

# Further Investigations on the Flow Around a Rotating, Isolated Wheel with Detailed Tread Pattern

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## ABSTRACT

Efforts in aerodynamic optimization of road vehicles have been steadily increasing in recent years, mainly focusing on the reduction of aerodynamic drag. Of a car's total drag, wheels and wheel houses account for approx. 25 percent. Consequently, the flow around automotive wheels has lately been investigated intensively.

Previously, the authors studied a treaded, deformable, isolated full-scale tire rotating in contact with the ground in the wind tunnel and using the Lattice-Boltzmann solver Exa PowerFLOW. It was shown that applying a common numerical setup, with velocity boundary condition prescribed on the tread, significant errors were introduced in the simulation. The contact patch separation was exaggerated and the flow field from wind tunnel measurements could not be reproduced.

This investigation carries on the work by examining sensitivities and new approaches in the setup. A new validation case, which has the wheel rotating with small ground clearance, is tested both numerically and experimentally. Thus, the effect of tread rotation can be investigated separately from the effect of a deformed contact patch. In the simulation this is achieved by including the whole wheel in a sliding mesh region. For the wind tunnel a new motor-driven support sting was built to enable wheel rotation without ground contact. In order to validate the test case, flow field measurements are captured in the wind tunnel using a twelve-hole probe. Moreover, the treaded tire is compared to a smooth tire of the same outer contour in order to evaluate the tread's influence on the flow field.

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## INTRODUCTION

### Motivation

In recent years the automotive industry's efforts to maximize the efficiency of road vehicles have been increasing steadily. There are two major reasons driving this development. First, regulatory institutions lower the limits for CO<sub>2</sub> emissions globally. And second, extending the range of new electric vehicle concepts is still one of the key challenges in establishing wide acceptance of electric mobility. Both targets call for a minimization of all driving resistances. At velocities higher than 70 km/h aerodynamic drag becomes the dominant force. According to Wickern et al. [1] wheels and wheel houses account for approximately 25 percent of a car's total drag. Considering the comparatively small geometric dimensions, this is a large share. Consequently, wheel aerodynamics is a field that has received a lot of attention in academic and industrial research over the last two decades.

Besides the influence of wheel designs, the research project, that this study is part of, aims at understanding the complex flow mechanisms around tires as well. Especially the use of computational fluid dynamics (CFD) to assess wheel and tire aerodynamics is a challenging task due to the complexity of the boundary conditions. The rotation of a tire including a tread pattern and a deformed contact patch at the same time would call for a coupled simulation of CFD and finite element analysis (FEA) solvers. But although this is possible in principle, it exceeds today's acceptable computational cost for an industrial application.

CFD solvers have to prove their ability to compute the flow around simplified cases like an isolated wheel before tire aerodynamics can be investigated reliably in the complex case of a full vehicle simulation. In order to enable the numerical simulation to deliver accurate results the influence of parameters like tire load and camber

angle has to be clarified. Furthermore, understanding fundamental flow mechanisms at an isolated wheel will help to implement tire rotation efficiently in future simulations.

## Literature Review

Over the last 40 years many researchers have carried out investigations in the field of wheel aerodynamics. In this section only the most relevant publications for this isolated wheel study are introduced. Fackrell and Harvey [2, 3] were the first ones to investigate an isolated, rotating wheel in contact with moving ground experimentally. They discovered the so-called jetting phenomenon in front of a smooth tire. It describes two outward facing lateral jets that are caused by high static pressure in the region where tire surface and moving ground converge. Moreover, it was shown that longitudinal grooves reduced this pressure peak by equalizing the pressure in front of and behind the contact patch. Cogotti [4] and later Mercker and Berneburg [5] described vortex systems behind isolated wheels. Vortex pairs originating from the upper tire shoulders as well as from the contact patch were identified as the main wake structures. Potthoff and Fiedler [6] compared wake planes behind a treaded and a smooth tire. The treaded tire's wake was found to be narrower at the ground and did not show the side lobes of the smooth tire. Investigations on race car tires with a large width to diameter ratio were carried out by Mears [7], Knowles [8] and Wäschle [9]. They examined the pressure distribution on the tire's surface, support sting interference effects as well as the flow topology using optical measurement technology like particle image velocimetry and laser Doppler anemometry. The ground vortices were observed to be dominant, eventually consuming the upper vortex pair downstream. Saddington et al. [10], Axerio and Iaccarino [11], Issakhanian et al. [12] and Sprot [13] conducted further studies on isolated race car tires analyzing the wake topology and also considering realistic brake cooling systems. Depending on the specific configuration the ground vortex pair was also observed to form in an asymmetrical shape.

This study continues the work of Schnepf et al. [14]. The flow around a deformable, isolated full-scale tire was examined in a single-belt wind tunnel and in the numerical simulation. For the first time a rotating, isolated wheel was exposed to a load of 5000 N thus forming a realistic contact patch. Wake measurements from a twelve-hole probe 20 mm downstream of a smooth 225/55 R17 tire showed a separation originating from the outer side of the contact patch. This was in agreement with the studies mentioned in the previous paragraph. However, behind a tire with additionally laser-carved tread pattern, but same outer contour, this separation was not detected. A possible explanation for this observation was proposed. The longitudinal grooves reduced the pressure peak and thus the jetting in front of the contact patch. Additionally, the rotating lateral grooves entrained some of the flow preventing the separation. However, this theory is yet to be proven. Using the Lattice Boltzmann solver Exa PowerFLOW the separation behavior could not be reproduced. The contact patch separation was exaggerated and the wake's shape was similar to the one of the smooth tire. One major reason was that the velocity boundary condition prescribed on the tread was not suitable for rotating treads. The idea to rotate a tire in a

small distance to the ground in order to compare it to sliding mesh simulations was concluded at the end of the study and has motivated the new experiments presented in this paper.

## Outline

The academic test case of a full-scale isolated wheel, equipped with a deformable tire, is investigated in the wind tunnel (WT) and by numerical simulation. The influence of the tread pattern is evaluated by comparison to a smooth tire featuring the same outer contour.

The flow field is captured in one plane behind the tire and one on the outer side using a twelve-hole probe. Using these planes the wake structure and the entrainment behind the tire are assessed. Moreover, the sensitivity of the flow to camber angle and tire load changes is examined. In the numerical simulation the influence of longitudinal grooves and numerical surface roughness on the tire wake is studied.

Eventually, the experiment is also conducted with a gap between the tire and the ground by using a modified, motor-driven support sting. The case of the lifted tire is used for validating numerical simulations which have the whole tire geometry rotating inside a sliding mesh region. In doing so, no physical boundary conditions from the experiment have to be violated in the simulation.

## METHODOLOGY

### Experimental Setup

The WT tests were conducted in BMW Group's AEROLAB. It is a Göttingen type tunnel with a three-quarter open test section, a 14 m<sup>2</sup> nozzle and a single belt rolling road system, 9 m long and 3.2 m wide. A boundary layer scoop together with a suction and tangential blowing system creates a constant velocity profile upstream of the measured object. The WT is described in more detail by Duell et al. [15] and Petz and Charwat [16]. During all measurements wind and moving belt velocity are set to 38.9 m/s (140 km/h).

Two deformable rubber tires of the dimension 225/55 R17 are investigated in this study. The first one is a Goodyear Excellence ROF (run-on-flat) tire with a laser-carved tread. The other one was manufactured in the same mold but has a smooth surface. Both tires share the outer contour as shown in [Figure 1](#) in order to isolate the influence of a detailed tread. A wheel cover made from hard foam exactly fills the volume between the spokes and creates a planar surface on the outside as shown in [Figure 2](#). Thus, ventilation effects of the wheel spokes are eliminated.

The wheels are mounted on two different support stings during the tests. Both of them feature a massive steel frame in order to minimize vibration, bending and torsion throughout the measurements under realistic loads of up to 6000 N. When examining a tire rotating in contact with the ground support sting S1 is used. Its camber angle is smoothly adjustable through a thread at the rear of the support sting. The wheel's elevation is furthermore determined by plates under the foot of the support sting. During a test, both parameters are fixed which leads to additional forces on the load cell due to the two reasons. First, the tire's radial expansion due to the centrifugal

force is prevented under the contact patch. Second, tire warming increases the pressure inside also increasing the force on the load cell. As a direct consequence, lift forces cannot be measured using this setup. Altogether, the effective vertical load on the tire depends on elevation, camber and inflation pressure as well as velocity.

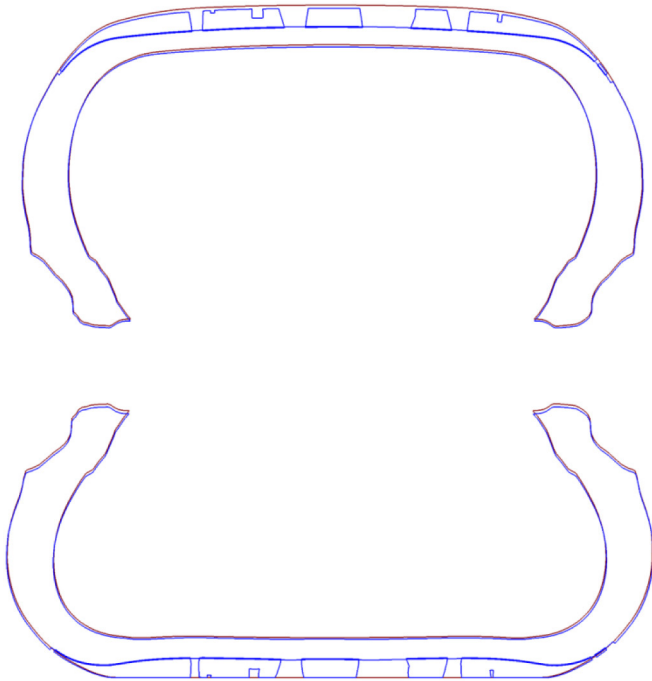


Figure 1. Cross sections (top and bottom) of deformed treaded and smooth tire at 140 km/h and 4800 N vertical load (FEA models).

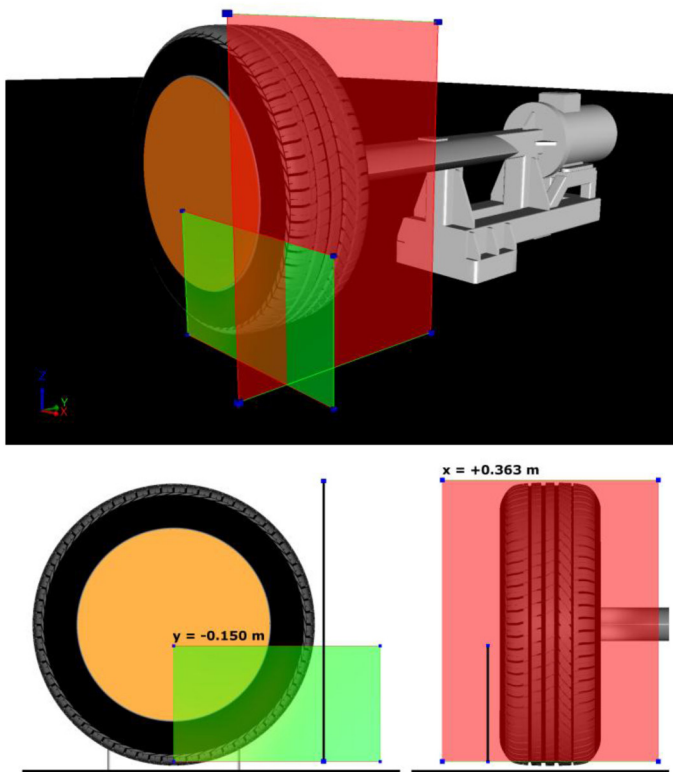


Figure 2. Wheel and motor-driven support sting. Measurement planes at  $y = -0.150$  m and  $x = 0.363$  m.

For the tests with the tire rotating without ground contact, support sting S2 is used as shown in Figure 2. Based on S1, the main differences are the motor driving the wheel rotation and the fixed camber angle of zero degrees. The size of the gap between tire and moving belt is determined by the plates below the support sting's foot. Two different gap sizes of 10 mm and 19 mm are tested. The rotational speed is given by the motor control. Two speeds of 119 rad/s and 114 rad/s are applied in this study.

The wheel is connected to the WT balance through the support sting. Therefore, drag measurements of the support sting alone are subtracted from the measurements of the full configuration including the wheel. Consequently, interference effects between wheel and support sting on drag cannot be separated from the results.

In order to analyze the flow topology around the tire, measurements are taken using an L-shaped Aeroprobe Omniprobe (twelve-hole probe) featuring a 6.35 mm tip diameter. It is able to capture flow angles of up to  $120^\circ$  at an accuracy of  $\pm 1.0^\circ$  and velocities at an accuracy of  $\pm 1.0$  m/s ([17]). Two traverse grids, shown in Figure 2, are examined in this study. Plane X is perpendicular to the main flow direction (x axis) and is located at  $x = 0.363$  m, 20 mm downstream of the tire. It is 0.52 m wide and 0.68 m tall starting 20 mm above the moving belt. Its purpose is to capture the wake structure. The second plane Y is perpendicular to the y axis and is located at  $y = -0.150$  m on the outer side of the wheel. It is 0.50 m wide and 0.28 m tall starting also 20 mm above the moving belt. Plane Y is used to gather more information about the ground vortex and the entrainment at the tire's rear end. Both measurement planes have a grid resolution of 20 mm and probe data is averaged over 3 s at each point.

### Numerical Setup

The numerical simulations in this study were conducted using the commercial software Exa PowerFLOW 5.0. It is based on the Lattice-Boltzmann method which, in contrast to the finite volume method, is derived from the statistical description of microscopic particle dynamics following the kinetic gas theory. It is inherently unsteady and valid for Mach numbers smaller than 0.4 which is true for most applications in the field of automotive aerodynamics. In order to handle the small turbulent scales an RNG-k-epsilon model is employed. Using a cubic voxel grid the boundary layer itself cannot be resolved. Therefore, a wall function following the logarithmic law of the wall and taking into account surface roughness and adverse pressure gradient effects is applied ([18]).

The numerical case contains tire, wheel and support sting but not the WT geometry. The Goodyear Tire and Rubber Company has provided FEA deformed tire models for the simulations which include the tread pattern in full detail. However, in the case of the loaded and thus deformed tire, a problem arises when lateral grooves are to be included. The sliding mesh approach which enables truly rotating geometry would also rotate the deformed contact patch and the intersected part of the ground. Instead, the tangential velocity component has to be prescribed on the static surface. However, static lateral grooves are obstacles that force exaggerated flow separation. Hence, it is not sensible to include the lateral grooves in the setup of a deformed tire.

Leaving a gap of 10 mm between tire and ground removes the contact patch deformation and provides enough space for a sliding mesh interface. Tire and wheel are then included in a cylindrical sliding mesh region with a distance of 5 mm between the interface and any geometry in its proximity. The reference frame, and thus the geometry included, rotates at a speed of 119 rad/s matching the WT conditions. In order to achieve good comparability with the experiment, the lifted FEA tires are deformed by the centrifugal force. A velocity of 38.9 m/s is prescribed at the inlet and ambient pressure at the outlet. The floor is modeled as a sliding wall of the same velocity as the free stream. All other walls bounding the simulation volume are defined as slip boundaries. The turbulent length scale is set to 3 mm and the turbulence intensity to 0.5 %, respectively. A physical time of 1.0 s is simulated which corresponds to 600,000 time steps for the high resolution case. A 4 mm thick offset around tire and wheel contains the finest voxel size of 0.5 mm. This leads to fine equivalent numbers of 100 million voxels and 15 million surfels. One simulation run that has the tire rotating inside the sliding mesh region at this level of resolution consumes 50,000 core hours. All CFD results are presented as an average of the last 0.6 s.

## RESULTS

### Drag With and Without Ground Contact

Measuring the aerodynamic drag of the tires the results listed in Table 1 are obtained. Different tendencies are observed for the cases with ground contact and the ones with a 10 mm gap. In contact with the ground, the drag area of the smooth tire is 0,011 m<sup>2</sup> larger than the one of the treaded tire. Leaving a 10 mm gap, however, the trend is reversed. The drag area of the smooth tire is 0,006 m<sup>2</sup> smaller compared to the treaded one.

Table 1. Drag area values for treaded and smooth tire with and without ground contact.

|                                 | Treaded tire         | Smooth tire          |
|---------------------------------|----------------------|----------------------|
| C <sub>d</sub> A ground contact | 0,064 m <sup>2</sup> | 0,075 m <sup>2</sup> |
| C <sub>d</sub> A 10 mm gap      | 0,074 m <sup>2</sup> | 0,068 m <sup>2</sup> |

### Tire Wake

#### Loaded Tire: Wind Tunnel Results

At first, the wake topology is analyzed in plane X. A couple of characteristic structures can be identified behind the treaded tire in Figure 3. On the outer side, a vortex created around the tire shoulder is observed. In the mid-section a strong downwash fills up the wake limiting the total pressure loss there. In the lower part at z = 0.1 m significant entrainment towards the midplane takes place. Furthermore, a small region of separated flow on the outer side is detected near the ground.

The wake behind the smooth tire in Figure 4 is different in a couple of aspects. Its upper limit lies approximately 100 mm lower than the treaded tire's. The downwash divides the wake in the mid-section distinctly and is stronger than behind the treaded tire. Near the ground the separation originating from the outer side of the contact

patch is significantly larger. This also prevents concentrated entrainment from the outer side from developing as in the case of the treaded tire.

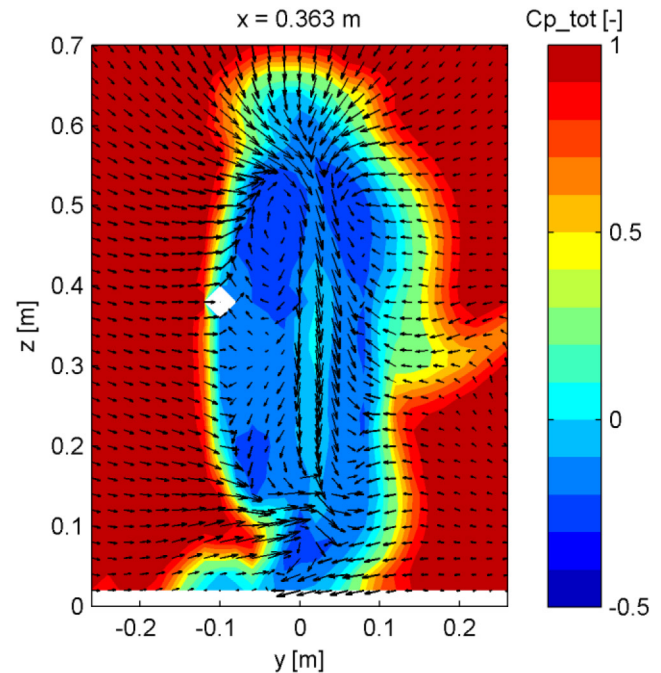


Figure 3. Wake plane at x = 0.363 m. Treaded tire, camber 0.2°, vertical load 5300 N, from experiment.

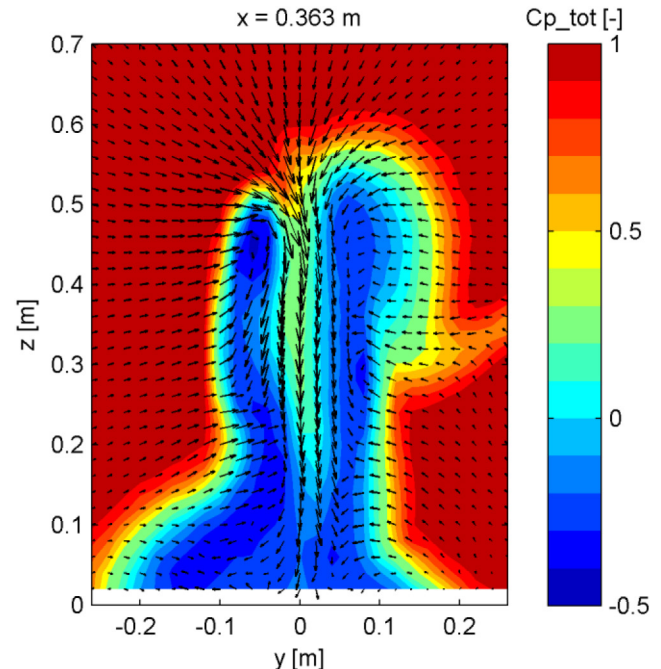


Figure 4. Wake plane at x = 0.363 m. Smooth tire, camber 0.25°, vertical load 5500 N, from experiment.

There is a small discrepancy between the old measurements by Schnepf et al. [14] and the new ones concerning the contact patch separation behind the treaded tire. In order to identify possible reasons, sensitivities of the lower wake to camber and load are investigated. Therefore, only the lower half of plane X is captured. Measurements under similar load but different camber angles show

equal wake structures in Figures 5 and 6. Varying the load, however, has a significant effect on the contact patch separation. In Figures 5, 7 and 8 the trend of lower loads causing larger separations is obtained for a range from 5000 N to 2200 N. Moreover, the entrainment from the outer side is displaced upwards by the separation.

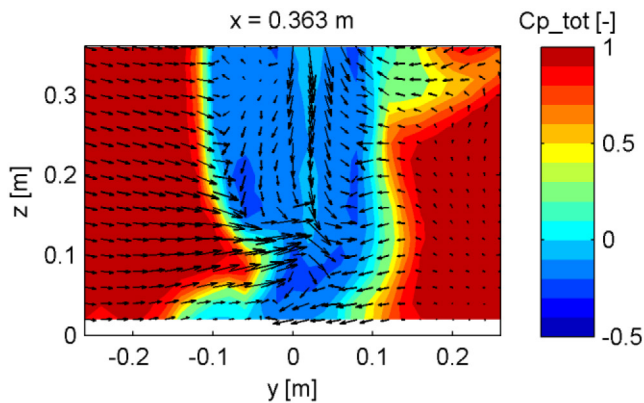


Figure 5. Lower wake structure for treaded tire. Load 5000 N, camber 0.0°, from experiment.

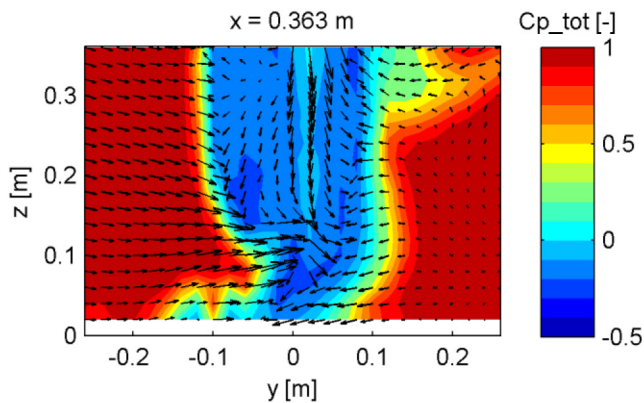


Figure 6. Lower wake structure for treaded tire. Load 4900 N, camber 0.6°, from experiment.

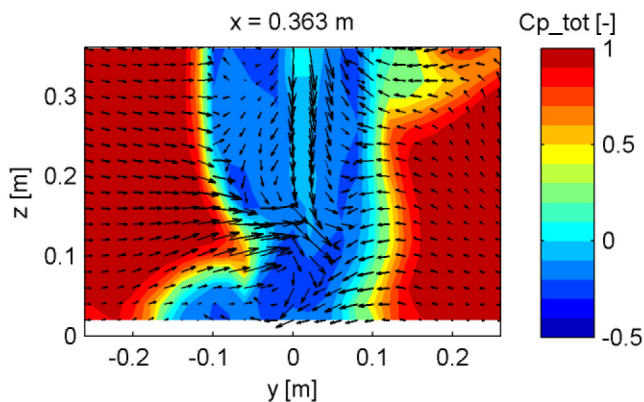


Figure 7. Lower wake structure for treaded tire. Load 3500 N, camber 0.0°, from experiment.

For the smooth tire, however, similar load and camber variations do not have a significant impact on the lower wake structure. The wake planes can be looked up in the [appendix](#).

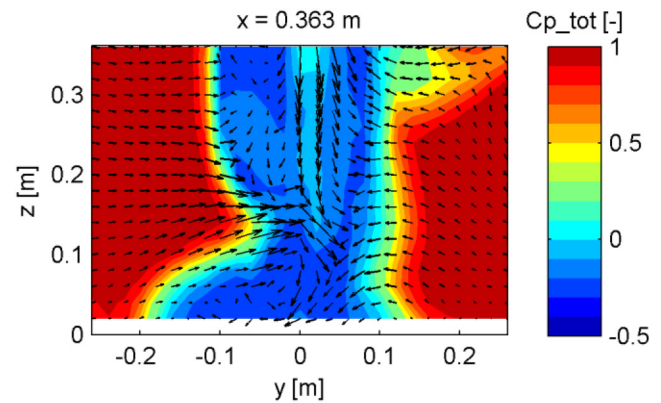


Figure 8. Lower wake structure for treaded tire. Load 2200 N, camber 0.0°, from experiment.

### CFD Results of the Loaded Tire

Three cases of the loaded tire were run in CFD using a tangential velocity boundary condition ("rotating wall"):

1. baseline case with the smooth tire
2. smooth tire with additional longitudinal grooves
3. smooth tire with longitudinal grooves and numerical surface roughness of 2 mm on tread area.

All cases include FEA deformed tires at a load of 4800 N and 0.0° camber. In Figure 9 the baseline case shows separated flow originating from the contact patch that is forced into rotation by the downwash in the mid-section and the entrainment from the outer side at  $z = 0.12$  m.

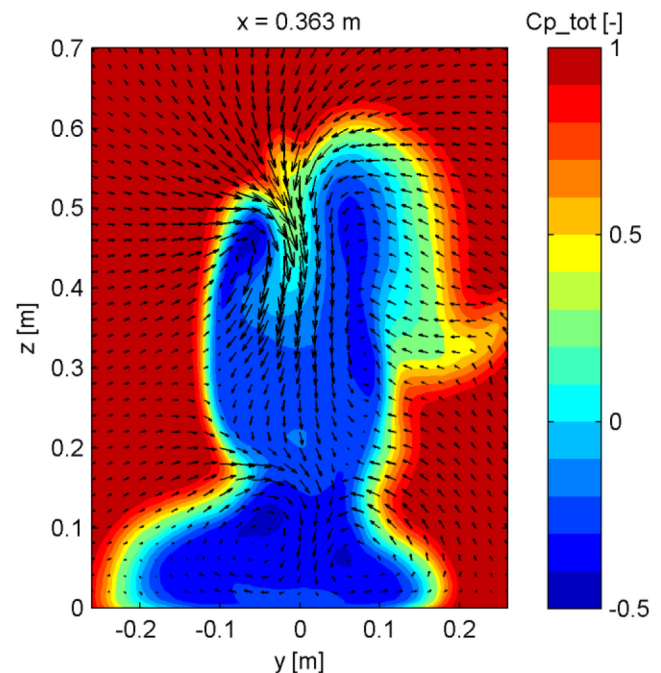


Figure 9. Wake plane at  $x = 0.363$  m. Baseline case with smooth tire. Load 4800 N, camber 0.0°, CFD result.