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2013

Proceedings of the Fortieth National Conference on Fluid Mechanics and Fluid Power

December 12-14, 2013, NIT Hamirpur, Himachal Pradesh, India

FMFP2013_154

Effects of a Moving Surface Boundary Layer Control Device (MSBC) on the Drag Reduction in Heavy Commercial Vehicles

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ABSTRACT

Rapid escalation in fuel prices has motivated the manufacturers of heavy commercial vehicles to focus their attention towards efficient aerodynamic design of surface transport systems such as trucks–trailers, railways etc. In order to reduce the drag force acting on truck–trailer assemblies, the flow separation phenomena, occurring on the roof of the trailers, need to be controlled. A number of add-on devices have been developed for this purpose by different investigators but most of these devices are still not being used for several reasons including difficult integration with the structure and non-optimal configuration. In the present study, based on the theory of moving surface boundary layer control, a novel fuel saving device has been developed, and its operation optimised, in order to control the flow separation. Computational Fluid Dynamics (CFD) based techniques have been employed to analyse the aerodynamic performance of a truck–trailer assembly, integrated with a moving surface boundary layer control device (MSBC). The device has been shown to be very effective in reducing the flow drag force being imparted on the truck – trailer assembly, and hence reducing the fuel consumption. Operation of MSBC device has been optimised to obtain a range of rotational speeds of the device over which it provides maximum reduction in aerodynamic drag.

Keywords: Computational Fluid Dynamics (CFD), Moving Surface Boundary Layer Control (MSBC), Navier-Stokes Equations, Drag Force, Fuel Consumption

1. INTRODUCTION

Heavy commercial vehicles (HCVs) play a major part when it comes to goods transportation across the globe. According to Malviya, 2011, around 70% of all the goods are transported by articulated truck–trailer units. Hence, when it comes to economy in the transportation industry, the fuel efficiency of truck–trailer units is the most important parameter. The maximum loading capacity factor has prevented trailer units from having any major aerodynamic design alterations over the years and if anything, these units have only increased in length and height.

As indicated by Modi, 1997, in case of a truck–trailer assembly, the incident flow usually separates at the leading edges of the trailer. Controlling the flow separation phenomena involves preventing or delaying the separation of the boundary layer (Schlichting et al., 2000). Rose, 1981 examined the effects of having externally mounted fuel saving devices using a full-scale truck model in a wind tunnel. The cab-roof mounted deflector, vortex stabiliser, trailer faring, air-turning vanes and a simple air dam have been tested individually, and in groups as well. It has been observed that 36% reduction in drag coefficient has been achieved by using the cab-roof deflector and the air dam together. Wong et al., 1981 has also carried out experiments using various types of add-on devices such as corner vanes, cab-mounted ducts, fairings, and horizontal and vertical curved plates. Wind tunnel tests have revealed a drag reduction of 30%.

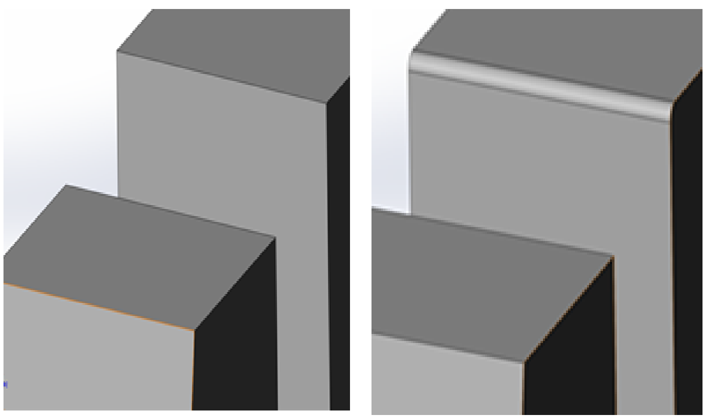
Apart from passive drag reduction devices, a number of active drag reduction devices and techniques have been investigated by various researchers around the world. One of such devices is the moving surface boundary layer control device (MSBC). The MSBC device operates by injecting momentum to the flow by increasing its velocity, and hence minimising the kinetic energy loss of the incident flow. This energy injection process prevents flow from slowing down, and therefore MSBC device have a profound impact on the velocity profile in the flow re-circulation area on the roof of the trailer.

Favre, 1938 has demonstrated the importance of utilizing this method in the aviation industry by running tests on an aerofoil with its upper surface made of a belt moving on two rollers. The results show that the separation of the boundary layer at the leading edge of the aerofoil has been delayed until the aerofoil is subjected to an angle of attack of 55°. Alvarez et al., 1961 placed a rotating cylinder between the wing and the flap of a V/S.T.O.L type aircraft. The tests confirm that the rotating cylinder re-energizes the boundary layer preventing separation.

The effectiveness of the MSBC method, for ground vehicles, has been investigated by Singh et al., 2005. It has been shown that an MSBC device, attached to the trailer unit, reduces the drag force acting on the truck–trailer assembly. Hence, it is clear that MSBC device has the potential of delaying/preventing the boundary layer separation in HCVs. However, detailed analysis of its effect on flow field around the vehicle is limited. Furthermore, investigations into the optimal operation of MSBC devices need to be carried out for widespread commercial acceptability of such devices. In the present work, drag force reducing capability of an MSBC device on an articulate truck–trailer assembly has been investigated using Computational Fluid Dynamics (CFD) based techniques.

2. NUMERICAL MODELLING

A conventional truck–trailer model has been chosen for this study, with only essential features of the assembly included to avoid complications in the modelling process, as shown in Fig. 1(a). The MSBC device has been modelled as a circular cylinder having a diameter of 0.2m, as per the legal requirements (Fig. 1(b)). The numerical investigations have been carried out at the two speeds including minimum and maximum allowed truck–trailer speeds on UK motorways i.e. 40mph and 56mph respectively. The rotational speed of the MSBC device ranges from 0 to 3 revs/sec.



(a) (b)

Figure 1.(a) Baseline and (b) MSBC Models

Three dimensional Navier Stokes equations have been numerically solved in an iterative manner, for a steady flow of air, using a commercially available CFD package. In order to accurately model the wake region formed on the roof of the trailer, Shear Stress Transport $k - \omega$ turbulence model has been employed due to its enhanced accuracy in predicting flow parameters in regions of adverse velocity gradients, as observed in case of flow separation.

The computational domain used in the present study has length, width and height of 13, 11 and 6 times the length of the truck–trailer model. The flow domain has been sub-divided into 5,000,000 tetrahedrons in such a way that 75% of the tetrahedrons are concentrated in the vicinity of the model. It has been observed that the aforementioned number of mesh elements result in fairly accurate prediction of aerodynamic forces being generated on the truck-trailer model/s. Rotational speeds have been specified to the MSBC device and the wheels of the truck–trailer model, whereas, the road has been specified as a translating wall.

3. RESULTS AND DISCUSSION

The results of the present study, along with the discussions on the results, are presented in the following sections.

3.1 Baseline Model

Figure 2 depicts the velocity variations in the vicinity of the truck–trailer baseline model at a cruising speed of 40mph. It can be seen that the flow velocity is comparatively lower in the region between the truck and the trailer (including their roofs) and at the rear of the trailer, as compared to the upstream flow velocity. Due to no-slip boundary condition being specified to the walls comprising the truck–trailer model, the flow velocity of the layer adjacent to these walls is zero, and hence a boundary layer forms between the flow and these wall surfaces. The bluff body shape of the truck–trailer baseline model, with its sharp edges, forces the incident flow to separate at the leading edge of the trailer, creating a wake region. The wake region comprises of negative pressure zone, increasing the drag force on the truck–trailer model significantly.

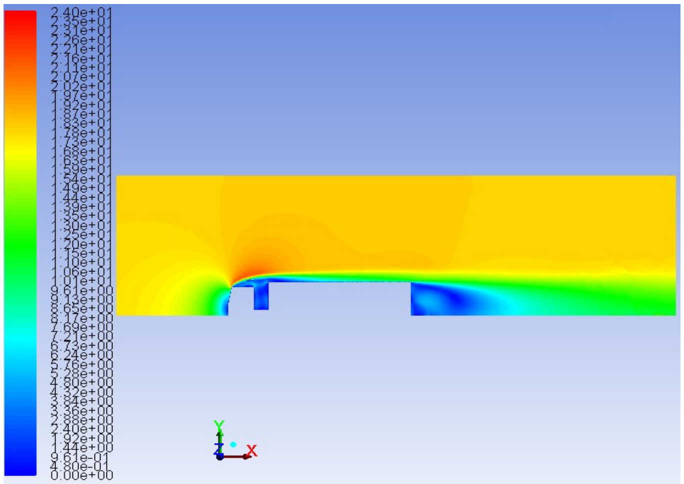


Figure 2. Velocity variations in the vicinity of the baseline model cruising at 40mph

Figure 3 shows the velocity profiles in the wake region only, on the roof of the trailer, at various distances from the leading edge of the trailer. It can be clearly seen that at the leading edge (represented by 0m), the axial flow velocity of 1.5m/sec is in the opposite direction. Furthermore, the wake region is 130mm in height from the roof of the trailer.

At a distance of 100mm from the leading edge of the trailer, it can be seen that the axial velocity in the opposite direction has reduced to 0.9m/sec (40%) and the height of the wake region has reduced to 110mm (15%).

Furthermore, at a distance of 200mm from the leading edge of the trailer, the wake region has vanished and the flow is in the positive axial direction.

Table 1 enumerates the drag force being experienced by the truck–trailer baseline model at different cruising speeds. It can be seen that as the speed of the truck–trailer model increases, the drag force also increases.

Table 1. Drag force for baseline model at various truck–trailer speeds

V	D
(mph)	(N)
40	1828
56	3550

3.2 Stationary MSBC Model

Figure 4 depicts the variations in the velocity magnitude difference between the baseline model and the MSBC model, where MSBC device is stationary.

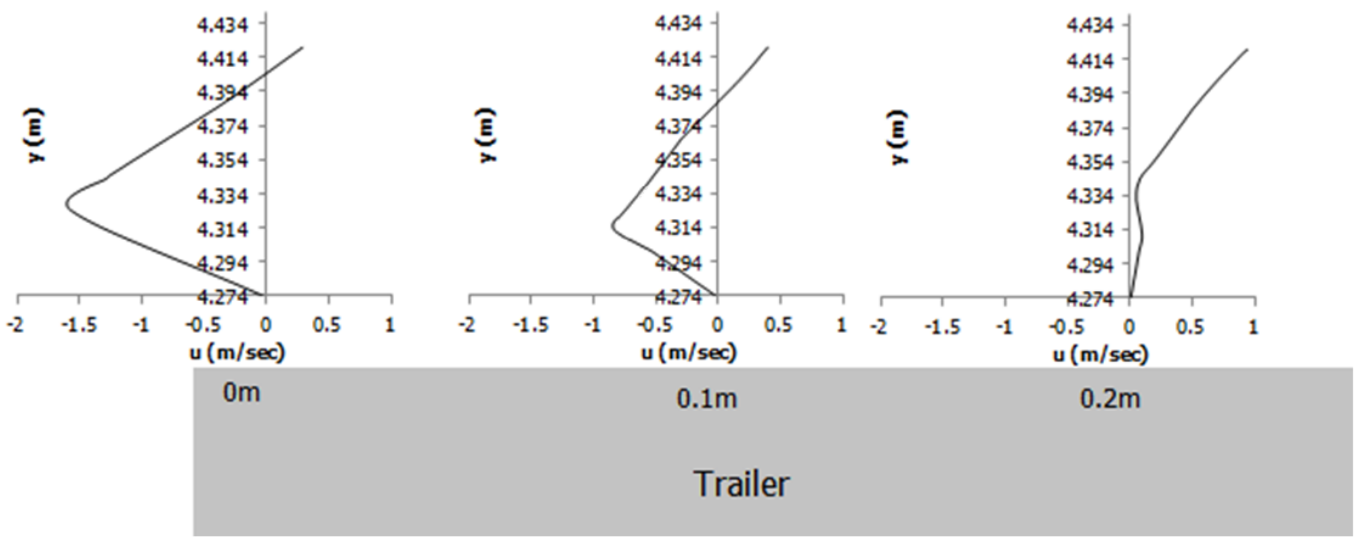


Figure 3. Axial flow velocity profiles at various distances from the leading edge of the baseline trailer

It can be seen that with the presence of the MSBC device, the flow velocity increases at the leading edge of the trailer. This increase in velocity is due to the shape of the MSBC device. The flow velocity increases by as much as6m/sec in the vicinity of the MSBC. It is expected that this increase in flow velocity will reduce the wake region and hence the drag force being exerted on the truck–trailer model.

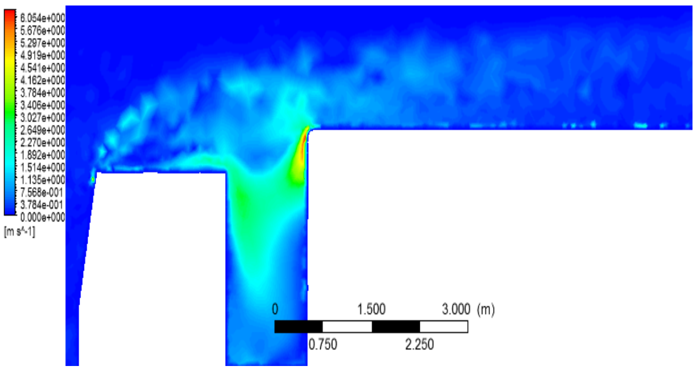


Figure 4. Variations in velocity magnitude difference between baseline and stationary MSBC models

Figure5 shows the velocity profiles in the wake region only, on the roof of the trailer, at various distances from the leading edge of the trailer. In comparison with Fig. 3, it can be seen that the axial velocity profile at the leading edge of the trailer remains the same for both the models.

However, at a distance of 100mm from the leading edge of the trailer for the model installed with MSBC device, the magnitude of the axial flow velocity has reduced considerably as compared to the baseline model. The axial flow velocity in the opposite direction is 0.4m/sec for MSBC model, which is 55% lower than for the baseline model. Furthermore, the height of the wake region, for the model having MSBC device, is 80mm, which is 20% lower than for baseline model at the same distance from the leading edge of the trailer.

It can also be seen that at a distance of 150mm from the leading edge of the trailer, for MSBC model, the wake region has diminished, whereas the wake region vanished at a distance of 200mm from the leading edge of the trailer in case of baseline model. Hence, the presence of MSBC device not only recovers the normal flow more quickly, the volume of the wake region is also appreciably lower as compared to the baseline model.

Table 2 enumerates the drag force being experienced by the truck–trailer model installed with MSBC device at various cruising speeds.

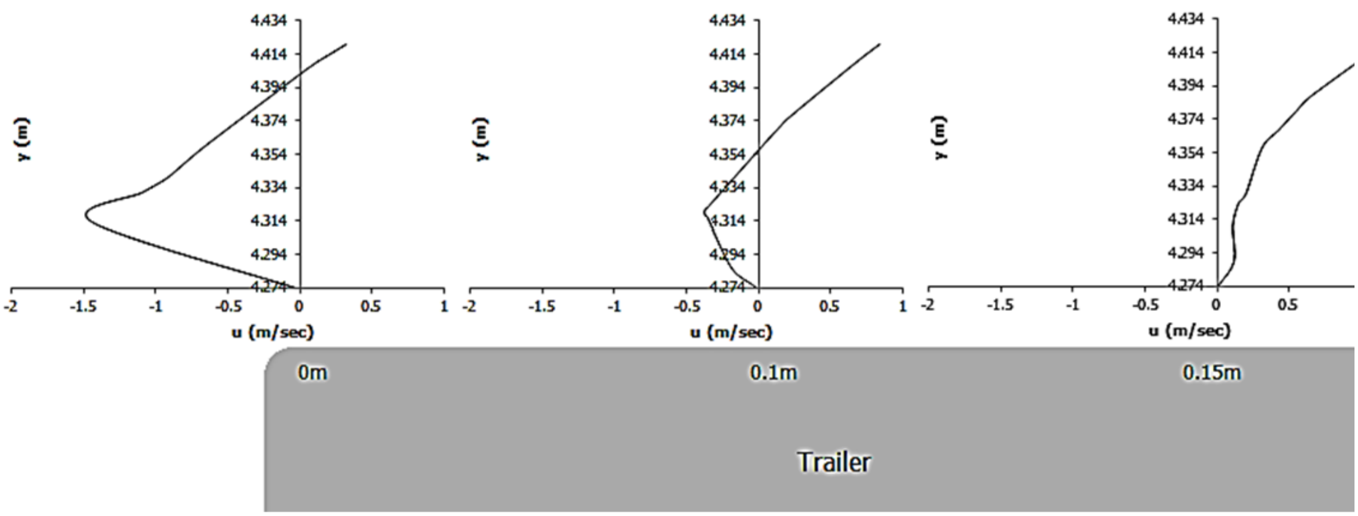


Figure 5. Axial flow velocity profiles at various distances from the leading edge of the trailer with MSBC device installed

It can be seen that as the presence of MSBC device reduces the drag force being exerted on the truck–trailer model by 15%, which is a considerable saving in terms of fuel consumption.

Table 2. Drag force for stationary MSBC model at various truck–trailer speeds

V	D	Difference in D w.r.t. Baseline Model
(mph)	(N)	(%)
40	1542	15.64
56	3006	15.32

3.3 Rotating MSBC Models

In order to optimise the operation of MSBC device for maximum drag reduction, investigations have been carried out at various rotating speeds of MSBC device, ranging from stationary to 3revs/sec, in increments of 0.5revs/sec. Figure 6 depicts the variations in the drag force being exerted on the truck–trailer model, cruising at 40mph, at various rotating speeds of the MSBC device. It can be seen that as the rotational speed of the MSBC device increases, the drag force being exerted on the truck–trailer model reduces until a certain speed of the MSBC device, after which increase in the rotational speed increases the drag force. The minimum drag force, being exerted on the truck–trailer model, is observed when the MSBC device is rotating at 0.5revs/sec.

Figure 7 depicts the variations in the drag force being exerted on the truck–trailer model, cruising at 56mph, at various rotating speeds of the MSBC device. Similar to Fig. 6, it can be seen that as the rotational speed of the MSBC device increases, the drag force, being exerted on the truck–trailer model, first reduces until a certain point, after which it increase again. The minimum drag force is recorded at 1revs/sec rotational speed. Hence, it can be concluded that an increase in the linear velocity of the truck–trailer model, increases the optimal operating rotational speed of the MSBC device.

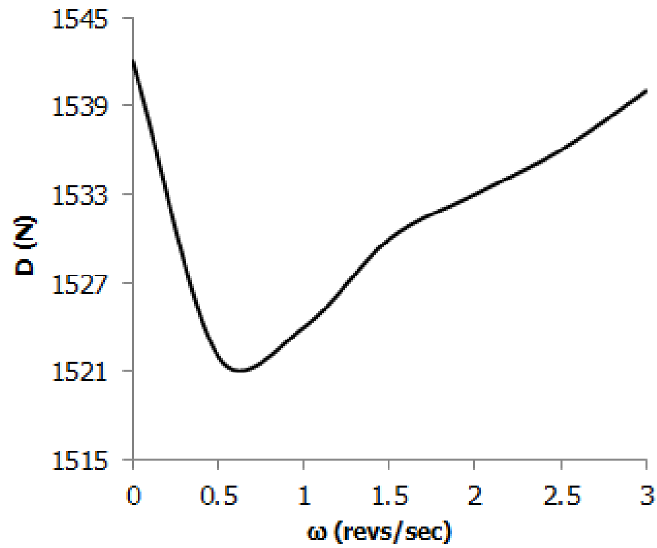


Figure 6. Variations in drag force at various rotating speeds of the MSBC device at truck–trailer's cruising speed of 40mph

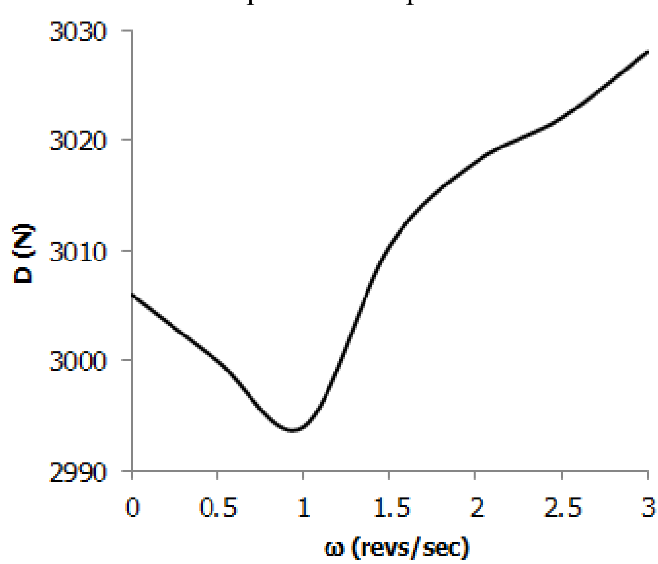


Figure 7. Variations in drag force at various rotating speeds of the MSBC device at truck–trailer's cruising speed of 56mph

4. CONCLUSIONS

Detailed numerical investigations have been carried out on the effects of a moving surface boundary layer control device on the drag reduction in heavy commercial vehicles. It has been concluded that then use of such devices reduces the drag force experienced by truck–trailer assemblies. The presence of MSBC device reduces the wake region by controlling the flow separation phenomena occurring at the roof of the trailer. Furthermore, it has been shown that there exists an optimal rotational speed of the MSBC device, for a particular vehicle speed, at which the drag force experienced by the truck–trailer assembly is minimum. This optimal operating rotational speed of the MSBC device increases as the linear velocity of the truck–trailer assembly increases.

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