The unsteady aerodynamics of static and oscillating simple automotive bodies

This item was submitted to Loughborough University's Institutional Repository by the/an author.

Additional Information:

- A Doctoral Thesis. Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University.

Metadata Record: https://dspace.lboro.ac.uk/2134/10967

Publisher: © J T Baden Fuller

Please cite the published version.
This item was submitted to Loughborough University as a PhD thesis by the author and is made available in the Institutional Repository (https://dspace.lboro.ac.uk/) under the following Creative Commons Licence conditions.

For the full text of this licence, please go to:
http://creativecommons.org/licenses/by-nc-nd/2.5/
The Unsteady Aerodynamics of Static and Oscillating

Simple Automotive Bodies

by

Joshua Thomas Baden Fuller

Doctoral Thesis
Submitted in partial fulfillment of the requirements
for the award of
Doctor of Philosophy of Loughborough University

August 2012

© J T Baden Fuller, 2012
Abstract

A wind tunnel based investigation into the effects of unsteady yaw angles on the aerodynamics of a simple automotive body has been carried out to increase the understanding of the effects of unsteady onset conditions similar to those experienced in normal driving conditions.

Detailed flow field measurements have been made using surface pressure tappings and PIV around a simple automotive model in steady state conditions and these have been compared to measurements made whilst the model was oscillating in the yaw plane. The oscillating motion was created by a motored crank which was used to produce consistent and repeated motion which produced a reduced frequency that indicated that a quasi-static response should be expected. The PIV data are used to compare the wake flow structures and the surface pressures are used to infer aerodynamic loads and investigate the development of the flow structures across the surfaces of the model. This includes a comprehensive comparison of the surface pressures on the sides of the model during a transient and quasi-static yaw angle oscillation. These results show differences between the two test conditions with the oscillating model results containing hysteresis and the greatest differences in the flow field occurring on the leeside of the model.

Two configurations of the same model with different rear pillar geometries were used to isolate model specific effects. Square rear pillars create strong and stable trailing vortices which are less affected by the model motion whereas radiused rear pillars created weaker and less steady vortices that mixed with the quasi-2D wake behind the model base and were affected to a greater extent by the model motion. The unsteadiness in the trailing vortex separation feeds upstream into the A-pillar vortex demonstrating that small geometry changes at the rear can affect the entire flow field around the model.
Acknowledgements

I would like to thank my supervisor Martin Passmore and visiting research fellow Jeff Howell for their continual support and advice throughout this project and to Martin for offering me the post in the first place. I would like to the technical staff of the department, particularly Rob Hunter, and also Stacey Prentice, Peter Stinchcombe and Martin Cramp and also all the other members of the department’s staff who have assisted me during my time here.

I would like to thank my fellow PhD students and researchers for their friendship and assistance during my time as a post graduate student; it would have been much more boring without you.

I would like to thank my Mum and Gary Peacock for proof reading the final draft and finally I would like to thank my girlfriend, Anna, for always being supportive, encouraging and showing interest in what I am doing.
5. Conclusions .......................................................................................................................... 155
6. Recommendations for Further Work .................................................................................. 158
7. References .......................................................................................................................... 160

Appendix 1. Audi A2 Case Study ......................................................................................... 175
Appendix 2. Lateral Oscillating Model Rig .......................................................................... 197
Appendix 3. Round Edged Model ......................................................................................... 206
Appendix 4. Square Edged Model ......................................................................................... 210
Figures

Figure 1, Wake flow structures behind the Ahmed model, taken from (3).................................4
Figure 2, Davis model wake vorticity, 0.5L behind the model base, taken from (10)..................5
Figure 3, Effect of rear slant angle on a model with upstream flow influences, taken from (11)...5
Figure 4, Instantaneous and mean vector fields behind a hatchback, taken from (12)..............6
Figure 5, Von Karmen vortex street, taken from (25).................................................................9
Figure 6, Strouhal numbers of rectangles, taken from (32).....................................................10
Figure 7, Squareback wake flow features, taken from (36)....................................................11
Figure 8, PIV vector fields behind a squareback, taken from (40)...........................................12
Figure 9, Notchback flow field, taken from (41)........................................................................12
Figure 10, Asymmetric surface pressures on a large saloon with yawed onset flow, taken from (46).14
Figure 11, Crosswind vectors .................................................................................................14
Figure 12, The effect of vehicle speed on yaw angles, taken from (47).................................15
Figure 13, Yaw angles experienced in the real world, taken from (48).....................................15
Figure 14, The wake frequency content of different built structures ......................................16
Figure 15, Vehicle response to different frequency inputs, taken from (53)...........................17
Figure 16, Onset flow yaw rates, Oettle data in the left graph, Walker data in the right graph....18
Figure 17, Static-static yaw testing in Volvo's full scale wind tunnel ......................................23
Figure 18, Oscillating aerofoils, taken from (79).....................................................................24
Figure 19, Turbulence generation system in the Pininfarina wind tunnel, taken from (48)......26
Figure 20, Durham University crosswind generator, taken from (84)......................................27
Figure 21, Wake survey behind the Durham geometry with crosswind, taken from (86)......28
Figure 22, Cranfield University crosswind track, taken from (64)...........................................29
Figure 23, Full scale, transient yaw sweep showing yaw moment coefficient phase lag ........29
Figure 24, The oscillating model rig, taken from (100)...........................................................33
Figure 25, Damped, self-sustaining and self-exciting model responses ....................................33
Figure 26, Effect of strake size on yaw moment coefficient gradient magnification, taken from (99)34
Figure 27, Willy model .............................................................................................................35
Figure 28, Flow field hysteresis in the wake of an oscillating Willy model, from (107)...........36
Figure 29, Dynamic stall, dashed line shows the steady state results, solid lines show the instantaneous transient loads, taken from (112)................................................................37
Figure 30, Oscillating motion energising the boundary layer on an aerofoil, taken from (113)...37
Figure 31, Vortex shedding after a transverse disturbance, taken from (25)............................38
Figure 32, Non symmetric shedding, the cylinder is moving perpendicular to the flow, taken from (117)..............................................................................................................38

viii
Figure 33, Symmetric shedding, the cylinder is moving back and forth in line with the onset flow, taken from (116) ................................................................................................................................. 38
Figure 34, Full scale assessment of crosswind stability, taken from (77) ......................................................... 39
Figure 35, Current production vehicles with strakes indicated by the red arrows ................................................ 41
Figure 36, A low drag, aero-stable car design, taken from (124) ........................................................................ 41
Figure 37, Loughborough University 1/4 scale wind tunnel ........................................................................ 44
Figure 38, Yaw motion of the balance ........................................................................................................ 47
Figure 39, Cranked oscillating model rig, isometric view ........................................................................ 47
Figure 40, Cranked oscillating rig installed beneath the working section floor ............................................. 48
Figure 41, Driven yaw oscillations, $K_M = 0.049$ ........................................................................................ 49
Figure 42, SAE coordinate system ............................................................................................................. 51
Figure 43, Pressure tapping arrangement on the Davis model ...................................................................... 52
Figure 44, Flexitubes in the Davis model shell ........................................................................................ 52
Figure 45, Flexitubes to produce the reference and distorted pressure signals ............................................ 54
Figure 46, Magnitude and phase distortion effects due to the flexitube ........................................................ 54
Figure 47, Effect of tubing correction on 50Hz pressure fluctuations ................................................................ 55
Figure 48, Schematic of the PIV equipment setup in the wind tunnel .......................................................... 56
Figure 49, Onset flow speeds with the seeding rake ..................................................................................... 57
Figure 50, Seeding rake induced freestream turbulence ............................................................................ 57
Figure 51, Round-edged model yaw moment coefficients, clean tunnel and with seeding rake ........ 58
Figure 52, PIV image calibration .............................................................................................................. 59
Figure 53, Davis model dimensions ........................................................................................................ 62
Figure 54, The two upper halves of the Davis model with different rear pillar geometries ...................... 62
Figure 55, Centreline pressure distribution of the round-edged model ...................................................... 63
Figure 56, Drag coefficient Reynolds number dependency ........................................................................ 64
Figure 57, Yaw moment coefficient repeatability ..................................................................................... 65
Figure 58, Side force coefficient repeatability ............................................................................................ 65
Figure 59, Wind tunnel working section roof and floor boundary layer velocity profiles .......................... 66
Figure 60, Lift coefficient Reynolds number sensitivity ............................................................................ 67
Figure 61, Surface flow visualisations, 0° yaw .......................................................................................... 69
Figure 62, Sketch of the friction lines on the rear of the round-edged Davis model ................................. 69
Figure 63, Sketch of the friction lines on the rear of the square-edged Davis model ............................... 71
Figure 64, Rear pillar, recessed step flows ............................................................................................... 72
Figure 65, Flow similarity with a notchback, the right hand image taken from (44) .................................. 72
Figure 66, Steady state pressures on the round-edged Davis model, 0° ..................................................... 73
Figure 67, Steady state pressures on the square-edged Davis model, 0° .................................................. 74
Figure 68, Mean Davis model wake vector fields, 0° .................................................................................. 76
Figure 69, Mean wake vorticity, 0.25L, 0º ................................................................. 77
Figure 70, Mean vorticity behind a Davis model at 0º, taken from (10) ......................... 78
Figure 71, Vorticity behind the Durham Geometry model at 0º, taken from Ryan (85) ........ 79
Figure 72, RMS pressure fluctuations on the round-edged Davis model, 0º ...................... 79
Figure 73, RMS pressure fluctuations on the square-edged Davis model, 0º ...................... 80
Figure 74, Davis model wake RMS velocities, 0º .......................................................... 82
Figure 75, Davis model wake RMS Vorticity, 0º ............................................................. 83
Figure 76, Instantaneous trailing vortex centres in the wakes of the two Davis models, 0º 84
Figure 77, Spectral content on the rear pillar of the round-edged model, 0º .................... 86
Figure 78, Alternate vortex strengthening, round-edged model, 0º ................................. 88
Figure 79, Vertical and lateral vortex core motion, round-edged model, 0º ................. 89
Figure 80, Changing downwash strength, square-edged model, 0º ................................. 89
Figure 81, Wake asymmetry at 0º model yaw angle, onset flow from the left of the image 90
Figure 82, Flow field asymmetry in the static pressures, taken from (85) ......................... 91
Figure 83, Sketch of the flow field over the rear of the square-edged model .................. 92
Figure 84, Sketch of the flow field over the back of the rear of the round-edged Davis model ... 93
Figure 85, Davis model side force coefficients ............................................................... 95
Figure 86, Davis model yaw moment coefficients .......................................................... 96
Figure 87, Location of longitudinal centre of pressure, non-dimensionalised against model length... 96
Figure 88, Davis model lift coefficient at yaw ............................................................... 97
Figure 89, Effect of model yaw angle origin ............................................................... 99
Figure 90, Side force coefficient Reynolds number dependency at 10º yaw angle ............ 100
Figure 91, Round-edged model flow visualisation, -5º yaw ........................................ 101
Figure 92, Square-edged model flow visualisation, -5º yaw ........................................ 101
Figure 93, Smoke flow visualisation of the A-pillar vortex and trailing vortex on a production Jaguar XF ......................................................................................................................... 102
Figure 94, Steady state surface pressures, round-edged model, -5º yaw ......................... 102
Figure 95, Steady state surface pressures, round-edged model, -10º yaw ...................... 103
Figure 96, Steady state surface pressures, square-edged model, -5º yaw ....................... 103
Figure 97, Steady state surface pressures, square-edged model, -10º yaw ..................... 104
Figure 98, ΔCp round-edged model, -10º yaw ............................................................ 105
Figure 99, ΔCp square-edged model, -10º yaw ............................................................ 106
Figure 100, Steady state, area weighted aerodynamic load coefficients ......................... 106
Figure 101, Steady state area weighted lift coefficients ................................................ 107
Figure 102, Yawed model wake flow fields ............................................................... 108
Figure 103, Mean wake vorticity at -10º yaw .............................................................. 110
Figure 104, Wake vorticity, -10º yaw, modified image from Davis (10) ....................... 111
Figure 105, Wake vorticity behind the Durham geometry model at -7º yaw, taken from (85) ........112
Figure 106, RMS surface pressure fluctuations, round-edged model -5º yaw ........................................113
Figure 107, RMS surface pressure fluctuations, round-edged model, -10º yaw ..................................113
Figure 108, RMS surface pressure fluctuations, square-edged model, -5º yaw ..................................114
Figure 109, RMS surface pressure fluctuations, square-edged model, -10º yaw ...............................114
Figure 110, RMS in-plane velocities at yaw, 0.25L ...........................................................................116
Figure 111, Leeside instantaneous vortex centre tracking, -10º yaw ..................................................117
Figure 112, RMS vorticity fluctuations, 0.25L behind the model at -10º yaw ....................................118
Figure 113, Broad spectral peak around 60Hz on the leeside of the model ....................................120
Figure 114, Instantaneous spectral peak around 60Hz on the leeside of the model ...............................120
Figure 115, Unsteady A-pillar vortex, round-edged model, -10º yaw ..................................................122
Figure 116, Unsteady leeside vortex mixing, round-edged model, -10º yaw ........................................122
Figure 117, Unsteady A-pillar vortex motion, square-edged model, -10º yaw ..................................123
Figure 118, Extra wake vortices, in-plane velocities square-edged model, -10º yaw .......................124
Figure 119, Extra wake vortices, swirl, square-edged model, -10º yaw .............................................124
Figure 120, Unsteady drag measurement power spectral density ...........................................................128
Figure 121, Comparison of steady state and continuously sampled side force coefficients ...............129
Figure 122, Comparison of steady state and continuously sampled yaw moment coefficients ..........129
Figure 123, 1Hz, ±11º driven yaw angle oscillations, KM = 0.049 .......................................................131
Figure 124, Creating small samples of pressure data to use with the Fourier transform .....................132
Figure 125, Round-edged model, phase locked PIV, 0º yaw angle distribution .......................................134
Figure 126, Deviation from true mean of a PIV vector, oscillating model wake ...................................135
Figure 127, Surface pressure hysteresis beneath the A-pillar, KM = 0.049 ..........................................136
Figure 128, Comparison of steady state and oscillating aerodynamic load coefficients, KM = 0.049 ....136
Figure 129, Oscillating front and rear side force coefficients, KM = 0.049 ...........................................137
Figure 130, Hysteresis in ΔC_p at -10º yaw ....................................................................................138
Figure 131, Differences between steady state and oscillating surface pressures .............................139
Figure 132, Phase and amplitude change between quasi-static and oscillating surface pressures, KM = 0.049 ...............................................................139
Figure 133, Changes in the dominant frequency of quasi-static and oscillating model surface pressures; A-pillar and trailing vortex interaction taken from the top of the A-pillar in the left hand plot and high pressure region in the right hand plot ..........................................................141
Figure 134, Approximate extents of the flow structures that couple with the oscillating motion ..........141
Figure 135, Round-edged model surface pressure hysteresis, -10º yaw angle ......................................142
Figure 136, Square-edged model surface pressure hysteresis, -10º yaw angle .....................................143
Figure 137, Phase change between steady state and oscillating model surface pressures on the backlight, KM = 0.049 ........................................................................................................144
Table 1, Underfloor balance load accuracy .......................................................................................... 50
Table 2, Force coefficients calculated from the surface pressures.......................................................... 73
Table 3, Aerodynamic force coefficient standard deviations, 0º .......................................................... 81
Table 4, Minimum and maximum vorticity in the trailing vortices....................................................... 110
Table 5, Side force coefficient standard deviations ............................................................................ 115
Nomenclature

A  model frontal area (m²)
a  model surface area surrounding a pressure tapping (m²)
b  backlight length (m)
CD  drag coefficient
CD*  drag coefficient standard deviation
CL  lift coefficient
CL*  lift coefficient standard deviation
CMz  yaw moment coefficient
CMzβ  yaw moment coefficient derivative
CP  pressure coefficient
CS  side force coefficient
CSβ  side force coefficient derivative
CSF*  front side force coefficient standard deviation
CSR*  rear side force coefficient standard deviation
e  ratio of model frontal area (A) to working section area (WA)
f  dominant unsteady frequency (Hz)
H  model height (m)
h  distance from floor (m)
KM  reduced frequency
l  model length (m)
P  pressure (Pa)
P∞  freestream dynamic pressure (Pa)
Re  Reynolds number
St  Strouhal number
Uo  freestream onset velocity (m/s)
Uc  model blockage corrected onset velocity (m/s)
W  model width (m)
w  distance from model centre plane (m)
WA  wind tunnel work section cross section area (m²)

β  yaw angle (°)
ρ  air density (kg/m³)
μ  absolute viscosity (Ns/m²)
1. Introduction

Road vehicle aerodynamics has only seen periodic interest during the 126 years since Karl Benz was granted the first patent for a car. The first period of systematic aerodynamic development occurred between the wars and led to streamlined cars. The interest in vehicle aerodynamics was only seriously followed up when the 1970’s oil crisis raised petrol prices and there was a drive to increase the efficiency of road vehicles, and this has been renewed in recent years with rising fuel bills and a desire to mitigate climate change.

Overcoming aerodynamic drag is a major power requirement, especially at high speed, and reducing drag is a vehicle aerodynamicists main task. Current design trends to help achieve this are for very rounded front ends, shallow back light angles with squared off rear ends, and for new versions of ‘saloon’ cars to have rear ends more representative of fastbacks. Active devices are increasingly common, for example cooling grills that close when not required and rear spoilers that raise and lower to give either rear end stability or low drag. However, geometry and detail changes that reduce drag often increase other unfavourable aerodynamic loads which compromise the vehicle’s stability and reduce subjective assessments of vehicle refinement. Drivers can experience issues in high speed straight line stability, cornering and braking, when changing lane, and, most commonly, with crosswind sensitivity. Therefore, a vehicle’s design needs to be an appropriate compromise between the drag and stability and refinement requirements.

Aerodynamic development is mostly carried out using steady state wind tunnel measurements and CFD simulations, which do not attempt to replicate the unsteady onset conditions that are experienced under normal driving conditions. On-road, naturally occurring wind conditions contain a wide range of frequencies from small scale turbulence through local wind effects created by road side topology and vehicle motion to very large scale changes in weather conditions. Unsteady onset conditions can create different flow fields, and subsequent aerodynamic loads, to those found under steady state conditions but the differences are not fully understood and there is no comprehensive description or model of the differences. There is a desire to better understand the unsteady effects to ensure both vehicle refinement and the safety of future vehicles. As cars get lighter, the aerodynamic loads will increase relative to the inertia of the vehicle which could lead to undesirable or even dangerous effects that are not found using a steady state approach; understanding the unsteady effects may also open new avenues for drag reduction. Research into unsteady aerodynamics has been piecemeal, often focusing on
a specific situation or type of onset flow, these test conditions can be classified by the reduced frequency term, Sims-Williams (1), given in equation 1.

\[ K_M = \frac{\pi f l}{u_a} \]  
Eq. 1

This thesis will add to this expanding body of research by investigating the aerodynamic unsteadiness associated with a simple fastback automotive body. It will compare the flow fields and aerodynamic loads created by a statically mounted model to those created by a model oscillating in yaw; this motion crudely approximates a time dependent crosswind. To provide context and isolate model specific effects, two fastback model configurations are used.

This introductory chapter will start by summarising the current understanding of the differences between steady state and unsteady flow fields around static models. The real world onset conditions and their effects on the vehicle and driver are investigated and the review will then focus on existing steady state and transient yawed model research, which will also include looking at more some more abstract, simple shape fluid dynamics experiments carried out in similar, unsteady test conditions.

1.1 Road Vehicle Flow Fields

Road vehicles are highly three dimensional and classified as aerodynamic bluff bodies with the flow field dominated by large regions of separation. Production vehicles come in a wide range of shapes but can be grouped into three basic types depending upon the shape of the rear of the vehicle fastback, squareback (estate) or notchback (saloon). The fastback shape is characterised by a slanted rear surface that the flow remains attached to; as the rear slant angle increases the flow detaches from the top of the backlight and produces a squareback flow field. The notchback shape has a rear slant and then an extended boot deck. Although this thesis uses a fastback model, the other two vehicle shapes will be considered to demonstrate that unsteadiness is important to all the vehicle shapes. All the results in this section were collected under steady state onset conditions, with a static model at 0° yaw, very low levels of freestream turbulence and high levels of flow uniformity.
1.1.1 Fastback

The fastback shape is characterised by the vehicle having a small backlight angle such that the flow remains attached until the rear edge of the vehicle. Current vehicles that have this characteristic include the Honda Civic, Jaguar XK and Citroen C4. There is also an increasing trend for ‘saloons’ to have a fastback rear end; examples of this include the Jaguar XF and XJ, Mercedes CLS and VW Passat CC.

One of the earliest investigations into the effect of rear slant angle was carried out by Morel (2). Initially using a cylinder with a streamlined nose, mounted streamwise with a slanted base, he investigated the effects of the base slant angle on the wake and aerodynamic forces. A critical angle, where there was step change in base pressure, drag force and beyond which shedding was found in the wake, was found at 47° from vertical, although the supporting wires upstream of the model slightly changed the critical angle. Changing the angle of attack of the cylinder produced hysteresis in the step change depending on whether the angle was increasing or decreasing. Using a shape more representative of a road vehicle, a similar step change was found, with the critical angle now occurring at 60°. (Morel measured from the angle from vertical but standard practice now is to measure the slant angle from horizontal, hence 30º). The step changes in the forces were of greater magnitude than with the cylinder and flow visualisations showed two very strong vortices present just below 60° and only very weak vortices present above this angle.

Ahmed et al (3) further investigated the effect of rear slant angle using the, now widely used, Ahmed model. This model had a simple rounded front end and long mid-section to isolate the flow field effects created by an interchangeable rear slant angle. Base surface pressures and wake velocities were recorded and these results were supplemented with flow visualisations in the wake. The time-averaged results showed two contra-rotating trailing vortices originating from the edges of model’s rear slant, Figure 1 with a quasi 2D separated region directly behind the model base. The trailing vortices induced a downwash on the backlight keeping the flow attached at larger angles than possible on a simple 2D flat plate. As the rear slant angle increased up to 30º, the vortices strengthened and two complex areas of recirculation were formed on the backlight, as shown in the right hand image. The stronger vortices created large amounts of induced drag which were greater than the reduction in drag from a smaller base region. At rear slant angles larger than 30º, the same angle as found by Morel, the flow over the rear of the model separated from the rear edge of the roof and overall drag reduced by 1/3. From smoke wand results Ahmed reported that the instantaneous flow fields were different to the time averaged flow fields, but this was not expanded upon.
Since its development, the Ahmed model has been widely used and its flow field has been thoroughly investigated both experimentally and as a CFD test case, the results of both adding to Ahmed’s results. Spohn and Gillieron (4) carried out detailed flow visualisations and found that the flows over the backlight were more complex than explained by Ahmed with additional flow structures present in the recirculations found on the backlight. Krajnović and Davidson (5), (6) and (7) also showed that the near wake behind the model base was more complex than sketched by Ahmed and that there are vortices extending along the length of the model at the edges between the model sides and floor. Guilmineau (8) showed that the shearing action of the trailing vortices distorted the wake behind the base of the model causing it to twist around the vortices in the upper corners. He also found that the recirculations on the backlight were highly unsteady and were the last structures to resolve within the CFD solver.

Bearman (9) and Davis (10) developed the Davis model, a 10th scale fastback model with interchangeable front and rear ends and a diffuser, designed to be more representative of a road vehicle than the Ahmed model, and carried out wake surveys in different planes behind the model. It was found that the vortices from the rear pillars were the strongest structures in the wake but the A-pillar vortices and vortices from the corners of the diffuser were also seen, Figure 2.
Howell (11) carried out a similar experiment to Ahmed and investigated the effect of rear slant angle and edge rounding using a model with more representative automotive shape than the Ahmed model. The step change in the aerodynamic coefficients was found for both model configurations but the critical angle and magnitude of the step change in drag on the model with the round edges were different from that reported by Ahmed. The model outline and drag and yaw moment coefficient results are in Figure 3, these plots also show the discontinuity in the lift and yaw moment occur at different backlight angles although the reasons for this were not investigated. These results demonstrate the importance of the rear edges to the wake implying that the flow structures created by production road cars may be slightly different from those found by Ahmed.

Details of one of the first experiments that showed an instantaneous flow field behind a simple fastback car model were published by Bearman (12). Using a very early PIV system, the results
included an instantaneous wake flow field in a plane parallel to the model base, shown in the left hand plot of Figure 4. Instead of two clearly defined vortices, the wake was made up of a large number of small, instantaneous vortices that were described as moving in a random way in time and space. However, when 10 instantaneous flow fields were averaged, the small, individual vortices were lost and the two dominant vortices described by Ahmed appeared, as shown in the right hand plot. It was concluded that assuming that the wake only consisted of two well formed vortices is an incomplete description of the flow field with the instantaneous flow field being highly unsteady.

![Figure 4, Instantaneous and mean vector fields behind a hatchback, taken from (12)](image)

Bearman also showed PIV derived flow fields on the vertical centre line of the model base. Vortex shedding from the lower edge of the rear slant, at a Strouhal number of 0.23 based on the height of the model’s boot, was found demonstrating that the quasi 2D wake behind the model base was also unsteady. Shedding from the lower edge of the rear slant, in agreement with Bearman, was also reported by Duncan et al (13) using a VLES CFD solver and the Ahmed model and by Sims-Williams and Duncan (14) who compared the simulated results to experimental results.

Strouhal number, defined in equation 2, is mathematically very similar to the reduced frequency term but has a very different meaning. The reduced frequency describes the unsteadiness in the onset flow whereas Strouhal number is a ratio of the inertial forces of an unsteady component of the flow field to the inertial forces of the velocity between two points of the flow field; it is used to describe periodic features within the flow field. Flow field periodicity can be found in nominally steady state test conditions; the classic example of a periodic low structure is the Von Karman vortex street behind a cylinder, in Figure 5. This flow structure creates a Reynolds number independent Strouhal number of 0.21 and this value can often be found in periodic flow.
fields generated by more complex geometries when calculating the Strouhal number using the characteristic dimension of the shape that is driving the motion.

\[ St = \frac{fL}{U_o} \]  

Eq. 2

The highly unsteady instantaneous trailing vortex structure found by Bearman was also reported by Shaw et al (15) who used hot wire data to produce instantaneous flow fields. This showed the small and seemingly random vortices mainly occurred at the edges of the time-averaged trailing vortices. This implies that the instantaneous unsteadiness is caused by the shearing action between the trailing vortices and the freestream flow.

Evidence that the time-averaged wake behind a hatchback production was not accurately described by the Ahmed model was provided by Sims-Williams et al (16) also in Sims-Williams (17). They investigated the wake behind a scale model of a Rover 200 using surface pressure tappings, a 5-hole pressure probe and a hot wire and compared the results to the wake of an Ahmed model with similar rear slant angle. Adding two different sized spoilers to the trailing edge of the roof of the Rover 200 caused progressive reductions in drag and lift, rather than the step change between the high and low drag wake structures that would be expected of the Ahmed model. This result was partially attributed to the rounded rear pillars of the Rover 200 model. However, wake surveys showed the presence of the A-pillar vortices that, in addition to other smaller upstream influences created by the detailed model surface, will have had an effect on the trailing vortices and wake, in agreement with Morel and Howell. The presence of distinct A-pillar vortices in the wake of a scale production car model was also found by Vino et al (18) when carrying out wake surveys using a cobra probe. The influence of upstream flow features was also demonstrated by Strachan et al (19) who increased the critical backlight angle of an Ahmed model by mounting it with a wing section sting from above, rather than on struts from the floor. Whilst the level of dependency of the trailing vortices and wake flows on upstream flow structures is unclear, the results of Morel, Howell, Sims-Williams and Strachan all lead to the conclusion that the upstream flow conditions are important to the formation of both the steady state and unsteady wake flow structures.

Sims-Williams also investigated the frequency content of the trailing vortices and near wake of the Rover 200 using a 5 hole pressure probe and identified two distinct shedding frequencies, one at St \( \approx 0.1 \) and the second at St \( \approx 0.3 \); calculated using free stream velocity and the square root of frontal area. The lower frequency was related to an asymmetric strengthening of the C-pillar vortices that was also reported by Duncan (13) in the wake behind the Ahmed body with a
25° rear slant angle. The higher Strouhal number was associated with a vertical oscillation of the trailing vortices. It was concluded that the spectral content of the wake was highly dependent upon background unsteadiness present within the wind tunnel; which is further evidence that upstream influences can have a significant impact on the wake. It was postulated that the trailing vortices were fed by small individual vortices that progressively pair up until they form a large C-pillar vortex and these proposed smaller vortices were further investigated by Sims-Williams et al (20) using the Ahmed model suspended in a water tank with ink injected along the rear pillar. The results showed the main trailing vortices contained smaller, discrete vortices periodically shed from the rear pillar. Once shed, they progressively paired up and formed into the main vortex. The discrete vortex shedding was independent of Reynolds number and was a function of rear slant angle occurring at Strouhal numbers between 8 and 12, with larger angles producing faster shedding rates. The initial small vortices were identified as Kelvin-Helmholtz instabilities, formed in the shear layer between the fast moving, separated bulk flow and the slower flow in the wake. Further downstream, due to the pairing process, the vortices grow and these small vortices present around the main vortex structures may be the small unsteady vortex structures found around the edges of the trailing vortices by Bearman and Shaw.

Another periodic flow feature was reported by Depardon et al (21) who found that shedding was coming from regions of recirculation found towards the top of the backlight, seen in the left hand image in Figure 1. No details of frequency were given but a similar feature is found in notchback wakes.

Schröck et al (22) used an SAE model with a rounded rear end and investigated the model’s wake in a clean tunnel and with 4% free stream turbulence. They found that the addition of the turbulence changed the phase of the shedding from each side of the model: in the low turbulence onset conditions the vortex fluctuations were anti-phase but with the increased free stream turbulence the shedding became in-phase. These results further confirm the influence that upstream and onset flow features can have on the wake flow structures.

Better understanding of the periodic flow features reported behind fastbacks can be gained from investigating the flows behind simple 2D shapes. Dependent upon Reynoldsl number and surface roughness, Basu (23), the wake behind a simple circular cylinder can contain a strong, alternating, asymmetric wake structure, Figure 5. Vortices are alternately shed from opposite sides of the cylinder with the unsteady flow field generating unsteady forces acting on the model, Houghton and Carpenter (24).
Kikitsu et al (26) showed that a finite length cylinder had a further shedding mode from the free end of the cylinder and that vortices shed from long cylinders can split along their length. Bearman and Tombazis (27) also found this result from a more fundamental aerodynamic experiment investigating the wake behind a long, half elliptic cylinder. Along the length of the model the Von Karman vortices would split; further work to control the lengthwise splitting found two shedding frequencies - each relating to shedding from different parts of the cylinder, there was also a much smaller third spectral peak that was related to switching between the two shedding modes, however no real explanation was given for these different shedding modes. Further to this, Irwin (28) found that splitting the vortices caused a reduction in drag. When investigating forces on high rise buildings with balconies, the balconies split the shed vortices and caused a reduction in the drag acting on the model. The cause of this drag reduction was found by Yeo and Jones (29) who explained that the drag reduction was caused by a swirling flow structure that formed on alternate sides of the cylinder. These were intensely low pressure and had the effect of delaying the vortex shedding causing it to split.

In addition to the Von Karman vortex street, Passmore et al (30) showed that close to the model surface rather than a single large vortex being shed there were smaller, higher frequency Kelvin Helmholtz instabilities, shed from the separation points on the sides of the cylinder. As these travelled downstream they formed into the main Von Karman vortex structure; this is a similar mechanism to that reported by Sims-Williams in the formation of the trailing vortices of the Ahmed model. Passmore’s result implies the Kelvin Helmholtz instabilities very close to the model are vital for the formation of the near wake slightly further downstream and any interference to these may cause greater changes to the near wake Von Karman vortex street than would be expected. This interference may come from upstream flow structures which agrees with the general findings using the automotive models that showed upstream influences had a large influence on the wake flows.

Flows around rectangular cylinders display similar shedding to circular cylinders, although Okajima (31) found that the Strouhal number was dependent upon Reynolds number and
slenderness ratio which is shown in Figure 6, taken from Deniz and Staubli (32). The plot shows two discontinuities at slenderness ratios of 2.8 and 6. These were caused by different flow fields around the rectangles, sketched in the figure based on findings of Shimada and Ishihara (33). The discontinuity at 2.8 was also found by Norberg (34) and Nakamura and Nakashima (35) and is caused by the vortices shed from the leading edges of the model impinging on the sides of the model as the length of the model increases. This is an unsteady process and there remains a strong interaction between the front vortices and those shed from the trailing edges. The discontinuity at a slenderness ratio of 6 is caused by the model becoming infinitely long, such that the separations from the leading edges have no interaction with the vortices in the wake.

![Figure 6, Strouhal numbers of rectangles, taken from (32)](image)

### 1.1.2 Squareback

The squareback body shape is usually found on estates, commercial vehicles and most hatchback cars

Duell and George (36) investigated the near wake behind a simple bluff, rectangular body, representative of a commercial vehicle by taking measurements of base surface pressures and using a hot wire to find mean flow speeds in the wake. A separated region made of two trapped transverse vortices enclosed by a shear layer boundary was found. The recirculation length was
unsteady and varied with time; upon reaching a critical length a vortex was shed from the tip of the separation area after which the recirculation length would reduce. This periodic process had a Strouhal number of 0.069 and is illustrated in Figure 7. It was also found that vortices were shed from the vertical rear edges of the model at a Strouhal number of 1.157. Further downstream the vortices paired up, increasing the size of the vortices and halving the frequency; this shedding was happening in anti-phase on opposite sides of the model. The high frequency, small vortices shed from the edges of the model originate from Kelvin-Helmholtz instabilities and are very similar to the vortices identified by Sims-Williams coming from the edges of the rear pillar and the vortices found in the near wake of a circular cylinder.

Figure 7, Squareback wake flow features, taken from (36)

A similar shape was investigated by Khalighi et al (37), using surface pressures, PIV and CFD to understand the effects of a stream wise plates mounted on the model base. Without the plates a spectral peak was found at St = 0.07. This corresponded to a pumping of the stagnation point that changed the size and shape of the separation behind the body which matches the results of Duell and George. This spectral peak was also found by Bayrakter et al (38), who used CFD on an Ahmed body with a 0° back angle and found spectral peaks in the wake at St = 0.106 relating to lift and St = 0.086 relating to side force; Al-Garni et al (39), who found shedding at St = 0.07 behind a generic SUV using PIV, and Krajnović and Davidson (5), who used CFD and found shedding at St = 0.073 behind an Ahmed model with 0° rear slant angle.

PIV results, Figure 8, taken from Littlewood and Passmore (40) clearly show the difference between a time averaged and instantaneous flow behind a squareback rear shape. In the right
hand image there is evidence of shed vortices in the shear layer from the trailing edge of the model, similar to those reported by Duell and George. However, this shedding was not a continuous process, the presence of the vortices in the instantaneous flow fields was apparently random; the reasons for this were not explored.

Figure 8, PIV vector fields behind a squareback, taken from (40)

1.1.3 Notchback

The third body shape is the notchback; cars of this shape are commonly called saloons or sedans and are characterised by a region of separated flow on the ‘bootdeck’. The first major investigation into this body shape was published by Nouzawa et al (41) who defined an ‘effective angle’ from the rear edge of the roof to the trailing edge of the boot. The influence of the effective angle on the drag coefficient was investigated and similar results to those found by Ahmed were found, albeit with a critical angle at 25° rather than 30°. The proposed flow field around the model at effective angles below the critical angle is in Figure 9.

Figure 9, Notchback flow field, taken from (41)
Further work by Nouzawa et al (42) found periodic shedding from the arch vortex at frequencies between 20 and 30 Hz (these give Strouhal numbers based on the square root of the frontal area of 0.09 and 0.14). Past an effective angle of 25°, the shedding intensity was reduced but could still be found in the instantaneous drag and lift forces. Gilhome et al (43) investigated the wake structure of a notchback using production vehicles. They found two dominant frequencies within the notch region, one caused by large scale shedding of the recirculation within the notch with associated changes in size, in agreement with Nouzawa, and one at a higher frequency caused by vortices present in the shear layer. The shedding from the arch vortex may be a similar mechanism to the base wake pumping found behind squarebacks, Duell and George (36), and the flow structures in the notch are very similar to the recirculations found at the top of the backlight of a fastback, Depardon (21).

Garry and Le Good (44) looked at the effect of mounting a rear wing on the boot of a saloon. As expected there were changes to lift and drag but surface flow visualisation showed the separation in the notch had become asymmetric. Asymmetry in the notch region has also been seen in a number of other studies; summarised by Gaylard et al (45) who put forward a number of possible causes for this, including that small perturbations in the onset flow have a greater effect than expected.

In general, the results for the three model shapes show two common themes: the instantaneous and unsteady flow fields are quite different from the steady state results and that upstream influences can have a large influence on wake flow features.

1.2 Yawed Onset Flow Conditions

Under normal driving conditions, road vehicles are subject to unsteady onset conditions with changing wind speeds and directions caused by changes in vehicle speed and direction, meteorological changes and the influence of other road users and local road side topography. With a none-zero onset flow yaw angle the flow field created around the vehicle is asymmetric creating side force, yaw moment and roll moment in addition to drag, lift and pitch. The effect of yaw angle on the steady state surface pressures on a large saloon car are shown in Figure 10, with the largest effects at the corners of the vehicle. There is a large suction peak on the leeward front corner and significant asymmetric forces also develop around the A-pillars and rear pillars of the vehicle. These lateral aerodynamic loads try to disturb the heading of the vehicle and turn the vehicle away from the wind direction.
The onset flow yaw angle is created by a vector sum of the vehicle speed and the angle of the wind, shown diagrammatically in Figure 11.

The vehicle speed, \(-V\), combines with the ambient wind, \(V_w\), to create the relative flow speed, \(U_o\), that acts at an angle of \(\beta\) to the vehicle. Typically the vehicle speed is significantly larger than windspeed and, shown in Figure 12 taken from Cooper (47), as the vehicle speed increases the yaw angles decrease. These results also shown large yaw angles are uncommon even at low vehicle speeds.
This is further confirmed in Figure 13 which shows a histogram of onset flow yaw angle data collected by Carlino et al (48) whilst driving at 140Km/H (84mph) on an autobahn in northern Germany in normal weather conditions. It shows the onset flow yaw angle is normally distributed, with a mean value \( \neq 0^\circ \) and standard deviation of \( \approx 3^\circ \) but with quite extreme outliers up to \( \pm 10^\circ \). The mean value is not 0\(^\circ\) because of prevailing winds that mean it would be rare for a mean yaw angle to ever \( = 0^\circ \).
cuttings and bridges. Apart from the gust profile caused by passing a large vehicle, which only happened when the instrumented vehicle was downwind, all the other gust profiles were recorded whether the mean wind direction was from the left or right. However, 30% of distinct ‘gusts’ found in the data could not be attributed to any specific road side feature and were attributed to general turbulence. A similar experiment was carried out by Wojcik et al (51) on roads in Germany. They found three distinct gust profiles repeated within the data; however no record of the local topography was taken so it was not possible to link these profiles to any source. Reoccurring trends in onset flows were also reported by Aynsley et al (52), Figure 14, who showed that the frequency domain of wakes from different types of built structure had distinct frequency contents.

Figure 14, The wake frequency content of different built structures, taken from (52)

Goetz (53), in Figure 15, showed the influence of unsteady yaw inputs on full scale production road vehicles is very frequency dependent and defined three boundaries of different types of vehicle response based on the onset flow frequency. These are different from the freestream turbulence frequency boundaries defined by Newnham (54) that are relevant for drag reduction and shape optimisation, reflecting that yawed flows affect vehicle handling.
Figure 15, Vehicle response to different frequency inputs, taken from (53)

- Range A, <0.5Hz, are experienced as quasi-static changes and lead to path deviation.
- Range B, 0.5Hz – 2Hz, is the most important for vehicle handling and stability. It corresponds with vehicle resonances and is characterised by resonance responses and lags.
- Range C, >2 Hz, is experienced as buffeting and noise and affects vehicle refinement. There is no effect on vehicle path deviation.

In addition to the yaw angle data, onset flow yaw rates have been calculated using on-road wind data provided by Oettle (55) and Walker (56), in Figure 16. Data collected on ‘calm’ and ‘windy’ days have been provided by Oettle, windspeed and direction was recorded using a 5-hole probe mounted 320mm above the roof of the test vehicle as it was driven along the A1(M) in North East England with data collected for 30 seconds at 500Hz. Walker recorded the three components of windspeed with a cobra probe mounted 500mm above the roof centreline. Data was sampled at 1000Hz for 10 seconds as the vehicle was driven at 70mph on the M1 in the East Midlands. Each data set had a general description of traffic conditions but the weather description was generalised for the test day. The yaw angle data was low pass filtered at 5Hz, based on Figure 15, to remove the effects of small scale turbulence that do not influence the bulk onset flow and the yaw rates were found using a simple backwards differencing method.

Oettle’s two data sets produce quite different results; the calm day shows a much narrower range of yaw rates, with the majority between ±20°/sec, than the results from the windy day.
The ‘windy day’ results have a much wider and smoother spread of yaw rates with a peak is around 10°/sec caused by the prevailing wind from the west.

![Figure 16, Onset flow yaw rates, Oettle data in the left graph, Walker data in the right graph](image)

The two highlighted results found using Walker’s data show the recorded yaw rates sit between two extreme cases. The green results line has a very narrow spread of yaw rates and high central peak, whilst the other, in red, is much wider and has a flatter distribution of yaw rates with no main peak and these two results encompass a wider range of yaw rates than Oettle’s. The yaw rates found in Oettle’s data imply a strong link between ambient conditions and the onset flow yaw rates but Walker’s data, collected on a single day in consistent weather conditions, show the range of yaw rates are independent of weather conditions which is in agreement with Smith and Wojciak.

All the on-road crosswind results indicate there are specific, repeated crosswind inputs experienced by road vehicles. This leads to the conclusion that recreating these in wind tunnel conditions would be useful towards better understanding the unsteady, transient, lateral aerodynamics of road vehicles. However, the majority of yaw rates in Figure 16 are within the range ±50°/s, using this with a typical production vehicle length (5m) and the motorway speed limit gives a reduced frequency of 0.07, which implies most on-road yaw angle changes fall within a frequency range generally considered quasi-static. This may indicate unsteady yawed flow testing is unnecessary or, more likely, that the reduced frequency term does not adequately describe the onset unsteadiness.

The circumstances that produce the large yaw rates and extreme yaw angles are likely caused by crosswind gusts due to the unusually windy conditions or the influence of nearby objects, rather than being feature of normal driving conditions. Published work uses the terms ‘crosswind’,
‘gust’ and ‘sidewind’ seemingly interchangeably, but the author would like to create a clearer definition of the terms for unsteady yawed flows. A gust is a sudden, high frequency change, a crosswind gust explains the gust creates a yaw angle, and a crosswind or sidewind is lower frequency and does not produce extreme yaw rates or angles and these definitions will be used throughout this thesis.

Schröck et al (57) further complicate the matter by describing an oscillating yawed onset flow as ‘turbulent’. Turbulence implies a level of variation from the mean wind speed and encompasses all frequencies from the largest scale caused by changing seasons to very small scales caused by sound waves. Newnham (54) postulated that turbulent effects can be classified into two categories dependent upon the turbulent length scales. When the turbulent length scale is comparable to or greater than the length of the model the effect is that of a low frequency, bulk flow change. Smaller turbulent length scales influence the shear layers around the model increasing pressure fluctuations and changing separation and reattachment points. Sims-Williams (1) also used turbulent length scale to classify the effect but proposed different boundaries. Quasi-static was defined with length scales greater than 300m on a full scale car and unsteady effects had length scales below 30m; between these two limits is a region where effects cannot easily be classified into one of the two. If the flow is sinusoidally yawing then the onset flow speed, relative to the vehicle axis, will be constantly changing with time. This can be mathematically described using ‘turbulence intensity’; however the strongly periodic content of the sinusoidal flow will not have the same effects as true stochastic turbulence containing no dominant frequencies. Furthermore, the length scales created by such onset flow are an order of magnitude larger than the model length and should be considered as a low frequency, bulk flow change.

1.2.1 The Influence of Aerodynamics on Vehicle Handling

On current production vehicles, road vehicle handling is dominated by tyre forces but unsteady aerodynamics can create problems if crosswinds or gusts cause the driver to lose control of the vehicle’s direction. The side forces and yaw moments created by yawed flows can turn or push a vehicle from its desired path and roll angles cause bump steer via the suspension geometry. There are also links between the lateral aerodynamic characteristics of a vehicle and its straight line stability that can manifest itself as undesirable lateral motion of the vehicle. In the future, light-weight cars will have smaller tyre forces and inertial loads but the aerodynamic loads will remain the same increasing the influence of aerodynamics on vehicle handling.
Wagner and Wiedemann (58) and Wagner (59) investigated a driver’s response to different crosswind inputs. They found that under steady-state conditions the driver was able to act against the crosswind with an equal and opposite steering input. As crosswind input frequency increased the phase of the response decreased, such that between frequencies 0.5Hz – 2Hz, with a maximum effect at 1.4Hz, the response from a typical driver was in phase with the input. This means the vehicle’s response to a crosswind was intensified by the actions of the driver. When considered alongside Goetz’s results, this is an important result as this frequency corresponds to vehicle resonances and is very influential to vehicle handling and stability.

Klein and Hogue (60) measured drivers’ responses to crosswinds and found that the lateral displacement caused by the steering response of the driver was greater than the initial disturbance from the crosswind. Using production cars and large fans Macadam et al (61) reported that different drivers have different steering responses to similar crosswind inputs. This leads to different amounts of path deviation but the drivers’ subjective stability assessments correlated well and there was a strong link between the static yaw moment gradient and the subjective crosswind ranking. Both these results and those of Wagner show that crosswinds cannot just be considered in isolation, the whole system of driver, vehicle and aerodynamic inputs needs to be considered to fully understand the effects.

Fuller et al (62) simulated a driver and hatchback in different sources of crosswind and then added in extra sources of unsteadiness that had been reported in various investigations into unsteady crosswinds. They found that the relatively large scale changes, inherent in the transient crosswind, had the greatest negative influence on the driver’s and vehicle’s response, adding further sources of aerodynamic unsteadiness on top of the transient input only worsened the response very slightly. These results demonstrate that with current vehicle designs, it is the yaw angle changes in the onset wind that are most important for vehicle handling, rather than the smaller scale effects that the transient yaw angles may create, despite these potentially being an intrinsic part of the aerodynamic response.

The influence of different vehicle chassis parameters on a vehicle response to a crosswind was investigated by Juhlin and Eriksson (63) using a bus modelled in ADAMS subjected to a crosswind gust that creates a yaw moment spike as the vehicle enters the gust (Chadwick (64)). The best improvement to the gust response was found when the centre of mass was moved forward. In general handling terms, this produces a vehicle more prone to understeer and less responsive to steer inputs. It also reduces the distance between the lateral centre of pressure and the centre of mass, reducing the yaw moment. The importance of the aerodynamic characteristics was also investigated and the most influential parameter was the yaw moment.
peak on entry to a crosswind gust; side force was less important. The importance of yaw moment over side force for vehicle crosswind wind response was also found by Buchheim et al (65).

Oraby and Crolla (66) carried out a similar experiment to Juhlin and also found the location of the centre of mass had the largest influence on a vehicle’s response to a crosswind. This was true in cases with an open loop control and with a closed loop model with a driver present.

Good high speed, straight line stability correlates with a low yaw moment gradient but is also directly linked to rear lift and pitching moment. Buchheim et al (65) showed that straight line stability was dependent upon pitching moment, with a positive pitch producing the most stable feeling vehicle. Howell and Le Good (67) reached a similar conclusion using a subjective testing method to assess the straight line stability of a range of different vehicles. The results showed one of the most important parameters for vehicle stability was the relative magnitudes of front and rear lift; cars with greater front lift were perceived as more stable than those with higher rear lift. The importance of rear lift was also found by Brassington (68) who investigated the cause of a number of high speed accidents involving the original Audi TT. It was found the rounded trailing edge of the TT’s boot produced undesirable levels of rear lift; the problem was solved with the addition of a rear spoiler to reduce rear lift and by suspension changes to promote understeer. Howell (69) added that undesirable aerodynamic characteristics can be masked by suspension settings, although this does slightly compromise the suspension design, but that handling sensitivities cannot be masked with aerodynamic characteristics.

Further evidence of a link between rear lift and vehicle stability is provided by Okada et al (70) and Nakashima et al (71) who carried out a thorough investigation into the stability of a notchback type production vehicle. Subjective testing showed transient changes to the rear ride height reduced the subject stability rating. The ride height changes originated in unsteady flow on the boot lid causing changes in the rear lift coefficient; reducing the unsteadiness of the rear lift coefficient improved the subjective vehicle stability.

Further research concerns crosswind induced accidents; Chen and Cai (72) investigated vehicles overturning on a long span bridge. As crosswind velocity increased the safe speed of a vehicle decreased linearly up to a critical crosswind speed beyond which there was no safe driving speed, for example in a hurricane; changing the road from a bridge to solid ground produced very similar results but with a higher critical crosswind speed. All accidents originated from a loss of load at the windward rear wheel and this is further evidence of a link between rear lift and lateral aerodynamics. Snæbjörnsson et al (73) did a probabilistic assessment of road safety
in ‘windy conditions’ created by yawed onset flow and found that there was a linear increase in accident likelihood up to vehicle speeds of 25m/s and beyond 30 m/s there was a constant probability of an accident >50%. This is in agreement with Chen and Cai, however Snæbjörnsson et al concluded that if the onset wind is from behind the vehicle, and assumed to be steady, then speeding up would reduce the onset flow yaw angle and actually increase safety.

1.2.2 Yawed Onset Flow testing

Although the on-road onset flow conditions are highly unsteady and contain a wide spectrum of frequencies the crosswind performance of most vehicles is tested under steady state conditions. The vehicle is yawed around the centre of the wheelbase and the entire vehicle is subject to the same onset flow angle. There is a general acceptance that this is a crude approximation of reality and there are a number of different methods that simulate the unsteady real world conditions by creating a transient onset flow yaw angle although none of these simulation methods fully recreate all the elements of the on road unsteadiness. However, wind tunnels that contain these tend to be owned and run by research institutions rather than vehicle manufacturers and even newly developed state of the art wind tunnels, such as BMW’s Windkanal (74) or Honda’s Full Scale Aero-acoustic Wind Tunnel (75), do not include full scale transient simulation facilities.

It was proposed by Macklin et al (76) that different yawed testing methods could be categorised into three types:

- Static – Static tests – the model and wind source are both steady during the measurements.
- Static – Dynamic tests – the model is stationary and the wind source can change.
- Dynamic - Static tests – the model is moved and the wind source is stationary.

1.2.2.1 Static – Static Tests

Static – static testing is the traditional and most common method of investigating a vehicles aerodynamics in yawed onset flow. The model or test vehicle is placed in a wind tunnel and a turntable is driven to move the vehicle to the desired yaw angle relative to the onset flow. The
flow field is given a short settling period before steady state measurements of the aerodynamic loads are taken; this type of test is also used in aero-acoustic and rain water management tests.

![Figure 17, Static-static yaw testing in Volvo’s full scale wind tunnel](image)

The yaw moment and side forces acting on the vehicle are generally linear and commonly quoted as gradients or derivatives, equations 3 and 4, rather than as specific coefficients. Hucho (77) states this linear relationship applies up to yaw angles of ±20° and that yaw angles larger than this are unlikely in normal conditions so there is no need to test at larger yaw angles; indeed, the measured yaw angles in Figure 13 indicate that 20° may be larger than necessary. This approach ignores very rare extreme gust conditions which are likely to lead to wind induced accidents but are not typical of normal conditions.

\[
S_{\beta} = \frac{dC_s}{d\beta} \quad \text{Eq. 3}
\]

\[
M_{z\beta} = \frac{dC_{Mz}}{d\beta} \quad \text{Eq. 4}
\]

In product development these gradients are used as an indication of the vehicle stability in crosswinds and targets are set from past experience and by benchmarking competitor vehicles. Almost all road cars have positive yaw moment and side force gradients with a lateral centre of pressure forward of mid wheel base; this is a directionally unstable yaw moment that turns the vehicle away from the wind but is inherent to typical road car shapes. From a driver’s perspective an ideal vehicle would have a benign response to onset flow yaw angle changes but mathematically, a negative yaw moment gradient is needed for stability.
The positive yaw moment gradient mostly originates from the suction on the front leeside of the vehicle. Steady state surface pressures on a large saloon at yaw were collected by Howell (46), shown in Figure 10. Pressure peaks were found on the leeside A-pillar, longitudinal roof edge, nose and the windward rear-pillar. The A-pillar was the main contributor to the side force, and the larger side force at the front of the vehicle than at the rear creates the positive yaw moment gradient.

Despite positive yaw moment gradients, the real world characteristics may not be as bad as implied by the steady state results; cars steer around the centre of gravity which is typically forward of mid axle and this may reduce the actual yaw moment experienced in the real world. Conversely, when fully loaded, the centre of gravity will move rearwards and the distance between the centre of pressure and centre of gravity is increased producing a larger yaw moment.

1.2.3.2 Static – Dynamic Tests

Static – dynamic tests change the yaw angle of the onset flow while keeping the model still.

Bearman and Mullarkey (78), Passmore et al (79) and Schröck et al (57) used oscillating aerofoils positioned upstream of the model to create a sinusoidally changing onset flow yaw angle, shown in Figure 18. This method can only create small yaw angles because of the dominance of the axial flow in the wind tunnel.

Figure 18, Oscillating aerofoils, taken from (79)
Bearman and Mullarkey, and Passmore et al used very similar experimental setups with oscillating aerofoils upstream of a Davis model, but found conflicting results. Bearman used an internal balance to measure the aerodynamic loads on the model and found steady state yaw moment and side force coefficients were larger than those found under transient onset flows. This result applied even at very low frequencies which might be assumed quasi-static. Passmore used surface pressure tappings on the sides of the model to calculate the aerodynamic loads acting on the model and found that the transient side force was smaller than under steady state conditions but the transient yaw moment coefficients were larger. Like Bearman, Passmore also found differences between steady state and transient results at low reduced frequencies, and, despite differences in the absolute values, both reported differences between steady state and transient coefficients. The surface pressure distributions found by Passmore show the transient yawing flow had the greatest influence on the A-pillar vortices, with large reductions in the amplitude along the A-pillar vortex reattachment lines, and smaller change at the rear of the model dominated by a phase lag. This meant that the transient flow field never reached a steady state condition, even with very low oscillation frequencies and large wavelengths. Bearman had postulated a mechanism such as this, but did not have the evidence to prove it.

Schröck et al (57) looked at the frequency response of the SAE model with notchback and hatchback rear ends, comparing this with the response of the model in a sinusoidally yawing, ‘turbulent’ onset flow. The notchback showed similar spectral results in both onset conditions, but the hatchback model produced a different response at low frequencies in the unsteady onset flow that was attributed to shedding from the rear, that was assumed to suppress lower frequencies. Small strakes were added to the vertical rear edges to modify the unsteady wake flow structures and the modified model response had high levels of coherence across the entire frequency range investigated. This demonstrates that the frequency of periodic flow field structures can be altered by different onset flow conditions and ‘lock in’ to the onset flow, as previously found by Sims-Williams (16) using a static model. Schröck also found the largest surface pressure fluctuations associated with the wake flows were towards the rear of the sides of the model, rather than on the base, as may have been expected. Howell (69) expanded on this, saying that previous investigations into wake unsteadiness generally only considered base pressures. The importance of the sides of the model is further shown by Howell and Baden Fuller (80) during an investigation into a link between rear lift and yaw moment. Further work by Schröck et al (81), using the same model and test facility found that instantaneous yaw moments found under transient conditions were larger than those found in steady state conditions. A second finding was that separation control strips added to the SAE model that did not produce any change to the yaw moment under steady-state testing, did show an effect under
transient onset yaw conditions. They concluded that transient testing is important because it shows effects not otherwise seen in steady state testing which influence vehicle handling during normal driving.

Sinusoidally yawing flow can be also be created in the Pininfarina full scale wind tunnel by oscillating the turbulence generation system (TGS) spires, described by Carlino et al (48) and illustrated in Figure 19.

![Turbulence generation system in the Pininfarina wind tunnel, taken from (48)](image)

Using different SAE model configurations, it was found that the instantaneous yaw moment and side force coefficients found in transient yawing flow could be larger or smaller than statically measured, dependent upon the frequency of the crosswind. Baden Fuller et al (82) also presented results collected using a production car in this facility which showed that the dynamic values of yaw moment were always greater than the steady state values.

Ryan and Dominy (83), (84) and Ryan (85) created a crosswind gust by adding a secondary wind tunnel to an open jet wind tunnel, shown in Figure 20. Altering the relative wind speeds of the main and crosswind flows created different yaw angles and the duration of the crosswind gust was controlled by the shutters.
Initial tests used a pressure tapped simple car model subject to a sudden 30º crosswind gust. The model was similar to that developed by Davis with a long A-pillar region and a 25º backlight angle but with greater detail including boat-tailing and tumbleholm. The surface pressures showed that the windward flow field quickly developed to a near steady state condition whereas the leeside pressures took longer to develop and in the duration of the gust, equal to three model lengths, did not reach a steady state condition. The side force, calculated from the pressures collected during the gust, peaked 18% higher than the steady state values but the yaw moment remained the same. No explanation was given for these results but the slow response time of the flows around the leeside of the model may be due to viscous and inertial effects. Ryan and Dominy (86) then carried out wake surveys using a pressure probe behind the model; these showed the two trailing vortices merged into a single vortex originating from the windward side of the model when at yaw. The leeside A-pillar vortex detached from the model, and a strong vortex was created from the leeside edge of the diffuser, Figure 21. The wakes created by static and transient crosswind inputs were very similar in structure, but the wake development of the flow field was fundamentally different, and this was partly attributed to differences in the flow experienced in the two tests. In the steady state tests the entire model was subject to a uniformly yawed flow, whereas in the transient gust conditions the front of the model experienced a different flow yaw angle from the rear of the model as the front of the crosswind traversed the model.
Figure 21. Wake survey behind the Durham geometry with crosswind, taken from (86)

Theissen et al. (87) carried out CFD simulations of a production saloon car in two different unsteady yaw conditions. In one, the yawed flow component travelled downstream with the onset bulk flow creating a sudden change in flow conditions: the second was a dynamic-static test which rotated the model in constant onset flow, creating a much lower frequency yaw angle change. This paper contained two interesting results: both types of unsteady crosswind created the same flow field changes and these changes occurred towards the rear of the vehicle and could be found in the wake. The consistency of flow field in different transient crosswind conditions has not been seen elsewhere and could be important when considering how the unsteady yawed testing methods apply to the conditions experienced when driving in normal conditions.

Tsubokura et al. (88) and Tsubokura and Nakashima (89) simulated a yawed flow that travelled downstream with the bulk flow over an articulated lorry. As the front of the yawed onset flow traversed the front of the model there was a maxima in yaw moment and a minima as the crosswind conditions moved from the rear of the model. The peaks in the yaw moment are caused by the crosswind only acting on the front or rear of the vehicle, with no side force at the other end of the model.

### 1.2.2.3 Dynamic – Static Tests

Dynamic – static tests move the model relative to the flow, to create an unsteady yaw angle. One of the earliest types of unsteady yaw test mounted a model on a track and moved it across the working section of a wind tunnel: combining the windspeed and the model velocity produces a yaw angle. An example of this type of facility at Cranfield University is shown in Figure 22. This test creates a sudden yawed input as the model enters the wind tunnel, and an
equally sudden change as the model leaves. This is often described as an extreme crosswind gust which may occur as a vehicle leaves a tunnel.

![Figure 22, Cranfield University crosswind track, taken from (64)](image)

In the 1960s, motivated by the rapidly growing American interstate highway network, Beauvais (90) used a crosswind track to investigate the stability of cars in crosswinds. The experiments used a 10th scale model with wind tunnel speeds up to 24m/s: the results were not Reynolds number independent, but some interesting conclusions were still reached. As the model started to cross the wind tunnel, there was a steady rise in side force and a large peak in yaw moment, which reduced as the model moved further across the wind tunnel. Once the model was three model lengths into the wind tunnel, the side force and yaw moment coefficients levelled out to steady state values. The difference in the aerodynamic coefficients at the start of the wind tunnel was identified as being inherent in the test method. As the model entered the wind tunnel, only the front of the model experienced the yawed flow. This creates a positive yaw moment, but there is no rear side force to create a counteracting yaw moment, creating a yaw moment peak that reduces as more of the model side is subject to the crosswind. The side force does not overshoot because it is dependent upon the side area of the model which increases linearly as the model enters the wind tunnel.

A similar method was used by Yoshida et al (91) with simple 10th scale road vehicle shapes. The Reynolds numbers of the tests were very small, but the results were in general agreement with Beauvais, showing a peak in yaw moment on entry crosswind entry followed by a negative peak as the model left the crosswind. Side force increased and decreased linearly.
This method has also been used more recently at Cranfield University by Cairns (92), Macklin (93) and Chadwick (64). Cairns compared aerodynamic coefficients of the Windsor model and a simple saloon, measured with the models mounted on the crosswind track to steady state values. The model motion along the track badly corrupted the data with noise and resonances meaning that extracting useful results was difficult. As the saloon model entered the crosswind, the side force increased in a linear fashion before settling to a ‘steady state’ value that was lower than the steady state value measured in the same static yaw angle. The linear increase in side force agrees with Beauvais, but the usefulness of these results needs to be questioned due to the contamination of the data.

Macklin, also in Macklin et al (76), reduced the signal contamination and used a range of simple 2 and 3 box models. The results showed an initial overshoot in the yaw moment and rear lift, although roll moment, side force and front lift all increased linearly. In the centre of the wind tunnel the coefficients settled to quasi ‘steady state’ values close to the steady state coefficients; as the models left the wind tunnel a negative peak was found in the yaw moment coefficient. The unsteady yaw moment and rear lift signals recorded on the transient model were closely linked, with similar fluctuations seen in both signals. A further finding was that the flow separation over the rear slant was delayed on transient model. This may be an effect of the test method: the model moves through the wind tunnel adding energy to the overall system, which may re-energise the boundary layer and prevent separation.

Chadwick, also Chadwick et al (94), used the same facility to investigate SUV aerodynamics using a range of simple 2 box models with particular focus given to the yaw moment maxima upon wind tunnel entry and the minima upon exit. As the model entered the crosswind, a region of separation on the leeside was created that contributed to the higher yaw moment. This could be a similar effect to the slower flow field response found on the leeside of the model by Ryan. Further into the crosswind this separation disappeared and the coefficients settled, although there was no clear trend between these and the steady state, static model values. The minimum upon crosswind exit was partially caused by the collapse of separation regions created by the crosswind conditions; the magnitudes of these maxima and minima were dependent upon body shape. Surface pressures showed that as the model passed through the crosswind, the flow field was never the same as the steady state flow field and it was concluded that the model was not in the crosswind for long enough. However, this conclusion is based on the assumption that a settled flow field developed in a transient crosswind is the same as would develop around a static model.
The results from Cairns, Macklin and Chadwick present a number of findings that match other work. The differences between transient model results and steady state results agree with Bearman, Passmore and Carlino, and the yaw moment peak on entry to the wind tunnel was also found by Beauvais and Yoshida et al.

Although this method has been used historically, it is now less favoured for automotive work because of the level of noise in the data that is inherent in the internally mounted balance within the model. However, this type of experiment is still commonly used to investigate train aerodynamics.

Corin et al (95) simulated an overtaking manoeuvre of two simple 2D bodies in a constant onset crosswind. Aerodynamic loads were calculated for a transient case and compared to results found under steady state conditions, they were found to be up to 400% larger than steady state. Pressures and streamlines were plotted and showed that the differences in aerodynamic loads were caused by entirely different flow fields around the two models. This supports the finding of Macklin that transient models can have a different flow field around them from those of a static model and this may lead to the conclusion that the flow field around a transient model is fundamentally different from that around a static model.

A further dynamic-static test method mounts the model onto a turntable and collects data continuously as the model rotates. This method was used by Garry and Cooper (96) with simple tractor and trailer models mounted on a variable yaw rate turntable, and found a phase lag between the steady state and unsteady measurements, but with no magnitude changes. This lag was present from very slow yaw rates (0.2°/s) and increased as the yaw rate increased, up to a yaw rate of 64°/s where the lag showed poor repeatability. Different models had different lags, with certain models producing a phase advance. It was concluded that aerodynamic forces and moments are very dependent upon flow field history and initial conditions, and that phase changes between static and dynamic results can be present from very low yaw rates. Similar experiments were carried out by Cairns (92), using the same test facility and a saloon model. Phase lags were reported but they were less distinct than those found by Garry and Cooper.

Phase lags were also found in a continuous yaw sweep of an early SUV at the full scale DNW wind tunnel. The results (Howell (69)) showed different phase lags in each coefficient with the yaw moment coefficient results shown in Figure 23. This was part of an investigation into quicker wind tunnel operation, rather than an unsteady aerodynamic test, and the test has not been repeated or the causes of the phase lags investigated.
Conflicting results concerning phase lags were reported by Lock (97), while demonstrating new capabilities of the full scale wind tunnel at MIRA. Using the upgraded underfloor balance, continuous readings were taken that showed a discontinuity at one yaw angle, but no consistent phase lag.

All these results are slightly questionable: those by Garry and Cooper and Macklin were collected at low Reynolds numbers and the two full scale balances were not designed to give instantaneous results. They are very heavy, with low natural frequencies, and long sampling periods are needed to produce repeatable steady state results and they were not designed for high frequency, instantaneous readings. Sims-Williams (98) also questions these results; the test conditions in the DNW test equate to a reduced frequency of 0.0007 which is well below the accepted threshold for unsteady behaviour explained in Sims-Williams (1), this is true for the majority of these tests.

One of the starting points of this thesis were the results collected by Mansor (99), also in Mansor and Passmore (100) and Passmore and Mansor (101), using an oscillating model rig. A Davis model, with a range of different rear slant configurations, was mounted from a sprung oscillating rig, shown in Figure 24. The model acted as a torsional pendulum; the aerodynamic yaw moment worked against the spring stiffness and changed the natural frequency of the system. By comparing the wind off and wind on frequencies, it was possible find the change in system stiffness and the yaw moment gradient. The side force gradient was found by changing
the axis of rotation, finding the modified yaw moment gradient and calculating the side force gradient using the two yaw moment gradients. The side force and yaw moment gradients derived from the model response were free from resonances or noise and were compared to steady state, balance measurements.

Figure 24, The oscillating model rig, taken from (100)

Dependent upon the model configuration and the reduced frequency of the system, one of three model responses was recorded. These were fully damped, self-sustained oscillations or self-excited oscillations; typical examples of these responses are shown in Figure 25. It was suggested that the different responses were related to vortex shedding from the rear of the model locking in to the oscillations that were driving the model motion.

Figure 25, Damped, self-sustaining and self-exciting model responses

The base model had all the edges rounded with a 20mm radius, and further work added progressively larger strakes to the rear pillars which reduced the steady state yaw moment gradient by an initial 40% just from squaring the edge, and increased the side force gradient, implying that the flow around the rear pillar is quite influential to the lateral aerodynamics of these models in agreement with Schröck (57) and the steady state surface pressures found by Howell (46). The transient model response showed a larger yaw moment gradient reduction than the steady state results. Although different sized strakes were tried, the greatest change in oscillating model response was in a change from rounded to square rear edges, increasing the strake height further reduced the yaw moment, but disproportionately from the physical change. Adding the strakes reduced the unsteadiness of the transient model responses, but did not
change the three types of model response. Self-excitation occurred below a reduced frequency of 0.23, a boundary Mansor suggested was a function of the friction within the system, and there was a distinct change in the results’ trends at this boundary, shown in Figure 26.

![Figure 26, Effect of strake size on yaw moment coefficient gradient magnification, taken from (99)](image)

The origins of the model responses were not investigated, but the self-excited model response could not be explained with linear approximations of yaw moment and spring force. This implies that unsteady aerodynamic effects created by the motion must be occurring to start the motion and then maintain it, continuously overcoming the friction within the system that would otherwise damp the motion away.

Berryman (102) used the same test rig with models that were more representative of passenger vehicles than the Davis model. Models with flow separation over the trailing edge of the roof were more prone to self-excitation, possibly indicating that trailing vortices act as ‘dampers’, and further showing the importance of the flows over the rear of the models. The results showed the transient model response derived side force and yaw moment coefficient gradients were greater than the steady state values. The larger yaw moment gradients found by Mansor and Berryman under transient yaw angles are in agreement with Passmore and Carlino, who both used oscillating aerofoils upstream of the model.

Watkins et al (103) explains that an oscillating model is only suitable to replicate low frequency crosswind changes, rather than a sudden gust. However, this is questioned by Wojciak (51) in a CFD study that showed both types of unsteady yawed flows created the same flow field changes around a generic executive car.

The oscillating motion creates a component of model surface velocity in line with the onset flow, either opposing or adding to the onset flow, and this would be greater further from the axis of
rotation. This means the instantaneous yaw angles along the length of the model are different, which may add a further complication to the analysis of the results.

There is a large body of work by Chometon et al (104), Guilmineau and Chometon (105), Gohlke et al (106), Guilmineau and Chometon (107), Gohlke et al (108) and Krajnović et al (109) investigating the aerodynamics of the Willy model in static and oscillating yawed flows. The Willy model, Figure 27, is an unusual shape with a very rounded front designed to maintain fully attached flow along its body at static yaw angles up to 10º, allowing for a study of the near wake with minimal upstream influences.

![Figure 27, Willy model](image)

In Chometon et al (104) PIV was used to collect flow field information in the wake of the Willy model at static yaw angles and phase locked while the model was oscillating. The flow fields showed differences between the static and oscillating model test cases, reported as hysteresis. Drag, calculated using the wake velocity deficit, also contained hysteresis as the model oscillated, with the amount of hysteresis dependent upon the distance from the model. At the plane closest to the model there was minimal hysteresis, but further away the hysteresis was much more obvious. This demonstrates that the wake close to the model is relatively independent from test conditions, it is the larger scale flow structures emanating from the body that form further downstream that are of most interest. Despite the interest in these results, they were collected at a low Reynolds number: the blockage ratio was 19% and only 100 PIV images were taken, which is not sufficient for an acceptably low level of error.

In Guilmineau and Chometon (107), an oscillating Willy model was simulated with CFD using a RANS solver, and simulated surface pressures were compared to experimental results, which
showed good agreement. Hysteresis, dependent upon the oscillation amplitude, was found in the surface pressures and drag, side force and yaw moment coefficients. Wake streamlines showed large scale flow field hysteresis and significant differences between flow fields around a static model and an oscillating model at the same angles, an example is shown in Figure 28.

![Figure 28, Flow field hysteresis in the wake of an oscillating Willy model, from (107)](image)

A program of oscillating model experiments by BMW is detailed in Theissen et al (110) and Wojciak et al (111). These experiments used detailed 1/2 scale models and a windspeed of 58m/s, giving a large Reynolds number but only a small 3° yaw angle oscillation amplitude. The results showed that the differences between the flow fields created by the static and oscillating models were towards the rear of the model and could be found in the wake with the largest differences on the leeside of the model, in agreement with Ryan and Chadwick. There was a gradual increase in phase lag along the model: the surface pressures at the front of the model were in phase with the steady state pressures, but towards the rear they lagged the model yaw angle. Among the 6 aerodynamic coefficients, lift and yaw moment coefficients showed the greatest differences from the steady state values, further indicating that there is a link between the two coefficients, as suggested by Howell and Le Good, and Macklin.

Similar to an oscillating model, dynamic stall is the name given to differences between steady state loads on a aerofoil and those when the wing is oscillating through a range of angles of attack. An example of this is in Figure 29, taken from Tsang et al (112), which shows the difference in the lift coefficient created by an aerofoil in static conditions and during an oscillation. Dynamic stall can also maintain attached flow over the wing at larger angles of attack than under steady state conditions, and the amount of hysteresis is dependent on the frequency of the oscillation.
Figure 29, Dynamic stall, dashed line shows the steady state results, solid lines show the instantaneous transient loads, taken from (112)

Ericsson and Reding (113) investigated the causes of dynamic stall and showed there are two main effects. There is a pure time lag that is a consequence of the time taken for flow to propagate down the length of the model. There are also flow modification terms that change the surface pressure distribution and alter separation lines. These are linked to the surface velocities created by the model motion that change the local onset flow velocity and re-energise the boundary layer, shown in Figure 30.

Figure 30, Oscillating motion energising the boundary layer on an aerofoil, taken from (113)

Möller and Pöttner (114) created an unsteady yaw angle by moving an Ahmed model laterally across the working section of a wind tunnel. Hysteresis was found in the flow field recorded using PIV. However, the validity of the experiment is questionable; wind tunnel flow speeds of 1m/s and 0.5m/s were used, leading to very low Reynolds numbers.

This type of lateral motion has been used with simple 2D cylinders with some surprising results. Meneghini and Bearman (25) simulated a sudden lateral shift of a circular cylinder using a simple CFD code. They found extra vortices were formed, as shown in Figure 31; associated with this was a large spike in drag and lift forces. The extra vortices and higher forces quickly disappeared and the typical flow field and aerodynamic coefficient patterns were re-established.
No explanation for the results was given and it was concluded that the near wake is not affected by the flow downstream of it.

Figure 31, Vortex shedding after a transverse disturbance, taken from (25)

Modified Von Karman vortex streets can be created by oscillating a cylinder perpendicular to the onset flow at frequencies close to the shedding frequency. Ongoren and Rockwell (115) and (116) carried out this experiment and showed that the shedding behind the cylinder can ‘lock in’ to the frequency of the cylinder, rather than shed at a frequency required to give a Strouhal number of 0.21. Dependent upon the oscillation frequency, the direction of the motion and, as shown by Blackburn and Henderson (117), the amplitude of the motion, extra vortices in the wake were produced, either in a symmetrical or asymmetrical fashion; examples are in Figure 32 and Figure 33.

Figure 32, Non symmetric shedding, the cylinder is moving perpendicular to the flow, taken from (117)

Figure 33, Symmetric shedding, the cylinder is moving back and forth in line with the onset flow, taken from (116)
The modifications to the flow fields are strongly dependent on the near surface vorticity, which is a similar conclusion to that reported by Yeo and Jones (29) when investigating the causes 3D flow effects on a long cylinder.

Blackburn and Henderson also showed that decreasing the cylinder motion frequency below the shedding frequency can produce a self-sustaining system, with the shedding in phase with the cylinder motion, giving energy to the cylinder, rather than damping the motion. This appears a similar situation to that found by Mansor with the Davis models. The change in the sign of the aerodynamic loads was non-linear and the cylinder response contained two branches and discontinuities. Deniz and Staubli (32) found that shedding from rectangular cylinders could lead to self-excitation, as did Bearman and Obasaju (118). Bearman and Obasaju also found that cylinder motion reduced the likelihood of the shed vortex splitting along its length, which is similar to Macklin and Mansor, who found transient test conditions helped prevent flow separation.

A final type of dynamic-static crosswind test that uses production vehicles that are driven across a row of fans with open and closed loop steering inputs, is detailed by Hucho (77) and shown in Figure 34. This method is used by some manufacturers as part of the benchmarking process and for subjective testing during the development process. However, the extreme nature of the crosswind gust used in the tests and its short duration mean that it is not usually used for research purposes but a rare usage is included in Yoshida (91).

![Figure 34, Full scale assessment of crosswind stability, taken from (77)](image-url)
1.2.3 Vehicle Design and Crosswinds

The current drive for low drag vehicles is disadvantageous for crosswind behaviour, as shape changes that reduce drag often lead to an increase in the yaw moment.

Barth (119) used a wide range of scale vehicle models and found those with rounded rear edges had larger yaw moment gradients than similar models with squarer edges. A more fundamental study on the effect of vehicle shape on yaw moment was carried out by Gilhaus and Renn (120). They found squareback body shapes were more aerodynamically stable than fastback or notchback shapes; rounding the rear pillars, commonly used to reduce drag, increased the yaw moment on all body shapes, but mostly on a fastback. It was concluded that, in general, shape changes that reduce drag have a negative effect on yaw moment. Howell (11) looked at the yaw moment effects of various shape changes to a Windsor model. In agreement with Gilhaus and Renn, it was seen that a squareback shape was the most stable shape, and that changing from a square to rounded rear pillar increased yaw moment, although further changes to the radius of the curvature had little effect; the significance of the change from square to round edges was also reported by Mansor.

Flow separation at the rear of road vehicles can be controlled by adding strakes to the rear pillars and edges of road vehicles. This is a common design feature applied to a wide variety of vehicles, examples are shown in Figure 35, to reduce the yaw moment gradient, drag, Mayer and Wickern (121) and lift, Beaudoin and Alder (122). They can be found in the rear pillars, along the side of the rear windscreen, or hidden in the clear plastic of the rear light moulding. However, features similar to aerodynamic strakes can be used in the rear light moulding to ensure the lights illuminate over the legally required viewing angle.

Stakes work by promoting flow separation, preventing flow accelerating around a curved surface and generating suction on that surface. This also has the benefit of reducing unsteadiness in the flow field, and Barnard (123) states that ‘An unstable location of the separation line at the rear of vehicles is a common source of crosswind instability’.
Howell and Baden Fuller (80) used historical data and results collected using a Windsor model to investigate the link between rear lift and yaw moment. It was shown that shapes with rear ends which produce lower values of rear lift also generate smaller yaw moment gradients; this agrees with Gilhaus and Renn’s (120) finding that squarebacks are most aerodynamically stable. The yaw moment was reduced on the shapes with less rear lift, because a region of suction beneath the windward rear pillar was reduced as the trailing vortices were weakened and further shows the importance of the rear sides of the model.

Despite general acceptance that low drag and low yaw moments are mutually exclusive, Broadley and Garry (124) proposed an aero-stable and low drag vehicle shape, in Figure 36. The most effective bodywork elements were the roof strakes, similar to a rear fin, which moved the centre of pressure rearwards.
1.3 Summary

With the literature reviewed in the previous section there are a number of consistent results and important points:

- The influence of crosswinds to a vehicle is important for vehicle safety. Currently major road vehicle manufacturers do not carry out significant unsteady aerodynamic development because the traditional steady state approach continues to be sufficient, but as vehicles get lighter, have less rotational inertia and low drag shapes, that are generally worse for crosswinds, this will change. It is important that the entire system of flow field, vehicle and driver are considered together to fully understand the effects of crosswinds but, despite this, there is little work that actually considers the whole dynamic system.

- Even under steady state conditions, the instantaneous flow fields and subsequent aerodynamic loads are highly unsteady. The large scale, time averaged flow structures only exist as an average description of the flow, the instantaneous flow fields can look similar but contain unsteadiness and periodicity that the averaged flow field does not describe.

- There are a wide variety of unsteady crosswind simulations with no single method finding overall favour. Different institutions have their own test methods and combining results from all the methods builds the understanding of unsteady yawed aerodynamics. However, this demonstrates the lack of any fundamental understanding of the phenomena created by transient crosswinds. If any single experimental approach gave a comprehensive simulation there would be a general focus on using that one technique; rather than the scattered approach that is currently happening.

- Flow fields over the rear half of models and in their wakes are strongly influenced by upstream influences, either flow features created by the model or by onset flow conditions creating different flow fields and lock-in of periodic flow field structures.

- Flow fields and subsequent aerodynamic loads created around statically mounted models at yaw are different from those around models subject to unsteady yawed test conditions. Differences are mostly found towards the rear of the models with greater differences on the leeside of the model than the windward side.
1.4 Objectives

This thesis will investigate the unsteady aerodynamics of a simple automotive fastback body by investigating and comparing steady state and unsteady results from a static model to results collected during unsteady yawing motion. It is impossible to cover all the points previously summarised, hence this work will focus on understanding the effects of strakes and possible differences in the flow field around static and oscillating models, building on the oscillating model work previously carried out by Mansor.

- Using statically mounted Davis models with different rear pillar geometry, the steady state and unsteady flow fields around the models at 0° yaw will be thoroughly investigated. This will involve surface flow visualisations, balance measurements, surface pressures and PIV. Using these techniques will allow for a thorough understanding of the steady state and unsteady flow fields around the model and the differences in the flow fields created by the different rear pillar geometries.

- The investigation of the aerodynamics of the Davis models will look at the flow fields generated with the models at none-zero yaw angles. This will use the same techniques as with the model at 0° yaw.

- Unsteady yaw angles will be created using a low yaw rate rotation of the model and by subjecting the models to driven yaw angle oscillations. As the balance yaws, data will be continuously sampled and compared to steady state results. The oscillating motion is based on that created by Mansor; a yaw angle range of ±10° will be used at a reduced frequency below 0.1. Mansor found this gave a self-excited response, which is fundamentally unsteady, and this is below the quasi-static boundary described by Sims-Williams. With the oscillating model, surface pressures and PIV data will be captured to allow a direct comparison to the statically mounted model results and a thorough understanding of the unsteady aerodynamics of the oscillating models.

The next chapter will explain how these experiments were carried out and discuss the potential sources of error within the results.
2. Experimental Facilities and Methods

This chapter gives an overview of the experimental facilities and techniques that were used during the course of this work. Where an individual experiment used a slightly different arrangement from that given here, details are given in the relevant results section.

2.1 Wind Tunnel

The experimental measurements detailed in this thesis were collected in the Loughborough University 1/4 scale wind tunnel, Figure 37, which is an open return wind tunnel in an unusual horseshoe layout. The wind tunnel has a closed working section, 1.9m wide by 1.3m high and can fit approximately 1/4 scale automotive models or 1/3 scale race car models with an acceptable blockage ratio.

![Figure 37, Loughborough University 1/4 scale wind tunnel](image)

The air is driven by a 9 blade, 140kW fan mounted on 8 stators which produces a maximum windspeed of 45 m/s in the working section with a base line turbulence intensity of 0.2%. The working section has a fixed floor with a boundary layer thickness of 60mm. Further details of the design and layout are in Johl et al (125).

The windspeed is measured with a pitot-static tube mounted from the roof of the tunnel at the start of the working section. The dynamic and static pressures are recorded by a Furness Controls model 332 digital manometer with a measurement range of ±250 mmH₂O and an output voltage range of ±10V; 1 mmH₂O = 0.04V. This is fed into the balance control PC and the windspeed is electronically controlled in a closed loop. During a run, the windspeed can fluctuate up to ±0.1m/s from the requested value.
The increase in the local airspeed around the model caused by the model blockage in the wind tunnel was corrected using the MIRA blockage correction, in equation 5. This is a volumetric flow rate continuity equation based on the frontal area of the model but does not take into account the increased frontal area when the model is at yaw. The correction term tries to compensate for the walls of the wind tunnel which are not present when the vehicle is in the real world but for this slightly abstract experiment which cannot be recreated in the real world or at full scale using a simple and widely used equation is suitable. More complex blockage corrections are available that consider in greater detail the yaw effects on the frontal area and the wake blockage but the extra complexity of these equations was unnecessary for these experiments. Details of this correction function and others can be found in the SAE report on boundary interference, (126).

\[ U_c = U_0(1 + e) \]  

Eq. 5

The temperature of the air in the working section is measured with a thermocouple mounted on the Pitot - static tube used for windspeed measurement and the temperature is updated continuously within the balance software. The wind tunnel draws air from outside meaning there can be a temperature difference up to 20ºC between the outside and the still air in the wind tunnel at the start of the day. Before any detailed measurements were taken the wind tunnel was run until the temperature in the working section was steady and matched the ambient outside temperature.

The atmospheric pressure is measured by a Druck DPI 142 barometer located in the wind tunnel control room. The atmospheric pressure required a manual input into the balance software and would typically get updated between batches of testing, at intervals of no longer than 1 hour.

Although a moving ground plane would correctly recreate the onset wind profile experienced on the road this was not installed. This would have created much greater model mounting complexity and is unnecessary for the large scale flow structures and relatively fundamental problems that are generally investigated in the wind tunnel. Despite the differences in the boundary layer, Howell and Hickman (127) showed the trends of the aerodynamic coefficients acting on a model with a moving ground or fixed floor were the same, implying similar flow structures were created in both test conditions. Further comparisons of ground simulation by Bearman et al (128) showed a moving floor mainly affected lift, had a small effect on drag and pitch and negligible effect on the lateral aerodynamic coefficients.
2.2 Transient Yaw Motion

Transient yaw motion will be created using the balance yaw drive and by driving the model in an oscillating yawed motion using a modified version of the oscillating model rig developed by Mansor.

The cranked oscillating motion is the main focus of this thesis. This motion was chosen in a continuation of Mansor’s work but with the addition of crank to drive the motion rather than the free oscillation employed by Mansor. This creates the long running, consistent motion required for PIV and surface pressure data collection. By adapting existing test equipment, the design, build and testing stages of commissioning the test rig and cost were significantly less than if an entirely new test procedure had been decided upon. Using a similar motion to create the unsteady yaw angles to that which has been used previously also allows easy comparisons of the results collected previously by Mansor and also other oscillating model work using the Willy model by Chometon et al (104) and (107) and using a generic executive car by Theissen et al (110) and Wojciak et al (111).

Tests where continuous aerodynamics load measurements were taken during a yaw sweep of the balance were also conducted because the capability became available following an upgrade to the balance software. This allowed a much slower yaw rate than the oscillating model but which previous work, such as Garry and Cooper (96) and Lock (97), had shown may still produce differences between the steady state and transient results. This motion is not the main focus of the thesis but provides an interesting and useful addition to the oscillating motion.

The yaw drive on the balance can rotate the model through a range of ±145°, accurate to 0.1°. The yaw motion characteristics are consistent and independent of the start and finishing points and the onset windspeed. The yaw motion recorded during a yaw sweep from -20° to 20° is shown in Figure 38. The model initially accelerates at 1°/s² for 2 seconds after which it moves at a constant speed of 2°/s. When nearing the required yaw angle the model comes to rest at a location very near to the final destination, a secondary motion moves the model to its final location; this can be seen in the Figure 38 in the yaw position and angular acceleration lines at 23sec. This type of slow yawing motion between a start and finish yaw angle is similar to that used by Garry and Cooper (96), Macklin (93) and Lock (97).
Figure 38, Yaw motion of the balance

To create consistent and long lasting sinusoidal oscillating motion an electric motor and crank replaced the springs used by Mansor. These were designed to be adjustable to give different yaw amplitudes and frequencies of motion. Two images of the mechanism and its installation are in Figure 39 and Figure 40.

Figure 39, Cranked oscillating model rig, isometric view
The model was held in place above the floor of the wind tunnel by bearings that supported the shaft from the model. The crank mechanism was beneath the floor of the working section. All the components were attached to the beam that was held in place by bolts, which were flush to the floor of the wind tunnel, such that the model was in the centre of the working section, in the same place as when taking steady state measurements.

![Figure 40, Cranked oscillating rig installed beneath the working section floor](image)

The motor was chosen to provide suitable torque to overcome the aerodynamic yaw moment and model inertia while turning at 1Hz. The linkages were designed to be low inertia and light weight and spherical bearings were used to allow for any out of plane motion caused by manufacturing tolerances. A set up plate and control arm were manufactured to ensure the oscillation was centred on 0º yaw.

With the model oscillating at 1Hz, in an onset windspeed of 40m/s, it produces a reduced frequency of 0.049 that Mansor found produced self-excitation. Using the definition of reduced frequency in Sims-Williams (1), these onset conditions produce a reduced frequency of 0.098 which means the motion should be expected to produce a quasi-static aerodynamic response from the model.

The crank length was chosen to create a yaw angle amplitude of ±10º, with a maximum yaw rate of 10º/s, which was based upon the yaw angle range considered by Mansor and also because it should produce significant differences in the flow field from the 0º situation without
reaching the upper yaw angle limit of the linear approximation of the lateral aerodynamics of the Davis models.

Although the motor driven motion is forced, unlike the free oscillations created by the springs, any periodic features in the flow field should lock into the motion of the model in a similar way to that shown in (129) and (17) where periodic features lock-in to the motion of the model.

The yaw angle created by the motion was quantified using an angular potentiometer attached to the base of the model shaft. This gives an output voltage between 0-5V with a linear response, accurate to 0.5%, based on the angle.

A 10 second sample of the model motion at 1Hz and 40m/s is shown in Figure 41. The motion was subject to cycle to cycle variations in amplitude and frequency. Slight asymmetry in the motion was also present due to lash within the gearing of the motor but was not more than ±0.2º.

The small inconsistencies in the frequency are due to small fluctuations in the voltage across the motor; this was minimised by using a stabilised voltage supply but the time period of the oscillations could vary up to ±0.02s from 1s.

The yaw angle amplitudes of the oscillations are slightly larger than the design specification caused by the motor flexing slightly when the model is at the largest yaw angles. This flex is caused by the inertia of the model acting onto the motor at the point of greatest rotational acceleration and the aerodynamic yaw moment reacting against the motor. Despite these, the yaw angle overshoot is very consistent, creating a yaw angle amplitude of 11º.
2.3 Data Collection

This section contains details of the general methods used to collect the data used in this thesis. Where an experiment has used a slightly different method, or where there are further considerations about the sources of error, notably created by the transient yawing motion, these are discussed in the relevant results section.

2.3.1 Balance

Beneath the working section of the wind tunnel is a six axis balance; the load ranges and accuracy are shown in Table 1. The model is mounted to the balance using struts that are adjustable for different models.

<table>
<thead>
<tr>
<th>Component</th>
<th>Design Load Range</th>
<th>Accuracy (%fsd)</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag</td>
<td>± 120N</td>
<td>0.05</td>
<td>0.12N</td>
</tr>
<tr>
<td>Side Force</td>
<td>±520N</td>
<td>0.05</td>
<td>0.52N</td>
</tr>
<tr>
<td>Lift</td>
<td>±500N</td>
<td>0.05</td>
<td>0.50N</td>
</tr>
<tr>
<td>Rolling Moment</td>
<td>±120Nm</td>
<td>0.05</td>
<td>0.12Nm</td>
</tr>
<tr>
<td>Pitching Moment</td>
<td>±60Nm</td>
<td>0.05</td>
<td>0.06Nm</td>
</tr>
<tr>
<td>Yawing Moment</td>
<td>±45Nm</td>
<td>0.05</td>
<td>0.045Nm</td>
</tr>
</tbody>
</table>

Table 1, Underfloor balance load accuracy

The weight of the model is taken as a tare and a wind off yaw sweep is used to find any non-zero wind off loads caused by the model and balance; these values are removed from the measured wind on loads in the processing of the data. Steady state data is sampled for 20 seconds to give an accurate mean and a 5 second settling period is used between any yaw motion and the start of the sampling period. The balance can also continuously sample the instantaneous aerodynamic loads at up to 300Hz, the only change from steady state sampling is in the software where an averaging function is disabled; further details of this is are in chapter 4.

Throughout this thesis the SAE coordinate system, shown in Figure 42, is used and the aerodynamic forces and moments have been converted to coefficients using the standard equations. Because the model does not have any wheels, the overall length has been used wherever a characteristic length is required unless stated.
2.3.2 Pressures

Surface pressures were recorded using two Esterline ESP-64HD Miniature Electronic Pressure Scanners. Each scanner had 64 separate pressure inputs with a range of ±232mmH_{2}O and accuracy of 0.2% of the full range, 0.9mmH_{2}O. At a tunnel speed of 40m/s, used for the data collection in the subsequent chapters, the dynamic pressure is 100mmH_{2}O, meaning the accuracy of the pressure coefficients is ±0.9%. The surface pressures were measured relative to the working section static pressure. The dynamic pressure, taken from the pitot-static tube at the start of the working section, was recorded in 1 of the channels of each scanner leaving 63 channels on each scanner for the surface pressure data collection.

The model was covered in 241 pressure tappings arranged symmetrically on the sides, backlight and base as shown in Figure 43. The pressure tappings are made of 25mm lengths of copper tubing with an internal diameter of 0.8mm which were inserted flush and normal to the model surface and glued in place.
The tappings were connected to the pressure scanners with 550mm lengths of flexi tube with an internal diameter of 1.4mm. The length was chosen to be usable for a range of models and the tail allows for the pressure transducer to be moved between models easily, a photograph of the set up is shown in Figure 44.
Data was sampled at 260Hz, triggered by an externally supplied TTL signal; this ensured simultaneous sampling of the two separate scanners and that the scanners started sampling at channel 1. All the surface pressure data were collected in batches of 8192 samples, representing 32 seconds of data. In the results chapters, the pressures are converted to pressure coefficients using the dynamic pressure, equation 6, and corrected for wind tunnel blockage using equation 7 which is a first order approximation of applying the area blockage to the $V^2$ dependant pressure terms.

\[ C_p = \frac{p-p_\infty}{\frac{1}{2} \rho V^2} \quad \text{Eq. 6} \]

\[ C_p = \frac{c_p+2\varepsilon}{(1+2\varepsilon)} \quad \text{Eq. 7} \]

Within the wind tunnel is a resonance at 9Hz and there are two strong frequencies dependant on the fan speed. At 40m/s the fan turns at 600rpm, this creates frequencies close to 80Hz from the fan stators and 90Hz related to the fan blades.

### 2.3.2.1 Tubing Correction

Recording surface pressures via a tube causes a distortion of the signal at the transducer due to attenuation and resonances created by the tube. This has no effect on mean values on a static model but does change the magnitude and phase of the instantaneous fluctuations around the mean recorded at the pressure scanner relative to those that occur on the model surface. The distortion created by the tubing is quantified and removed using an experimentally derived correction function. The method used is similar to that used by Sims-Williams and Dominy (129) and is a development of the method used previously by the author (130). An overview of the problem and different methods to quantify it are in Irwin et al (131). Using an experimentally derived correction using the same equipment as used to collect the actual results in chapters 3 and 4, rather than a theoretical model based on pipe resonances, means that the correction function inherently considers all the possible effects of the system, including possible effects at the disconnect in the tail and any resonances in the small volumes within the pressure scanner.

To derive the correction a loud speaker attached to a signal generator was used to produce swept sine waves which were then measured through the entire tubing and tail system and also through a very short length of tube ($\approx 15\text{mm}$) to give a reference signal. A close up photo showing this is in Figure 45. A tube of 15mm creates a first mode resonance above 5.7kHz and the attenuation from the viscous forces on the sides of the tubes are very small due to its short length meaning that the signal is as close to a true representation of the output from the speaker as is practically
possible using this equipment. Different amplitudes of signals were used to check for any influence of this parameter but none was found.

Figure 45, Flexitubes to produce the reference and distorted pressure signals

The correction function was found by comparing the reference and distorted signal and producing a frequency dependent transfer function between the two. The effects of the tubing on the magnitude and phase can be seen in Figure 46. Most notably the signal was affected by a resonance at 95Hz, attenuation effects were not found due to the relatively low frequencies involved.

Figure 46, Magnitude and phase distortion effects due to the flexitube

To apply the correction function the distorted signal from the pressure scanner was decomposed into the frequency domain using a Fourier transform. Each frequency was multiplied by the corresponding magnitude factor and the phase was added before the signal was reconstructed using an inverse Fourier transform.
The pressure scanner reads the pressures from each tapping sequentially and, additionally to the distortion created by the tubing; the correction function resampled the data from all the channels so that it is sampled concurrently rather than sequentially from channel 1 to 64. This improves the accuracy of the time dependent component of the data.

An example of implementation of the correction function is in Figure 47. This shows the reference signal, raw pressure signal and corrected pressure data created using a loud speaker with a 50Hz input. The corrected signal is a significant improvement over the uncorrected data removing a phase lag and reducing the magnitude of the pressure fluctuations.

![Figure 47, Effect of tubing correction on 50Hz pressure fluctuations](image)

### 2.3.3 Particle Image Velocimetry

Particle image velocimetry (PIV) is a relatively non-intrusive flow field measurement technique that, in recent years, has become widely used and well developed. For more information on the general method, a thorough overview of the technique is given in Raffel et al (132).

The equipment and processing software used in this thesis is a commercially available system supplied by La Vision. The general arrangement of the cameras, seeding rake and laser is shown
in Figure 48 and was used to collect PIV data in two planes behind both the static and oscillating models.

Figure 48, Schematic of the PIV equipment setup in the wind tunnel

Seeding particles of neutrally buoyant, atomised olive oil with mean diameters between 1 - 10µm were created with a six jet Laskin nozzle atomiser. Seeding the flow in an open circuit wind tunnel is difficult because the seeding particles need to be continuously replaced. Preliminary testing with the rake in the settling chamber left large areas of the images captured behind the oscillating model unseeded so the rake was mounted at the start of the working section upstream of the model. The lowest crossbeam rested on the floor to get seeding particles into the boundary layer and higher crossbeams were in the freestream. However, this added turbulence to the onset flow and because the rake does not extend to the full height of the working section there was a speed difference between the indicated windspeed and the onset flow speed at the model location. These were investigated by traversing a hot wire over a range of heights above the centre of the balance to find the instantaneous flow velocities. 10 seconds of data were collected at 1000Hz at each height and the mean onset flow velocities are shown in Figure 49 and the turbulence intensities are shown in Figure 50.
There is no evidence of a wake directly behind the crossbeam of the rake in the freestream; however there is an overall reduction of 1 m/s in the freestream speed from the indicated speed. Figure 50 shows the freestream turbulence, quantified using the same hot wire data as used for the mean velocities. The rake increases the baseline turbulence intensity to $T_u \approx 4\%$ and increases boundary layer thickness. As with the mean velocity results, there are no obvious wake effects directly behind the rake crossbeam.

The effect of the increased freestream turbulence and any possible flow field interference from the cameras is investigated in Figure 51 that shows the steady state yaw moment coefficient in the clean tunnel and with the PIV equipment in place.
Newnham (54) showed increased freestream turbulence can alter the aerodynamic loads acting on the model but Figure 51 shows the changes are limited and the moment acting on the round-edged model in the clean tunnel and in the wind tunnel with the seeding rake mounted upstream are very similar. This implies the increased freestream turbulence from the seeding rake is not fundamentally changing the flow field around the model and that results from the clean tunnel and with the seeding rake in place can be compared.

Two LaVision Imager Pro cameras with a 4 megapixel CCD chip were used to collect the images. The cameras were mounted in glass fronted boxes for protection from debris and to keep them clean of the seeding olive oil. To prevent condensation forming on the camera lenses packets of silica gel were put in the boxes with the camera. The boxes could rotate and move along lengths of aluminium extrusion to be aligned on different planes. The cameras were mounted symmetrically, one on each side of the working section. The angle between the two cameras was 60° and each camera was 30° to the main axis of the wind tunnel based on the findings of Coudert et al (133). They found this was a good compromise between accuracy (which Raffel (132) reports is best at 90°) and the physical space requirements.

The PIV data was collected in a plane parallel to the base of the model when at 0° yaw. The focal planes of the cameras were at 30° which was rotated to be in the same plane as the laser sheet using a scheimpflug mount, located between the camera and the lens, which rotates the lens relative to the camera. Both cameras used a 50mm lens, giving a 400mm*400mm window, with the f-stop set to 2.8 and an optical filter mounted on the lens. These only admitted a small
bandwidth of light centred on the wavelength of the laser and helped remove background light and increase the relative intensity of the seeding particles in the images.

A Litron Lasers Nd:YAG Pulsed laser was used to illuminate the seeding particles. This has a power of 200 mJ and produces a green laser with a 532nm wavelength. It is a class 4 laser but was made safe with interlocks and comprehensive operating procedures. The laser was mounted on the roof of the wind tunnel meaning the relative angle and reflected light from the seeding particles between the laser sheet and each camera was the same, which was beneficial for the image processing.

A calibration plate, shown in Figure 52, has precisely arranged marks and is used by the software to calculate the number of pixels per millimetre and dewarp the image into the focal plane. The marks are on two planes and this allows the through plane scaling to be found and the calibration process also sets the same origin for both cameras.

For each test case 1010 image pairs were collected; 10 were used to create a mean background to be subtracted from the remaining 1000 images to enhance the intensity of the seeding particles relative to the background. 1000 image pairs has been shown by Hollis (134) and in Passmore (30) to be a reasonable compromise between the time taken to collect data, the amount of data and the accuracy of the mean results. Using in-plane velocities, Passmore
showed that 1000 images lead to an accuracy of ±2% in the mean value with a 99% confidence of a vector towards the edge of a vortex. In the freestream, where the local RMS is much lower, the error is an order of magnitude smaller. These values are dependent upon local RMS and the mean velocity; the freestream velocities are steadier, but the mean value is an order of magnitude lower than at the edge of the vortex, hence a small error has a larger percentage effect.

With the static model, an internal trigger at 3.5Hz operated the cameras and laser and with the oscillating model an external trigger was used to collect images with the model at specific instantaneous yaw angles.

Both static and oscillating model images were collected with a tunnel speed of 40m/s, an interframe time of 30µs gave the best compromise between in plane motion of the seeding particles and them passing through the laser sheet. This created a mean pixel shift of 5, which is slightly below optimum but avoided peak locking and gave good results. Longer interframe times would give larger pixel shifts, but with an increased likelihood that the seeding particles would pass through the laser sheet during the interframe time; a shorter time would increase the capture of particles but with increased peak locking.

Calculation of the vector fields from the raw images was carried out using the commercially available DaVis software (135) with subsequent post processing carried out using Matlab. Velocity vector calculation was carried out using four passes, initially using 128*128 pixel integration cells, then 64*64 and finally two at 32*32 with 50% overlap. A median filter was used to remove spurious results and a final filter compared the vector fields found using the images from each camera. This leads to a lower number of 1st choice vectors than typically seen using a single camera but a higher confidence in the results which is especially useful for the large fields of view used and the number of first choice vectors remained quite high at >85%.

2.3.4 Hotwire

Instantaneous velocity measurements were collected using a commercially available single wire Dantec hotwire probe, calibrated up to 60m/s prior to being used. It was mounted on a stiff traverse within the working section to allow precise movement and positional control of the hotwire. Hotwire measurements were only used for calibration and set up purposes.
2.3.5 Flow Visualisations

Surface flow visualisations were carried out using the traditional method of a mixture of titanium oxide, paraffin and linseed oil. The three ingredients were mixed together to a paint-like consistency and applied to the model with a brush. The tunnel was run until the mixture had dried, which typically took 5 minutes, before being photographed.

2.3.6 Signal Recording

Electronic signals from the external triggers and the angular potentiometer on the model shaft were recorded using a National Instruments BNC-2090 input / output block. This was connected to a PC and a simple data logging Labview VI was used to record the signals.

2.4 Davis Model

This work used two configurations of a fastback Davis model. These two models have a long front slant, a short roof and a 20° backlight angle with different rear pillar geometries and are more representative of a production car than the more commonly used Ahmed model which does not have a slanted front. The Davis models were originally developed by Davis (10) and they are a family of simple bodies (defined by Le Good and Garry (136)). Simple bodied test models produce results that are very useful for determining fundamental flow field characteristics because they lack surface details that could either mask the fundamental effects or produce results that are very model specific. This means that the results gained using the Davis models in this thesis should be generally applicable to a range of production vehicles. Furthermore, the two Davis model configurations used in this thesis have been previously used by Mansor and similar models have been used in unsteady crosswind research by Bearman and Mullarkey (78), Ryan (85) and Passmore et al (79) allowing for direct comparisons of the results presented in this thesis with previously published work.

The overall dimensions of the models used are shown in Figure 53. The model is approximately 1/6 of full scale with a 20° backlight angle which maintains attached flow until the backlight trailing edge. The models are made of 3mm thick fibre glass making them light weight with a low rotational inertia. The models are in two parts, a top body shell and a lower base which is common to both configurations. The models are mounted with a single Ø20mm metal shaft in the geometric centre of the model’s floor with a ground clearance of 40mm above the floor of the wind tunnel, in continuation of the set up used by Mansor.
The base model configuration has all the edges rounded with a 20mm radius with all the surfaces smooth, the second model is the exactly the same apart from the rear pillars that are squared off rather than rounded, shown in Figure 54. Throughout the thesis these will be known as the ‘round-edged model’ and the ‘square-edged model’ respectively. There is a small recess on the rear pillar of the square-edged model to which Mansor attached extensions to the rear strakes but these are not used in this work and in chapter 3 it is shown that they do not have any negative influences on the overall flow field and are ignored in the remainder of the thesis.
The centreline pressure distribution over the top surface of the round-edged model is shown in Figure 55. The pressure tappings were located at 25mm intervals along the length of the model and the lower surface was not tapped because it was considered that the support shaft would produce erroneous results.

![Figure 55, Centreline pressure distribution of the round-edged model](#)

From the stagnation point at the very front of the model the flow accelerates up the slanted front as the cross-section of the model increases. The pressure tapping at \(x/L = 0.55\) is located right on the join between the front and roof, in the region of very high speed flow as it travels from the front surface onto the roof. This has also been seen in CFD simulations of the steady state pressures carried out by Newey (137). Further along the roof the pressures remain low demonstrating the high speeds around the largest cross section of the model. Down the backlight the flow remains attached and there is pressure recovery until close to the trailing edge of the backlight when the flow reaccelerates into the wake.

The Reynolds number dependency of the drag coefficient of the two models is investigated in Figure 56.
Both models show Reynolds number independence above $Re = 1.3 \times 10^6$. Neither model showed any significant hysteresis whether the windspeed was increasing or decreasing. All the testing using the Davis models in this thesis was carried out at $Re = 1.7 \times 10^6$, with a windspeed of 40m/s.

### 2.5 Repeatability

Taking balance measurements allows a direct comparison of results collected for this thesis and results collected by Mansor up to five years previous. Figure 57 and Figure 58 show the side force and yaw moment coefficients of the round-edged model between $\pm 16^\circ$ yaw, the yaw angle range used by Mansor. Test 1 was carried out some months prior to tests 2 and 3, which took place on the same day without removing the model, but with a few hours between the two runs.
The figures show that the repeatability is very good. The repeatability from Mansor to this work in both the yaw moment and side force is better than ±10%. In terms of counts, the yaw moment varies by a maximum of 7 counts, in a total value of 0.102, which is 7%. In side force the maximum difference is 24 counts, in a total side force value of 0.303, which is 8%. Within the yaw angle range of range ±12°, the difference in aerodynamic loads is below the quoted accuracy of the balance for both the yaw moment and side force.

A final consideration is the location of the model during the tests. The oscillating model rig was mounted on the roof of the wind tunnel with the model suspended from the roof of the working section whereas this work located the model on the wind tunnel floor. To ensure Mansor’s
results were not caused by an unexpected difference in boundary layer and that results from the roof and floor of the wind tunnel can be directly compared a boundary layer survey was carried out using a hot wire probe. Data was collected at 1000Hz for 10 seconds and the mean velocity profiles are shown in Figure 59 demonstrate they are the same.

Figure 59, Wind tunnel working section roof and floor boundary layer velocity profiles
3. Static Model

The flow fields around the static Davis models was thoroughly investigated to create a base case for comparison to those created by the oscillating model detailed in chapter 4. The first section of this chapter details the flow fields around the two models at 0º yaw and section 3.2 investigates the flows around the models when at yaw. This chapter concentrates on understanding the flow fields; balance measurements are included but only covered relatively briefly. The conclusions of both chapters 3 and 4, which contain the results of the experiments, are in chapter 5 which uses these to produce some broader, more widely applicable conclusions.

3.1 0º Yaw

3.1.1 Time Averaged Results

3.1.1.1 Aerodynamic Coefficients

With the models mounted to the underfloor balance, all six load components were recorded. Figure 60 shows the relationship of Reynolds number with lift coefficient for the two models, the dependency of drag on Reynolds number has been shown in Figure 56.

![Figure 60, Lift coefficient Reynolds number sensitivity](image-url)
The square-edged model produces approximately 150 counts more total lift than the round-edged model and this overall increase is made up of increases in both front and rear lift. The rear lift changes are a consequence of the changes to the rear pillar geometry and the small increase in the front lift is likely caused by the front stagnation point moving downward as more flow goes over the model.

On both models the front lift coefficient is much smaller than the rear lift coefficient. This is because of the geometry and proportions of the model. The front of the model is wedge like and the downforce this creates is counteracted by positive lift created by the A-pillar vortices. The ‘front’ of the model extends for 55% of the length of the model meaning that the two positive lift generating surfaces, the roof and backlight, are behind the model centre line and only recorded in the rear lift coefficient.

Both configurations of the Davis model show a small Reynolds number dependence in the lift coefficient above $\text{Re} = 1.3 \times 10^6$ at which drag became insensitive. Between this Reynolds number and $\text{Re} = 2 \times 10^6$, the maximum achievable, the lift coefficients increased by 30 and by 49 counts for the round-edged model and the square-edged model respectively.

The trends in the lift and drag results for the two models agree with results from different configurations of delta wings; Anderson (138) reported that those with sharp leading edges have higher lift and drag coefficients than delta wings with rounded leading edges.

3.1.1.2 Surface Flow Visualisations

Surface flow visualisations were carried out over the rear of the two model configurations to give an initial indication of the flow fields. Figure 61 shows a comparison of the flow patterns on the two models; for clarity, an interpretation of the friction lines seen on the two models are sketched in Figure 62 and Figure 63.
Both models show separation lines down the sides of the backlight with inline flow down the lower half of the centreline of the backlight, these flow patterns are similar to that described by Ahmed et al (3) for an Ahmed model with a sub-critical backlight angle. Despite the superficial similarities, the details of the results on the two Davis model are quite different from each other.

Figure 62 shows two areas of recirculation below the backlight header, one on each side of the centreline. These are fed by flow from the corners of the roof and spiral towards separation points in their centre. These are bounded by flow lines created by saddle points on the roof trailing edge and 1/3 of the way down the centreline of the backlight. These structures, which
are common to both models, are given further consideration following the description of the square-edged model’s flow visualisation.

For the first 1/4 of the rear pillars the flow remains attached, flowing from the side of the model around the rear pillars onto the backlight. Further down the rear pillar the flow separates and the separation line curves around the rounded rear pillar before splitting and between these separation lines would be a secondary vortex, similar to that found on a delta wing (Houghton and Carpenter (24)), but there are no friction lines visible on the model. The reattaching flow from the trailing vortices extends towards the model centre line down which only a small amount of flow travels before separating from the trailing edge.

On the model base, on each side of the model centreline, is a weak, round structure. The directions of these flow structures were unclear from either watching the flow patterns develop or in the photographs; they just show that the paint has migrated away from the indicated line. These are only found on the base of the round-edged model; there are no clear features on the base of the square-edged model where the brush strokes still remained after 5 minutes of the wind tunnel running. It is unclear what is causing this flow pattern, Ahmed et al proposed a torus flow around the edges of the base, but no flow patterns are seen on the square-edged model base which has geometry closer to that of the Ahmed model. The circular shape of the structures on the base may imply a link with the trailing vortices suggesting that the flow structures around the rear of the round-edged model are different from those over the Ahmed model.

The sketch of the friction lines seen from a flow visualisation of the square-edged model is in Figure 63.
Figure 63, Sketch of the friction lines on the rear of the square-edged Davis model

As with the round-edged model there are two recirculations at the top of the backlight which spiral towards the centre.

The trailing vortices are present from the start of the rear pillars separating from the sharp edge of the rear pillar and there is a second separation line slightly inboard of the edge, between these there is evidence of a weak secondary vortex. Both the separation line and the secondary vortex are located only on the backlight and do not wrap around the rear pillar. Both of these are a result of the square rear pillars which create a fixed separation line to initiate the trailing vortices that is independent of surface velocity. This means the flow on the side of the model always remains attached and the separated flow is limited to the backlight only. Compared to the round-edged model, the trailing vortices do not extend as far inboard, more flow travels down the centreline of the model and there are no flow patterns on the model base.

Below the rear pillars of the square-edged model there are 1mm recessed steps that were used by Mansor (99) to attach strake extensions which are not used in this work. The flow pattern over this edge is shown in Figure 64. There is a very small vortex present in the vicinity of the red dashed line, but the flow fully reattaches to the side of the model before reaching the intersection between the side of the model and the backlight. Any effect from this small step was judged to be inconsequential and this step will be given no further consideration in this thesis.
On both the round and square-edged models the recirculations at the backlight form an unusual shape and this is highlighted in the left hand photograph in Figure 65 which shows the square-edged model. The shape and the direction of the flow in the recirculations are similar to that found on the backlight of a notchback type car. An example from Garry and Le Good (44) of such a flow structure is also shown for comparison. This similarity has been previously noted by Gilhome et al (43) and similar conclusions can be reached from the flow field sketches in Spohn and Gillieron (4) on an Ahmed model and from PIV results in Depardon et al (21) who measured the flow field just above the backlight of scaled Citroen C4 model. They found two recirculations on the backlight with a shedding mechanism from the trailing edge of the roof. The sketch of the structure of this flow field feature closely matches the hairpin vortex shedding described by Gilhome (43) emanating from the notch region of a saloon car.

3.1.1.3 Surface Pressures

All the pressure results presented in this thesis have been corrected for tubing effects using the method detailed in chapter 2 and the pressures have been turned into pressure coefficients relative to dynamic pressure using equation 6. Due to the number of tappings on the model it was not possible to record all the pressures concurrently, sampling was split into two batches.
with the pressures on both sides of the models collected concurrently and the pressures on the backlight and base in a second batch.

An indication of the contribution of the backlight and model base to the overall forces acting on the model is found by integrating the surface pressures to find the forces acting normal to the model surface using equation 8. These forces have been converted into force coefficients and presented in Table 2.

\[ F = \int_a P\,da \quad \text{Eq. 8} \]

<table>
<thead>
<tr>
<th></th>
<th>Backlight Lift</th>
<th>Backlight Drag</th>
<th>Base Drag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round-edged Model</td>
<td>0.254</td>
<td>0.092</td>
<td>0.009</td>
</tr>
<tr>
<td>Square-edged Model</td>
<td>0.303</td>
<td>0.110</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 2, Force coefficients calculated from the surface pressures

The larger drag and lift on the square-edged model agree with the values measured on the balance. These results also show that this difference mainly occurs on the backlight; the base drag on the two models is very similar. This is further confirmed by plotting the mean surface pressures on the different faces of the models.

The pressure coefficients, shown in Figure 66, on the different faces of the model are arranged in the form of a net centred on the model base; the lines between the pressure results represent the projected intersections between the different faces. The x and y axes have been non-dimensionalised against model width and height respectively and the same colour scale is used throughout this thesis for consistency and ease of comparison between the figures.

The time averaged surface pressure coefficients on the round-edged model are in Figure 66.
At the backlight header is an area of low pressure caused by the flow accelerating from the roof onto the backlight but the two recirculations seen in the flow visualisations are not distinct features in the time averaged pressures. The surface pressures along the sides of the backlight are lower than those on the centreline because of the high velocity flow caused by the trailing vortices and flow around the rear pillars. Along the centreline of the backlight there is pressure recovery as the cross section of the model reduces; before the pressure gradient reverses towards the trailing edge of the backlight as the flow accelerates around the curved trailing edge of the backlight into the near wake. Along the trailing edge of the backlight there are two small and distinct regions of low pressure that appear related to the trailing vortices. High velocity flow around the rear pillars onto the backlight and into the trailing vortices is found along the entire rear pillar. There is no distinction in the surface pressures between the top of the rear pillar and lower down, despite the flow visualisations showing fully attached flow at the top and a separation line developing 1/3 of the way down the rear pillar. Low pressures caused by the A-pillar vortices are found beneath the A-pillars and extending along the edges of the roof onto the rear pillar; there is also low pressure on the vertical rear edges of the model as the flow accelerates into the wake. The low pressures are concentrated around the edges of the model with the majority of the model’s sides under fairly uniform surface pressures.

The surface pressures on the base of the model are slightly asymmetric and indicate that something slightly different from the quasi 2D wake found behind an Ahmed model is occurring. This result is in general agreement with the surface flow visualisations which indicate there is a weak structure on the base of the model.

The mean surface pressures on the square-edged Davis model are shown in Figure 67.

![Figure 67, Steady state pressures on the square-edged Davis model, 0°](image)

Similar to the round-edged model, at the backlight header is a region of low pressure caused by the acceleration of the flow over the roof onto the backlight and there are no features that directly relate to the two recirculations seen in Figure 63. The pressures along the sides of the model...
backlight are lower than on the round-edged model, indicating the greater strength of the main trailing vortices. Down the centre line of the backlight is pressure recovery as the model cross-section reduces and, unlike on the round-edged model, the pressure gradient does not reverse approaching the trailing edge of the backlight. The triangles of low pressure in the lower corners of the backlight are extensions of the low pressures down the edges of the backlight and caused by the trailing vortices leaving the backlight.

On both sides of the model there are low pressures under the A-pillar vortices which extend along the roof but there is significantly less flow acceleration around the rear pillars onto the backlight and into the trailing vortices than on the round-edged model, the square edge has increased the pressure upstream of it and this effect is also seen when strakes are added to a production car in Appendix 1. The vortices forming on the backlight is in agreement with the flow visualisations which showed separation occurring from the edge of the backlight rather than on the curved rear pillar and this is the same effect as reported by Mayer and Wickern (121) when strakes were added to the rear light cluster moulding of a production saloon car. These results also confirm that the small step in the rear pillars, evident in the flow visualisations, is not affecting the overall flow fields. The vertical rear edges of the model are rounded, Figure 54, and cause small regions of low pressure to form as the flow accelerates around them into the wake, most obviously on the left hand side of the model. However, this is much weaker than on the round-edged model indicating a strong link between the rear pillar flows and those around the vertical edges on the round-edged model.

The pressures on the model’s base indicate fully separated flow which is in agreement with the lack of flow features in the flow visualisation, Figure 63.

3.1.1.4 PIV

Downstream of the model, PIV was used to measure the flow field. Using the arrangement described in section 2.3.3, images were collected in the yz plane, normal to the onset flow, 0.25L and 0.5L behind the base of the model.

The measured flow fields behind the two models are shown in Figure 68. All three components of velocity were captured by the PIV but it was found that only showing the two in-plane velocities, \(v_x, v_y\), gave the best clarity in the results figures. The background colours indicate the velocity magnitude as a percentage of the onset velocity and vector arrows show the flow direction; the scaling and colours are the same in all the PIV velocity results in this thesis and a
simplified model outline is also included in each of the figures. The x and y axes are non-dimensionalised with model width and height respectively.

The results from the 0.25L plane show the wakes behind both models consist of a pair of trailing vortices with a central downwash, by the 0.5L plane these flow structures have mostly dissipated. In both wakes, the peak velocity of 50% of the onset flow is located between the two trailing vortices. Despite these similarities the details of these wakes are very different. Behind the round-edged model the trailing vortices are nearer the model centreline and closer to the ground plane than behind the square-edged model. Because the square-edged model has a greater distance between the vortices the central downwash is more extensive but less concentrated than in the round-edged model’s wake.

In the 0.5L plane only the central downwash remains behind the round-edged model as the vortices have mostly dissipated, whereas behind the square-edged model, the vortex centres are still visible. This shows the square-edged model’s trailing vortices are stronger with less mixing.
with the surrounding flows than those from the round-edged model and this is confirmed in Figure 69, which shows the vorticity contained within the mean velocity fields 0.25L behind the models. The results from the two models make up halves of the same figure and to avoid the slight flow field asymmetry corrupting the results, the square-edged model’s results are taken from the left hand side of the wake and mirrored to give a true comparison of the two results.

This figure reinforces the differences in the trailing vortex location and strength inferred from the velocity plots. The vorticity behind the square-edged model is approximately twice the value and concentrated in a much smaller area than in the wake of the round-edged model. This is in agreement with the differences in the surface pressures on the backlights of the two models. The vorticity behind the square-edged model is further from both the ground plane and the centreline than behind the round-edged model, leaving space for a separate turbulent, quasi-2D wake directly behind the base. This is fed from the trailing edge of the backlight and the floor and is in agreement with the general flow structure described by Ahmed et al (3) for a sub-critical backlight angle. The location of the wake vorticity behind the round-edged model precludes this from happening and indicates the trailing vortex and base wake mix producing a different flow structure, which has not been explicitly described in previously published results where models typically have flow separation locations defined by model geometry around the rear edges. Projecting the vorticity from the round-edged model upstream, the location of the

Figure 69, Mean wake vorticity, 0.25L, 0°
vorticity agrees with the small areas of low pressure on the trailing edge of the backlight (Figure 66) and the weak structures seen in the flow visualisation on the base on the model (Figure 62).

Figure 69 can be compared to previous work by Davis (10) and Ryan (85) shown in Figure 70 and Figure 71 respectively.

Davis used a configuration of the model with a diffuser and supported it with a central string above a moving floor. Vorticity is plotted from the flow velocities recorded with a pressure probe that was traversed behind one half of the model and the results mirrored to create a full plot.

![Figure 70, Mean vorticity behind a Davis model at 0°, taken from (10)](image)

Davis found three areas of vorticity on each side of the model, the lower region was from the diffuser, the middle region was the trailing vortices and the upper region was from the A-pillar vortices. However, it is possible that there was an interaction between the A-pillar flows and a horseshoe vortex that formed around the base of the roof strut strengthening the A-pillar vortices allowing them to be seen in the wake, unlike in Figure 69. This flow field is quite different from those in Figure 69 but these differences are caused by differences in the experimental set ups which created additional flow structures, rather than a more fundamental difference to the flows over the rear of the model. Despite these differences, the value of the vorticity of the trailing vortices falls between the two values of vorticity found in the wakes of the two versions of the Davis model used in this thesis.

Figure 71 shows the vorticity found behind the Durham geometry model recorded by Ryan using a pressure probe which was traversed across the entire width of the model.
Ryan only found two regions of vorticity in the wake, both caused by the trailing vortices. This result agrees with the mean vorticity in Figure 69 with the shape of the vorticity closely matching that found behind the round-edged model although the vorticity values are slightly higher.

### 3.1.2 Unsteady Flow Fields

As explained in chapter 1, mean and instantaneous flow fields are quite different and to fully understand the flow fields around the Davis models it is important that the unsteady components of the flow field are investigated. This section will initially investigate the general flow field unsteadiness before identifying specific unsteady flow structures.

#### 3.1.2.1 RMS Unsteadiness

The RMS surface pressure fluctuations, presented in the form of $C_p$, found in the round-edged model pressure data are shown in Figure 72.
The results are dominated by large fluctuations on the rear edges of the model and on the model base; there is a further small area of large fluctuations on the backlight between the two recirculations seen in the flow visualisations. The surface pressures along the edges of the backlight under the trailing vortices and over the majority of the sides of the model are very steady with small increases along the A-pillar due to the A-pillar vortices. The large surface pressure fluctuations on the rear edges of the model are caused by the model’s round edges which create unsteady separation lines, this unsteadiness feeds into the near wake and creates a highly unsteady near wake directly behind the model base. This is further evidence to support the theory that there is a previously undescribed flow structure in the near wake. The strength of these fluctuations is quite asymmetric, the cause of this is currently not known but there is a discussion of the flow field asymmetry seen in all this chapter’s results in section 3.3. The pressure fluctuations between the two flow recirculations seen in the flow visualisations is in agreement with Krajnović and Davidson (7) who reported that the saddle point between the two recirculations is very unstable.

The RMS surface pressure fluctuations on the square-edged model are in Figure 73. It is very obvious that on all the surfaces of the model the pressure fluctuations are lower than on the round-edged model.

![Figure 73, RMS pressure fluctuations on the square-edged Davis model, 0°](image)

Down the centreline of the backlight is a small increase in surface pressure fluctuations from the unsteady saddle point 1/3 of the way from the start of the backlight and this feeds downstream to the trailing edge of the backlight. There is an increase in the size of the pressure fluctuations on the trailing edge of the backlight caused by unsteady flow separation around the curved surface of the model. The surface pressure fluctuations under the A-pillar vortices and on the front half of the model closely match those on the round-edged model. The fluctuations on the rear pillars and vertical rear edges, which are rounded, are smaller and those on the model base
are significantly reduced and these changes result from the different flow structures in the near wake.

As seen in the mean surface pressures on the round-edged model, Figure 66, there is a link between the low pressures on the rear pillars and vertical edges, implying the near wake is energised by flow coming into it from the rear pillars and from around the vertical edges. This is a very different flow structure to that proposed by Ahmed (3) and allows the flow to remain attached longer but this mechanism is highly unsteady and affects all the separation lines and the flow structures within the separation lines producing the large pressure fluctuations on the separation lines and model base. Behind the square-edged model, the flow structures are quite different; distinct trailing vortices form on the backlight and a separate, weak quasi 2D wake is formed directly behind the model base.

Integrating the instantaneous surface pressures enables an estimate of the unsteady components of the aerodynamic forces; the standard deviations of the forces have been converted to force coefficients and presented in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>$C_D^*$</th>
<th>$C_L^*$</th>
<th>$C_{SF}^*$</th>
<th>$C_{SR}^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round-edged Model</td>
<td>0.007</td>
<td>0.013</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>Square-edged Model</td>
<td>0.004</td>
<td>0.009</td>
<td>0.003</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 3, Aerodynamic force coefficient standard deviations, 0°

Although the square-edged model has a smaller drag and lift standard deviations than the round-edged model, the side force standard deviations are the same on both models despite clear differences in the contour plots. This is because the actual differences in the pressures acting on the model are quite small and the process of integrating the pressures to create forces and converting them to coefficients makes the individual contributions nearly insignificant, indeed the large scale differences on the backlight only create a 0.004 change. The larger standard deviations of lift and drag on the round-edged model are consistent with Mansor’s (99) finding that the oscillating motion of the round-edged model was more unstable than that of the square-edged model.

The instantaneous PIV results are not time resolved but can be used to investigate the wake unsteadiness. Only the data from the 0.25L plane is used because Figure 68 shows the wake has largely dissipated by the 0.5L plane. The RMS values of the mean in-plane velocity magnitudes are shown as a percentage of the onset flow speed in Figure 74. The round-edged model’s results are on the left of the figure and the square-edged model’s results from the left side of the
model are mirrored to the right hand side of the figure. The largest velocity fluctuations in the wakes of both models are associated with the trailing vortex cores and the base wake. The large RMS values in the bottom corners of the figure are caused by poor seeding in the extremity of the image.

The mixing of the trailing vortices and the wake behind the base of the round-edged model is demonstrated by the big, single region of large velocity fluctuations. In contrast, behind the square-edged model there are two distinct regions of large fluctuations, where the trailing vortex fluctuations are separate from the fluctuations due to the wake behind the model base, albeit with the vortex distorting the wake behind the base and entraining it into the vortex. Similar results to these are presented by Lienhart and Becker (139) in the wake of an Ahmed model with a 25º rear slant.

The sources of the unsteady wake velocities are identified in Figure 75 by plotting RMS vorticity fluctuation to isolate those parts caused by the trailing vortices.
In the wake of the round-edged model the location of the RMS vorticity matches the location of the RMS velocity in Figure 74, demonstrating that the trailing vortex and wake behind the base are indistinct behind the round-edged model. Behind the square-edged model the RMS vorticity fluctuations are only concentrated in the trailing vortex with significantly lower values in the base wake where the velocity fluctuations were of a similar magnitude to those in the vortex. This confirms that the trailing vortex is distinct from the wake behind the base of the model, unlike behind the round-edged model.

The differences in the trailing vortices are further investigated by finding the instantaneous trailing vortex centres in each of the 1000 instantaneous vector fields. This uses the method of Grosjean (140) which is based on calculating the centre of angular momentum. To avoid conflicts between the left and right trailing vortex, only the vectors to the left of the model centreline have been used and if more than one vortex existed in the instantaneous vector field only the location of the strongest was recorded. Only the left half of the square-edged model’s vector fields have been used with the results in Figure 76 mirrored.
The locations of the vortex centres for both models agree with the locations of the mean and RMS vorticity in Figure 69 and Figure 75 respectively with the round-edged model producing a much greater spread of results indicating a much more unstable wake structure than behind the square-edged model. The flow around the round-edged model’s rear pillars contains a large component of inboard velocity and minimal vertical velocity. This creates a weak vortex, close to the surface of the backlight. When it leaves the end of the backlight it rolls up and mixes with the base wake creating a much larger trailing vortex. This extends away from the model as the flow is carried downstream, but the rotation is fed upstream and creates the weak features seen on the model base in Figure 62. The mixing of the weak trailing vortex and the wake behind the base means the trailing vortex is located behind the base and the inboard flow component of the flow over the backlight means that the vortex is closer to the model centre line.

The square rear pillars create a fixed separation line and limit the inboard flow and increase the vertical momentum producing strong and stable longitudinal vortices above the backlight of the model. Because the trailing vortices are located higher above the backlight, they do not mix with the base wake except though the trailing vortices entraining flow and shearing against the wake behind the base.
3.1.2.2 Unsteady Flow Structures

The frequency content of the surface pressure is found from the 8192 instantaneous pressure samples. The data did contain the wind tunnel resonance and fan speed frequencies found around 9Hz, 80Hz and 90Hz which were not removed from the data. The spectral results were found using the ‘pwelch’ function in Matlab; the data was split into smaller samples 1024 data points long with a 75% overlap and windowed using the ‘Hamming’ function. This produced final result from an average of 32 smaller data sets with maximum and minimum frequencies of 130Hz and 2Hz respectively.

Neither model has any distinct frequencies under the recirculations seen in the flow visualisations or in the large pressure fluctuations between them despite the shedding reported by Depardon et al (21). Under the trailing vortices, on the backlight of the round-edged model is a dominant frequency between 12 and 13Hz which is found in place of the 9Hz wind tunnel resonance, but on the square-edged model only the wind tunnel resonance is found. Similar results are found on the sides of the models under the rear pillars; the square-edged model pressure data only showed the 9Hz wind tunnel resonance, but towards the rear of the round-edged model this resonance is replaced by the 12-13Hz spectral peak, as shown in Figure 77. This is a relatively low flow field frequency implying a large scale flow field oscillation or pumping effect. Converting this frequency to a Strouhal number, using the square root of the frontal area, gives St = 0.06. This directly matches the Strouhal number of base pumping found behind a squareback by Duell and George (36) but the coupling between this frequency and the wind tunnel resonance means this may not be a true result. The increase in the frequency from 9Hz to 12Hz implies that the periodic flow field feature may have a natural, un-coupled frequency higher than recorded. In line with this Sims-Williams et al (16) found an alternate strengthening of the trailing vortices occurring at St = 0.1 which may be a possible explanation but investigating the phase relationship between the two sides of the model at this frequency only produced inconclusive results.
Along the trailing edge of the backlight of the round-edged model are spectral peaks between 6.5 – 7.5Hz. These are half the frequency associated with the trailing vortices and further evidence of a link between the trailing vortices and the wake behind the model base.

In the same locations on the square-edged model are spectral peaks between 120Hz and 125Hz. This is a much higher frequency, caused by a shear layer instability which may extend into a large scale flow change further away from the model. This gives a Strouhal number of St = 0.56 which agrees with previous work by Sims-Williams et al (16) and Sims-Williams and Duncan (14) using Ahmed bodies with sub-critical backlight angles. They found dominant frequencies in the wake at St = 0.58 and shedding from the trailing edge of the floor of an Ahmed model at St = 0.52 respectively. In both studies this periodic feature affected the strength of the downwash between the two vortices, which would affect the flow over the trailing edge of the backlight. Calculating the Strouhal number using the base height gives a value of 0.23 which matches Bearman (12) and indicates that this shedding is related to the separation directly.
behind the base. However, the pressures recorded on the base of both models contain no notable
frequency content.

The un-time resolved PIV images can be used to investigate unsteady flow structures within the
wake through statistical methods. The raw images were collected independently from any flow
field feature; hence among the 1000 instantaneous flow fields there will be individual flow
fields that show the maxima and minima of any periodic features. These can be found using
conditional averaging which allows the investigation of large scale unsteady flow structures
contained within general broadband turbulence.

From the 1000 flow fields, each individual vector has a normal distribution. The instantaneous
vector fields are ordered based on the size of single vector and those ±2 standard deviations
away from the mean are averaged to produce two results that show the flow field associated
with the extreme values of the vector. The conditionally averaged results are shown side by side,
the left hand plot shows the result from -2 standard deviations and the right hand plots show the
results from +2 standard deviations. Only PIV data from the 0.25L is used and the flow fields
are presented in the same format used throughout this thesis with the addition of a cross to show
the location of the vector that the conditional averaging was based upon. Only results that show
large scale flow field changes are shown, most vectors produced results that only showed
general, unstructured turbulence.

Two interesting results are found in the wake of the round-edged model. By selecting a vector
slightly inboard of the vortex core an alternate strengthening of the central downwash associated
with each vortex is found and this is shown in Figure 78. This was only found on a small
number of vectors on the inboard sides of both trailing vortices but is similar to the periodic
feature found by Sims-Williams at a St = 0.1.
A second, more common, vortex motion, shown in Figure 79, is found by selecting vectors behind the centreline of the model base. This shows the trailing vortex cores moving vertically and horizontally and the central downwash strengthening. In the left hand image the central downwash is weak and the vortex cores are further from the ground plane and model centreline than in the right hand image. In the right hand image the vortex cores are around 25mm closer to the centreline and level with the floor of the model and the central downwash is stronger. Whether this is primarily driven by a base wake pumping, instability in the trailing vortices or a combination of the two is unclear.

The vortex motion shown in Figure 79 is similar to a second type of vortex motion reported by Sims-Williams et al (16) in the wake of a 1/4 scale Rover 200 model at St = 0.31 created by a vertical motion of the vortex cores associated with the vortices strengthening and weakening. This frequency was not found in the pressure data but Sims-Williams reported that both the alternate vortex strengthening and the vertical motion of the vortices are generally weaker and harder to identify closer to the surface than further away.
This flow field change is responsible for some of the vortex core motion behind the round-edged model, as seen in Figure 76, but most of the variation of the vortex core is due to general unsteadiness within the flow where the vortex cores move independently of each other in a turbulent fashion rather than a periodic fluctuation.

Using the data from the wake of the square-edged model and choosing a vector at any height behind the model on the centreline produces results that show changes to the central downwash and the strength of the trailing vortices.
The two plots in Figure 80 show the strength of the downwash varies significantly but the vortex cores remain in a consistent location. Associated with this, the vorticity in the right hand flow field is 20% higher than in the left hand flow field with a clear relationship between the stronger vortices and the stronger central downwash. This agrees with the flow structure found behind Ahmed models by Sims-Williams et al (16) and Sims-Williams and Duncan (14) and demonstrates the structure associated with the shedding from the trailing edge of backlight of the square-edged Davis model at St = 0.52. This motion is similar to that in Figure 79 but it is not clear if these are manifestations of the same unsteady flow field effect with differences created by the rear pillar geometry and its influence on the mixing of the trailing vortices and base wake or whether these are fundamentally different.

3.1.3 Flow Field Asymmetry

Results in this chapter consistently showed unexpected levels of asymmetry between the left and right hand sides of the model which are independent of the models and the experimental method. Similar levels of asymmetry were also seen in some early 2D planar PIV data that is not presented in this thesis.

A flow visualisation photo that clearly demonstrates the asymmetry is in Figure 81, showing the pattern of flow visualisation drops on the floor of the wind tunnel behind the square-edged model.

![Figure 81, Wake asymmetry at 0° model yaw angle, onset flow from the left of the image](image)

The causes of this asymmetry are not fully understood but are likely due to two different reasons and further compounded by a common experimental approach.
• Model centreline symmetry. The models used in this thesis are not perfectly uniform with slight differences side to side. These originated in the manufacture of the model but are within typical manufacturing tolerances for a wet layup composite part and are no greater than the dimensional differences found in other models produced within the department which apparently show more symmetrical wakes. It is worth noting that no matter how tight the dimensional tolerances a model has; there will always be slight side to side differences.

• Onset flow uniformity. Although the onset flow velocity uniformity shows only a ±0.3% deviation from mean across the working section, there remain small differences in the onset flow. Considering notchback shapes, Gaylard et al. (45) postulates that small, seemingly inconsequential, non-uniformities in the onset flow can have a larger than expected effect on the overall flow field enhancing or diminishing flow structures on each side of the model.

Further to these, there is often an assumed symmetry plane along the model centreline and when a model is at 0° yaw it is common to only investigate one half of the model, assume symmetry and mirror the results. This approach prevents any asymmetry being recorded; hence small levels of asymmetry that may otherwise be commonly observed across a range of models are unexpected when the entire width of the model is considered. A symmetry plane was used by Davis (10) to produce the results in Figure 70 but Ryan (85) carried out a full wake survey to produce Figure 71 which does show slight asymmetry, although the static pressures in Figure 82 show this more clearly. Littlewood et al (141) who was also working in the Loughborough University ¼ scale wind tunnel, comprehensively pressure tapped the base of a Windsor model and found comparable surface pressure asymmetry on the base of a squareback model.

![Figure 82, Flow field asymmetry in the static pressures, taken from (85)](image-url)
3.1.4 0º Yaw, Flow Field Description

Having thoroughly investigated the mean and unsteady aerodynamics of the two configurations of the Davis model at 0º yaw, it is possible to describe the flow field and the unsteady motions found in the wakes of the two models. Although the wakes of both models are dominated by trailing vortices, the differences to the rear pillars significantly alters the formation of the vortices and the wakes behind the two models are quite different.

3.1.4.1 Square-Edged Model

A sketch of the inferred, time averaged, flow field over the rear of the square-edged Davis model is in Figure 83.

![Figure 83, Sketch of the flow field over the rear of the square-edged model](image)

The flow field is generally similar to that described by Ahmed et al (3) with a sub-critical backlight angle. Slight differences occur due to the relative sizes of the backlight and base on the Davis model compared to the Ahmed model.

At the backlight header is a complex area of recirculation which is the same for both models. The square rear pillars create fixed separation lines along their entire length creating strong vortices above the edges of the backlight. Associated with the strong vortices is a strong central...
downwash and the combination of these creates high values of drag and lift. The trailing vortices do not mix with the wake behind the base, although they do entrain it at the outer edges. There is weak periodic shedding from the trailing edge of the backlight associated with a strengthening of the central downwash and the trailing vortices. Because the wake behind the base and trailing vortices are distinct the flow structures, and hence the aerodynamic loads, acting on the model, are relatively stable. Krajnović and Davidson (7) postulated that the trailing vortices downstream of an Ahmed model would disappear and the base wake would become the dominant flow structure, but because of the longer backlight and smaller base of the Davis model the opposite is, in fact, the case.

3.1.4.2 Round-Edged Model

A sketch of the time averaged flow structures over the rear of the round-edged model is shown in Figure 84. For a relatively small geometry change the changes to the flow field are significant.

![Figure 84, Sketch of the flow field over the back of the rear of the round-edged Davis model](image)

At the backlight header the complex area of recirculation is the same as found on the square-edged model but further down the backlight the flow structures are different from those over the square-edged model and described by Ahmed et al (3). The round rear pillars allow acceleration of the flow from the sides towards the model centre line and for the first 1/3 of the trailing pillar
the flow is attached before a separation line develops. This creates trailing vortices that are weak, close to the surface of the model and extend inboard toward the centreline of the model. Upon leaving the backlight, the relatively low and weak trailing vortices mix with the wake behind the base of the model, creating trailing vortices that are behind the base of the model and close to the centre line. This rotation feeds weakly upstream onto the base of the model. The mixing of the trailing vortices and the wake behind the base is an unsteady process with large variations in the locations of the vortex centres, the vortex cores also exhibit some periodicity and move up and down and alternately strengthen. The unsteady mixing of the trailing vortices and base wake and the periodic motion of the vortex cores create larger unsteady aerodynamic forces acting on the model than on the square-edged model.

3.2 Yawed Model

This section considers the aerodynamics of the two Davis models at non-zero yaw angles. It builds on the findings and ideas of section 3.1 and completes the static model analysis to create a comprehensive test case for comparison to the oscillating model results in chapter 4. In keeping with the findings of the literature review, this section mainly considers side force, yaw moment and lift. To find the limits of the trends seen at small yaw angles the balance testing used a much larger range of yaw angles than the surface pressure or PIV testing which concentrates on -5º and -10º yaw angles.

3.2.1 Time Averaged Results

3.2.1.1 Aerodynamic Coefficients

3.2.1.1.1 Side Force Coefficient

The total side force coefficients for both models are shown in Figure 85a and the front and rear side force coefficients are in Figure 85b.
For both models there are two regions in the total side force coefficient results; between ±10° yaw the side force coefficient gradient is lower than at larger yaw angles. This transition is gradual and there is no distinct yaw angle at which the boundary between the two different gradients lies. The square-edged model has a larger side force gradient than the round-edged model and Figure 85b shows that this difference is from the rear of the model. The front side force gradients for the two models are very similar which is consistent with the repeated frontal geometry on the two models.

### Yaw Moment Coefficient

Figure 86 shows the yaw moment coefficients of the two models. Approximating the results as a straight line across the entire yaw angle range, the square-edged model yaw moment coefficient gradient is 40% smaller than the round-edged model’s yaw moment gradient. The differences in the yaw moment gradients are caused by the two models’ different rear side force coefficients where the larger rear side force coefficient on the square-edged model creates a lower yaw moment gradient. This change in the yaw moment gradient between the two models is much larger than would be expected by adding small strakes to a production vehicle, an example of which is in Appendix 1 and Baden Fuller et al (82), where strakes added to production vehicle only reduced the yaw moment by 7% at full scale and 5% at model scale.
The change in gradient at ±10° seen in the side forces is evident in the yaw moment coefficients for the square-edged model, although the change in gradient in the results for the round-edged model change is less distinct. At ±28°, the yaw moment gradient for the round-edged model reduces possibly suggesting that the flow structures present up to that yaw angle have started to break down.

The lateral centres of pressure, calculated using the side force and yaw moment coefficients of the two models are in Figure 87. The location of the centre of pressure is non-dimensionalised against model length and is quoted relative to the model centre line with a positive result indicating a location towards the front of the model.
The centres of pressure of both models are forward of the mounting shaft as expected given both models’ positive yaw moment gradients. The centre of pressure on the round-edged model is approximately twice as far further forward than on the square-edged model, which is in agreement with the larger yaw moment gradient on the round-edged model. The anomalous looking results close to 0º yaw are caused by small values of side force and near zero yaw moments which are close to the accuracy threshold of the balance. The asymmetry in both model’s results is caused by a small positive offset between 0º yaw and where the yaw moment and side force coefficients cross the x axis. This is common to both models showing that it is fundamental to the model shape and is also seen in the loads inferred from the surface pressure results in Figure 100.

3.2.1.1.3 Lift Coefficient

The total, front and rear lift coefficients of the two models at yaw are shown in Figure 88.

At yaw, the total lift reduces on both models; this is a combination of less rear lift and more negative front lift. At very large yaw angles the round-edged model’s results show a distinct change in the results trend caused by a step change in the flow field that existed at smaller yaw angles. This is similar to the change seen in the yaw moment results and is also found in the drag results.

Figure 88, Davis model lift coefficient at yaw
The reduction of the lift coefficient at yaw is not typical of simple automotive shapes or production vehicles where lift increases at yaw. However, all the previous research using either model, (100) (99) (79) (101) (142), has only considered side forces and yaw moments and has shown the models to produce good and usable results demonstrating that this is a peculiarity of the models, rather than something problematic.

Both Davis (10) and Ryan (85) found their respective models produced lower lift coefficients at yaw but both models had a diffuser and the reductions in lift coefficient were not discussed. Katz (143) also reported increasingly negative lift coefficients at yaw for a generic, open wheel, race car with a flat floor and this was attributed to increased suction under the floor of the model caused by increased flow under the vehicle from the windward side. Using the balance results alone it is impossible to state the cause of the reduction in lift on the Davis models and this result is given further consideration later on in this chapter in Figure 101.

The square-edged model has a lower yaw moment coefficient and larger lift coefficient at 0º yaw than the round-edged model and this appears to contradict previous work by Howell and Le Good (67) and Howell and Baden Fuller (80) who both report a beneficial link between geometry changes at the rear of a model that reduce rear lift also reduce the yaw moment coefficient gradient. Howell and Baden Fuller concluded with a series of geometry changes where this relationship did not apply, such as underfloor and diffuser changes and elongating the boot deck on a saloon car. The rear pillar changes on the Davis model appear to be a further exception to this general rule. To confirm this, both Davis models were tested with a simple 8mm high, 90º spoiler attached across the trailing edge of the backlight to reduce rear lift. The aerodynamic loads of both models were measured at 0º and 15º yaw angles, in keeping with the method used in Howell and Baden Fuller with an onset flow speed of 40m/s. In agreement with the general trend, the rear spoiler reduced the rear lift and yaw moment coefficients of both models, with yaw moment reductions of 13% for the round-edged model and 6% for the square-edged model, and confirm that the results from the rear pillar changes are a further exception to the general rule.

3.2.1.1.4 Steady State Flow Field Hysteresis

Normally, yaw sweeps start at 0º and then the model is rotated in each direction to progressively larger yaw angles to avoid the potential for hysteresis to develop if the yaw sweep starts at a none zero yaw angle. Steady state yaw angle hysteresis on the Davis model was tested by altering the starting yaw angle of the model. Initially, the model was at 0º when the fan started
and once the fan was up to speed, the model was yawed to 10° and data was collected. In the second test the fan was turned on with the model at 10° and the flow field development only occurred at 10° yaw. Both tests were repeated 50 times and the results found using the round-edged model are shown in Figure 89. The individual results are shown by the single points and an ensemble average of each data set is shown by the dashed lines.

![Figure 89, Effect of model yaw angle origin](image)

The results for the two test methods are very similar showing that the steady state flow field is not subject to any yaw angle based hysteresis. The results gained using the traditional test method are slightly larger but the averages from both data sets are within 1 yaw moment count of each other, which is below the accuracy threshold of the balance, and the difference between the two results is exaggerated by the scale of the y axis.

### 3.2.1.1.5 Yawed Reynolds Sweep

In a standard Reynolds sensitivity test the model is mounted at 0° yaw and only drag or lift coefficients are considered. However, in normal driving, a none-zero yaw angle is likely present from starting the car, hence the 0° yaw Reynolds number test results may not apply. This was investigated with a Reynolds sweep with the models at 10° yaw. In addition to the lift and drag coefficients, the Reynolds sensitivity of the lateral coefficients was also tested. The side force coefficients of the two models, measured during a Reynolds number sweep with the model at 10° yaw, are shown in Figure 90.
Reynolds number independence occurs at Re > 1.3x10^6 with no hysteresis whether the windspeed is increasing or decreasing and both these results agree with the 0° drag coefficient results shown in Figure 56. Similar results to these are found for the other aerodynamic coefficients with the model at yaw demonstrating that Reynolds effects at yaw are no different from those at 0°.

3.2.1.2 Flow Visualisations at Yaw

Figure 91 shows the surface flow visualisation on the leeside of the round-edged model at -5° yaw angle and Figure 92 the square-edged model. Within each figure, the left hand image shows the photograph and the right hand image is a sketch representing the best interpretation of the friction lines seen on the model surface. Only the leeside of the two models are shown because this is the location of greatest interest as there was little different on the windward side from the 0° yaw results apart from on the round-edged model where the windward trailing vortex separation line was further around the rear pillar, extending onto the edge of the backlight.
The flow visualisations show the leeside A-pillar vortex and trailing vortex are linked on both models. Below the rounded A-pillar is the A-pillar vortex separation line and further down the side of the model there is the reattachment line, between these is a large secondary vortex, much larger than seen on a model with a sharp A-pillar in Howell et al (144). At the top of the A-pillar the separation and reattachment lines continue, the separation line moves onto the roof, inboard and onto the backlight where it defines the edge of the leeside recirculation at the top of the backlight. The reattachment line remains on the side of the model until the start of the rear pillar where it moves onto the edge of the backlight and becomes the rear pillar separation line. The secondary A-pillar vortex feeds into the trailing vortex which is rotating in the same direction. The surface flow lines from the primary A-pillar vortex can be seen on the side of the model up to the start of the rear pillar beyond which they disappear indicating that the vortex has detached from the model surface.

This may be a model specific result based on the long A-pillar and short roof of the Davis model but a similar flow structure is found on a production Jaguar XF. A smoke flow
visualisation, shown in Figure 93, was carried out at the MIRA full scale wind tunnel and shows the flow from the A-pillar vortex feeds into the trailing vortices which could potentially produce similar surface flow visualisation patterns as seen on the two Davis models.

![Figure 93, Smoke flow visualisation of the A-pillar vortex and trailing vortex on a production Jaguar XF](image)

### 3.2.1.3 Surface Pressures at Yaw

The surface pressures have been non-dimensionalised with dynamic pressure, arranged in a net and the contours coloured using the same scale as previously in this chapter. In both the pressure and PIV results, the right hand side of the model is windward and the left hand side leeward. The mean surface pressures on the round-edged model at -5° yaw are in Figure 94 and at -10° yaw are in Figure 95.

![Figure 94, Steady state surface pressures, round-edged model, -5° yaw](image)
At yaw, the surface pressures are asymmetric with large differences between the two sides of the model. The changes in surface pressures at -10° are a continuation of the changes in the surface pressures at -5° yaw and the discussion will focus on the larger yaw angle as it gives clearer changes from 0° yaw.

The largest differences between the two sides of the model are under the A-pillars and around the rear pillars. There are stronger suctions under the leeside A-pillar and around the windward rear pillar onto the backlight demonstrating stronger vortices in these locations and there is also low pressure around the vertical rear edge on the windward side. Corresponding to this, the windward A-pillar vortex, leeside trailing vortex and flow around the leeside vertical rear edge weaken.

The surface pressures on the yawed square-edged model at -5° yaw are shown in Figure 96 and at -10° in Figure 97 and, as with the round-edged model, the discussion will focus on the larger yaw angle.
The differences in surface pressures associated with the A-pillar vortices are very similar to those on the round-edged model because the fronts of the two models are the same but it does not extend as far onto the rear pillar. There is a small increase in suction along the windward rear pillar but the largest increase associated with the stronger windward vortex is found on the windward edge of the backlight in keeping with the trailing vortex forming on the backlight as described in section 3.1.4.1.

These results are in general agreement with the results in Ryan and Dominy (83) who used a similar model with square rear edges. They showed a large area of suction under the leeside A-pillar vortex with pressure increasing towards the rear; on the windward side were higher pressures with a slight reduction towards the rear pillar with an intense area of suction on the windward edge of the backlight.

The largest differences between the two models are around the windward rear pillar, on the side and backlight of the models. The windward trailing vortex on the round-edged model forms on the side of the model and wraps around the rear pillar onto the backlight, creating strong suction on the side of the model. On the square-edged model, the trailing vortex forms on the backlight, creating intense suction along the windward edge of the backlight and much less suction on the side of the model. Further to these differences directly created by the trailing vortex formation, the different interactions between the trailing vortices and the wake behind the base create a much smaller suction peak on the vertical rear edge of the square-edged model than on the round-edged model.

The differences in the sources of the side forces is further explored by considering the difference in surface pressure between the two sides of the models at -10° yaw, found using equation 9. The results of this are shown in Figure 98 and Figure 99 for the round and square-edged models respectively.
The main sources of the side force acting on the model are along the rear pillar, on the vertical rear edge and the largest difference is below the A-pillar, which agrees with the positive yaw moment gradient recorded on the balance. The surface pressure differences on the rear half of the model are caused by the flow into the windward trailing vortex and near wake, creating suction which acts with the suction under the leeside A-pillar vortex to create the positive yaw moment gradient. The surface pressures on lower rear halves of the model are very consistent between the two sides. The extent of the A-pillar region is in agreement with the previous work using this model by Passmore et al (79) and despite the considerable differences in shape, the sources of side force generally agree with those found on a large production saloon by Howell (46).

The largest surface pressure difference on the square-edged model, Figure 99, is also under the A-pillar vortex. There is a small increase in suction on the windward rear pillar but it is 0.3Cp less than on the round-edged model and covers a smaller area of the model. There is no effect at the vertical rear edge of the model as the consistent surface pressure on both sides of the model extends back to the vertical rear edge. These two differences in the surface pressures between the two models create a larger rear side force and smaller yaw moment on the square-edged model than on the round-edged model.
In addition to the balance results, the area weighted surface pressures can be used to infer the side force and yaw moment coefficients, as shown in Figure 100. These results do not add to the understanding of the static, yawed flow fields but are presented as a reference case in preparation for the next chapter.

In both plots, the calculated normal pressure loads are smaller than those measured on the balance. This is because the tappings do not cover the entire side of the model and the resolution is not enough to find the precise pressure peaks on the surface of the model. Over the range of yaw angles, ±12º, the results for the two models are very similar; it is only at the larger yaw angles that any significant differences between the two models appear. This fits with the side force and yaw moments recorded on the balances which show coefficient gradients that are very closely matched at small yaw angles, only above ±10º do the differences between the models become clear.
The results for both models are slightly asymmetric with $Y = 0$ crossed at a yaw angle of $2^\circ$ which is slightly larger than the slight positive offset, $<1^\circ$, in the balance results, Figure 85 and Figure 86. The offset is caused by the fundamental shape of the two models. Both were made from the same hand finished mould hence both models have the same overall dimensions and any asymmetry in the original mould will be transferred to each model. The pressure tappings on each side of the model were positioned parametrically based on the model dimensions, so any slight side to side differences in the model geometry will be transferred to the pressure tappings and this is demonstrated by the consistent asymmetry in the results of the two models.

Figure 88 showed the lift force acting on the model recorded by the balance reduces at yaw. The source of this reduction is investigated by finding the area weighted lift on the backlights of the two models and these results are shown in Figure 101.

![Figure 101, Steady state area weighted lift coefficients](image)

Figure 101 shows the lift generated on the backlight of the two models increases with yaw angle. This indicates that the downforce must be originating from the floor of the model in general agreement with Katz (143). Between $0^\circ$ and $5^\circ$ the lift coefficients only change by 2 and 12 counts for the round and square-edged models respectively, but between $5^\circ$ and $10^\circ$ the lift increases by 7 and 19 counts. This agrees with the trend seen in the side force and yaw moment measured on the balance that showed a change in the coefficient gradients between small yaw angles and larger yaw angles.

There are two factors of the general shape of the models used in this experiment that that causes the increased under floor flows. The models are mounted relatively high above the ground plane.
of the wind tunnel compared to other models and the lower edges of both models are rounded. These two features encourage flow under the model to a greater extent than would be expected using a more typical model.

### 3.2.1.4 PIV at Yaw

Vector fields in the wake of both models 0.25L behind the model are shown in Figure 102 with the models at -5 and -10º yaw angle. The results are presented in the same format as in Figure 68 and the model outline shows the model yawed and pointing towards the left.

![Figure 102, Yawed model wake flow fields](image)

At -5º yaw the wakes of the two models are quite similar to the wakes of the models at 0º yaw, shown in Figure 68, but with the leeside trailing vortex slightly stretched towards the lower corner of the model base. In agreement with the increase in side force and yaw moment coefficient gradients above ±5º, there are much larger changes to the wake at -10º consistent with the larger side force gradients. The leeside trailing vortex much is closer to the lower
corner of the model and there is a weak vortex behind the leeside edge of the roof. However, the changes are limited to the leeside of the model, the windward trailing vortex changes little between 0° and 10° on either model.

The weak vortex in line with the model roof is the A-pillar vortex and these results confirm that it detaches from the model surface on the roof, as implied by the surface flow visualisations in Figure 91 and Figure 92.

The changes to the leeside trailing vortex are caused by a new flow structure, only present when the model is at yaw. As flow passes under the model from the high pressure windward side to the lower pressure leeward side, a vortex is created along the leeside edge of the floor, which rotates in the same direction as the leeside trailing vortex. This flow structure is in agreement with the downforce generating flow mechanism described by Katz (143), and contributes to the decrease in overall lift. The flow fields in Figure 102 show that the interaction between this leeside floor vortex and the leeside trailing vortex is quite different for the two models, with the leeside trailing vortex from the round-edged model less distorted than that of the square-edged model. These differences originate from the different trailing vortices and their interaction with the near wake on the respective models.

In the wake of the round-edged model the trailing vortices mix with the turbulent, separated wake behind the model base; the leeside floor vortex adds to this flow structure and moves the mean vortex core downwards and towards the leeside corner of the model. This creates a single, well defined, leeside trailing vortex unlike the stretched and distorted flow structure behind the square-edged model. The trailing vortices form on the backlight of the square-edged model and are higher above the ground plane than on the round-edged model. Consequentially, this vortex is distorted by the leeside floor vortex creating a stretched vortex with no single, obvious vortex core.

The differences in the trailing vortices and the presence of the A-pillar vortex are confirmed in the mean vorticity results, Figure 103.
The distorted and stretched characteristic of the square-edged model’s leeside vortex is clearly seen as is the influence of the leeside floor vortex on the round-edged model that causes the trailing vortex to stretch slightly towards the lower corner of the model. The leeside A-pillar vortex of each model is of similar strength, but is slightly closer to the floor in the wake of the round-edged model compared with the square-edged model.

The maximum vorticites in the trailing vortices of the two models appear more closely matched despite the different rear pillar geometry than at 0° yaw. This is explored in Table 4, which gives the strongest vorticity from the leeside and windward trailing vortices at 0°, -5° and -10° yaw.

<table>
<thead>
<tr>
<th></th>
<th>0° Yaw</th>
<th>5° Yaw</th>
<th>10° Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
<td>Lee</td>
</tr>
<tr>
<td>Round-Edged Model</td>
<td>-1.0702</td>
<td>1.1545</td>
<td>-0.9645</td>
</tr>
<tr>
<td>Square-Edged Model</td>
<td>-3.0696</td>
<td>1.8808</td>
<td>-0.9234</td>
</tr>
</tbody>
</table>

Table 4, Minimum and maximum vorticity in the trailing vortices

The vorticity values in the leeside vortex are similar for the two models and quite consistent across the range of yaw angles, as any reduction in the trailing vortex strength is made up for by an increase in the strength of the leeside floor vortex strength. The changes to the windward trailing vortex are different for the two models; the maximum vorticity increases behind the round-edged model but reduces in the wake of the square-edged model. The increase in the vorticity behind the round-edged model is caused by the increased flow around the rear pillars; the yaw angle of the model distorts the trailing vortex towards the centreline of the model, augmenting the vortex line that is found at 0° yaw. Conversely, this reduces in the maximum
vorticity in the wake of the square-edged model. At 0° yaw the trailing vortices on the square-edged model are very tight, and form close to the edges of the backlight; by yawing the model, the onset flow moves the formation of the vortex away from the edge, increasing its size and making it more diffuse, thereby reducing the maximum vorticity.

Wake surveys of the two Davis models used in this thesis have not been carried out before, but the flow fields can be compared to those collected behind similar models by Davis (10) and Ryan (85). Davis yawed his models positively, so the results in Figure 104 have been mirrored for a direct comparison.

Figure 104, Wake vorticity, -10° yaw, modified image from Davis (10)

The windward vortex (A) is much larger than the leeside trailing vortex (B), which has doubled in strength from that recorded at 0° yaw, Figure 70. Davis did not comment on this, but it may be caused by a strong interaction with the A-pillar vortex (C), which is the same strength as the windward trailing vortex. With a similar result to those in Figure 103, Davis found a leeside floor vortex (E), but this did not mix with the leeside trailing vortex because of the presence of vortex (D) from the edge of the diffuser.

The results reported by Ryan (85), Figure 105, match those in Figure 103 much more closely. His results were found at 0.75L behind the Durham geometry model in a -7° yawed flow, shown in Figure 105. The model was negatively yawed with the right hand side of the model windward.
The leeside A-pillar vortex has detached from the model and is seen as a distinct feature, with a similar strength to the windward trailing vortex. In agreement with Figure 103, the leeside trailing vortex is stretched and mixed with a flow structure from the leeside edge of the floor, described by Ryan as ‘underfloor vorticity’. Due to the spacing of the vorticity contours, there are no apparent changes to the maximum or minimum vorticity, but at larger yaw angles the vorticity in the windward trailing vortex increased and the leeward vortex’s vorticity reduced. This is a further trend for the respective strengths of the trailing vortices, agreeing with neither Davis nor the results in this thesis, implying that the changes to the vortex strength are an unexpectedly complex flow mechanism and does not follow the trends of vortex strengthening and weakening found by changing the angle of attack of a delta wing.

3.2.2 Unsteady Flow Fields

3.2.2.1 RMS Unsteadiness

Figure 106 and Figure 107 show the RMS surface pressure fluctuations on the round-edged model at -5º and -10º yaw. The pressures on the backlight, base and windward side show a consistent trend as the yaw angle increases, but the leeside of the model shows a much greater change.
The unsteady pressures on the backlight are highly asymmetric. The results on the windward side of the model are little changed from 0° yaw, Figure 66, but on the windward edge of the backlight they increase, due to the separation lines of the stronger windward trailing vortex moving around the rear pillar onto the backlight. Towards the leeside rear edge of the model, there is an increase in the surface pressure fluctuations caused by the leeside floor vortex, but the changes in the pressure fluctuations under the A-pillar vortex are very different. Similar to the windward trailing vortex, the leeward A-pillar vortex strengthens at larger yaw angles, but the large scale increase in fluctuations between -5° and -10° has a further cause. In the PIV results, Figure 102, at -5° yaw the A-pillar vortex is not a distinct feature in the wake, whilst at -10° yaw it is and has detached from the model surface. It is likely that this separation is unsteady and this feeds upstream into the A-pillar flows on the model surface.

The RMS surface pressure fluctuations on the square-edged model at -5° yaw are in Figure 108 and at -10° in Figure 109.
On the windward side of the model, as on the round-edged model, the results are very similar to those at 0° yaw, Figure 67. The flows over the backlight are much steadier than on the round-edged model; the movement of the windward trailing vortex towards the model centreline is shown by the widening region of pressure fluctuations, but they remain very tight to the backlight windward edge. The A-pillar vortex fluctuations follow a similar trend to those on the round-edged model, with the fluctuations at -10° yaw much larger than those at -5° yaw. The reasons for this are the same as for the round-edged model, but the fluctuations at -10° yaw are smaller than on the round-edged model implying greater steadiness in the location of the A-pillar vortex separation. Unsteadiness from the leeside floor vortex is clearer on the square-edged model than on the round-edged model, and this feeds into the unsteady separation on the leeside vertical rear edge of the model.

From the instantaneous area weighted aerodynamic loads, Table 5 shows the unsteady component of the mean side forces and yaw moment with the model at -10° yaw.
<table>
<thead>
<tr>
<th>Yaw Angle</th>
<th>Round-edged Model</th>
<th>Square-edged Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
<td>% of mean</td>
</tr>
<tr>
<td>Front Side Force RMS</td>
<td>0.008</td>
<td>7%</td>
</tr>
<tr>
<td>Rear Side Force RMS</td>
<td>0.006</td>
<td>90%</td>
</tr>
<tr>
<td>Yaw Moment RMS</td>
<td>0.038</td>
<td>8%</td>
</tr>
</tbody>
</table>

Table 5, Side force coefficient standard deviations

The absolute spreads of the aerodynamic loads acting on the two models are very similar. However, when given as a percentage of the mean value there is a large difference between the unsteadiness of the rear side force coefficients on the two models.

Figure 107 and Figure 109 show that the largest difference in the RMS surface pressures between the sides of the two models is under the A-pillar vortex, but these area-weighted forces show that the actual levels of unsteadiness in the forces acting on the models are very similar. This is partly because the actual differences in the loads in Table 5 are very small, similar to the 0º yaw results in Table 3 but it is also possible that the unsteadiness within the A-pillar is not coherent along its length and hence does not integrate to give a larger unsteady side force. If the entire vortex strengthened or weakened at the same point in time, the RMS side force would be larger, but this is not the case. The changes to the leeside A-pillar vortex may be caused by a periodic feature within the A-pillar vortex or, as previously suggested, may originate from unsteady separation as the vortex detaches from the model surface over the roof. This source of unsteadiness may be model specific but, while not affecting the overall forces, would cause considerably greater wind noise and possibly create a poor subjective rating in vehicle refinement tests.

The RMS velocity fluctuations taken from the PIV data in a plane 0.25L behind the model at yaw are in Figure 110.
In the wakes of the two models at -5° yaw there is a small effect from the leeside A-pillar vortex and behind the base of the model the fluctuations associated with the trailing vortex are distorted and altered from those at 0° yaw by the leeside floor vortex. On the windward side, the results closely match those found at 0° yaw and this result is similar to that seen in the surface pressure coefficients on the windward side of the models.

At -10° the effects of yaw angle are much clearer, with large scale effects on the leeside whilst the results on the windward side still closely resemble those at 0° yaw. Behind the leeside of the model, the fluctuations related to the trailing vortex are significantly reduced and there is a new, separate area of fluctuations at (-0.25, 1.2) from the A-pillar vortex. These are much greater behind the round-edged model than the square-edged model, in agreement with the RMS surface pressure results. The strength of the tail from this region down towards the base wake indicates a stronger interaction between unsteadiness in the A-pillar vortex and the trailing vortices and base wake than on the square-edged model. The source of the differences in the A-pillar vortex unsteadiness is likely to be an interaction between the A-pillar and trailing vortices on the backlight header, as seen in the flow visualisations, which causes unsteadiness in how the A-pillar vortex detaches from the model surface. Extrapolating the effects of the different rear
pillar geometries on the trailing vortices onto the A-pillar vortex, the round-edged model creates a more unsteady separation than on the square-edged model.

The peak RMS velocity fluctuations in the windward trailing vortices of the round-edged model are larger than those behind the square-edged model, which is different from 0° yaw, where the peak RMS velocity fluctuations in the wake of both models were more closely matched. This is a consequence of the stronger windward trailing vortex on the round-edged model, and the weaker windward trailing vortex on the square-edged model.

The large velocity fluctuations in the lower left hand corner are due to a lack of seeding in this area, as previously explained. They are bigger than at 0° yaw, due to the yawed model drawing more unseeded flow from further out on the left hand side into the image. The anomalous blobs in the upper right corner of the square-edged results are caused by drops of oil which have landed on the glass in front of the camera.

The instantaneous vortex centres found in the leeside wake of the two models are found using the same angular momentum method of Grosjean et al (2000), as used previously in this chapter. The windward trailing vortex results are unremarkable, with no significant differences from the results at 0° yaw. Therefore the results in Figure 111 only show the vortex motion on the leeside of the model; the vector field was split into two sections at h/H = 0.8 to differentiate between the A-pillar and trailing / floor vortices.

Figure 111, Leeside instantaneous vortex centre tracking, -10° yaw

Behind both models the leeside floor vortex is relatively stable, with the instantaneous centres concentrated in a small area. As previously explained, there are differences in how the leeside trailing and floor vortices mix and these cause slight differences in the spreads in the results.
In the upper region, the spread of the vortex centres is larger behind the round-edged model, in agreement with the larger surface pressure fluctuations, Figure 107, and the wake RMS velocities, Figure 110. In the wake of the two models, the vortex centres extend from above the roof line down to the trailing edge of the backlight, implying that the vortices are not only from the A-pillar, but could also be the leeside trailing vortex which may unsteadily mix with the leeside floor vortex. The distributions of the leeside vortex centres behind both models agree with the RMS vorticity results, Figure 112.

![Figure 112, RMS vorticity fluctuations, 0.25L behind the model at -10° yaw](image)

There is greater vorticity fluctuation in the windward trailing vortex than behind the leeside of both models and the distributions closely match those found at 0° yaw, Figure 75. However, unlike at 0° yaw, where the peak RMS vorticity behind the square-edged model was twice as large as that behind the round-edged model, the peak RMS velocity fluctuations in the windward trailing vortices are closely matched.

The peak RMS vorticity behind the leeside of the models is associated with the leeside floor vortex; the spread of the RMS vorticity towards the A-pillar vortex is caused by the A-pillar vortex and possible instances when the leeside trailing vortex does not mix with the leeside floor vortex, which is further explored in section 3.2.2.2.

Combining the results of the instantaneous vortex centres, Figure 111, the mean vorticity, Figure 103, RMS vorticity, Figure 112, and the RMS velocities, Figure 110, leads to another finding about the leeside flow structures that applies to both models. The mean vorticity of the leeside trailing vortex is comparable to that of the windward trailing vortex, yet the RMS velocity fluctuations associated with this vortex are much smaller than those from the windward trailing vortex and the instantaneous vortex centres show that the leeside trailing vortex is relatively stable. Behind the square-edged model at 0° yaw, a strong and relatively stable vortex
creates large RMS vorticity and velocity fluctuations, but this is not the case with the leeside vortices on the two models. This combination of results: high vorticity, stable vortex centre and low RMS velocity, is caused by a vortex whose strength is dependent upon its location. Variations in location of the vortex away from its location of highest strength cause a weakening of the vortex and it is this mechanism that leads to a high mean vorticity, created by a very stably located vortex with low RMS fluctuations.

3.2.2.2 Unsteady flow Structures

The dominant frequencies of the flow structures around the models were found by considering the power spectral densities of the unsteady surface pressures. The results are quite different from those found in the pressure data with the models at 0º yaw.

There are no dominant frequencies under the A-pillar on the windward or leeward sides of either model and the 13Hz peak associated with the trailing vortices of the round-edged model no longer exists. This is potentially an important result. Scaling this result to full scale gives a frequency of \( \approx 2 \text{Hz} \), which is in the region defined by Goetz (53) as being important for vehicle handling. If this shedding mechanism were inconsistently present on a real vehicle, it could potentially lead to significant changes in the handling of the vehicle, or to inconsistent changes to the wind noise around the vehicle, which would be perceived as poor refinement.

Both models show an increase in energy centred around 60Hz in the region of high surface pressure fluctuations on the side of the models caused by the leeside floor vortex, shown in Figure 113; it is also present in the leeside edge base tappings and, on the square-edged model only, in the pressure tapping in the bottom leeside corner on the backlight and the energy content is greater.
This is centred on a Strouhal number of 0.28, based on the square root of the frontal area, which
does not match anything seen in the existing literature. However, when calculated using the
model height, the Strouhal number = 0.23, which is close to the fundamental Strouhal number
≈0.21, indicating that this frequency is dependent upon the model height. The location of this
result indicates that this is a function of the leeside floor vortex and how it mixes with the
leeside trailing vortex thus showing that this mechanism may contain a periodic element.
60Hz is also half the frequency found on the backlight trailing edge of the square-edged model
at 0º yaw associated with a periodic strengthening of the trailing vortices and the central
downwash. The result shown in Figure 113 is stronger on the square-edged model implying a
link between the mechanisms that drive these periodic flow field changes.

The mean vector fields, shown in Figure 102, only show a weak A-pillar vortex in the wake but
it is more easily seen in the instantaneous vector fields. Figure 114 shows a typical
instantaneous vector field behind the round-edged model with the A-pillar vortex clearly visible
in the vectors located around (-0.25, 1.3). The vortex is present in all the instantaneous vector
fields but is very unsteady, moving vertically and laterally with significant but seemingly
uncorrelated changes to its size and strength.
Further understanding of the A-pillar vortex unsteadiness in the wake of the round-edged model is gained using a cross-correlation based conditional averaging. Rather than base the conditional averaging on a single vector, this method, based on Konstantinidis et al (145), cross correlates all the vector fields to find those with a similar flow structures. These are then averaged to create the conditionally averaged flow fields. The results of this are shown in Figure 115 which shows there are two repeated modes within the A-pillar flow of the round-edged model, each present in approximately 5% of the instantaneous results. This shows that the A-pillar vortex can remain attached all the way down the backlight, in the left hand plot, or that it can separate from the roof, in the right hand plot. This A-pillar vortex unsteadiness contributes to the spread of the instantaneous vortex centres in Figure 111.
A further source of vortex centre unsteadiness is found by investigating the mixing of the leeside floor and trailing vortices. Analysis of the instantaneous PIV results did not show any distinct repeated modes despite the spectral results in the surface pressure data. However, there is unsteadiness in the mixing of the two leeside vortices and this is illustrated in Figure 116, which shows the vorticity in two instantaneous vector fields.

The A-pillar vortices are labelled ‘A’, ‘B’ shows the location of the trailing vortex and ‘C’ marks the leeside floor vortex. The leeside floor vortex is relatively stable, as expected from the results shown in Figure 111, but the presence of the leeside trailing vortex shows that it does not always mix smoothly with the leeside floor vortex to create a single vortex, but can remain separate and when it does, it is quite unsteady.

Beyond these findings about the A-pillar and trailing vortices, the instantaneous vector fields behind the yawed round-edged model flow fields do not show anything else noteworthy. In
itself, this is an interesting result as it shows that the lateral and vertical vortex centre motion found in the wake with the model at 0° yaw is not present in the wake of the yawed model, agreeing with the spectral results which did not contain a 13Hz peak. This inconsistency within the flow field is a further source of unsteadiness and if such changes existed on a production vehicle, which would likely be a negative influence on subjective assessments of refinement.

In the wake of the square-edged model, the cross-correlation conditional averaging found a similar mode of A-pillar vortex motion as seen in the round-edged model data; shown in Figure 117.

![Figure 117, Unsteady A-pillar vortex motion, square-edged model, -10° yaw](image)

Although a similar to the results of the round-edged model the percentage of instantaneous vector fields represented by each flow field is somewhat lower, being between 2% - 3%. In addition, in the left hand plot the A-pillar vortex is further above the floor and has less interaction with the trailing vortex than in the round-edged model results. Furthermore, in the large number of remaining instantaneous vector fields, the variation in the strength and location of the A-pillar vortex is less, giving the lower velocity RMS fluctuations shown in Figure 112. The unsteady separation of the A-pillar vortex from the model surface occurs along the edge of the roof and onto the backlight header and the flow visualisation results show that there is an interaction between the A-pillar vortex and the trailing vortices. These results, and those showing the same effect on the round-edged model, confirm the A-pillar unsteadiness is strongly influenced by the trailing vortices and unsteadiness created by the different rear pillar geometries, feeds into the leeside A-pillar vortices. These results explain the differences in the unsteady results for the A-pillar vortices, seen in the surface pressures and PIV data, of the two models.
A further unsteady mechanism in the wake of the square-edged model is shown in Figure 118 and Figure 119, which show the in-plane velocities and the swirl contained within the velocities respectively. These conditionally averaged results were found using the vector length based method, the chosen vector is at (0.1, 0.95) and marked with an ‘x’. The changes between the two flow fields concern the mixing of the leeside floor and trailing vortices and the strength of the central downwash, the A-pillar vortex is the same in both and is in line with the roof of the model. The right hand plot shows the leeside trailing vortex does not always mix with the leeside floor vortex and, associated with this is an increase in the strength of the central downwash. At 0° yaw there is a spectral peak at St = 0.56 showing a periodic strengthening of the two trailing vortices and the central downwash, the results shown in Figure 118 and Figure 119 show an similar effect. This demonstrates the higher energy content around 60Hz in the spectral results is a modification of the St = 0.56 shedding frequency caused by the effects of yaw.

Figure 118, Extra wake vortices, in-plane velocities square-edged model, -10° yaw

Figure 119, Extra wake vortices, swirl, square-edged model, -10° yaw
3.2.3 Flow Field Description

In general, the effect of yaw on the two models’ flow fields is similar for both models. At small yaw angles the flow field is similar to that found with the model at 0º yaw, but between 5º and 10º there is a large scale change to the flow field. This is caused by the growth in strength of the A-pillar vortex, its unsteady separation from the roof and its interaction with the leeside trailing vortex. Furthermore, a leeside floor vortex is created which contributes to the reduction in lift acting on the model and this mixes with the leeside trailing vortex, creating a stretched and distorted vortex on the leeside. All the major changes to the flow field are on the leeside of the model while on the windward side, the flow structures remain highly comparable to those found with the model at 0º yaw and are much more stable than the leeside flow structures.

The differences between the flow structures on each side of the model are due to how they form. The windward side of the model is moved into the onset flow which has to move around it but on the models’ leeside a void is created which induces the flow into this ‘wake’ region of relatively low pressure. This is a weaker mechanism and leads to large scale, unsteady changes to the leeside flows whilst on the windward side the flow structures are more stable and consistent with smaller yaw angles.

The leeside vortices are unsteady; the A-pillar vortex can detach from the roof or remain attached all the way down the backlight; the leeside trailing vortex can mix fully with the leeside floor vortex or remain separate; only the leeside floor vortex is relatively steady. The unsteady A-pillar separation is a weak periodic feature, but the majority of the A-pillar vortex unsteadiness is uncorrelated. The spread of the A-pillar vortices is greater in the wake of the round-edged model than the square-edged model because the unsteady characteristics of the trailing vortices are fed into the A-pillar vortices at the interaction between the two flow structures on the backlight header.

On the square-edged model, the windward trailing vortex decreases in strength, whilst on the round-edged model the windward trailing vortex increases in strength as a consequence of how the vortices form around the rear pillars of the respective models.

There is a periodic feature at St = 0.28 behind both models which is a stronger feature on the square-edged model than on the round-edged model. It is an effect of the model height and is related to the strengthening of the trailing vortices and central downwash found behind the square-edged model at 0º yaw at twice the Strouhal number.
The source of the lower yaw moment on the square-edged model is along the rear pillars and down the vertical rear edges. The square rear pillar limits the flow around the rear pillar whilst on the round-edged model the flow around the rear pillar is enhanced, creating lower pressure which acts to increase the yaw moment. Because the trailing vortices feed into the wake behind the base of the round-edged model there is also greater flow, hence lower pressures, around the windward vertical rear edge of the round-edged model.
4. Dynamically Yawing Model

This chapter will present the results of the data collected while the two Davis models were dynamically yawing, and compares these results to those found under steady state conditions, detailed in the previous chapter.

Data was collected with the models subject to two separate yaw motions. Continuously sampled balance data were collected as the balance rotated through a range of yaw angles and surface pressure and PIV data were collected with the models mounted to the driven oscillating rig. The experimental methods are described prior to the results, detailing the different processing methods needed for the transient model data and the additional sources of error present in these tests.

4.1 Balance Yaw Sweeps

In this experiment, the models were mounted to the underfloor balance and data was collected as the balance yawed between ±30º. Data were sampled at 300Hz using the same software as in the steady state tests but with an averaging filter within the software disabled.

4.1.1 Yawing Motion

The yaw motion created by the balance yaw drive is described in detail in section 2.2, Figure 38. It travels at 2º/s with different acceleration profiles at the start and end of the motion. To avoid any complications created by the end effects, whilst maintaining the potential to show any phase or magnitude changes in the results, the data in this chapter were collected during a yaw sweep from -30º to 30º and results only presented for the yaw angle range ± 20º.

4.1.2 Balance Frequency Response

The resonances of the balance and model were determined by collecting instantaneous aerodynamic load data using the round-edged Davis model. This was mounted in the wind tunnel as described in section 2.4 and data was sampled at 300Hz for 100 seconds at tunnel speeds of 30 m/s and 40 m/s, to isolate any onset flow dependencies. The power spectral densities of the drag forces at the two wind speeds are in Figure 120.
Below 50 Hz, both data sets contain 6 clearly defined spectral peaks, with two broad humps above 50Hz that are harmonics of the resonance at 33 Hz. The sources of these were investigated using a calibrated hammer and an accelerometer attached to the balance and model mounting strut. These tests showed that the two lowest frequency resonances are functions of the balance, and the higher frequencies are from the model mounting strut and the shaft attached to the model. This demonstrate that the frequency content of the data is dominated by resonances of the system and does not show any evidence of aerodynamic shedding or flow field periodicity. This is confirmed by comparing the results collected at 30m/s and 40m/s; the spectral peaks are at the same frequencies in the two data sets, whereas Strouhal number consistency would require a 25% lower frequency at the slower test speed. Hence, this data is unsuitable for frequency analysis, but using a low pass filter would remove the high frequency resonances whilst preserving any large scale, low frequency effects.

4.1.2 Transient Yaw Sweep Aerodynamic Coefficients

30 data sets of continuously sampled data were collected during transient yaw sweeps from -30º to 30º at tunnel speeds of 20, 30 and 40 m/s using both Davis models. Combining these tunnel speeds with the yaw rate of 2º/s gives reduced frequencies of 0.00053, 0.00035 and 0.00027 respectively, which are very low and considered quasi-static, Sims-Williams (1). They are,
however, of the same order of magnitude as the full scale results from the DNW wind tunnel, Figure 23, which appear to show unsteady effects.

Each data set was low-pass filtered at 4 Hz to remove the resonances from the balance and mounting shaft. The aerodynamic loads were ensemble averaged based on yaw angle and the loads caused by the rotational inertia of the model, found from the ensemble average of 10 wind-off data sets, were removed. The windspeed was corrected for model blockage using the MIRA blockage correction and the aerodynamic loads converted into coefficients. Data were collected for all six aerodynamic coefficients and Figure 121 and Figure 122 show side force and yaw moment coefficients respectively. The relationships between the steady state and transient data seen in these results are typical of those seen for the other aerodynamic load coefficients.

![Figure 121, Comparison of steady state and continuously sampled side force coefficients](image1)

![Figure 122, Comparison of steady state and continuously sampled yaw moment coefficients](image2)

The transient yaw moment coefficients are noisier than the side force coefficients, but neither Figure 121 nor Figure 122 show any evidence of phase or magnitude changes between the
steady state and the transient results. The reduced frequencies indicate that quasi-static results should be expected but published work showing similar tests at comparable reduced frequencies do appear to show transient effects; however, further consideration of these published results shows that they may be questionable.

Garry and Cooper (96) and Cairns (92) reported phase changes for a variety of shapes with round front edges, at reduced frequencies between 0.00036 to 0.00913, which would typically be considered quasi-static. Garry and Cooper tested at a low Reynolds number of 637000, which is significantly below the typical value required for Reynolds number independency. Newnham (54) showed that a 1-box model with round front edges was subject to significant Reynolds effects at 0°, and also steady state hysteresis dependent upon yaw angle. These two influences may be present in Garry’s and Cooper’s results and interpreted as transient effects caused by the model motion. Cairns used an updated version of the test equipment and different models, but the tests remained at a low Reynolds number (Re = 860000) and the doubts over the validity of the results remain.

Lock (97) reported a moving turntable experiment using a full size production vehicle after the MIRA full scale wind tunnel balance was updated with new software to enable continuous sampling. Only lift showed any notable change from the steady state results and this was in the form of a discontinuity at a single yaw angle, which was described as a ‘phase lag’, which, in this author’s opinion, is inferring too much from this single result. More fundamentally, a balance sized for production vehicles needs to be very heavy and would have a very low natural frequency, requiring long sampling periods to remove the influence of this from the mean data. Continuous sampling does not allow for this and the results may be significantly affected by this, rather than showing an aerodynamic effect.

Continuously sampled turntable data were also collected at the DNW wind tunnel, Howell (69). This test rotated a full scale production vehicle in test conditions that created a reduced frequency of 0.0007. The results showed different phase lags in each aerodynamic coefficient with lift showing a quasi-static response. This test was only ever carried out once, using one vehicle, as part of an internal investigation to find quicker ways of collecting steady state yaw data. Despite the results implying significant transient effects, whether the results are real or are due to effects within the balance, is unknown. Similar to the MIRA wind tunnel, the balance will have low frequency resonances, which is likely the cause of the apparent transient effects, and the different phase changes in each aerodynamic coefficient arise from different stiffnesses in each plane.
At best, the results from the continuous balance sampling during a yaw sweep are questionable. The lack of phase or magnitude changes between the transient and steady state results is in keeping with the very low reduced frequency, but contradicts other, similar tests. This may be a real result: however, the limitations of using a balance designed for steady state measurements to collect instantaneous data and the inconsistent results in other published work, mean that isolating the real effects of transient yaw angles at a very low reduced frequency using this method is not currently possible.

4.2 Oscillating Yaw Motion

Surface pressure and PIV measurements were taken as the model was driven in sinusoidal yaw angle oscillations. This motion is described in detail in section 2.2, and Figure 123 shows a plot of yaw displacement against time.

![Figure 123, 1Hz, ±11° driven yaw angle oscillations, KM = 0.049](image)

4.2.1 Data Collection and Processing

The surface pressure and PIV data were collected using the same equipment as described in chapter 2 but the model motion meant that different processing methods were required and additional sources of error were created.

4.2.1.1 Surface Pressures

The same surface pressure tappings and miniature pressure scanners were used to sample the oscillating model surface pressures as for the steady state pressures. Sampling was externally triggered at 260Hz, and data sets of 8192 pressure samples were collected, lasting 32 seconds. The model yaw angle and the trigger signal for the pressure scanners were simultaneously recorded using a simple Labview data acquisition program. Without stopping the model between tests, this was repeated 33 times for each model; in total 2 gigabytes of surface pressure
data were collected. Discrete data sets were collected rather than continuous data, due to the large size of the data set that would have otherwise been created.

The surface pressures were processed in the frequency domain. Each 8192 point data set was split into sub-sets 512 samples long, containing data from slightly less than two oscillations, starting as the model yaw angle was increasing from zero, schematically illustrated in Figure 124. Using Matlab, the Fourier transform of each 512 sample data set was found, and this was repeated for all 33 data sets, producing 1000 Fourier transforms for each pressure tapping. The 1000 results were averaged and the resultant Fourier transform was converted back into the time domain using an inverse Fourier transform.

Processing the surface pressure data in this way removes the effects of the small cycle-to-cycle variations in frequency and magnitude due to the supply voltage and the effect of the forces on the motor, and creates a mean time-history of the surface pressures during an oscillation.

A sample of 512 data points is a factor of $2^9$ which is beneficial for the quality of the Fourier transform results and contains $\approx 2$ seconds of data. The low frequency cut-off is 0.5Hz, which is below the model motion frequency at 1Hz and the lowest frequency periodic results found in the steady state data. The angular potentiometer gave a linear response, with linearity accurate to $\pm 0.5\%$, between 0V and 5V for 360º, giving a scaling factor of 0.1389V/º. The analogue voltage signal from the potentiometer was read by a 16 bit A/D card meaning the quantisation error is insignificant. Sampling of the trigger signal and model yaw position was at 2000Hz, meaning
the yaw angle corresponding to a trigger signal could be wrong by up to 0.035º, which is 0.16% of the overall range of the motion, and is insignificant.

4.2.1.2 PIV

PIV images were collected in the same planes as the steady state results and were phase locked to the model motion using an optical sensor attached to the motor that triggered the image capture. Images were collected at four yaw angles to allow for a direct comparison to the steady state results and investigate any transient effects:

- 0º as the model passed from a negative to positive yaw angle.
- -5º with an increasing yaw angle.
- -10º with an increasing yaw angle. (This was near the maximum yaw angle amplitude and when the yaw rate was low.)
- -5º as the yaw angle was decreasing.

Collecting phase locked PIV images created a number of new sources of error not present with the static model.

There was a fixed time delay between the signal from the optical trigger and the image capture due to the laser pumping. The image capture trigger was set up to allow for this, but the slight cycle to cycle variations in the model motion meant that the actual yaw angle at which the image was taken varied slightly each time. To quantify this, the camera trigger signal and the voltage from the angular potentiometer mounted on the model shaft were recorded using a simple Labview data logging program. This sampled at 20kHz and this very fast sampling was required to capture the extremely short duration of the camera trigger signal. The distribution of the instantaneous yaw angles while collecting 0º yaw angle images behind the round-edged model is in Figure 125.
The mean model yaw angle in this data is 0.13° and the mean yaw angles of all the phase locked PIV results do not exactly match the steady state values. Most of the instantaneous yaw angles are concentrated in a yaw angle range of just ±0.1°, with a very low probability of an extreme outlier up to ±1° from the desired value; this distribution is typical for all the phase locked PIV image sets. Further to this, the model continued to move between the first and second image being captured but, at most, this could only be 3x10^{-4} degrees as the model passes through 0°.

The requirement for 1000 image pairs with a static model has been established in Passmore et al (30) and its applicability to the wake of an oscillating model is investigated in Figure 126, which shows mean velocities from small sample subsets and the 99% standard error confidence bands. Similar to the results in Passmore et al, a vector on the edge of the right hand side trailing vortex has been selected.

Sample sizes above 250 give mean results very close to the true mean, and 1000 images create a 99% confidence band with a variation of 0.22m/s, which would need an error bar of 2% on the vector in question. Unlike the results in Passmore et al, sample sizes smaller than 50 can produce results that fall outside the 99% confidence bands. These are created when the motor speed is at either the upper or lower limit of the low frequency motor speed changes that occurred during the test.
Around the edges of the mean result plots, where the in-plane velocities are low, the contours are noisier than around the main flow structures and in the steady state results. This was caused by the model motion affecting the quality of the seeding by disrupting the seeded flow over the model, and entraining unseeded flow into the images. Because the main flow structures were well seeded and the effects were only towards the edges of the results in regions of little interest, this was acceptable.

Coupling the PIV image capture rate to the model motion increased the length of time needed to collect 1000 images from 5 minutes for the static model to 20 minutes, meaning that the seeding was running for much longer. Consequentially more olive oil landed on the model and on the front of the camera boxes. Some of the oscillating model results have larger secondary reflections from the wet surfaces of the model and from droplets on the camera box than seen in the previous chapter. However, these small regions of erroneous vectors do not adversely influence the overall results and the large scale flow structures remain clear.
4.2.2 Oscillating Model Results

The surface pressures measured beneath the A-pillar on the round and square-edged Davis models are in Figure 127.

![Figure 127, Surface pressure hysteresis beneath the A-pillar, KM = 0.049](image)

The hysteresis seen at this location is typical for all the pressure tappings on the models, and, despite the low reduced frequency, the results cannot be considered quasi-static. The consequence of the surface pressure hysteresis is seen by plotting the oscillating drag, lift and yaw moment coefficients, found by integrating the surface pressures over their surrounding area. The steady state values are also shown to give a direct comparison with those from the oscillating model.

![Figure 128, Comparison of steady state and oscillating aerodynamic load coefficients, KM = 0.049](image)

The three coefficients all show hysteresis and differences between the steady state and oscillating model results. The round-edged model has slightly less hysteresis in drag and lift than the square-edged model, but they are very similar in yaw moment. There is no clear trend in the oscillating drag and lift as to whether they are larger or smaller than the steady state results, and the mean yaw moment gradients are lower than in the steady state results. The higher levels of lift and drag on the square-edged model and larger yaw moment gradient of round-edged model are in agreement with the steady state results.
The oscillating front and rear side forces that create the yaw moments in Figure 128 are in Figure 129.

![Figure 129. Oscillating front and rear side force coefficients, $K_M = 0.049$](image)

The front side force dominates the lateral forces acting on the model and has levels of hysteresis an order of magnitude greater than the rear side force, whose hysteresis is the same order of magnitude as that in the drag and lift values, demonstrating the link between the forces directly influenced by the trailing vortices. The unsteady front side force acting on the two models is very similar, because the frontal geometry of the models is the same: the main difference between the models is in the rear side force. The round-edged model shows a negative rear side force coefficient gradient, whereas the square-edged model has a very slightly positive gradient. As in the steady state results, it is the differences in the rear side forces on the round and square-edged models that creates the different yaw moment gradients.

Guilmineau and Chometon (107) calculated the aerodynamic loads on an oscillating Willy model using CFD. Similar to the results in Figure 128, they reported hysteresis in drag and lift that created different trends to the steady state results, but with no clear overall trend between the two. However, the hysteresises in the oscillating side force and yaw moment coefficients was centred on the steady state coefficients, suggesting that the changes in the gradients of the oscillating model yaw moment coefficients in Figure 128 are a consequence of the flow...
structures moving relative to pressure tapping locations, rather than a change in the strength of the flow structure.

The larger hysteresis in the front side force of the two models can be seen in Figure 130, which shows the surface pressure distribution over the side of the round and square-edged models at -10°, as the yaw angle was increasing and decreasing.

![Figure 130, Hysteresis in ΔC_F at -10° yaw](image)

These plots also show that the sources of the yaw moments on both oscillating models are the same as in the steady state results, shown in Figure 98 and Figure 99. The A-pillar vortex dominates the side force, and the rear half of the square-edged model has a smaller influence on the side force than on the round-edged model.

A full side by side comparison of the steady state and oscillating model surface pressures is in appendices 3 and 4, and a selection of the plots that illustrate the differences on the sides of the two models, created under the two test conditions, are in Figure 131.

These plots show that there are differences across the entire side of the model, but especially under the A-pillar vortex and around the rear pillar. On the oscillating models the extent of the A-pillar vortex is less, and the flows around the rear pillar and vertical rear edges of the models are also reduced.
A quantitative comparison of the changes to the surface pressures is found in the frequency domain, by comparing the surface pressures on the oscillating model to those in a quasi-static yaw oscillation, where the steady state pressures are arranged in a time series to simulate the effects of a yaw oscillation. The results, in Figure 132, show the differences in the phase and amplitude of the signals.

Figure 132, Phase and amplitude change between quasi-static and oscillating surface pressures, $K_M = 0.049$

The phase and amplitude changes on the front halves of both models are very similar, consistent with the front side force results in Figure 129. Under the A-pillar vortex is a phase lag, which is largest at the front of the model and reduces further up the A-pillar and lower down the side of
the model. Along the edge of the A-pillar the amplitudes are very close to the quasi-static values, but below the A-pillar the gain reduces to a minimum close to a value of 0.7 along the A-pillar vortex reattachment line.

In the centre of the model the gain is greater than 1 and phase lag is close to 0, but the phase results on the rear half of the models and at the top of the A-pillars are dominated by large values and extreme gradients, the cause of which is explored further in Figure 133.

On the rear pillars of both models, the amplitudes of the transient surface pressures have a gain value below 1, and this reduction is greater on the square-edged model than on the round-edged model. The phase results on the round-edged model show a lag compared to the quasi-static results, but there is no clear trend on the square-edged model. However, the proximity of the fully separated flow on the vertical rear edge of the model, and the unusual results from the pressure tappings in the centre of the model, mean that these results are based on data from only a few pressure tappings, and the results are slightly unclear.

The importance of the A-pillar vortex to the side force of this model has been previously explored in section 3.2 and the minimum in the amplitude along the A-pillar vortex reattachment line agrees with the results in Passmore et al (79). However other oscillating model research using the Willy model in Chometon et al (104) and Guilmineau and Chometon (107) did not show any transient effects at the front of the model: neither did Theissen et al (110) and Wojciak et al (111), who used a scale model of a generic executive car. These results are typical of a general consensus that transient effects are found only at the rear of a vehicle. However, two papers published in 2012 do show the influence of transient effects on the front of production vehicles. CFD simulations on the front window of a Jaguar XF in a 2Hz yaw oscillation carried out by Oettle et al (146), showed that there can be hysteresis in the surface pressures in this region. This is the same car as used for the smoke flow visualisation in Figure 93, and potentially demonstrates the relevance of these results to production vehicles, despite the large differences in the geometry between the two bodies. Also showing transient effects at the front of road cars, Tsubokura et al (147) simulated the aerodynamics of two configurations of a saloon car during a sinusoidal steering input, and found that differences in the vortices emanating from the front wheel arch manifested themselves as surface pressure differences at the rear of the vehicle.

Figure 133 shows a comparison of the quasi-static and oscillating model surface pressures at two pressure tappings. One is taken from the top of the A-pillar and the other from lower down the model, in the region of high pressure that moves along the side of the models.
These plots show that the dominant frequency of the pressure signals changes from 2Hz in the quasi-static data to 1Hz in the oscillating model data, albeit with a small 2Hz component. Hence, comparing these results will produce peculiar results in the phase and amplitude plots because the flow field mechanism driving the surface pressures has fundamentally changed and the surface pressures are now coupled to the model motion. These differences in the dominant frequencies in the quasi-static and oscillating model surface pressures occur in the same regions on both models, indicating that this is either a consequence of the general model geometry or a fundamental difference between quasi-static and oscillating model results. Further consideration of the surface pressure plots in the appendices 3 and 4 shows that there are two flow structures that are affected by this; the approximate extents of these are shown in Figure 134.

The upper region, the hatched shading, is caused by the A-pillar vortex and flow into the trailing vortex. Under steady state conditions, low pressure under the leeside A-pillar vortex extends to the top 1/3 of the rear pillar, as seen in Figure 95; on the windward side of the model, this region also has low surface pressures due to the flow into the trailing vortices. These two sources of low pressures create a dominant quasi-static surface pressure frequency in this region of the model of 2Hz. On the oscillating models, the A-pillar vortex does not extend as far backwards over the model surface, meaning that the surface pressures are dominated by either the A-pillar vortex or by flow around the windward edges of the model. There remains a small
influence from the other flow structure, but the dominant frequency changes from 2Hz to 1Hz, and the mean surface pressures at these tappings also significantly change because there is only one dominant flow structure.

The lower region, shown by the speckled shading, is created by the high pressure region that moves fore and aft along the side of the model as it rotates. When windward, the high pressure region is towards the front of the model, and it moves rearwards when on the leeside. This occurs on both the quasi-static and oscillating model, but there is a subtle difference in the movement of this high pressure region which changes the dominant frequency from 2Hz to 1Hz.

Although the coupling of the surface pressures to the model motion is an interesting result, comparing Figure 134 to Figure 129, which shows the sources of the side force on the model, shows that the regions of the model that this applies to only have a minimal contribution to the overall forces acting on the model. This results agrees with the findings of McCroskey (148) working on oscillating aerofoils, where it was reported that the individual surface pressures show a much greater variation from steady state than the subsequent side forces and yaw moments, which are shown in Figure 128.

Hysteresis can also be found on the backlights of both models but the base flows are quite consistent between the static and oscillating models. This is shown in Figure 135 and Figure 136, which show the surface pressures at -10° yaw with the model yaw angle increasing and decreasing.

![Figure 135, Round-edged model surface pressure hysteresis, -10° yaw angle](image)

142
The general pattern of the surface pressures on the backlights of the oscillating models is the same as when steady state, in Figure 95 and Figure 97. The flow into the windward trailing vortices creates low pressure along the windward rear pillar: along the centreline of the backlight there is pressure recovery as the body tapers before the surface pressure decreases, as the flow enters the near wake of the model.

There is hysteresis along the edges of the backlights of both models, caused by the strength of the trailing vortices. As the yaw angle is increasing, the windward trailing vortex is weaker than when the yaw angle is decreasing, after the flow structures have had longer to develop. This is shown in Figure 137, which shows the phase relationship of the quasi-static and oscillating surface pressures on the backlight.
Figure 137, Phase change between steady state and oscillating model surface pressures on the backlight, $K_M = 0.049$

Figure 137 clearly shows that the pressures along the edges of the backlight, affected by the trailing vortices, lag the quasi-static response by approximately 0.8 radians on both models, which equates to a length of 5m. The similarity of the phase lags on both models implies that the source of the lag is common to both models and, despite the flow into the trailing vortices being quite different on both models, as explained in chapter 3, the large lag suggests that it may be an aerodynamic effect in the formation of the trailing vortices rather than just an effect of the test conditions.

The pressures in the centre of the backlight are more complex, with changes in the dominant frequency between the quasi-static and oscillating model, but unlike on the sides of the model, there is no clear trend of the pressures coupling with model motion to create a 1Hz frequency: merely the dominant frequencies are different. Also, the amplitude results are quite asymmetric and do not show any clear trends. However, this is in partial agreement with the integrated forces in Figure 128, which do not show any clear trends and have larger levels of asymmetry than the steady state results.

Passmore et al (79) reported increasing phase lags along the side of the round-edged Davis model up to -140º on the rear pillar and this value was consistently found at test frequencies between 1-8Hz. Wojciak (111) also reported lags in the surface pressures at the rear of the model, shown in Figure 138, that equated to lengths 4 times greater than the model.
All these results show that the lags in the flow field at the rear of the model are more than just a feature of the test conditions and that there is an effect coming from the vortices in the wake of the models that increases the lags; however the actual mechanism that drives this needs further investigation.

The differences in the flow fields between steady state and oscillating model flow field can also be seen in the phase locked PIV results. The mean, phase locked flow fields at 0° yaw behind both oscillating models are in Figure 139.

Compared to the steady state results in Figure 68, the biggest difference is in the left hand side trailing vortex. It is closer to the ground and surrounded by lower velocities than the right hand side vortex, and is similar in structure to the leeside trailing vortices found behind the models at
-5° yaw, shown in Figure 102. The right hand side vortex is a closer match to the trailing vortex found at a steady state 0° yaw angle. The asymmetry is more clearly seen in Figure 140, which shows the vorticity contained within the mean velocity results.

![Figure 140, Mean wake vorticity, phase locked 0° yaw, K_M = 0.049](image)

In the 0° yaw results, the rear of the model was moving from right to left, meaning that the left hand side of the model was previously leeward, and these results show that the leeside flow structures have a slower response to the model motion than the windward flow structures.

The differences in the flow fields behind the two Davis models at -5° yaw, with the yaw angle increasing and decreasing, are in Figure 141. Like the flow fields in Figure 140, the largest differences between the increasing and decreasing yaw angle results are found in the leeside flow structures.

The windward trailing vortex behind the two models changes little despite the different motion history, but the leeside trailing vortices show significant hysteresis. As the yaw angle increases, the leeside vortex is less well formed, shown by the noisy contours especially on the left hand edge, and has a smaller extent than when the yaw angle is decreasing. As in the steady state results, Figure 102, there is no evidence of the A-pillar vortex in the wake as the yaw angles is increasing or decreasing, of either model.
At -10° images were captured as the model yaw angle was increasing only. The mean transient velocity and vorticity results in the wake of the two models are in Figure 142 which shows the same general flow structures as the steady state results. On the leeside, the trailing vortex is distorted by the leeside floor vortex: the A-pillar vortex is present and the windward trailing vortex appears little changed from 0° yaw, albeit with the presence of strong secondary reflections from the backlight trailing edge.

Although the flow fields behind both oscillating models are similar to the steady state results, in Figure 103, there are some important differences common to both models. The peak velocities in the central downwash, and on the inboard side of the trailing vortices, are lower in the oscillating results than in the steady state results. The peak vorticity in both the leeward and, by a larger magnitude, in the windward trailing vortex is lower in the oscillating results, although the vorticity from the A-pillar vortex closely matches the steady state values. The surface pressures, Figure 131, indicated a reduction in the strength of the A-pillar vortex. This difference implies that the A-pillar vortex is forming in a different location on the model and that the peak values of the surface pressures are not recorded by the tappings, which agrees with the explanation of the different gradients in the yaw moment, Figure 128.
The round-edged model has two further differences between the steady state and oscillating model PIV flow fields. The velocities on the outboard side of the leeside trailing vortex are lower. In the steady state results, the leeside trailing vortex core was well defined as a low speed region surrounded by higher velocity flows but in the oscillating results the outboard side of the vortex has negligible in-plane velocities, resulting in an poorly defined vortex core and a reduction in the vorticity that is not seen to the same extent on the square-edged model. The second difference is that the A-pillar vortex is closer to the ground than in the steady state results, whereas in the wake of the square edged model it is at the same height relative to the model.

In all these PIV results the greatest differences between the steady state and oscillating model flow structures are on the leeside. This is due to a combination of the onset flow reaching the windward side of the model before the leeside, due to the rotation of the model, which creates a lag in the leeside flows, and differences in how the flow field develops around the yawed model. The windward side the model is moved positively into the onset flow and the flow field has to react to the new obstacle, whilst on the leeside of the model a void is created, which the flow can move into. The flow field response is dominated by the viscosity and inertia of the air, and
is slower on the leeside than on the windward side of the model. This is similar to the results in chapter 3.2, where the largest differences between the 0º and yawed model results are on the leeside of the model. The differences in the response times of the flows on each side of the model have been previously reported by Ryan (83), and Oettle et al (146) also report that the differences in surface pressures under the A-pillar vortex of a production car are greatest when leeward, rather than on the windward side.

4.2.3 Instantaneous Results

This section considers the instantaneous components of the surface pressure and PIV data, using the unprocessed pressure signals and the individual, phase locked PIV images to investigate the variations within the flow field away from the means that have been described in the previous section.

The frequency content of the pressure data on both models was dominated by the 1Hz motion frequency and harmonics of this, as seen in Figure 133. On the sides of the round-edged model, the spectral peak in the steady state data at 13Hz and associated with the trailing vortices at 0º yaw, Figure 77, was not found in the pressure data. This implies that this flow field mechanism was no longer present in the same form as seen on the static model: it may have coupled with the model motion or, similar to the steady state yaw results, the model motion could have prevented it occurring. A similar result is found in the PIV images; using both the vector length and cross-correlation based conditional averaging on the instantaneous 0º yaw results did not show any repeated flow structures within the unsteady flow field. The vector fields were dominated by small-scale, turbulent changes to the strengths and relative locations of the asymmetric vortices, but there is no evidence that these changes are periodic, or of any interlinking between the two trailing vortices.

There is no notable frequency content on the sides of the square-edged model, or on the base or backlight, where there was a peak in the energy content at 120 Hz found along the trailing edge at a static 0º. Despite this, conditional averaging of the instantaneous PIV data shows that the periodic strengthening and weakening of the central downwash is still present, shown in Figure 143. The results are noisier than the static model results because of increased unsteadiness in the flow field due to the model motion. This result is not found in the instantaneous surface pressures because the separation line may have moved slightly further around the curved trailing edge of the backlight, away from the pressure tappings.
Although the frequency of this periodic flow structure is beyond the upper limit of that which would influence vehicle handling, the consistency of the periodic results between the steady state and oscillating conditions is an indication that the flow fields are less affected by the model motion than those around the round-edged model.

Using the cross-correlation based conditional averaging produces the flow fields in Figure 144 for the round-edged model at -10° yaw and Figure 145 for the square-edged model at -10°.
These flow fields show the same flow field changes as seen in the instantaneous results of the static models, Figure 115 and Figure 117. However, behind the round-edged model the low A-pillar vortex flow field is present in twice as many vector fields as the detached vortex, whereas behind the square-edged model the two conditions had a similar frequency of occurrence. The more common lower A-pillar vortex is in agreement with the mean, phase locked, wake flows of the round-edged model in Figure 142, which shows the A-pillar vortex to be closer to the ground than in the steady state results.

The separation of the A-pillar vortex from the model surface is at the complex interaction of flows at the top of the rear pillar, shown in Figure 91; the square rear pillars create consistent flow separation on both the static and oscillating models, but on the round-edged model the likelihood of the A-pillar vortex remaining attached down the backlight is increased. This result is in general agreement with both Mansor (99) and Macklin (93), who both concluded that transient model testing reduces the probability of the flow separation around the model.

### 4.2.4 Discussion of the Oscillating Model Results

The surface pressure and PIV measurements collected during the oscillating motion have produced some extremely interesting results. Both the surface pressures and PIV results show that the flow structures and resultant aerodynamic loads on the oscillating models are strongly influenced by transient effects, and are quite different from the steady state results. This demonstrates that in this instance the aerodynamic response predicted by the reduced frequency is incorrect. This agrees with Mansor’s (99) results, which showed that the low reduced frequency, self-excited response of both models could not be explained using a quasi-static
approximation, although a similar experiment detailed in Appendix 1 produces results that are in line with the approximations based on the reduced frequency.

The differences between the quasi-static and oscillating models can be generalised into a number of consistent changes, despite the differing rear pillar geometries. All the forces and moments contain hysteresis; lift and drag show significantly different trends and greater asymmetry, while the yaw moment has a slightly different gradient and creates an ellipse slightly offset from the steady state results. The changes to the lift and drag mostly originate from a phase lag in surface pressures along the edges of the backlight, which is a function of both the test conditions and the trailing vortices. The yaw moment hysteresis is mostly created by a phase lag and a reduction in the amplitude of the surface pressures under the A-pillar vortices. There is also a lag below the rear pillars; this, as well as the lag on the edges of the backlight, creates less well formed and weaker vortices in the wake, especially on the leeside of the model.

These results can be explained by a combination of two effects created by the models’ motion; these are the same as those which cause dynamic stall on a pitching aerofoil, explained in Ericsson and Reding (113). There are two transient effects that modify the flow field; there is a pure lag effect which is a fundamental feature of the length and motion of the model, and there is a flow field modification term that produces different flow fields around the transient models from those around the static models. The changes to the flows around the Davis models are a created by combination of these two effects.

The pure lag term is a consequence of the time taken for the onset flow to travel the length of the model. As the model is oscillating the flow at the front of the model is always experiencing a different model yaw angle from that which the onset flow experienced momentarily earlier. This creates a near linear increase in phase lag towards the rear of the model, which mainly influences the flows into the trailing vortices affecting lift and drag but cannot explain the large lags on the sides of the backlights and has a much smaller influence on the A-pillar flows. The large changes to the A-pillar vortices are caused by flow field modification effects of the model motion. The rotational model motion means that all points on the model surface contain a component of velocity that is in line with the onset flow. As the yaw angle is increasing, the models surface is moving in the same direction as the lateral flow across the front of the model into the leeside A-pillar vortex. Although the surface velocity is only small, at most 0.06m/s, it re-energises the boundary layer and reduces the relative onset flow velocity on that side of the model. The reduction in the relative flow velocity reduces the severity of the surface pressure gradient around the A-pillar, which enables the flow to remain attached slightly further around
the A-pillar than on the static model. Separation is also delayed around the A-pillar as the model motion re-energises the boundary layer in an effect analogous to adding blowing in to the boundary layer. When the model is moving back towards 0° yaw the leeside of the model is moving into the onset flow and the effects are reversed and flow separation would occur earlier than on the static model. These effects also occur on the windward side of the model, where the relative direction of the surface velocity is reversed. However, because the flow is attached around the windward A-pillar vortex, the windward A-pillar flows are less affected by the model motion. Although these effects are most notable in the A-pillar flows, they will also modify the separation lines on all the curved surfaces around both models. This includes the leeside floor vortex and the separation into the trailing vortices on the round-edged model. The separation lines created by the square rear pillars are unaffected, because they are set by the model geometry and are independent of the onset velocity and model motion: this leads to subtle differences in the oscillating model results for the two models.

On the round-edged model the probability of the A-pillar vortex remaining attached to the backlight is higher than on the square edged model, whose static and oscillating model results are very similar. The mixing of the leeside trailing vortex and leeside floor vortex in the wake of the oscillating round-edged model is also less steady than in the wake of the square-edged model. The model motion reduces the strengths of the leeside trailing vortex and the leeside floor vortex, meaning that the mixing of the two flow structures into the single leeside vortex seen in the steady state results is weaker and less well defined.

On the square-edged model, the fixed rear pillar separation line consistently forms the leeside trailing vortex on the backlight of the model, and, although the leeside trailing floor vortex is weaker than in the steady state results, the interaction between the two vortices is much closer to that seen in the wake of the static model.

The greater similarity between the square-edged model’s static and oscillating model results are in agreement with one of Mansor’s findings, where he reported that the transient yaw moment gradient on the square-edged model was a closer match to that on the round-edged model. This is also seen in Appendix 1 when strakes are added to the rear edges of a scale model of a hatchback. The causes of the self-excited response reported by Mansor have not been explicitly found, but, given the results in this chapter, it seems likely that it is the A-pillar vortices that cause this response, rather than model motion coupling with periodic shedding in the wake, as postulated by Mansor. The positive yaw moment gradient is created by the strength of the A-pillar vortices, whereas the rear side force, which is strongly influenced by the rear pillar geometry on both models, would create a negative gradient without the effects of the front side
force. Section 3.2.2.1 shows that there are significant differences in the unsteadiness of the surface pressures below the A-pillar vortices, which originate from the separation of the vortices from the model surface at the top of the rear pillar, with the round-edged model having much greater unsteadiness. In this chapter, the surface pressures show that the front side force is affected by the model motion to a much greater extent than the rear side force, and the model motion increases the unsteadiness of the A-pillar vortex at the top of the A-pillar. This theory is further supported when it is considered that both models showed this type of response, with differences in the unsteadiness of the response. This leads to the conclusion that the cause of the motion was common to both models: the front of the model, and the unsteadiness within the responses was caused by the differences to the rear pillar geometry. In addition, Section 3.1.2.2 shows that the wakes of the models do not appear to contain any strong periodic shedding that would drive the motion.

The larger side force gradient reported by Mansor is contradictory to other published research, which typically show a larger yaw moment coefficient primarily created by a phase lag at the rear of the model that reduces the rear side force. Mansor calculated side force using two model rotation axes, and found the side force from the difference between the two yaw moment gradients. This approach relies upon the assumption that the flow fields created by the model with the two rotation axes are the same. Given the apparent large scale dependence of the A-pillar vortex on the model surface velocities, changes to the rotation axis and hence the surface velocities, would be likely to significantly alter the flow fields over the models, rendering this approach flawed in practice.

It is possible that the transient effects could be explained by effects of increased freestream turbulence, despite describing the differences between turbulent and yawing flows in chapter 1. The oscillating motion of the model creates low frequency, periodic changes to the relative onset flow speed that can be described as freestream turbulence. Newnham (54) showed that increasing small scale freestream turbulence reduced the critical Reynolds number around a radiused leading edge, and promoted attached flow. However, this explanation is not suitable in this instance. The oscillating motion creates a longitudinal turbulence intensity of 0.0004 and a lateral turbulence intensity of 0.04. These values are extremely low and below the baseline freestream turbulence intensity present within the wind tunnel. Furthermore the turbulent length scales created by the oscillating motion are far larger than the model and the theoretical limit proposed by Newnham that should interact with the shear layers and modify the flow field.
5. Conclusions

An experimental investigation into the effects of rear pillar geometry and unsteady yaw angles has been carried out using two configurations of a fastback Davis model.

At 0° static yaw, the square-edged model produces a flow field very similar to that described by Ahmed et al (3) with separate trailing vortices and quasi-2D wake behind the base. Rounding the rear pillars results in weaker trailing vortices which mix with the wake behind the base of the model creating a different wake structure that contains greater unsteadiness.

The near wake of a statically mounted fastback model is very dependent upon the rear edge curvature of the model and a relatively small change in this region produces large changes to the flow field. This result is also likely to be directly applicable to notchback shapes and to a lesser extent, squarebacks.

At static yaw angles, the main changes to the flow fields around the two models are on the leeside while the windward flow structures remain very similar to those found on both sides of the model at 0° yaw. The changes to the leeside flow structures contain greater unsteadiness than those on the windward side and this is a fundamental consequence of the differences in mechanisms that drive the flow fields on the two sides of the models.

The statically mounted square-edged model has a higher side force gradient and lower yaw moment gradient than the statically mounted round-edged model; these are created by higher surface pressures upstream of the rear pillars.

As the steady state yaw angle increases, the windward trailing vortices change strength relative to those in the wake at 0° yaw although there is no clear trend as the round-edged model’s wake contains a stronger vortex whereas that of the square-edged model is weaker. The mechanisms that drive the changes in vortex strength are likely more complex than previously expected and are a function of the rear pillar geometry and how the flow around these feeds into the windward trailing vortex.

In both static and transient testing, the A-pillar vortex is the dominant contributor to the yaw moment and side force of the two models. Despite finding very similar mean values of front side force in both types of testing there are significant differences in the unsteady component demonstrating the importance of investigating the unsteady components of a flow field even in nominally steady state conditions.
When the models are at yaw, there is a strong interaction between the leeside A-pillar vortex and the leeside rear pillar and trailing vortex. The leeside A-pillar vortex detaches from the model surface at the top of the rear pillar and the different levels of unsteadiness created by the two models’ rear pillar geometries is fed upstream into the A-pillar vortex on the side of the model.

The measurements taken during the oscillating model tests show that the flow fields around both Davis models at a reduced frequency of 0.049 is highly transient and does not fit with the expected quasi-static approximation for such a low reduced frequency.

A combination of two factors that are inherent to the transient testing create the differences in the flow fields to those seen in static testing conditions. There is a pure lag term which is a consequence of the time taken for the flow to travel the length of the model and there is a flow modification term that affects the separation lines on curved surfaces by changing the relative local flow velocity and re-energises the boundary layer.

Flow structures created by separation lines that are fixed by model geometry are less affected by either transient effect and increasing the amount of fixed separation lines reduces the potential for differences in the flow field between a steady state and transient model by minimising the effects of the flow modification term.

The greatest transient effects on the aerodynamic loads acting on these models are found at the front of the model in the A-pillar flows. This demonstrates that the commonly held assumption that transient effects only occur at the rear is incorrect and in the future similar investigations should consider the entire model.

The largest changes to the strength and structure of the flow structures found around the models and in their wakes in steady state and transient conditions are on the leeside of the model. This is due to the weaker mechanisms that drive these flow features than on the windward side which allows the transient effects to have a greater influence on the flows.

During the oscillating model tests, the surface pressures along the sides of the backlights of both models lagged the model motion by a large amount. This was significantly greater than that which would have been expected from the pure lag term and indicates that this may be a fundamental characteristic of the trailing vortices.
The differences in the flow fields around the round and square-edged models show that controlling flow separation creates stronger and steadier flow structures than where separation is allowed to occur naturally on a curved surface.

The conflicting changes to the strengths of the windward trailing vortices on the two models and the large lags along the edges of the model backlight demonstrate that the flow mechanisms driving the trailing vortices are more complex than previously realised and not fully understood.

Around both models, the leeside is the source of the greatest unsteadiness and changes in the flow field, both in the change from 0° to yaw and from static to transient testing, whereas the changes to the flows on the windward side are much smaller. This is a consequence of the weaker mechanisms that drive the leeside flows and shows that the leeside of the model is more important than the windward side when considering effects of yaw.
6. Recommendations for Further Work

This thesis used the Davis model for continuity with previous work but it is not commonly used in other research. It may be useful to repeat elements of this work with a more commonly used model or simulate a full scale production vehicle to test the dependence of the results on the model used.

The square edged model only has square edges on the rear pillars, all the other edges of the model are rounded which adds undesirable complexity to the flow structures and interpretation of the results. It may be useful to further modify this model such that all the rear edges are squared off and the separation lines are fully defined. Further to this, a systematic investigation into the effect of separation control created using sharp edges all over the model on the time averaged and unsteady aerodynamics could be very informative.

The increased complexity of the flow fields with the model at yaw is not well understood as detailed flow field analysis, typically used for drag optimisation is most often carried out in 0º yaw flows. This is not an accurate description of the mean conditions experienced on the road and it would be beneficial for more of this type of work to consider, at the very least, small yaw angles <3º so that a more complete description of the aerodynamic properties could be developed.

The influence of the oscillating motion on the A-pillar region was an unexpected result. This may be model specific but with newer car designs increasingly having a very small angles at the intersection between the bonnet and windscreen, there is the potential for A-pillar vortices to develop along the entire front side edge of the vehicle and for the A-pillar vortex to become increasingly important. This should be further investigated, especially with the growing popularity of light weight, 1 box cars that are known to be sensitive to crosswinds.

Only one type of transient yaw motion was used in this thesis, the test rig was designed to provide a number of different amplitudes and mean yaw angles but during the course of this thesis there was not time to investigate other motions. It is anticipated that the results will show some dependency on the motion frequency, amplitude, centre of motion and reduced frequency but the extent of this is unknown. Although there is some research into this from a dynamic stall and aeronautical perspective, the significantly greater complexity of automotive bluff body aerodynamics means this will probably require specific research.
Other types of unsteady motion should also be investigated, appendix 2 shows that there are unsteady aerodynamic effects with a sprung laterally oscillating model, but other types of motion, such as rolling, pitching and constantly changing onset flow speeds will also have a, currently unknown, influence on the flow fields.

As has been seen throughout the thesis, the reduced frequency term does not correctly describe the unsteady aerodynamic effects witnessed with this model and its use throughout aerodynamic research is inconsistent. It would be very beneficial for this term to be better investigated with the aim of creating a definitive definition of the term and its applicability, building on the analysis of Sims-Williams (1)

This thesis, along with others before it, has used the impending reduction in vehicle masses and subsequent, relative increase in aerodynamic loads as partial justification for the research. Whilst this is intuitively the case, the importance of this has not been properly investigated and there is no comprehensive analysis of aerodynamic and vehicle handling associated with a lightweight vehicle. The work that been published has generally used simplistic parameter changes, rather than considering the large scale changes to the vehicle chassis that would come about from a significant reduction in the weight of the vehicle. These changes could include reductions in vehicle inertia, changes to the location of the centre of mass and changes to suspension stiffnesses and a basis for this is provided by the work of Fuller et al (62)
7. References


55. Oettle, N; Sims-Williams, D; Dominy, R; Darlington, C; Freeman, C; Tindall, P. The Effects of Unsteady On-Road Flow Conditions on Cabin Noise. 2010, SAE World Congress and Exhibition, Detroit, MI. SAE Technical Paper Series, 2010-01-0189.


62. Fuller, Joshua; Best, Matt C; Garret, Nikhil; Passmore, Martin A. The importance of unsteady aerodynamics to road vehicle dynamics. 2012, Journal of Wind Engineering and Industrial Aerodynamics. In review.


69. Howell, J P. Private Conversations and Correspondence.


74. Duell, G; Khararzi, A; Muller, S; Ebeling, W; Mercker, E. The BMW AVZ Wind Tunnel Centre. 2010, SAE World Congress and Exhibition, Detroit, MI. SAE Technical Paper Series, 2010-01-0118.

75. Koremoto, K; Kawamura, K; Kuratani, N; Nakamura, S; Arai, T; Galanaga, F; Walter, J; Martindale, B; Duell, E; Muller, S. The Characteristics of the Hinda Full Scale Aero-acoustic Wind Tunnel equipped with a Rolling Road System. 2010. 8th MIRA International Vehicle Aerodynamics Conference, Grove, Oxfordshire. pp. 416-432.


168


98. Sims-Williams, David. Private Conversations and Correspondence.


146. Oettle, Nicholas; Mankowski, Oliver; Sims-Williams, David; Dominy, Robert; Freeman, Claire; Gaylard, Adrian. Assessment of a Vehicle's Transient Aerodynamic Response. 2012, SAE World Congress and Exhibition, Detroit, MI. SAE Technical Paper Series. 2012-01-0449.


Appendix 1. Audi A2 Case Study

This appendix details a case study into the unsteady aerodynamics of the Audi A2, a small production car that had small strakes added to the rear light mouldings to improve a handling sensitivity identified during prototype testing.

The A2 is an interesting test case; during the prototype development stage the test drivers reported the car was prone to a lateral sensitivity in certain onset flow conditions. This was improved with the addition of small vertical strakes in the rear light moulding that slightly reduced the steady state yaw moment coefficient gradient but improved the subjective ratings more than expected, given the small change in the aerodynamic loads. The implication is that both the initial handling issue and the addition of the strakes were related to transient effects not seen in steady state wind tunnel conditions.

To investigate this, a quarter scale model of an Audi A2 was subjected to range of static and transient experiments and the results compared to those found in chapters 3 and 4 using the round and square-edged Davis models. Sections of this appendix have been published in Baden Fuller et al (82) which also includes moving turntable testing and full scale results.

A1.1 Experimental Details

A1.1.1 Audi A2

The Audi A2 was a small supermini car in production from 1999 – 2005. It was relatively tall and narrow with a tapered roof giving a drag coefficient between 0.25 and 0.29 depending on model specification. It was mainly constructed from aluminium giving it an unladen weight below 1000Kg, meaning the longitudinal position of the centre of gravity was very dependent on the number of passengers and load in the car. The production cars had strakes in the rear light moulding as shown in figure A1.1.
Although the strakes were on the rear vertical edge of the A2, apparently directly influencing the flow into the quasi 2D wake directly behind the model base, this model provides an opportunity to compare the results gained using the Davis models, which are simple automotive bodies, to a scale model of a production vehicle and investigate the potential usefulness of the Davis models’ results.

The quarter scale model of the Audi A2, shown in Figure A1.2, is made of fibre glass laid up in moulds supplied by Audi. The model has a shaped floor and is fitted with a representative exhaust system and solid wooden wheels and does not include internal cooling flows. The model can be mounted in the wind tunnel either with pins into each wheel or with a single central shaft. Although described as a quarter scale model, subsequent measuring showed that it was not an exact similarity to a production vehicle but whether this was inherent to the moulds or due to subsequent assembly is not known.
A1.1.1.1 Strake Scaling

On the production vehicle the strakes were 4mm high and Audi also tested a larger strake which was 15mm high and twice as long. To overcome problems associated with testing small details at model scale the strakes were scaled relative to the boundary layer thickness rather than with a simple geometric scale. The production vehicle was approximated as a flat plate and the boundary layer thickness was found using the 7th power law, shown in equation A1.

\[ \frac{\delta}{x} = \frac{0.16}{Re_x^{0.77}} \]  

Eq. A1

The heights of the strakes were found as a percentage of the boundary layer thickness, this was used to calculate the height of the required strake height on the model based on the boundary layer thickness at the rear of the model found using the same equation. The exact sizes were rounded to the nearest integer millimetre value, giving a production strake height of 2mm and a large strake height of 5m, these were and made from adhesive backed foam, as shown in Figure A1.3.

Figure A1.3, Scaled strakes

The moulds included geometrically scaled strakes and this allowed a simple test of the effectiveness of the scaling methods. Table 1 shows the steady state yaw moment coefficient gradients approximated as a straight line, for the model with no strakes, 1mm high geometrically scaled strakes and 2mm high boundary layer scaled strakes.
<table>
<thead>
<tr>
<th>Model Configuration</th>
<th>No Strakes</th>
<th>1mm Strakes</th>
<th>2mm Strakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw Moment Coefficient Gradient (º)</td>
<td>0.0108</td>
<td>0.0108</td>
<td>0.0103</td>
</tr>
</tbody>
</table>

**Table 1, Strake effectiveness**

The geometrically scaled strakes have no effect on the yaw moment coefficient gradient but the boundary layer scaled strakes do cause a reduction, demonstrating the scaled strakes are having an effect and scaling against the boundary layer is preferable to geometric scaling in this instance.

The tests detailed later in this chapter will use three rear end configurations; no strakes, 2mm strakes and 5mm strakes, representing the production sized and large experimental strakes used at full scale.

**A1.1.1.2 Pressure Tappings**

Surface pressure tappings were arranged around the rear of the model covering the surfaces around the strakes and onto the base of the model with further tappings around the model’s waist line. A sketch of the locations is shown in Figure A1.4. The pressure tappings are in the same locations on both sides of the model.

![Figure A1.4, Pressure tapping locations](image)

**A1.1.2 Experimental Methods**

The driven oscillating rig used in chapter 4 was designed for the Davis model which has smaller aerodynamic loads and a polar moment of inertia ten times smaller than the A2 model. This meant it was not strong enough to use with A2 so Mansor’s sprung oscillating rig was used instead. An overview of the experiments discussed in this chapter is in Table 2 and more details of each method will be given prior to the respective results.
<table>
<thead>
<tr>
<th>Testing Method</th>
<th>Static or Transient</th>
<th>Speed (m/s)</th>
<th>Yaw Angle Range (°)</th>
<th>Reduced ($\frac{\pi f_l}{U}$) Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance</td>
<td>Static</td>
<td>40</td>
<td>-20 to + 20, in 2° steps</td>
<td>0</td>
</tr>
<tr>
<td>Pressure Tapings</td>
<td>Static</td>
<td>40</td>
<td>0 -12°, in 2° steps</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Oscillating Model</td>
<td>Transient</td>
<td>10 - 40</td>
<td>Initial 15° excitation</td>
<td>0.05 – 0.5</td>
</tr>
<tr>
<td>Pressure Tappings,</td>
<td>Transient</td>
<td>10 - 40</td>
<td>Initial 15° excitation</td>
<td>0.05 – 0.5</td>
</tr>
<tr>
<td>Oscillating Model</td>
<td>Transient</td>
<td>10 - 40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2, Different experiments

A1.2 Results and Discussion

The discussion of the results mainly focuses on side force and yaw moment as these are the aerodynamic inputs that are most likely to cause lateral deviation. Furthermore, the oscillating model rig can only output these results and full scale data provided by Audi (149) also focused on these coefficients.

A1.2.1 Balance Results

Steady state wind tunnel data was collected using the quarter scale A2 in the Loughborough University wind tunnel with the three strake configurations. The model was mounted to the underfloor balance, centred about the mid wheelbase with pins in each wheel giving 3mm clearance under the wheels. Data was collected at a tunnel speed of 40m/s, giving a Reynolds number based on overall length of $2.5 \times 10^6$. The results have been corrected for model blockage using the MIRA blockage correction and wind off, tare loads have been removed. The steady state yaw moment coefficient gradients for the scale model with the three strake configurations are summarised in Table 3, the percentage change is relative to the ‘no strakes’ case. Also included are the full scale test results which were provided by Audi and collected using a production Audi A2 in low drag configuration in the Pininfarina wind tunnel.
At both full and model scale, the production strakes cause a small reduction in yaw moment gradient. The larger strakes create a further reduction in the yaw moment disproportionate to the increase in the strake size; it was the initial addition of the strakes to the base model that produces the largest change. This is in agreement with Mansor (99) who showed the largest change to the yaw moment gradient on the Davis model came with the change from round rear pillars to square rear pillars and Howell (11) found a similar result when changing from a square-edged to rounded edges; the largest change was in the initial change whilst increasing the radius of the rounding had a minimal effect.

The differences in the absolute values of the full and model scale results can be generalised as being due to scaling factors, differences in the experimental set-ups and shape and detail differences between the production vehicle and scale model although of particular note is the lack of cooling flow on the scale model which would increase the yaw moment gradient.

The front and rear side force coefficient gradients that create the yaw moments acting on the quarter scale model with the different strake configurations are shown in Table 4.

<table>
<thead>
<tr>
<th></th>
<th>Front Side Force Coefficient Gradient (°)</th>
<th>Rear Side Force Coefficient Gradient (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Strakes</td>
<td>0.0281</td>
<td>0.0087</td>
</tr>
<tr>
<td>Production Strakes</td>
<td>0.0280</td>
<td>0.0091</td>
</tr>
<tr>
<td>Large Strakes</td>
<td>0.0282</td>
<td>0.0097</td>
</tr>
</tbody>
</table>

Table 4, Front and rear side force coefficient gradients

The strakes reduce the yaw moment coefficient gradient by increasing the rear side force gradient which counteracts the front side force gradient. The front side force coefficient gradient is independent of the strake configuration and this is a similar result to that seen on the Davis models in chapter 3.2, where changing a detail at the rear of the model caused the rear side force
to change whilst the front side force remained consistent between the different model configurations.

Howell and Baden Fuller (80) showed a beneficial link between lower yaw moment gradients and reductions in rear lift for certain geometry changes. The rear pillar changes on the Davis model were an exception to this theory but the addition of the strakes to the A2 is in agreement; in addition to reducing the yaw moment gradient the production strakes reduce rear lift by 5 counts and the large strakes caused a 10 count rear lift reduction at 0° yaw.

A1.2.2 Surface Pressures

Surface pressure data were collected on the static model at 260Hz for 32 seconds, giving a total of 8192 data points at each pressure tapping. The model was mounted with the central shaft to produce set up conditions similar to those when the oscillating model rig is used. Apart from the different mounting, the model was unchanged from the set up used for the balance results, and the gap between the wheels and the floor was 3mm.

The effect of the strakes on the surface pressure distribution over the rear of the model at 0° yaw is shown in Figure A1.5. The results are arranged as if looking at the base of the model with the sides ‘unwrapped’. The edges of the model are curved, but the approximate intersection between the base and sides of the model is shown by the vertical dashed lines at w/W = -0.5, 0.5. The shaded-out triangles represent the tumblehome and base curvature of the model: the gaps in the data in the lower corners are from where the pressure tappings avoid the wheel arches. The approximate locations and size of the strakes are shown by the thick black lines.
Figure A1.5, Effect of the strakes on the steady state surface pressures, 0° yaw

On the base model there are regions of low pressure around the upper half of the rear edges of both sides of the model, created by flow travelling around the rear pillars into the trailing vortices. The strakes reduce the size of these regions of low pressure, implying a reduction in the strength of the trailing vortices, and create a very small region of positive pressure directly upstream of the strakes. This is similar to the increase in surface pressure seen on the square-edged model upstream of the rear pillars.
The rear edges of the A2 are rounded and the wake may be similar to that found behind the round-edged model. In chapter 3 it was shown there is a strong interaction between the trailing vortices and the wake directly behind the model base. By reducing flow around the vertical rear edges of the model, the strength of the trailing vortices may be reduced. This agrees with the reduced rear lift, as weaker trailing vortices produce less central downwash and higher pressures on the backlight, resulting in lower rear lift values.

When interpreting the results, there are two issues to be aware of. It is likely that the extent of the high pressure region upstream of the strakes is exaggerated by the spacing of the pressure tappings; one column of tappings was very close to the strakes, and interpolating between the columns of tappings to create the surface pressures contours increases the size of the small high pressure region. The surface pressures are also slightly asymmetric and there are two causes of this. The model is asymmetric especially on the floor, and there are also likely to be small levels of asymmetry arising from the model assembly. There are also slight side to side differences in the locations of the pressure tappings; in regions of steep pressure gradients this produces greater asymmetry in the results than really exists on the model surface.

Figure A1.6 shows the steady state surface pressures with the model at -10° yaw: consistent with chapter 3.2, the right hand side of the model is windward.

On the base model there is a large region of low pressure on the windward rear edge, extending from the roof down to the wheel arch, created by attached flow accelerating into the wake. This low pressure on the windward side of the model works with the low pressure under the leeside A-pillar vortex to create a large yaw moment gradient. The production strakes reduce the extent of this low pressure region, limiting it to the rear pillar only, and create a small area of high pressure directly upstream of the strake. The small high pressure region on the leeside of the model is unfavourable, but is negated by the advantageous flow field modifications created on the windward side of the model.

The larger strakes increase the size and magnitude of the high pressure regions upstream of the strakes on both sides of the model, but the low pressure at the top of the windward side is the same as that found on the model with production sized strakes. The increase in the high pressure on the windward side increases the rear side force which reduces the yaw moment acting on the model disproportionately to the increase in the size of the strakes. The larger strake was extended downwards, leaving the top edge of both sized strakes at the same height. Figure A1.6 shows that the influence of the both the standard strakes and the large strakes on the flow...
around the windward rear pillar into the trailing vortex is very similar, despite the different strake sizes, hence the influence of the larger strakes is less than expected, given its larger size.

![Figure A1.5, Effect of the strakes on the steady state surface pressures, -10° yaw](image)

Integrating the surface pressures over the area surrounding each pressure tapping gives an indication of the effect the strakes have on the rear side force. However, this only covers a small area of the rear of the model and is not representative of the overall rear side force acting on the model, only the localised effects of the strakes. The total side force coefficients calculated from the pressure tappings are in in Figure A1.7, and the contributions from the leeward and
windward sides of the model are shown in Figure A1.8. The values have been converted to coefficients, but, because the area of the model covered by the pressure tappings is small, the forces are also and the coefficients are therefore quoted to more than the usual three decimal places.

![Figure A1.7, Side force coefficients integrated from steady state surface pressure](image)

The strakes reduce the negative rear side force gradient, and the large strakes make the rear side force coefficient gradient integrated from the surface pressures positive. Figure shows the contributions to the side force from each side of the model, the gradients of these lines are shown in Table 5.

![Figure A1.8, Leeward and windward side force coefficients](image)
Table 5, Windward rear side force gradient from integrated surface pressures

<table>
<thead>
<tr>
<th></th>
<th>No Strakes</th>
<th>Standard Strakes</th>
<th>Large Strakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windward Side Force</td>
<td>-0.0074</td>
<td>-0.0036</td>
<td>0.0006</td>
</tr>
<tr>
<td>Coefficient Gradient (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leeward Side Force</td>
<td>0.000020</td>
<td>0.000002</td>
<td>-0.000020</td>
</tr>
<tr>
<td>Coefficient Gradient (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The main change to the side force gradient is on the windward side of the model. The leeside side force coefficient gradient remains nearly constant despite the different model configurations. This demonstrates that the adverse flow field changes created by the strakes on the leeside of the model shown in Figure A1.6 are negligible when compared to the improvements on the windward side of the model. The production strakes halve the windward side force gradient and the large strakes produce a positive side force gradient. These effects are magnified due to the small area covered by the pressure tappings, which is concentrated around the strakes and does not cover the flow around the rear pillar into the trailing vortices.

The strakes also influence the unsteady component of the side force. The standard deviation of the steady state side force coefficient calculated using the instantaneous surface pressure data is in Figure A1.9, which shows the effects of model configuration and yaw angle on the side force unsteadiness.
The strakes reduce the unsteady component of the side force integrated from the surface pressures at all yaw angles. The reductions to the unsteadiness are relatively constant across the yaw angle range, apart from at 9° and 10°, where there is a change in the general trend of the results in the data from all three model configurations. The reduction in the unsteady component of the side force is in agreement with the Davis model results in chapter 3.2, where the round-edged model had a larger unsteady component of side force than the square-edged model. The reasons for this are the same: the strakes on the A2 reduce the unsteadiness in the rear separation lines; the strakes also reduce the unsteadiness in the drag force.

Investigating the frequency content of the instantaneous surface pressures reveals that the strakes have further effects. In the data from all three model configurations at 0° yaw there are no spectral peaks of interest in the surface pressures on the sides or base of the model; this changes when the model yaws, and the results are summarised in Table 6.

<table>
<thead>
<tr>
<th></th>
<th>5° Yaw</th>
<th>10° Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Strakes</td>
<td>15-16 Hz</td>
<td>26Hz</td>
</tr>
<tr>
<td>Standard Strakes</td>
<td>17-20 Hz</td>
<td>23Hz</td>
</tr>
<tr>
<td>Large Strakes</td>
<td>17-20 Hz</td>
<td>20-22Hz</td>
</tr>
</tbody>
</table>

Table 6, Wake frequency content

The dominant frequencies for the three model configurations are similar; however, the effect of the slight changes to the frequencies could be larger than expected, due to the relationship between the aerodynamic periodicity and the natural frequencies of the full scale vehicle. A quarter scale model frequency of 15Hz represents a full scale frequency of 3.75Hz; although higher than would usually be expected for vehicle body natural frequencies, the Audi A2 was light weight and this may have created a body motion natural frequency higher than normal. If this were the case, a frequency of 3.75Hz would have a larger effect than would be normally expected. As the yaw angle increases, the dominant frequency also increases; this change could mean inconsistent vehicle handling, leading to low driver confidence.

The strakes altered both these effects; the strakes cause the aerodynamic frequency to be slightly higher at 5° yaw than on the base model, and the shedding frequency to change less at larger yaw angles. The slight increase in the frequency at 5° may be enough to lessen the effect of the unsteady aerodynamics on the vehicle handling and the greater similarity in the dominant aerodynamic frequencies between the yaw angles would mean that the handling would be more consistent across a range of yaw angles. Both of these effects would be beneficial to the vehicle handling, and would be felt as an improvement by the driver.
A1.2.3 Oscillating Model Rig

This recreates the experiment carried out by Mansor, but using the Audi A2 model rather than the Davis models, as shown schematically in Figure A1.10. The model acts as a torsional pendulum; the aerodynamic loads on the model change the stiffness of the system, altering the natural frequency of the oscillations. The change in the system stiffness is found by comparing the wind-on and wind-off oscillation frequencies, and from this the yaw moment gradient is calculated. A full derivation of the theory behind this method can be found in Mansor (99), with overviews in (101) and (100). The calculation of the yaw moment gradient from the instantaneous model position data was carried out using the same computer scripts as used by Mansor.

![Figure A1.10, Oscillating model rig schematic, taken from (99)](Image)

The model was mounted to the oscillating rig with a shaft in the centre of the wheelbase, with 3mm clearance under the wheels. To overcome the greater polar moment inertia and larger yaw moment of the A2 model compared to the Davis model, a different range of spring stiffnesses, Table 7, were used to create the range of reduced frequencies.

<table>
<thead>
<tr>
<th>Spring</th>
<th>Stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>1.86</td>
</tr>
<tr>
<td>K2</td>
<td>2.16</td>
</tr>
<tr>
<td>K3</td>
<td>3.42</td>
</tr>
<tr>
<td>K4</td>
<td>6.37</td>
</tr>
</tbody>
</table>

*Table 7, Spring stiffnesses*
Using the 4 different springs and varying the tunnel speeds between 10 and 40m/s produced reduced frequencies in the range 0.05 – 0.5. The model was given an initial yaw angle displacement of ≈15º and was free to yaw as prescribed by the springs and aerodynamic loads acting on the model, the model response being recorded using an angular potentiometer mounted to the model support shaft. This was carried out for each combination of spring, wind speed and strakes configuration, with the mounting shaft only located in the mid wheelbase: hence the side force gradient could not be calculated. However, given the doubts over this method explained in chapter 4, this is not a significant omission.

Figure A1.11 shows frequency ratio plotted against reduced frequency. Frequency ratio is the ratio of the wind-on frequency to the wind-off frequency, and the smooth curve shows that, despite 4 discrete spring stiffnesses and 5m/s windspeed steps, the results are continuous and not an effect of the individual test conditions.

The results from each model configuration all fall onto a single curve, and this was unexpected. The frequency ratios found by Mansor using the round and square-edged Davis models were different at low reduced frequencies, as shown in Figure A1.12. Frequency ratio is a consequence of the yaw moment gradient; the change in yaw moment of the Davis models is 40%, but the changes in the yaw moment gradient created by the strakes on the Audi are very small, hence any changes to the frequency ratio are indistinct within the results.
The A2 always produced a fully damped response; unlike the Davis models, there was no self-sustained or self-excited model response, irrespective of the reduced frequency. The causes of the self-excitation on the Davis model are not known hence it is not possible to explain why the A2 did not reproduce this response. This may be a mechanical effect related to the increased inertia of the A2 model but, if the Davis model self-excitation is an effect of the A-pillar vortices, it may be because the A-pillar vortices are weaker on the A2 and that the location of the strakes on the vertical edges rather than on the rear pillars does not have the same upstream effect on the A-pillar vortex unsteadiness as on the Davis model.

Using the oscillating model responses to derive the yaw moment gradient produces the results in Figure A1.13. All the yaw moment gradients are normalised using the steady state no-strakes yaw moment gradient as measured on the balance. The steady state values for the three model configurations are also included for reference.
Figure A1.13 shows that the yaw moment gradients derived from the model response for each A2 model configuration are generally larger than the steady state yaw moment gradient and this result matches those from Mansor (99) and Berryman (102), gained using this method. Within the results there are no apparent relationships between the yaw moment gradient and reduced frequency, such as in Figure 26, which may be because the models did not produce a self-excited model response.

Using the mean values of oscillating yaw moment gradient for each test configuration, the production strakes caused a 6% reduction in yaw moment gradient from the no-strakes configuration, and the large strakes produced mean yaw moment gradient reduction of 10%. The yaw moment reductions caused by the strakes follow the same trends as seen in the steady state results, but the reductions in the yaw moments from the oscillating results are slightly larger. This is a similar result as reported by Mansor who found that the average reduction in yaw moment gradient created by the square rear pillars was greater in the oscillating results than in the steady state results.

The strakes reduce the difference between the mean oscillating yaw moment gradients and the steady state yaw moment gradients, with the larger strakes further reducing this difference. This is also in agreement with Mansor, and the change from round to square rear pillars on the Davis
model. As explained in chapter 4, this is likely to be because the strakes increase the length of the separation lines at the rear of the model which are independent of the local surface velocity and pressure gradients, and are unaffected by the oscillating model motion.

These results do not allow for any greater understanding of the transient aerodynamics of the Audi A2, but they do show that the general results of the oscillating model rig can be applied to a detailed scale model of a passenger car.

The same oscillating model experiment was repeated whilst recording instantaneous surface pressures. A typical set of results collected at a high reduced frequency, showing the model motion and the side force coefficients integrated from the surface pressures, are in Figure A1.14: results for low reduced frequency are in Figure A1.15. The quasi static result is calculated using the rear side force gradient found from the results in Figure A1.7 and the instantaneous yaw angle.

![Figure A1.14, Oscillating model instantaneous side force coefficients, reduced frequency 0.29, base model, standard strakes and large strakes left to right.](image)

At high reduced frequencies the instantaneous side force coefficients on the oscillating model and the quasi static response are very different. The side force coefficient on the oscillating model is much smaller than the quasi-static response, irrespective of the strake configuration on the model.

At lower reduced frequencies, Figure A1.15, the instantaneous side force coefficient is much closer to the quasi static model response, in agreement with the trend that smaller reduced frequencies produce a response closer to the steady state response.
Figure A1.15, Oscillating model, surface pressure results, reduced frequency = 0.09, base model, standard strakes, large strakes, left to right

The base model has larger side force coefficients integrated from the pressure tappings, leading to greater clarity in the results than in the other two, which have increased damping and a smaller signal-to-noise ratio. The similarity of the instantaneous and quasi-static side force coefficients is in disagreement with the results in chapter 4, which showed large scale transient effects at a reduced frequency of 0.049. This may be because the transient effects mainly affect the flows around the front of the model, as on the Davis model, and the pressure tappings towards the rear of the model do not record flow structures that are significantly affected by the transient model motion. However, this result gives further support the conclusion that the use of a reduced frequency as a non-dimensional parameter to characterise unsteady aerodynamic inputs is limited.

The phase and amplitude relationship between the oscillating and quasi-static data is investigated in Figure A1.16, but the small signal-to-noise ratio in the data collected with the strakes present and the increased damping means that this analysis is limited to the base model only.
The phase lag has a near linear trend towards larger lags at lower reduced frequencies. This agrees with the time lag described by Ericsson and Reding (113) created by the time taken for the onset flow to propagate along the length of the model and a similar result was reported by Wojciak et al (111). At larger reduced frequencies the aerodynamic input is more unsteady and the model yaw angle is changing more rapidly relative to the onset flow speed than at low reduced frequencies. The amplitude results are less clear but there may be a weak trend of amplitude factors close to 1 at low reduced frequencies which reduce at higher reduced frequencies. Both these results are in general agreement with the typical understanding of the effects of reduced frequency and unsteady inputs and do not add give any indication of how the strakes modify the transient aerodynamics of the A2.

A1.3 Conclusions

This case study has two aims. Firstly, it uses some transient and steady state testing methods to investigate the aerodynamics of the Audi A2 and the effect of strakes added to the production vehicle to improve the lateral sensitivity issue. The second aim is to test the applicability of the Davis model results gained in this thesis and by Mansor to a detailed scale model of a production vehicle.
The strakes create a small decrease in the steady state yaw moment coefficient gradient primarily by promoting flow separation on the windward vertical rear edge of the model. This prevents attached flow accelerating around the windward edge of the model creating a region of suction which is detrimental to the overall yaw moment of the model. In addition to preventing the suction, directly upstream of the strake there is a small region of positive pressure which further reduces the yaw moment.

The larger strake shows the same effects as the smaller one, but the surface pressures show the flow into the windward trailing vortex is unaffected by the increase in strake size which extends downwards, partially explaining why the increased strake size does not provide a decrease in yaw moment proportional to the change of the size of the strake.

The strakes modify the frequency content of the wake, increasing the frequency of the lowest peak and making the frequency content more consistent across the yaw angle range. Both of these would be beneficial to the vehicle’s handling and may help explain the greater than expected subjective vehicle handling assessment by Audi’s test drivers.

The oscillating model rig results showed reductions in the yaw moment gradient slightly larger than the steady state results; this also may help explain the subjective handling improvements of the production vehicles. The oscillating surface pressures show the flow field at the rear of the model contains phase lags caused by the time taken for the onset flow to travel along the length of the model. The variations in the transient rear surface pressures created by the oscillating model motion are smaller than the quasi-static response at large reduced frequencies but at small reduced frequencies the rear side forces integrated from the surface pressures showed a near quasi-static response.

Comparing these results to those gained with the Davis model shows some good agreement between the models and demonstrates the potential usefulness of the Davis model results to production vehicles. The strakes reduce the yaw moment by increasing the surface pressures upstream of the strakes, which matches the Davis model results in chapter 3.2. The strakes also reduced the unsteady component of the rear side force and the spectral content of the flow fields and these are similar results to those found in the change from round to square rear pillar. However, unlike the Davis models, the A2’s strakes reduce rear lift implying a reduction in the strength of the trailing vortices.
Using the oscillating model rig the yaw moment gradients are generally larger than the steady state results and the yaw moment gradient reductions caused by the strakes are greater than in the steady state results; both of these results are in agreement with Mansor’s Davis model results. Unlike the Davis model, the A2 only produced a damped response and at low reduced frequencies the transient surface pressures closely match the quasi-static results unlike the Davis model results in chapter 4. These conflicting results demonstrate the reduced frequency does not accurately describe the level of unsteadiness in the test conditions. As suggested by Sims-Williams (1) the reduced frequency term may need modifying or there should be greater clarification of the length scales or amplitudes used.
Appendix 2. Lateral Oscillating Model Rig

This section describes the initial development of a new transient model experiment carried out by the author and Dr Mansor. It does not show any definitive results but demonstrates that there is an effect that may be worth investigating in the future and records the progress made in the design of the test rig so that any future work using this method should benefit from our experimentations.

A2.1 Introduction

As explained in chapter 1, a wide range of different methods have been used to create transient yaw conditions in a wind tunnel either by changing the angle of the onset flow or by moving the model relative to the flow.

Mansor (99) used an oscillating model rig that was free to oscillate in yaw only with results derived from the model angular response. Using a new experimental set up, it was decided to investigate if a similar experiment could be carried out with the model only free to move laterally.

At the start of this research project, the author was not aware of any published work directly related to automotive aerodynamics that used a laterally moving model. However in 2010 Möller and Pöttner (114) published a paper showing PIV results of the wake of an Ahmed model moving laterally across the flow of a wind tunnel. The test used very low Reynolds numbers which makes the results questionable but they showed the wake was subject to flow field hysteresis and different from steady state.

Oscillating the model laterally across the onset flow creates a yaw angle from the vector sum of the onset flow and the model lateral motion, shown in Figure A2.1. The model motion was driven by a pair of springs which created damped simple harmonic motion. This type of lateral model motion does not create any component of surface velocity in line with the onset flow, unlike the yawing motion in chapter 4, but the transient pure time lag effect should still be present.
A2.2 Initial Design

The lateral oscillating model motion was created by a pair of springs. The model was given an initial lateral displacement and the subsequent model motion was recorded. It was hoped that changing the tunnel speed and spring stiffness would create different model responses which could be related to an unsteady aerodynamic effect or be used to extend Mansor’s work.

The initial design mounted the model via a central shaft to a carriage mounted on linear bearings. The bearings limited the model’s motion to the lateral plane only. The carriage had 4 linear bearings and there were two parallel rails on either side of a slot through which the model support shaft passed. The range of motion was based upon the availability of suitably long springs and was set at 300mm. The motion of the carriage was recorded using a draw wire potentiometer with a second, identical potentiometer used to counter balance the spring force created by the potentiometer, although only one sensor was used for data collection. A lightweight version of the round-edged Davis model, detailed in chapter 2, was manufactured, the mounting shaft of which was made of carbon fibre and did not allow for any adjustment of the location. This apparatus was mounted on the roof of the work section of the wind tunnel and a photograph of the general set up is shown in Figure A2.2.
A2.3 Testing and Rig Development

The round-edged Davis model with at 20° rear slant angle was used for the first tests but it very quickly became apparent the experiment was not working as hoped. The carriage was coming to rest very quickly with no effect of the onset windspeed between 0 and 30m/s. At the higher tunnel speeds it was also apparent that by making the model as light weight as possible there had been a trade off in model stiffness and the model could be seen to be pitching and flexing about its mounting shaft. For fear of breaking the model, tunnel speeds used at this stage of testing did not go above 30m/s.

To improve the experiment it was decided to reduce the friction of the linear bearings and to increase the side force acting on the model. The side force was increased by enlarging the side area of the model by adding a back to the model to reduce the slant angle from 20° to 0°.

Reducing the friction of the bearings was more complex and took a number of iterations. The first change was to remove 2 of the bearings so that the carriage was held by bearings at two of the corners; this improved the situation but not enough. It was then found the carriage’s friction was inconsistent along the length of the rails. This appeared to be because the rails were not parallel along their length, this was corrected but the friction remained inconsistent. The straightness of the rails was checked and it was found they were very slightly curved and this was enough to interfere with the tolerances of the bearings. Using the straighter of the two rails for the bearing to run on, two PTFE pads were made in place of the bearings to run along the
other rail. This meant that one side of the carriage was floating and only constrained in the vertical plane. A further improvement was found by only using 1 linear bearing on the rail and using an ‘n’ shaped section of PTFE in place of the other. An attempt to replace all the bearings with PTFE sections was unsuccessful as this removed the reaction to pitch and roll moment and the model moved unacceptably when given a lateral excitation. Further friction reductions were achieved by removing the grease from the one remaining bearing and by coating the rails in WD40; PTFE spray and ‘3 in 1’ oil were also tried but WD40 worked best.

Using this improved test configuration with the squareback Davis model produced data that showed an aerodynamic effect. Figure A2.3 shows the model response at 0 and 30 m/s and was the first indication that there may be something worth investigating, with an increase in the motion damping at higher wind speeds.

![Figure A2.3, Model response](image)

Although there is clearly an effect of windspeed on the model response, it was felt that the differences in the model response at different windspeeds were too small to draw any good conclusions from.

To improve the results the forces expected to be acting on the model were given further consideration. The side forces expected to act on the model were small; an order of magnitude
smaller than the forces that would be produced by the extension of the springs initially used. A much lighter spring, with a stiffness of 20N/m, rather than 240N/m from the initial spring, was tried but did not work because the forces in the springs could not overcome the friction of the bearings.

With this approach not giving good results a different experimental method was tried. The model was mounted in the carriage at \(\approx 10^\circ\) yaw and only one spring, to oppose the side force created by the model, was used. The theory behind this was that by recording the spring extension the side force acting on the model could be recorded. The carriage was given an initial displacement and the model response was recorded but the method did not work for three reasons:

- The response of the model was jerky due to friction which caused the model to move in steps rather than a smooth motion.
- The model yaw angle was set by human judgement and was an unknown angle
- This method caused one of the linear bearings to break.

Because of these, this method was not investigated further and the testing returned to using the standard reciprocating method.

In order to increase the side force further a larger Davis model was found in storage. The larger model is about 50% bigger and details of the two models are given in Table 1 and they are shown in Figure A2.4.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
<th>Mass (kg)</th>
<th>Colour</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>625</td>
<td>225</td>
<td>160</td>
<td>2.7</td>
<td>Black</td>
</tr>
<tr>
<td>Large</td>
<td>905</td>
<td>320</td>
<td>230</td>
<td>1.9</td>
<td>Blue</td>
</tr>
</tbody>
</table>

Table 1, Model dimensions
The larger model was better than the smaller model in a number of ways. The larger size meant the forces acting on the model were larger, reducing the effect of the friction of the system and it was lighter so the reciprocating motion was less affected by the mass of the model. It was also stiffer that the smaller model, due to the solid Styrofoam construction, and could therefore be used in tunnel speeds of up to 40m/s. These three factors produced a much improved model response; the motion taking longer to damp away giving more usable data and more clearly showing the aerodynamic effects.

A2.4 Results

The results in this section aim to demonstrate an aerodynamic effect worthy of greater investigation by focusing on the motion frequency and damping rather than showing definitive results.

Using the best set up found during initial testing, including the bigger Davis model, the model response was recorded. Data were collected at tunnel speeds from 0 – 40 m/s in 10 m/s steps using three different springs with stiffnesses of 240 N/m, 450 N/m and 660 N/m. The frequency of the model response was found from the peak of a power spectral density of the data and the motion decay half life was found using linear interpolation.

The frequency of the model response under different test conditions is in Table 2 and plotted against reduced frequency in Figure A2.5. Table 2 shows that the model motion frequency is independent of the windspeed and Figure A2.5 shows that the same result applies to the reduced
frequency. This demonstrates the aerodynamic forces acting on the model do not change the stiffness of the system.

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 N/m</td>
<td>2.075</td>
<td>2.075</td>
<td>2.075</td>
<td>2.22</td>
<td>n/a</td>
</tr>
<tr>
<td>450 N/m</td>
<td>2.808</td>
<td>2.686</td>
<td>2.686</td>
<td>2.563</td>
<td>2.824</td>
</tr>
<tr>
<td>660 N/m</td>
<td>3.296</td>
<td>3.296</td>
<td>3.296</td>
<td>3.296</td>
<td>3.052</td>
</tr>
</tbody>
</table>

Table 2, Model response frequency, Hz

This is a different result than obtained from the oscillating model rig where the model motion frequency was very dependent upon the onset windspeed as the aerodynamic loads reduced the system stiffness. It also implies the analysis used by Mansor based on the change in the system stiffness is unsuitable for this experiment.

To investigate the damping of the model motion the times to half amplitude were found. These are shown in Table 3 and plotted against reduced frequency as shown in Figure A2.6.
<table>
<thead>
<tr>
<th>Windspeed (m/s)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>0.759</td>
<td>0.665</td>
<td>0.534</td>
<td>0.396</td>
<td>n/a</td>
</tr>
<tr>
<td>450</td>
<td>0.663</td>
<td>0.646</td>
<td>0.382</td>
<td>0.384</td>
<td>0.308</td>
</tr>
<tr>
<td>660</td>
<td>0.573</td>
<td>0.490</td>
<td>0.440</td>
<td>0.355</td>
<td>0.348</td>
</tr>
</tbody>
</table>

### Table 3, Model response time to half amplitude

<table>
<thead>
<tr>
<th>Spring Stiffness (N/m)</th>
<th>250N/m</th>
<th>450N/m</th>
<th>660N/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.759</td>
<td>0.663</td>
<td>0.573</td>
</tr>
<tr>
<td>10</td>
<td>0.665</td>
<td>0.646</td>
<td>0.490</td>
</tr>
<tr>
<td>20</td>
<td>0.534</td>
<td>0.382</td>
<td>0.440</td>
</tr>
<tr>
<td>30</td>
<td>0.396</td>
<td>0.384</td>
<td>0.355</td>
</tr>
<tr>
<td>40</td>
<td>n/a</td>
<td>0.308</td>
<td>0.348</td>
</tr>
</tbody>
</table>

**Figure A2.6, Model motion decay plotted against reduced frequency**

These results show trends towards a shorter time to half amplitude at lower reduced frequencies and these are grouped by the spring stiffness. Whether the results for each spring are tending towards a common value or are independent is unclear from the number of data points collected, but the data does indicate there is an effect worth further investigation.

However, extrapolating the general trends from the data it can be postulated that the results would start from (0, 0) and trend asymptotically towards the half life time found at 0m/s; shown by the dashed line. The results must start at (0, 0) because at higher windspeeds the damping increases and the reduced frequency reduces and ultimately this must lead to (0, 0). The results would asymptote towards the time to half amplitude at 0m/s because the reduced frequency at 0m/s is infinite.
A2.5 Conclusions and Further Work

Despite only having a very small set of usable results, the results do demonstrate this is an experiment that does show an aerodynamic effect and would be worthy of further investigation. Oscillating lateral motion rather than yawing motion has produced a dynamic system with stiffness independent of windspeed and reduced frequency where the damping is dependent upon reduced frequency.

Analysis of the equations of the model motion needs to be carried out to derive what aerodynamic effect is causing the changes to the system damping and how to calculate any forces from the model response. Although the mechanics that drive this are not currently known, it seems intuitive that by combining the findings from the yawing and laterally oscillating model rigs it may be possible to gain greater understanding than from looking at each set of results independently.

To improve the test method, more effort should be given to reducing the friction of the system so that the aerodynamic effects can be more clearly seen. Particular attention should be given to the bearings and the use of a laser based displacement measuring device would be very beneficial.
Appendix 3. Round Edged Model

<table>
<thead>
<tr>
<th>Yaw Angle</th>
<th>Static</th>
<th>Oscillating</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td><img src="image" alt="Static 0°" /></td>
<td><img src="image" alt="Oscillating 0°" /></td>
</tr>
<tr>
<td>1°</td>
<td><img src="image" alt="Static 1°" /></td>
<td><img src="image" alt="Oscillating 1°" /></td>
</tr>
<tr>
<td>2°</td>
<td><img src="image" alt="Static 2°" /></td>
<td><img src="image" alt="Oscillating 2°" /></td>
</tr>
<tr>
<td>3°</td>
<td><img src="image" alt="Static 3°" /></td>
<td><img src="image" alt="Oscillating 3°" /></td>
</tr>
<tr>
<td>4°</td>
<td><img src="image" alt="Static 4°" /></td>
<td><img src="image" alt="Oscillating 4°" /></td>
</tr>
<tr>
<td>5°</td>
<td><img src="image" alt="Static 5°" /></td>
<td><img src="image" alt="Oscillating 5°" /></td>
</tr>
<tr>
<td>6°</td>
<td><img src="image" alt="Static 6°" /></td>
<td><img src="image" alt="Oscillating 6°" /></td>
</tr>
<tr>
<td>7°</td>
<td><img src="image" alt="Static 7°" /></td>
<td><img src="image" alt="Oscillating 7°" /></td>
</tr>
<tr>
<td>8°</td>
<td><img src="image" alt="Static 8°" /></td>
<td><img src="image" alt="Oscillating 8°" /></td>
</tr>
<tr>
<td>9°</td>
<td><img src="image" alt="Static 9°" /></td>
<td><img src="image" alt="Oscillating 9°" /></td>
</tr>
<tr>
<td>10°</td>
<td><img src="image" alt="Static 10°" /></td>
<td><img src="image" alt="Oscillating 10°" /></td>
</tr>
</tbody>
</table>
Appendix 4. Square Edged Model

<table>
<thead>
<tr>
<th>Ya Angle</th>
<th>Static</th>
<th>Oscillating</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td><img src="image" alt="Static 0°" /></td>
<td><img src="image" alt="Oscillating 0°" /></td>
</tr>
<tr>
<td>1°</td>
<td><img src="image" alt="Static 1°" /></td>
<td><img src="image" alt="Oscillating 1°" /></td>
</tr>
<tr>
<td>2°</td>
<td><img src="image" alt="Static 2°" /></td>
<td><img src="image" alt="Oscillating 2°" /></td>
</tr>
<tr>
<td>3°</td>
<td><img src="image" alt="Static 3°" /></td>
<td><img src="image" alt="Oscillating 3°" /></td>
</tr>
<tr>
<td>4°</td>
<td><img src="image" alt="Static 4°" /></td>
<td><img src="image" alt="Oscillating 4°" /></td>
</tr>
<tr>
<td>5°</td>
<td><img src="image" alt="Static 5°" /></td>
<td><img src="image" alt="Oscillating 5°" /></td>
</tr>
<tr>
<td>6°</td>
<td><img src="image" alt="Static 6°" /></td>
<td><img src="image" alt="Oscillating 6°" /></td>
</tr>
<tr>
<td>7°</td>
<td><img src="image" alt="Static 7°" /></td>
<td><img src="image" alt="Oscillating 7°" /></td>
</tr>
<tr>
<td>8°</td>
<td><img src="image" alt="Static 8°" /></td>
<td><img src="image" alt="Oscillating 8°" /></td>
</tr>
<tr>
<td>9°</td>
<td><img src="image" alt="Static 9°" /></td>
<td><img src="image" alt="Oscillating 9°" /></td>
</tr>
</tbody>
</table>