

Aerodynamic Effects of Different Tire Models on a Sedan Type Passenger Car

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ABSTRACT

Targets for reducing emissions and improving energy efficiency present the automotive industry with many challenges. Passenger cars are by far the most common means of personal transport in the developed part of the world, and energy consumption related to personal transportation is predicted to increase significantly in the coming decades. Improved aerodynamic performance of passenger cars will be one of many important areas which will occupy engineers and researchers for the foreseeable future.

The significance of wheels and wheel housings is well known today, but the relative importance of the different components has still not been fully investigated. A number of investigations highlighting the importance of proper ground simulation have been published, and recently a number of studies on improved aerodynamic design of the wheel have been presented as well.

This study is an investigation of aerodynamic influences of different tires. Two different tire models were investigated in combination with three different wheel designs using the Volvo Aerodynamic Wind Tunnel; including moving ground and rotating wheels. In addition to force measurements, flow field investigations were also performed using both surface pressure probes and 12-hole pressure probes. The tire sizes investigated in this study were 215/50R17 and 215/55R16. An investigation of changes to the tire geometry for 215/55/R16 tires was also performed using two high speed cameras in the wind tunnel.

Results show that different tire types have a significant effect on not only aerodynamic drag, but also on lift to some extent. Drag differences between 5 - 10 drag counts were measured depending on wheel and vehicle configuration. It was also concluded that the drag difference between tire types was dependent on wheel design. The flow field investigations showed noticeable changes to the front wheel wake structures as well as significant changes in the rear wheel and base wake structures. Investigations of the tire deformations showed changes in wheel lift, as well as radial expansion and axial compression correlating with the observed drag changes.

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INTRODUCTION

Energy efficient mobility is a great challenge to both industrial and academic institutes. The passenger car is the by far most common means of personal transportation in the developed world and the energy consumption related to personal transportation is predicted to increase significantly over the coming decades [1], [2]. Furthermore, the European Union has endorsed targets on reducing green house

emissions by 20 %, as well as improve energy efficiency by 20 %, compared to 1990 levels, by 2020 [3].

This puts major challenges on the automotive community to push development towards ever more energy efficient solutions. It involves numerous fields and will occupy engineers and researchers for the foreseeable future. Focusing on the operation of passenger cars there are still several factors that affect energy consumption. The three largest

contributors are propulsion system efficiency, parasitic drag, and the different forces that need to be balanced by the engine to be able to operate the vehicle under different driving conditions. Propulsion system efficiency, describes how much of the energy available in the fuel is transformed into useful work; and parasitic drag contains all energy consumption not essential for operating the vehicle, for example interior climate control, electrical heating, or in vehicle entertainment systems.

The forces making up the driving resistance are summarised in [Equation 1](#) and consist of aerodynamic drag, inertia-, rolling- and climbing resistance.

$$F_{drive} = \frac{1}{2} \rho U_{\infty}^2 C_D A_p + m \frac{dU}{dt} + mg f_r \cos \alpha + mg \sin \alpha \quad (1)$$

Minimising the forces in [Equation 1](#) is essential in reducing energy consumption; but the relative importance of the different factors in [Equation 1](#) depends very much on the load case considered. Three out of four terms in [Equation 1](#) contain mass, whereas aerodynamic drag contains vehicle size, shape and velocity. When considering a driving cycle such as the New European Driving Cycle (NEDC), which has a low average velocity of only 33 kph and several acceleration sections in it, the relative importance of mass increases compared with aerodynamic drag. For an average passenger car in this test, a reduction in vehicle mass gives approximately twice as large a reduction in fuel consumption compared to an equivalent reduction in aerodynamic drag [4]. On the other hand, when driving at typical highway velocities the relative importance of aerodynamic drag increases significantly and becomes the largest part in [Equation 1](#). Furthermore, as vehicles get lighter, and kinetic energy recovery systems are introduced in vehicles, the relative importance of aerodynamic drag will also increase when considering the NEDC. Consequently, there are good reasons to continue improving the aerodynamic performance of passenger cars in order to continue to reduce the energy consumption.

Wheels and wheel housings have been shown to be important regions for aerodynamic drag, generating up to 25 % of the overall aerodynamic drag [5]. Part of this comes not only from the force on the actual components, but also from interference effects with the general underbody and base wake flows. The effects of the wheels on passenger cars have been studied for several years and the effects of ground simulation is well documented [6], [7], [8], [9], [10]. Recently several investigations have been published focusing on the aerodynamic performance of wheels as well [11], [12], [13], [14]. However, to the author's knowledge, only limited research into the effects of tire tread has been published at this point. Mercker et. al. [15] presented results from wind tunnel measurements on four different tire treads tested with identical wheels, and reported drag changes within 5 drag counts. This was however performed on unloaded tires which ignores the effects of tire deformation during operation.

This paper investigates the aerodynamic effects of different commercially available tire models from different manufacturers. Three different wheel designs were used with both set of tires and experiments were conducted in the Volvo Aerodynamic Wind Tunnel on a full size vehicle. Flow field measurements using 12-hole pressure probes, as well as surface pressure probes were also performed. The goal with the investigation was to identify any differences in both measured aerodynamic forces as well as flow field between the different tires when using fully loaded tires in the wind tunnel.

METHODOLOGY

A full size production sedan type vehicle was investigated in the Volvo Car Aerodynamic Wind Tunnel. [Figure 1](#) shows an overview of the car. The vehicle was installed in the test section using the standard method of struts connected to the balance in combination with the wheel drive units. As a consequence, the vehicle ride height was kept constant for all configurations. The wind tunnel is a closed circuit tunnel with a slotted wall test section. A 5-belt moving ground system from MTS is installed in the test section along with boundary layer scoop, suction and tangential blowing. A detailed description of the wind tunnel can be found in the presentation by Sterneus et. al. [16]. The vehicle base was equipped with 62 surface pressure probes in order to measure the base pressure for each configuration.

A number of flow field measurements were also performed using the wind tunnel traversing system. Two 12-hole pressure probes were used to measure local flow pressures from which the flow properties could be determined. The probe calibrations were performed by the manufacturer, and state an uncertainty of less than 1 % in flow magnitude and 0.5 degrees in flow angles with the pressure system accuracy in the wind tunnel [17]. A PSI 8400 system with a 64 pressure port PSI ESP Pressure Scanner was used for the pressure measurements. In order to maintain a high level of accuracy, the pressure system was calibrated using the automated calibration system available in the wind tunnel. The measurements were performed point by point style but with different grid resolution depending on measurement location to achieve an acceptable compromise between resolution and measurement time.

[Figure 2](#) shows the two probes attached to the traversing unit, in a position 100 mm downstream of the rear bumper. A vertical plane mapping half of the base wake was investigated in this longitudinal position. Furthermore, a smaller vertical plane 500 mm downstream of the front wheel centre was also investigated with the pressure probes.

As a first step for investigating changes and differences in tire geometries an optical study using cameras was also carried out. [Figure 3](#) show the experimental set up for this investigation. The wind tunnel time available only allowed for an investigation of the front right wheel, focusing on one of the wheels with two different tires. Two high speed



Figure 1. Overview of the wind tunnel model with base pressure measurement set up to the right.

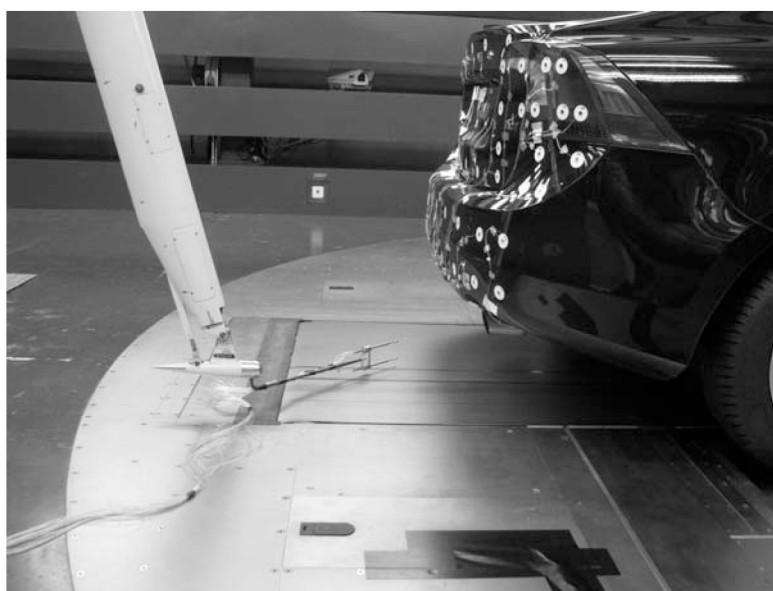


Figure 2. Wake measurement set up with traversing system behind the vehicle.

cameras with a frame rate of 1 kHz were used together with spot lights as shown in [Figure 3](#). This work was performed with technical support from Volvo Cars safety centre that also performed post processing of the raw data. It should also be mentioned that this part of the investigation was performed without wind and only wheel rotation. The effect of the flow on the shape of the tires was however considered insignificant.

CONFIGURATIONS

In total three different wheel designs were investigated with two different tire models. [Figure 4](#) show the three wheels. Each wheel was investigated with two different tire designs, denoted Tire 1 and 2 in this study. Wheel 1 is 16" diameter whereas Wheels 2 and 3 are 17" diameter. The same specified tire width, 215 mm, was used for all configurations with constant wheel offset. However, as will be presented

later in the results section, the measured tire widths were not the same.

Wheel 3 was also investigated using an aluminium cover plate creating a closed wheel, in order to investigate effects of interaction between the wheel and tire. Wheel 3 was also investigated with different tire thread depth and tire pressures. [Table 1](#) gives a summary of all configurations investigated during the primary wind tunnel session. All configurations were run at 140 kph using moving ground and rotating wheels. Configurations 1 to 6 were investigated with both open and closed cooling air inlets. All wheels and tires were also investigated without the front wheel spoilers.



Figure 3. Set up of high speed cameras and spotlights for tire geometry investigation.



Figure 4. Overview of wheel design, denoted Wheel 1- 3 from left to right. Wheel 1 is 16" and Wheels 2 and 3 are 17".

Table 1. Configuration overview.

Conf. No.	Wheel	Tyre	Details
1	1	1	Open/Closed cooling
2	1	2	Open/Closed cooling
3	2	1	Open/Closed cooling
4	2	2	Open/Closed cooling
5	3	1	Open/Closed cooling
6	3	2	Open/Closed cooling
7	3	1	Covered wheels
8	3	2	Covered wheels
9	3	2	- 2mm tyre depth
10	3	1	-0.4 bar
11	3	1	+0.2 bar
12	1	1	Front wheel spoiler off
13	1	2	Front wheel spoiler off
14	2	1	Front wheel spoiler off
15	2	2	Front wheel spoiler off
16	3	1	Front wheel spoiler off
17	3	2	Front wheel spoiler off

The relative importance of the front and rear wheels was also investigated and Table 2 gives a summary of these configurations. These configurations were investigated during a separate supplementary wind tunnel test session. Configurations 1 - 2 and 5 - 6 in Table 1 were also re-run during this wind tunnel session. The pressure measurement equipment had been removed from the vehicle, thus limiting the results from these configurations to only force measurements.

Table 2. Front and rear tire configurations.

Conf. No.	Wheels	Front Tyre	Rear Tyre	Details
18	1	1	2	Open/Closed cooling
19	1	2	1	Open/Closed cooling
20	3	1	2	Open/Closed cooling
21	3	2	1	Open/Closed cooling

Figure 5 shows front views of both tires used in this investigation. As can be seen in Figure 5, there is a noticeable difference in width between the stationary tires on the car. In

this set up, Tire 2 was approximately 5 mm narrower than Tire 1, with slightly more than half the difference on the inner side of the tire (towards the vehicle centre line). The effect on the projected area, and consequently computed drag coefficients, is however still smaller than the measurement uncertainty. However, having a narrower tire is likely to affect the flow field in favour of the smaller tire, as for example shown by Mercker et.al. [15]. A second geometric difference that can be observed is the difference in tire shoulder profile where Tire 2 has a slightly sharper edge between the sidewall and tread. The tire diameter was also measured but no significant difference was observed. The black and white chequered strips in Figure 5 are calibrated stickers used within crash testing that were used as references.

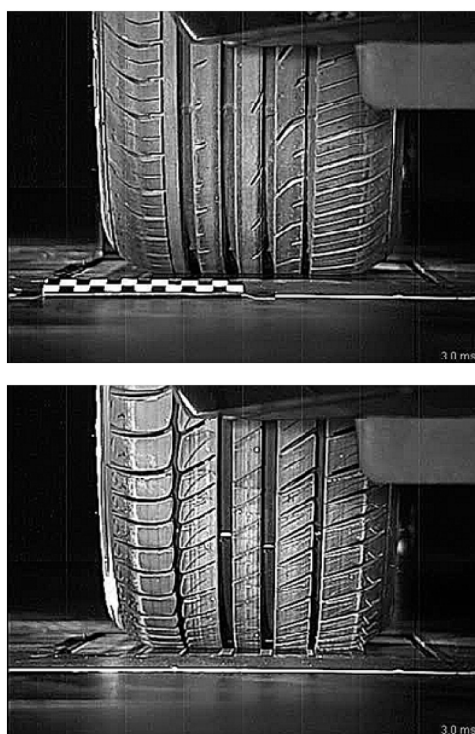


Figure 5. Tire models used in this investigation for the 16" wheel. Top: Tire 1. Bottom: Tire 2. Both tires have the specified dimension 215/55R16.

RESULTS

The results section is in three parts. First the changes in overall aerodynamic drag and lift are discussed. The second section presents the flow field results and relates the observed flow changes with the trends in forces. In the third and final section the results from the geometric investigation are presented.

AERODYNAMIC FORCES

Table 3 gives a summary of changes in aerodynamic drag and lift for all configurations. It should be noted that in

different tables individual references were used depending on configuration and wind tunnel session. For example, results with closed cooling and configurations without front wheel deflectors are presented with individual references. The changes in drag due to the different tires was found to be fairly large, 7-8 drag counts was observed for Wheels 1 and 2, with Tire 2 giving a drag reduction for all cases. This highlights the importance of the tire design with respect to aerodynamic drag as this difference is comparatively large. Wheel 3 also gave a reduction in favour of Tire 2, but with a slightly smaller difference of approximately 5 drag counts. Consequently, there are also aerodynamic interactions between the wheel and the tire. Furthermore, it is interesting to note that the smallest difference measured between the tires in this investigation is of the same magnitude as the largest difference reported by Mercker et. al. [15]. This shows that creating an on road contact patch and sidewall deformation has a significant effect on the aerodynamic performance of the tires.

Lift also showed variations due to the tire design, especially Wheel 3, which experienced a large change in front axle lift. Rear axle lift showed only small variations for all wheels. It should also be mentioned that all configurations in Table 3 and 4 were re-run in different wind tunnel sessions with correlating results.

The first six configurations were also investigated with the cooling air inlets covered using adhesive tape. Drag and lift changes for these configurations are presented in Table 4. The drag difference generally increased for all wheel designs. Also lift increased with closed cooling inlets, especially for front wheel lift which is a result of the strong influence of cooling air flow on front axle lift.

Removing the front wheel spoiler has a slight effect on the measured drag differences between different tires. Tables 5a and 5b gives a summary of these force changes for the different wheel and tire combinations. It should be noted that the open and closed cooling values are presented with separate references. Small changes were observed for drag with changes within 2 drag counts. More interestingly, Wheel 1 and 2 experienced minor reductions in deltas whereas Wheel 3 experiences a slightly larger increase in delta value. The changes to both drag and lift was not surprising as the front wheel deflector has a large influence on the flow condition into the wheel housing, and by removing the deflector a larger region of the tire is exposed to the oncoming underbody flow; and more high momentum flow also enters the front wheel housing. This of course also affects the interactions with the rear underbody, and rear wheels, which results in changes in both front and rear axle lift.

This work focused on zero yaw configurations at 140 kph, but it should also be mentioned that different test velocities as well as varying yaw angles were used. The general observations from these additional measurements were that increasing speed tends to increase the drag deltas slightly between the two tires whereas increasing yaw angles reduces