Design and analysis of low cost Aerodynamic aids for heavy duty trucks using composite materials for fuel saving purposes and CO₂ reduction

Master’s Thesis in the Master’s programme of Mechanical Engineering and Aeronautics
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1. Introduction

For heavy vehicles such as tractor-trailer combinations and buses, pressure drag is the dominant component due to the large surfaces facing the main flow direction and due to the large wake resulting from the bluntness of the back end of such vehicles.

Although friction drag occurs along the external surfaces of heavy vehicles, particularly along the sides and top of buses and trailers, its contribution to overall drag is small (10% or less) and is not a strong candidate for drag-reduction technologies. For heavy-duty vehicles, such as tractor-trailer combinations, the drag coefficient increases significantly with yaw angle.

In cold climates, the aerodynamic drag in winter can be nearly 20% greater than at standard conditions, due to the ambient air density. For highway tractor-trailers and intercity buses, this results in about a 10% increase in fuel consumption from drag when compared to the reference temperature, further emphasizing the importance of aerodynamic drag reduction.

One of the most important environmental issues within the truck automotive industry today is to reduce the fuel consumption and emissions. Combined with the increased fuel price and the future shortage of fuel reserves has resulted in a “green race” within automotive companies in order to stay competitive and develop fuel efficient products.

The constant fluctuation on the fuel prices over the last 10 years makes it even more important to invest in techniques and ways to diminish our need for fuel as much as possible. This can be achieved by improving efficiency of the engine, reducing rolling resistance and improving aerodynamics.

![Figure 1: Retail Gasoline Prices (U.S Energy Administration Information, 2015)](image-url)
1.1 Background

First generation drag reduction devices, developed in the 1970s and 1980s consisted primarily of aerodynamic shaping devices for the tractor. Fairied hoods and bumpers, air fairings and tractor skirts were the primary technologies that have led to the current designs that have become the dominant models from the tractor manufacturers. These technologies provided a reduction in aerodynamic drag on the order of 30%, relative to the classic tractor designs. Most of the devices such as roof fairings, side extenders, side fairings, tractor skirts, roof defectors, gap splitters, are designed based on the tractor. The focus of recent drag reduction technology for tractor-trailer combinations has been placed on second-generation drag-reduction devices. The second generation of drag-reduction technologies for tractors-trailers is primarily directed at lowering the drag associated with the trailer as well as the aerodynamic interactions between the tractor and trailer, since 55% of the total drag is caused from the trailer. They are focused on three main areas of concern, tractor-trailer gap and forebody, trailer underbody and trailer base. Devices such as trailer fairings, vortex generators, edge fairings, rounded edges are applied on the trailer side. Those are the ones that have until know the least absorbability in the trailer industry.

*Figure 2: Distribution of drag areas on a truck (Richard M. Wood, 2004)*

Various projects like OptiFuel Lab 2 (Renault, 2015) conducted by Renault in collaboration with Lamberet trailer manufacturer, Navistar Super Truck project (Navistar, 2014) and Aero Trailer (Daimler, 2011) design study by Mercedes Benz indicated that by redesigning or by treating the above areas we could reach to drag reduction up to 22% which means less fuel consumption and lower CO₂ emissions. The power needed to overcome aerodynamic drag and rolling resistance as a function of speed for a loaded
truck of 40 tons is shown in Figure 3. There is a cubic increase of drag, whereas the rolling resistance grows linearly with speed. Approximately above 80 km/h (50 mph) the aerodynamic drag becomes dominating, which makes aerodynamics very important for long-distance transport where speeds up to 90-110 km/h is common. However, it should be mentioned that aerodynamic drag is still important below this speed, although not to the same extent. By reducing drag, less power is needed and fuel consumption is reduced.

1.2 Incentives

One of the incentives of this study was originated from the fact that Greece stands in the 4th position in the European Union of which nearly 98% of its inland freight transport is performed by truck (Eurostat, 2016) and its yearly imports of gasoline are calculated nearly 4.4 million tons per year. Over the last five years huge investments have been made on reconstructing and improving most of the main national roads in the country, which is in favor of making such an investment since the cost damping will be a lot higher than before. The main objective though is to investigate the effect of add-on devices, obtain an understanding of drag contribution from different areas around the truck and design devices that can be applicable on every truck, easily installed, customized according to each truck needs, and cost effective for someone to invest in it.

*Figure 3: Aerodynamic drag and Rolling resistance for a truck with a Cd of 0.6 (R.C. McCallen et al., 2004)*
2. Procedure

In the current project a full scale detailed truck – trailer for long distance transports was used. The research will focus on the areas of trailer underbody, base region of the trailer and the forefront area of the trailer. The devices are tested, compared and evaluated by means of Computational Fluid Dynamics (CFD) in order to acquire an understanding of the flow field around the truck and how combinations of the devices affect drag behavior. Structural analysis of the devices is included by means of finite element method. In the design process European legislation is taken into consideration regarding the overall dimensions of the devices.

2.1 Fluid Dynamics

Solidworks Flow Simulation solves the Navier-Stokes equations, which are formulations of mass, momentum and energy conservation laws for fluid flows. The equations are supplemented by fluid state equations defining the nature of the fluid, and by empirical dependencies of fluid density, viscosity and thermal conductivity on temperature.

\[ \nabla V = 0 \quad \text{Continuity equation (1)} \]

\[ \rho \frac{\partial V}{\partial t} = -\nabla p + \mu \nabla^2 V + \rho g \quad \text{Momentum equation (2)} \]

\[ \rho c_p \frac{dT}{dt} = k \nabla^2 T + \Phi \quad \text{Energy equation (3)} \]

Where \( V \) = velocity field, \( \rho \) = density, \( t \) = time, \( p \) = pressure, \( \mu \) = viscosity, \( g \) = gravity field, \( C_p \) = specific heat capacity, \( T \) = temperature, \( k \) = coefficient of thermal conductivity, \( \Phi \) = viscous dissipation function. The continuity and momentum equations can be solved independently of the energy equation and when temperature is constant, as assumed in this project, the energy equation is neglected. The continuity and momentum equations describe the motion of the fluid and are solved for velocity and pressure.

Flow Simulation computational approach is based on locally refined rectangular mesh near geometry boundaries. The mesh cells are rectangular parallelepipeds with faces orthogonal to the specified axes of the Cartesian coordinate system.
A laminar/turbulent boundary layer model is used to describe flows in near-wall regions. The model is based on the so-called Modified Wall Functions approach. This model is employed to characterize laminar and turbulent flows near the walls, and to describe transitions from laminar to turbulent flow and vice versa. The modified wall function uses a Van Driest's profile instead of a logarithmic profile. If the size of the mesh cell near the wall is more than the boundary layer thickness the integral boundary layer technology is used. The model provides accurate velocity boundary conditions.

2.2Computational Fluid Analysis

Laminar and turbulent flow was chosen with turbulent intensity 5% and turbulence length 0.025m. The air speed was set at 25m/s (90km/h), frontal area of the truck was calculated 9.5m², 0° and 5° deg yaw angle and constant air density 1.205kg/m³. Each simulation process was set for 500 iterations allowing the model to converge smoothly.
Table 1: Conditions and parameters of CFD

<table>
<thead>
<tr>
<th>General Parameters</th>
<th>Static Pressure: 101325.00 Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air density: 1.205 kg/m$^3$ (constant)</td>
</tr>
<tr>
<td></td>
<td>Steady Time</td>
</tr>
<tr>
<td></td>
<td>No slippery walls – road</td>
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<tr>
<td></td>
<td>No rotating wheels</td>
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<tr>
<td></td>
<td>Laminar and Turbulent flow</td>
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<tr>
<td>Velocity parameters</td>
<td>Velocity in X direction: 25 m/s</td>
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<tr>
<td>Turbulence parameters</td>
<td>Turbulence intensity and length</td>
</tr>
<tr>
<td></td>
<td>Intensity: 5.00 %</td>
</tr>
<tr>
<td></td>
<td>Length: 0.025 m</td>
</tr>
<tr>
<td>Truck Dimensions (Overall dimension including Tractor and Trailer)</td>
<td>Length : 15.9m</td>
</tr>
<tr>
<td></td>
<td>Width : 2.5m</td>
</tr>
<tr>
<td></td>
<td>Height : 3.9m</td>
</tr>
</tbody>
</table>

2.3 Truck Aerodynamics

Aerodynamic drag consists of two components: pressure drag (force acting normal to surface) and friction drag (force acting tangential to surface). Friction drag is due to shear stress between the fluid and the surface, whereas pressure drag is due to a pressure difference between the front and the rear of the body. For a truck, and other blunt bodies, the pressure drag is the most dominating one and contributes to more than 90 percent of the total drag. In addition to the tractor front, the regions that represent the main drag-contributing areas around a truck are: the gap between the tractor and the trailer, the base wake behind the trailer and the undercarriage. Friction drag is not taken in consideration in the calculations due to its small influence in the overall drag count.
The drag force applied on the truck is given by the equation:

\[ F_d = \frac{1}{2} \rho U_\infty C_d(\psi_\infty)A \]  \hspace{1cm} (4)

Whereas, \( F_d \) is the drag force, \( \rho \) is the density of the fluid, \( U_\infty \) is the speed of the fluid, \( \psi_\infty \) is the effective yaw-angle of the surrounding air, \( C_d(\psi_\infty) \) is the drag coefficient, which varies with yaw-angle and \( A \) is the projected frontal area of the vehicle (Marc Belize, 2012). For heavy-duty vehicles, such as tractor-trailer combinations, the drag coefficient increases significantly with yaw angle. In this paper only 0° yaw angle of surrounding fluid is studied.
3. Finite Element Analysis (Patran – Nastran)

3.1 Reinforced Plastics (ABS)

Important questions, such as material choice, supports, load distribution and device durability are all answered by performing various configurations and reaching to the most profitable solution in terms of strength and weight.

The material chosen to design the panel is Acrylonitrile Butadiene Styrene (ABS) reinforced with 40% chopped short glass fibers. The choice was based on the fact that ABS has many applications in the automotive industry because it combines good mechanical properties, low weight. The material is considered isotropic.

<table>
<thead>
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<th>Table 2: Material Properties (RTP, 2017)</th>
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<tr>
<td>Acrylonitrile Butadiene Styrene (ABS)</td>
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<td>1 Glass fiber reinforcement</td>
</tr>
<tr>
<td>2 Specific gravity</td>
</tr>
<tr>
<td>3 Tensile Modulus</td>
</tr>
<tr>
<td>4 Tensile Strength</td>
</tr>
<tr>
<td>5 Flexural Modulus</td>
</tr>
<tr>
<td>6 Flexural Strength</td>
</tr>
</tbody>
</table>

4. Results

4.1 Reference truck CFD analysis for 0° deg yaw angle

The air flow analysis of the reference truck confirmed the problematic areas mentioned above and in Figure 6, four low-pressure areas are observed. One at the roof of the tractor (on the deflector), one at the fore part of the trailer roof, one at the rear area of the trailer and one region underneath the tractor which is fading as we move towards the trailer undercarriage.
The low-pressure areas on the cab are an effect of flow acceleration over the edges, as the flow stays attached to the surface. The low-pressure bubble at the trailer roof is caused by the wake that is created when the flow separates at the trailing edge of the tractor’s roof-deflector. The wake itself contains low pressure and low velocities and forces the air to go around it. This causes an acceleration of the around-going flow and hence an expansion of the low-pressure region.

On the undercarriage of the trailer, we can see that the air is already separated and turbulent due to flow disturbances from underneath the tractor. A very small amount of air seems to travel throughout the whole undercarriage region and a lot of swirls are created along the trailer underbody. Just behind the trailer a large wake is generated as air separates from the surface at the trailing edge at the rear of the trailer.

A low-pressure region is created behind the trailer when the separation occurs and air is sucked into the wake from all the sides. The low-momentum flow that exits from the undercarriage turns upward straight after the trailer and generates an upwash and a swirl behind the trailer. In the center of a swirl a substantial low pressure is obtained.

At the upper part of the base wake, larger swirls are also created due to the higher velocity of the air that travels over the roof. Low pressure areas are “pulling” the truck backwards, causing turbulences, instabilities and increasing fuel consumption.

The flow analysis showed a drag coefficient of $C_d = 0.624$ for the truck. This result will be used as a reference value in order to evaluate the effect of the devices that will be placed on the truck and calculate drag reduction and thus the impact on the fuel consumption.
4.2 Reference truck CFD analysis for 0° deg yaw angle

As expected in this case the drag coefficient is a lot higher than the previous configuration reaching up to 34%. The large swirls at the left side are a result of the increased airflow through the gap and the undercarriage.

In spite the fact that there are a lot of differences between the two yaw conditions, the three main problematic areas discussed in the beginning still remain and in this case are even more intense, especially the underbody region where most of the turbulent phenomenon are located.
4.3 Gap area (Deflector)

4.3.1 Analysis for 0° deg yaw angle

As the vehicle starts to accelerate, air flow is entering the gap and comes in contact with the trailer front face increasing pressure on the trailer front which respectively causes the drag to increase. Even though the angle of the tractor roof deflector directs air over the gap still a lot of air enters the gap creating swirls and low pressure regions between the tractor and the trailer. The top of the gap is where most of the air exits and probably contributes to the separation bubble at the fore part of the trailer roof. Some of the air also leaves the gap through the side clearance.
Figure 8: Comparison between current deflector (left column) and new Deflector (right column): (Top) Velocity Streamlines X-Y(m/s), (Middle) Velocity Streamlines X-Z(m/s)-3m from ground, (Bottom) Surface pressure trailer front area(Pa)

In most cases deflectors are preinstalled by tractor manufacturers. Their main disadvantage is that they are designed individually without taking into consideration the trailer that the tractor will tow. This indicates that their ability to divert air properly and smoothly depends whether the trailer type is “dimensionally” suitable for the existing deflector or not.

The preinstalled reference deflector is not sufficient enough to divert the air above the trailer front thus we have increased pressure on the surface (Figure 7) and a lot of air enters the gap creating big swirls and low pressure regions.

The new deflector is parametrically designed (Ira H. Abbott, 1960) using aerodynamically approved and tested bodies in order to cover its tractor-trailer needs individually resulting to a far better aerodynamic behavior. The air is deflected above the
trailer front area smoothly reducing separations and turbulences. In addition the exposed area of the trailer front is decreased substantially. The air entering the gap is reduced and the swirls are decreased. Low pressure wakes are still present but not so intense. In spite the use of the deflector a small area on the trailer front it is still directly exposed to the streamline. This can be treated by altering, redirecting or extending the existing side extenders.

The analysis showed an overall decrease of 4.56% on the drag coefficient in comparison with the original deflector installed by the manufacturer. The result is a noteworthy value taking into consideration that trailers are blunt bodies with low aerodynamic behavior.

### 4.3.2 Analysis for 5° deg yaw angle

In this case more air enters the gap between the tractor - trailer creating slightly more turbulences and swirls at the forefront area of the trailer comparing with the 0° deg yaw angle. The overall drag reduction is only reduced by 0.15%, which means that the yaw angle is not actually affecting the reduction provided from the deflector in the first place.
Figure 9: Comparison between current deflector (left column) and new Deflector (right column) (Top) Velocity Streamlines X-Y(m/s), (Middle) Velocity Streamlines X-Z(m/s)-3m from ground, (Bottom) Surface pressure trailer front area(Pa)

4.3.3 FEM Analysis

The deflector consists of three panels attached to each other. The positions of the support were set by taking in consideration the pressure load applied on the deflector. The values for the load were extracted from the Flow analysis by using the pressure coefficient surface plot. Maximum load is applied homogeneously to all surfaces. Gravity is also included in our analysis.

\[
C_{p_{\text{max}}} = \frac{p_{\text{max}} - p_{\text{atm}}}{\frac{1}{2} \rho V^2} \quad \text{Pressure coefficient} \quad (5)
\]
The thickness of the panels was calculated at 3 mm and the analysis showed maximum displacement of 3.5 mm on the side panels and the maximum stress tensor did not exceeded 3 MPa, which is substantially smaller compared to the material’s tensile strength.

The weight of the deflector is low and was calculated at 19.7kg. It is very important to achieve the best combination of strength and low weight because if too much weight is added on the tractor it will eventually counterbalance the fuel economy achieved from drag reduction.

4.4 Underbody region (Side skirts)

4.4.1 Analysis for 0° deg yaw angle
Up to 30% of the total drag is a result of the region below the trailer. The complicated geometry and the accessories (leg supports, storage rooms for tools etc.) are the major factor for turbulences and flow separation, which lead to handling issues and sometimes safety problems.

Many devices have been designed and used in order to deal with problem. Devices such as, bogie covers, trailer – tractor wheel covers, mud flaps, flow directing panel have also been used successfully with positive results but their complexity is their main disadvantage. Side skirts have been proved so far to be the most effective and driver friendly. Their purpose is to prevent the airflow from entering the underbody, decreasing the turbulences and improving the handling.

![Figure 11: Side skirts placed on the trailer](image)

Operational and maintenance issues are the main concerns of the fleet owners. Introducing such devices means that they have to change in some cases the standard procedure of loading and unloading of cargo. These devices might require extra attention from the operator and some training regarding their handling and damage control. Yet their purpose can be more than deflecting the airflow from entering the underbody region. By placing side skirts around the trailer body we can prevent accidents with bicycles, motorcycles and even pedestrians.

Figure 9 of the airflow underneath the trailer indicate a very disturbed and chaotic behavior. The air that reaches the undercarriage of the trailer is already separated and turbulent due to flow disturbances from the tractor. Simulations revealed low velocities under the trailer and many large swirls at the fore part of the trailer undercarriage, indicating that almost all the air that exits here enters at the posterior part of the undercarriage. A very small amount of air seems to travel throughout the whole undercarriage region.
The use of side skirts decreases the amount of turbulence and preventing airflow from entering near the wheels. Swirls and turbulence behind the trailer are decreased substantially while drag coefficient was reduced 4.18% compared with the reference truck that has no skirts attached.

**Figure 12**: Velocity Streamlines (m/s) 600mm from ground: Without side skirts (top), with side skirts (bottom)

### 4.4.2 Analysis for 5° deg yaw angle

There is a great advantage with Side skirts in yaw condition where it prevents the undercarriage from cross-winds. It thereby reduces the flow disturbances underneath the trailer and directs the flow along the trailer side. The positive effect with Side skirts is also confirmed by comparing the two figures below. Visualizing the air flow underneath the trailer a large reduction of swirls and low pressure areas is especially in the region
around the wheels and wheel axles which reduces the pressure drag and creates a lot of turbulences.

**Figure 13**: Velocity Streamlines (m/s) 600mm from ground: Without side skirts (top), with side skirts (bottom)

### 4.4.3 FEM Analysis

Side skirts consist of 4 panels for each side. Two small, one on the left and one on the right side and two bigger panel who are the major ones covering the wheels.
Figure 14: Side skirts dimensions (mm) and panel supports

Base supports are placed on the top side of the panel that allows them to rotate like a hinge mechanism, which enables the driver to lift each panel up and get access in the underbody region.

Three support beams extend from the frame of the trailer between the panels, as it is shown on figure 12, and support the panels in two points. Each point supports both panels on the left and on the right side. The point supports are assumed as ratchet mechanism allowing the driver to unfasten them easily without needing tools to dismantle.

Accessibility of the underbody region, mounting and easy handling of side skirts are very important, since these are the main reasons that they are not so popular amongst other devices. Truck drivers do not want to put extra work or effort on their trips and truck owners do not want to spend extra money on devices that may eventually not pay off.

The analysis indicated a maximum displacement on the lower region of middle panels of 9mm. The results were as expected and such a displacement can be considered insignificant relative to the size of the panels. Maximum stress appeared on the lower point supports at a maximum value of 3.8 MPa. Overall weight is calculated at 82kg for each side and panel thickness of 5mm.
4.5 Trailer base region (Boat tail)

4.5.1 Analysis for 0° deg yaw angle

The trailer base is the last source of drag for tractor trailers and the area that is most difficult to treat due to operational and legislation restrictions that we have.

Low pressure on the trailer base causes a net pressure differential that generates turbulences causing overall drag increase. This pressure differential is the primary source
of drag for most heavy vehicles. Introducing devices at the trailer base areas, like the boat tail, will reduce this differential and reduce the net drag on the vehicle.

Drag-reduction technologies for the trailer are aimed at increasing this backpressure. Research has shown that optimal length for base flaps is between 0.6 m – 0.8m (K. Salari, 2010). Yet the restrictions from the current legislation, the handling and the functionality of such devices are important factors since they are directly connected to the loading and unloading process.

![Diagram of trailer with and without boat tail, showing pressure coefficient and velocity streamlines.](image)

**Figure 16: Trailer without boat tail (left column) and with boat tail attached (right column): Pressure coefficient (top), Velocity Streamlines XY(m/s) (bottom)**

In the zero yaw degree angle especially the top plate and the two side plates, are very effective at guiding the air and reducing the base wake.
Flow separation occurs in the rear area of the trailer creating a low pressure area and swirls sucking the air inside it. The use of the boat tail delays the flow separation and deflects the air smoothly away from the rear region (Figure 16). Low pressure “bubble” and swirls remain but their intensity is reduced, which corresponds to a drag reduction of 3.30% compared with the reference truck.

4.5.2 Analysis for 5° deg yaw angle

In this case the effect of the frame extension is reduced up to 1.3% compared to the 0° deg yaw angle and the iso surface shows how the pressure and the wake are slightly reduced. The air flow is pushed away from the rear area but not sufficiently as before. Probably in this case maybe a longer extension maybe required to achieve at least the same drag reduction.

![Figure 17: Trailer without boat tail (left collum) and with boat tail attached (right collum): Pressure coefficient (top), Velocity Streamlines XY(m/s) (bottom)]
4.5.3 FEM Analysis

Boat tail consists of three panels for each side of the trailer rear doors. Two horizontal panels are placed on the top and on the bottom, and a vertical one on the left and right side of the trailer respectively.

Since both sides are identical the study will be performed only on one side. However results apply for both sides. Vertical panel are supported in three points and the horizontal ones in two points (Figure 15). The forearms supporting the panels are all attached on the trailer door and when the device is not used it can be folded on the door so they do not occupy much space and not cause problems when opening the doors for loading and unloading.

Pressure load applied on the panel were extracted from the CFD analysis using the pressure coefficient equation, for the maximum value. Maximum displacement on the top and bottom panel is calculated at 4.76mm and maximum stress tensor at 4.17MPa. The weight for one side is 15.6kg and the thickness of the panel is only 4mm.

Boat tail devices face the same problems as side skirts. Easy handling is very important and the truck driver must interact as little as possible. Otherwise, if the driver is always interfering with the operation of the device will eventually discourage the owner to invest on it. Automatic folding and unfolding can be installed but in that case the cost of the investment would be a lot bigger and therefore unapproachable for the majority of truck owners.

As we mentioned on the beginning European legislation indicates that aerodynamic devices exceeding 600 mm on the rear area of the trailer are to be type approved before being placed on the market. This means that the current device is not surpassing the length limit and can be used without any legal problem and certifications. The current design of boat tails is not surpassing the limits set by EU and therefore there is no need to be type approved. This is an extra bonus for the future investor since there will no need for bureaucratic paperwork.
Figure 18: Dimensions (mm) and panel supports

Figure 16: Stress tensor (MPa) (left), Displacements (mm) (right)
4.6 Combination of all devices: Deflector, Side skirts, Boat tail

4.6.1 Analysis for 0° deg yaw angle

By combining the new deflector, side skirts and boat tail drag contributing areas around the truck are treated. Drag reduction nearly reached up to 15% in comparison with the reference truck. From Figure 19 we can see that the combination of boat tail and side skirts results in a better base wake pressure than the combination does. In addition swirls are decreased and deflected further away from the rear area of the truck.

**Figure 19:** Velocity Streamlines X-Y (m/s) (top), Pressure coefficient (middle), Velocity Streamlines X-Z (m/s)
4.6.2 Analysis for 5° deg yaw angle

Drag reduction reached up to 15.15% in comparison with the reference truck and slightly higher than the 0° deg yaw angle results. Even though swirls are decreased they still dominate at the rear area of the trailer creating instabilities. A big change can be noticed on the underbody area whereas higher amount of air exits the underbody of the truck.

Figure 20: Velocity Streamlines X-Y (m/s) (top), Pressure coefficient (middle), Velocity Streamlines X-Z (m/s)
5. Summary results of all the devices

As it is shown from the results in Figure 21, for the zero degree yaw angle simulations, the deflector individually gave the biggest drag reduction of 4.56%. Side skirts resulted in 4.18% while boat tail was slightly smaller at 3.30%. By combining all devices we managed to succeed nearly 15% in drag reduction.

On the contrary, for the 5° degree yaw angle simulation, side skirts resulted to the higher amount of drag reduction whilst the boat tail affect was significantly reduced by 1.3%.

When working with CFD simulations it is important to remember that the results are calculated approximations of a real airflow and that assumption has been made in order to solve the flow equations. Comparing the results with previous research and studies performed, values are slightly lesser. This phenomenon can be addressed to the fact the devices where tested with no rotating wheels. By performing test with rotating wheels it will show substantially higher drag reduction especially for side skirts and base frame devices.

![Figure 21: Drag coefficient for all devices](image-url)
Table 4: Overall changes in drag values of the truck

<table>
<thead>
<tr>
<th></th>
<th>0 deg yaw angle</th>
<th>5 deg yaw angle</th>
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<tr>
<td></td>
<td>$C_d$</td>
<td>$DC_d$ (%)</td>
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<tr>
<td>Reference Truck</td>
<td>0.624</td>
<td>-</td>
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<tr>
<td>Deflector</td>
<td>0.597</td>
<td>4.56</td>
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<td>Side Skirts</td>
<td>0.599</td>
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<td>Extension base</td>
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Trucks, buses and coaches produce about a quarter of CO$_2$ emissions from road transport in the EU and some 5% of the EU’s total greenhouse gas emissions – a greater share than international aviation or shipping. Despite some improvements in fuel efficiency, CO$_2$ emissions from HDVs rose by some 36% between 1990 and 2010, mainly due to increasing road freight traffic. Projections indicate that, without policy action, total HDV emissions would still be close to current levels in 2030 and 2050.

This is clearly incompatible with the goal of reducing greenhouse gas emissions from transport by around 60% below 1990 levels by 2050. While CO$_2$ emissions from new cars and vans are being successfully reduced under recent EU legislation, the HDV strategy, adopted in May 2014, is the EU’s first initiative to tackle such emissions from trucks, buses and coaches.

Despite the economic importance of fuel consumption, CO$_2$ emissions from HDVs are currently neither measured nor reported. The strategy therefore focuses on short-term
action to certify, report and monitor HDV emissions - an essential first step towards curbing them.

As we discussed in the beginning the main purpose of this study was to prove that by installing aerodynamic aids on long-haul truck trailers we could achieve an adequate fuel economy that can trigger an owner’s attention to proceed in such an investment.

Fuel consumption varies considerably depending on, the type of truck, the type of traffic, roads, driving behavior, maintenance and fuel quality. An average indication of a typical heavy duty truck is shown on Table 5 and as we can see there is a noticeable fluctuation of nearly 15% consumption in an empty truck and an 18.8% for full load truck.

This fluctuation is associated with the driving skills and behavior of each driver. The importance of training the driver depending the situation such as, payload delivering, road behavior and firm driving can lead to a much lower fluctuations on fuel consumption.

| Table 5: Fuel consumption for a typical truck trailer (Volvo, 2014) |
|---------------------------------|-----------------|------------------|-----------------|
| Typical fuel consumption in liters per 100km |
| Payload in tons | Total Weight in tons | lit/100km for empty truck | lit/100km for full load truck |
| 40 | 60 | 27-32 | 43-53 |

It has been well recognized, within the truck industry, that for every 2% reduction in aerodynamic drag there is roughly a correlating 1% reduction in fuel consumption. Such a correlation has been extracted over the years with wind tunnel testing of various devices and real on road measurement on different configurations and conditions. Nevertheless

Therefore a targeted decrease of 1% in aerodynamic drag could potentially result in up to a 0.5% decrease in fuel consumption (T.M.A, 2007). By using the results from the simulations we can calculate the fuel economy for either an empty truck or a full load truck.
As it is shown on Table 7 for an empty truck fuel economy can reach up to 2.65 liters per 100km and for a full loaded truck up to 4 liters when combining all devices, the results are very interesting taking into consideration that a typical truck performs approximately 120,000 km per year and nearly 80% of those are on highway speeds with average fuel consumption of 40 lit/100km. Average fuel cost is currently estimated at 1.22 euros/lit. Thus the yearly fuel expenses for a truck can be estimated at approximately 46,000 euros (highway consumption only) and taking into consideration the fluctuations on the oil prices, even the smallest reduction on fuel consumption it very valuable for the owner.

Individually, the deflector is giving the best results and savings can reach up to 1000 euros per year and if we combine all devices the capital we can save is approaching 3500 euros. The capital saved can be used for other purposes such as maintenance expenses for the truck owner or for operational costs.

The environmental impact of the devices should be highlighted as well since reduction on CO\textsubscript{2} emissions reach up to 6.8 tons per year depending on the combination of devices.

\textbf{Table 6: Overall changes in drag values of the truck}

<table>
<thead>
<tr>
<th>Fuel economy in liters per 100km for each device</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 deg yaw angle</td>
</tr>
<tr>
<td>Empty truck</td>
</tr>
<tr>
<td>Deflector</td>
</tr>
<tr>
<td>Side Skirts</td>
</tr>
<tr>
<td>Extension base frame</td>
</tr>
<tr>
<td>Combination of devices</td>
</tr>
</tbody>
</table>
This factor is very important taking in consideration that the purpose is to make the freight transport as environmental friendly as possible.

**Table 7-a: Cost information from the use of devices on highway speeds (average values)**

<table>
<thead>
<tr>
<th>0 deg yaw angle</th>
<th>Lit/100km saved</th>
<th>Euros saved per year</th>
<th>Tons of fuel saved per year</th>
<th>Reduction in CO₂ (tons/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflector</td>
<td>0.9</td>
<td>1050</td>
<td>0.87</td>
<td>2</td>
</tr>
<tr>
<td>Side Skirts</td>
<td>0.82</td>
<td>970</td>
<td>0.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Extension base frame</td>
<td>0.65</td>
<td>770</td>
<td>0.62</td>
<td>1.5</td>
</tr>
<tr>
<td>Combination of devices</td>
<td>2.95</td>
<td>3500</td>
<td>2.84</td>
<td>6.8</td>
</tr>
</tbody>
</table>

**Table 7-b: Cost information from the use of devices on highway speeds (average values)**

<table>
<thead>
<tr>
<th>5 deg yaw angle</th>
<th>Lit/100km saved</th>
<th>Euros saved per year</th>
<th>Tons of fuel saved per year</th>
<th>Reduction in CO₂ (tons/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflector</td>
<td>0.86</td>
<td>1010</td>
<td>0.82</td>
<td>1.97</td>
</tr>
<tr>
<td>Side Skirts</td>
<td>1.80</td>
<td>2114</td>
<td>1.73</td>
<td>4.14</td>
</tr>
<tr>
<td>Extension base frame</td>
<td>0.41</td>
<td>481</td>
<td>0.39</td>
<td>0.95</td>
</tr>
</tbody>
</table>
7. Conclusions and future work

This thesis verifies the possibilities of improving the aerodynamics around a truck in order to reduce the fuel consumption and calculate the money saved from adding such devices on heavy duty trucks and the reduction on CO$_2$ emissions.

Decreasing the cost of production for the panels and calculating the cost damping of the investment can be individually studied and developed in order to make these devices affordable and applicable for most truck owners.

Trailer devices have a great potential of reducing drag. Compared to the tractor, the trailer is much more susceptible for aerodynamic drag improvements and thus the fuel consumption can be substantially reduced by using trailer devices. By combining the devices, even larger drag improvements can be achieved. In addition different yaw angles should be studied in order to investigate the aerodynamic behavior of the devices and how they affect the overall drag results.

Front area of the trailer, undercarriage and the base of the truck are the three regions where the greatest effects are achieved when adding aerodynamic devices to the trailer. The new deflector showed a very interesting aerodynamic behavior in comparison with the old one. Side skirts and Frame extension have a large potential to improve the flow in these regions and should be of great interest for further development.

Related companies should consider the whole truck during the aerodynamic development. In order to do this, a co-operation between the tractor and trailer manufacturers is recommended and communication between these two should be established. The advantage if the tractor and the trailer were to be developed together especially applies to the interface between the cab and the trailer front, but also between the chassis and trailer underbody.

Naturally, the results of CFD simulations need to be verified with experimental data, such as wind-tunnel test, to ensure reliability of the results. Hence, the continuing work should include other types of trailers to see the efficiency of the trailer devices on different truck configurations. To verify the importance of developing tractor and trailer together it is also recommended to involve adjustments on the tractor when adding trailer devices.
It is important, from a safety aspect, to study the impact on the stability of the truck when using the different devices. To some extent, they increase the exposed frontal area of the truck, seen from the wind direction’s perspective, and heavy cross-winds can thus have a negative influence on the stability of the truck, as more air hits the trailer surface and increase the side forces. Even though there are many devices on the market today, they are not very common on the road.

7. References-Bibliography


