POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Project report - Aerodynamics of Transport Vehicles

AERODYNAMIC DRAG REDUCTION ANALYSIS OF A STANDARD EURO TRUCK DESIGN

Author: Arman Babaei, Joseph Noel Kiren, Leonardo Ungureanu, Shlok Anand

Professors: Prof. Paolo Schito, Prof. Alex Zanotti

Assistant professor: Ing. Stefano Negri

Academic year: 2024-2025

---

1. Introduction

The transportation sector is critical to the economy, in recent times it faces increasing pressure to become more efficient fuel-wise as we become more energy and environmentally conscious. Of the many issues, aerodynamic drag plays a key role in fuel consumption and hence the energy and environmental impact of heavy-duty vehicles (semi-trucks) especially at higher highway speeds. These exhibit significant aerodynamic drag due to flow separations, large gaps between the tractor and trailer and vortices. These especially at higher high-way speeds where aerodynamic losses dominate over "roll-over" risks, that is the trucks' roll-resistance is less significant than the drag it generates, which causes a significant fuel consumption penalty [1][2].

Historically, the push to improve the aerodynamics of the truck came in the '70s due to the energy crisis [1], due to which fuel conservation became an important concern. Later advancements, such as the integration of fairings, side skirts, and frame extensions, showed the potential of aerodynamic design modifications to reduce drag. These have been used extensively due to the need for conserving the energy and also nowadays the stringent regulations (emissions) for the environment.[1][4]

A critical issue is the gap between the truck's tractor and the trailer that causes high pressure zones and creates wakes which contributes considerably to the overall drag. Eliminating this gap by connecting the structures and with fairings has proven to reduce the drag.

Another issue is the rear of the trailer where we have flow separation and vortex shedding, to address this there are modifications like frame extensions and other designs that have been shown to reduce the drag further. These modifications also contribute to vehicle stability on top of reducing fuel consumption, which is good for both fuel economy and the environment, due to the reduced emissions.[2][3][4][5]

This study employs CFD study using **ANSYS Fluent** to simulate and evaluate aerodynamic improvements for different modifications. The study focuses on the drag reduction due to the gap reduction, the mounting of fairings that connect the tractor and the trailer, and the mounting of frame extensions at the end of the trailer.

This study aims to improve the flow nature around the truck using these design modifications in order to reduce drag. A study of flatter fairing profile effect on the drag, and the taper angle of the frame extension is also done in the report.

2. Numerical Setup

2.1 Mesh Independence Study

The mesh independence study is done to prove the independence of the CFD results with respect to the grid sizing (resolution). The computational domain was discretized by means of a hybrid meshing approach, structured (boundary layer near the truck surface) and unstructured (enclosure-domain and the face meshes for the truck surface) with cell counts ranging from 0.5 million to 5 million cells (5 different runs in total). The results were evaluated with our reference paper based on the drag coefficient (Cd), and the study revealed that beyond 2.6 million cells the variation in Cd was less than 1% (0.806-0.81). The drag coefficient stabilized at a value of approximately 0.81, indicating the mesh-independence, as shown in **Fig 1** (Cd vs cell no.). Based on this analysis, a mesh with 3.5 million cells was selected as optimal for the computational cost vs accuracy trade-off.

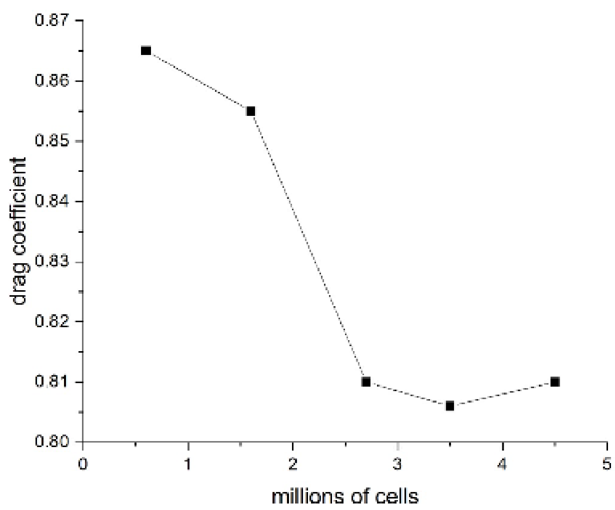

Fig 1 Cd vs. no. of cells in millions.

2.2 Solver and Turbulence Model

The simulations were carried out using a finite-volume based CFD solver, solving RANS, Reynolds-Averaged Navier-Stokes equations set with the following settings:

1. **Solver settings:** Steady-state, Pressure-based
2. **Turbulence Model**: Standard k-ϵ model, used for external aerodynamic flows to estimate moderate flow separation around a body.

2.3 Boundary Conditions

- **Inlet**: Velocity inlet (uniform value of velocity field).
- **Outlet**: Pressure outlet (set to ambient, to be computed).
- **Symmetry**: symmetric cutting plane for computational efficiency
- **Walls**: No-slip condition on truck surface (stationary wall), road (moving wall with inlet velocity) with standard wall functions for near-wall treatment.

2.4 Discretization Scheme

- **Momentum, Turbulence Equations**: Second-order upwind scheme.
- **Pressure-Velocity Coupling**: SIMPLE algorithm.

3. Case of study: Base and Modifications for Study

The geometry of the truck-trailer system is a critical factor influencing aerodynamic drag. For this study, the base design of the truck has been taken from [6] **Fig 2.1** which emulates a classic euro truck **Fig 2.2**

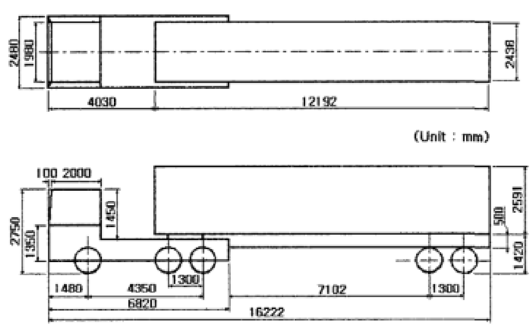

Fig 2.1 Baseline Geometry dimensions.

The gap between the tractor and trailer is a significant contributor to the drag, which creates a recirculation zone that increases aerodynamic drag. Studies [7] have shown that reducing or eliminating this gap significantly improves the overall aerodynamic efficiency of heavy vehicles. The CFD analysis by [7] demonstrated a 20% reduction in drag when the gap was reduced to a minimum, highlighting the importance of this design modification in long-haul trucks [7]. To increase the drag reduction, in the present study the gap between the tractor and trailer has been eliminated.

Another aerodynamic modification is the addition of deflector plates at the trailer's rear. This helps to mitigate the pressure drag caused by flow separation at the trailer's base. [8] conducted a CFD study revealing that base plates contributed a 7% reduction in drag by smoothing wake patterns and reducing turbulence in the wake region [8]. Hence these modifications are justified for the present study.

Fig 2.2 Classic Heavy Euro-truck Semi.

Geometry specifications:

Gap reduction is done by extending the trailer (**Fig 3**)

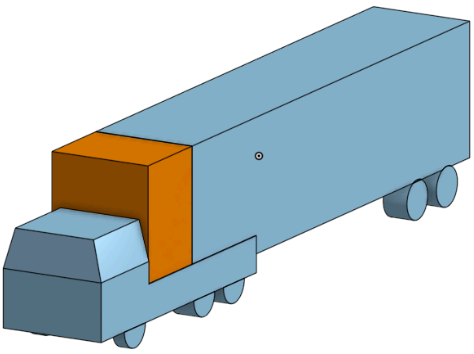

Fig 3 Truck with gap modification. The filled region is highlighted.

Fairings: Two possible fairing designs are proposed from [10]: a straight one, model F1 (**Fig 3b**), and curved one, model F2 (**Fig 3a**).

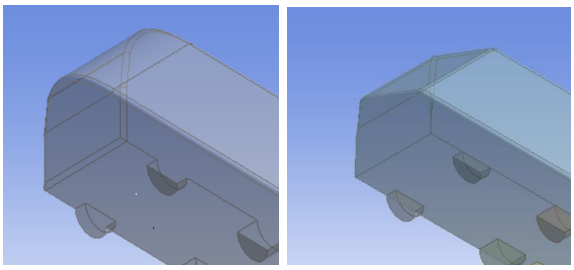

Fig 3a) Curved F1 **Fig 3b)** Straight F2

Base plate: a base plate of length ¼ of the trailer width and varying angles (5-20 deg) [11] is done on the better performing fairing design. (**Fig 4**)

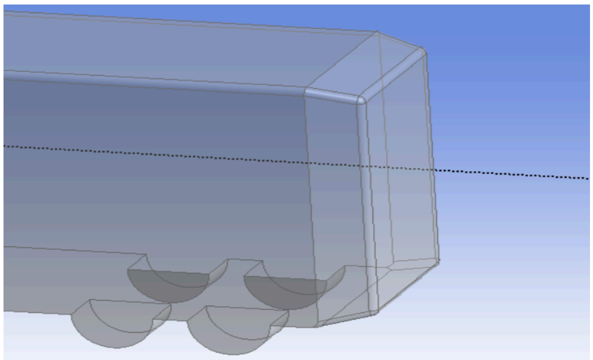

Fig 4 Base plate for a 15 deg configuration.

4. Computational domain

Package used: **Design Modeller** (Ansys)

An **enclosure** (**Fig 05**) with sufficient bounds to capture the flow is created around the body with a focus on the downstream of the truck body. (2L upstream, 5L downstream, 2L height & 2L width where L is the length of the truck-16222mm) [6]

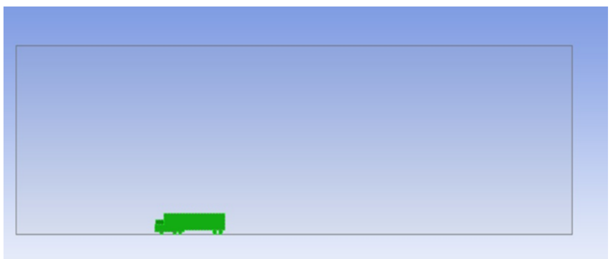

Fig 5 The enclosure around the truck.

A **Boolean subtraction** of the truck and the enclosure is done to differentiate the solid truck from the computational domain. A **symmetry cut** is executed to lower the computational cost along the symmetry (XY plane of the truck).

5. Meshing setup

- Package used: **Fluent with Fluent meshing** (Ansys)
- Add local sizing - element sizes on the truck's surface are set, with a growth rate of 1.2 and a target mesh size of 30mm.
- Creating local refinement regions: a set of local refinements are created to better capture the flow nature around the truck's body (**Fig 6**). Two refinement regions at the vicinity and downstream of the truck are added. And a third general increase in domain refinement is added.
- Surface mesh (on the truck) is generated

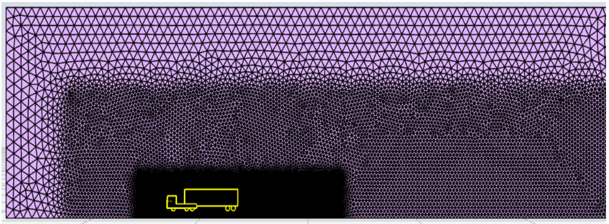

Fig 6 Result of local refinements. Surface mesh.

- Add Boundary layers*: on the truck's body a last ratio offset type boundary layer, with 15 layers and a 1.2 growth ratio is generated (**Fig 7**). In order to keep the Y plus value within the range of 30-35 a first cell height of 1.235 mm is set. Y plus value has been accurately checked for every simulation (**Table 1**).

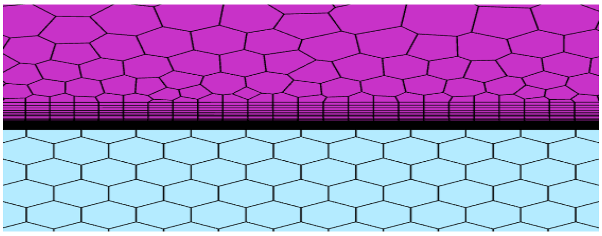

Fig 7 Boundary layering.

Boundary layer features	
Offset Method Type	last-ratio
No. of Layers	15
Transition Ratio	0.272
First Cell's Height [m]	0.00123499
Growth rate	1.2

Table 1 Boundary layer's specifications

**for the model that features a gap the BL over the whole region was split into 2 one as previously and other over the gap region this was done to enable a smooth transition*

- Volume Mesh generated: The mesh was filled with poly hex core type cells (**Fig 8**)

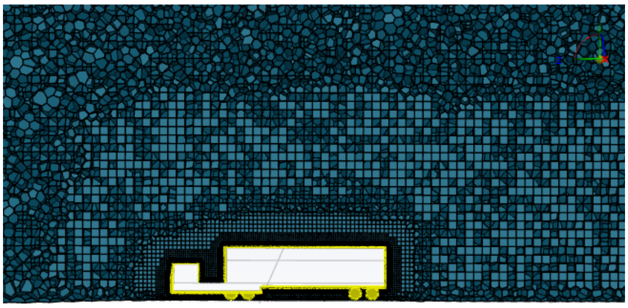

Fig 8 Volume mesh with poly-hex core cells fill.

For the case of the base geometry the final 3D mesh details are shown below (**Table 2**).

3D mesh	
Nodes	7,864,858
Edges	5,174
Faces	14,188,558
Cells	3,453,598

Table 2 Mesh specifications.

6. Results and Discussions

6.1 Base Truck Geometry:

The gap in the geometry between the tractor and the trailer caused significant re-circulation regions causing higher drag, in **Fig 9** the velocity contour with streamlines it can be seen that: the flow in the gap between the tractor and trailer shows strong recirculation, with low-speed areas (indicated by the blue regions in the contour) compared to the surrounding airflow part of the overall low-pressure area caused by flow separation as air is forced to move around the gap geometry.

The interaction of the lower speed recirculating flow with the faster airflow leads to turbulent shear layer, energy loss, and disrupted reattachment of the flow onto the trailer. This process increases aerodynamic drag by enhancing pressure drag and causing unsteady downstream airflow [12].

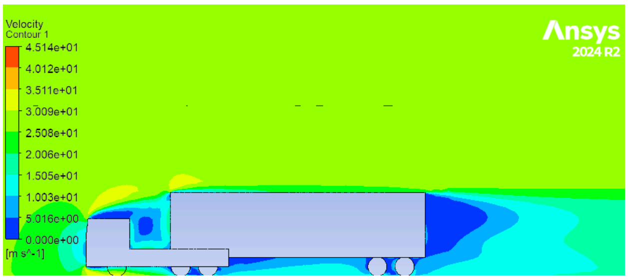

Fig 9 Baseline model velocity contour.

6.2 Truck without Gap:

The gap is then removed by the extension of the trailer, this caused much lower recirculation (the region above the tractor as seen in **Fig 10a**) and caused a significant drag reduction (from Cd 0.806 to 0.73).

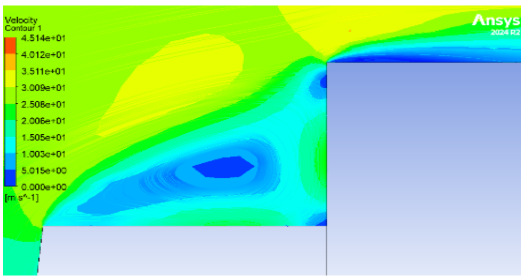

Fig 10a) Gap-filled model velocity contour.

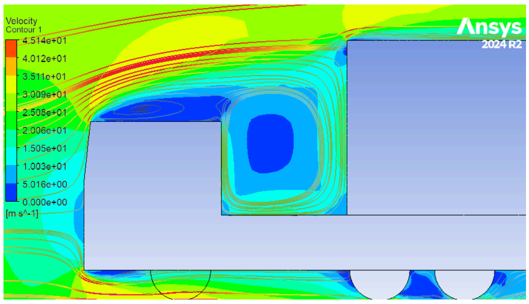

Fig. 10b) Insight of Fig 9.

6.3 Effect of the Fairing:

The gap-filled model exhibits a drag reduction, however, the step-like transition between the tractor and trailer creates significant aerodynamic issues including: ***flow separation, recirculation zones and turbulent wake formation***. This abrupt geometry disrupts smooth airflow, leading to regions of reversed flow that interact with the mainstream, increasing aerodynamic drag. The sharp transition also produces adverse pressure gradients, contributing to higher pressure drag and energy losses, which ultimately reduce vehicle efficiency. Introducing fairing helps address these challenges by streamlining the transition, reducing flow separation, and minimizing recirculation zones and wake turbulence. Fairings guide airflow smoothly across the gap, suppress vortices, and reduce adverse pressure gradients, significantly reducing drag [13].

We approach the modeling of the fairing as previously discussed [10] with a straight and curved fairing design, **Fig 3a&b)**.

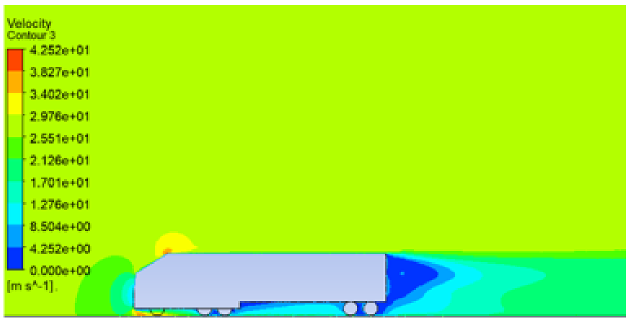

Fig 11a) Straight (triangle) fairing - model F1 velocity contour.

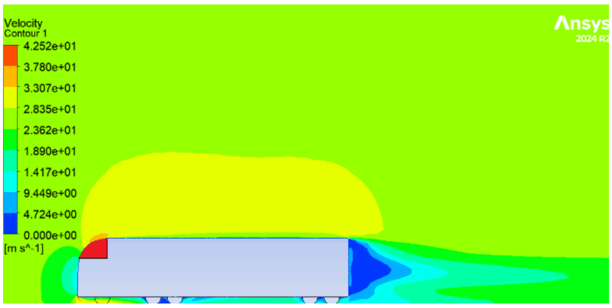

Fig 11b) Model F2 velocity contour.

The velocity contours clearly illustrate the aerodynamic differences between the straight and curved fairings. The straight fairing (**Fig 11a**) creates a sharper transition, resulting in increased flow separation due to recirculation zones, larger wake regions, which elevate the drag coefficient (Cd=0.56). In contrast, the curved fairing (**Fig 11b**) ensures a smoother flow transition by maintaining attached flow and thereby reducing recirculation zones and wake turbulence. This smoothening minimizes flow energy losses, leading to a lower drag coefficient (Cd=0.48). This highlights the aerodynamic superiority of the curved fairing design. This design is labelled as model F2 and we proceed to the baseplate modifications to further improve the aerodynamics.

6.4 Effect of the Baseplate:

The aerodynamic performance of the truck model F2 design was analyzed with varying base plate deflection angles between 5°, 10° and 15°. Flow separation occurs by 15° shown by an increasing Cd so we stop the taper.

It can be noticed from the images **Fig 12a,b&c** that the increase in taper angle increases the velocity of the flow over the truck body refers to the yellow region growth between **Fig 11b** and **Fig12a,b&c** series, in **Fig12b** and **Fig12c** the high-velocity points at the faring head is seen along with a reduction in wake size due to the increasing velocity and can be interpreted as the higher taper angles (10° and 15°) direct more airflow downward, which helps compress the wake region behind the truck and reduces the size of the low-velocity recirculation zone.

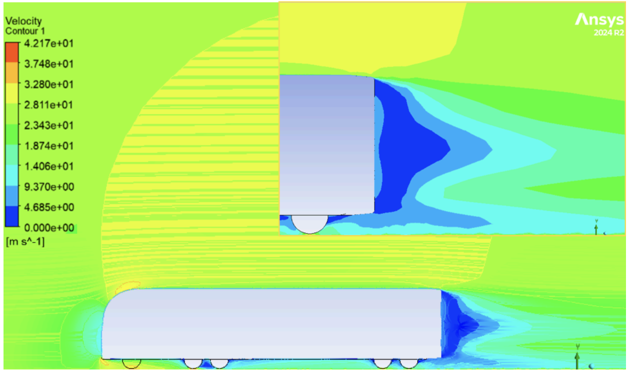

Fig 12a) Model F2 + 5° boat tail velocity contour.

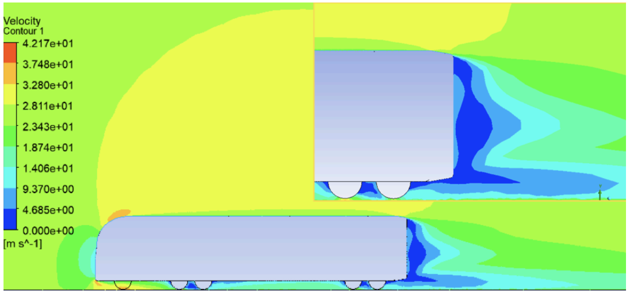

Fig 12b) Model F2 + 10° boat tail velocity contour.

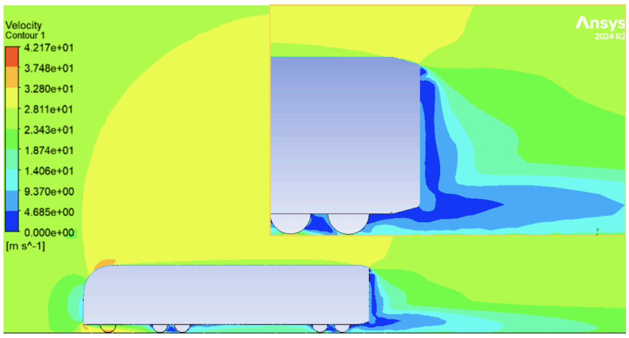

Fig 12c) Model F2 + 15° boat tail velocity contour.

Although increasing the taper angle from 5° to 15° reduces the wake region size, the aerodynamic efficiency and drag reduction are superior at 5°. This is primarily due to the more symmetric and stable wake at 5° **Fig 12a**, which reduces lateral energy losses and minimizes turbulence intensity. In contrast, higher taper angles (10° and 15°) compress the wake but increase shear stress and turbulence near the truck's base - a longer region “tail” of low-velocity blue region is seen in Fig 12b&c when compared to **Fig 12a**, where the airflow struggles to realign after extreme deflection leading to greater energy dissipation and higher surface drag. The smoother flow transition at 5° helps balance wake control with drag reduction more effectively, resulting in superior aerodynamic performance.

5° deflection was found to yield the lowest drag coefficient (Cd) by effectively reducing wake size and turbulence intensity behind the truck. It has been observed that modest deflection angles help reduce pressure drag by minimizing adverse pressure zones at the base of the vehicle (see [14]). On the other hand, the 10° and 15° deflections expand the wake (the "tail" discussed before), increasing turbulence and, consequently, higher drag values.

Furthermore, the velocity increase near the fairings in the 10° and 15° deflection cases highlights stronger recirculating flow that amplifies turbulence in the wake region, which indicates that excessive rear-end modifications can disrupt downstream flow symmetry (seen in **Fig 12** series) and worsen the aerodynamic losses [15]. The extended wake zones associated with larger deflections also create a more significant pressure deficit (velocity increase causing low-pressure regions), amplifying drag penalties. Therefore, the 5° deflection emerges as the optimal configuration, balancing wake control and flow symmetry to achieve efficient drag reduction.

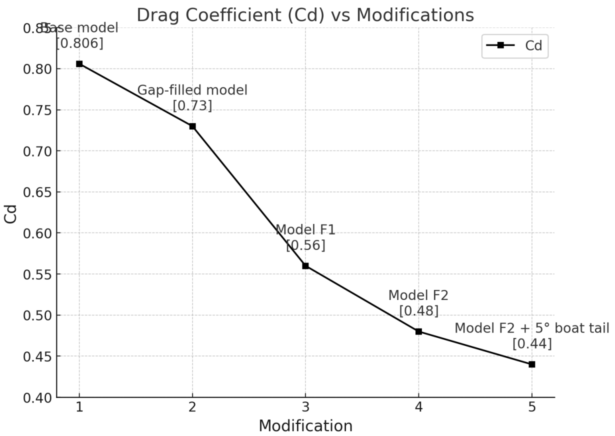

Fig 13 Cd values after every modification.

From **Fig 13** and **Table 3** we can note the improving aerodynamics of the truck design as the design modifications in a step-wise manner are implemented. It can be seen that the drop in drag is significant for removing the gap and implementation of the fairing for overcoming the abrupt steplike discontinuity, by enabling a smoother flow turning. The latter is more significant than the former, hence allowing us to deduce that the flow turning is more critical to lower the drag, hence proving the usefulness of fairings.

Model	Cd value
Baseline	0.806
Gap-filled	0.73
F1	0.56
F2	0.48
F2 + 5° boat tail	0.44

Table 3 Cd values for the different configurations tested.

The implementation of base plates shows a modest improvement in aerodynamics, i.e. a modest Cd drop.

6.5 Additional fairing designs

Bio-inspired fairing A completely different fairing design in terms of the flow turning has been studied to try to investigate the improvement in aerodynamic drag. A different approach to fill the gap has been used such that the flow turning is much smoother. The fairing shape is bio-inspired [16] as it emulates sea lion's anatomy, **Fig 14**. It differs from previous cases for two main reasons: the fairing features a complex, multi-curvature, continuous contour keeping in mind the flow guidance around the truck body in comparison to the initial roof modifications, which featured simple geometry and the gap was eliminated before introducing further remodelling.

This new geometry, further referred to as model F3, is expected to guide the flow smoothly to every side of the trailer.

The meshing and simulation setup remained unchanged.

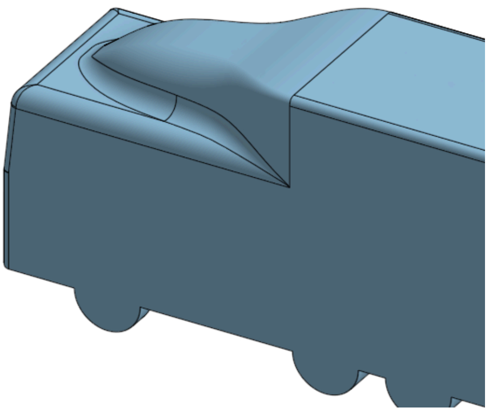

Fig 14 Bio-inspired fairing design, model F3.

Results and comparison: the long fairing extension has shown to further decrease drag coefficient with respect to model F1 and F2 (**Table 4**). Model F3 shows a wake of comparable velocity magnitude with model F2, while the low-velocity region is shorter (**Fig 15**). The main difference in flow field lies on the fairing region, as the higher-velocity region above the truck is drastically reduced, this can be attributed to the smoother flow turning which in the case of thin airfoils has shown to delay the separation.

Fig 15 Model F3 velocity contour.

Model	Cd value
F1	0.56
F2	0.48
F3	0.46

Table 4 Cd values for F1, F2, F3 models.

7. Conclusions

The final model has 0.44 Cd compared to the 0.806 Cd of the base model, this amounts to a total of about 46% drag reduction, quite a significant improvement in aerodynamics of the truck, this approximately translates to important fuel savings assuming a generic diesel truck at 100 kmph, the financial resources saved is significant for long haul trucks covering thousands of kilometers.

However, it must be stressed that the study is not ideal, that is not replicating exactly the real world effects and interactions like the rotating wheels and skin friction losses, driver actions, environmental conditions, infrastructure and other real world interactions and phenomena that affect negatively the aerodynamics and especially the fuel consumption, as that is the vital resource we ultimately aim to conserve for both financial and environmental reasons.

8. Future scopes

Future scopes for this work can include a more accurate modelling with dynamic meshes (which introduces more accuracy but still not real world). This can provide to us an aerodynamically optimised model after further modifications (like side skirts), a scaled down model can then be produced to carry out a wind tunnel test, equipped with a moving belt to simulate the wheel rotations. The set of modifications that can be easily realised and implemented in the real world trucks can then be effected giving to us finally a economic and environmental benefit.

9. REFERENCES

[1] NASA Dryden Flight Research Center. (2021). *Aerodynamic truck studies*. National Aeronautics and Space Administration.

[2] Neural Concept. (2023). *Truck aerodynamics: Enhancing performance and fuel economy*. Retrieved from https://www.neuralconcept.com.

[3] Ortega, J. M., Moniot, A. L., & Wadsworth, D. C. (2012). *Aerodynamic drag reduction of class 8 heavy vehicles.* SAE International. Retrieved from https://digital.library.unt.edu.

[4] Wood, R. M., & Bauer, S. X. S. (2003). *Simple and low-cost aerodynamic drag reduction devices for tractor-trailer trucks.* NASA Langley Research Center.

[5] Cooper, K. R. (2003). *Truck aerodynamics reborn: Lessons from the past.* (SAE Technical Paper 2003-01-3376). SAE International. https://doi.org/10.4271/2003-01-3376.

[6] Kim, C. H., & Youn, C. B. (2005). Aerodynamic effect of roof-fairing system on a heavy-duty truck. *International Journal of Automotive Technology, 6*(3), 221-227.

[7] Li, X., Wang, J., & Zhang, P. (2016). Numerical simulation and optimization of tractor-trailer aerodynamics using CFD. *Journal of Wind Engineering and Industrial Aerodynamics, 152*, 1–10.

[8] Ahmed, S., Kumar, R., & Patel, P. (2018). Effects of boat-tail plates on drag reduction in heavy trucks: A CFD study. *International Journal of Automotive Engineering, 34*(5), 123–131.

[9]https://www.ttnews.com/articles/xstream-launches-articulated-device-close-tractor-trailer-gap

[10] Elshazly, A., Abdelaziz, A. I., & Elbaz, A. (2023). A computational study on the effects of installing cap roof deflectors on the drag reduction of trucks. *International Journal of Research Publication and Reviews, 4*(12), 464–468. Retrieved from http://www.ijrpr.com

[11] Håkansson, C., & Lenngren, M. J. (2010). *CFD analysis of aerodynamic trailer devices for drag reduction of heavy duty trucks* (Master's thesis, Chalmers University of Technology).

[12] Fu-Hung Hsu and Roger Davis. "Tractor-Trailer Drag Reduction Strategies Determined from CFD," AIAA 2008-4307. *38th Fluid Dynamics Conference and Exhibit*. June 2008.

[13] Browand, F., and Lay, P. (1987). *The Influence of Trailing Gap Geometry on the Aerodynamic Drag of Trucks*. SAE Technical Paper 870705.

[14] Wood, R. M., & Bauer, S. X. S. (2003). *Simple and low-cost aerodynamic drag reduction devices for tractor-trailers.* SAE Technical Paper 2003-01-3377.https://doi.org/10.4271/2003-01-3377

[15] Ahmed, S. R., Ramm, G., & Faltin, G. (1984). *Some salient features of the time-averaged ground vehicle wake.* SAE Technical Paper 840300. https://doi.org/10.4271/840300

[16] Jeong Jae Kim, Jiwoo Hong, Sang Joon Lee. Bio-inspired cab-roof fairing of heavy vehicles for enhancing drag reduction and driving stability

http://dx.doi.org/10.1016/j.ijmecsci.2017.08.010