

Comparison of Computational Simulation of Automotive Spinning Wheel Flow Field with Full Width Moving Belt Wind Tunnel Results

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ABSTRACT

One of the remaining challenges in the simulation of the aerodynamics of ground vehicles is the modeling of the airflows around the spinning tires and wheels of the vehicle. As in most advances in the development of simulation capabilities, it is the lack of appropriately detailed and accurate experimental data with which to correlate that holds back the advance of the technology.

The flow around the wheels and tires and their interfaces with the vehicle body and the ground is a critical area for the development of automobiles and trucks, not just for aerodynamic forces and moments, and their result on fuel economy and vehicle handling and performance, but also for the airflows and pressures that affect brake cooling, engine cooling airflows, water spray management etc.

In the present exercise, the purpose is to supply this experimental data around the wheels and tires on two configurations of one production level vehicle in order to compare the results of CFD prediction with this data. In order to assure the most accurate experimental data, we conducted the vehicle tests in a wind tunnel with a full width belt simulation of the road movement instead of a fixed ground or a 5-Belt system commonly used in automotive work.

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INTRODUCTION

A number of studies have been made attempting to document the flow field around a spinning tire either as a separate body or as mounted on a road-going vehicle [1, 2, 3, 4, 5]. However, none of the studies to date combine all of the elements of the following:

1. Having a full width moving belt simulation of the ground underneath the vehicle and tire (not fixed ground or 5-Belt system)
2. Utilization of a production vehicle with production wheels and tires.

3. Documentation of the vehicle attitude changes and tire section changes at rest and at speed.
4. Documentation of the tire tread, shoulder, sidewall and section details at rest and at speed.

Therefore, the purpose of this investigation is to combine all of these elements in order to simulate a full moving ground plane, or on-road condition with production components. This data then would provide the best comparison to CFD simulations of the conditions actually presented in an on-road condition.

EXPERIMENTAL APPROACH AND SET UP

For this study it was critical that the boundary conditions of the moving road underneath the vehicle and especially the tires were replicated as closely as possible. Therefore the vehicle was tested at the Windshear Rolling Road Wind Tunnel [6].

The Vehicle

The vehicle used for this comparison is a production minivan. The vehicle was tested in an unmodified condition with the vehicle attitude set to a condition consistent with the so-called EPA loading of 68 kg in each front seat and a full tank of gas. Relevant dimensions are given in [Table 1](#). The vehicle was restrained in the wind tunnel by solid circular struts attached to the chassis frame rails behind each front wheel ([Figure 1](#)), as described in [6]. As discussed there, the vehicle restraint system allows the suspension, vehicle body, and tires to react to the aerodynamic and internal tire forces much as they would in an open-road condition.

Table 1. Vehicle Dimensions

Overall Length	5151 mm (202.8")
Wheelbase	3078 mm (121.2")
Overall Height	1725 mm (67.9")
Overall Width	1999 mm (78.7")
Front/Rear Track	1664 mm (65.5") / 1646 mm (64.8")
Drivetrain	Front Wheel Drive
Engine	3.6L V-6 / Automatic Transmission
Wheels and Tires	P225/65R17 on 17"x 6.5" rims – Michelin Energy Saver A/S
Frontal Area	3.00 m ² (32.3 ft ²)



Figure 1. Test Vehicle in Windshear Wind Tunnel

Configurations

The only configuration changes that were made to the vehicle relate to the wheel design. The reference condition included a flush convex wheel cover while the alternative configuration removed the wheel covers and exposed the production aluminum wheels, both configurations are shown in [Figure 2a](#) and [2b](#).

The vehicle attitude was set by loading the vehicle in a static condition to wheel lip heights. This dimension was allowed to vary as a result of tire section changes with speed and due to the lift being

generated on the vehicle. This allowed the tire section to grow with speed and raise the vehicle by an additional amount, as would take place in an on-road driving condition. Photographs were taken of the vehicle and tires at rest and at speed to measure vehicle attitude changes and changes in the dimensions and shape of the tire. [Figures 3, 4, 5](#) show these photographs. These changes in the shape of the tire were also applied to the CFD geometry by morphing the static scanned surface of the tire.



Figure 2a. Baseline Wheel (aluminum) and tire



Figure 2b. Flush Wheel Cover (aluminum) and tire

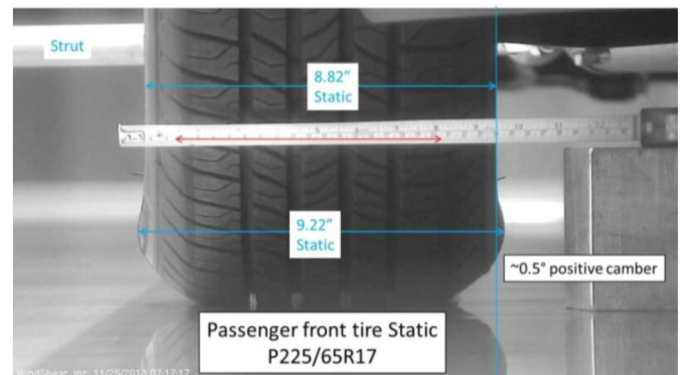


Figure 3a. Front tire tread and profile - loaded vehicle at rest

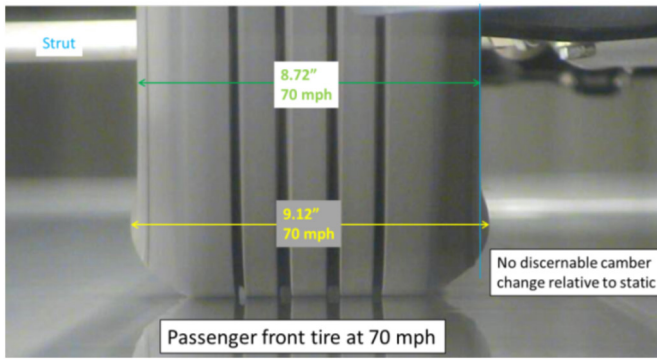


Figure 3b. Front tire tread and profile - loaded vehicle at speed

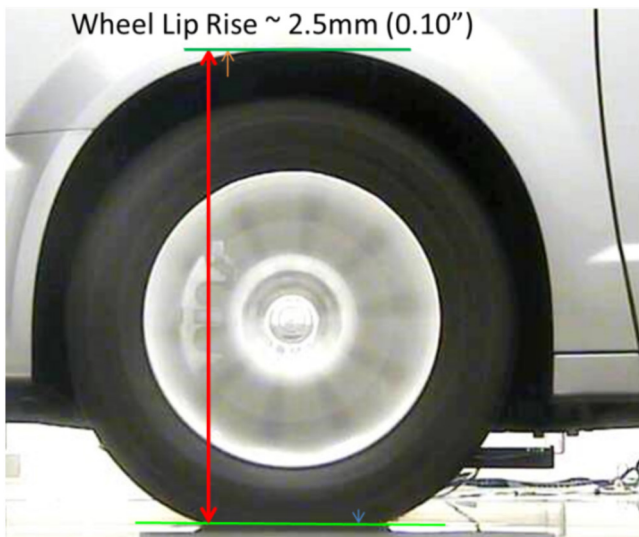


Figure 4. Baseline tire and wheel at speed 31.3 m/s

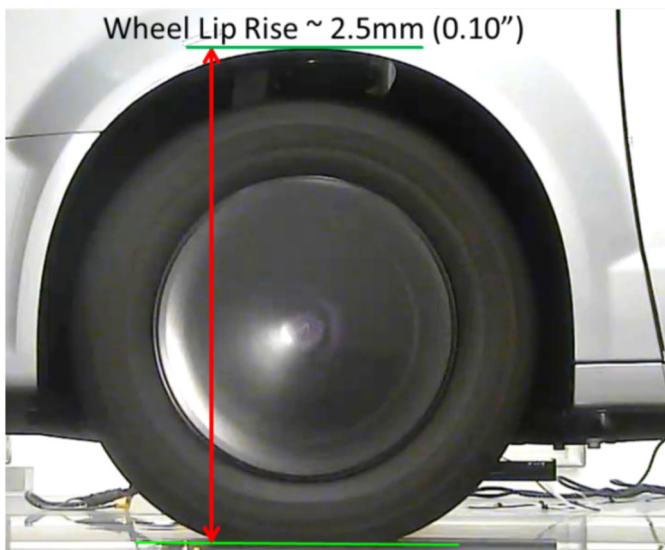


Figure 5. Flush Wheel Cover configuration at speed 31.3 m/s

The static ride heights of the vehicle were set to 758 mm at the front wheel lip and 775 mm at the rear wheel lip. The increase in tire section height both front and rear increased the vehicle set up height by approximately 2.5 mm both at the front and the rear of the vehicle.

No additional vehicle attitude change was detected due to the aerodynamic lift generated on the vehicle body which is quite low especially at 31.3 m/s (70 mph).

The Instrumentation

An Aeroprobe system including an Omniprobe and a two-dimensional traversing system was employed to acquire pressure and three-dimensional velocity data in the Windshear tunnel. The geometry of the Omniprobe is shown in Figure 6. This probe is a 12-hole probe with the ports spaced over the surface of the spherical tip. This design, once calibrated, gives it the ability to measure flows that have angles that measure a total angle change of up to 150° from the axis of the probe.

Figure 6. Omniprobe Geometry (image from www.aeroprobe.com)

The Omniprobe used in this test had the following specifications:

1. Flow speed accuracy of $\pm 3\%$ or 1 m/s, whichever is greater
2. Angular accuracy of $\pm 1.5^\circ$
3. Angular range of 150° (cone angle)
4. Spatial resolution of $\frac{1}{2}$ tip diameter (9.53mm and 6.35mm tips used during testing)
5. Frequency response is <50 Hz (set up for time averaged flow)

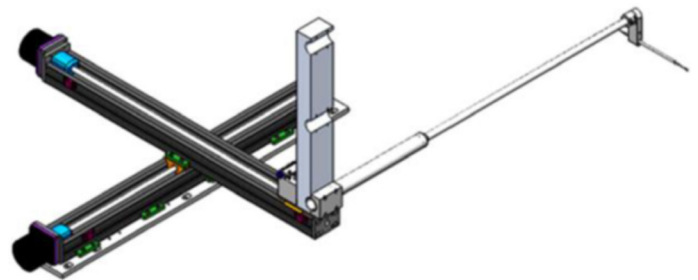


Figure 7. Traversing Mechanism Geometry (courtesy of Aeroprobe Corp.)

The probe was carried by a traversing system also supplied by Aeroprobe. Figures 7 and 8 show the traverser design and the set up in the Windshear wind tunnel.

The Wind Tunnel

The Windshear Rolling Road Wind Tunnel [6] is a semi-open jet test section with low interference effects and minimal static pressure gradient such that a good simulation of the on-road flow conditions can be expected. For the ground boundary condition, it

includes a single stainless steel belt, 3.2 m wide by 9 m long, which covers the entire area underneath the vehicle as well as to the side, fore, and aft of the vehicle. This provides an excellent simulation of the translation of the road underneath the vehicle. This boundary condition was considered by the authors to be a superior simulation of the road relative to the single center belt and small under tire mini-belts of the more commonly used 5-belt moving ground plane simulation. In the classic sense, the boundary layer thickness over the belt is very nearly zero when upstream boundary layer control systems are used in conjunction with the moving belt. [6]

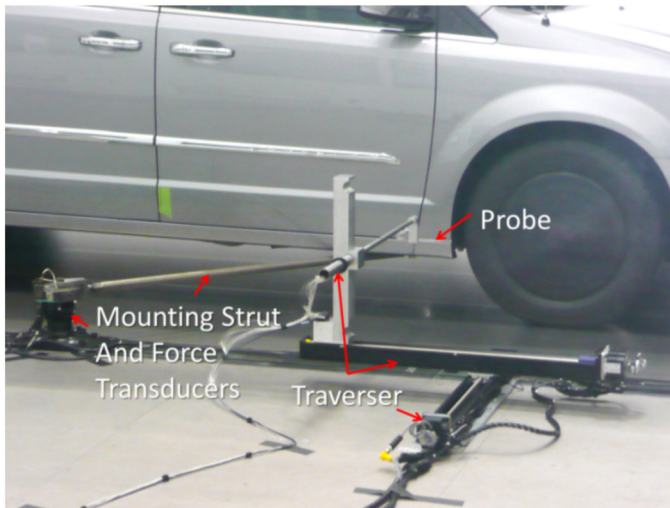


Figure 8. Flush Wheel Cover configuration installed in the Windshear wind tunnel

The only compromises to the boundary conditions around the vehicle are the smoothness of the moving ground surface (smoother than an actual road surface), the inherent interference and blockage effects of the wind tunnel, the open jet shear layer relative to freestream conditions on the open road, and the attachment force measurement system which introduces the two restraint struts into the flow field behind the front tires. Although other attachment options exist, the strut attached to the underbody aft of the front tire was judged to be the best choice for limited flow field interference.

EXPERIMENTAL DATA

Experimental data was collected consisting of full vehicle forces and moments as well as the measurements done with a 12-hole probe to document the flow field around the spinning tire and wheel on the minivan.

Summary of Forces

Table 2 documents the forces and moments generated on the two configurations of the minivan tested during this study. Corrections for blockage and horizontal buoyancy were applied to the measured data, as described in [7]. However, in Table 2 no correction was applied to remove the drag contribution of the mounting struts as the struts are also included in the CFD simulation. (Therefore the overall drag levels reported do not relate to the exact drag level of the production minivan.) The results show the reduction in overall vehicle drag from adding the flush wheel cover, with $\Delta C_D = -0.015$. The flush wheel

cover also increases front and rear lift. It is expected these effects of the flush wheel cover on the vehicle forces occur because blocking the flow through the wheel reduces some flow impingement on the wheel and tire, reducing drag, while also reducing the underbody flow speed and increasing the underbody pressure. These effects are explored further in the sections below.

Table 2. Aerodynamic Forces from Experimental Measurements

Configuration	C_D	C_L	C_{LF}	C_{LR}
Aluminum Wheels	0.336	-0.005	-0.014	0.010
Flush Wheel Covers	0.321	0.058	0.018	0.040
Delta	-0.015	+0.062	+0.032	+0.030

Sampling Planes and Probe Measurements

Data from the 12-hole probe was collected on four sampling planes as illustrated in Figures 9, 10, 11, 12. These were located to collect as much data as possible in the areas of the flow around the spinning wheels that are relevant for determining how well the CFD solution is replicating the critical flows.

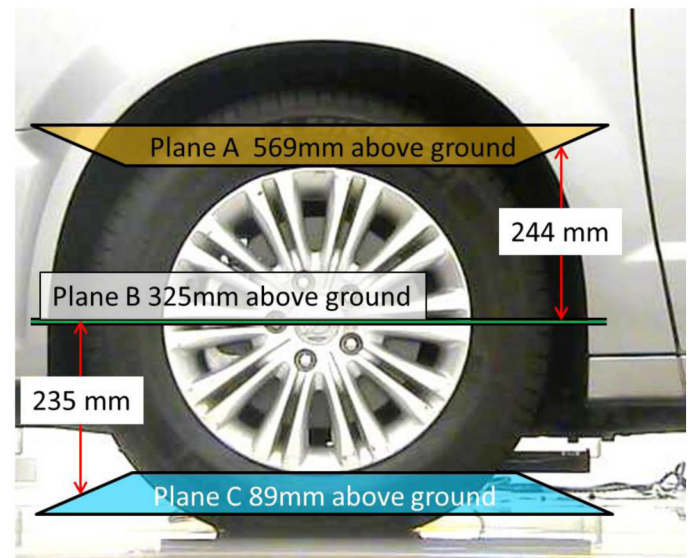


Figure 9. Three Constant Z planes

At each of the point locations, the 12 static pressures on the probe tip were sampled along with a static reference pressure, the local temperature and a reference dynamic pressure. The reference dynamic pressure was measured by a Pitot-static probe inserted into the flow at the nozzle exit plane. The reference static pressure was also taken from this probe, but was used only for the (very small) compressibility corrections to the measured probe data. Although the flow field was influenced by the vehicle at this position, it nevertheless provided an adequate means of scaling the volume flux in the CFD solutions to the wind tunnel measurements without resorting to detailed modeling of the contraction and nozzle. In addition to this reference measurement, several grid points closer to the vehicle but outside regions of viscous losses were also selected for this purpose.

Z-Plane Datapoints

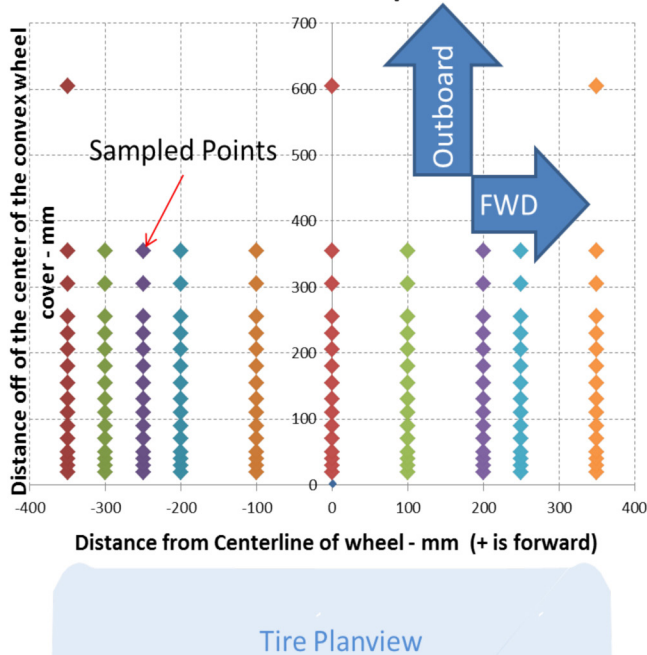


Figure 10. Data Points on Each Z Plane

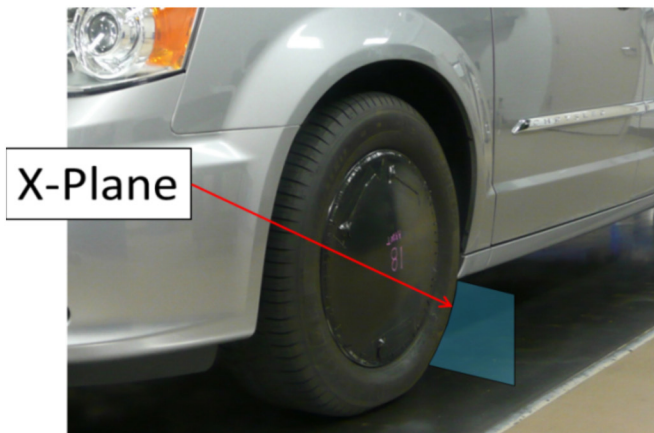


Figure 11. The X Constant X Sampling plane (also behind rear tire)

X-Plane Datapoints

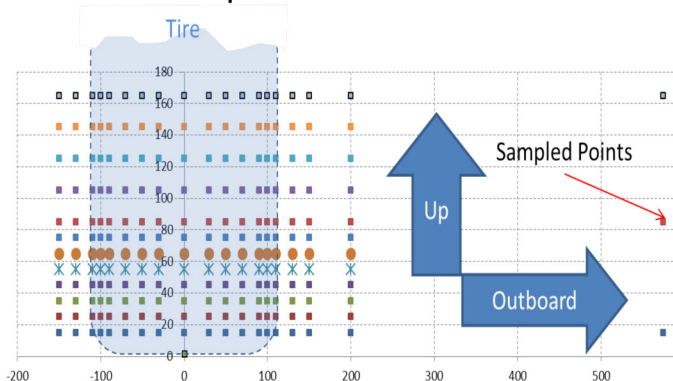


Figure 12. The X Plane Data points

The probe data were reduced into parameters through the probe calibration. The following parameters were produced and graphed on the Z and X planes:

- Velocity magnitude - V_{mag}
- X component of velocity - u , or V_x
- Y component of velocity - v , or V_y
- Z component of velocity - w , or V_z
- Velocity Magnitude Mach Number - Mach
- Air Density - Density (kg/m^3)
- Static Pressure - P_o (Pa)
- Pressure - P_s (Pa)
- Temperature T_o - ($^{\circ}\text{C}$)
- Temperature T_s - ($^{\circ}\text{C}$)
- Cone angle (deg)
- Roll (deg)
- Pitch (deg)
- Yaw (deg)

Experimental Results for Velocity on Z-Aligned and X-Aligned Planes

In this paper, the reduced experimental data for X-, Y- and Z-velocity from the 12-hole probe are shown in five measurement planes (see [Figures 13, 14, 15, 16, 17](#)). On the front wheel, three Z-aligned and one X-aligned planes are shown for both the aluminum wheel and wheel with flush wheel cover. On the rear wheel, data is shown only for one X-aligned plane for the test with flush wheel cover. The velocity components are shown graphically using both in-plane vectors and colored contours to provide insight into the flow structure around the wheel and tire.

High Z-Aligned Plane on the Front Wheel

The velocity data on the front wheel for the high Z-aligned plane at $Z = 569$ mm above the floor is shown in [Figure 13](#). Results are shown for both the aluminum wheel ([Figure 13a](#)) and flush wheel cover ([Figure 13b](#)). The location and extent of this plane relative to the model are shown in the figure. The vector results show the X-velocity deficit near the tire representing a thick shear layer exiting the body surface at the wheel opening and passing by the top of the rotating tire. At the top of the tire the surface is rotating forward at a speed equal to the freestream flow speed ($V_x = -31.3$ m/s), creating a large velocity gradient which contributes to the thick shear layer and has a flow reversal in the tire boundary layer. The measured X-velocity values at $Z = 569$ mm show a minimum value of zero since the closest point is too far from the tire surface to show the flow reversal.

The shear layer grows rapidly in the downstream direction over the surface of the tire. The lateral flow effect of both the overall vehicle aerodynamics and the rotating tire are shown in the Y-velocity contours, with Y-velocity shown on a scale from -5 to $+5$ m/s, with “positive” lateral velocity being defined as moving away from the vehicle centerline. The lateral velocity shows outflow of about 5 m/s

on the front half of the tire and wheel opening, due to the lateral acceleration of the flow passing around the vehicle. As the flow passes the tire, it turns downstream. Close to the tire a small region of inflow is induced with a lateral velocity of -5 m/s due to flow attachment to the tire surface and flow into the wheel house behind the tire. The vertical flow shows the upwash/downwash of the flow around the tire. Away from the tire the vertical velocity is near zero for this plane. In the region of inflow mentioned above a downwash is also induced with vertical velocity of about -5 m/s as the flow attaches to the tire and travels into the wheel house.

The effect of the wheel rim geometry and wheel spoke rotation can be deduced by comparing the aluminum wheel results to the results with flush wheel cover. The effects noted above are similar with the flush wheel cover, except that the shear layer thickness is reduced, as can be seen in the vector plots and velocity contours. This suggests that the motion of the wheel rim creates some of the turbulent flow losses in the shear layer separating from the front fender, increasing the shear layer thickness in the time-averaged flow. The inflow and downwash into the wheel arch remains but occurs in a narrower layer.

Mid Z-Aligned Plane on the Front Wheel

Next, the velocity data on the front wheel is shown in [Figure 14](#) for the mid Z-aligned plane at $Z = 325$ mm above the floor. In this figure the effect of wheel rotation on the nearby flow field can be seen. The X-velocity contours show acceleration of the flow up to about 35 m/s around the side of the vehicle, with the highest velocity near the wheel, while the Y-velocity contours show that some flow into the wheel is occurring with a Y-velocity of about -2 m/s immediately near the wheel rim. On the front half of the wheel, the wheel rim induces a slight downwash due to rim rotation with Z-velocity equal about -1 m/s, and on the rear half a slight upwash with Z-velocity equal about $+1$ m/s. The overall acceleration of the flow and inward flow direction is accompanied by an overall upwash in the flow in this plane as a result of the flow through the wheel. These effects are more evident when comparing with the flush wheel cover case.

For the flush wheel cover the situation is different. The flow separation and shear layer remain attached to the tire and wheel cover surface. There is no inflow or outflow induced by the wheel so the Y-velocity is more neutral compared to the aluminum wheel case. Further, the flow further from the wheel does not show the trend of increased X- and Z-velocity shown in the aluminum wheel case, but the flow field looks more similar to the high Z-aligned plane described in the previous section. Inside the separated shear layer near the wheel cover, the cover rotation and flow separation induces a general downwash of about $Z = -2$ m/s in the shear layer.

Low Z-Aligned Plane on the Front Wheel

The velocity data on the front wheel is shown in [Figure 15](#) for the Z-aligned plane nearest the ground at $Z = 89$ mm height. At this plane the velocity vectors show a large separation occurring on the tire

surface near $X = 0$ m on the plot (which is the X location of the front axle). The separation induces a strong outward flow outside the shear layer with Y-velocity equal about 5 m/s, accompanied by an upwash with Z-velocity equal about 5 m/s. Inside the shear layer, the X- and Y-velocity are both reduced to about zero while the Z-velocity shows a downwash of about -4 m/s behind the tire. In general the flow around the bottom of the tire is moving at high speed and turning around the tire, but it cannot remain attached to the surface and so creates a separated flow near the tire.

The flush wheel cover changes the flow near the bottom of the tire, inducing a more parallel flow to the wheel in general and reducing the obstacle to the flow caused by the rotating wheel rim. The flow remains more attached and does not show the shear layer present with the aluminum wheel. The Z-velocity shows that with the flush wheel cover there remains some upward flow in the front section of the bottom of the tire, and some downward flow on the rear section, as the flow near the ground moves upward and outward to around the tire, stays attached on the tire surface, and then moves back down and inward on the rear surface of the tire.

X-Aligned Plane on the Front Wheel

The velocity field in a cross-sectional X-plane behind the wheel is shown in [Figure 16](#), for both the aluminum wheel and wheel with flush wheel cover. In this plane the high speed flow in the underbody near the ground is exiting laterally behind the wheel with positive Y-velocity of about 7 m/s and an X-velocity of about 30 m/s. This flow encounters the wheel wake and creates a vortex system which can be seen in the vector plot. The vertical velocity shows a slight upwash around $y = 0$ mm on the plot, and outward of this location shows a strong downwash to form a vortex.

The general features of the flow in this plane are similar with the flush wheel cover, but the reduced flow separation at the bottom of the tire (described in the previous section) reduces the size and strength of the vortex near the outside of the tire.

To summarize the effects of the wheel cover on the front wheel shown in all four planes, the wheel cover:

- Reduces the shear layer thickness and velocity changes near the top and bottom of the wheel rim
- Blocks the flow entering the wheel and the associated turning of the flow further from the tire that occurs with the aluminum wheel
- Has an attached shear layer on the middle Z-plane. Since the flow does not go into the wheel, an attached shear layer is present on the middle Z-plane near the wheel axle, which is not found in the aluminum wheel case due to flow entering the wheel.
- Reduces the vortex size at the base of the tire.