

# Links between Notchback Geometry, Aerodynamic Drag, Flow Asymmetry and Unsteady Wake Structure

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## ABSTRACT

The rear end geometry of road vehicles has a significant impact on aerodynamic drag and hence on energy consumption. Notchback (sedan) geometries can produce a particularly complex flow structure which can include substantial flow asymmetry. However, the interrelation between rear end geometry, flow asymmetry and aerodynamic drag has lacked previous published systematic investigation.

This work examines notchback flows using a family of 16 parametric idealized models. A range of techniques are employed including surface flow visualization, force measurement, multi-hole probe measurements in the wake, PIV over the backlight and trunk deck and CFD.

It is shown that, for the range of notchback geometries investigated here, a simple offset applied to the effective backlight angle can collapse the drag coefficient onto the drag vs backlight angle curve of fastback geometries. This is because even small notch depth angles are important for a sharp-edged body but substantially increasing the notch depth had little further impact on drag.

This work shows that asymmetry originates in the region on the backlight and trunk deck and occurs progressively with increasing notch depth, provided that the flow reattaches on the trunk deck and that the effective backlight angle is several degrees below its crucial value for non-reattachment. A tentative mapping of the flow structures to be expected for different geometries is presented.

CFD made it possible to identify a link between flow asymmetry and unsteadiness. Unsteadiness levels and principal frequencies in the wake were found to be similar to those for high-drag fastback geometries. The shedding of unsteady transverse vortices from the backlight recirculation region has been observed.

## INTRODUCTION

As is well known, the rear end geometry of road vehicles can have the greatest influence on aerodynamic drag coefficient and hence on energy consumption for highway driving. Understanding of the link between rear end geometry, flow structure and drag is therefore of central importance. Of the three classical rear end geometries (square-back, fastback, notchback), the complex flow structure behind the notchback, (three box / sedan / saloon) has been the least well understood.

Notchbacks, like fastbacks, exhibit a maximum drag associated with strong trailing vortices from the c-pillars and this occurs when the time-averaged flow separates over the backlight but reattaches just before the rear of the vehicle. For notchbacks the effective (or apparent) backlight angle has been used as the geometry parameter for characterizing when the flow will transition from this maximum drag condition to a fully separated (and lower drag) rear end flow. [Figure 1](#) illustrates the backlight angle ( $B$ ) and effective backlight angle ( $B_{\text{eff}}$ ) for a notchback. Nouzawa et al [1] found that the drag coefficient changes with rear end geometry were less extreme for notchbacks than for fastbacks. It should be noted that the effective backlight angle is far from being a perfect index to rear end flow structure, with critical effective backlight angles varying significantly between different notchback geometries (eg: [1] vs [3]). This is further

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illustrated by Howell [3] (summarizing unpublished work by Windsor) which shows that the use of effective backlight angle cannot collapse the drag of different notchback geometries. Improving on the effective backlight parameter for the classification of a wider range of notchback geometries is one of the aims of the present work.

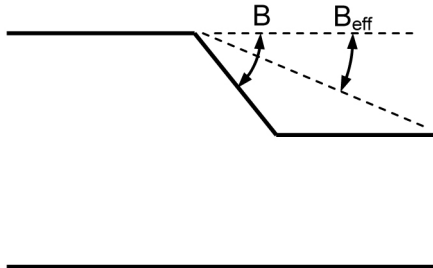


**Figure 1. Definition of Effective Backlight Angle**

Perhaps the most intriguing aspect of notchback rear end flows is the common presence of an asymmetric rear end flow for symmetric geometries. Gaylard et al [4] compiled a number of cases (eg: [5], [6], [7], [8], [9]) in which asymmetry has been observed in the wake structure of notchback vehicle types, including real vehicles and idealized geometries. In most cases these observations were anecdotal to the subject of the original investigation. Gaylard et al [4] highlighted that further work was required to understand the effects of different notchback geometries. Additionally, it remains unclear what the effects of asymmetry are, if any, on the lift and drag performance of the vehicle. The link between notchback geometry and asymmetry has lacked previous systematic investigation and this will be one of the aims of this work.

Notchbacks, like other road vehicles, have rear end flows dominated by significant flow separation, which in turn leads to significant flow unsteadiness. Gilhome et al [10] have proposed an unsteady flow topology for notchbacks and this will be investigated for the geometry used here. Some detailed flow structure measurements were made for a notchback by Jenkins [11] however, these were confined to a geometry with a symmetric flow structure and so this work will focus, in particular, on the case of asymmetric flow.

This work seeks to achieve the following objectives:

- To assess how wake structure, including in particular any asymmetry, depends on notchback geometry.
- To assess the dependence of the drag of a notchback on rear end geometry (including noting any links with asymmetry).
- To provide a clearer understanding of the time-averaged wake structure behind a notchback.
- To investigate the unsteady nature of the wake behind a notchback, including identifying Strouhal numbers and

testing the unsteady topology put forward by Gilhome et al [10].

## APPROACH

Wind tunnel tests and CFD simulations were performed using a family of basic geometries. The front end geometry of Ahmed et al [12] was adopted as this provides a clean flow onto the rear of the model and avoids the presence of artifacts from the front end flow (eg: A-pillar vortices) confusing observations of the rear end flow or introducing geometry-specific interactions.

The experimental phase of the work used 16 interchangeable rear end geometries assembled from machined Aluminum tooling plate for the purpose of this study. Geometries were selected to provide effective backlight angles including reattaching and separated flows and backlight angles ranging from fastback to 90° while maintaining constant trunk deck height and model length. The aim here was to capture symmetric and asymmetric as well as high and low drag flow structures. The models were nominally equivalent to 25% scale, as used by [12]. Testing was in the Durham University 2 m<sup>2</sup> open jet wind tunnel in fixed ground configuration (described in [13], [14]); the resulting cross sectional area blockage was 5.6%. The Reynolds number, based on model length, was  $1.9 \times 10^6$ .

A subset of the geometries were simulated using Ansys Fluent (version 6.3). The simulations were performed at the same Reynolds number as the experiments but with a larger computational domain (0.4% blockage with inlet and outlet both 16 model lengths away from the model). Following a study of turbulence model and grid-independence, the Spallart-Almeras turbulence model was used with a structured mesh of approximately  $1.2 \times 10^6$  cells, corresponding to  $y^+$  values between 25 and 75. Both steady and time resolved simulations were performed, the latter with a time step of 0.005 s and simulation time of 2.5 s.

## RESULTS

### SURFACE FLOW VISUALIZATION - ASSESSMENT OF ASYMMETRY

Surface flow visualization was performed for all of the models in order to assess asymmetry in the rear end flow. This was done using fluorescent toner mixed with paraffin, with UV lighting to better view the resulting patterns. Ink drop flow observations were used to confirm flow directions wherever this was unclear.

The flows can be divided into three classifications: Fully Separated, Reattaching Symmetric, and Reattaching Asymmetric. For the steepest effective backlight angles the flow was clearly fully separated over the entire backlight and

trunk deck; there was no evidence of asymmetry in any of these cases. For low effective backlight angles the flow separated at the sharp top of the backlight but reattached on the backlight itself (for the lowest backlight angles) or on the trunk deck. For some geometries this reattaching flow was symmetric while for others it exhibited different levels of asymmetry. Where possible, critical points are identified. [Figure 2](#) illustrates a reattaching symmetric flow while [Figure 3](#) illustrates a strongly asymmetric reattaching flow. The range of levels of asymmetry that were observed seems to indicate that the asymmetry develops progressively rather than being a fundamental change in the flow topology.

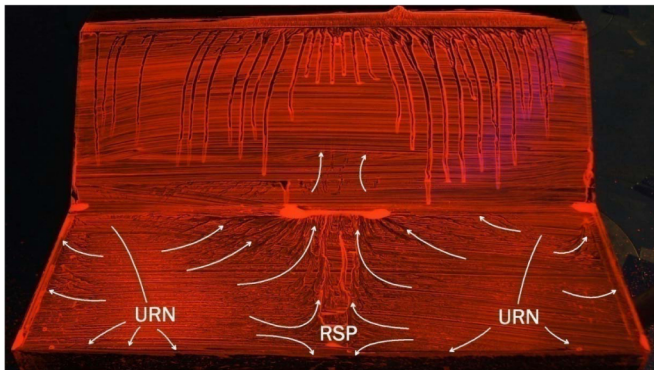


**Figure 2. Surface Flow - Symmetric Reattaching ( $B_{eff} = 21^\circ$ ,  $B = 42^\circ$ )**

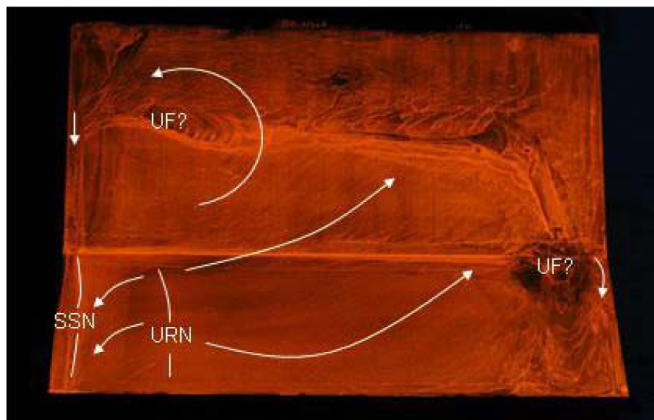


**Figure 3. Surface Flow - Reattaching Asymmetric ( $B_{eff} = 17.8^\circ$ ,  $B = 31.8^\circ$ )**

## FORCE MEASUREMENTS

Aerodynamic forces were recorded for all 16 geometries. Forces were corrected according to [15], the correction on the coefficients in this case is about 1%. The total repeatability in this facility is 0.002 on  $C_D$ .

[Figure 4](#) presents the measured drag coefficient plotted against the effective backlight angle and [Figure 5](#) illustrates

the rear lift coefficient. Reattaching and fully separated cases are labeled based on the surface flow visualization. As expected, at relatively low effective backlight angles the drag increases as effective backlight angle increases up to a maximum drag condition. This corresponds to a flow which is separated over the backlight and trunk deck but which reattaches just before the end of the trunk deck. When the effective backlight angle exceeds  $25^\circ$ – $30^\circ$  the flow separates without reattachment and once this condition is reached the drag is reduced to essentially the same value as for a squareback. The rear lift coefficient (defined in this case based on the lift at the rear mounting legs) also increases with increasing effective backlight angle for the reattaching flows and then drops to a lower and more universal level for the fully separated cases.

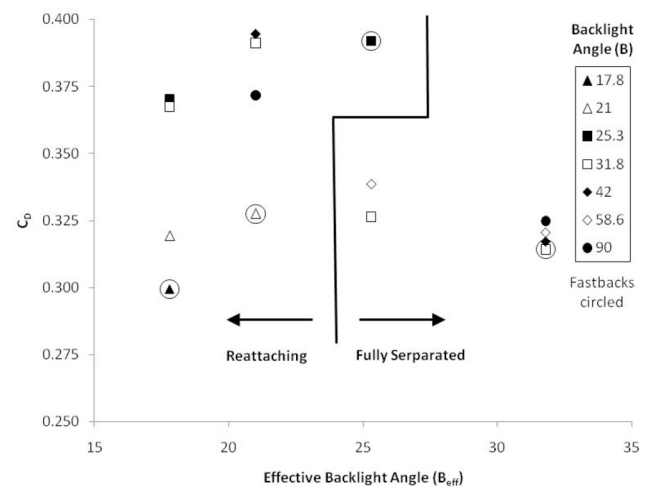


**Figure 4. Drag and Flow Structure Dependence on Effective Backlight Angle**

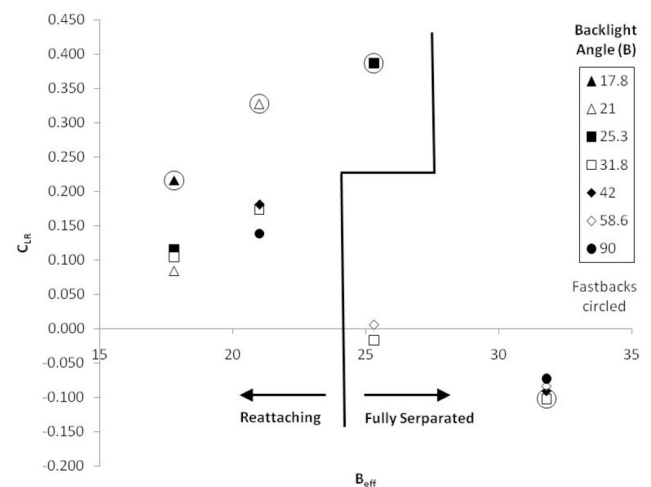


**Figure 5. Rear Lift Dependence on Effective Backlight Angle**