

Experimental Comparison of the Aerodynamic Behavior of Fastback and Notchback DrivAer Models

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ABSTRACT

The experimental investigation was conducted with a 25%-scaled realistic car model called "DrivAer" mounted in a wind tunnel. This model includes geometric elements of a BMW 3 series and an Audi A4, accommodating modular, rear-end geometries so that it represents a generalized modern production car. The measurements were done with two different DrivAer rear end configurations (fastback and notchback) at varying side-wind conditions and a Reynolds number of up to $Re=3.2 \cdot 10^6$. An array of more than 300 pressure ports distributed over the entire rear section measured the temporal pressure distribution. Additionally, extensive flow visualizations were conducted.

The combination of flow visualization, and spatially and temporally resolved surface pressure measurements enables a deep insight into the flow field characteristics and underlying mechanisms. Moreover, static pressure fluctuations indicate regions with a high turbulence level due to flow separation and interaction between different vortical structures. A directional decomposition of the pressure coefficient is demonstrated and acts generally normal to the surface of the vehicle, in the drag and lift direction.

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INTRODUCTION

The aerodynamic efficiency is becoming increasingly important in the development process of new vehicles in order to meet increasing comfort, safety, and economic requirements. However, reduction of aerodynamic drag and thus, the vehicle's fuel consumption is the main motivation for the innovation process. In addition, modern lightweight constructions and lighter materials make aerodynamic loads more dominant, relative to the inertia forces. Therefore, the driving behavior and dynamic stability depends more on these forces. Moreover, the development of electric or hybrid cars fundamentally enhances the percentage of aerodynamic losses by substituting the engine's thermal losses. In summary, improvements in aerodynamic design are essential to make future cars more efficient.

In the last few decades, fundamental research has been often conducted on generic models with limited applicability to realistic cars. Those aerodynamic studies were conducted for example at the Ahmed Body, SAE-body and ASMO II, and were often considered with a zero yaw angle. Therefore, the new DrivAer-model was developed, the process of which is explained in more detail in the following section. However, dominant effects for non-zero angles are observable. Those

effects are important not only for drag but also for lift forces and are, therefore, important for stability and safety reasons. Moreover, yaw angle studies often investigate mean global coefficients without a consideration of local and time-resolved properties. Therefore, this manuscript presents a steady-state yaw angle investigation on the realistic DrivAer-model with the discussion of time-resolved and localized flow characteristics.

EXPERIMENTAL SETUP

Wind Tunnel Setup

The aerodynamic study was conducted in the closed-loop wind tunnel at the Institute of Fluid Dynamics and Technical Acoustics at the "Technische Universität Berlin" (Figure 1). The test section has a cross-sectional area of $2\text{m} \times \sqrt{2}\text{m}$. The maximum freestream velocity is $c_\infty \approx 41\text{m/s}$, which enables a Reynolds number up to $Re=3.2 \cdot 10^6$ based on the model's length L . The freestream turbulence intensity is less than 0.5%. The air speed was measured by using a Pitot tube above the model. No moving belt is available. A horizontal splitter plate cut off the lower wind tunnel boundary layer to minimize boundary effects on the model.

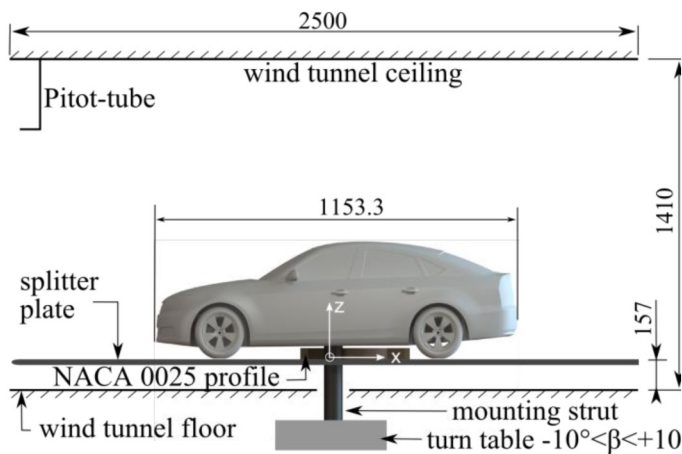


Figure 1. Experimental setup of the 1:4 scale DrivAer model in the wind tunnel test section. Values are in mm.

The mounting strut which holds the model is affixed to the turn table and penetrates through the wind tunnel's floor and splitter plate. A NACA0025 profile covered the mounting strut to minimize aerodynamic interferences. Additionally, an inner NACA-support channel provides the accessibility for the power supply, the differential pressure sensor cables, and the pressure reference tube. The turn table's yawing motion enables the study of side wind conditions. In this study yaw angles $-10^\circ < \beta < +10^\circ$ are examined. The clearance between the lowest point of the model's tire and splitter plate is $t_{\text{gap}} = 1.5\text{mm}$ to allow force measurements and yawing motion. The blockage of the model in the test section at $\beta = 0^\circ$ is $\phi = 5.4\%$. Therefore, a correction of all aerodynamic forces and moments is applied by correcting the freestream velocity.

DrivAer Model

The DrivAer-model is developed at TU München in cooperation with the automotive industry companies BMW and Audi [4, 5]. It is a design hybrid of an "Audi A4™" and a "BMW 3 series™". Compared to simplified models, such as the Ahmed Body or SAE-Model, the DrivAer model includes all outer geometry details of realistic cars. Furthermore, there are some design options available: three different rear ends such as fastback, notchback and fullback, and a smooth or detailed underbody. More detailed information regarding the model's design is provided by Heft et al. [4]. Other studies also consider more complex model variations such as applied engine compartment flow with heat exchanger and under floor interactions [3]. The geometry of the DrivAer model is openly available for the research community.

In this study, fastback and notchback rear ends were investigated (Figure 2). The DrivAer model is 1:4 scale with a total model length of $L = 1.15\text{m}$ and a cross-sectional area of $A = 0.135\text{m}^2$. The model has a smooth underbody and non-rotating wheels. Furthermore, the model is hollow which enables the placing of the measurement equipment inside. Additional details regarding the model's design are described by Strangfeld et al. [1].



Figure 2. The DrivAer -model with two different rear ends: notchback (top) and fastback (bottom).

Force Measurements

An internal balance is located in the inner DrivAer-model and connects the mounting strut and the inner DrivAer-mounting plate. The 16-bit internal six component balance enables the time-resolved measurement of all aerodynamic loads. The sampling rate was set to $2^{12} = 4096\text{Hz}$ with an amplifier low pass filter of 2500Hz . The maximum nominal loading is 1000N for forces and 20Nm for moments with a measurement error of 0.5% at full scale. The reference point for the moments is defined on the model's plane of symmetry, at the midpoint between the two wheel axes in the streamwise direction, and 1.5mm above the splitter plate. The aerodynamic coefficients were normalized by dynamic pressure, cross-sectional wetted area, and total model length.

Pressure Measurement

Pressure measurements were carried out for both rear ends and in each case at the vehicle's base and rear fender. Apart from a few reference taps, all static pressure taps were distributed on one side of the model to provide a high spatial resolution with the least amount of pressure sensors. The fastback and the notchback module (see Figure 3) have 211 and 143 pressure taps, respectively.

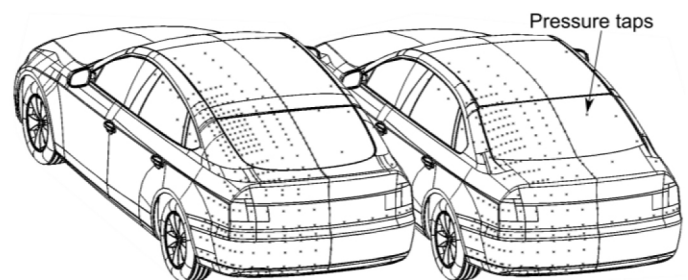


Figure 3. Pressure tap distribution over DrivAer models' rear section for both rear ends.

A previous investigation [1] at TU Berlin was conducted for the fastback configuration with only 142 pressure taps. The increased amount of pressure taps in the present study allows for capturing the pressure gradients more precisely. Moreover, the measurement area was enlarged. Numerous tabs are located at the c-pillars at each rear end to identify streamwise vortices due to the low static pressure footprint [9]. The base,

the rear fender, and the plane of symmetry have 62, 39, and 16 pressure taps, respectively. Overall, more than 300 pressure taps are distributed over the model. However, only 74 synchronized time-resolved pressure sensors were available. Hence, the measurements were conducted in six different pressure sensor setup configurations to record all tap locations on the model. The piezo-resistive sensors acquire a differential pressure range of $\pm 1000\text{Pa}$ at 16 bit resolution. The maximum sensor error is listed with 0.5% full scale. Each sensor features its own brazing plate with its own power supply and amplifier. Due to this custom-made design the size of each sensor is small. All pressure sensors are located inside of the hollow model. As a result, the tubing system between the sensors' membrane and tap orifice is approximately 40mm. The length of the pressure taps depends on the model's shape and position, which is about 15-30mm. By shortening the overall tubing length, distortions in frequencies and amplitudes become negligible [8]. The required reference static pressure for the differential pressure sensors was taken from a Pitot tube above the model, located at the wind tunnel ceiling. The sampling rate was set to 4096Hz. The samples size is $2^{19}=524288$ samples. All sensors were calibrated between 0Pa and 1000Pa for each configuration.

Flow Visualization

Surface flow visualizations were performed for both rear ends at three different cross wind angles of $\beta=0^\circ$, -5° and -10° . The Reynolds number was set to $\text{Re}=3.2 \cdot 10^6$ in order to capture the Reynolds independent flow field. Some flow visualizations for the fastback at $\text{Re}=2.8 \cdot 10^6$ (corresponding to [1]) were conducted as well. Generally, they show nearly the same flow structures with a slightly smaller region of separated flow over rear window. Lawson [6] noticed a slight Reynolds number dependence for the notchback configuration at $\beta=0^\circ$ at the rear window flow field between $\text{Re}=3.08 \cdot 10^6$ and $\text{Re}=4.93 \cdot 10^6$. However, only the $\text{Re}=3.2 \cdot 10^6$ was considered due to the maximum velocity of the wind tunnel. Oil-based white paint was mixed with petroleum. The mixture was thinly deposited with paint rollers to reduce large accumulations of liquid in recirculating flow regions. Otherwise, due to the complex geometry and separated flows, there would have been liquid swirls that required a long time in order to dry completely. Dried surface traces were recorded with a reflex camera.

RESULTS

The flow visualization, the spatially and temporally resolved surface pressure measurements, and the static pressure fluctuations offer an extended insight into the vehicle's flow phenomena, flow separation and interaction between different vortical structures. The directional decomposition of the pressure coefficient in the drag and lift direction is shown and points out dominant sections for drag contribution.

Force Measurement under Crosswind Conditions

The Reynolds dependence of the drag coefficient is examined for both rear end configurations at a yaw angle of $\beta=0^\circ$. This is an important step to check that the obtained measurement data reproduce realistic properties. Strangfeld et al. [1] demonstrated a nearly independent behavior of the drag coefficient for Reynolds numbers above $\text{Re}=2.25 \cdot 10^6$ on the fastback configuration by analyzing the static pressure distribution in the plane of symmetry and also by using an internal balance. The current study confirmed Strangfeld's results for the fastback and also shows the same behavior for the notchback (not illustrated here). However, the drag coefficient converges to a constant value with increasing the Reynolds number.

The drag coefficient C_D of the fastback and the notchback configuration at different angles of attack is illustrated in Figure 4. The zero side wind force defines the zero yaw angle $\beta=0^\circ$. At zero yaw angle, the fastback's drag coefficient is $C_D=0.258$ and the notchback's is $C_D=0.254$. Heft et al. [4] determined nearly the same drag coefficients of $C_D=0.258$ for the notchback and $C_D=0.254$ for the fastback configuration for the DrivAer model containing the same geometry (smooth underbody and side mirrors). Several different boundary conditions of the test facilities may be the reason for the deviation in the drag measurements (e.g., open or bounded test section, splitter plate, or mounting strut). Figure 4 reveals a substantial increase in drag with yaw angle. Both rear ends obtain the maximum drag coefficient $C_D \geq 0.278$ at $\beta=9^\circ$. This yields an additional drag of 7.5% for the fastback and 9.7% for the notchback configuration. Moreover, Gaylard [2] illustrated a higher increase in drag about $\Delta C_D \approx 20\%$ for $\beta=10^\circ$.

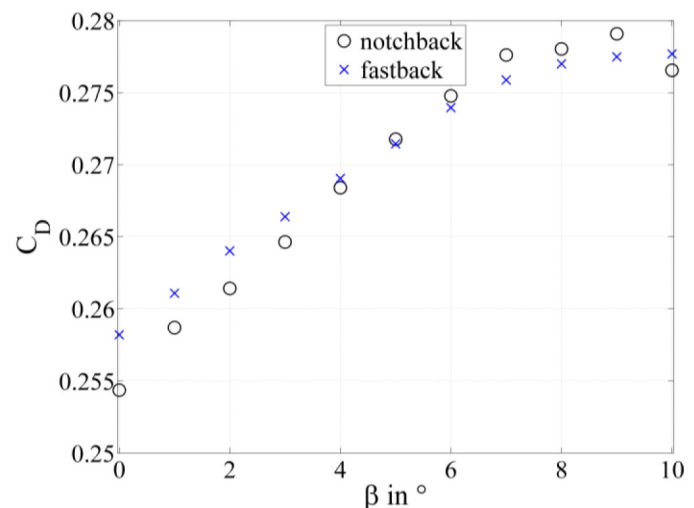


Figure 4. Drag coefficient C_D at varying side wind conditions ($0^\circ \leq \beta \leq 10^\circ$) for $\text{Re}=3.2 \cdot 10^6$.