

Investigation of the Influence of Tyre Geometry on the Aerodynamics of Passenger Cars

Teddy Hobeika
 Chalmers University of Technology

Simone Sebben and Christoffer Landstrom
 Volvo Car Corporation

ABSTRACT

It is well known that wheels are responsible for a significant amount of the total aerodynamic drag of passenger vehicles. Tyres, and mostly rims, have been the subject of research in the automotive industry for the past years, but their effect and interaction with each other and with the car exterior is still not completely understood. This paper focuses on the use of CFD to study the effects of tyre geometry (tyre profile and tyre tread) on road vehicle aerodynamics. Whenever possible, results of the numerical computations are compared with experiments.

More than sixty configurations were simulated. These simulations combined different tyre profiles, treads, rim designs and spoke orientation on two car types: a sedan and a sports wagon. Two tyre geometries were obtained directly from the tyre manufacturer, while a third geometry was obtained from our database and represents a generic tyre which covers different profiles of a given tyre size. All geometries were deformed based on measured wind tunnel data under a defined load and rotating conditions of 100 kph.

Results have shown that the main grooves consistently lead to a decrease of both drag and lift. The edge pattern however, did not show a clear trend for drag and lift with respect to the different configurations studied, although its influence was always more noticeable on the sports wagon. The larger profile of the generic tyre resulted in higher drag and lift values with relation to the tyres obtained from the manufacturer. For a given rim, a drag difference was observed between two tyre geometries with same profile but different tyre tread. These findings lead to the conclusion that tyre profile, as well as tyre pattern, are important to consider. These results were confirmed by wind tunnel tests. In conclusion, the work of aerodynamic optimization of rims cannot be separated from the tyre itself.

CITATION: Hobeika, T., Sebben, S. and Landstrom, C., "Investigation of the Influence of Tyre Geometry on the Aerodynamics of Passenger Cars," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(1):2013, doi:10.4271/2013-01-0955.

INTRODUCTION

For the past years, sustainability and energy efficiency have become a major area of research and development for the automotive industry. With stricter regulations and tax rates being introduced every year on CO₂ emissions and fuel consumption, car manufacturers are pushed into seeking solutions that fulfil legislation requirements and at the same time do not compromise the vehicle performance. Aerodynamics is one of the several fields where such solutions are pursued.

The forces defining the driving resistance of a ground vehicle are summarised in equation (1):

$$F_{drive} = F_{drag} + F_{acceleration} + F_{rolling\ resistance} + F_{gradient} \quad (1)$$

Minimizing the forces in equation (1) is necessary in order to reduce fuel consumption, and aerodynamic drag plays an important role.

Wheels and wheelhouses are shown to contribute to about 25% of the total aerodynamic drag of a vehicle [1]. The wheel rotation creates a wake which interacts with the car exterior as well as with the under body, influencing the drag contribution of both. The effects of wheel rotation and rim design on passenger cars have been the topic of several studies for the past years. References [1,2,3,4,5,6,7,8] are examples of such studies. However, a limited number of publications into the effects of tyre profile and tyre tread are available in the literature. Some contributions to this topic can be seen in the works of Mercker et al. [9], Landström et al. [10], and Sebben and Landström [11].

This paper focuses mainly on the effects of tyre geometry (tyre profile and tyre tread) on the aerodynamic forces of a vehicle. Both numerical computations and wind tunnel tests were conducted, and the results will be compared to each other whenever possible. However, many of the tyre pattern combinations carried out in the CFD study were not possible to physically reproduce in the tunnel. The study combined different configurations involving tyre profile, tyre pattern, rim design, spoke orientation (CFD only) and body type (sedan and sports wagon). The aim was to understand the drag contribution of different tyre features and decide which details are needed to take into consideration when performing CFD analysis. All numerical and experimental results reported in this paper are for moving ground and rotating wheel conditions.

METHODOLOGY

Both numerical simulations and wind tunnel tests were conducted in this work. Only a brief description of the procedures used will be given in this paper.

Numerical Setup

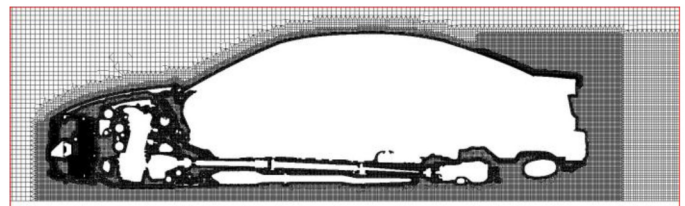
The numerical work followed to a large extent the numerical procedure described by Chron  r et al. [13]. The size of the computational domain is 50m $\times$ 10m $\times$ 10m (length $\times$ width $\times$ height). The vehicle is placed in the virtual tunnel so that its front end is positioned at about one third of the tunnel length. Upstream and downstream distances are considered to be large enough to minimize the influence of the computational walls.

Meshing was performed using Harpoon v4.4 with final mesh sizes in the range of 110 to 120 million cells depending on level of detail on the tyres. When necessary, a resolution of 1.25 mm was used on the surface to accurately resolve the tyre pattern. In general, surface resolution over the whole model ranged from 1.25 to 5 mm. This ensured sufficient near wall resolution in order to achieve y^+ values below 300 in most regions of the car. Several refinement regions with maximum cell length ranging from 1.25 to 40 mm were used in the fluid around the vehicle in order to obtain good resolution in important areas. [Figure 1](#) shows two examples of mesh resolutions near the wheels and in the base of the vehicle.

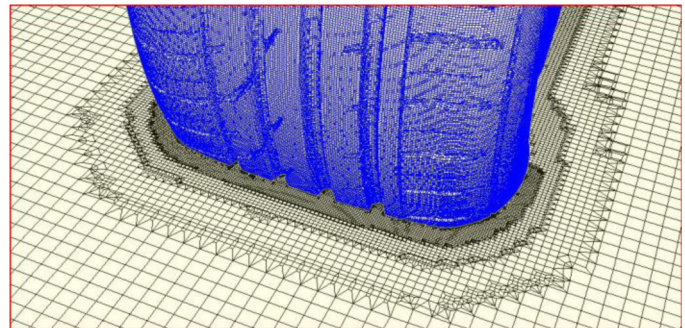
ANSYS Fluent v13x was used as solver. The Realizable k - ϵ turbulence model was used together with second order upwind discretization for the momentum equations, and a coupled pressure-velocity solver. A uniform velocity inlet profile of 100 kph, turbulence intensity of 0.1 percent, and viscosity ratio of 200 was used in all simulations. The side walls of the numerical wind tunnel were set to symmetry boundary condition and a pressure-outlet condition was prescribed on the outlet surface. The solution was considered to be converged when the residuals of all dependent variables had decreased at least 3 orders of magnitude and drag coefficients had stabilized for the last 1000 iterations. Each

simulation ran for 3000 iterations, with drag coefficients oscillating within ± 0.001 .

All simulations presented in this study were performed using steady state RANS. Wheel rotation was modelled using Multiple Reference Frames (MRF) according to the recommendations given in [14]. Although a limitation, the use of MRF is a common practice in CFD since it reduces and simplifies the computational effort. A more realistic approach for the representation of the wheel rotation is the use of sliding meshes. However, this was not an option for the authors due to the large number of configurations investigated. In addition, some preliminary studies using MRF on the effect on drag and lift of different tyres had shown reasonable agreement with experiments.



(a)



(b)

Figure 1. (a) A clip of the mesh at $y=0$, and (b) The surface mesh of the tyre and the mesh expansion into the fluid.

Experimental Setup

Wind tunnel experiments were carried out in the Volvo Car Aerodynamic Wind Tunnel. The wind tunnel is of G  ttingen type with a slotted wall test section. A 5-belt moving ground system along with boundary layer scoop, suction and tangential blowing are installed in the test section. A detailed description of the wind tunnel can be found in the presentation by Stern  s et al. [12].

[Figure 2](#) show the test car installed in the wind tunnel along with two examples of rim configurations that were investigated. The test car was supported on struts keeping the car at a fixed ride height throughout the test. All aerodynamic forces are measured by a six component balance located below the turn table. The uncertainty level between two configurations during the same test occasion has been

statistically established to $\Delta C_D \leq 0.001$, $\Delta C_{LF} \leq 0.001$, and $\Delta C_{LR} \leq 0.005$.

Unfortunately the test object in the wind tunnel and numerical model used in the computations are not exactly the same. The main difference between them is in the different powertrains. It was not possible at the time of this investigation to find a test object which matched the available CFD model. However, since the focus of this investigation is the effect on delta Cd of different tyre geometry properties, it is believed and assumed that powertrain differences do not affect our conclusions.



Figure 2. Test object in the wind tunnel (left) and two of the rims investigated (right): Oden (top), and Flat (bottom).

CONFIGURATIONS

Two vehicle types were considered in the numerical work: the Volvo S60 and the Volvo V60. Experimental results, however, were only performed in the S60, due to time constraints.

More than sixty configurations were simulated in CFD. These simulations combined different tyre deformation techniques, different tyre profiles and pattern, in addition to rim designs and spoke orientation. Two tyre geometries were obtained directly from the tyre manufacturer, while a third geometry was obtained from our database and represents a generic tyre which covers different profiles of a given tyre size. An overview of these configurations is presented in this section.

Tyre Deformation

The tyre deformation under the weight of the car and due to the rotation of the wheels needs to be replicated in the numerical model. Previous work by Sebben and Mlinaric [14], and Landström et al. [10] have described and measured the deformations of the tyre due to centrifugal forces from wheel rotation. The applied deformation also preserved the contact patch measured on a real tyre at stationary position. It is not possible for the authors to measure changes in contact patch area due to wheel rotation during the course of wind

tunnel tests. The main difference between the two types of deformations investigated was the preservation, or not, of the tyre main grooves at the ground plane.

Figure 3 shows the contact patch area when deformations 1 and 2 are applied. Preserving the main grooves as in Figure 3 (b) is a more realistic deformation of the tyre.

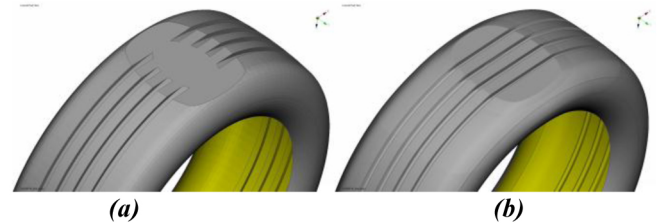


Figure 3. View of the tyre main grooves at contact patch: (a) Deformation 1, grooves are interrupted at ground, and (b) Deformation 2, grooves are connected at ground.

Tyre Profile

The tyre profile referred to in this paper is the inflated section drawing of the tyre (see Figure 4). The two CAD tyres obtained from the manufactures are hereafter referred to as Tyre 1 (T1) and Tyre 2 (T2), while the tyre obtained from our database is referred to as Generic Tyre (G), and it is more “balloon” shaped. Figure 4 shows the difference between the T1 and G profiles investigated. Tyre 1 and 2 have very similar profiles except for a very small side groove.

Note that the main grooves were manually created in the Generic Tyre and have a more “rectangular” shape. Most of the results reported in this paper involve Tyre 1.

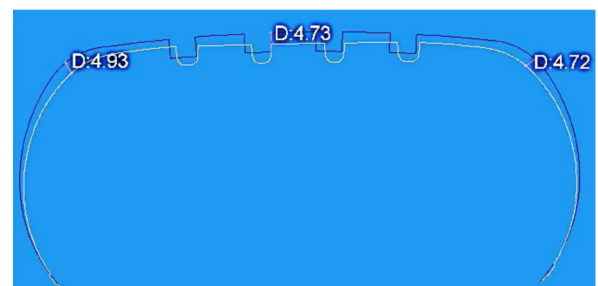


Figure 4. Tyre profiles investigated: Generic Tyre (dark blue contour) and Tyre 1 (white contour). Distances in mm.

Tyre Pattern

Three main pattern features were identified for this study, namely: main grooves, side grooves and edge pattern. A total of eight combinations were evaluated with these features for T1. The pattern features are shown in Figure 5, each separately on a slick tyre. The features investigated are highlighted with a darker colour.