

An Investigation into the Wake Structure of Square Back Vehicles and the Effect of Structure Modification on Resultant Vehicle Forces

2011-37-0015

Published
06/09/2011

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doi:[10.4271/2011-37-0015](https://doi.org/10.4271/2011-37-0015)

ABSTRACT

A large contribution to the aerodynamic drag of a vehicle (30%⁽¹⁾ or more depending on vehicle shape) arises from the low base pressure in the wake region, especially on square-back configurations. A degree of base pressure recovery can be achieved through careful shape optimization, but the flow structures and mechanisms within the wake that cause these base pressure changes are not well understood. A more complete understanding of these mechanisms may provide opportunities for further drag reductions from both passive shape changes and in the future through the use of active flow control technologies.

In this work surprisingly large changes in drag and lift coefficients of a square-back style vehicle have been measured as a result of physically small passive modifications. Tests were performed at quarter scale using a simplified vehicle model (Windsor Model) and at full scale using an MPV. The full scale vehicle was tested with and without a flat floor. During both tests the vehicle base region was fitted with a series of low profile, horizontal slats to disrupt any steady wake structures acting close to the vehicle base surface. Force balance, static pressure and PIV measurements have been used to investigate the flow structures in the vehicle wake.

This paper summarizes the results and relates the global drag and lift changes that arise from the horizontal slats to the base pressure from both model and full scale and to the PIV measurements from the model tests.

INTRODUCTION

It is clear that the reduction of CO₂ emissions from road vehicles is currently, and will continue to be, a significant area of research for the automotive industry. The effect on CO₂ emissions from fossil fuelled vehicles as a result of reduced aerodynamic drag forces is dependent on what drive cycle is used in the calculation⁽²⁾, but can be significant. The effect of aerodynamic drag also becomes important when considering vehicle range requirements for low energy density power sources such as batteries and fuel cells.

It is worthy of note that whilst aerodynamic drag coefficients (C_d) have fallen significantly over the past thirty years, vehicle frontal areas have seen an increase⁽³⁾. This inverse tendency illustrates the difficult tradeoffs faced by vehicle manufacturers when considering consumer requirements and buying trends, but it is apparent that vehicle package and styling are still dominant factors when creating vehicle body shapes.

For this reason the vehicle aerodynamicist must use ever more discreet means of achieving drag reductions such as air spoilers, wheel deflectors⁽⁴⁾, underbody smoothing⁽⁵⁾ and sealing of under bonnet gaps⁽⁵⁾. In recent years active flow control techniques have been of research interest due to their potential ability to achieve flow modification and drag reductions without the need for physical shape changes, however they have yet to be proven in a real world vehicle application. Previous experiments using the Windsor reference model and steady blowing⁽⁶⁾ as a means of flow control have found large reductions in drag forces, that arise through modification of the wake structure to create an increase in base pressure. Littlewood⁽⁶⁾ reported that the mechanisms that appear to be important in these changes might also be effected through passive modifications. Therefore the current work uses passive techniques with the aim of modifying the wake structure and are used as a means of understanding how flow mechanisms and structures within the wake of a squareback vehicle can influence drag forces.

The majority of the experimentation has been conducted at $\frac{1}{4}$ model scale, however the opportunity arose to conduct limited tests on a full scale vehicle, so these have been reported here. Within the limited time available to test at full scale only a small number of configurations could be tested, however the results verify that the effects seen are not exclusive to model scale testing. Although the findings are a means of understanding wake structure modification, the small passive modifications made could have implications or an application within a passive optimisation of current passenger or haulage vehicles.

BACKGROUND

In previous investigations⁽⁷⁾ the author has linked the modification of wake size via a small passive optimisation to an increase in base pressure and as such a reduction in vehicle drag. This is illustrated by [Figure 1a\)](#) and [1b\)](#) which show PIV images on streamwise centreline planes in the near wake of the $\frac{1}{4}$ scale square back Windsor model. [Figure 1b\)](#) illustrates the wake size reduction when a 12 degree high aspect ratio slant is applied to the roof trailing edge. This small passive modification results in a C_d reduction of 12 counts.

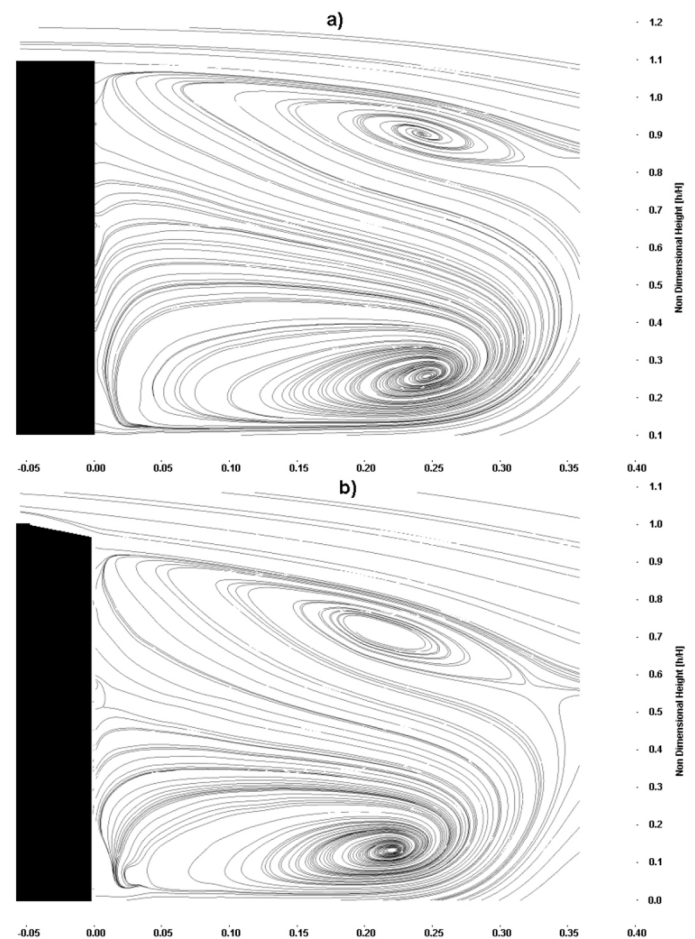


Figure 1. a) Time averaged PIV streamlines of squareback wake structure; b) Time averaged PIV streamlines of squareback wake structure incorporating a 12° roof trailing edge chamfer

Previous investigations have tried to link the size of the wake of bluff bodies to the pressure seen on the body base⁽⁸⁾⁽⁹⁾. Some studies argue larger wakes lead to increased base pressure while others claim the opposite. In the case of the work reported in Littlewood et al⁽⁷⁾ the wake size is inferred from PIV data from a single centreline plane, and it is concluded that the reduction in overall wake size is linked to higher base pressures. The conclusion is supported by the detailed base pressure data.

Later experiments using constant blowing applied at the rear roof trailing edge⁽⁶⁾ of the same model generated C_d reductions of up to 35 counts, or approximately 10%. However when PIV images were taken of the blown and unblown case the wake size did not decrease as much as might have been expected from the passive optimisation studies for such a large C_d change. The baseline wake structures differ slightly between [Figure 1](#) and [Figure 2](#)

because the model underbody conditions were modified between the tests.

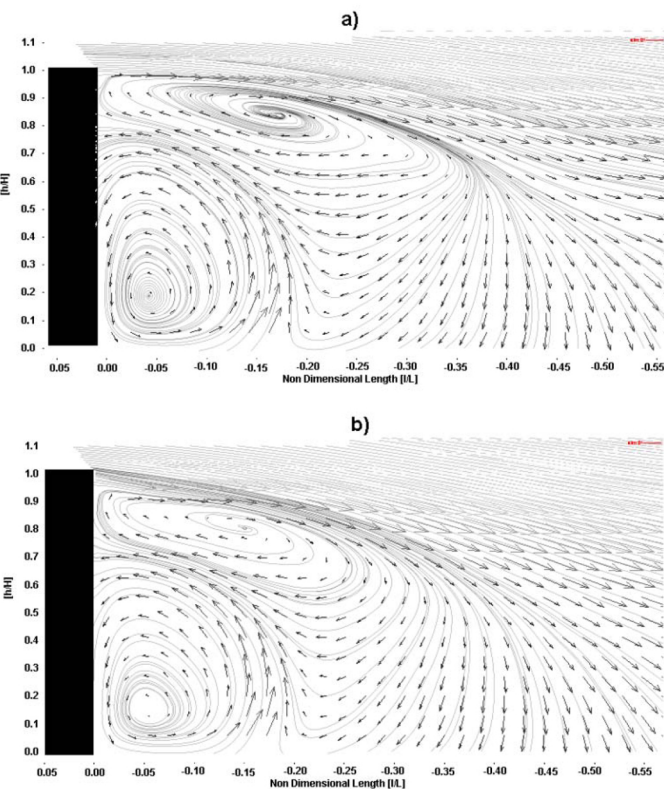


Figure 2. a)Time averaged PIV of baseline case squareback wake structure b)Time averaged PIV of constant blowing case, squareback wake structure

Describing the entire wake structure in line with the ‘cavity model’ outlined by Rhosko⁽⁸⁾ it would seem that the global ‘in wake’ or ‘in cavity’ pressure can be influenced by overall wake/cavity size. However if this is the case, for the configurations shown in Figure 2a) and 2b) it might be reasonable to expect a larger change in wake size than is observed for such significant C_d changes. From this analysis it is apparent that the pressures seen on the base surface of the model must be influenced by more than just wake size alone. It can be seen from Figure 2 that the time averaged vortex structures close to the vehicle base impart a large flow velocity close to the base surface which in turn creates a suction component. It was hypothesized that a means of interrupting or slowing the surface flow velocity on the base may lead to an increase in base pressure in this region of suction.

The current work uses small passive modifications to the base of the model in an attempt to disrupt the flow velocity close to the model base. The objective is to show that disrupting the wall velocities can have an influence on wake structure and hence, base pressure. Additionally the study aims to

demonstrate a new passive method for influencing base pressures other than altering the wake size alone.

EXPERIMENTAL SETUP AND DATA ACQUISITION

MODEL SCALE TESTING

The Windsor model⁽¹⁰⁾, used in this work is shown in Figure 3. All the leading edges are well rounded to avoid separation with radii of 0.05m, with the exception of the roof leading edge which has a radius of 0.20m. The longitudinal and rear edges are sharp. A NACA0021 wing profile with 150mm chord protrudes from the centre of the model floor, to below the wind tunnel floor. This wing is fitted as shielding for tubing and cabling that may need to be routed inside the model. The standard configuration of the base surface is flat and perpendicular to the onset flow direction. The model was fitted with small 1mm thick, 8mm deep slats on the lower half of its base surface, as shown in detail A of Figure 3. The first slat added was positioned 35mm above the model floor and additional slats were spaced 35mm apart. The configurations tested are described in Table 1.

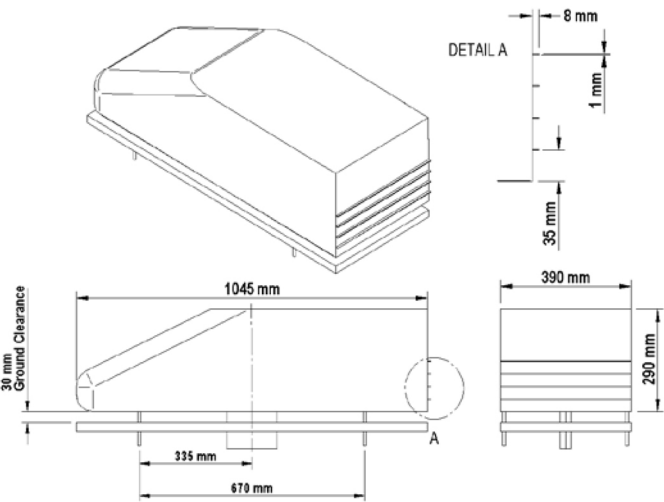


Figure 3. Windsor model illustrating the position of slats

Table 1. Scale model configurations

Configuration Number	Description
0	Baseline configuration no slats added to model
1	3 Slats added to the base surface of the model spaced evenly 35mm apart from the floor of the model
2	4 Slats added to the base surface of the model spaced evenly 35mm apart from the floor of the model