Effect of Combination Yaw Angle Variation and Base Bleeding for Tractor-Trailer Drag Reduction through Experimental Investigation and CFD

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Abstract. This study focuses on the effect of variations in yaw angle and base bleeding configuration on the reduction of tractor-trailer drag. Detailed experimental and CFD investigations are introduced. Crosswind is used to simulate the yawed flow conditions. Three bleeding hole settings are arranged in the tractor base area. Experiments and CFD are done using 1:32 scale model, after validating the results of the CFD extended to a full-scale model. In the CFD investigation, the structure and rotation of the flow around the tractor-trailer and the gap area are examined. Experimental investigations was Carried out in an open jet wind tunnel. The results showed that when the yaw angle is greater than 3 °, a drag reduction is clearly observed. At the yaw angle of 12 ° maximum drag reduction occurs in the form of drag coefficient is 19%, 21% and 23% for bleeding coefficient of 0.04, 0.05 and 0.06. Through the results of CFD predictions, the effects of bleed increase entrainment flow in the gap and reduce the wake area on the leeward side of the trailer and consequently produce a significant reduction in drag. This result is caused by a large flow separation zone that forms along the underside of the trailer when there is no bleeding which increases vehicle drag. The appropriate bleeding area of the tractor base is an alternative that allows in reducing the drag in the tractor-trailer gap.

1. Introduction
The geometry of heavy tractor-trailers may have many aspects of geometric configurations that contribute to drag and can be articulated as a source of drag. Computational Fluid Dynamics (CFD) application studies have emphasized the prediction of flow around heavy vehicles using simplified geometry [1] or generic conventional models (GCM) as tractor-trailer geometry. Experimental studies and CFD on tractor base bleeding for aerodynamic drag reduction of heavy vehicles was carried out by [2]. Experimental and CFD studies on tractor base bleeding for aerodynamic drag reduction of the heavy vehicle were performed by [3 and 4]. Experimental demonstration carried out on drag reduction devices for trailer underbody and bases by [5]. The determination of the coefficient of aerodynamic drag trucks and trailers Model done using wind tunnel tests.

This work focuses on induced drags in the tractor-trailer gap region. In this zone, the free stream flow turns into a tractor-trailer gap. As a result, the momentum exchange was imparted to the vehicle and aerodynamic drag increased. The effect of combination yaw angle variation and drag reduction from tractor base bleeding is evaluated quantitatively based on both wind tunnel experiments using a 1:32 scale model and CFD analysis.
2. Computational analysis

CFD runs are conducted for two main cases: (Case 1) is performed to simulate the experimental work with Reynolds number of $70 \times 10^3$ based on a scaled model (1:32) and a tunnel velocity of 11.1 m/s. After validating experimental and CFD results, CFD is extended to a full-scale model. Therefore (Case 2) is performed to simulate the real geometry with a Reynolds number of $5.5 \times 10^5$ based on a full-scale CFD model and a highway speed of 30 m/s. Fig. 1 shows the basic dimensions of the model. The geometry considered in the present study is a Kenworth tractor-trailer T600A. Since geometry is complex, it is not useful to create a computational model using primitive shapes. Thus (1:32 scaled model) is digitized; this step provides an initial stage to create and build up other geometrical entities progressively and is thus important. The data obtained from the digitizer are used to construct the surface and other accessories of the vehicle using the Solid Works 2015 software. Consequently, a three-dimensional solid model is obtained.

In the present work, a polyhedral mesh is employed. This method can reduce the overall cell count. Agglomeration based on cell skewness can also be used to convert regions with highly skewed cells to a polyhedral, thereby improving the mesh quality by converting the grid to a polyhedral mesh. The automatic nature of these mesh agglomeration techniques saves the run time; the convergence is also fast because the polyhedral mesh contains as few as one-fifth of the number of cells in the original tetrahedral mesh.

In the present study, a high order element type is used for mesh generation to precisely calculate the boundaries of high curvature. The entire domain encloses seven sub-domains (volumes) of approximately 7.5 million polyhedral cells, as shown in Fig. 2. The domain is created in such a way that the inlet, outlet, sides, and ceiling are placed far away that it does not affect the flow predictions. The first two sub-domains surround the vehicle model. The smaller sub-domain (volume 1) barely surrounds the vehicle model and contains extremely fine meshes of five layers. This sub-domain is used to record the behavior of boundary layer flow and encloses approximately 4.5 million cells. The second sub-domain (volume 2) immediately surrounds the smaller sub-domain and contains fine polyhedral elements; this sub-domain is used to record the strong vortices developed at the gap between the tractor and trailer and to predict the separated flow formed at the base of the trailer. The second sub-domain encloses nearly 2 million polyhedral cells. The five other outer sub-domains contain five volumes surrounding (volume 2) with approximately 1 million polyhedral cells.

Figure 1. Basic dimension of tractor-trailer model

In the present study, similar boundary conditions and mesh strategy are adopted for all yaw angles. Thus, validating whether critical cases, such as a yaw angle of 15°, can satisfy the QRST rules can also validate all other cases of yaw angles of less than 15°. Fig. 3 shows that the average value of $y+$ for the vehicle surface is less than 110; this value is within the value range of the SST $k$-$\omega$ turbulence model as recommended by [6]. In the mesh distribution, the transition from small cells to large ones
must be smooth. The growth rate of cells from fine mesh to coarse mesh does not exceed 20%. The results of the drag coefficient indicate that a grid size resolution of approximately 7.5 million cells provide sufficient accuracy.

3. Experimental setup and procedure
The model which is a detailed representation of Kenworth T600A tractor-trailer is constructed from medium density plastic. The tractor is attached to a 38 cm-long model trailer that includes filleted edges at the leading edge and roof of trailer with a cross member and landing gear on the trailer underside. The tractor gap is fixed to 3.17 cm. The test model is modified by mainly implementing the bleeding at the tractor base. The concept of active flow control (AFC) is introduced to control the flow pattern within the tractor-trailer gap for three suggested sets of bleeding coefficients \( C_{μ} = 0.04, 0.05, \) and 0.06, where \( C_{μ} = (A_{b} U_{b})/(A_{o} U_{o}) \), \( U_{o} \) free stream velocity \( (U_{o}) \), bleeding velocity \( (U_{b}) \), tractor base area \( (A_{o}) \) and bleeding area \( (A_{b}) \), as shown in Fig. 4.

The basic equipment and measuring tools for the test rig are as follows: a- Low speed open-circuit wind tunnel attained a maximum speed of 20 m/s at tunnel exist, b- Model support is designed and manufactured to suit the test rig and tractor-trailer model, c- Air compressor model ZB - 0.1/8-BAMA, d- Pneumatic regulation valve model AR 2000-01 is equipped to the discharge pipe of the compressor tank to maintain pressure level and hence to obtain a constant airflow rate of bleeding jet, e- Flow meter type NGX Series- 100 mm nominal, f- Standard Pitot-static tube is calibrated according to the
British standard, g- Electrical load cell sensor type LSB200, and h- Data acquisition system (DAQ). The schematic diagram of the experimental test rig is shown in Fig. 5. The modification is performed by introducing a uniform jet at the tractor base area. The internal surface of the tractor base area is strengthened with a 0.5 cm-thick layer of fiberglass putty. Holes are drilled on the base of the tractor cabin. The modification of the tractor cabin (bleeding holes) does not impede the utility of the fundamental tractor design. A small bleed chamber made from Perspex is equipped to the tractor cabin from the inside to bind the base area of drilled holes from one side and internal cabin surfaces from the other sides. The bleed chamber is completely sealed to avoid air leakage. Four 90° elbows of 0.75 cm radius are connected to the lower side of the bleed chamber for introducing air to the chamber and the drilled holes. Base bleed is provided by directing compressed air into the bleed chamber using service tubes. Fig. 6 illustrates the arrangement and model of the holes modification.

![Figure 6. Cabin base, blowing Holes and bleeding system modification](image)

4. Scale model experimental and cfd results
The experimental data for 1:32 scale model includes results from both the positive and negative yaw angles ($\theta$) ($-15^\circ$, $-12^\circ$, $-9^\circ$, $-6^\circ$, $-3^\circ$, $0^\circ$, $3^\circ$, $6^\circ$, $9^\circ$, $12^\circ$, and $15^\circ$). To measure the geometric asymmetry: the geometry is truly symmetric when the values of the positive and negative yaw angles are the same. Therefore, any differences between the measured data indicate geometric asymmetry and imperfection of the model. To measure the experimental uncertainty: the resulting drag reduction is obtained to be within $\pm 5 \times 10^{-3}$, which includes sensor accuracy and average measurement repeatability. The effect of bleeding coefficients on the vehicle performance (aerodynamic drag reduction) with crosswind effect is evaluated by rotating the model with yaw angles from $0^\circ$ to $15^\circ$ as shown in Figs. 7.

![Figure 7. Experimental and CFD results of the effect of bleeding coefficient and yaw angles](image)

It is shown that the contribution of the bleeding coefficient of drag reduction has a small effect with zero yaw angles. When the yaw angle is greater than $3^\circ$, a high reduction in drag is observed. This result is attributable to the large flow separation zone formed along the leeward side of the trailer when $C_\mu = 0$ (no bleeding) that increases the drag of the vehicle. However, when $C_\mu > 0$, the effect of the bleed enhances the flow entrainment in the gap and reduces the wake region at the leeward side of the trailer and consequently results in a significant reduction in drag. It is also shown that for a yaw angle greater than $12^\circ$, the reduction in drag ($\Delta C_D$) decreases, this can be attributed to the unsteadiness
of the flow region created on the leeward side of the truck which is dominated by highly turbulence flow, leading to massive flow separation. It can be shown that both experimental and CFD results trend the same behavior. Specifically, ΔC_D increases with the yaw angle.

5. CFD results of the full-scale model
The computations are performed using ANSYS Fluent 15. The reduction in the drag coefficient induced by the tractor base bleeding is computationally obtained using a range of yaw angle and bleeding coefficients as shown in Fig. 8. The results of the full-scale model show the same trend and behavior as those of the scaled model. In particular, the increase in the bleeding flow leads to an increment in drag reduction due to a decrease in the aerodynamic drag. Furthermore, the reduction in the drag coefficient decreases when the yaw angle is larger than 12°. The maximum reduction in the drag coefficient is observed when the bleed coefficient is large (C_μ = 0.06). The drag coefficient further reduces by 21% when the yaw angle is 12°. Thus, the results of the rotational and particle trace of flow fields are presented only for C_μ = 0.06.

![Figure 8. Effect of bleeding coefficient upon drag reduction with yaw angle variation](image)

6. Rotation and particle trace of flow fields
The flow structure around the model is examined to illustrate the vortical nature of the flow by plotting an Iso-Q surface. Consequently, the effect of the tractor base bleeding on the aerodynamic characteristics can be quantified. The criterion of the stroke cycle of vortices is used to obtain the vortical nature of the flow using the following equation [7]:

\[ Q = \frac{1}{2} \left( R_{ij} R_{ij} - S_{ij} S_{ij} \right) \]  (1)

Where: \( R_{ij} \) is the angular rotation tensor, and \( S_{ij} \) is the rate of strain tensor. The velocity gradient tensor is given by:

\[ \frac{du_i}{dx_i} = S_{ij} + R_{ij} \]  (2)

The high value of Coherent flow structure (Q) suggests coherent vortical flow structure. For compactness, only the results of yaw angles (θ = 0° and 15°) and (C_μ = 0 and 0.06) are presented. Fig.9 shows the Iso-Q surface around the tractor-trailer.

![Figure 9. Iso-Q surface identify regions of flow dominated by rotational flow](image)

The gap region and the leeward-downstream side of the trailer are dominated by the formation of wake in the vicinity of base bleed because of the highly three-dimensional nature of the velocity field in the gap accompanied by a large pressure gradient. When the bleeding effect is introduced (i.e., C_μ > 0), the bleeding flow reduces the amount of wake and the flow entrainment in the tractor-trailer gap; consequently, the value of Q (vortical flow) decreases because of the uniform flow entrainment. A comparison of the Iso-surface of Q reveals that the base bleed can significantly reduce the entrainment...
flow on the gap region; the bleed flow pattern is also uniformly distributed over the leeward side of the trailer. This effect is evident when the yaw angle is 15°.

In demonstrating the effect of tractor bleed on the flow entrainment, a three and two-dimensional particle trace is presented in form of ribbons to investigate the gap wake and the flow vortices occurring on the leeward side of the model as shown in Fig. 10. The flow separation and the large vortices are generated in the gap region and extended to the leeward side of the vehicle when $C_\mu = 0$. These separated flow and vortices driven by crosswind flow significantly reduce when $C_\mu > 0$. The bleed effect also re-uniforms the circulated flow and improves flow re-attachment on the leeward side of the trailer. This effect is significant when the yaw angle is large, such as $\theta = 15^\circ$.

![Figure 10. Three and two dimensional particle trace around the vehicle model](image)

7. Conclusion
Effects of yaw angle variations and base bleeding on the drag reduction of the tractor-trailer are investigated. Detailed experimental and CFD investigations were introduced. Crosswind is used to simulate the yawing flow conditions. Numerical results reveal that the flow of physics in the tractor-trailer gap contributes significantly to the reduction of drag. The bleeding coefficient increases, the rate of entry air from the free stream to the gap decreases. Experimental results and CFD simulation showed that tractor base bleeding significantly reduces the aerodynamic drag of the vehicle with the presence of crosswind. The result provides useful information to reduce the aerodynamic drag of heavy vehicles.

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