

Measurements of the cross-flow velocity field in the wake of an idealized pickup truck model using particle image velocimetry

Abdullah M. Al-Garni

Dept. of Aerospace Engineering, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia,
amg@kfupm.edu.sa

Abstract An experimental investigation has been conducted to measure the cross-flow velocity field in the near wake of an idealized pickup truck using Particle Image Velocimetry (PIV). The goal is to characterize the streamwise vortex structures in the near wake of the truck. Of particular interest and complexity are the symmetric and asymmetric separated vortex flows which develop behind the cab and the tailgate. A secondary objective of the research is to obtain a comprehensive experimental data set for validation of CFD models. The experiments were conducted at a Reynolds number of 8.5×10^5 . The PIV measurements of the cross-flow velocity field (normal to the free stream) behind the cabin and tailgate have been obtained at four streamwise locations. The PIV data are processed to obtain not only the instantaneous velocity field but also the mean flow and turbulence properties by averaging 300 instantaneous realizations. The instantaneous PIV data show concentrated vortical structures of size small compared to the width of the model, and located randomly in space and time, and a persistent downwash at the symmetry plane of the model. The mean velocity in the near wake of the cab shows a pair of vortices and strong lateral and downward flow into the bed of the model. The mean velocity data downstream of the tailgate shows a pair of counter-rotating vortices of size comparable to the width of the model, which induce strong downwash at the symmetry plane. This downwash promotes attached flow behind the tailgate, thus resulting in a pressure recovery that reduces drag.

1. Introduction

The aerodynamics of road vehicles has been an important area of research for many years. Among the more popular road vehicle geometries in use today are pickup trucks. The aerodynamics of pickup trucks is far more complex than that of other simplified geometries researched in the past, because the short length of the bed can result in interaction of the bed walls and tailgate with the separated shear layer formed at the edge of the cab. The complexity of these flows makes drag prediction tools, including CFD based methods, unreliable. The main goal of the present research is to gain a better understanding of pickup truck aerodynamics using detailed measurements that can also be used for validation of computational models.

In a previous investigation the mean and unsteady surface pressures, and PIV velocity data in the streamwise direction were obtained documenting the complexity of the flow in the near wake of a pickup truck (Al-Garni 2003). Unsteady surface pressure measurements in the bed and tailgate showed a spectral peak at a non-dimensional frequency based on model width and free stream velocity of 0.07, and large fluctuation energy at low frequency. The former is due to the turbulent flow in the near wake, while the latter was attributed to the amplification of very small disturbances in the free stream. In that work, the development of the shear layers in the near wake was determined using PIV. The shear layers at the bottom and side edges of the tailgate are stronger than the cab shear layers. For this particular geometry, the cab shear layer does not reattach on the bed or the tailgate and extends to approximately the same downstream location as the tailgate shear layers. An interesting feature of the flow is the strong downwash in the symmetry plane of the model. The mean pressure distribution on the tailgate show a lower pressure coefficient on the inside surface of the tailgate compared to the outside surface suggesting that the tailgate reduces aerodynamic drag.

The aerodynamics of road vehicles has frequently been studied in simplified geometries to

separate the effect of various components on aerodynamic drag and on the near wake flow dynamics. A review of early work in this area can be found in Hucho (1998). Balkanyi et al. (2000, 2002) and Khalighi et al. (2001) studied the effects of drag reducing devices on the near wake flow of a simplified automotive bluff body. PIV and unsteady pressure measurements show that the near wake turbulence structure is modified by the drag reducing devices. The turbulence intensity is reduced while the shape and downstream extent of the recirculating flow region is not strongly affected by the devices. Lanser et al. (1991) conducted full scale tests of a tractor-trailer vehicle. The spectrum of the base pressure fluctuations shows a peak at a Strouhal number of around 0.12. These values are comparable to the values measured in the near wake of a simpler three-dimensional bluff body such as a sphere (~ 0.1 see Wu and Faeth 1999).

Duell and George (1999) report unsteady flow effects in the near wake of a three-dimensional bluff body with a blunt base similar to the one used by Balkanyi and co-workers. They differentiate between unsteady effects in the separated shear layer at the edge of the body and in the closed recirculating flow region. The former is associated with the initial development of the separated shear layer which is dominated by vortex roll-up and merging processes with a characteristic Strouhal number of ~ 1 . The latter are described as wake pumping associated with unsteadiness of the recirculating flow region, which has a characteristic Strouhal number of ~ 0.07 .

Lietz et al. (1999) have reported results of numerical simulations and experiments of the flow behind the tailgate of a pickup truck. The study focuses mainly on the results of CFD simulations for different configurations of the bed. The experimental data were limited to a small region behind the tailgate which show two counter-rotating vortices in the cross-flow plane and no recirculation region in the symmetry plane behind the tailgate. The simulation results, however, show a small recirculation region behind the tailgate which is in contradiction with experimental results.

Bearman (1997) studied the formation of streamwise vortices in the near wake of a 1/8th-scale car model. He used PIV measurements to determine the instantaneous flow on cross-sectional planes normal to the freestream direction in the near wake. The instantaneous flow field show randomly located vortical structures. This suggests the concept of a road vehicle wake consisting of a pair of persistent counter-rotating vortices is not correct. Instead, the results show that the wake of a road vehicle consists of compact small scale vortex structures located randomly in space and time and, consequently, the near wake dynamics appears to be much more complicated than the classical high-aspect-ratio-wing wake problem. The mean flow field shows a well-defined counter-rotating vortex pair. However, this vortex pair is not symmetric around the symmetry axis which may be due to the PIV setup as will be discussed in Sec. 2.3.

The present study thus focuses on the streamwise vortex structures in the near wake of a pickup truck. It is motivated by the PIV results obtained along the symmetry plane and the pressure recovery behind the tailgate reported earlier (Al-Garni 2003). PIV data were obtained at four cross-flow planes behind the cab and the tailgate. These measurements can highlight streamwise vortical structures generated from the cab and side shear layers and provide a better understanding of the downwash found in the symmetry plane behind the tailgate.

2. Flow facilities and PIV setup

2.1. Wind tunnel facility

The experiments were conducted in the 2'×2' Wind Tunnel at the Aerospace Engineering Department at the University of Michigan. This is an open-return suction wind tunnel with glass side and bottom test section walls for optical access. The maximum speed of the tunnel is approximately 35 m/s and the test section cross-section area is approximately $0.60 \times 0.60 \text{ m}^2$. The test section has 0.14 m fillets at the bottom corners to suppress corner flows. For the present tests a

2-m long ground board mounted 0.1 m below the top wall of the test section was used to simulate ground effects on the pickup truck flow. The ground board spans the cross section of the tunnel and has a rounded leading edge of elliptical cross section with aspect ratio 4:1. Figure 1 shows a schematic diagram of the wind tunnel test section with the pickup truck model installed and the PIV setup.

2.2. Pickup Truck Model

The pickup truck model is shown schematically in Fig. 2. The main features are a relatively long cabin (the “Cab”) and a short bed (the “Bed”) compared to other truck geometries. For the tests, the model was mounted upside down on the bottom side of the ground board with attachment points at the wheels. Holes in the wheels provided access for pressure lines and/or electrical cables. The front bumper is located approximately 0.4 m from the leading edge of the ground board. As shown in Figure 2, the length of the model is 0.432 m, the width is 0.152 m, and the height is 0.148 m measured from the ground board. The maximum cross section area is 0.023 m^2 , which gives a blockage area ratio of 7.6%. Although the blockage is small, it has a significant effect on the flow causing significant acceleration of the flow around the model and a reduced static pressure at the bottom of the test section under the model. To account for blockage effects, the static pressure on the fillets was measured during the tests and used to calculate the pressure coefficient. Also shown in Fig. 2 is the origin of the coordinate system used in this paper. The x-axis is in the flow direction with origin at the front bumper. The y-axis is in the horizontal direction across the flow with origin at the symmetry plane of the model. The z-axis is in the vertical direction with origin at the surface of the bed cover.

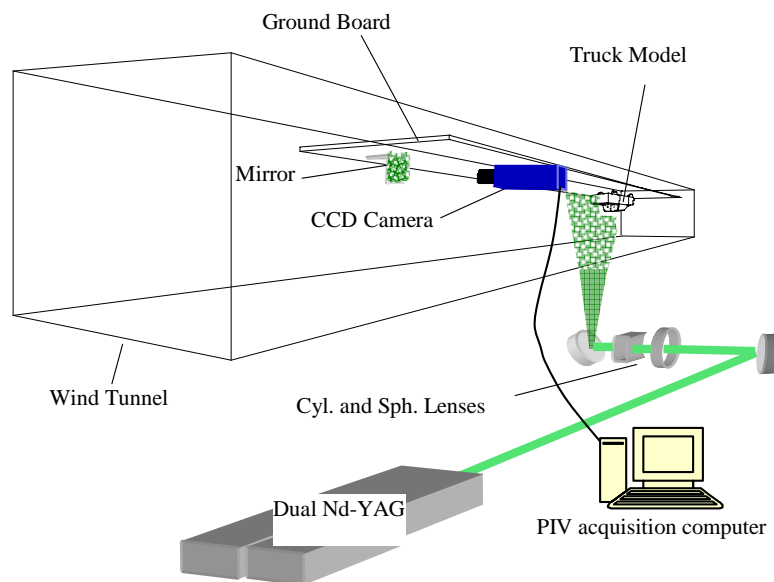


Fig. 1 Schematic diagram of the wind tunnel and PIV setup.

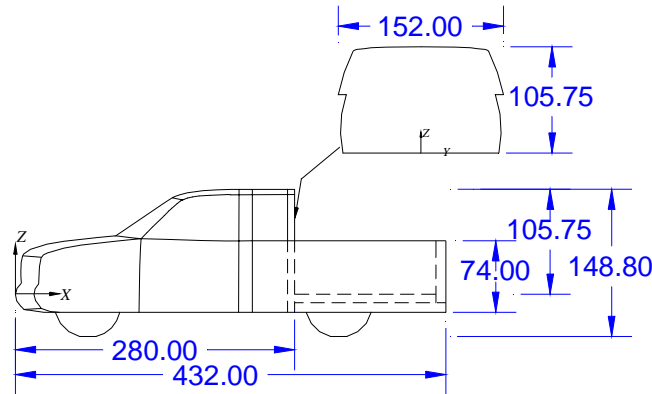


Fig. 2 Side view drawing of the pickup truck model and rear view of the cab base showing in the insert. Dimensions are in mm

2.3. Particle image velocimetry

The velocity field on selected planes was measured using a two-frame digital PIV system. The flow was illuminated using two Nd-YAG lasers. The output beams were merged and directed into the test section by a set of mirrors. The resulting beams are shaped into a light sheet normal to the free stream by a combination of spherical and cylindrical lenses. The optical setup produced a laser sheet 0.5 mm thick by 400 mm wide. The lasers were synchronized to illuminate the flow twice with a short time delay between the two exposures. Because the velocity component normal to the laser sheet is very large compared to the cross-flow velocity components, time delays in these experiments were set to 4 μ s. The flow was seeded with small oil particles generated by a smoke generator located upstream of the settling chamber. The smoke was directed into a 'smoke box' designed to produce a uniform smoke stream. The cross-section area of the smoke stream in the test section was 20 \times 20 cm.

As shown in Fig. 1, a small (7.6 \times 10 cm²) mirror attached to the trailing edge of the ground board is used to image the cross-section planes with the camera mounted outside the tunnel. This optical recording configuration minimizes flow interference. However, since the velocity component normal to the sheet is large, any small departure from perfect optical alignment results in a significant contribution of the downstream component of the velocity to the measured cross flow velocity components. In order to assess these effects and correct for any deviation in the alignment of the camera, the model was removed from the tunnel and a set of measurements were taken. These data were used to compute the contribution of camera misalignment to the measured flow on the cross-section planes. The mean and instantaneous velocity fields on cross section planes reported here were computed by subtracting this mean flow without the model from the measured data with the model installed in the tunnel.

The light scattered by the seeding particles was recorded with a dual-frame digital camera (1280 \times 1024 pixels). The field of view of PIV images was around 200 \times 160 mm which corresponds to a spatial resolution of 6.5 pixels/mm. The particle displacements are limited by the velocity component normal to the sheet and were approximately 0.3 pixels. The images were sampled at a rate of 1 Hz limited by the transfer time of the digital images to the data acquisition computer. A total of 360 PIV images were recorded at each plane.

The PIV images were processed using an image shifting algorithm consisting of two steps. In the first step the images are processed using a standard cross correlation algorithm on un-shifted interrogation windows to determine the particle displacement at each grid point. The interrogation window size is large enough to accommodate the expected particle displacement. In the second step

cross correlation analysis between shifted interrogation windows is used. The window shift at each grid point is the particle displacement obtained in the first step. The main advantage of this technique is that the measurement resolution is decoupled from the magnitude of the particle displacement and consequently the noise level of the PIV measurement is improved. The interrogation window used in the second step determines the spatial resolution of the measurement. For the present measurements the interrogation window used was 64×64 pixels and the grid spacing was 16 pixels, which correspond to a spatial resolution in the flow of 10×10 mm and 2.5 mm grid spacing.

The PIV data were processed to obtain mean and turbulence properties in the wake of the pickup truck. The grids used were 74×24 points for the flow at $x = 375$ and 410 mm and 74×58 points at $x = 482$ and 550 mm. In the analysis of turbulent data, each PIV velocity field is treated as an independent realization of the flow since the time between each sample is long compared to the turbulence time scales. Ensemble averages of 300 instantaneous fields are reported. The uncertainty of the mean velocities is estimated to be less than 2.6%.

3. Results and discussion

PIV measurements of the pickup truck flow field were obtained at several vertical and horizontal planes (parallel to the freestream) and four cross-flow planes (normal to the freestream). These measurements were conducted at a freestream speed of 30 m/s which corresponds to a Reynolds number of 8.5×10^5 . The streamwise locations of the cross-flow planes are $x = 375$, 410 , 482 and 550 mm. The first plane is located 35 mm ahead of the tailgate and the second plane is at the inner edge of the tailgate. The other two planes are located in the near wake of the tailgate. These planes were selected based on the results of the vertical and horizontal planes. The PIV measurements in the first two planes can highlight streamwise vortical structures generated from the cab top and side shear layers. On the other hand, the cross-flow planes behind the tailgate can provide a better understanding of the downwash found in the symmetry plane and the vortical structures due to the separated shear layers from the top and sides of the tailgate.

3.1. Streamwise Mean Flow Field

Figure 3 shows the mean streamlines of the flow. The plot includes the mean streamlines inside the bed obtained in separate tests. The streamline pattern inside the bed matches well with the streamline pattern outside the bed. A recirculating flow region exists behind the cabin but there is no recirculation behind the tailgate. Instead the mean flow shows very strong downwash at the symmetry plane. The attached flow behind the tailgate causes the mean pressure on the outside surface of the tailgate to be higher than on the inner side of the tailgate (Al-Garni 2003). This means that the force acting on the tailgate is in the forward direction, thus reducing aerodynamic drag. The downwash is believed to be due to the presence of a strong streamwise vorticity behind the tailgate as it will be evident from the results of the cross flow planes presented below. For the bed flow, these measurements show that the flow enters the bed at the tailgate and leaves near the cab base resulting in a recirculation region in the front part of the bed with a center at approximately 40 mm behind the cab base.

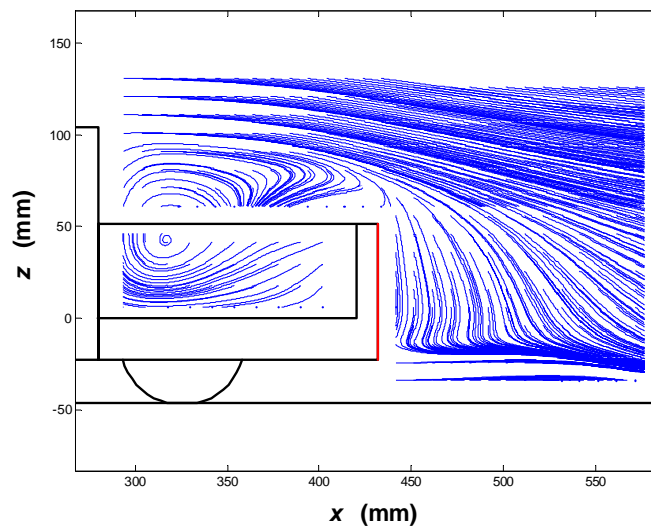


Fig. 3 Streamlines of the mean flow field in the symmetry plane of the wake of a pickup truck.

3.2. Instantaneous Cross Flow Fields

In order to gain a better understanding of the mechanism responsible for flow attachment shown in figure 3 and pressure recovery observed behind the tailgate of the truck, PIV measurements of the cross-flow (normal to the freestream) velocity fields were obtained in the pickup truck wake at four streamwise locations, $x = 375, 410, 482$ and 550 mm. The first plane is located 35 mm ahead of the tailgate and the second plane is at the inner edge of the tailgate. The other two planes are located in the near wake of the tailgate. Figure 4 shows typical instantaneous flow fields in the near wake of the cab at $x = 375$. As can be seen, the flow in the near wake of the cab is very complicated and highly three dimensional. The main features of the flow are compact vortex structures located randomly in space. These structures originate from the separated cab shear layers and their interactions with the walls of the bed. The spanwise velocity is stronger in the sides and weaker near the symmetry plane where the flow enters the bed.

Figures 5 show typical instantaneous flow fields in the near wake of the tailgate at $x = 482$ mm. Similar to the other planes, the data in this plane show a random distribution of compact vortex structures. This suggests that the concept of a permanent pair of counter-rotating vortices in the near wake of a road vehicle is incorrect in agreement with the Bearman observations for a car model (Bearman 1997). It can be seen that the underbody flow at both sides of the symmetry plane moves upward faster than at the symmetry plane. This motion of the underbody flow is caused by the difference between the pressure under the model and behind the tailgate. Steady pressure measurements show that the underbody pressure coefficient is around -0.10 compared to -0.16 behind the tailgate (Al-Garni 2003).

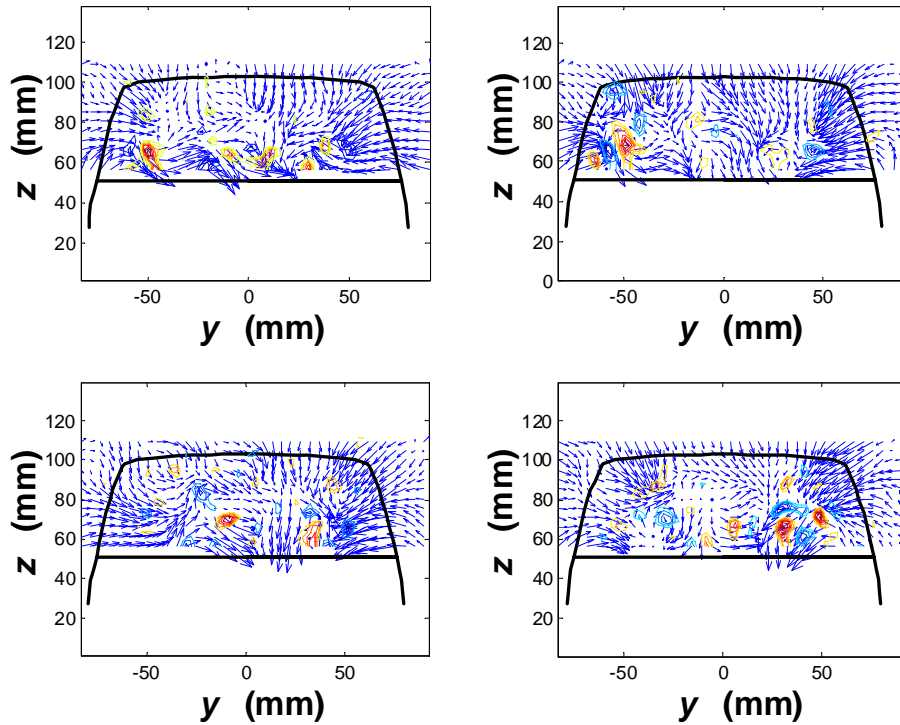


Fig. 4 Typical Instantaneous flow fields in the near wake of the pickup truck at $x = 375$ mm.

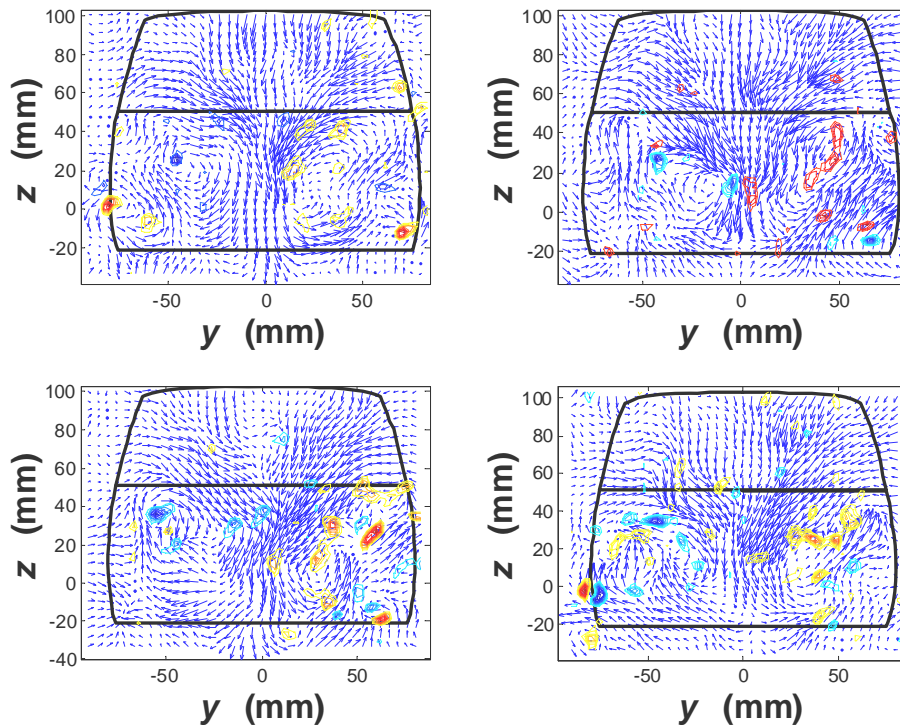
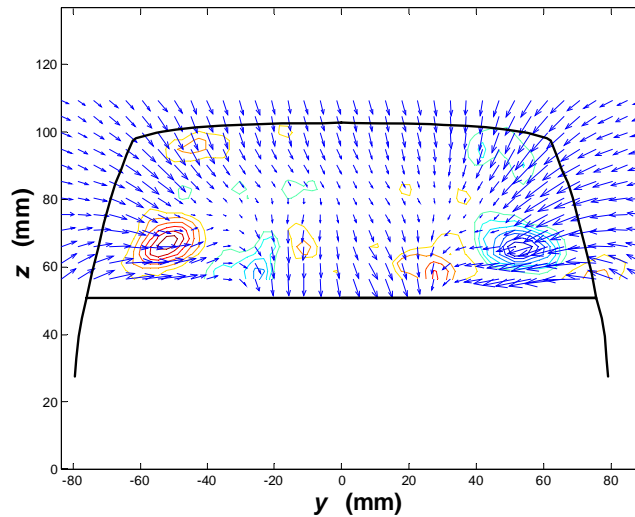


Fig. 5 Typical Instantaneous flow fields in the near wake of the pickup truck at $x = 482$ mm.

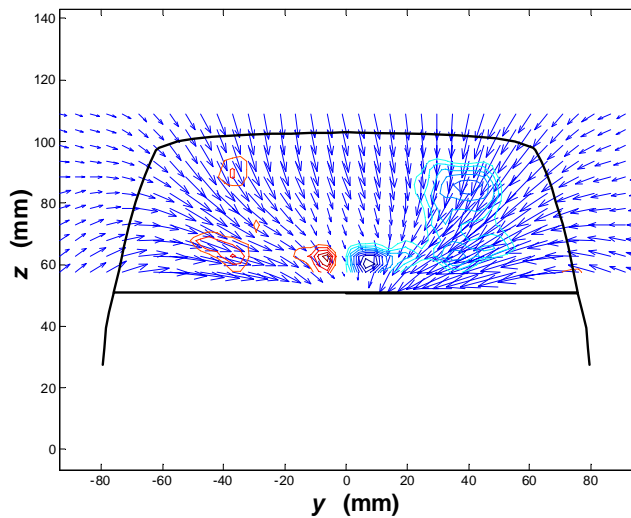
3.3. Mean Cross Flow Field

Mean flow fields in the near wake of the cab ($x = 375$ mm) and at the tailgate ($x = 410$ mm) are shown in Figure 6. A pair of counter-rotating vortices appears behind the cab with their centers at $y = \pm 52$ mm as shown in Figure 6(a). Figure 6(b) shows compact vortex structures at the symmetry

plane near the tailgate edge resulted in strong pressure fluctuations near the tailgate. The measured rms value of the pressure fluctuations is around 1.9% of the dynamic pressure compared to 0.4% at the base of the cab. In addition, the pair of counter-rotating vortices at $x = 375$ mm becomes weaker near the edge of the tailgate. The figure also shows that the flow in the sides is stronger than on the central portion of the bed and the flow enters the bed near the tailgate. These observations are consistent with the results in the other planes.



(a)



(b)

Fig. 6 Mean velocity and vorticity fields plane in the near wake of the cab: (a) $x = 375$ mm and (b) $x = 410$ mm (at the edge of the tailgate).

The mean flow field in the near wake of the tailgate is shown in Figure 7 at $x = 482$ and 550 mm. An interesting feature of the flow is a pair of strong counter-rotating vortices behind the tailgate. These vortices drag the flow behind the tailgate thus inducing strong downwash at the symmetry plane as shown earlier in the symmetry plane results. The centers of these vortices are not well defined. Another weaker pair of vortices that may originate from the interaction of the bed flow in both sides of the symmetry plane with the tailgate appears above the stronger pair of vortices. Note that the weaker pair of vortices rotates opposite to the stronger one. In addition, the figure shows weaker vortex structures that originate from the bottom corners of the model. This

figure clearly shows the strong downwash observed in the symmetry plane. Another interesting feature of the flow behind the tailgate is the underbody flow which deflects upward more rapidly on the sides than at the symmetry plane. The two pairs of vortices moves down toward the ground board as they travels downstream as shown in Figure 7(b). Comparing between Figure 7(a) and (b), vortices at $x = 482$ mm have moved down about 10 mm toward the ground board. In addition, as these vortices travel downstream, they move away from each other. These streamwise vortices can result in an increase of aerodynamic noise which can affect the level of comfort in the passenger compartment (Haruna et al. 1991). On the other hand, the downwash induced by these vortical structures promotes attached flow around the symmetry plane behind the tailgate, thus generating a pressure recovery which in turns reduces aerodynamic drag. The steady pressure results in the inner and outer sides of the tailgate shows that the tailgate reduces aerodynamics drag (Al-Garni 2003)

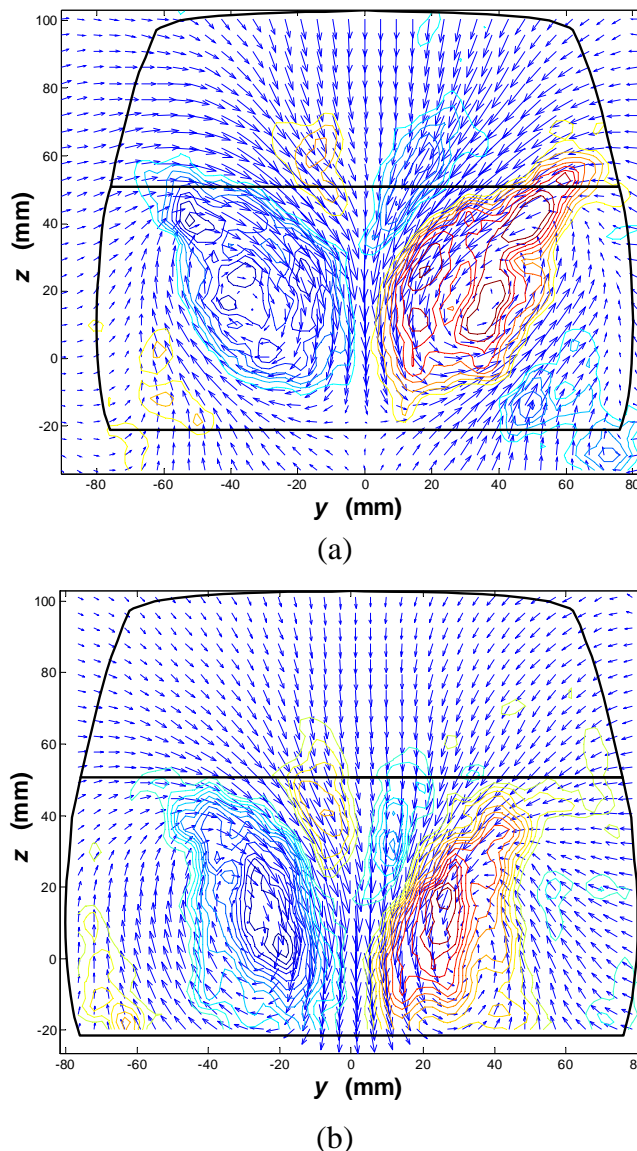


Fig. 7. Mean velocity and vorticity fields in the near wake of the tailgate at: (a) $x = 482$ mm and (b) $x = 550$ mm.

4. Conclusion

An experimental investigation of the near wake flow of the pickup truck was conducted at

Reynolds numbers in the range of 8.5×10^5 based on the lengths of the model. The results reported in this paper are PIV measurements of the velocity fields in the near wakes of a generic pickup truck. The mean velocity field measurements in the symmetry plane show a recirculating flow region over the bed bounded by the cab shear layer. One of the more striking features of the pickup truck flow is the downwash on the symmetry plane behind the tailgate. Instantaneous flow fields in the cross-flow planes of the pickup truck near wake show compact vortex structures located randomly in space. This suggests that the concept of a persistent pair of counter-rotating vortices in the near wake of a road vehicle is incorrect in agreement with Bearman observations in a car model.¹² Mean flow fields in the near wake of the cab show a weak pair of counter-rotating vortices behind the cab. In the cross-flow planes behind the tailgate, the mean flow fields show strong counter-rotating vortices behind the tailgate. These vortices drag the air to the symmetry plane thus inducing strong downwash at the symmetry plane. The downwash generated between them promotes attached flow on the central portion behind the tailgate. This observation is consistent with the mean pressure measurement results which show higher pressure outside the tailgate (Al-Garni 2003). The velocity data in the cross flow planes show that the lateral flow is stronger in front and after the tailgate than in the bed or further downstream the tailgate.

Acknowledgments

The support of King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia is gratefully acknowledged. This research was supported in part by General Motors Corporation.

5. References

- Al-Garni, A. M., Bernal, L. P., and Khalighi, B. (2003) Experimental investigation of the near wake of a pickup truck. SAE Paper 2003-01-0651.
- Balkanyi, S. R., Bernal, L. P., Khalighi, B., and Sumantran, V. (2000) Dynamics of manipulated bluff body wakes. AIAA Paper 2000-2556, 2000.
- Balkanyi, S., Bernal, L.P. and Khalighi, B. (2002) Analysis of the near wake of bluff bodies in ground proximity. ASME Paper 2002-32347.
- Bearman, P. W. (1997) Near wake flows behind two-dimensional and three-dimensional bluff bodies. *J. of Wind Eng. Ind. Aerodyn.* 69-71: 33-54.
- Duell, E.G. and George, A.R. (1999) Experimental study of a ground vehicle body unsteady near wake. SAE Paper 1999-01-0812.
- Haruna, S., Nouzawa, T., Kamimoto, I., Hiroshi, S. (1990) An experimental analysis and estimation of aerodynamics noise using a production vehicle. SAE Paper 900316.
- Hucho, W. H. (1998) *Aerodynamics of road vehicles*, SAE International, Warrendale, Pa.
- Khalighi, B. Zang, S., Koromilas, C., Balkanyi, S., Bernal, L.P., Iaccarino, G. and Moin, P. (2001) Experimental and computational study of unsteady wake flow behind a body with a drag reduction device. SAE Paper 2001-01-1042.
- Lanser, W.R., Ross, J.C. and Kaufman, A.E. (1991) Aerodynamic performance of a drag reduction device on a full-scale tractor/trailer. SAE Paper 912125.
- Lietz, R., Pien, W., Hands, D., and McGrew, J. (1999) Light truck aerodynamic simulations using a lattice gas based simulation technique. SAE Paper 1999-01-3756.
- Wu, J.-S. and Faeth, G. M. (1994) Sphere wakes at moderate Reynolds numbers in a turbulent environment. *AIAA Journal*, 32(3): 535-541.