

Investigation of Wheel Ventilation-Drag using a Modular Wheel Design Concept

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ABSTRACT

Passenger car fuel consumption is a constant concern for automotive companies and the contribution to fuel consumption from aerodynamics is well known. Several studies have been published on the aerodynamics of wheels. One area of wheel aerodynamics discussed in some of these earlier works is the so-called ventilation resistance.

This study investigates ventilation resistance on a number of 17 inch rims, in the Volvo Cars Aerodynamic Wind Tunnel. The ventilation resistance was measured using a custom-built suspension with a tractive force measurement system installed in the Wheel Drive Units (WDUs). The study aims at identifying wheel design factors that have significant effect on the ventilation resistance for the investigated wheel size.

The results show that it was possible to measure similar power requirements to rotate the wheels as was found in previous works. The magnitude of the measured ventilation resistance confirms the conclusion that this effect should be taken into account when designing a wheel.

It was found that some of the rim design factors have greater influences on the ventilation resistance than others. It was also shown that one of the investigated rims had lower ventilation resistance than measured for the fully-covered wheel configuration.

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INTRODUCTION

With constantly growing fuel prices and toughening of environmental legislation, the vehicle industry is struggling to reduce fuel consumption and decrease emission levels for the new and existing vehicles. One of the ways to achieve this goal is to improve aerodynamic performance by decreasing aerodynamic resistance. This paper presents a summary and analysis of the results obtained during the thesis work performed at Volvo Car Corporation, see Bonitz [1] for more information.

There are different areas of the vehicle that are known to be of great importance for aerodynamic drag; in this paper the

area of wheelhouse will be discussed. Rotating wheels together with the wheelhouses can produce up to 35% of the total aerodynamic drag [2], [3]. Furthermore, there are power losses associated with the resistance moments acting on the wheels; originating from the relative movement of the wheels in the air. In order to better understand those losses a closer look at forces acting on the rotating wheel is required.

In [Figure 1](#) moments acting on the rotating wheel around the rotation axis and forces resulting in such movements can be found. T is the torque applied from the gearbox through the driveshaft; it is counteracted by a number of moments and forces.

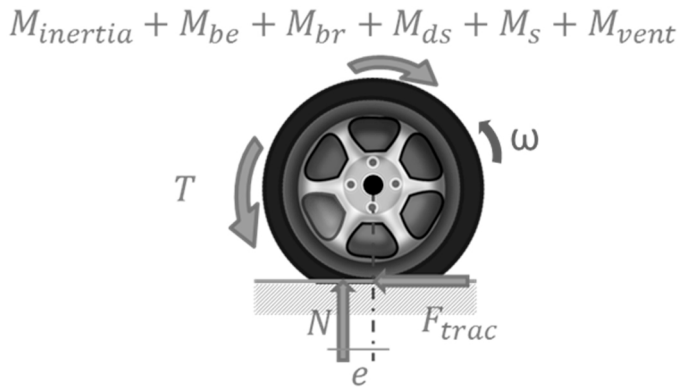


Figure 1. Moments acting in the direction of wheel rotation and forces resulting in such moments

Firstly, there is a resistance moment $N \cdot e$ produced due to uneven distribution of load in the contact patch of the tyre. Secondly, different resistance moments exist due to inertia of the wheel, shaft and gearbox $M_{inertia}$, and due to frictional losses in bearings M_{be} , brakes M_{br} and driveshaft M_{ds} . Thirdly, one can identify resistance moment M_s occurring due to relative slip between the tyre and ground surface in the contact patch. Fourthly, there is a moment produced by tractive force F_{trac} acting in the contact patch, this force also includes rolling resistance force. The last moment M_{vent} is called ventilation moment and it occurs due to the wheel rotation in the airflow.

This resistance moment was previously investigated both experimentally [3], [4] and using CFD simulations [5]. In this paper ventilation resistance is considered to be a result of three effects acting simultaneously:

- the uneven normal pressure distribution around the tyre;
- the surface friction between the air and the wheel;
- the fan-blade effect, which produces air rotation and creates pressure differences on the wheel rim blades

If considering aerodynamic resistance of a vehicle in general, one should take into account both aerodynamic drag force and ventilation resistance [4]. This can be achieved by expressing ventilation resistance in terms of drag coefficient C_D and combining aerodynamic $C_{D(AD)}$ with ventilation $C_{D(vent)}$. Ventilation resistance coefficient in this case can be defined similarly to aerodynamic drag coefficient:

$$C_{D(vent)} = \frac{F'_{trac}}{\frac{1}{2} \rho V_{\infty}^2 A} \quad (1)$$

where F'_{trac} is a part of traction force that corresponds to ventilation resistance, ρ is air density, V_{∞} is a free stream velocity and A is a reference area.

EXPERIMENTAL SET-UP

The measurement of ventilation resistance cannot be done on an isolated wheel, as ventilation resistance is affected by the airflow inside the wheelhouse; therefore a complete-vehicle test is required.

All measurements were conducted in the Volvo Car Corporation full-scale aerodynamic wind tunnel using a Volvo S60 standard production car as a test vehicle. The test section of the wind tunnel has a cross sectional area of 27 m^2 with slotted wall inserts. An overview of the tunnel and its different systems is shown in Figure 2.

The tunnel is equipped with a five belt moving ground system, installed on a turntable. The system consists of a centre belt running in-between the wheels and four Wheel Drive Units (WDUs) rotating the wheels, see Figure 3. The WDUs are also connected to the wind tunnel balance below the turntable. The measurement balance is used to obtain forces and moments acting on the vehicle.

The vehicle is restrained in position and supported by four struts that are also connected to the balance, and allow to change to the vehicle ride height during the experiment, and to lift it up if required. Figure 4 shows the raised test vehicle held by the struts. In order ensure realistic boundary conditions, the five belt system also includes distributed suction zones and tangential blowing as can be seen in Figure 2.

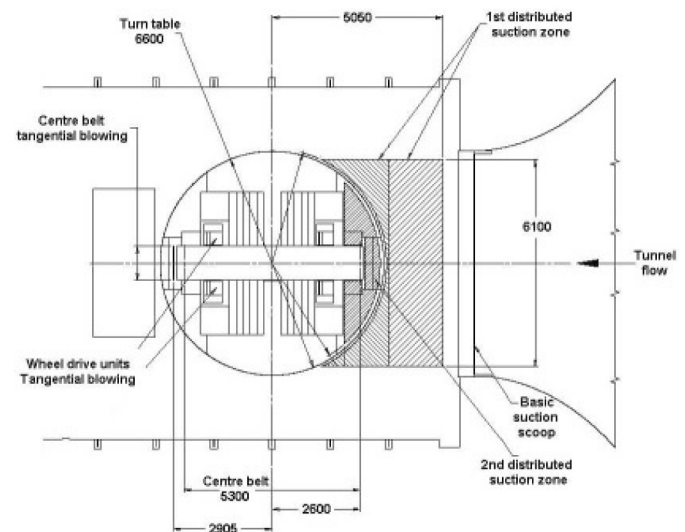


Figure 2. Overview of Volvo wind tunnel section [6]

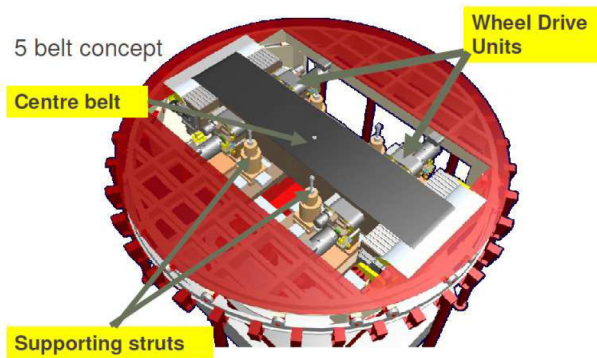


Figure 3. Five belt moving ground system [6]

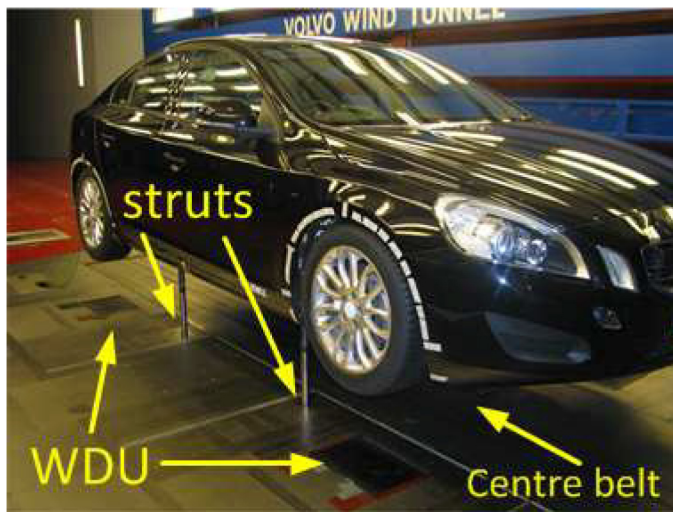


Figure 4. Test vehicle raised using struts

As described earlier, the four vehicle struts and four WDUs are all standing on the balance frame. Thus any force between the vehicle tyre and WDU will be an internal force; therefore it is not measured by the balance. The reason for having this set-up is that it makes rolling resistance an internal force as well, meaning that aerodynamic drag force can be measured directly without compensating for rolling resistance. In order to assess ventilation resistance the moment required to rotate the wheel at operational velocity needs to be calculated. Hence, traction force, i.e. the longitudinal component of the force acting in the contact patch, has to be measured. For that purpose WDUs are equipped with load cells that allow measurement of the tractive force. Knowing the tractive force, the power requirement to rotate the wheel is easily computed.

MINIMIZING VARIOUS LOSSES

In order to separate the power required to overcome ventilation resistance from the power losses due to other resistances, all other sources of losses and resistances acting on the wheel have to be either eliminated or measured.

Minimizing rolling resistance is achieved by using a special suspension set-up. The shock absorbers are removed and replaced with restraint posts, see Figure 5. This makes it possible to control the position of the wheel inside wheelhouse with the aid of a threaded rod. In this case the weight of the vehicle is almost completely supported by the struts of the wind tunnel and therefore rolling resistance is minimized.



a. Front suspension



b. Rear suspension

Figure 5. Modified suspension at front and rear

As the wheels are driven by the WDUs and not by the car's engine, the contact between the wheels and WDUs must be maintained, hence there is always some residual rolling resistance.

When preparing for the test the vehicle is placed on the struts and the ride height is set, then the wheels are lifted up inside wheelhouses using the restraint posts in order to give only a slight contact. To ensure same vertical load on each wheel a simple weight scale is used. The posts are adjusted to have a load of 4 kg per each wheel. The rolling resistance coefficient f_{rr} of 0.008 is assumed; therefore a residual rolling resistance force can be calculated using following equation:

$$F_{rr} = f_{rr}N$$

(2)

