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AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF VEHICLE SPACING ON BOUNDARY LAYER CHARACTERISTICS IN THE 2-VEHICLES PLATOON

A.Motin and M.A.T. Ali

Department of Mechanical Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

ABSTRACT

Aerodynamic shape of a moving object is a major concern of the researchers from many years. Though different accessories, engine parts and passenger compartment for example in the moving vehicle are needed to be available, perfect aerodynamic shape of any body, like passenger car, is not possible to maintain. In this circumstance, alternate factor other than body shape which can affects the vehicle performance is required to keep in consideration. For this, aerodynamic characteristics of two vehicles moving in platoon maneuver are investigated as the function of vehicle spacing (space between two vehicles) in this study. To conduct this investigation, 1/32 scale models of a saloon car are tested in the 300x300 mm wind tunnel facility of the Department of Mechanical Engineering, BUET. Velocities in the vertical plane through the centre of the wind tunnel are measured by pitot static tube which is interfaced with a computer through pressure transducer for data acquisition and is traversed by a computer controlled 3-axes co-ordinate positioning device. The integral analysis of the boundary layer is used to quantify the behavior of the aerodynamic characteristics and the effects of vehicle spacing on the boundary layer characteristics and skin friction. The zone of flow separation approaching laminar-turbulent transition is also investigated. In this study the displacement and momentum thicknesses on the trailing vehicle are found to be higher for smaller vehicle spacing. The flow strikes the front of the vehicle and is accelerated over the bonnet and is observed to be separated from the rear zone of the bonnet but reattaches in the leading edge of the roof. The flow reattachment becomes little bit earlier in the trailing vehicle than that in the leading vehicle.

Keywords: Boundary Layer, Flow Separation, Platoon Vehicle, Friction Drag, Friction Coefficient.

1. INTRODUCTION

The aerodynamic forces on automotive vehicles traveling in close proximity to each other are investigated in a wind tunnel. Scaled vehicle models are longitudinally aligned in a “platoon” configuration with various separation distances between the models. The velocity distributions along stream wise direction are measured by Pitot-static tube (United Sensor, U.S.A) along with pressure transducer (FC014-Micromanometer, Furness Controls, U.K.) interfaced with computer to quantify the transient interactions of the vehicle flow fields [1]. The integral analysis of boundary layer proposed by Theodore Von Karman and K. Pohlhausen in separate papers in 1921[2] is used to quantify the aerodynamics parameters. Due to friction present on the surface, the flow near the surface is retarded, so that the streamlines must be displaced outward to satisfy continuity. The flow separation is frequently quite sensitive to small changes in the shape of the body, particularly if the pressure distribution is strongly affected by the change of shape of the body as found by H. Schlichting [2]. There is always a possibility of separation in regions where the pressure increases, and it is even greater when the rate is larger, particularly for bodies with blunt rear sides. As a result of the backflow close to the wall, a strong thickening of the boundary layer takes place and with this boundary layer mass is transported away into the outer flow. At the point of separation, the streamlines leaves the wall at a certain angle and the wall shear stress τ_w vanishes. As a result fluid from the outer downstream zone moves towards the wall and fluid near the boundary is drawn right into the main flow leading to flow separation. Thus the separation point is defined as the boundary between the forwards and backflow in the layer closest to the wall.

Aerodynamics has a strong influence on the design and performance of a vehicle. The components of aerodynamic forces and moments experienced by a vehicle are shown in figure 1.1. In characterizing the aerodynamic behavior of road vehicles, a drag force is one of the most important factors from the viewpoint of fuel economy as found by JL. Tsuei et.al.[3]. From control and stability point of view, however, the side force and yawing moment are the most crucial aerodynamic characteristics of a vehicle [3]. Lift force and pitch movement is especially important to light weight and high speed vehicles used in racing cars [4] and roll movement is critical in some specific circumstances where strong gust occurs, Skibor-Rylski [5]. Earlier publications discussed the issues related to road vehicle aerodynamics can be found in Scibor Rylski[5], Hucho & Sovran [6].

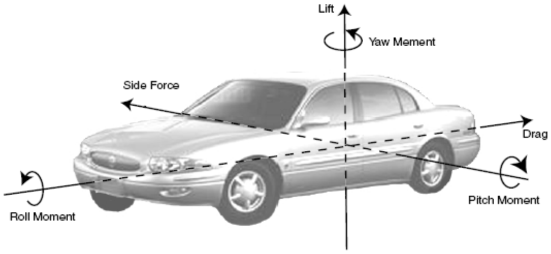


Fig 1. Force and moment on a vehicle.

These reviews discussed the fundamentals of fluid dynamics, experimental results and various automobile designs related to vehicle aerodynamics. However, their results are found mostly on the performance of single vehicle and covered relatively less material of the aerodynamic interactions involved with more than one vehicle. Several studies have discovered that a running car experiences a significant change of drag, side force and yaw moment induced by an overtaking vehicle, which may severely affect the overtaken car control [7], [8].

2. EXPERIMENTAL

The investigations of the study are conducted only on the top surface of the vehicle and at Z=0 along the axial direction along with available Y direction. The velocity profiles underneath the vehicle and in the side wall are not considered in this investigation. Hence, the total effect of boundary layer around the model car can not be analyzed. But the interaction of flow through ground clearance of the vehicle with the wake/eddies and vortex is observed by taking velocity profiles behind the vehicle at Z=0 but different X and Y positions. Before performing the experiment with the test model, the accuracy of the data acquisition system and the continuity of the test section are checked [9]. The flow stability and flow variation in the test section of the wind tunnel is also analyzed with the help of this investigation.

The model cars are placed along axial direction in the centre line of the bottom plane of the wind tunnel maintaining vehicle ground clearance of 25 mm. Testing is carried out at three different vehicle spacing i.e. ¼, ½ and 1 car length and at U_∞= 21.5 m/s (78 km/hr). The data are taken by Pitot - static tube which is interfaced with computer through pressure transducer. The Pitot - static tube is traversed by the computer controlled 3-axes co-ordinate positioning device [1]. The velocity distributions along vertical axis are taken at the number of planes in the stream wise direction from 150 mm ahead of the leading vehicle to 50 mm behind the trailing vehicle in the platoon maneuvers. The model car used for this experiment has the length of 130 mm including spare wheel casing in the rear of the vehicle.

The local velocities along the stream wise direction are made dimensionless by dividing the corresponding free stream velocity (U_∞). The X-axis is taken zero at the front edge of the leading vehicle and Y-axis is taken zero at the bottom surface of the wind tunnel. The X-axis and Y-axis are made dimensionless by dividing it by the car length (lc). Two different length scales i.e x/lc and x_c/lc are introduced to analyze the flow characteristics of the model in the test section. The x/lc is used for indicating the location of the vehicles in the test section with respect to zero (X_0) position. The x_c/lc is introduced to investigate and compare the boundary layer characteristics with respect to individual positions of each vehicle. The car dimension is shown in fig. 2.

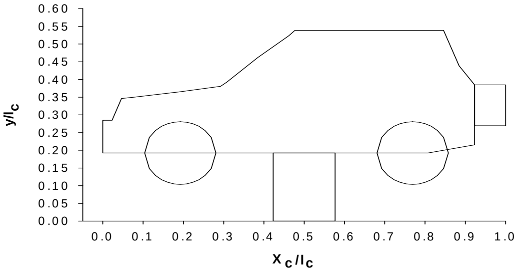


Fig 2. Model car dimension

From the number of velocity profiles along the stream wise direction, the contours of velocity are plotted for different experimental conditions. The numerical integration techniques are used for calculating the displacement thickness and momentum thickness and the finite difference techniques are used for calculating the friction coefficient. All the aerodynamic parameters are plotted in the non-dimensional form.

3. RESULT AND DISCUSSION

Fig.3 and fig.4 show the velocity profiles ahead of the leading vehicle and on the leading vehicle respectively of 2-vehicles platoon which are found to be similar in nature with those of single vehicle for U_∞= 21.5 m/s investigated by A.Motin [10][11]. In figure it is seen that when the vehicle spacing is small i.e. ¼ car length, the front of the trailing vehicle is affected by the wake generated behind the leading vehicle. As a result, no air thrust is present in the front of the trailing vehicle causing reduction of pressure drag on the front of the trailing vehicle. As the vehicle spacing increases, this effect reduces and it is observed for 1 vehicle spacing that the air flow strikes to the front of the trailing vehicle with a velocity of around U/U_∞= 0.6 producing more resisting force in the front in comparison to the small vehicle spacing. As a result, it can be said that the trailing vehicle with small vehicle spacing requires less amount of fuel on this count to drive the vehicle due to comparatively small restricting force present in the front.

Fig.6 shows that for ¼ vehicle spacing in the leading edge of the trailing vehicle (*x/lc* = 1.25), there is no air flow from y/lc = 0.39 to 0.46 due to generation of wake behind the leading car. In the case of ½ vehicle spacing the flow pattern in the same position of the vehicle (x/lc = 1.5) is found similar with the smaller vehicle spacing. But the magnitude of U/U_∞ is greater i.e. U/U_∞= 0.43 at y/lc = 0.39 and 0.46 and at y/lc = 0.54 the U/U_∞ is found to be about 0.73. When the vehicle spacing is equal to 1 car length, the U/U_∞ at y/lc = 0.46 is reduced to about 0.67 from about 0.72 at y/lc = 0.39. This means that in the case of 1 vehicle spacing comparatively high air velocity strikes in front of the trailing vehicle and is circulated. On the half way of the bonnet of the trailing vehicle (x/lc = 1.40, 1.65 and 2.15 for ¼, ½ and 1 vehicle spacing respectively) the flow velocity gradually increases in the vertical direction from the surface for ¼ vehicle spacing but for ½ and 1 vehicle spacing it reduces from the surface up to the point of y/lc = 0.46 and then increases smoothly. It can be illustrated from that the air flow just attaches on the half away of the bonnet for ¼ vehicle spacing. It is also observed that the maximum flow velocity is attained at the level of the roof wall x/lc = 0.54 on the bonnet for all the vehicle spacing. The velocity profiles on the top wall of the vehicle for all the vehicle spacing is observed similar in nature and magnitude. From fig.7, it is seen that the velocity profiles behind the trailing vehicle of 2-vehicles platoon is almost similar in nature with the velocity profiles in between the leading and trailing vehicle illustrated in fig.5. But the magnitude of air velocity in the level of bottom surface of the trailing vehicle is less that that of the leading vehicle.

The contour plots of velocity for 2-vehicles platoon at different vehicle spacing are shown in fig. 8. For ¼ car spacing, it is seen that in the leading vehicle the maximum flow velocity occurs just on the surface of the top wall. But for the trailing vehicle the maximum velocity of flow is observed about 30 mm above the surface of the top wall of the vehicle. This phenomenon occurs due to the boundary layer formation in the downward direction. It is also observed that the wake generated behind the leading vehicle is interfered up to about mid point on the bonnet of the trailing vehicle for ¼ vehicle spacing. As a result the flow circulation occurs on the bonnet in the trailing vehicle when the vehicle spacing is low (1/4 vehicle length). For ½ car spacing it is seen that the wake generated behind the leading vehicle affects the zone up to the front edge of the trailing vehicle when the vehicle spacing is 1/2 of the vehicle length. Hence, the flow circulation i.e the back flow occurs at the leading edge of the trailing vehicle.

For 1 car spacing the flow circulation due to wake generated behind the leading vehicle occurs in the front of the trailing vehicle and the slow moving air strikes at the front of the vehicle. When the vehicle spacing is small, the wake generated behind the leading vehicle in platoon interfere more to the trailing vehicle than that of larger vehicle spacing. As a result, pressure drag can be reduced as vehicle spacing becomes small. On the other hand, the thickness of boundary layer on the trailing car is a function of vehicle spacing but inversely related (shown in fig.8). It is clearly seen that the boundary layer in the down stream of the trailing vehicle for ¼ vehicle spacing is greater than that for ½ and 1 vehicle spacing. According to the boundary layer principle, higher the boundary layer thickness higher the mass flux and momentum flux deficit [2]. Since, the momentum flux is directly related to the skin-friction drag; hence the skin-friction drag may be more for shorter vehicle spacing although the pressure drag is reduced with smaller vehicle spacing.

Fig.9 shows that both the magnitude and variation of displacement thickness of the leading vehicle remain nearly the same as that of the single vehicle found by A.Motin [10][11]. In the trailing vehicle the variation pattern remains the same as the leading vehicle but its magnitude increases about 2 times than those of the leading vehicle. It is seen that the displacement thickness for ¼ vehicle spacing is greater than that for ½ and 1 vehicle spacing. As the wake generated behind the leading vehicle interferes more for smaller vehicle spacing (as described earlier), the displacement thickness on the trailing vehicle becomes higher for ¼ vehicle spacing than that of ½ and 1 car spacing.

In fig.10, it is seen that in the case of trailing vehicle, it is observed that up to about x_c/l_c=0.15 in the downward direction from the leading edge of the trailing vehicle, the momentum thickness for ¼ vehicle spacing is smaller than that for ½ and 1 vehicle spacing. After this point the trailing vehicle at ¼ vehicle spacing in platoon maneuver shows higher momentum thickness than that at ½ and 1 vehicle spacing. From velocity profile for ¼ vehicle spacing described earlier in, it is observed that there is no flow on the bonnet of the vehicle. Since, the flow velocity is zero there is no momentum on the surface of the bonnet. As a result, the momentum thickness is low in the front of the trailing vehicle for ¼ vehicle spacing than that of ½ and 1 vehicle spacing. It is also observed that the momentum thickness on the trailing vehicle (from x_c/lc=0 to1) decreases with the increase in vehicle spacing. From fig.10, it is seen that the momentum thickness for a specific location in the stream wise direction in the trailing vehicle is higher than that in the same location in the leading vehicle.

Fig.11 shows that the friction coefficient is observed zero at x_c/l_c = 0.1, 0.27 and 0.5 in the downward direction of the leading vehicle which indicates that the point of flow separation and flow reattachment respectively. The highest friction coefficient is observed on the bonnet where the flow tends to separate and the minimum friction coefficient is found to be at x_c/l_c = 0.325. It is also seen that the friction coefficient is observed negative from x_c/l_c = 0.27 to 0.5 in the downward direction which means that the back flow occurs here. In the case of trailing vehicle it is seen that for ½ and 1 vehicle spacing the friction coefficient is negative from the leading edge of the of the top wall. This is because of flow circulation which occurs due to wake generated behind the leading vehicle in the leading edge and in the front of the trailing vehicle for ½ and 1 vehicle spacing respectively. But in the case of ¼ vehicle spacing the flow separation occurs in the mid point of the bonnet in the trailing vehicle as observed earlier in fig.8. For this reason, the friction coefficient for ¼ vehicle spacing is observed positive and maximum at the leading edge of the trailing vehicle and zero at about the mid point of the bonnet (about x_c/l_c =

0.15 in the downward direction). For both leading and trailing vehicle, after the flow reattachment at $x_c/l_c = 0.5$, the friction coefficient is observed positive due to boundary layer development on the top wall of the vehicle.

Fig.11 also shows that the friction coefficient on the leading vehicle in platoon maneuver is positive up to $x_c/l_c = 0.27$ in the downward direction. At $x_c/l_c = 0.27$ of the vehicle the flow is separated and reattaches at $x_c/l_c = 0.5$ in the downward direction. On the other hand, for the trailing vehicle the friction coefficient is found to be negative up to $x_c/l_c = 0.5$ from the leading edge of the trailing vehicle and at this point the flow is reattached. After that point the trend of friction coefficient for leading vehicle and trailing vehicle is almost identical.

Fig.12 shows the variation of local friction drag coefficient as a function of vehicle spacing for leading and trailing vehicles. From both the curves it is seen that the variation of vehicle spacing in platoon maneuver has no significant effect on the local friction drag coefficient. From fig.12 it is observed that the friction drag on the leading vehicle is high on the front of the vehicle and reduces up to the mid point of the bonnet. After that point the value of drag coefficient rises up to $x_c/l_c = 0.31$ in the downward direction. It indicates that in the intersection zone of bonnet and front wind shield the momentum flux deficit is occurred. It is also observed that at the leading edge of the trailing vehicle the friction drag coefficient for ¼ vehicle spacing is slightly lower than that for ½ and 1 vehicle spacing and it observed reduces exponentially.

In fig.12, it is seen for the ¼ vehicle spacing that the friction drag coefficient in the trailing vehicle is higher than that in the leading vehicle. It is also observed that in the trailing vehicle the friction drag coefficient decreases exponentially. For ½ and 1 vehicle spacing, it is seen that the local friction drag coefficient in the trailing vehicle is higher than that in the leading vehicle up to $x_c/l_c = 0.31$ of the vehicle. After that point the friction coefficient in the leading and trailing vehicle remains almost the same.

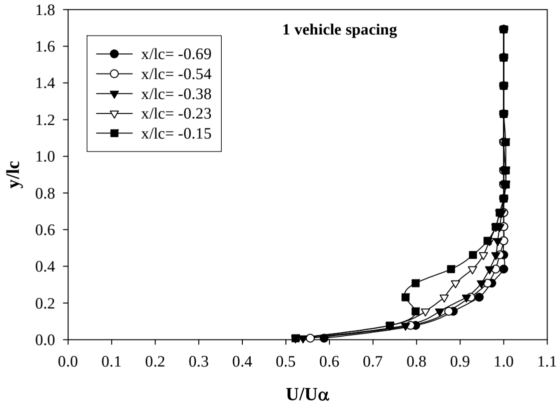


Fig 3. Velocity profiles ahead of the leading car

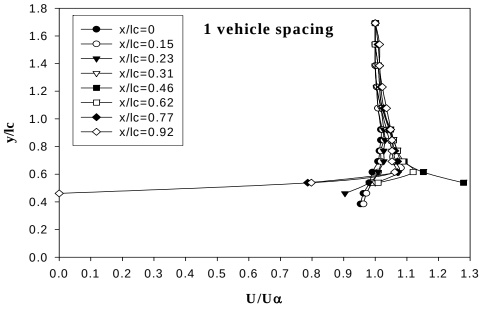


Fig 4. Velocity profiles on the leading car.

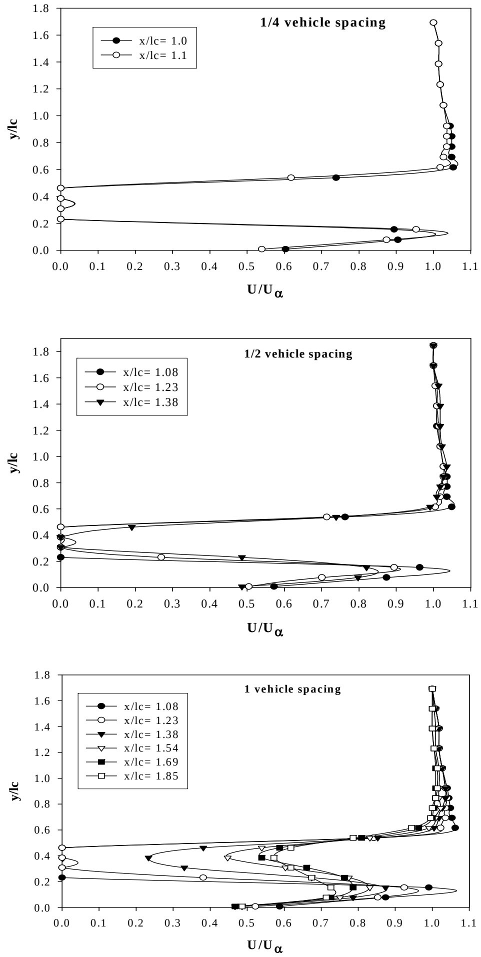
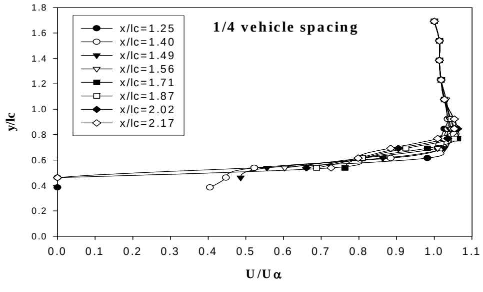


Fig 5. Velocity profiles in between leading and trailing car.



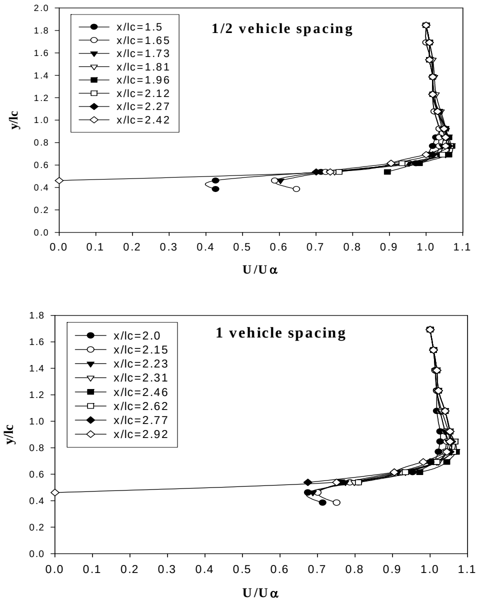


Fig 6. Velocity profile on the trailing car

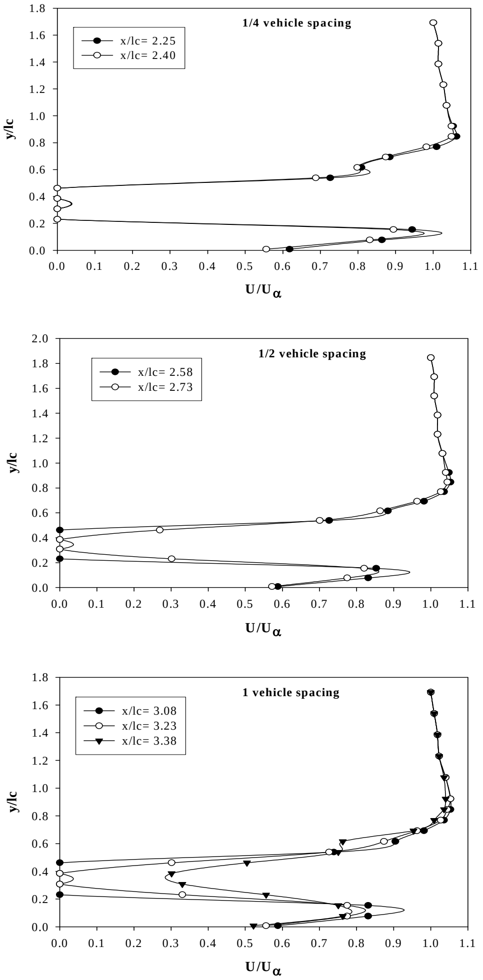


Fig 7. Velocity profiles behind the trailing car

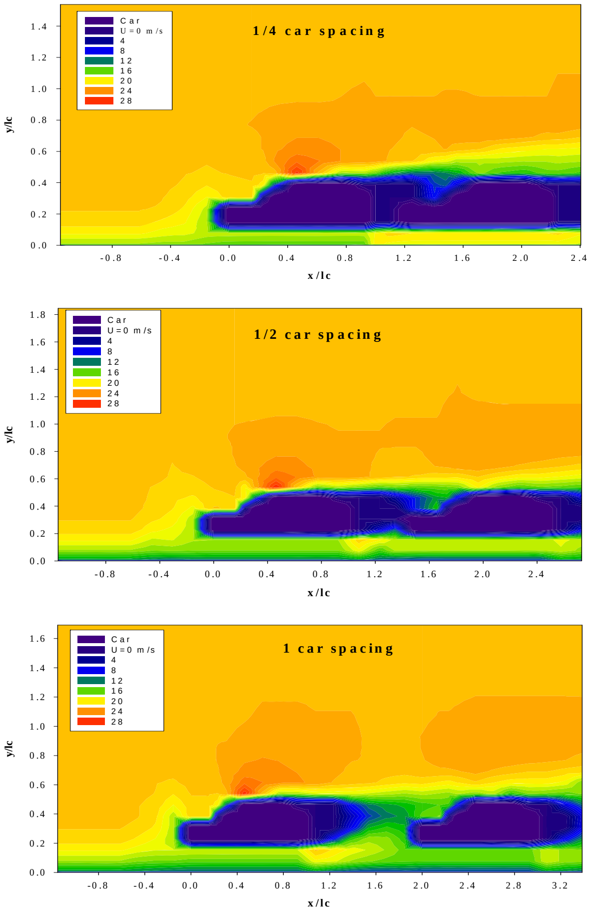


Fig 8. Contour plot of velocity for 2-cars in platoon.

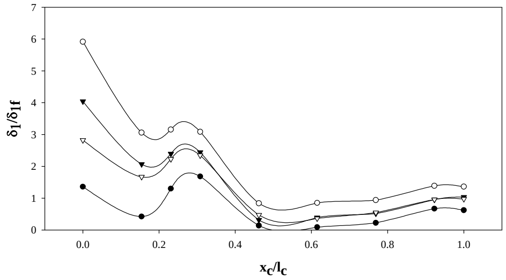


Fig 9. Variation of displacement thickness.

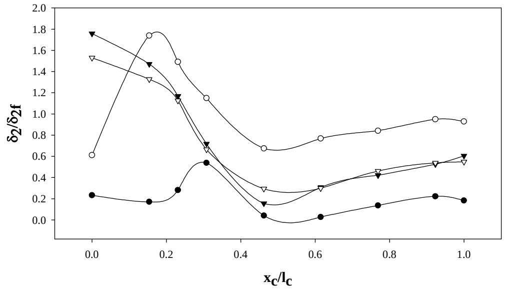


Fig 10. Variation of momentum thickness.

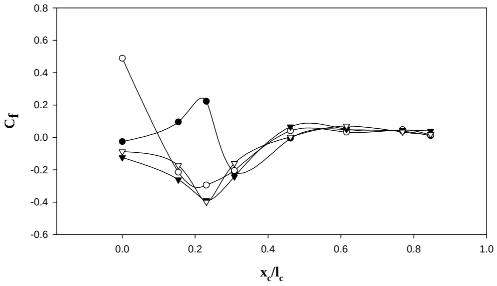


Fig 11. Variation of skin friction coefficient.

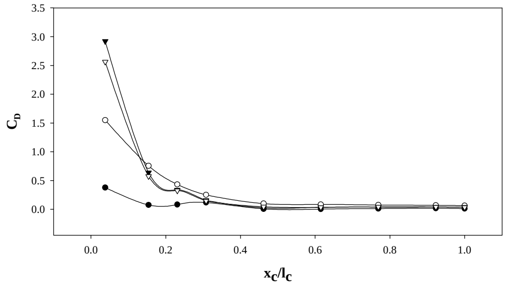


Fig 12. Variation of local friction drag coefficient.

4. CONCLUSION

From the present research work the following conclusions may be drawn.

1. Effect of boundary layer developed on the platoon vehicles at all the vehicle speed and spacing vanishes at y/lc>1.0.
2. The displacement and momentum thickness over the 2nd car is more than that over the leading car
3. The displacement thickness on the 2nd decreases with the increase of vehicle spacing. At the leading edge of the 2nd vehicle (x_c/lc=0.0) the δ_1 reduces to 50% as the vehicle spacing increases from ¼ to 1 car length.
4. At x_c/lc=0, the momentum thickness on the 2nd vehicle increases by 2.7 times as the vehicle spacing increases from ¼ to ½ car length and reduces to 90% as the vehicle spacing increases from ½ to 1 car length.
5. The separation of flow in the leading vehicle occurs at the end of the bonnet (x_c/lc=0.3) and the flow reattaches at the leading edge of the roof (x_c/lc=0.5).
6. At x_c/lc>0.5 the change of vehicle spacing has no significant effect on the friction coefficient and friction drag coefficient.
7. On the 2nd vehicle at x_c/lc=0 the friction drag increases by 45% as the vehicle spacing increases from ¼ to ½ car length and reduces by 11% as the vehicle spacing increases from ½ to 1 car length.

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6. NOMENCLATURE

Symbol	Meaning	Unit
U	Local velocity	m/s
U_∞	Free stream velocity	m/s
δ_1	Displacement thickness	mm
δ_{1f}	Free stream displacement thickness	mm
δ_2	Momentum thickness	mm
δ_{2f}	Free stream momentum thickness	mm
C_f	Skin friction coefficient	--
C_D	Friction drag coefficient	--
l_c	Characteristic car length	mm
x_c	Stream wise distance along the model car from the front of the car.	mm

7. MAILING ADDRESS

A.Motin
Department of Mechanical Engineering,
Bangladesh University of Engineering and Technology,
Dhaka-1000, Bangladesh
E-mail: amotin@me.buet.ac.bd