

Bluff Body Drag Reduction with Ventilated Base Cavities

Jeff Howell

Tata Motors European Technical Centre

David Sims-Williams, Adam Sprot, Fred Hamlin and Robert Dominy
Durham University

ABSTRACT

Various techniques to reduce the aerodynamic drag of bluff bodies through the mechanism of base pressure recovery have been investigated. These include, for example, boat-tailing, base cavities and base bleed. In this study an Ahmed body in squareback configuration is modified to include a base cavity of variable depth, which can be ventilated by slots. The investigation is conducted in freestream and in ground proximity. It is shown that, with a plain cavity, the overall body drag is reduced for a wide range of cavity depths, but a distinct minimum drag condition is obtained. On adding ventilation slots a comparable drag reduction is achieved but at a greatly reduced cavity depth. Pressure data in the cavity is used to determine the base drag component and shows that the device drag component is significant. Modifications of the slot geometry to reduce this drag component and the effects of slot distribution are investigated. Some flow visualisation using PIV for different cavity configurations is also presented.

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INTRODUCTION

Aerodynamic drag of a typical passenger car arises from a near equal split between the styled upper surfaces and the less visible components comprising; cooling airflow, underbody, wheels and wheelarches. On the upper surfaces the major drag component, 60%, occurs at the rear of the car, and dominates the drag from the front end, skin friction and protuberances such as mirrors. This constitutes approximately 30% of the overall aerodynamic drag and it results from the suction which occurs on the rearward facing surfaces, especially those in the separated flow regions at the base of the car. Similarly, from the less visible components, the wheels and wheelarches contribute approximately 30% of the overall aerodynamic drag. Any investigation into drag reduction must concentrate on these significant contributors.

Improving the rear end drag must primarily concentrate on increasing the pressure on the base and comes under the general heading of 'base pressure recovery'. The main routes for achieving this are, rear body tapering (boat-tailing), base cavities and base flow injection. Boat-tailing effects can be seen in saloon and fastback car shapes, and although the top surface tapering for these vehicles tends to be excessive, rear bodyside tapering contributes to an increase in base pressure. It has also been exploited on 1- and 2-box shapes through the

combined effects of roof and bodyside curvature, although design constraints have limited these benefits. Significant drag reduction has been demonstrated on trucks with the use of angled base boards to provide a combination of cavity with boat-tailing effects, as exemplified by Cooper (1) and Browand et al (2). Very few experiments on base flow injection, applicable to road vehicle type bodies, have been reported. Exceptions are the work of Englar (3), with high velocity Coanda type jets, and Sykes (4) and Howell et al (5) using low velocity bleed flow. Interestingly, the latter study showed that a significant part of the drag reduction achieved came from the cavity

While a significant amount of research has been conducted on the effect of base cavities on drag reduction for axisymmetric bodies at high Mach numbers relevant to missile aerodynamics, as shown, for example, in the comprehensive review by Viswanath (6), very few studies have been at the low subsonic Mach numbers relevant for automobiles. Exception are Morel, (7), who tested a slender axisymmetric shape of small diameter in freestream and Duell, (8,9), who investigated a small model of square section near to a ground plane. Morel showed that useful drag reduction was obtained with a simple cavity, but also that ventilating that cavity produced a similar benefit but at a reduced cavity depth.



In addition to the truck cases cited earlier, Mason and Beebe (10) reported on the application of a plain cavity to a truck model, while Hucho (11) includes a reference to tests with a plain cavity added to the rear of a light van. Both showed useful drag benefits, but more recently Irving Brown et al (12) investigated base cavities on an SUV and found the drag reduction was insignificant.

To explore the potential for drag reduction from base cavities it was decided to conduct a similar study to that of Morel, but using a larger model, more representative of a car shape, with a rectangular cross section. The cavity would be plain and ventilated, of variable depth and the body would be tested both in freestream conditions and in ground effect.

EXPERIMENTAL STUDY

MODEL

The model used was a copy of the Ahmed body, (13). It was originally made by Rover, many years ago, as a reference body and was of wooden construction. The overall model dimensions were: length 1.044m, width 0.389m, height 0.288m. The leading edge radius is 0.10m. The model was modified by removing some internal structure at the rear to facilitate a plain cavity, and the removeable upper body sections were replaced with a fixed squareback shape with an open base. A sliding back-plate for the cavity, which could be positioned from outside the model, gave a maximum cavity depth of 0.25m. The cavity walls were 0.012m thick and longitudinal ventilation slots were cut into the walls. The model and the slot arrangement are shown in Figure 1.

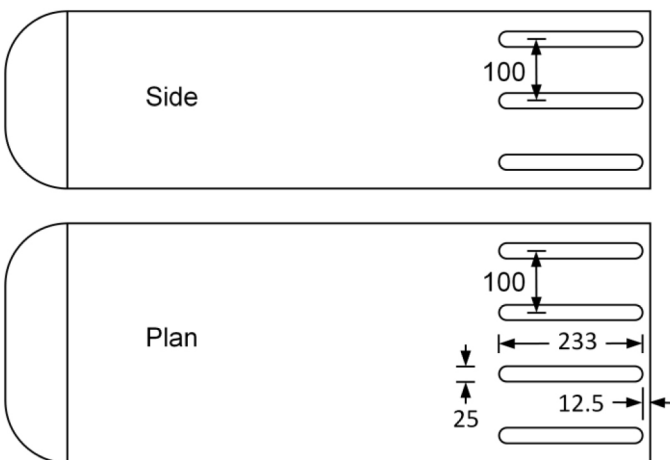


Figure 1. Ahmed body showing cavity ventilation slot dimensions (mm).

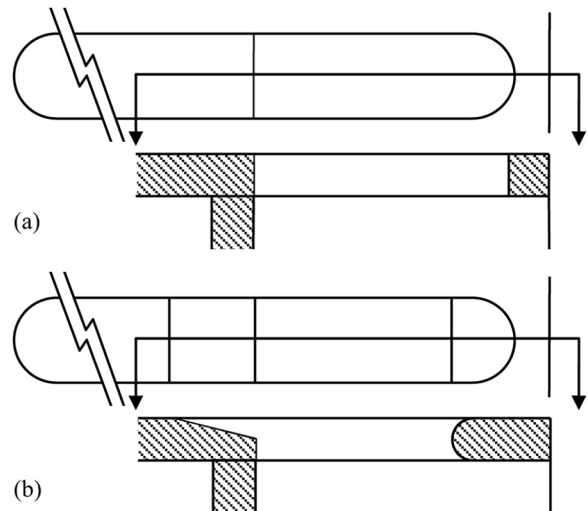


Figure 2. Ventilation slot details (a) Square edged, (b) Tapered.

The 14 slots were uniformly spaced at 0.10m and were cut into the top, bottom and side body surfaces. Each slot was 0.233m long and 0.025m wide. The slot ends were semicircular and the distance between the slot end and the body trailing edge was 0.0125m. For cavity depths less than the maximum slot length the forward section of the slot was filled and the slot leading edge shape was squared off. A section through the slot is shown in Figure 2(a), and is here called a square edged slot. A subsequent modification to try and reduce the drag due to the slot, known as the device drag, following Viswanath (6), and which is here called a tapered slot is shown in Figure 2(b).

WIND TUNNEL

The wind tunnel used in this experiment is a low speed, open jet, straight through wind tunnel in the School of Engineering and Computing Sciences at Durham University. It has a nozzle 1.75m wide by 1.15m high and the working section is 5m long. The normal operating speed of the tunnel is 25m/s. The wind tunnel can be operated with a moving belt or a solid floor for ground simulation, but for all tests conducted here the tunnel was operated with a fixed ground. The model was mounted to an under floor 6-component balance, which could be yawed. Total repeatability for the facility is ± 0.002 for drag coefficient and multiple repeats of the baseline configuration were within that range. Further details of the facility are available in (14), (15).

The model is shown in the wind tunnel in Figure 3 with tapered ventilation slots. The slots on the lower wall of the cavity are, in this case, filled. In ground proximity the model was mounted on cylindrical legs, diameter 0.025m, and the ground clearance was set at 0.060m. Wind tunnel blockage was 5.6% and the forces were corrected for blockage according to SAE SP 1465, (16). In nominally freestream conditions the model was mounted on elongated legs which positioned the model centrally relative to the nozzle.

The nominal freestream wind velocity was 25m/s in all cases except where the effect of Reynold's Number was investigated. The nominal test speed gave $Re = 1.80 \times 10^6$ based on model length. Drag coefficient showed a small consistent reduction with increasing Reynold's Number. For all configurations increasing Re from 1.08 to 1.8×10^6 produced a drag coefficient reduction in the range of $\Delta C_D = 0.010$ – 0.014 , which represents approximately 3-4% of the total drag for the squareback model without a cavity.

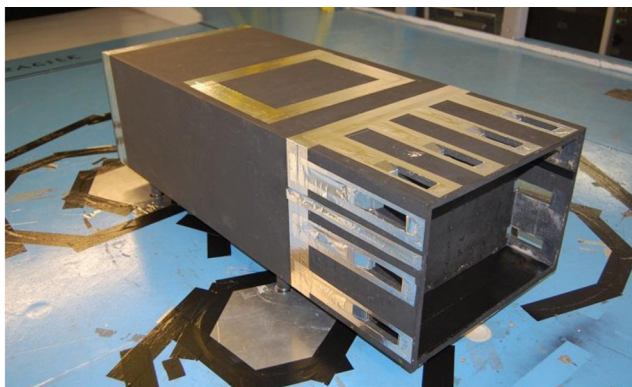


Figure 3. Ahmed body with ventilated cavity in the Durham University Wind Tunnel

PARTICLE IMAGE VELOCIMETRY (PIV)

PIV was used in the longitudinal orientation (x-y plane) on the model centerline at three different cavity depths. The system comprised a pulsed 120mJ dual head Nd:YAG laser, which was placed 2.2m downstream of the model trailing edge. Two cameras (12 Bit Sensicam 1280×1024 with chip cooling) were used to take simultaneous instantaneous flow fields. The image field of each camera was 0.18m wide by 0.20m high and the cameras were traversed to three locations downstream of the model base, where the six fields were stitched together electronically to create the final flow field maps. The flow was seeded using DEHS oil distributed by a compressed air fed atomizer, which produced consistent particles of around 1µm diameter. These were fed into the flow upstream of the nozzle contraction via a purpose built smoke delivery rake. The system was synchronised electronically and the pulse separation was set to 15 µs. This allowed adequate particle separation between images to pick up fine resolution of velocities but was also small enough to prevent drop-out, where a particle from the first image is no longer present in the image field of the second exposure. Each interrogation involved 200 image pairs, which were selectively averaged to include only valid vectors.

5-HOLE PRESSURE PROBE

Additional flow field data were obtained using a 5-hole probe. The probe has a head dimension of 3mm and comprises a stainless steel body with a rapid-prototyped

acrylic head which can be replaced if damaged in service. The probe was calibrated to provide a pitch and yaw range extending to $\pm 60^\circ$. The focus of the present work was on time-averaged measurements and so no time-resolved calibrations were performed but the probe nevertheless provides some information about levels of unsteadiness, characterized by the level of pressure fluctuation seen at the centre hole.

RESULTS

The initial tests of the modified Ahmed model were conducted out of ground effect. The effect of a cavity depth for a plain cavity, ie with no ventilation slots, is shown in [Figure 4](#). The incremental drag coefficient is measured relative to the standard Ahmed body in squareback configuration with no cavity. In this test the baseline drag coefficient, C_D , was 0.339, although it should be noted this included a substantial tare drag correction for the elongated support struts. As cavity depth increases, drag is initially reduced rapidly, but then levels off with a minimum drag coefficient at a cavity depth of 0.140m.

Adding the ventilation slots, the drag reduction due to cavity depth is initially similar to the solid walled cavity, but at a cavity depth of 0.060m the minimum drag is achieved and at greater depths the drag increases rapidly. At a cavity depth of 0.125 m the drag becomes equal to that of the basic body. The vented cavity shows no improvement over the plain cavity.

The central slot on the side and the two middle slots on the top and bottom surfaces of the body were taped over to investigate crudely the effect of ventilation area on the drag. The minimum drag was the same as that obtained with the full set of ventilation slots. The penalties arising from the slots at cavity depths greater than the optimum could, however, be mitigated by reducing the ventilation area. This suggests that the slots are a source of drag.

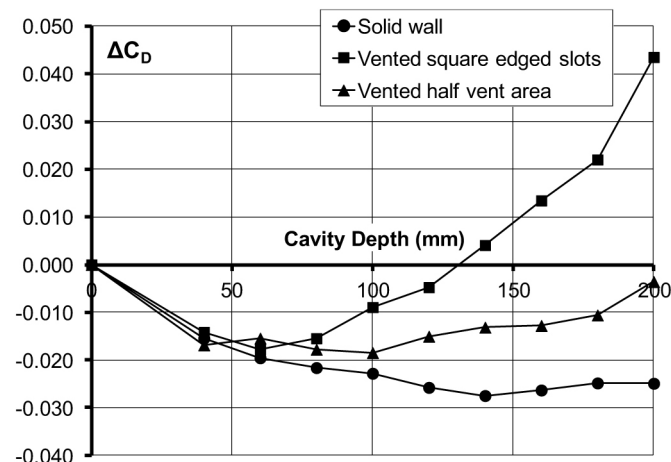


Figure 4. Effect of cavity depth for body in 'freestream'.

The body was then set up close to the ground with a ground clearance of 0.060m and the effects of cavity depth on