

An Experimental Study on Truck Side-Skirt Flow

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ABSTRACT

The underbody of a truck is responsible for an appreciable portion of the vehicle's aerodynamic drag, and thus its fuel consumption. This paper investigates experimentally the flow around side-skirts, a common underbody aerodynamic device which is known to be effective at reducing vehicle drag. A full, 1/10 scale European truck model is used. The chassis of the model is designed to represent one that would be found on a typical trailer, and is fully reconfigurable. Testing is carried out in a water towing tank, which allows the correct establishment of the ground flow and rotating wheels. Optical access into the underbody is possible through the clear working section of the facility. Stereoscopic and planar Particle Image Velocimetry (PIV) set-ups are used to provide both qualitative images of and quantitative information on the flow field. The planar PIV set-up employs novel techniques developed in-house, including the use of two laser sheets to reduce shadow regions, and frame averaging such that presented results are produced using an average of up to 1800 independent data points. It is shown that one drag-reducing mechanism of side-skirts at zero-degree yaw is the prevention of high-momentum flow at the side of the vehicle entering the upper half of the underbody. However, the flow topology varies significantly with vertical position, and side-skirts are shown to have effects on near-ground flow which could have a detrimental effect on vehicle drag. It is therefore likely that an optimum value exists for the height of a side-skirt from the ground.

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1. INTRODUCTION

The aerodynamics of commercial vehicles is becoming an increasingly pertinent topic. In 2012, Heavy Goods Vehicles (HGVs) in the UK consumed nearly 8 billion litres of fuel [6]. High fuel costs along with heightened pressure to protect the environment mean that commercial operators are looking for ways to reduce vehicle fuel consumption.

When travelling at constant velocity on flat terrain, the fuel consumption of a vehicle is directly proportional to the resistive force that it must overcome. The total resistive force can be simplistically broken down into a rolling resistance and an aerodynamic drag component. Figure 1 shows how the force components vary with vehicle velocity, based on the simplified force relation given in Equation 1.

$$F_D = \frac{1}{2} \rho_a U_\infty^2 C_D A + N C_{rr} \quad (1)$$

Values for the $C_D A$ (drag coefficient multiplied by the frontal area) and C_{rr} (rolling resistance coefficient) are from coast-down testing undertaken by the Centre for Sustainable Road Freight [11], and are assumed to remain constant with velocity (in reality they vary slightly with velocity). At European motorway speeds of 56mph, the aerodynamic drag is accountable for approximately 45% of the power requirement. There is thus scope to make a significant reduction to the fuel consumption by lowering the aerodynamic drag.

The aerodynamic drag of commercial vehicles is frequently broken down into four sources, the cab, the gap between the cab and the trailer (the cab gap), the rear, and the underbody [3, 7]. Of particular interest, due to its lack of previous consideration, is the underbody. Approximately 15-30% of the aerodynamic drag is attributed to this area [3,7].

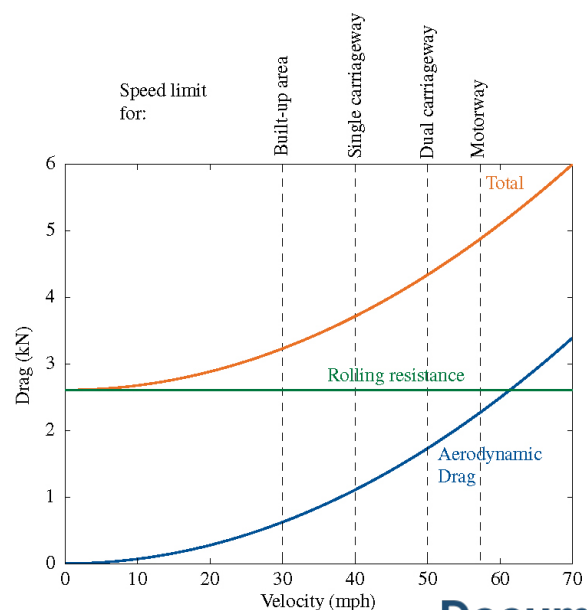


Figure 1. Aerodynamic and rolling drag as functions of the vehicle velocity.

The majority of published literature concerning the underbody of a HGV focuses on the performance of specific aerodynamic devices. The most popular device is the side-skirt, which has been shown to be effective at reducing the drag of commercial vehicles by numerous studies [1,2,3,4,5, 9, 12, 13, 17,18,19,20]. However, these investigations only consider the associated drag, and offer little insight into the flow physics of these devices. This paper uses a novel method documented by Stephens et. al. [16] to analyse the flow around side-skirts, with the aim of giving an insight into how these devices could be optimised.

2. METHODOLOGY

For a detailed description of the methodology used to obtain the results in this paper, the reader is referred to Stephens et. al. [16]. A brief outline of the methods used to establish the flow and take planar PIV measurements is however given below. This is followed by a more detailed description of the stereoscopic PIV method which is not discussed in the aforementioned paper.

The experiments make use of the Cambridge University Engineering Department water towing tank facility, shown in Figure 2. This allows for the correct establishment of the ground condition, along with rotating wheels. It also allows good optical access for Particle Image Velocimetry (PIV) diagnostics. The water towing tank is 7m long with a usable cross-section of $1\text{m} \times 0.8\text{m}$. It has a belt-driven translating carriage. The facility operates at Reynolds Numbers in the range of $Re_w = 6.3 \times 10^5 - 7.8 \times 10^5$, depending on the temperature of the water at the time measurements are taken. This is of the order of the minimum testing value recommended by the SAE [15].

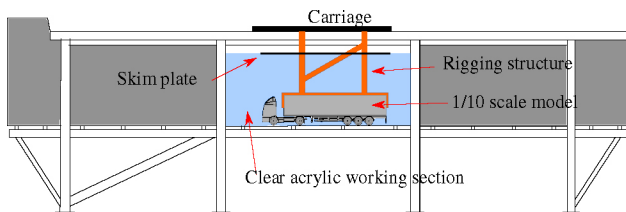


Figure 2. Schematic drawing of water towing tank.

Figure 3 shows a schematic of the 1/10th scale model used for the experimentation. The basic configuration has underbody components that would typically be found on a truck. Figure 3 highlights these components. The ride height of the vehicle, taking into account the compression of the vehicle wheels, is measured using a camera set-up. The height is constant for all measurements to an accuracy of $\pm 0.75\text{mm}$. The testing blockage is 17%. Although this is relatively high, its most significant effect would be on the absolute drag forces. An application of Maskell's method [10] leads to an approximate drag coefficient correction of $C_D = 0.7C_{D,measured}$. Its impact on the pressure distribution around the vehicle is however expected to be small. Therefore, as this paper studies flow differences between underbody devices, this blockage should not influence the outcomes of the investigation.

Measurements are taken at a zero yaw angle only. The efficiency of side-skirts is known to increase with yaw angle as they prevent the cross-flow from entering the underbody. However results from the

zero yaw case demonstrate drag reduction mechanisms that are independent of cross-flows. The understanding of these mechanisms is instrumental to the design of side-skirts.

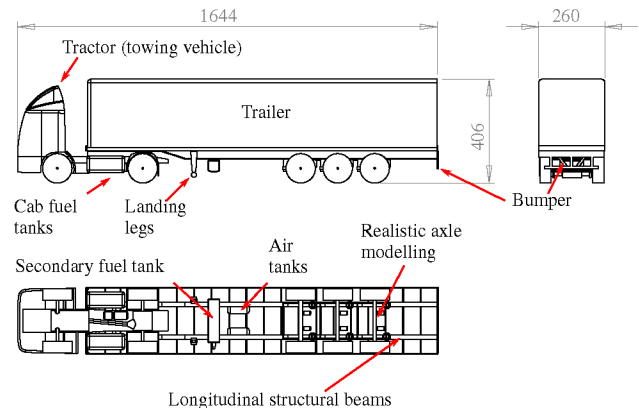


Figure 3. Scale drawing of truck model (dims in mm).

This paper presents results from three different model configurations, which are illustrated in Figure 4. Configuration I: basic configuration with no side-skirts, Configuration II: addition of mid side-skirts, Configuration III: addition of mid and rear side skirts.

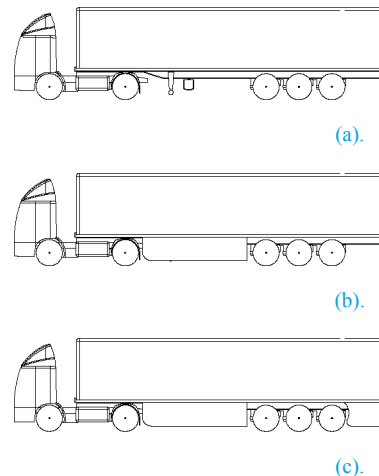


Figure 4. Model configuration drawings. (a) Configuration I: basic configuration with no side-skirts. (b) Configuration II: addition of mid side-skirts. (c) Configuration III: addition of mid and rear side skirts.

2.1. High Speed PIV System

Particle Image Velocimetry (PIV) is used to obtain flow velocity information. The system comprises a double cavity high speed laser with a maximum frequency of 20kHz, capable of producing an output of 30mJ per pulse per cavity at 1kHz at a wavelength of 527nm. Two Phantom Miro 310 high speed cameras are used to obtain planar or stereo data, with a maximum resolution of $1280 \times 800\text{px}$. Particles of titanium dioxide are used to seed the flow. They have a characteristic diameter of $45\mu\text{m}$, and are approximately neutrally buoyant. Images are checked for peak locking by ensuring that particles are smeared over several pixels, and that the probability density function of the processed velocity field shows no tendency towards integer velocities. This paper presents results from two different PIV arrangements.

2.1.1. Setup (a): Planar PIV Setup

A schematic diagram of the planar PIV setup is shown in Figure 5. The positions of the laser sheet, which are varied in the vertical direction to give results in multiple planes, are shown in Figure 8 labelled (A), (B), (C) and (D). The laser is aligned to the measurement plane with an accuracy of ± 1 mm. The acquisition frequency is set to 2.5 kHz such that a velocity of 3 m/s corresponds to a particle movement of 5 pixels. The images from two cameras are stitched together to increase the field of view (FOV). Prior to stitching, the FOV of each camera is approximately $340 \text{ mm} \times 214 \text{ mm}$. PIV analysis windows of $16 \times 16 \text{ px}$ are used, giving a vector resolution of 4.3 mm. A large overlap region is used for stitching, which spans the width of the model. Each planar PIV result is formed of an ensemble average of 5 experimental runs. As a further measure to significantly improve their quality, results are also frame (time) averaged. For details of this averaging method the reader is referred to Stephens et. al. [16] This method gives a total number of averages of up to 1800 within the vehicle underbody.

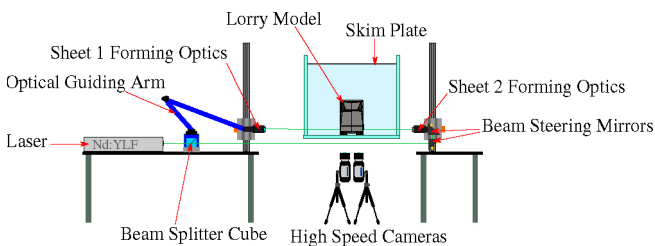


Figure 5. Planar PIV Setup, end view [16].

2.1.2. Setup (b): Stereoscopic PIV Set-Up

To allow for the measurement of the third velocity component, a stereoscopic PIV arrangement is also used. This method additionally allows for data to be collected in the whole of the underbody, as opposed to on one plane. Figure 6 shows a schematic drawing of the setup. A laser beam is guided underneath the water tank by an Optical Guiding Arm. The beam is intercepted by sheet forming optics on the underside of the tank which form a vertical sheet across the truck model. The laser sheet is aligned to the measurement plane with an accuracy of ± 1 mm. The cameras are both focused on the laser sheet, one upstream and one downstream, and are angled at approximately 45° . Water-filled prisms are attached to the underside of the tank to reduce refraction effects. Sheimpflug adaptors fitted to the cameras adjust the angle of the focal plane, so that it is parallel to the plate. To further increase the accuracy of the calibration, a stereoscopic PIV self-calibration procedure is performed on the collected data. This procedure uses the presumption that both cameras are photographing identical particles to correct misalignments of the laser sheet to the calibration plane. Wieneke [21] demonstrates that, even for very large initial misalignments, this method is able to determine the position of the centre of the laser sheet and implement a correction to an accuracy of 0.1 px. This corresponds to a spatial accuracy of 0.03 mm in this experimental set-up. In this arrangement, a PIV processing window of $32 \times 32 \text{ px}$ with 50% overlap is used. An in-plane vector resolution of 5.2 mm is then obtained.

For the stereoscopic PIV arrangement, the acquisition frequency is set to 3 kHz so that a particle remains in the laser sheet for several frames before moving out in the streamwise direction. Checks are made to ensure that in-plane particle movements are sufficient to give accurate in-plane results. Each stereo PIV result is formed of an ensemble average of 5 experimental runs. Results are also averaged in blocks of 5 in the streamwise sense, reducing the streamwise resolution from 1 mm to 5 mm in favour of increasing the number of averages.

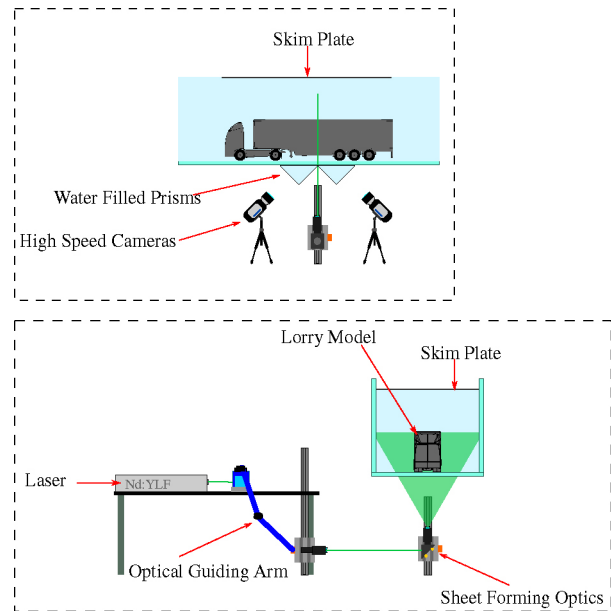


Figure 6. Stereoscopic PIV Set-up.

With this laser and camera arrangement, issues arise when underbody components obstruct a camera's view of the PIV particles. Figure 7 shows an example of this where the trailer fuel tank (T) obstructs the upstream camera's view of the laser sheet. In this case, PIV processing algorithms have difficulties distinguishing between a true PIV particle image, and noise induced by camera obstruction from opaque objects. Due to fluctuating light intensities in the underbody caused by varying strengths of reflections, it is difficult to account for this using traditional masking algorithms which detect regions of particles based on average light intensities. Masking for results presented in this paper is instead derived from a computer simulation of the cameras' views using a CAD model of the truck.

The simulation is carried out using the following method:

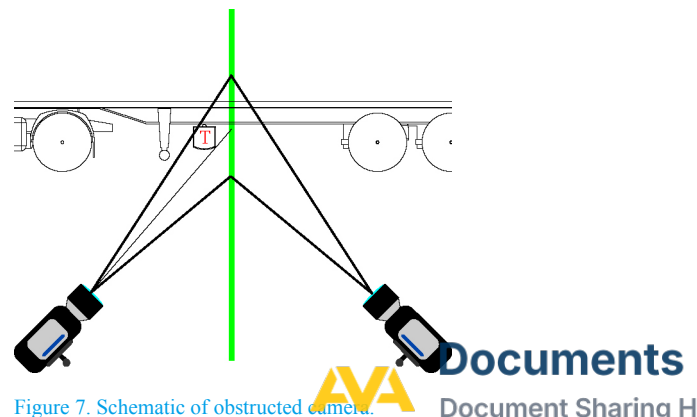


Figure 7. Schematic of obstructed camera.

- The CAD model of the truck is converted into a 3D logical matrix with 1mm resolution representing space occupied or void
- The angle of the cameras is assumed to be 45°
- The distance of each camera from the measurement plane is calculated from the PIV calibration photos for the set-up
- The vision of the cameras (i.e. which parts of the model they can see) is calculated for all streamwise positions as it moves past the camera / laser arrangement, in steps of 1mm
- The 2D measurement plane is split into squares of 4mm x 4mm. For each square, lines are traced from the vertices to each camera. A searching algorithm is then applied to the logical model matrix. If at least one matrix element within the extent of these four lines is marked as occupied space, then the mask is applied for that square. Otherwise, no mask is applied
- This method gives a final in-plane resolution of 4mm, which is of similar magnitude to the resolution of the PIV velocity fields.

2.1.3. Processing Error

Errors in PIV processing originate from inadequate statistical methods, amongst others. According to Raffel [14], the error can be broken down into a bias and rms component as shown in [equation 2](#).

$$\epsilon = \epsilon_{\text{bias}} + \epsilon_{\text{rms}} \quad (2)$$

It is possible to assess the magnitude of these errors by creating an artificial PIV image pair with known displacements and applying the processing algorithm to them. The image pair is created by taking one real PIV image and displacing it by a certain number of pixels in both vertical and horizontal directions. The errors from this for the planar PIV set-up are shown in [table 1](#). The variables u_{expd} and v_{expd} indicate the velocity that is expected from the given pixel displacement for the particular setup used for this investigation. This method however does not account for processing errors where there are velocity gradients, or errors with the alignment of the image and laser planes.

Table 1. Planar PIV processing errors.

Displacement	1px	2px	3px	4px	5px
$\frac{u_{\text{expd}}}{U_{\infty}} = \frac{v_{\text{expd}}}{U_{\infty}}$	0.22	0.45	0.67	0.89	1.11
$\frac{\epsilon_{\text{bias},u}}{U_{\infty}}$	0.1%	0.2%	0.2%	0.3%	0.4%
$\frac{\epsilon_{\text{bias},v}}{U_{\infty}}$	0.1%	0.2%	0.3%	0.4%	0.5%
$\frac{\epsilon_{\text{rms},u}}{U_{\infty}}$	0.1%	0.2%	0.3%	0.4 %	0.5%
$\frac{\epsilon_{\text{rms},v}}{U_{\infty}}$	0.1%	0.2%	0.3%	0.4%	0.5%

The simulation of errors in the stereoscopic PIV setup is more involved as the generation of synthetic images giving rise to a constant known velocity is non-trivial. However, Lawson & Wu show that the ratio of out of plane errors to in-plane errors for a stereoscopic setup with camera angles of 45° is unity [8]. The bias and rms processing errors for the stereoscopic arrangement are therefore expected to lie in the range seen above, i.e. $\pm 0.5\%$.

3. RESULTS

[Figures 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32](#) show both streamwise velocity contours and streamlines for the three model configurations, on the four horizontal planes shown in [Figure 8](#).

[Figures 33, 34](#) and [35](#) show results from the stereoscopic PIV investigation for Configurations I & II on planes (E) $x/b = 2.51$, (F) $x/b = 3.47$ and (G) $x/b = 7.89$. The locations of these planes with respect to the model are also shown in [Figure 8](#). Each results figure also shows difference contours of Configuration II - Configuration I. In each case, half of the vehicle is shown. The contours show the normalised streamwise velocity, and the arrows show in-plane velocity vectors. The vector arrows have been coloured to have good contrast when superimposed onto the contours. Solid black areas show regions of intersection between the laser sheet and model, whilst solid grey areas show regions of camera blockage calculated using the method described in [section 2.1.2](#).

4. DISCUSSION

4.1. Mid Side-Skirts

Firstly, comparisons are made between the basic case (Configuration I), and the case with mid side-skirts only (Configuration II). Significant differences in the flow topology are seen between the four different planes (A)-(D). The planar PIV results are discussed systematically.

Close to the ground, in plane (A), the streamwise velocity contours show a strong separation emanating from the front tractor wheel at around $x/b = 0.5$ in both configurations. The streamlines for this plane show a strong lateral outwards movement from the separation point. For both configurations, the flow in the underbody between $x/b = 2$ and $x/b = 2.5$ is formed of two low momentum wake regions behind the tractor wheels, and a region of moderate momentum where flow has passed underneath the tractor unit. For Configuration I with no side skirts, the flow within the underbody of the vehicle between $x/b = 2$ and $x/b = 4$ also moves laterally outwards ([Figure 12](#)). In contrast, the presence of mid side-skirts in Configuration II prevents flow in the underbody from moving outside of the vehicle, and the streamlines remain approximately parallel to the trailer sides. The velocity contours show that the trailer side-flow, which initially has low momentum due to the tractor wheel separation, has an increase in momentum around $x/b = 4$ for Configuration II ([Figure 10](#)). For Configuration I, this increase occurs much later ([Figure 9](#)). This is perhaps due to the insertion of the low-momentum underbody flow into the trailer side flow in Configuration I which does not occur in Configuration II. The contours also show that the momentum of the flow immediately upstream of the trailer wheels at $x/b = 3.9$ is higher for Configuration II than for Configuration I.

In plane (B), the velocity contours still indicate the presence of a tractor front wheel separation. In this plane, the lateral movement of the streamlines in the tractor wheel separation is far less severe, and they run parallel to the trailer sides between $x/b = 2$ and $x/b = 4$ for both Configurations I & II. In this plane, the outward movement of