

On the Effects of Wind Tunnel Floor Tangential Blowing on the Aerodynamic Forces of Passenger Vehicles

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ABSTRACT

Many aerodynamic wind tunnels used for testing of ground vehicles have advanced ground simulation systems to account for the relative motion between the ground and the vehicle. One commonly used approach for ground simulation is a five belt system, where moving belts are used, often in conjunction with distributed suction and tangential blowing that reduces the displacement thickness of the boundary layer along the wind tunnel floor. This paper investigates the effects from aft-belt tangential blowing in the Volvo Cars Aerodynamic wind tunnel. First the uniformity of the boundary layer thickness downstream of the blowing slots is examined in the empty tunnel. This is followed by investigations of how the measured performance of different vehicle types in several configurations, typically tested in routine aerodynamic development work, depends on whether the tangential blowing system is active or not. Numerical simulations are also used to explain the flow field origin of the force differences measured in the wind tunnel. Results show that even though the displacement thickness behind the blowers varies along the width of the blowing slots, it is significantly reduced compared to the case of no blowing; furthermore, it is also shown that deactivating the blowing altogether has an effect not only on the absolute forces but also on the deltas measured between different configurations, and that this phenomenon is more prominent if the vehicle has a larger base area.

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INTRODUCTION

In recent years, sustainability and reduced environmental impact has become one of the main focus areas in automotive research and development. One aspect of the environmental friendliness of a vehicle is its fuel consumption, which is influenced by a number of attributes, of which aerodynamics is an important one.

The classical tool for aerodynamic evaluation and optimization is the wind tunnel. In order to properly simulate the correct relative movement between a vehicle and the ground, an automotive wind tunnel should be equipped with a ground simulation system. There are three common methods used in such systems; moving belts, distributed suction, and tangential blowing. These methods are often used in conjunction, for example, in a five belt system. The layout and operation of the ground simulation has a significant impact on the aerodynamic forces measured on the vehicle, as has been well pointed out in the literature. For example, Wiedemann [1] showed that not only the absolute values of drag but also the differences between configurations are affected by the ground simulation technique employed in the tunnel. Furthermore, it was showed that the effects from the ground simulation are not only present for geometry changes to the underbody close to the ground, but also to alterations of the top hat such as adding a rear wing.

Previous studies of tangential blowing in automotive wind tunnels mainly treated tangential blowing as an alternative for distributed suction or a moving belt [2, 3, 4]. The studies concluded that tangential blowing is a good alternative to distributed suction due to a lower impact on the pitch angle of the flow. However, a major shortcoming is that it has to be calibrated to give an optimal displacement thickness at a single longitudinal position downstream of the blowing slot, often at the position of the front wheels. An alternative application of tangential blowing is to use it upstream of a moving belt to refill the momentum deficit of the boundary layer created upstream of the belt, as investigated by Cogotti [5] and Potthoff [6].

A less commonly studied tangential blowing configuration is to extend the apparent length of a moving belt by applying the blowing just downstream of the belt. The present paper investigates such a setup in the Volvo Cars aerodynamic wind tunnel. First, the boundary layer displacement thickness downstream of the tangential blowers is examined for the empty tunnel, followed by a study of the impact from this tangential blowing arrangement on the force deltas measured between aerodynamic configurations on two production

cars. The two configurations showing the largest sensitivity to blowing are then investigated using CFD and the flow field differences leading to the force changes are discussed.

METHODOLOGY

Wind Tunnel

All physical tests presented in this paper were performed in the Volvo Cars Aerodynamic wind tunnel in Gothenburg, Sweden. The tunnel is a slotted wall, closed return (Göttingen) wind tunnel with a test section cross-sectional area of 27.06 m². It was built in the mid 1980s to be fully operational 1986 and was upgraded with a more powerful fan and a five belt boundary layer control system (BLCS) in 2006, as described by Sternéus et al. [7]. The full BLCS consists of a basic suction scoop, two distributed suction zones, five moving belts and five tangential blowers, as outlined in Figure 1.

Four out of the five tangential blowers are mounted behind the wheel drive units (WDU), and one behind the centre belt. Each WDU blower unit consists of a 600 mm wide and 0.6 mm tall blowing slot at the exit of a settling chamber. The centre belt blower is constructed in a similar way, but with a blowing slot that is 1000 mm wide and 1 mm tall. All five blowers are connected to the same compressor, with a valve before each blower unit to allow for tuning of the pressure in each individual settling chamber and thereby the blowing speed and momentum injected into the boundary layer.

The tangential blowers are calibrated to minimize the displacement thickness 800 mm downstream of each blower for every freestream velocity. This location was chosen during the commissioning of the wind tunnel as a reasonable distance for the blower to compensate for the stationary ground between the wheels, as well as allowing the main part of the velocity overshoot behind the blower to flatten out. The freestream velocity dependency is achieved by slaving the fan speed of the compressor driving the blowers to the freestream wind speed.

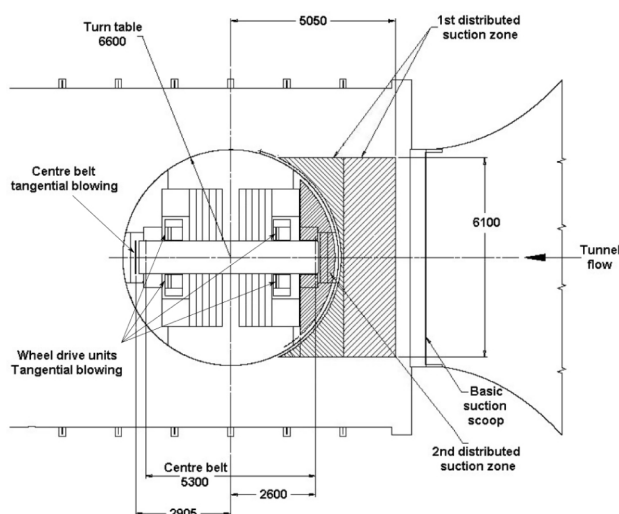


Figure 1. Wind tunnel floor layout with boundary layer control systems. Adapted from [7].

Table 1. Force coefficient repeatability within a test.

Force	Coefficient	Repeatability
Drag	C_D	± 0.001
Front lift	C_{LF}	± 0.001
Rear lift	C_{LR}	± 0.005

As for all measurements, wind tunnel data has a level of uncertainty. In the case of the force measurements in the wind tunnel considered here, this level is quantified by the repeatability of the force coefficients between two tests and within a test, the difference being whether or not the car is removed and reinstalled between the measurements. For the present work, the car is not removed between measurements, which is why the within test repeatability given in Table 1 is applicable.

Boundary Layer Thickness Measurements

In order to measure the boundary layer thickness behind the tangential blowers in the empty tunnel, a rake of total pressure probes was mounted on the wind tunnel traversing gear and positioned such that the first probe was located 2 mm above the tunnel floor. The rake consisting of 22 probes over a total height of 109 mm can be seen in Figure 2. The longitudinal position of the rake was fixed 800 mm downstream of the blower while the rake was traversed throughout the width of the slot at a sweep speed of 20 mm/s with a sampling frequency of 20 Hz and 5 frames per sample, thus resulting in roughly one measurement per millimeter.

The thickness of the boundary layer was quantified using the displacement thickness δ^* , defined as

$$\delta^* = \int_0^{\infty} \left(1 - \frac{u(z)}{u_{\infty}} \right) dz,$$

with z directed upwards from the floor and the local velocity $u(z)$ calculated as

$$u(z) = \sqrt{\frac{2q(z)}{\rho_s}}.$$



Figure 2. Boundary layer rake mounted on the traversing gear.

The dynamic pressure $q(z)$ was found from the total pressure measurements using the compressible flow relation

$$q(z) = \frac{\gamma}{\gamma + 1} P_s \left(\left(\frac{P_t(z) - P_s}{P_s} + 1 \right)^{\frac{\gamma-1}{\gamma}} - 1 \right),$$

where $\gamma = 1.4$ is the ratio of specific heats for air, P_s the test section static pressure and $P_t(z)$ the total pressure measured by the probe rake.

Tangential Blowing Influence on Aerodynamic Force Deltas

The influence from tangential blowing on aerodynamic force deltas for a number of common aerodynamic configurations was investigated using two similar cars with different rear end shapes, namely a notchback Volvo S60 and a squareback Volvo V60. Apart from the shape difference at the rear, the two cars were identical with respect to powertrain, wheels and styling levels.

Physical experiments in the wind tunnel were used to quantify sensitivities and interactions, while numerical investigations were used to gain insight into the flow field changes potentially causing the phenomena observed in the physical tests.

Experimental Setup

For each car, seven factors were tested using a design of experiments approach with a two-level 2^{7-3}_{IV} fractional factorial design [8] in order to be able to quantify both main effects and two factor interactions. The tested factors can be seen in Table 2, which also shows the two levels for each factor used in the experimental design. A selection of the factors is shown mounted on the cars in Figure 3. All factors except the cooling flow blanking, bootlid spoiler and aero blades were screwed in place, ensuring reliable positioning between the runs. The cooling blanking, spoiler and blades were fastened using tape, with great care taken to accurately fix them in the same position for each run in order to minimize any variability. The seven factors were chosen since they were expected to influence the aerodynamic forces by changing the mass flow under the car and/or the properties of the base wake. For the squareback, the bootlid spoiler was replaced by aero blades. The baseline configuration was taken as the configuration that was expected to have the highest drag value, which meant open cooling, high ride height and no aerodynamic devices mounted.

The experimental design was chosen to fulfill a requirement on the maximum number of runs estimated to fit into the allocated wind tunnel time. However, since the design is of resolution four, two factor interactions are confounded with other two factor interactions and can thus not be uniquely estimated [8]. The confounding pattern for the two factor interactions of the employed design can be seen in Table 3. Consider for example the AF interaction, with the confounding structure $AF + BG + DE$. This means that we cannot estimate AF itself, but just the sum of the interactions between ride height and covered rims (AF), bootlid spoiler/aero blades and cooling flow (BG), and underfloor panels and front wheel deflectors (DE). In order to avoid this two factor confounding, a design with a resolution

of at least five would need to be employed, which for this case would lead to an unacceptable fourfold increase of the number of performed test runs from 16 to 64.



(a). Underfloor panels off

(b). Underfloor panels on



(c). Air dam



(d). Front wheel deflector



(e). Aero blades (squareback only)



(f). Bootlid spoiler (notchback only)

Figure 3. The tested configurations.

For each run in the experimental design, the aerodynamic forces on the car were measured both with the tangential blowing on and off. Each force coefficient was then compared to the baseline with the same blowing setting. In this way, each run resulted in two delta values for each force coefficient; one for tangential blowing on, and one for off. The response variable considered is the delta-of-deltas, i.e. the difference between those two deltas, which means that if the delta measurement is robust with respect to the tangential blowing, the response will be zero.

Table 2. Investigated factors and their levels in the experimental design.

Factor	Encoding	Low level	High level
Ride height	A	-15 mm	Reference
Bootlid spoiler/aero blades	B	Off	On
Air dam	C	Off	On
Underfloor panels	D	Off	On
Front wheel deflectors	E	Off	On
Covered rims	F	Off	On
Cooling flow	G	Closed	Open