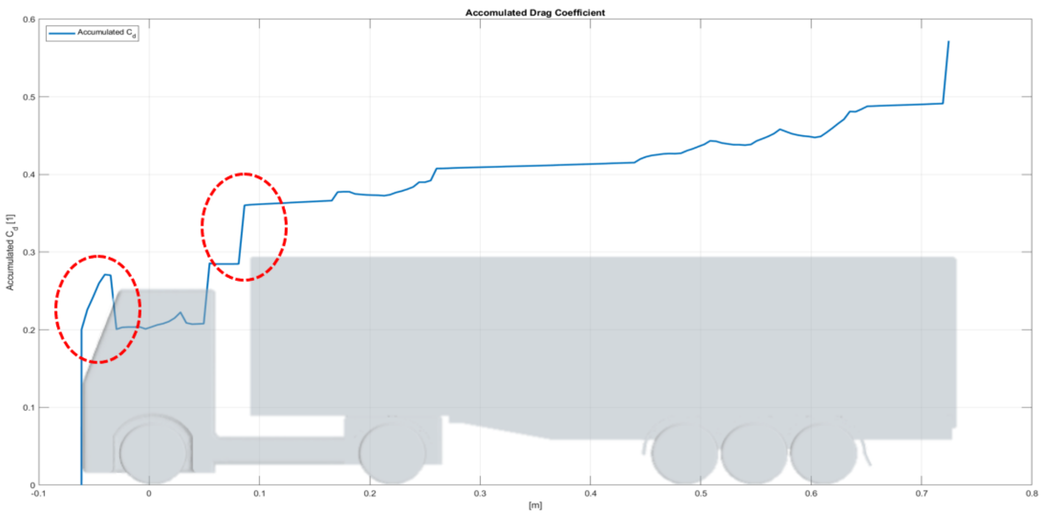


Figure 6: Accumulated C_d in X direction of the truck

After studying the CFD results the critical areas where improvements could be made are identified. The areas are shown in Figure 7.

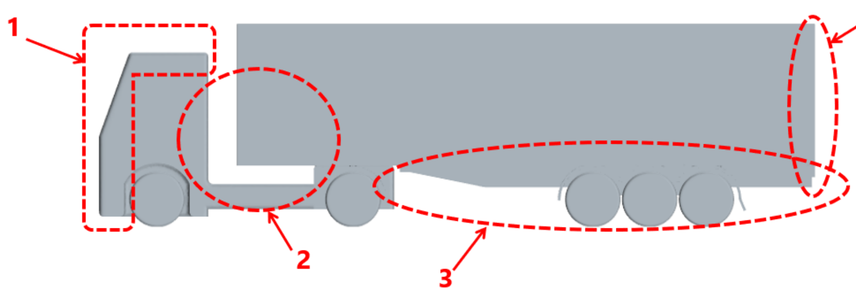


Figure 7: Identified areas of improvement

The most important area of improvement is the front of the cab and the upper part of the trailer which faces the driving direction. There is, as mentioned before, a high pressure coefficient on both surfaces which have a big impact on the drag and therefore also high potential of improvement. The idea is to better guide the flow over the cap also around the sides. The second area is addressing the gap between tractor and trailer. Figure 8 shows the air stream over the gap between the tractor and the trailer.

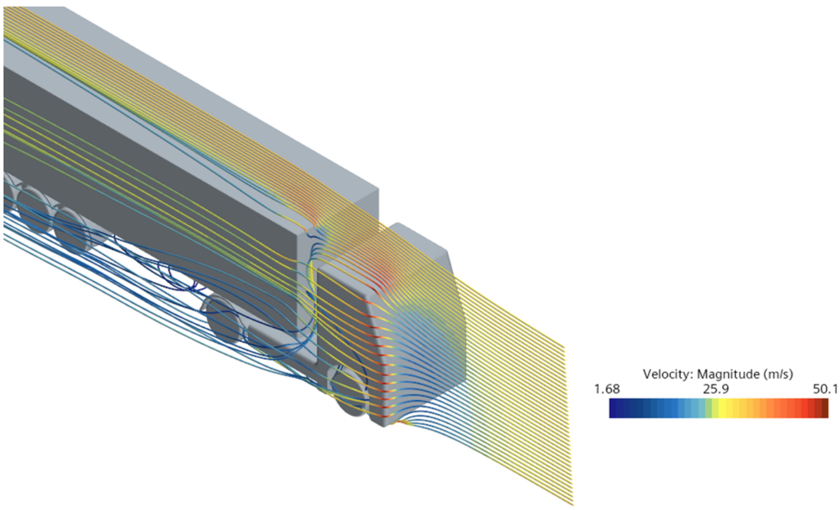


Figure 8: Flow disturbance between tractor and trailer

A cover up would prevent the interaction between both truck sides which is critically important when driving in cross-winds. Additionally the flow will not be sucked into the space between tractor and trailer. The third area is the whole open under body of the trailer. This allows air to also be sucked in, which is observed in Fig. 8, and creates re-circulation and detachment of the flow. A cover here would prevent that and also improve cross-wind stability. The fourth and final area is located at the rear. The idea here is to reduce the rear wake with vortex generators and a rear cavity.

3.2 Design of modifications

In this section, the modifications that were constructed, implemented and tested, will be presented and motivated, based on the theory presented in Sec. 2.

3.2.1 Cab shape

It is of great importance to design the cab shape wisely, so that the air flow is separated as little as possible. If large separation regions are generated, it will drastically diminish the effectiveness of the add-ons that are situated further downstream on the truck. A combination of modifications to the baseline model was made.

The first modification was to incorporate an air shield on top of the cab, a so-called roof fairing. The idea was to smoothly direct the air flow over the trailer, thus shielding the part of the trailer that protrudes above the cab. Having an angled and curved shield would prevent the air from stagnating, hence rendering a lower pressure on the front surface of the truck. If properly aligned horizontally with the trailer, it would also provide a smoother transition between the cab and the trailer and thus prevent big flow separations. A model of a roof fairing mountable on the top of the cab had already been made, and was therefore reused.

The cab of the baseline model had sharp edges which generated large unwanted flow separations. A solution would be to round off the corners of the cab so that the air flow would be directed to the side of the cab in a less drastic manner. This would allow the air to reattach sooner and thus decrease the separation area. Since no changes to the actual wooden truck model were allowed, smoother corners were incorporated in a frontal nose cone that was added to the cab. The radius of the sides are limited by an optimal radius. After it is reached, the improvements gained by increasing the radius over the optimal one are marginal. The optimal radius is $r = 150\ mm$. The nose cone was also angled to reduce the stagnation area in the front . The flow was to be directed from the front nose over the cab air shield and then over the trailer. Since the trailer and the tractor are rarely staying together a continuous design that guides the flow further over the trailer was not considered. The front nose cone along with the roof fairing is shown in Fig. 9 below.

3.2.2 Cab-trailer gap cover

As previously discussed in Sec. 3.1, the gap between the cab and the trailer is problematic from an aerodynamical point of view. It allows air to collide with the front of the trailer, as well as generating energy consuming vortices. It also allows air to flow between the sides of the truck which impairs the vehicle stability, in particular it makes the truck very sensible to cross-wind instability, especially for yaw angles different from zero. Potentially, significant benefits regarding both stability and drag could be made in this area.

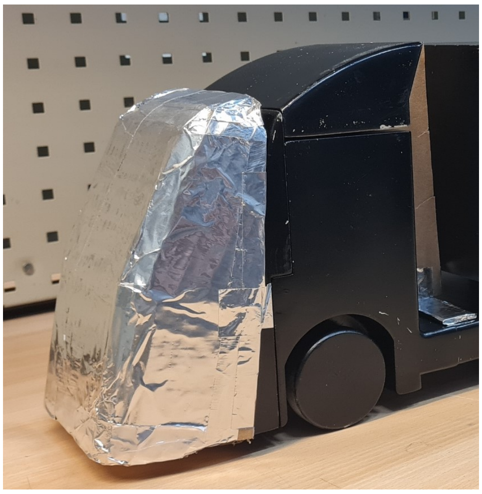


Figure 9: Frontal nose cone add-on made out of cardboard and aluminium tape.

Two add-ons were fabricated to address the gap issue. The first one was made with aluminium tape and two cardboard flaps, that completely covered the cab-trailer gap. It would prevent any air from entering the gap and therefore also prevent the problems that arise with it. An add-on of this type is not practically applicable since the truck must be able to turn, but was incorporated anyway in order for conclusions to be made about the full potential of similar solutions.

The other add-on was a cardboard flap that was taped down between the cab and the trailer in the middle of the gap. It would serve as a splitter plate by splitting up the air flow in the gap into two independent vortices, dissipating less energy. This type of add on is more realistic and can be implemented in real life. The modifications made to the cab-trailer gap can be seen in Fig. 10 below.

(a) Complete coverage of the cab-trailer gap.

(b) Splitter plate in the cab-trailer gap.

Figure 10: Cab-trailer gap solutions

3.2.3 Side covers

To further improve the critical gap between the cab and trailer two side covers were created, one for each side. As for the solutions described in Sec. 3.2.2, the aim is to avoid flow passing from one side of the truck to the other, especially in the zone where the cab and the trailer overlap vertically, creating drag and inducing instability. The add-ons were constructed in cardboard, cut with the same dimensions of said gap, then covered in aluminium tape. Such modification would be impractical in real life as the trailer needs to be free to rotate with respect to the cab, but a different design with the same aim may be possible to implement. A real life implementation can be done by adding a fabric that falls from the trailer and covers the gap in a more flexible way. The add-on can be see in Fig. 11.

(a) Side cover with a tuft applied.

(b) Side cover mounted on the truck.

Figure 11: Side covers.

3.2.4 Side skirts

The underbody of the truck is a very sensible area of the truck that needs to be addressed since creates high drag and cross-wind instability. The main problem is the flow passing from one side to the other of the truck creating vortices and re-circulation, as can be seen in Fig. 8. One critical aspect of the underbody is the air flow hitting and passing through the rear axles and rear wheels. Due to their shape and structure they create obstacles for the flow that hits them. Moreover, in a real truck rotating wheels also create vortices, but such phenomena were not investigated in this study. In an attempt to address this problem and to prevent air flowing into the underbody, side skirts were created using cardboard and tape. The side skirts were attached to a structure supposed to work as a protection for the rear axles and wheels and as a diffuser in the rear part of the trailer. The goal was to make the bottom surface of the trailer flat, preventing the air flow from hitting the rear axles. At the same time, the diffuser was designed in an attempt to balance the rear wake. From the flat bottom two side skirts extended and connected to the trailer, to further reduce the infiltration of air into the underbody. The rear wheels were also covered to minimize their drag. Such a solution is already implemented on real vehicles. The solution presented here is an extremization of it, since it would not be practical for maintenance and repairing, and at the same time does not allow the wheels to spin correctly. The underbody cover can be seen in Fig. 12.

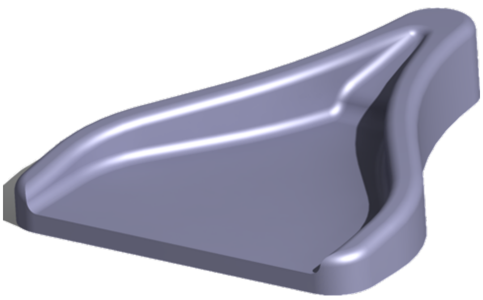
(a) Inside of the underbody.

(b) Underbody mounted on the truck.

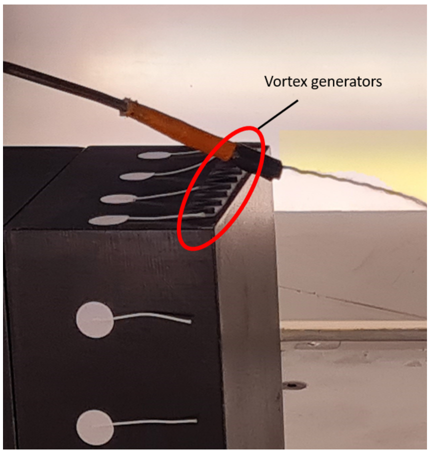
Figure 12: Underbody.

3.2.5 Vortex generators

Vortex generators were added to the rear part of the trailer roof. The idea was to energize the flow near the roof surface with the help of small counter-rotating vortices. This would potentially decrease the thickness of the boundary layer making the flow stay attached for longer and thus decrease the wake size. For the design, inspiration was taken from **[AirTab 2024]**. Due to the time limitation of the project, a simpler version was modeled using the CAD program Catia. A render of the CAD model is displayed in Fig. 13a below. The CAD model was used to print out physical versions using a Fused Deposition Modeling (FDM) printer. For the wind tunnel testing, the 3D-printed vortex generators were attached to the truck model using double-sided tape. Fig. 13b shows the 3D-printed vortex generators attached to the rear of the trailer.



(a) Vortex generator render

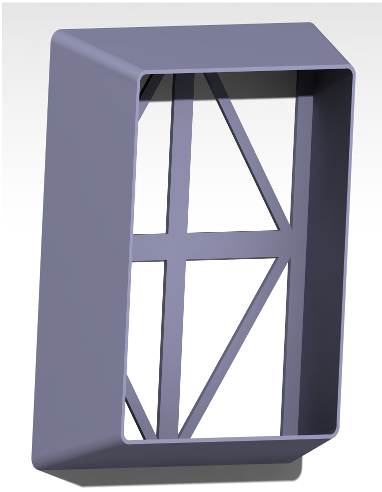


(b) Vortex generators implemented

Figure 13: Modifications applied to the back of the truck

3.2.6 Rear cavity

In an attempt to further delay separation and decrease the wake size, a cavity was designed and 3D-printed. A render of the CAD model can be seen in Fig. 14a. If working properly, the cavity would delay separation and allow for pressure recovery which in turn would decrease the drag. The cavity was made with a 20° angle on all four sides, functioning like a boat tail. It would serve to direct the flow inwards from all sides, reducing the wake size and the total drag. The cavity was attached to the rear base of the truck model using double-sided tape, see Fig. 14b.



(a) Render of the cavity CAD model.

(b) The cavity attached to the trailer.

Figure 14: Rear cavity

3.3 Wind tunnel testing

To examine the effect of the modifications on the aerodynamic qualities of the truck, the truck was tested using Chalmers wind tunnel. Tufts were attached throughout the length of the model in order to visualize where flow separation occurred and how it behaved in close proximity of the truck's surface. The zones where the attention was focused on were: the rear part of the cab, the front part of the trailer and the final end of the trailer, as can be seen in Fig. 15. Smoke was also used as a means of visualizing the air flow, but it turned out to be difficult to clearly see the smoke path due to its low intensity and complex lightning.

To begin with, the truck was mounted on the struts with zero yaw angle. A Reynolds sweep was then executed using wind velocities from $5\,m/s$ to $60\,m/s$ with increments of $5\,m/s$ for each test. A Reynolds sweep was carried on to determine at which wind velocity that various aerodynamic coefficients, i.e. drag coefficient C_d, become approximately independent of the wind velocity.

Having completed a Reynolds sweep, the baseline performance was determined for yaw angles from 0° to 10° (increments of 2°) using a wind speed of $35\,m/s$, the speed suggested by the lab supervisor. The forces acting on the struts were recorded and saved for later comparison with the modified versions of the truck. The flow behaviour was also studied by looking at the tufts.

The add-ons were then attached one by one from front to back in the streamwise direction. In the case of when a modification did not decrease the drag of the model, it was removed before attaching more add-ons and conducting the next test. The order in which the modifications were added can be seen in Tab. 1 below, where the presence or absence of a modification is marked with “1” and “0” respectively.

	Test number							
	1	2	3	4	5	6	7	8
Cab shape	0	1	1	1	1	1	1	0
Gap cover	0	0	1	1	1	1	0	0
Small side cover	0	0	1	1	1	1	1	1
Side skirts	0	0	0	1	1	1	1	1
Vortex generators	0	0	0	0	1	0	0	0
Rear cavity	0	0	0	0	0	1	1	1
Splitter plate	0	0	0	0	0	0	1	1

Table 1: Table of the tested combinations of the aerodynamic modifications.

During testing, configuration 6, visible in Fig. 15, resulted in the lowest drag coefficient C_d and was therefore considered the most successful combination of modifications. Said configuration was hence tested for yaw angles from 0° to 10°, so that the side wind performance of the final truck model could be compared with the baseline model.

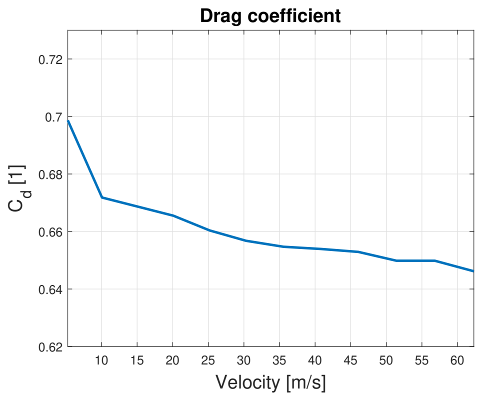
Figure 15: Configuration 6 with applied tufts

4 Results and discussion

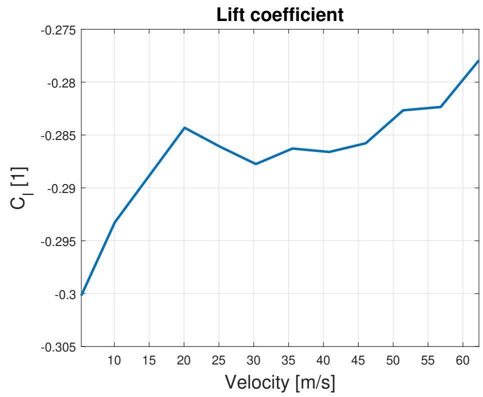
4.1 Reynolds sweep

Through the Reynolds sweep was possible to identify the values of the non-dimensional coefficients of the truck. The coefficients showed to be Reynolds independent from around a value of $30 m/s$, as can be seen in Fig. 16. The averaged values that were found are:

$$C_d = 0.653 \qquad C_l = -0.285$$



(a) Drag coefficient



(b) Lift coefficient

Figure 16: Reynolds sweep

Even if for trucks, due to their massive weight, the lift coefficient often is not considered in the analysis, due to the particular results that the analysis gave. The truck in this configuration showed a negative C_l, meaning that it was actually producing downforce. This value at first glance could seem strange and wrong but several reasons were found that can confirm these values. Analysing the CFD model, even if the conditions were not exactly the same, a similar result was found. In the CFD model the truck had $C_d = -0.153$, showing again the creation of downforce. After plotting the accumulated lift coefficient, in Fig. 17, regions creating negative lift can be identified. The front part of the cab is the part creating the most downforce, this is due to the floor being completely flat and very sharp in the front, this creates a very low pressure zone and a high acceleration resulting in suction in the underbody. At the same time the front of the cab has a very high pressure coefficient, as can be seen in Fig. 3, and due to its shape and inclination it will push the nose down creating more downforce. Then the roof of the cab and of the trailer will create lift since the flow is separated in these regions. Along all the trailer underbody once again suction is experienced. Non rotating wheels also can be one of the reasons why downforce is experience, since they would change significantly the flow's behaviour.

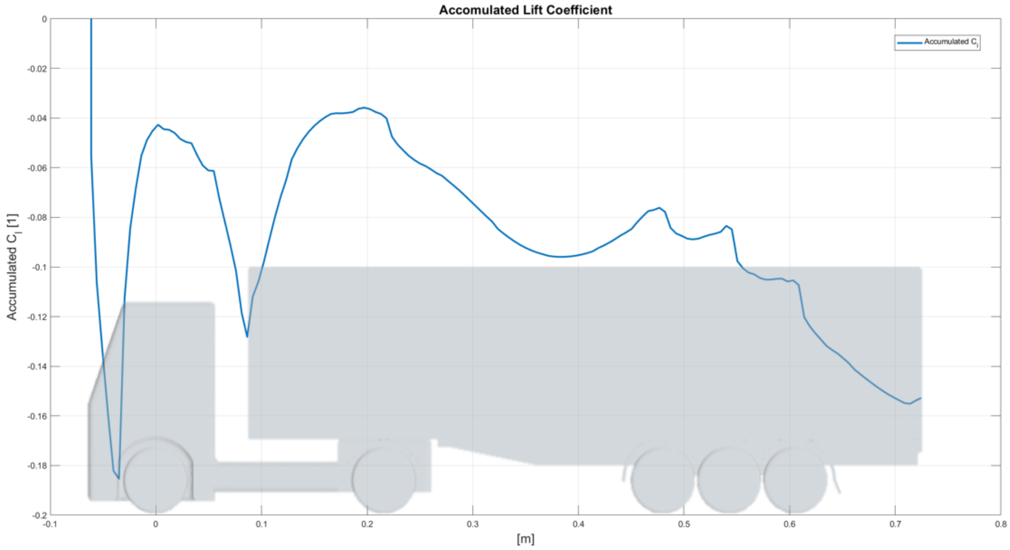
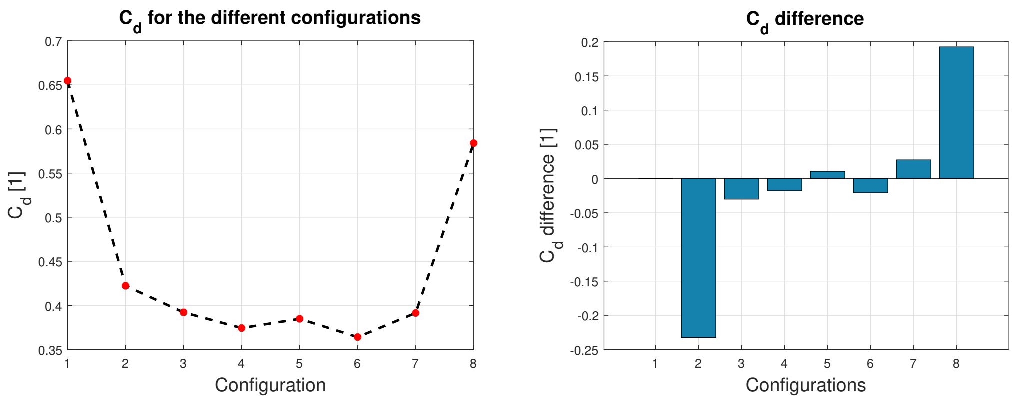


Figure 17: Accumulated C_l in X direction of the truck

4.2 Step-by-step implementation of the add-ons

Following the implementation plan seen in Tab. 1, the add-ons were mounted on the truck. Since the main goal was to reduce drag, the attention was focused on C_d and its dependence on all the modifications that were applied to the truck. The trend followed by C_d during the tests can be seen in Fig. 18.



(a) C_d for different configurations

(b) C_d difference respect to previous configuration

Figure 18: C_d adding the modifications

The modification that contributed the most to drag reduction was the "cab shape", with a total reduction of 232 counts. This modification included many characteristics that helped reduced the drag, such as: smoother corners radius allowed streamlines to follow better the cab and remain more attached on the truck as a whole, higher front screen angle that reduced the stagnation area in the front by offering and less flat areas to the flow, roof fairing that forced the flow to pass over the higher part of the trailer avoiding the creation of the stagnation present on the trailer, lower front dam that reduced the quantity of air going towards the underbody and subsequently hitting the axles.

The "gap cover" and the "small side cover", since they completely covered the gap between cab and trailer, did not allow the flow to pass from one side of the truck to the other, avoiding the creation of vortexes in the gap, reducing the drag of 30 counts, meaning 262 counts total. They were particularly relevant while testing at different yaw angles, since no flow could pass from the higher pressure side to the lower one, thus reduced the drag at higher yaw angles.

Implementing the "side skirts" reduced the drag of a further 18 counts, 280 counts in total. They resulted in a double outcome, by covering laterally the underbody of the trailer, they had the same working principle as the "gap cover" and "small side cover"; at the same time they covered the very complex parts of the rear wheels and rear axles, so that no flow could hit them, thus reducing drag even more.

The "vortex generators" proved to be unsuccessful, incrementing the drag of the truck by 11 counts, thus they were removed. The failure of this modification is related to the difficult implementation, by nature, of any type of vortex generator on any vehicle, since the shape, positioning, number and orientation need many iterations to achieve satisfactory results.

Drag was reduced of a further 19 counts thanks to the addition of the "rear cavity". This add-on allowed for a smaller and more stable wake, together with providing more pressure recovery, thus decreasing the base pressure difference between front and rear, decreasing the pressure drag.

Configuration 7 was compared with configuration 6 in order to find the best one of the two different solutions created to address the gap between cab and trailer. The test proved that the "gap cover" solution was better than the "splitter plate", with a difference of 27 drag counts. The reason is to be found in the nature of these two modification, while the first modification completely closed the gap, the second only separated the vortex structures that create inside the gap. So the "splitter plate" proved still to be beneficial for drag, but not in the same way as the "gap cover".

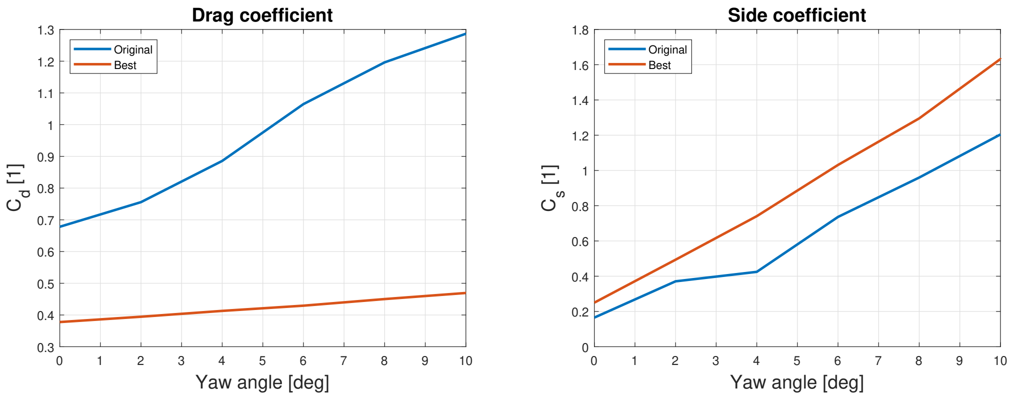
Configuration 8 was tested by mounting on the truck add-ons that can be implemented only by trailers OEMs, to investigate how the truck could be improved by only modifying the trailer. This new configuration, respect to configuration 6 drag was greatly worsed, highlighting once again the importance of the "cab shape", but was still an improvement over the original configuration, with a drag reduction of 73 counts.

Overall the best configuration was found to be configuration 6, with a total drag reduction of 291 counts. The improvements on stability, due to the aerodynamics implementations, were directly visible in the wind tunnel by just observing the truck. The vibrations that the original truck suffered at $35 m/s$, were much bigger than the ones suffered by the modified truck.

4.3 Yaw angle sweep comparison

Since configuration 6 was found to have the least drag, it was decided to test it at different yaw angles to see its behaviour when subject to side wind and how its drag and side force coefficients were influenced. The results were compared with the results of the original configuration. In particular, drag was greatly reduced at all yaw angles, see Fig. 19a, at the maximum yaw angle drag was reduced of 817 counts. These improvements are explained by the nature of the modifications which closed most of the lateral gaps that previously allowed the flow to pass from the high pressure zone of one side to the low pressure zone of the other, creating drag. At the same time vortexes creation was mitigated and the wake reduced in dimension and instability, resulting in an overall improved dependence of drag on the yaw angle, showing also a smoother increase.

The downside of these improvement come clear observing the side force coefficient C_s in Fig. 19b, where is possible to see that, for every yaw angle, it increased its value. This is mostly due to once again the nature of our modifications, since, by covering all the gaps and extending the length of the truck, the total lateral surface was increased, thus increasing the side force acting on the truck. A secondary reason can be also found in the actual manufacturing of the add-ons, which probably were not completely symmetrical.



(a) Drag coefficient

(b) Side coefficient

Figure 19: Force coefficients at different yaw angles

4.4 Tufts and smoke analysis

The flow's behaviour in the close proximity of the truck surface was studied through tufts, in order to validate the implementations that were mounted on configuration 6. The zones where the test was focused on are highlighted in Fig. 15, the test was conducted at different yaw angles. The test results are summarized in Tab. 2. The modifications proved to be successful since in all the highlighted regions the flow separated at higher yaw angles, showing that the truck is now less sensible to cross winds and more stable.

	Original	Number 6
Rear cab	6°	10°
Front trailer	6°	10°
Rear trailer	8°	> 10°

Table 2: Yaw angle at which separation occurred

The long tuft was used to investigate the wake and see the improvements that the rear cavity offered. When positioning it around 10*mm* from the rear end of truck in the original configuration, a big and unstable wake was detected. By implementing the rear cavity, and doing the test again, it was noticed that the wake started further back than before, was smaller and more stable, thus decreasing drag and validating the add-on.

Smoke was used to detect any unwanted separation, its used was mainly focused on the front of the cab and its modification. The flow, as can be seen in Fig. 20, remained attached to the truck both when testing on the upper and on the lateral side of the cab, showing that the cab modifications were producing no unwanted vortexes and separations, thus reducing drag.

Figure 20: Smoke visualization, upper side

5 Conclusions

In conclusion, configuration number 6 was found to be the best one, with a total drag reduction of 291 counts. This will result in an overall improved stability at every yaw angle, less vibrations, less dependence on side winds and finally reduced fuel consumption.

However the widespread implementation of the suggested changes faces obstacles primarily due to regulatory constraints. Here are the reasons contributing to this challenge: Firstly, Original Equipment Manufacturers (OEMs) responsible for tractor production typically do not extend their responsibilities to include enhancements on trailers, and vice-versa. Secondly, legislative measures, such as fixed length regulations, impose limitations that hinder the incorporation of augmentations like nose or rear improvements, making it difficult to introduce these changes. Moreover, the installation of a rear add-on presents logistical challenges concerning trailer loading procedures, adding complexity to the process. Additionally, finding a universally applicable solution for the gap between the truck and trailer proves to be intricate, given its dependency on trailer specifications, further complicating the implementation of these modifications. Similarly, complexities arise in the installation of roof add-ons on tractors, as they need to accommodate variations in trailer design, which adds another layer of difficulty to the process. Lastly, ensuring adequate ground clearance is imperative to navigate uneven terrains effectively, preventing potential contact between the truck and the ground, which adds to the complexity of introducing these changes.

These improvements were made to study what the best case scenario could be for the truck, with their current design they cannot be applied to real vehicles, but the values and result obtain with them can be used as good reference and as aim for engineers to reach in the future, with more practical add-ons. Due to their effectiveness, OEMs should focus on developing the front part of the cab, which proved to be the one that can lead to the highest drag reductions. At the same time, even if in smaller magnitude, the trailer-only modifications still were an improvement over the original configuration, thus researcher from trailer OEMs should focus on these add-ons, in order to reduce the overall drag, even if the same trailer is used with different cabs. All the add-ons and modifications made can work as a lead, to inspire future designers, engineers and aerodynamicists improving the truck's aerodynamics, safety and reducing fuel emissions of one of the most CO2 producing sectors in the world.

References

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