Optimizing Fuel Savings in Articulated Tractor-Trailer with Aerodynamic Venturi Passage Combinations

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Abstract - *The environmental issues continue to rise and that forces automobile engineers to develop new concepts to lower fuel consumption and emission levels. This study focuses on the application of aerodynamic enhancement on heavy articulated trucks and investigates the effectiveness of novel aerodynamic trailer design with the combination of cab roof deflectors to minimize drag at the trailer head. Complete model designed using computer graphics and analyzed by computational fluid dynamic (CFD) for each configuration, to optimize class 8 vehicle structure. The test results reveal that early flow separation, pressure difference, and high base wake regions are primary contributors to high drag value. Analysis demonstrates the use of a novel venturi passage design with the combination of cab roof deflectors prominently reduces 17.38% drag coefficient compared with a conventional trailer. Notably, implementation of this combination approach results in a 14% increase in drag performance compared to vehicles that only feature cab roof deflector. These findings will be potentially helpful in the field of Automotive to enhance fuel efficiency and sustainability of heavy commercial vehicles.*

Key Words: **Fuel Consumption, Aerodynamics, Computational Fluid Dynamics, Venturi Passage, Drag Reduction.**

1. INTRODUCTION

Fuel consumption in the automotive sector has increased dramatically, and heavy commercial vehicles are the major contributor to the high economic loss experienced by the nation. The significant impact that heavy-duty vehicles have on the total amount of fuel used on roads, with articulated trucks being especially important in such scenarios, which subsequently leads to considerable amounts of air pollution [1]. It is important to analyze and put new methods that will potentially improve fuel efficiency.

Aerodynamic improvement is one of the most important methods when it comes to fuel saving, according to recent studies on fuel reduction techniques for trucks. About 52% of the fuel is used by a large commercial vehicle travelling at 100 km/h to provide the power needed to overcome aerodynamic drag. That significant effect is air drag after 90 km/h on heavy commercial vehicles [2]. These class 8 trucks travel between 150,000 and 200,000 miles annually, making their fuel demand high in the automotive industry [3]. Because of its high mileage, any small decrease in aerodynamic drag will lead to fuel savings and a reduction in emissions of carbon dioxide and other pollutants. There are still a lot of opportunities for improvement, especially by aerodynamic drag reduction.

Despite a number of drag-reducing devices including side skirts, cab-roof fairings and vanes, base flaps, gap seals, boat tails, and underbody fairings, have been researched in the literature for heavy commercial trailer trucks [4-8] there is still a significant research gap when it comes to modifications that are specifically designed to increase aerodynamic performance at the trailer body. However, Client demands for the maximum volume capacity of trailers have slowed down the development of trailer modifications for better aerodynamic performance. As a result, the installation of components to optimize the truck cab's aerodynamic performance became the manufacturer's primary focus [9]. In order to close this research gap, the purpose of this paper is to examine how effectively a new aerodynamic trailer design will reduce aerodynamic drag. Through Computational fluid dynamics (CFD), the effectiveness of these designs in combination with traditional drag reduction techniques is studied.

2. NUMERICAL CONTEXT

2.1 Aerodynamic Drag Force

One of the most significant aerodynamic parameters is the drag force or F_d. This represents the total aerodynamic resistance acting on a vehicle when moving forward. Equation 1 defines the drag force expression, where ρ is the surrounding medium density, A is the vehicle's frontal area, and V is the vehicle velocity in relation to the air [10].

$$Fd = \frac{1}{2} C_d \rho A V^2 \quad (1)$$

Hence, the drag force increases with the square of the velocity and is proportional to the Cd value.
The needed power to overcome the drag force is calculated by multiplying the drag force with the vehicle velocity. The expression can be written as shown in Equation 2.

$$P = F_d V \quad (2)$$

This emphasizes how crucial it is to minimize Cd through aerodynamic design in order to decrease the total drag of a vehicle and increase vehicle fuel efficiency.

2.2 Bernoulli Equation

According to Bernoulli, the equation is essential to the study of the airflows surrounding a vehicle. The relationship between air speed and pressure at a specific point is provided by this equation, where p is the static pressure, ρ is the air density, and V is the air speed, is preferred for an aerodynamic analysis [10].

$$p + \frac{1}{2}\rho V^2 \tag{3}$$

Here, the sum of the two terms is constant so that more pressure generates the lower air velocity, and the lower pressure results in the high air velocity at the same spot. This Venturi effect can be utilized for drag reduction by providing a smooth flow of air streams over the vehicle body.

3. METHODOLOGY

The complete articulated tractor-trailer was configured and analyzed using Solidworks 2022 and the complete vehicle including cabin, trailer, tyres, and chassis components was assembled using CAD with high precision to ensure the actual representation of the articulated truck. The dimensions of the articulated truck lorry are as follows, length of trailer =15 m (excluding truck cab), width =3.07m, height =4m (including the truck cab), frontal area of contact =11.16m^2. This 1:1 scale model represents typical heavy commercial vehicles of European and American trucks which is shown in Figure 1. This was a 6 axle heavy loading vehicle with a 1.2m gap between cabin and trailer. In order to replicate real-world conditions, the wind tunnel apparatus had a closed-loop design with versatile airflow parameters controls using CFD airflow. Computational domain setup in such a way that different conditions can be observed including, base wake, air streamlines, and flow separation.

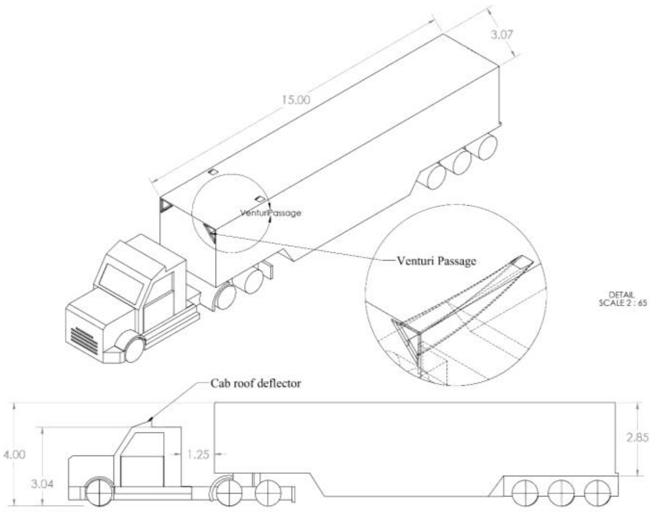

Fig - 1: Articulated lorry with venturi passage configuration

Additionally, triangular venturi vents are designed to meet the lowest possible coefficient of drag, with 0.5m each of shorter sides which allows maximum intake of air at the trailer front area. Figure 1 shows how gradually the area of the venturi passage was reduced to maintain streamlined airflow with gradual pressure difference throughout the passage to create the lowest possible pressure difference with outside of air. The exit of the passage was designed in a square shape configuration, with each side of two sides 0.3m in length allowing low turbulence and smooth exit. As shown in Figure 2, the length of the total arrangement from entry to exit is 2.5m with an inside edge guided curve fillet of 0.03m. For maximum drag reduction trailer air entry passage designed with 0.06m fillet over 0.05m of chamfer allows minimum flow separation and helps to create a smooth channel for streamline airflow.

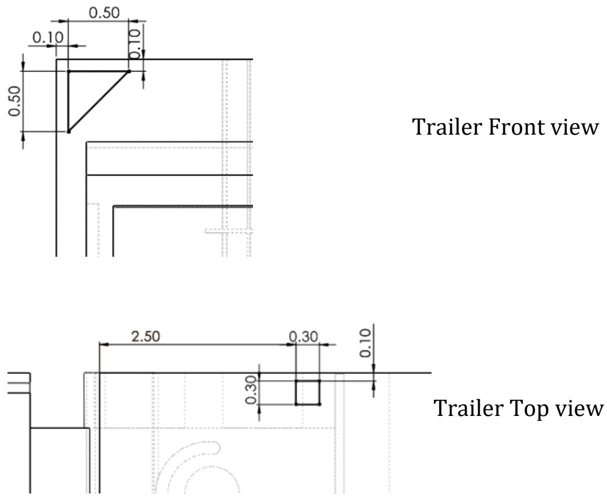

Fig - 2: Design dimensions of venturi passage

To identify the effectiveness of designed system over existing drag reducing devices for Articulated vehicles different configurations of trailer combinations have been investigated which are as follows:

- Baseline testing: Conventional truck model (Fig 3) without any type of drag reducing devices and aerodynamic enhancements.
- Venturi passage testing: Novel trailer design equipped with venturi passage (fig 4) to evaluate effectiveness through drag reduction.
- Cab roof deflector testing: Articulated model equipped with Cab roof deflector (fig 5) at various angles to observe coefficient of drag values.
- Combined Venturi passage and Cab roof deflector testing: The articulated model was equipped with both Venturi passage and Cab roof deflector enhancements (fig 6) to verify drag reduction values, with different deflector angles.

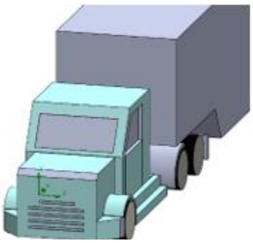

Fig - 3: Conventional truck trailer

Fig - 4: Venturi passage configured trailer

Fig - 5: Cab roof deflector testing

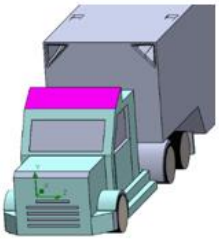

Fig - 6: Combined Venturi passage and Cab roof deflector

3.1 Computational Fluid Dynamics (CFD) Setup

CFD simulations were performed at full-scale models throughout all tests using identical simulation domains and configurations. Predefined SI(m-kg-S) unit systems were used; however, velocity parameters were defined in km/hour. Analysis type, flow at the external body only with considering gravity, which acts on the air stream. The CFD analysis type was configured without rotation and free surface conditions. Project fluids are taken as air (gases) with flow characteristics laminar and turbulent, considering no humidity conditions. Roughness of wall was 0 μm along with adiabatic wall parameters as a default thermal state. Additionally, thermodynamics parameters include pressure = +10^5 Pa, temperature = 20.05 C°, and velocity defined in 3D vector with variable velocity of air for different scenarios in vehicle direction with turbulent intensity and length 0.1%, 0.031 m respectively

Moreover, the computational domain in three-dimensional simulation with size of X = 33.1m and -13.45m, Y = 8.3m and -0.43m, Z = 5.5m and -2.39m including no boundary conditions. Using a mesh of three-dimensional rectangular cells, SOLIDWORKS flow simulation represents fluid and solid volumes using the Finite Volume (FV) method. This advanced computational approach ensures equal distribution of mass, energy, and momentum at each cell. The cell slider on 7 in global automatic cell setting allows the study of air flow behaviour accurately. The mesh cell count during tests was 479k whereas the number of cells contacting solids was ~ 33k. These CFD tools were able to provide accurate results with data by processing it by solver settings.

4. RESULTS AND DISCUSSIONS

The findings of the CFD analysis represented base(conventional) testing as blunt body with a coefficient of drag of 0.7245, without any enhancement of the articulated trailer. That value was supported by [11] which confirms, without any aerodynamic shaping the Cd value ranges between 0.7 to 0.9. The model was designed in SolidWorks with 4m of trailer height from ground and 3.04m of cab height, calculated t/c ratio = 1.315. Air density is 1.225 kg/m^3, and the velocity of air, taken as a constant flow, at 30 m/s (108 km/hour) throughout the computation. As per Figure 7(a), an air separation bubble was visible in the velocity profile at the front of the vehicle and at the front trailer's edge areas, where an increase in air pressure causes an abrupt drop in velocity. The CFD calculated a high drag value due to the large base bake regions, as this low-pressure region generated due to slow momentum of air resulting in flow separation.

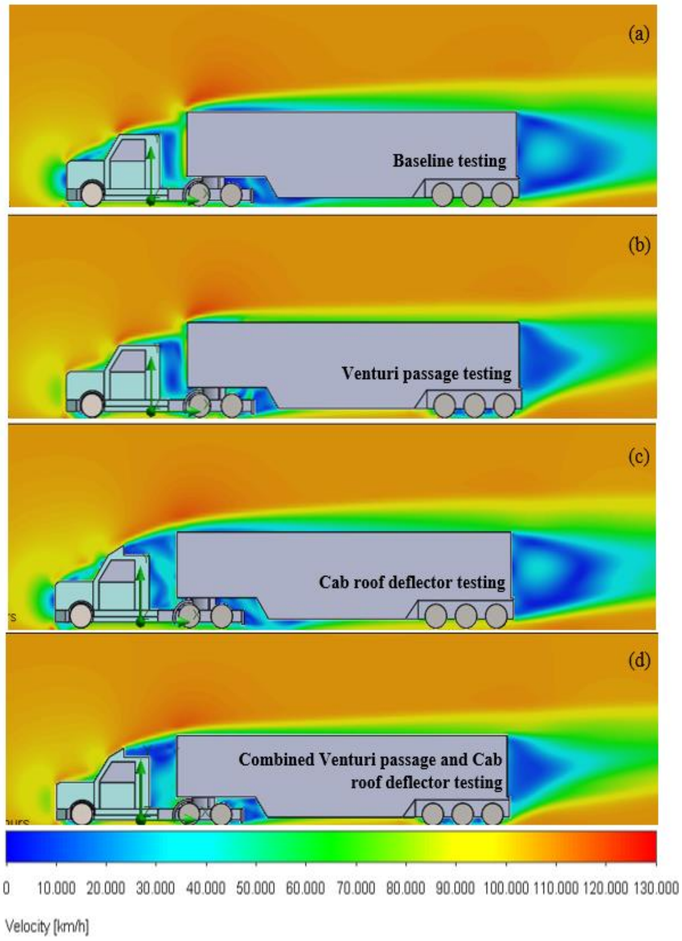

Fig - 7(a-d): Velocity profile of different Aerodynamic configurations

The Low-Pressure bubbles as per Figure 8 promote high velocity generation, where the flow remains connected and streamlined over the articulated vehicle body which contributes to lowering the value of the coefficient of drag.

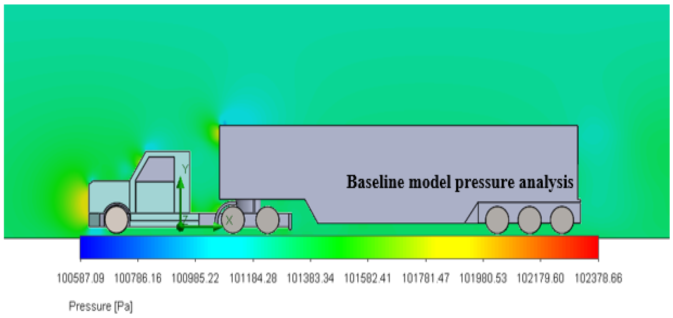

Fig - 8: Baseline model pressure analysis

The conventional body was subjected to a high drag coefficient due to sharp edges. However, venturi vents provide passage to pass air by trailer. The construction only consumes 0.5 to 0.7% volume of cargo. Venturi passage as an aerodynamic enhancement decreased Cd approximately from 0.5 to 2% with no additional drag reduction attachments. Nonetheless, the design was significantly effective with high speeds, as arrangement provides more atmospheric air capture at high speeds. Compared to a conventional trailer, this novel design was able to reduce the flow separation on the trailer leading edge considering some air passes through a venturi passage and gradually merges with the surrounding air with the lowest possible level of pressure difference. Moreover, the passage provides more controlled flow over the surface, minimizes pressure difference, and helps to keep down base wake as represented in Figure 7(b).

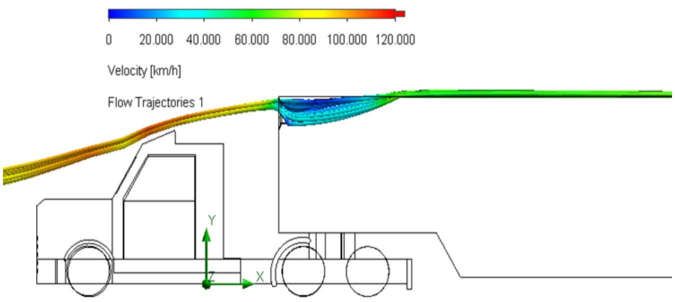

Fig - 9: Velocity profile of airstream passing through Venturi passage

By utilizing Bernoulli's principle as per equation 3, when pressure of air decreases, velocity of air increases. Figure 9 makes this very noticeable, that high channel pressure at entry caused the air velocity to decrease, and the low pressure at exit caused air velocity to increase. The passage was optimized to minimize pressure difference with the outside atmosphere. Air velocity increases as it travels through the venturi passage, which prevents air restriction within the passage.

Cab roof fairings play a major role in reducing air drag and fuel consumption. According to previous research [12], a cab deflector contributes to reducing the drag coefficient of heavy vehicles by 30% at 30 m/s vehicle driving speed. Cab deflectors are specifically made to improve the vehicle's overall aerodynamics by directing airflow over the body of the vehicle and lowering the amount of air that strikes the trailer directly. Comparison between venturi passage and deflector construction reveals the difference of base wake as per Figure 7(b) and (c) respectively. Compared to the deflector tailer model Figure 7(c), the venturi passage model Figure 7(b) exhibits a smaller wake region considering that the deflector modifications cause notably wider separation layer width above the trailer surface.

Furthermore, a variety of parameters, such as the deflector angle, the distance between the cab and trailer, the shape of the vehicle, the cab nose, and the operating conditions, have a significant impact on the drag coefficient values. This is because different vehicle heights and dimensions result in different optimisation angles.

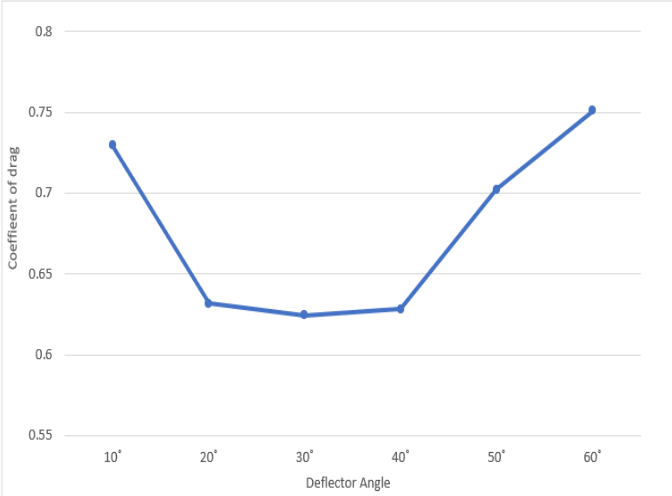

Chart 1: Cd values at various deflector angles

The articulated truck is tested at a speed of 30 m/s on various cab deflector angles from 10° to 60°. As a result, the minimum angle of 10° is subject to 0.729 Cd, while the minimum drag resistance of 0.6244 is visible at a 30° deflector angle, and after 40° drag starts to rise again from 0.628 to 0.75. This high drag after a 40° angle was because the air contact area on the vehicle body increases, causing an earlier separation of the flow and the generation of turbulent flow, which creates a high wake region at the end of the vehicle.

As an advanced technique, a combination of cab roof deflector and the venturi passage produces better results. This is caused by the venturi passage's ability to let air pass through and reduce air pressure, which directly acts on the vehicle trailer. Additionally, the deflector helps to increase overall performance by providing a guided streamlined flow. Since the deflector's angle can greatly contribute to improving the angle of air attack over the venturi entrance. Therefore, it is most effective to position that at a specific angle range from 20° to 40°, as Chart 1 represents.

Moreover, deflectors have a limit on how much drag they can reduce at a given angle, vehicles that use an advanced combination approach with venturi passage designs (VPDs) offer greater flexibility and optimisation for a variety of articulated vehicle sizes and shapes.

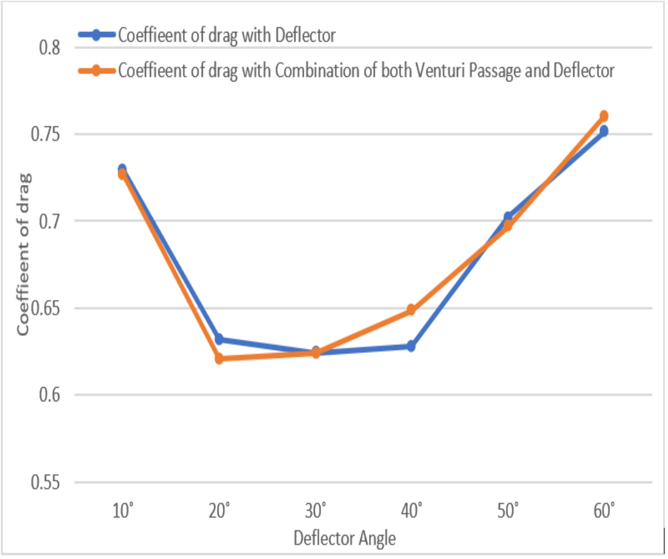

Chart 2: Combined Venturi passage and Cab roof deflector analysis

Chart 2 shows that a combination approach with a deflector angle of 20° to 30° at a velocity of 30 m/s achieved the highest fuel economy by minimizing drag value. Also, it was clear that the Cd will rise further after 30° because the high deflector angle increases the vehicle's overall drag force (F_d) and creates negative air pressure between the trailer body and the cab. As a result, a combination of both VPD and optimum deflector ranging from 20° to 30° CFD provided exceptional values of Cd and that will continue to decline as vehicle speed increases.

Table – 1: Drag coefficient with different Tractor-trailer configurations at 30m/s.

Trailer model	Drag coefficient	Drag force (N)	Difference (%)
Conventional	0.728	4482.7	-
Venturi passage	0.724	4457.2	- 0.58
Cab roof Deflector	0.631	3866.0	- 15.29
Combined venturi passage and cab roof deflector	0.620	3819.0	- 17.38

The optimisation of the combined VPD and deflector model, as shown in Table 1, reveals that the advanced combination of both systems achieves the lowest coefficient of drag 0.62. Compared with the conventional (base) model, the one with the 20° deflector angle can help reduce drag by 17.38%. A vehicle with only a deflector installed facilitates drag reduction of 15.29%, which was 14% higher drag compared to combination approach.

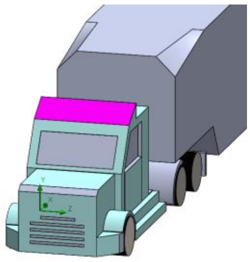

Fig – 10: Combined Top Edge Aero Profile with Cab roof deflector

According to the vehicle CFD analysis, an aerodynamic trailer without an enclosed shape (figure 10) that mimics venturi open aerodynamic structure design over the trailer edge aids in directing airflow over the vehicle without further obstructing it. The similar profile of VPD over the vehicle as an aerodynamic profile trailer edge provides less design complexity and simpler structural integration with the overall design. Nonetheless, an examination of the quantity of air streamline showed that the aero profile edge was not as effective as VPD, which could potentially increase turbulence and create a high negative wake region at the vehicle's end. According to Chart 3, Aero profile leads to a high drag value compared to the VPD approach.

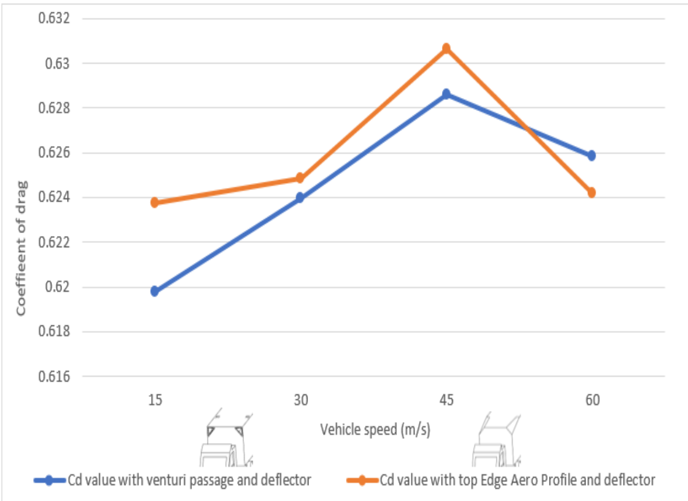

Chart - 3: Combined Venturi passage and Aero profile combinations analysis.

The venturi passage with deflector arrangement produced positive outcomes with a drag of 0.619 when the vehicle was travelling at 15 m/s. This is followed by 0.623 when the Aerofoil profile trailer edge is used. The negligible Cd difference continues to maintain up to 45m/s vehicle speed. According to equation 1 drag force is proportional to the square of velocity ($F_d = 1/2\ C_d\ \rho AV^2$), where V is vehicle velocity. This indicates that as speed increases, the effect of drag on the vehicle increases. The venturi passage design combined with the deflector was more efficient in reducing flow separation and turbulence compared to the trailer top edge Aero profile setup up to 45m/s of speed.

5. CONCLUSIONS

This CFD study successfully demonstrated the feasibility of venturi passage design with the combination of cab roof deflector enhancements in an Articulated Lorry. The complete comparable experiment was investigated at 30m/s speed considering no crosswind condition and cross-sectional area of the vehicle was 11.16m^2. A complete computational study performed by actual scale model 1:1 demonstrated that the use of appendable devices can make drag reduction on heavy vehicles. Pressure and velocity CFD profile discovered that the addition of venturi passage design on trailer edge is able to deliver high fuel efficiency by coefficient drag reduction on heavy commercial vehicles.

The test results displayed that earlier flow separation, pressure difference, and base wake regions were the major contributors to high drag values. In comparison with the conventional (baseline) trailer, 0.58 % drag reduction was noted using a trailer that features a venturi passage. However, the combination of venturi passage and cab roof deflector as novel drag reducing approaches competent in up to 17.38 % of Cd reduction compared to the conventional approach. Cab roof deflector solely accounts for 15.29% of total air drag reduction compared to baseline. Despite this, implementing a combination technique resulted in a 14% increase in performance, which allows transportation companies to avoid spending a significant amount of fuel.

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