ADVANCED AERONAUTIC COMPONENTS FOR REDUCING FUEL CONSUMPTION AND EMISSIONS IN COMMERCIAL TRUCKS

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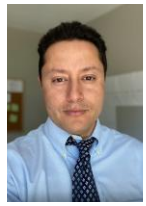

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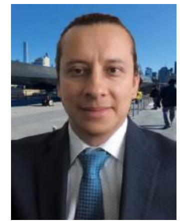

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ABSTRACT

The heavy-duty truck sector is under pressure to boost fuel efficiency and lower environmental impact. With over 25 million Euro 5 and Euro 6 trucks, these vehicles are vital to global freight but contribute significantly to emissions and fuel use [1][2]. As stricter emissions standards emerge, the industry must adopt new technologies. This document presents a study that examines using aeronautic components—like Venturi tubes, aerodynamic profiles, flaps, slats, and vortex generators—on rigid and articulated trucks to improve efficiency. The study's goal is dual, optimization: reducing drag and generating lift. Phase 1 used computational fluid dynamics (CFD) simulations to assess the impact of these components on Euro 5 and Euro 6 trucks, identifying areas needing improvement. Phase 2 refined these optimizations through further CFD analysis, targeting long-haul scenarios where fuel efficiency is critical. Results show significant fuel reductions, from 3.6% to 13.6%, especially in long-distance transport vehicles. These improvements lower CO_2 emissions, delivering both cost fuel savings and environmental benefits. The study confirms that aeronautic-inspired solutions are effective for enhancing fuel efficiency in heavy-duty trucks, helping meet emissions targets while reducing operational costs [3][4]. In summary, integrating aviation technology into Euro 5 and Euro 6 trucks presents a groundbreaking method for improving fuel efficiency and sustainability in trucking. The substantial fuel savings make a strong case for widespread adoption, paving the way for a more efficient, eco-friendly future in global transport.

KEYWORDS

Climate change mitigation, Innovations in heavy vehicle systems, Aerodynamics, Fuel Efficiency, Computational Fluid Dynamics, Greenhouse Gas Emissions, Drag Reduction, Lift Generation, Fleet Optimization, Sustainability.

INTRODUCTION

The global transportation sector, responsible for approximately 25% of CO_2 emissions, faces increasing pressure to reduce greenhouse gases [1]. Heavy-duty trucks, due to their high fuel consumption, contribute significantly to these emissions [2]. With the implementation of stricter environmental standards such as Euro 5 and Euro 6, improving fuel efficiency and reducing emissions in these vehicles has become a priority. Aerodynamic drag, particularly at highway speeds, is a major factor affecting fuel consumption. While numerous technologies have been developed to mitigate drag, additional aerodynamic improvements remain an area of opportunity [3].

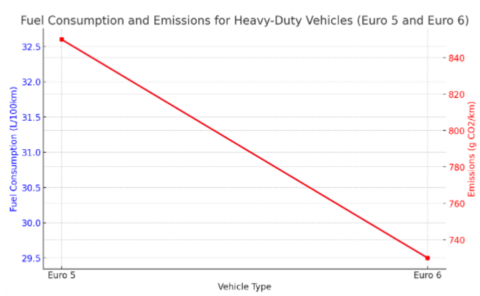

Figure 1: Comparison of fuel consumption (liters per 100 km) and average CO_2 emissions (grams per kilometer) for heavy-duty Euro 5 and Euro 6 vehicles.[1][2].

This study explores the application of aerodynamically optimized components, including Venturi tubes, aerodynamic profiles, flaps, slats, and vortex generators, originally developed in the aviation industry, to heavy-duty trucks. These components aim to reduce drag while also generating lift, potentially contributing to overall vehicle efficiency [4]. The controlled generation of lift has been proposed as a means to offset part of the vehicle's load, which, in combination with drag reduction, may lead to improvements in fuel consumption, emission reductions, tire longevity, and infrastructure wear.

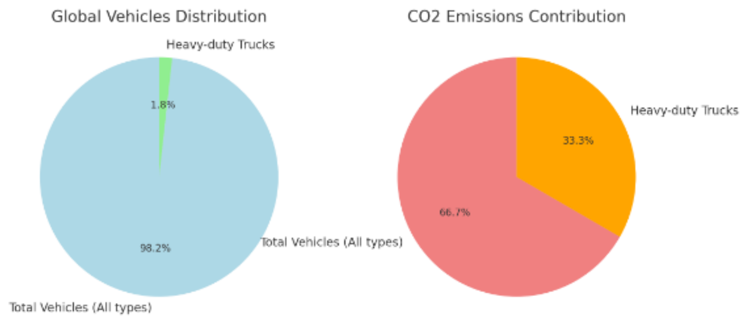

Figure 2: Comparison gas emission contribution between total global vehicles and cargo vehicles.

According to the International Energy Agency (IEA), the global vehicle fleet exceeded 1.4 billion units in 2021, with heavy-duty trucks representing a significant source of transportation-related emissions [1][3]. Additionally, the International Council on Clean Transportation (ICCT) estimates that heavy-duty vehicles in the EU account for approximately 25% of transportation-related CO_2 emissions, while globally, they contribute around 33.3% [2]. These figures underscore the potential impact of aerodynamic optimizations on a large scale.

To evaluate these aerodynamic improvements, multiple phases of Computational Fluid Dynamics (CFD) testing were conducted, both internally and independently with IDIADA in Spain. Phase 1 consisted of general CFD simulations, while Phase 2 focused on detailed aerodynamic optimizations for Euro 5 and Euro 6 heavy-duty truck models.

This study assesses the effects of integrating advanced aerodynamic components into heavy-duty trucks, demonstrating measurable reductions in fuel consumption and emissions. Furthermore, it highlights the potential role of controlled lift in commercial vehicle aerodynamics, emphasizing that its effectiveness depends on specific conditions such as vehicle speed and airflow. In regions with higher wind speeds or greater vehicle velocities, the lift generation could be significantly enhanced, further improving aerodynamic efficiency and its practical application in freight transportation.

METHODOLOGY AND RESULTS

Computational Fluid Dynamics (CFD) is a numerical method used to simulate fluid flow, playing a crucial role in optimizing aerodynamic components for vehicles. In this study, CFD simulations were employed to evaluate the aerodynamic performance of heavy-duty trucks, with a particular focus on drag reduction and lift enhancement. The simulations were conducted internally and externally audited by IDIADA to ensure validation and accuracy.

The study adhered to European heavy-duty truck standards but acknowledges that aerodynamic performance may vary in vehicles from other regions due to differences in structural design and speed regulations. Key simulation parameters included a constant vehicle speed of 90 km/h, with drag and lift coefficients calculated for configurations with and without aerodynamic modifications. A symmetric vehicle geometry allowed for half-model simulations, and the computational domain was sufficiently large to prevent blockage effects. The simulation domain consisted of approximately 90 million cells, with a core mesh of 65.5 million hexahedral cells and 24.5 million cells in the Prism Layer Mesh. The physics setup employed a steady-state, three-dimensional space with air at a constant density of 1.1767 kg/m^3, utilizing the RANS K-Omega SST turbulence model. Boundary conditions included a tunnel inlet velocity of 90 km/h and a wheel rotational rate of 55.35 rad/s. This setup provided a controlled simulation environment to accurately assess the aerodynamic performance of the tested components under steady-state conditions.

Study Phases Overview

The study was divided into two phases to systematically evaluate the aerodynamic impact of integrating advanced aerodynamic components into heavy-duty trucks. These phases analyzed fuel consumption, drag reduction, lift generation, and overall efficiency improvements. Both phases were conducted by IDIADA's aerodynamic team to ensure expert validation and support throughout the study.

Phase 1: General Analysis and Concept Testing

In Part 1, a proof of concept was conducted using CFD simulations to evaluate the potential aerodynamic benefits of integrating advanced aerodynamic components into heavy-duty trucks. Elements such as Venturi tubes, flaps, slats, and vortex generators were applied to a simplified truck model at a constant speed of 90 km/h to assess their impact on drag reduction and lift generation.

Part 2 focused on optimizing the positioning, size, and configuration of these components on detailed truck models, ensuring compliance with European standards regarding weight, speed, and size. This phase aimed to refine aerodynamic efficiency through systematic adjustments. CFD tests were conducted by IDIADA, providing an external validation of the results. Findings from both parts of Phase 1 indicated potential reductions in fuel consumption and greenhouse gas emissions, offering valuable insights for further aerodynamic optimizations.

Phase 2: Detailed Vehicle-Specific Optimization

Phase 2 aimed to refine the aerodynamic component integration on specific commercial truck models and was divided into two parts:

- **Part 1:** A 2020 model, 9-ton non-articulated truck was analyzed, focusing on drag reduction and lift generation. This phase aimed to optimize the aerodynamic setup while ensuring vehicle stability.
- **Part 2:** The aerodynamic components were tested on an articulated truck to evaluate their effectiveness in a more complex vehicle configuration, ensuring performance consistency across different truck types.

The final analysis compared the results from both parts, assessing the potential fuel savings and emissions reductions achievable in Euro 5 and Euro 6 trucks. The study also examined the broader implications of aerodynamic optimization on fleet efficiency and environmental impact.

Results of Proof of Concept (Phase 1 - Part 1)

During Phase 1, Part 1, CFD simulations were performed by IDIADA's aerodynamics department to analyze the aerodynamic impact of various configurations of Venturi ducts, airfoils, flaps, and winglets on heavy-duty trucks. The simulations measured changes in the drag coefficient (Cd), lift coefficient (Cl), and aerodynamic forces under highway conditions at a constant speed of 90 km/h.

The baseline truck, without aerodynamic modifications, exhibited a drag coefficient (Cd) of 0.566 and a lift coefficient (Cl) of -0.059, corresponding to 1787 N of drag and -184 N of lift (downforce). The tests demonstrated notable improvements in both drag reduction and lift generation across different configurations, highlighting the potential for further optimization of aerodynamic performance in heavy-duty trucks.

Case	Cd (Drag Coefficient)	Lift Coefficient (Cl)	Drag Force (N)	Lift Force (N)
C01 (Baseline)	0.566	-0.059	1787	-184
C01	0.536	-0.023	1703	-19
C02	0.455	-0.041	1444	-131
C03	0.427	-0.098	1300	-298
C04	0.452	0.066	1535	255
C05	0.457	0.126	1551	429
C06	0.442	0.069	1503	234

Table 1: Coefficient of Drag and Lift concept test phase 1, part 1.

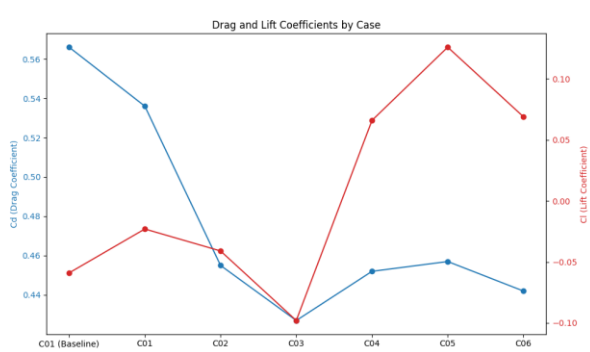

Figure 3: Coefficient of Drag and Lift concept test.

Analysis of Results with Percentages

This study aimed to optimize the balance between drag reduction and lift generation in heavy-duty trucks to improve overall aerodynamic efficiency. Phase 1 CFD simulations conducted by IDIADA tested various aerodynamic components, leading to significant performance improvements. Starting with a baseline drag coefficient (Cd) of 0.566, configuration C01 achieved a 5.3% reduction in drag. Configuration C02 reduced drag by 19.6% (Cd 0.455), while C03 achieved the highest reduction at 24.6% (Cd 0.427). Although C04 and C05 did not surpass C03 in drag reduction, they still provided meaningful decreases of 20.1% and 19.3%, respectively, while also enhancing lift.

Regarding lift performance, C01 increased lift by 61%, whereas C04 achieved a positive lift value of 0.066, corresponding to a 211.9% increase. Configuration C05 yielded the highest lift enhancement, reaching a 313.6% improvement (Cl 0.126), effectively balancing both lift generation and drag reduction. While C03 demonstrated the greatest drag reduction, it led to a decrease in lift, whereas C05 provided an optimal balance with a 19.3% reduction in drag and a 313.6% increase in lift.

These findings validate the potential of aerodynamically optimized components in enhancing truck efficiency. However, the achieved lift values remain dependent on local regulations and atmospheric conditions, as the effectiveness of lift is closely tied to impact velocity. Given that vehicle speed limits vary across different regions, and external airflow conditions fluctuate, further research and development could potentially lead to exponential improvements in lift performance under higher-speed scenarios or optimized aerodynamic designs.

Important Observations

During the simulations, a notable aerodynamic phenomenon was observed, needing adjustments in the project's design approach. The study, conducted on European truck models, revealed that the interaction between the cabin and incoming airflow significantly influenced component performance. Specifically, the movement of the cabin against the air mass generated an increase in frontal pressure, causing a localized airspeed reduction before impact with the vehicle's structure. This effect, referred to as the "Vehicle Frontal Pressure Bubble", altered the expected airflow behavior by increasing pressure, decreasing velocity, and shifting the flow from laminar to turbulent. This phenomenon presented a key challenge in the aerodynamic optimization process, influencing the refinement of future component designs. Addressing these effects through targeted modifications and additional studies could further improve aerodynamic efficiency in heavy-duty trucks, particularly in regions where different vehicle morphologies and speed regulations may lead to varied aerodynamic behaviors.

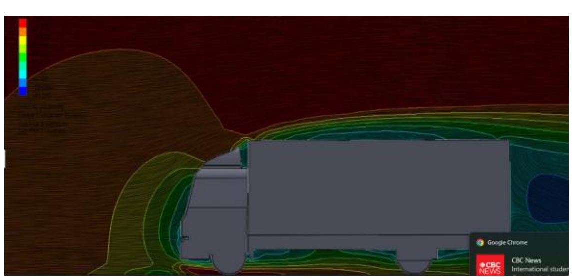

Figura 4: Cabin impact zone, **"Vehicle Frontal Pressure Bubble"**.

The phenomenon known as the **"Vehicle Frontal Pressure Bubble"** was identified as a critical factor influencing aerodynamic performance. This effect, caused by increased pressure around the truck cabin, impacted the airflow behavior around aerodynamic components. To address this, the initial closed-component designs were modified into open configurations to better adapt to the aerodynamic characteristics of European heavy-duty trucks.

Given that European regulations impose a strict speed limit of 90 km/h, the aerodynamic effects observed in this study may differ in regions with higher speed limits. In such cases, aerodynamic performance improvements, including greater fuel savings and emissions reductions, could be further enhanced due to increased airflow velocity and its effect on lift generation. Additionally, European size regulations influenced the design approach, leading to the consideration of future aerodynamic components that would be fully integrated into the cab and trailer structure to ensure regulatory compliance while maximizing aerodynamic efficiency.

General Optimization of Part 1 (Phase 1 - Part 2)

Building on the insights gained from Phase 1 - Part 1, the study focused on developing simplified aerodynamic components tailored for European heavy-duty trucks. The primary objective was to adapt these components to the specific frontal pressure conditions observed in these vehicles. By analyzing the initial data, each component was refined to optimize the balance between drag reduction and lift generation, with the ultimate goal of improving fuel efficiency and reducing emissions.

The study aimed to develop an integrated aerodynamic system that enhances overall vehicle performance by optimizing both lift and drag characteristics. The results of this phase are detailed in the following sections.

Case	Cd	Area (m2)	CdA (m2)	Cl	Aero Lift (N)	Aero Drag (N)
Base	0.566	8.58	4.859	-0.059	-184	1787
1	0.536	8.63	4.628	-0.023	-73	1703
2	0.455	8.63	3.929	-0.041	-131	1444
3	0.427	8.28	3.537	-0.098	-298	1300
4	0.452	9.23	4.171	0.066	225	1535
5	0.457	9.23	4.217	0.126	429	1551
6	0.442	9.24	4.085	0.069	234	1503
7	0.454	8.28	4.589	0.018	57	1687
8	0.457	8.51	3.899	0.155	484	1430
9	0.432	9.32	4.024	0.261	892	1478
10	0.41	10.54	4.322	0.293	1152	1597
11	0.425	10.55	4.49	0.336	1302	1650
12	0.487	8.28	4.034	-0.055	-168	1484
13	0.435	10.55	4.588	0.312	1210	1686
14	0.498	8.28	4.122	-0.049	-148	1516
15	0.386	10.55	4.071	0.29	1124	1496
16	0.395	8.51	3.361	0.079	247	1236
17	0.384	9.32	3.577	0.211	722	1316
18	0.369	10.54	3.891	0.247	960	1430

Table 2: Coefficient of Drag and Lift for Truck Configurations Tested Using CFD Analysis.

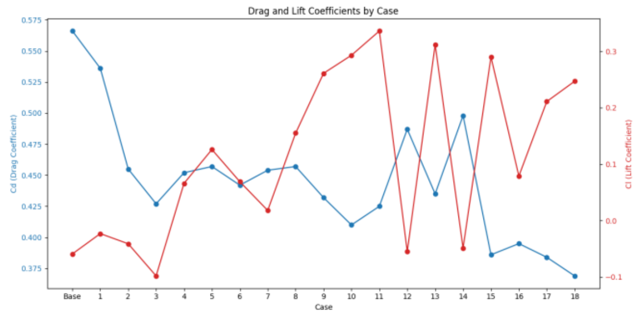

Figure 5: Coefficient of Drag and Lift for Truck Configurations Tested Using CFD Analysis.

Analysis of Results with Percentages:

In this analysis, the results of each case are compared to both the **baseline (Base)** and **Case 14 (Simplified truck version)**, aiming to identify the most efficient configuration in terms of drag reduction and lift increase.

IDIADA has considered **baseline** as a detailed truck with a non-rounded cargo box, which represents a vehicle with limited aerodynamic improvements. **Case 14** is considered a simplified truck that serves as the base for analyzing the remaining cases, and it is more representative of standard vehicles used in these results. The focus is on identifying the best balance between drag and lift, and the best possible result in terms of fuel consumption reduction and green house emission reduction, which ends being achieved in **Case 16**.

Case comparison

Building on the findings, Case 16 emerges as the best configuration for balancing drag reduction and lift enhancement, making it the optimal choice for Phase 2, where we will focus on Euro 5 and Euro 6 vehicles. **Case 16 Analysis:** Compared to the baseline, Case 16 achieves a 30.2% reduction in drag and a 233.9% increase in lift. This setup also outperforms Case 14, with 20.7% less drag and 261.2% more lift. This balance makes Case 16 highly effective for improving fuel efficiency and reducing emissions, positioning it as the configuration to optimize further in Phase 2 testing on Euro 5 and Euro 6 heavy-duty trucks.

In comparison:

- Case 1, while showing a 5.3% drag reduction and a 61.0% lift increase from the baseline, lags behind with 8.0% higher drag than Case 14.
- Case 10 achieves a substantial lift improvement (596.6%) but lacks the balanced performance of Case 16.
- Case 18, with the highest drag reduction (34.8%), does not offer the optimal lift levels needed for our goals.

Thus, Case 16 offers the best compromise between drag reduction and lift maximization, making it the focus for further optimization.

Case	Lift (N)	DLift (%)	Drag (N)	DDrag (%)	Bd (lt/100km)	DBd (%) from C14
Baseline	-184	-	1787	-	25.5	-
1	-73	50%	1703	12%	24.9	5.8%
2	-131	11%	1444	-5%	23.0	-2.1%
3	-298	101%	1300	-14%	22.0	-6.5%
4	225	252%	1535	1%	23.7	0.5%
5	429	390%	1551	2%	23.8	1.0%
6	234	258%	1503	-1%	23.4	-0.4%
7	57	138%	1687	11%	24.7	5.2%
8	484	427%	1430	-6%	22.9	-2.8%
9	892	703%	1478	-3%	23.3	-1.3%
10	1152	878%	1597	5%	24.1	2.0%
11	1302	980%	1650	9%	24.5	3.9%
12	-168	14%	1484	-2%	23.3	-0.9%
13	1210	918%	1686	11%	24.8	5.1%
14	-148	0%	1516	0%	23.5	0%
15	1124	859%	1496	-1%	23.3	-0.8%
16	247	267%	1236	-18%	21.5	-8.7%
17	722	588%	1316	-13%	22.0	-6.3%
18	960	749%	1430	-6%	22.9	-2.8%

Table 3: Coefficient of Drag and Lift and fuel consumption factor for Truck Configurations Tested Using CFD Analysis By IDIADA.

Fuel and Emission Savings

Although these cases were initially conceptual designs and partial integration tests of various aerodynamic components in commercial trucks, the results demonstrate the feasibility of simultaneously increasing lift while reducing drag, leading to measurable fuel savings. In the second phase of this study, these findings will inform the development of an integrated aerodynamic design, allowing for further validation and refinement under real-world conditions.

Among the tested configurations, Case 16 proved to be the most effective, achieving an 8.7% reduction in fuel consumption compared to Case 14. It is also important to highlight that each baseline case in this study included an air deflector installed on the truck. Consequently, vehicles without pre-existing aerodynamic enhancements could potentially achieve even greater fuel savings and emissions reductions. Applying these theoretical savings to Euro 5 and Euro 6 trucks suggests that significant reductions in fuel consumption and emissions could be realized, reinforcing the potential impact of aerodynamic optimization in the heavy-duty transportation sector.

Fuel Savings for Euro 5 and Euro 6 Trucks:

Euro 5 trucks consume about 33 liters per 100 km, while Euro 6 trucks use around 30 liters. With an 8.7% fuel reduction from Case 16, Euro 5 trucks would drop to approximately 30.14 liters per 100 km, saving 2.86 liters, and Euro 6 trucks would lower to around 27.39 liters, saving 2.61 liters. For annual saving we can interpolate, for trucks driving 100,000 km per year, a Euro 5 truck would save about 2,860 liters annually, while a Euro 6 truck would save 2,610 liters. To determine the CO2 annual emissions, we can say that according with historical information each liter saved avoids 2.64 kg of CO2 emissions, leading to a reduction of 7.55 tons per year for Euro 5 and 6.89 tons for Euro 6 trucks.

The benefits of this fuel reduction translate to significant cost savings and reduces emissions, aligning with environmental regulations. Adopting Case 16 optimizes fuel use, cuts costs, and supports emission reduction efforts, benefiting both operators and the environment.

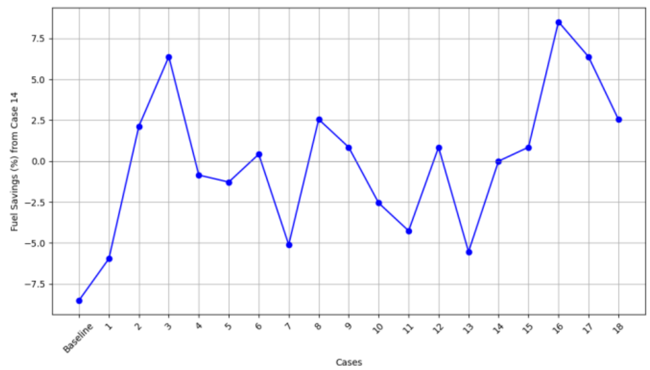

Figure 6: Fuel consumption savings.

Phase 2 - Part 1: Non-Articulated Truck Analysis

The Aerodynamics Department at IDIADA not only conducted and verified CFD simulations but also validated the fuel consumption calculation method based on "El Consumo de Combustible y Energía en el Transporte" by Ricardo A. Marchese and Marcos A. Golato, ensuring accurate, real-world data for fuel savings. In Phase 2 - Part 1, IDIADA performed detailed aerodynamic simulations on a 10-ton non-articulated truck to optimize EETS configurations. The main goal was to maximize drag reduction, lift increasing, and fuel savings for Euro 5 and Euro 6 vehicles, ensuring stability under real driving conditions. Two baseline configurations were used: **C01 (Sharp Edges):** A non-aerodynamically optimized truck and **C02 (Rounded Edges):** A truck with rounded box corners.

The remaining configurations were assessed for fuel efficiency, drag, and lift improvements compared to C01 and C02. Both cases also included the manufacturer's air deflector.

Vehicle Configuration	Cd	% ΔCd C01	% ΔCO2	A [m²]	CdXA [m²]	Drag [kgf]	Lift [kgf]	% ΔLift C01	% ΔLift CO2	Lift front [kgf]	Lift rear [kgf]
C01 Sharp edges	0.569	-	-	8.584	4.884	182.9	-22.5	-	-	52.6	-75.0
C02 Rounded edges	0.446	21.7%	-	8.721	3.886	145.7	-28.4	-26.2%	-	36.0	-64.4
C03 Rounded edges Venturi	0.43	24.4%	3.4%	8.93	3.842	144.0	-48.3	-114.1%	-69.7%	20.2	-68.5
C04 Rounded edges Venturi Chamfer	0.419	26.3%	5.9%	8.93	3.746	140.5	6.8	130.1%	123.9%	12.0	-5.2
C05 Rounded edges Venturi 201 Chamfer	0.413	27.3%	8.1%	8.955	3.702	138.8	18.2	180.8%	164.0%	18.1	0.1
C06 Rounded edges Venturi 201 Techo AirFoil	0.399	29.9%	10.4%	8.955	3.574	133.8	-11.2	50.2%	60.6%	28.8	-40.1

Table 4: Coefficient of Drag and Lift for Phase 2 straight cargo vehicle.

Vehicle Configuration	Bd (lt/100km)	% ΔBd C01	% ΔBd C02
C01 Sharp edges	35.4	-	-
C02 Rounded edges	31.7	-10.4%	-
C03 Rounded edges Venturi	31.6	-10.8%	-0.4%
C04 Rounded edges Venturi Chamfer	31.2	-11.9%	-1.7%
C05 Rounded edges Venturi 201 Chamfer	31.0	-12.4%	-2.2%
C06 Rounded edges Venturi 201 Techo Airfoil	30.5	-13.6%	-3.6%

Table 5: Fuel consumption calculations Phase 2 straight cargo vehicle.

The **C06** configuration stands out as the optimal choice for fuel efficiency and aerodynamic performance on Euro 5 and Euro 6 trucks, achieving substantial improvements over the baseline cases for straight cargo comercial trucks. C01 represents a non-aerodynamic truck with a fuel consumption of 35.4 liters/100 km, a drag coefficient (Cd) of 0.569, and a lift of -22.5 kgf (downforce), making it the primary reference for comparison.

With basic aerodynamic enhancements, C02 consumes 31.7 liters/100 km (10.4% less than C01), has a Cd of 0.446 (21.7% reduction), and -28.4 kgf of downforce, providing better but still limited optimization. C06 achieves a fuel consumption of 30.5 liters/100 km, showing a 13.6% reduction from C01 and 3.6% from C02. Its Cd drops to 0.399, reducing drag by 29.9% compared to C01 and by 10.5% compared to C02. With a downforce of -11.2 kgf, C06 cuts downforce by 50.2% from C01 and 60.6% from C02. C06 demonstrates the best fuel efficiency and aerodynamic balance, making it ideal for reducing fuel consumption and emissions in Euro 5 and Euro 6 straight trucks.

Fuel Efficiency and Emission Benefits for Euro 5 and Euro 6 Vehicles

Using Euro 5 and Euro 6 trucks as references and data from the International Council on Clean Transportation (ICCT) and European Environment Agency (EEA) [5] [6]:

Euro 5 (compared to C01): With an average fuel consumption of 33 liters/100 km, applying the C06 configuration achieves a fuel saving of 4.5 liters/100 km, totaling 4,500 liters annually. Using the standard factor that each liter of diesel produces 2.64 kg of CO2 [7] [8], a Euro 5 truck without optimization emits approximately 87.12 tons of CO2 annually. With the EETS system (C06), this reduces emissions to 75.24 tons, saving about 11.88 tons of CO2 per year. **Euro 6 (compared to C01):** For Euro 6 trucks with an average consumption of 30 liters/100 km, the C06 configuration leads to a saving of 4 liters/100 km, totaling 4,000 liters annually. Without optimization, these trucks emit around 79.2 tons of CO2 annually; with C06, emissions reduce to 68.64 tons, yielding an annual CO2 saving of approximately 10.56 tons.

These reductions apply per vehicle, but scaling the EETS system across fleets of Euro 5 and Euro 6 trucks offers substantial savings in both fuel costs and emissions. Additionally, the EETS system allows Euro 5 trucks to meet and even exceed Euro 6 efficiency standards, providing older fleets an effective solution to reduce costs and emissions without needing to upgrade to new models.

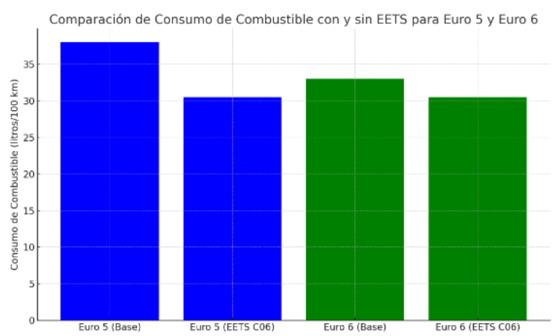

Figure 7: Coefficient of Drag and Lift for Truck Configurations Tested Using CFD Analysis.

Phase 2 - Part 2: Articulated Truck Analysis

For Phase 2 - Part 2, the reference vehicle was a model with the highest number of existing aerodynamic improvements. This setup aimed to test the EETS system's maximum potential impact on fuel consumption and emissions on a aerodynamically optimized semi-truck. However, the improvements observed here represent a near-limit scenario, and even better results are expected in other configurations, such as American trucks with different body shape aerodynamics.

Aerodynamic simulations were conducted on an articulated truck to optimize EETS performance, focusing on improvements in drag coefficient (Cd), lift forces, and fuel consumption. All CFD simulations and fuel calculations were verified and audited by IDIADA, ensuring data accuracy and real-world relevance.

Vehicle Configuration	Cd	A [m²]	CxA [m²]	Drag [N]	Lift [N]	Lift front [kgf]	Lift rear [kgf]
C01 Baseline	0.536	10.49	5.626	2081.8	330.0	-9.4	339.4
C02 Alar	0.479	11.0	5.262	1947.4	227.9	147.1	80.8

Table 6: Fuel consumption calculations Phase 2 straight cargo vehicle.

Vehicle Configuration	Bd (lt/100km)	% ΔBd C01
C01 Baseline	38.0	-
C02 Alar	36.7	-3.5%

Table 7: Fuel consumption calculations Phase 2 straight cargo vehicle.

The optimized configuration (C02 Alar) achieves a 3.5% reduction in fuel consumption compared to the baseline (C01), Over an annual distance of 100,000 km, this translates to 1,300 liters saved, significantly reducing operational costs. Additionally, the drag coefficient (Cd) decreased by 10.6%, with total drag force dropping by 6.5% from 2081.8 N to 1947.4 N, enhancing fuel efficiency and lessening mechanical strain on the vehicle.

The front lift increased from -9.4 kgf (downforce) to 147.1 kgf, a 1667.2% rise that helps balance aerodynamic forces and contributes to drag reduction. Meanwhile, the rear lift decreased by 76.2%, from 339.4 kgf to 80.8 kgf, which stabilizes the vehicle's aerodynamic profile. In this test, non-aerodynamically optimized vehicles were not used as a baseline. Therefore, it is estimated that the aerodynamic improvements from the EETS system could be even greater on vehicles with different baseline configurations or without aerodynamic enhancement elements.

Environmental and Economic Benefits for semi-trucks

Beyond fuel savings, drag reduction and lift generation, the integration of aerodynamic components in heavy-duty trucks contributes to a significant reduction in environmental impact by lowering CO_2 emissions.

Picture 2: Second prototype tested in Ontario, Canada.

For Euro 5 trucks, using C01 as the reference case, the baseline fuel consumption is 33 liters per 100 km. With the C02 configuration, fuel consumption decreases to 31.85 liters per 100 km, representing a 3.5% reduction. Over an annual distance of 100,000 km, this results in 1,150 liters of fuel savings, corresponding to an estimated reduction of 3.04 tons of CO_2 per vehicle, based on an emission factor of 2.64 kg CO_2 per liter of fuel. For Euro 6 trucks, using C01 as the reference case, the baseline fuel consumption is 30 liters per 100 km. With the C02 configuration, fuel consumption is reduced to 28.95 liters per 100 km, also a 3.5% reduction. Over 100,000 km annually, this leads to 1,050 liters of fuel savings, corresponding to an estimated reduction of 2.77 tons of CO_2 per vehicle.

For a fleet of 1,000 vehicles, these reductions become substantial. Euro 5 trucks would achieve total savings of 1.15 million liters of fuel and 3,040 tons of CO_2 annually. Euro 6 trucks would save 1.05 million liters of fuel and reduce emissions by 2,770 tons of CO_2 per year. Thus, depending on the vehicle type, a fleet of 1,000 trucks could achieve annual fuel savings of 1.05 to 1.15 million liters and CO_2 emission reductions ranging from 2,770 to 3,040 tons, highlighting the potential environmental and economic impact of aerodynamic optimizations in commercial transportation.

DISCUSSION

This study highlights the substantial impact of aerodynamic optimizations on fuel savings, energy efficiency, vehicle range, and emissions reduction for Euro 5 and Euro 6 trucks. For non-articulated trucks, the C06 configuration achieved a 13.6% fuel savings over the baseline, with an additional 3.6% improvement compared to an already optimized setup. Articulated trucks also showed a 3.5% reduction in fuel consumption when aerodynamic modifications were applied. These results suggest that some Euro 5 vehicles equipped with aerodynamic enhancements could achieve fuel consumption and emissions levels comparable to Euro 6 standards.

Beyond fuel savings and emissions reduction, another key factor observed in this study is the role of lift generation in improving vehicle efficiency. While traditionally overlooked in ground transportation, controlled lift can help offset part of the vehicle's weight, reducing rolling resistance and energy demands. The effectiveness of lift, however, is highly dependent on vehicle speed, air velocity, and local regulations. In regions with higher speed limits or different truck morphologies, the aerodynamic benefits of lift generation could be significantly amplified, leading to even greater efficiency improvements.

Additionally, these findings emphasize the potential impact of aerodynamic optimizations in regions with higher speed limits and different vehicle configurations. Since aerodynamic forces increase with velocity, the benefits observed in this study could become even more pronounced in operational environments where trucks travel at higher speeds or have different geometries. This suggests that further studies focusing on a broader range of truck types and speed conditions could provide deeper insights into optimizing aerodynamic performance globally.

Given these promising results in European markets, an important question remains: How will the EETS aerodynamic optimizations perform when adopted across different regions of the world, with diverse truck configurations and varying operational conditions?

CONCLUSIONS

This study demonstrates the significant impact of aerodynamic optimizations on fuel efficiency and emissions reduction for both non-articulated and articulated Euro 5 and Euro 6 trucks. In non-articulated trucks, aerodynamic modifications resulted in a 13.6% fuel savings compared to the baseline C01 configuration, contributing to lower operational costs and CO_2 emissions. For articulated trucks, a 3.5% reduction in fuel consumption was achieved, improving overall energy efficiency. For Euro 5 vehicles, these optimizations are particularly relevant, as they allow some trucks to reach fuel consumption and emissions levels closer to those of Euro 6 models. This underscores the potential of aerodynamic enhancements to improve fleet sustainability without requiring vehicle replacement.

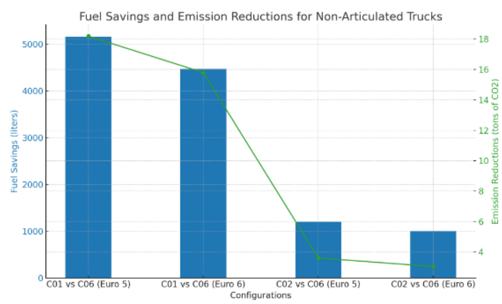

Figure 8: Fuel Savings and Emission Reductions for Non-Articulated Trucks.

Furthermore, applying these aerodynamic optimizations in regions with higher speed limits and different vehicle designs, such as North America, could yield even greater benefits. In markets where such technologies are less common, vehicles may experience higher fuel savings and emissions reductions, further enhancing the impact of aerodynamic improvements.

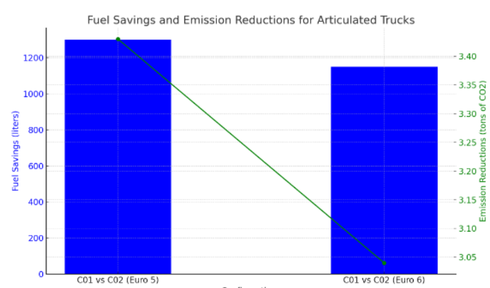

Figure 9: Fuel Savings and Emission Reductions for Articulated Trucks.

In conclusion, integrating these aerodynamic modifications offers a practical approach to reducing operational costs and CO_2 emissions in existing fleets, contributing to global sustainability efforts. Expanding this study to validate these optimizations across a broader range of operational conditions and vehicle configurations will provide fleet operators with valuable insights to further enhance economic and environmental performance.

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