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Analyzing the profile modification of truck-trailer to prune the aerodynamic drag and its repercussion on fuel consumption

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Abstract

The present numerical analysis deals with the effect due to change in profile of truck-trailer on aerodynamic drag and its repercussion on fuel consumption. This numerical analysis is done by using CFD software i.e. ANSYS fluent, with Shear stress transportation (SST) turbulence model on both unmodified and then modified profile of truck-trailer. The comparison has been done with respect to coefficient of drag, coefficient of lift, pressure contours, velocity streamlines and vectors between unmodified and modified profile. The profile modification has been done on basic truck-trailer model by providing wind deflector on truck's cabin, vortex trap, mini skirt, vortex strake and aerodynamic revolute. It has been analyzed that, due to profile modification the reduction in aerodynamic drag is up to 21 %, which reduces the fuel consumption by 4 liters for 100 km for diesel powered truck. The analysis of modified truck-trailer profile with external rear view mirror also has been done, due to the external rear view mirror the coefficient of drag is increase by 3.23%.

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Keywords: Aerodynamic drag, truck-trailer, ANSYS fluent, profile modification, CFD.

1. Introduction

Fuel consumption is one of the main factors which increase the operating cost of the freight industry, operating cost further increases with day to day increase in fuel prices. Therefore, improving the fuel economy by modifying the aerodynamics design of an automobile is one the potential area of research interest. The present study is concerned with the classical truck-trailer model and initial numerical analysis was carried out considering it as an aerodynamic tool to reduce the drag force on its profile.

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The preliminary numerical analysis on the truck-trailer profile showed that there were certain places like the trailer part, truck cabin, annular space between truck and trailer, can be modified to reduce the aerodynamic drag. The profile design modification has been done by attaching a wind deflector on the roof of the truck cabin, using a six panel vortex trap at annular space between truck and trailer, attaching a vortex stake at an angle of 30° at the rear end of the trailer, providing a mini-skirt (MS) device at the trailer undercarriage, and extending the frame at the end of the trailer called aerodynamic revolute.

Nomenclature

CFD	computational fluid dynamics
SST	shear stress transportation
C_d	coefficient of drag
C_l	coefficient of lift
MS	mini skirt
ν	Kinematic viscosity in m^2/s
u_∞	incoming air flow velocity in m/s
L	fuel consumption in litres per 100 km
F_d	aerodynamic drag force in N
L_1	distance between inlet section of the wind tunnel and the front portion of the vehicle
L_2	length of the collector region
H	overall height of wind tunnel
W	overall width of the wind tunnel
L_o	overall length of the prototype
α	rear slant angle
ρ	density in kg/m^3
r_{min}	minimum lateral edge radius
atm.	Atmospheric pressure

1.1. Basic and modified truck-trailer model

The modeling of both basic (unmodified) and modified truck-trailer has been done in modeling software package i.e. Pro-E. The overall dimension for both basic and modified truck-trailer model geometry is same and is given in table1.

Table 1. Overall dimension of truck-trailer.

Geometrical parameter	Quantity in meter
Overall length	14.9
Overall height	4.335
Overall width	2.64
Trailer length	12
Trailer height	2.7
Total height to cabin height ratio	1.3
Minimum ground clearance	0.375

The minimum lateral radius (r_{min}) for front lateral edges of truck's cabin adapted from following relation [1],

$$r_{min} \approx 1.3 \times 10^5 \frac{\nu}{u_\infty} \quad (1)$$

In equation (1), ν is the kinematic viscosity of the air in m^2/s and u_∞ is the incoming air flow velocity in m/s . The figure 1 shows the basic and modified truck-trailer model built in Pro-E modelling software. In modified profile vortex-trap is equal to 8.76 % of the trailer width and mini skirt equal to 60 % of the ground clearance were selected as they are well optimized for practical robust commercial truck [2].

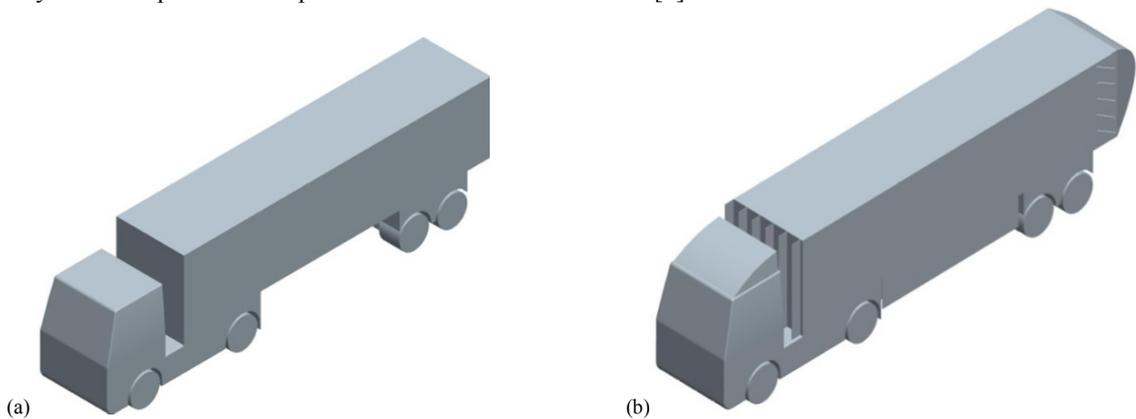


Fig. 1. (a) Basic truck-trailer model; (b) Modified truck-trailer model

1.2. Devices used in modified truck-trailer

Wind deflector deflects the flow over the truck cabin roof and makes it more streamlined to prevent the trapping of flow and formation of a wake. A total 5 % of drag reduction was estimated by using a wind deflector on the roof of the truck. In the annular space six vortex-trap panels consisting aerodynamically sharp leading edges, which separates the flow and forms a vortex in the spacing between panels. The formation of vortex creates a low pressure on the forward facing surface of the trailer and hence reduces the wake formation in the annular space. Vortex stake separates the streamlined flow and directs to the rear over the frame extension and hence reduces the vortex formation at the rear end of the vehicle. Total 3 % of drag reduction was estimated by using vortex stake. The MS device provides a large ground clearance without sacrificing drag reduction of the trailer undercarriage. Its two panel design makes use of vortex to control and capture flow entering the under carriage of the trailer. The outer panel generates a vortex that turns the incoming flow upward where the inner panel captures the vortex induced up wash field and redirects the captured low stream wise. One of the basic advantages with double panel skirt is it will provide more ground clearance when compared to the single panel skirt. Frame extension (aerodynamic revolute) at the end of the trailer detaches the flow smoothly and hence reduces the turbulence at the rear end. A total 5 % of drag reduction was estimated by using aerodynamic revolute.

1.3. Relation of aerodynamic drag force with fuel consumption

The fuel consumption is directly proportional to the resistance overcome by the engine. The aerodynamic drag force is one of the resistances which are significant in magnitude at higher speed. The experiments show that the C_d for typical practical robust truck is around 0.7 [3]. The empirical relation was developed by Subrato Roy from their experiments on diesel powered truck, which correlates aerodynamic drag force with fuel consumption and are given in equation (2) [3]. Where L is fuel consumption in liters per 100 km and F_d is aerodynamic drag force in N.

$$L = (0.008051 \times F_d) \quad (2)$$

1.4. Wind tunnel dimension

Many researches had been carried out both experimentally and theoretically on aerodynamics of heavy vehicles. Hucho described the wind tunnel specification in the ‘Aerodynamic of road vehicles’ [4], according to that the minimum blockage ratio for the wind tunnel testing of a ground vehicle should be less than 5 % to prevent tunneling effect and get accurate result. The dimensions of wind tunnel for the present numerical analysis adapted in such a way that blockage ratio should be less than 5 % [4] and given by in equation (3).

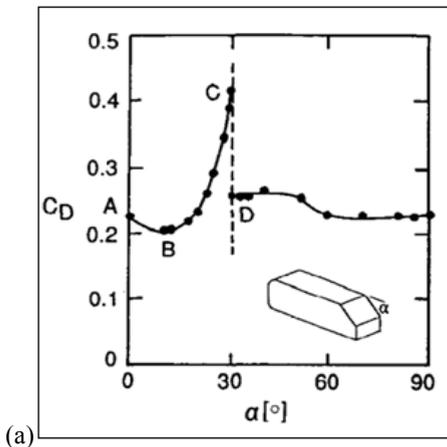
$$L_1=2 L_o, L_2=4 L_o, H=2.2 L_o, W= 1.52 L_o \quad (3)$$

Where L_1 is the distance between inlet section of the tunnel and the front portion of the vehicle, L_2 the length of the collector region, H is overall height of wind tunnel, W the overall width of the wind tunnel and L_o is the overall length of the prototype i.e. total length of truck-trailer. The blockage ratio was estimated for this wind tunnel is 1.49 % which is acceptable as it is less than 5 %, whereas the frontal projected area of prototype is 11.12 m².

2. Numerical simulation

2.1. Validation of numerical methodology

Numerical solutions are approximated one, which is needed to validate with experimental results. For the validation of the present numerical methodology, the results were compared with the experimental results for simplified geometry (Ahmed body) conducted by S R Ahmed. The figure 2 (a) shows the plots between C_d and various rear slant angles (α) of Ahmed body. Similarly, the numerical simulation carried out on Ahmed body at $\alpha=10^\circ$, 20° and 30° for validation. The figure 2 (b) shows the velocity streamlines on Ahmed body with $\alpha=20^\circ$, the C_d obtained by using numerical simulation on Ahmed body at $\alpha=10^\circ$, 20° and 30° are 0.2, 0.289 and 0.35 respectively, and they are compared with experimental C_d obtained by Ahmed and numerical results shown good agreement with the experimental results.



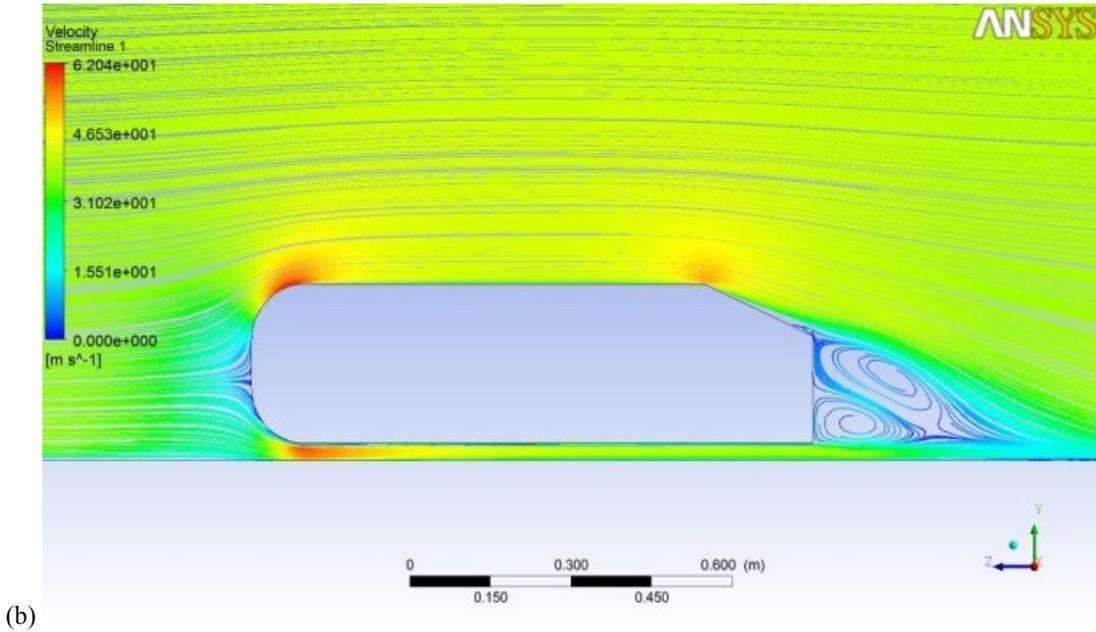


Fig. 2. (a) Experimental results by Ahmed [5]; (b) Velocity streamlines on Ahmed body with $\alpha=20^\circ$.

2.2. Numerical Simulation

Numerical simulation to the truck-trailer for both the basic and modified profiles was obtained by using ANSYS fluent software. Meshing to the geometrical model was done by opting ‘body of influence’ mesh insert technique to vary the element size in air domain in wind tunnel. The air domain was meshed with fine mesh near the model and coarse mesh away from the model. Tetrahedron method was used for elements selection and the model was meshed with a total of 814262 nodes and 3303674 elements. The fluid was assumed to be incompressible air and its properties were constant. The Navier-Stokes equations selected for the conservation of mass, momentum and energy were given in equation (4), (5) and (6) respectively [6].

$$\frac{\partial}{\partial t} \rho + \nabla(\rho \vec{V}) = 0 \quad (4)$$

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} \rho u_i u_j = \frac{\partial}{\partial x_j} \tau_{ij} + \rho b_i \quad (5)$$

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho \varepsilon_i v_i + P v_{i,i} - \tau_{ij} v_{i,i} + q_{i,i} - pr = 0 \quad (6)$$

2.3. Boundary condition

The boundary condition applied in this numerical simulation are given in table 2

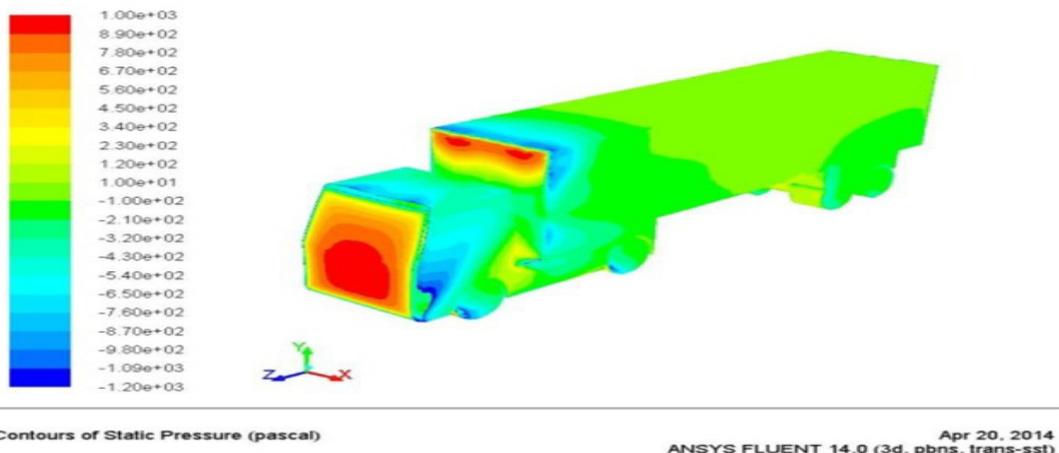
Table 2. Boundary condition

Boundary condition parameter	Boundary condition type	Quantity
Inlet	Velocity inlet	30 m/s
Outlet	Pressure outlet	1 atm.
Wall (truck-trailer)	Stationary wall with no slip condition	0 m/s
Wall (road)	Moving wall with no slip condition	30 m/s
Wall (Inside to the wind tunnel)	Symmetry	--

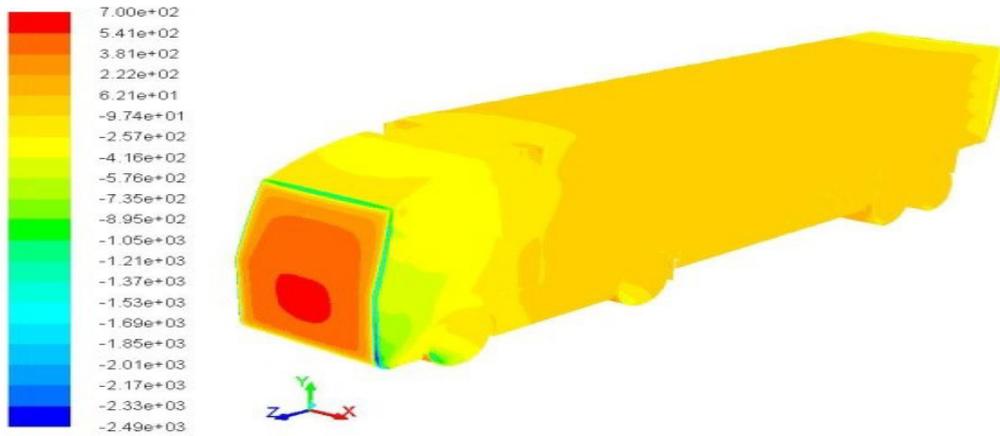
Solutions to the governing equations were obtained by using SST turbulence model. SST is an appropriate model for the aerodynamic analysis as it uses two turbulence techniques. Near the aerodynamic interface it uses $k-\omega$ turbulence model and to rest of the area it uses the $k-\varepsilon$ turbulence model. Wake formation in aerodynamic modeling can be represented more clearly by adapting SST technique in numerical simulations [7].

3. Results and discussion

Numerical simulations were obtained for both the simplified truck-trailer and truck-trailer with aerodynamic modifications in the form of static pressure contours, turbulence kinetic energy contours, velocity streamlines, velocity vectors and swirling vortices. Numerical results were also generated in terms of pressure contours for truck-trailer with external rearview mirror. The pressure contours on basic and modified profile are shown in figure 3.



(a)

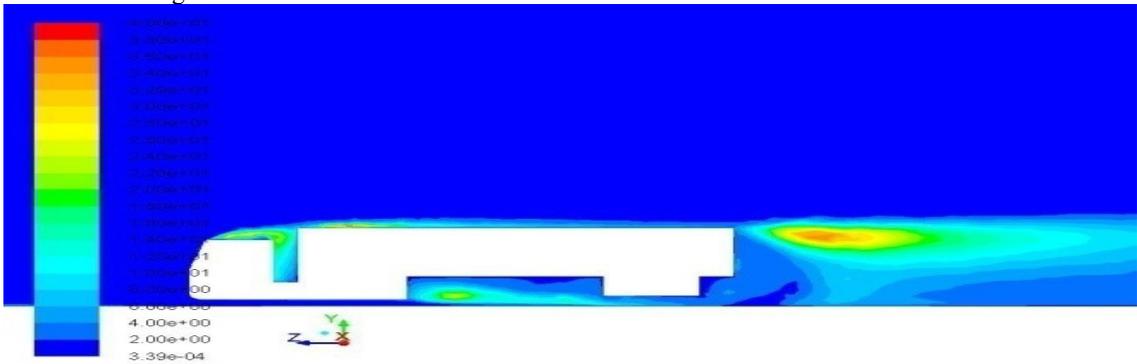


Contours of Static Pressure (pascal) Apr 24, 2014
ANSYS FLUENT 14.0 (3d, pbns, trans-sst)

(b)

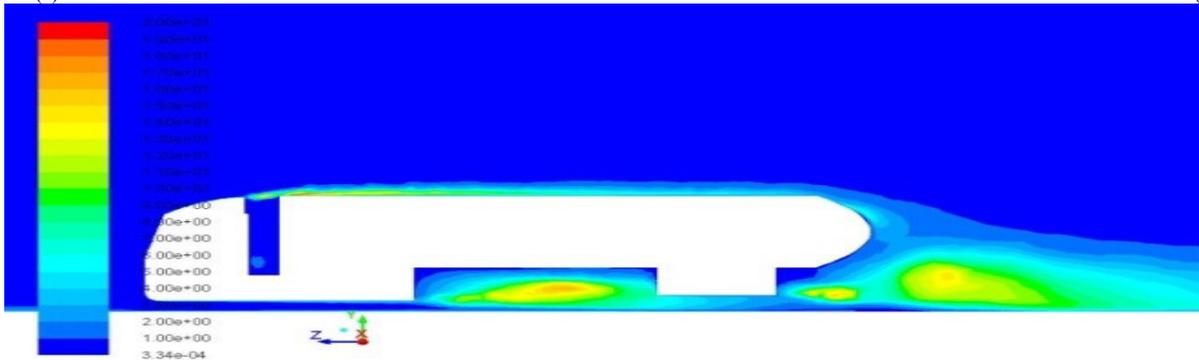
Fig. 3. Static pressure contours (a) on basic model; (b) on modified model

In the figure 3 pressure contour of basic model shows that the stagnation point lies above in comparison of modified one the pressure distribution across the profile is more uniform in modified one in comparison of basic model and by using drag reduction devices it reduces the formation of adverse pressure gradient at rear and provide better control and drag reduction.



Contours of Turbulent Kinetic Energy (k) (m2/s2) Apr 24, 2014
ANSYS FLUENT 14.0 (3d, pbns, trans-sst)

(a)



Contours of Turbulent Kinetic Energy (k) (m2/s2) Apr 22, 2014
ANSYS FLUENT 14.0 (3d, pbns, trans-sst)

Fig. 4. Turbulence kinetic energy contours (a) for basic model; (b) for modified mode

Contours of turbulence kinetic energy for both basic and modified model are shown in figure 4. It was observed from figure 4 that, at the roof and in the annular space there is formation of high turbulence and formations of turbulent eddies and at rear end of trailer high turbulence is formed because of adverse pressure gradient and the flow separation occur at edges. The modified truck –trailer model because of wind deflector at the roof and 6 vortex stake panels in annular space provide smooth flow over the roof and annular space, and at rear end due to the aerodynamic revolute the flow separation is delayed and reduces the turbulence and wake formation.

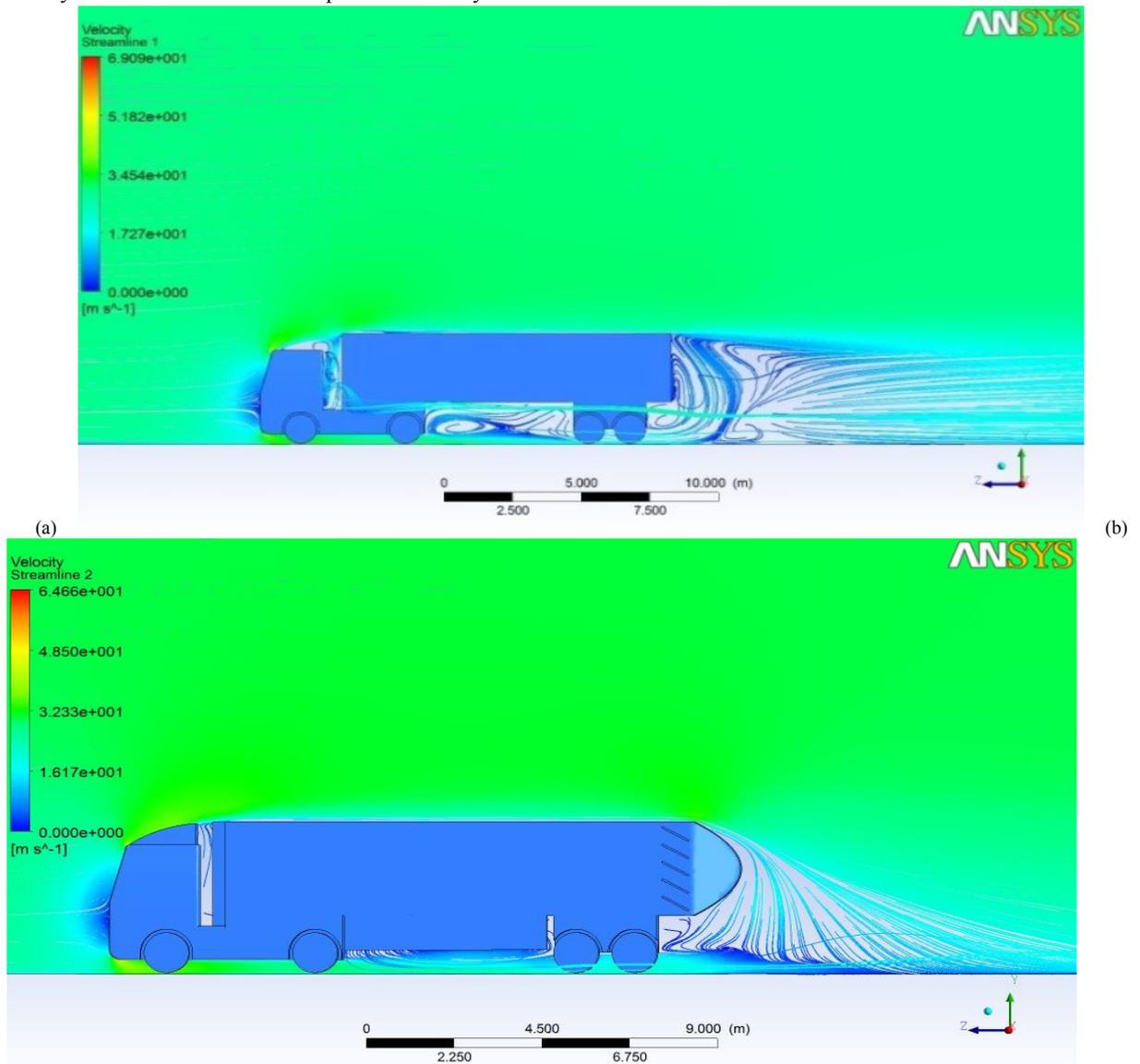


Fig. 5. Velocity streamlines (a) Basic truck-trailer model; (b) Modified truck-trailer model

Velocity streamlines shown in figure 4, for (a) basic truck-trailer model and (b) modified truck-trailer model. It was observed that, these velocity streamlines gives clear view about the flow around the profile of modified as well as basic truck. In basic profile at rear end streamlines are not smoothly separated from the trailer, but in case of

modified profile streamlines are smoothly separated mainly because aerodynamic revolute.

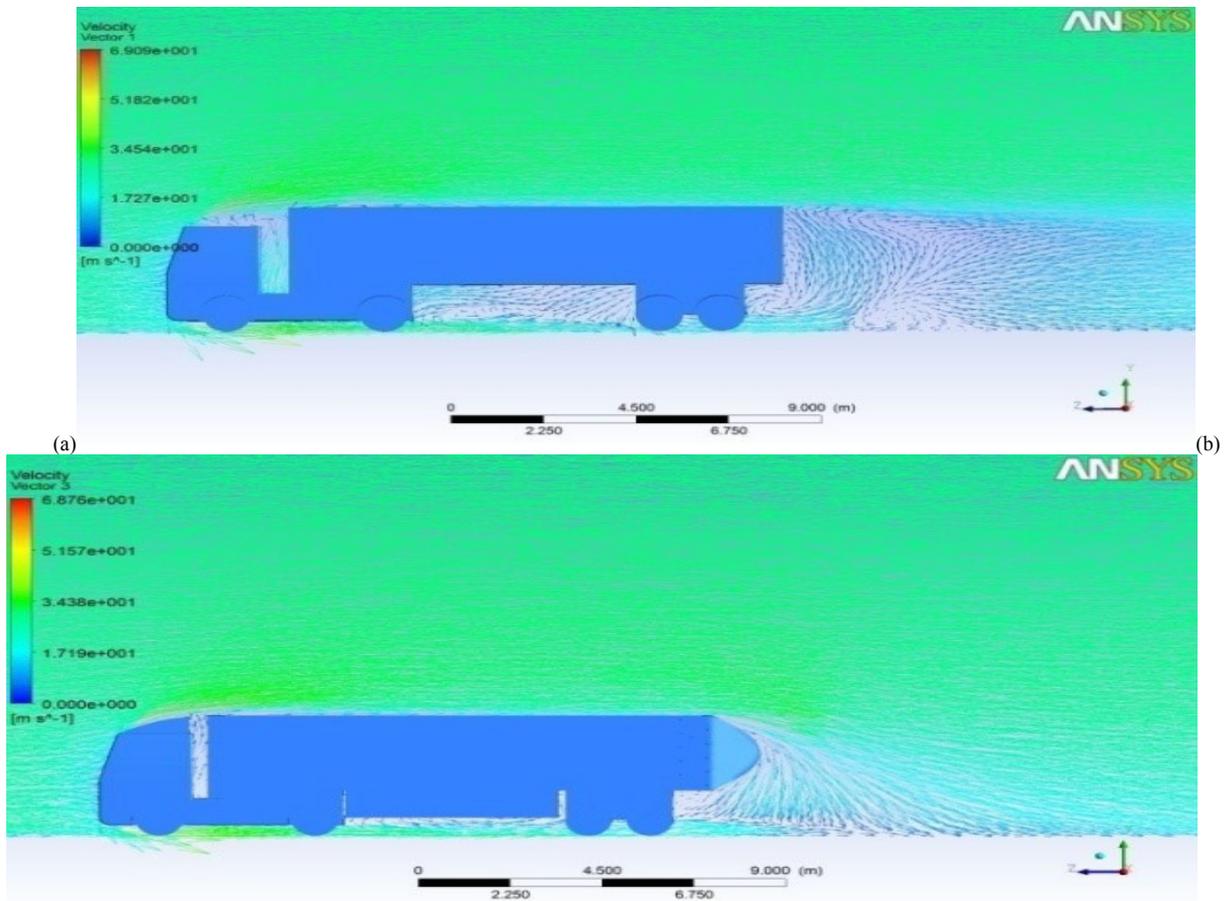
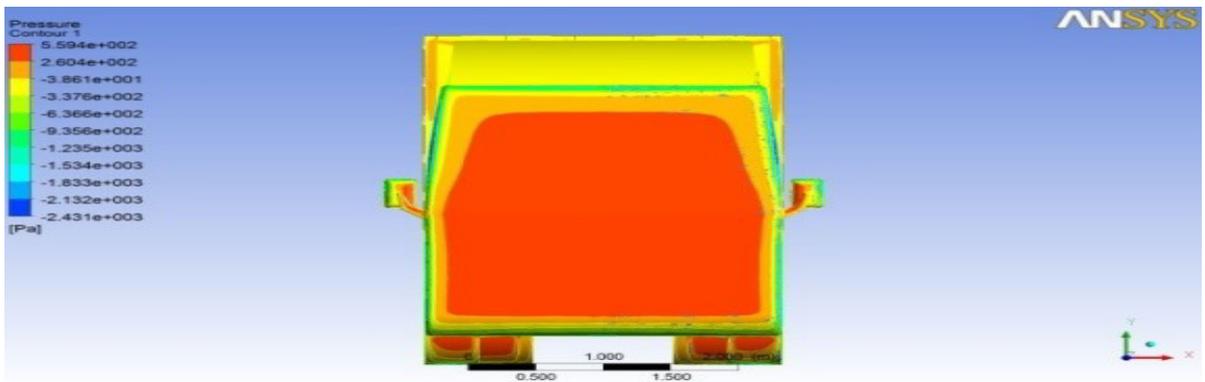
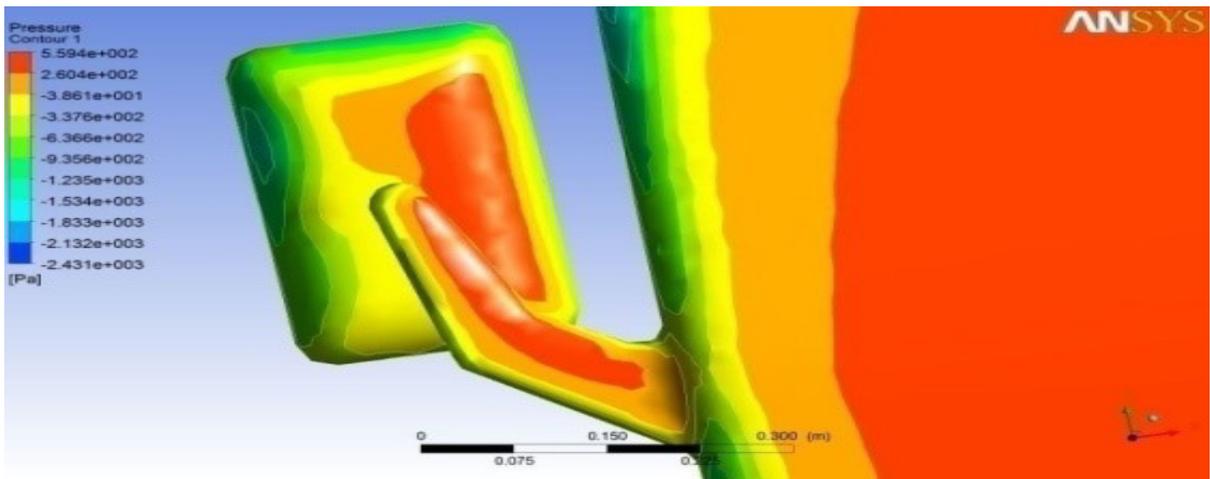


Fig. 6. Velocity vectors (a) Basic truck-trailer model; (b) Modified truck-trailer model

Above figure 6 shows the velocity vectors distribution on basic and modified truck-trailer profile that, in basic model the velocity vector are random and disoriented at rear and annular space, where as in the modified profile velocity vectors are aligned to the surface, and vectors are smoothly around the overall profile. At the rear end of trailer velocity vectors are smoothly separated because of aerodynamic revolute and reduces the mud splashing at rear.



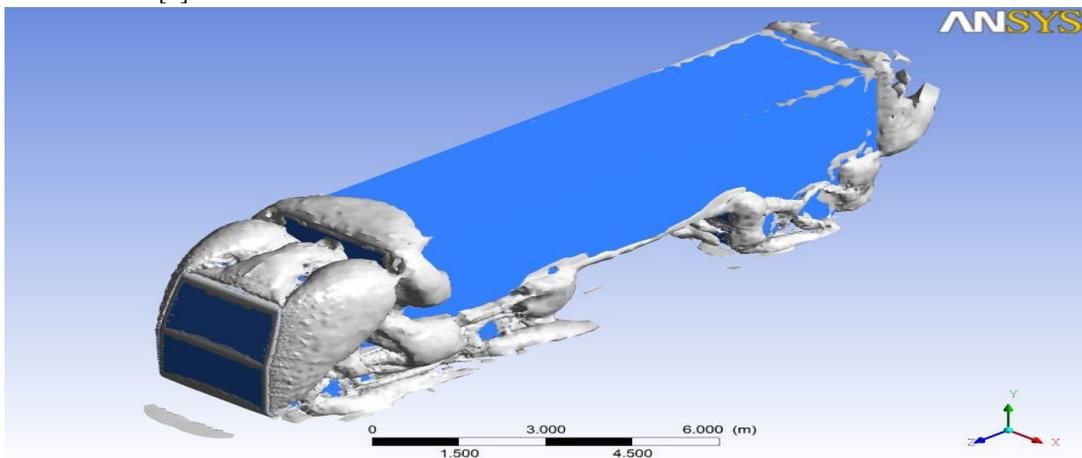
(a)



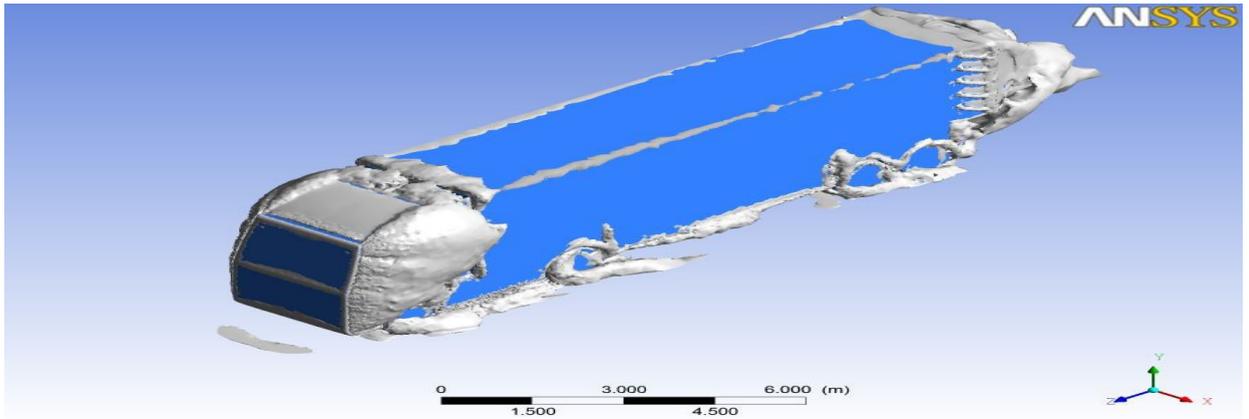
(b)

Fig. 7. (a) Pressure contours on modified truck with rear view mirror (b) pressure contours on the mirror

Pressure contours on the modified truck-trailer with rear view mirror, were given in figure 7 (a). Enlarged image of external rear view mirror is given in figure 7 (b) for better visualization of pressure contours on it. The effect of protruded profile like external rear view mirror on aerodynamic of truck-trailer are mainly, increase in C_d by 3.22 % and generation of wind noise. The separated flow from stagnation point is responsible for formation of low pressure region at edges of mirror, which is responsible for formation of adverse pressure gradient at edges due to which potential wakes are formed and induces the wind noise. These potential wakes further creates Dipole source of wind noise [7].



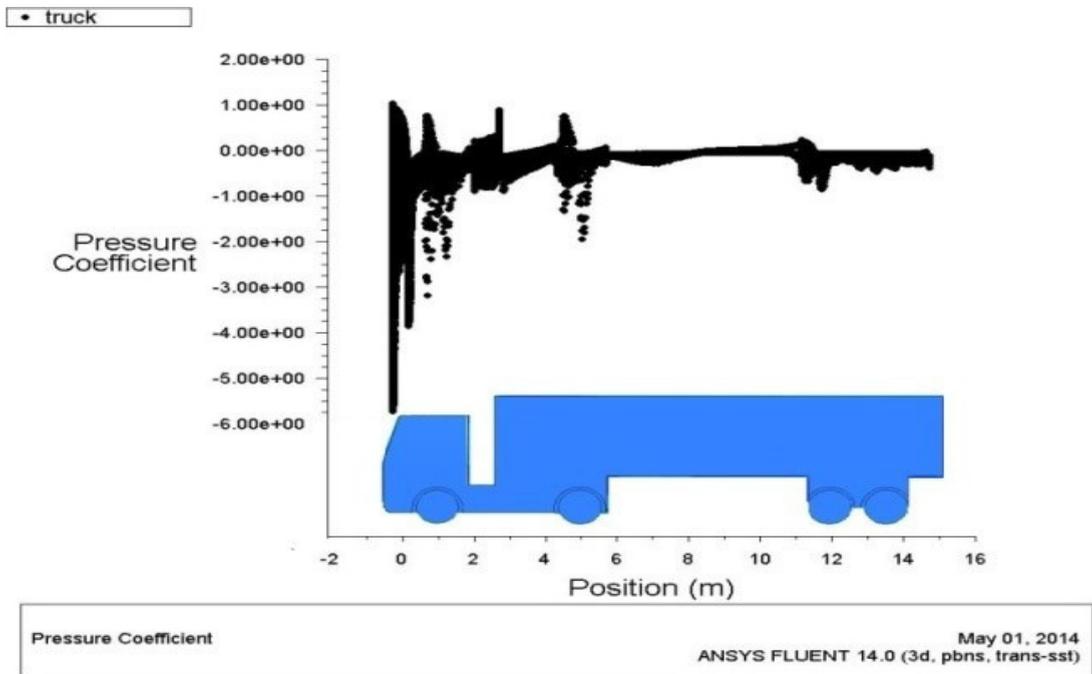
(a)



(b)

Fig. 8. Swirling vortex (a) Basic truck-trailer model; (b) Modified truck-trailer model

From figure 8 (a) that, intense vortex formation with sharp detachment was observed in basic truck-trailer geometry. Whereas in figure 8 (b) it was found that, vortex detachment was very smooth. This in turn reduces the possibility of wake formation at rear end and undercarriage of the truck-trailer.



(a)

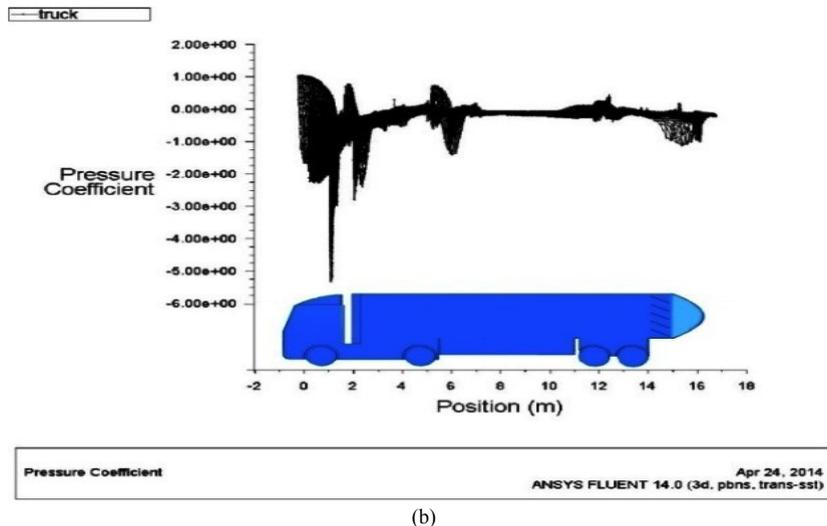


Fig. 9. Variation of pressure coefficient with axial position of the truck-trailer (a) Basic truck-trailer model; (b) Modified truck-trailer model

It was observed from figure 9 (a) and (b) that; pressure variation was more uniform for the modified truck-trailer model when compared to the basic model. Pressure coefficient was found to be reduced at the front portion of the truck-trailer with modifications made to its geometry. Pressure coefficient became low at the rear end and also at the annular space of the truck-trailer geometry. This in turn reduces the tendency of formation of a wake.

Drag assessment was carried out in terms of C_d for both the basic and modified models of the truck-trailer. It found that value of C_d was equal to 0.76 and 0.6 respectively for both the models. This shows that a significant reduction in aerodynamic drag was achieved by profile modifications. Similarly lift assessment was carried out in terms of C_l for both truck-trailer models. It found that the value of C_l was equal to -0.07 and 0.05 respectively for both the models. There was an increase of around 3.3 % in C_l with modified truck-trailer design comparing with that of the basic design. This is due the reduction in Reynolds number at the undercarriage of the modified truck-trailer design. C_d assessment was also done for exterior rear view mirror of the truck-trailer and was found that there was an increase of 3.22 % in relative C_d value.

4. Conclusion

Aerodynamic modifications to the basic truck-trailer lead to a reduction in drag by 21 %, which is equivalent to a reduction in drag force from 23 kN to 18.14 kN. This leads to an improvement in fuel economy of around 4.2 litres per 100 km at an average speed of 30 m/s of the truck-trailer. Aerodynamic modifications made to the basic truck-trailer design tend to an increase in lift force by 3.3 %, which is equivalent to an upward lift force of 151 N for a 20 Ton truck-trailer. This reduces the traction force on the truck-trailer by 0.79 %, which had a negligible effect on the truck stability but at the same time provides significant reduction in rolling resistance. Exterior rear view mirror on truck-trailer geometry increased the drag by 3.22 % in relative comparison of with and without using the rear view mirror on truck.

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