

Cranfield University
College of Aeronautics
Department of Aerospace Science

PhD Thesis
1994

Robert Stuart Cairns

**Lateral Aerodynamic Characteristics of
Motor Vehicles in Transient Crosswinds**

Project Supervisor Dr. Kevin P. Garry

July 1994

This thesis is submitted in fulfilment of the
requirements for the Degree of Doctor of Philosophy

Abstract

Motor car crosswind stability can be adversely affected by reductions in both vehicle mass and drag coefficient. As these are two likely results of future developments the importance of research into vehicle aerodynamic stability is set to increase, moreover, there is evidence that transient effects will be the critical. An experimental facility has been designed and constructed and tests have been carried out to investigate the implications of simulating dynamic flowfields. Vehicle models of approximately 1/6th scale have been propelled along a test track, in the laboratory, to pass through a simulated crosswind gust of variable resultant yaw angle. Force and moment measurements have shown the aerodynamic inputs to be highly repeatable, though the technique has been restricted somewhat by the presence of mechanical "noise".

Additional dynamic yaw experiments were conducted on a bluff-body model mounted in the College of Aeronautics' Oscillatory Facility. In some ways this technique is not as realistic as the Crosswind Track in its simulation of the full scale flow, however, despite its simplicity valuable aerodynamic data was derived from this test.

Quasi-static tests have also been conducted and demonstrate that for certain model configurations a clearly defined yaw angle range exists where two different wake flow-structures are possible. At any given yaw angle, the dominant structure is determined by the flowfield history - essentially the direction in which the model is moved. This causes hysteresis in the forces and moments generated. In such a situation the flow is referred to as being bi-stable.

Both track and dynamic yaw tests indicate that the bi-stable flow phenomenon, witnessed in quasi-static experiments, can influence the dynamic forces and moments measured on a model. The flow structures associated with bi-stability are viscous-dominated and the slow development of viscous loads can be an important feature. It is possible that various vehicle configurations could induce bi-stable flow. If such flow behaviour is apparent then quasi-static forces and moment measurements will not provide an adequate engineering estimate of the transient aerodynamic loads. In this event it is imperative that the automotive engineer conducts investigations into the vehicle's dynamic performance.

Acknowledgements

Without the help and support of several people, the completion of this work would not have been possible.

First I would like to thank my supervisor Dr. Kevin Garry who during the course of research set, by example, an extremely high standard of work. Apparently able to undertake the work of (at least) three supervisors I have long had my suspicions that he is really Clark Kent. In reality Kevin works all the hours that God sends and for this reason I forgive him for not having time to go out for a beverage.

I am extremely grateful to the other collaborators of this SERC funded project and, in particular, to Dr. Jeff Howell.

I owe a huge debt to the Cranfield workshop staff for help in design and manufacture of the crosswind track facility, together with models, carriages and balance, also with repair of same after various catastrophic (and shattering) equipment failures.

I would like to thank Holger Babinsky for the use of both his equipment and expertise which made possible the high speed filming of the crosswind track in action.

Finally I am deeply grateful to my parents and my wife for financial and moral support during this "magnum opus".

Contents

Abstract
Acknowledgements
Contents
List of Abbreviations
Notation

	Page
1. INTRODUCTION	
1.1 The Importance of Transient Aerodynamics	1
1.2 Aims of the Research	2
2. LITERATURE REVIEW	
2.1 The Nature of the Problem	3
2.2 Methods of Testing Vehicles for Crosswind Stability and Related Work to Date	6
2.3 Theoretical Methods	17
2.4 Summary	19
3. TEST FACILITIES	
3.1 Introduction	21
3.2 The Design of the Crosswind-Track Test Facility	23
3.3 The Oscillatory Facility	30
3.4 Quasi-Static Tests	32
4. QUASI-STATIC AERODYNAMICS	
4.1 Introduction	33
4.2 Flow Visualization Studies	33
4.3 Force and Moment Measurements	38
4.4 Discussion	43

5. CROSSWIND-TRACK TESTS	
5.1 Introduction	44
5.2 Development of the Facility	44
5.3 Characteristics of the Track Facility	47
5.4 Track Results	53
5.5 Discussion	55
6. DYNAMIC YAW TESTS	
6.1 Introduction	56
6.2 Development of the Facility	56
6.3 Characteristics of the Oscillatory Facility	57
6.4 Test Results	60
6.5 Discussion	64
7. CONCLUSIONS	65
8. RECOMMENDATIONS FOR FURTHER WORK	67
REFERENCES	69
APPENDICES	
APPENDIX A Flow Characteristics of the Boundary Layer Wind Tunnel	73
APPENDIX B Data Acquisition and Processing	75
B1 Quasi-Static Tests	75
B2 Track Tests	77
B3 Dynamic Yaw Tests	80
APPENDIX C Special Software	82
C1 Standard Packages	82
C2 CoA Software Developments	83
C3 Software Written by the Author	84
APPENDIX D Additional Dynamic Test Results	85
D1 Track Tests	85
D2 Dynamic Yaw Tests	86
FIGURES	

List of Abbreviations

A/D	Analogue to Digital
APT	Advanced Passenger Train
ASCII	American Standard Code for Information Interchange
BASIC	Beginners All-purpose Symbolic Instruction Code
BR	British Rail
BLWT	Boundary Layer Wind Tunnel
CoA	College of Aeronautics
DOS	Disk Operating System
FIR	Finite Impulse Response
GPIO	General Purpose Interface Bus
HGV	Heavy Goods Vehicle
IEEE	Institute of Electrical and Electronic Engineers
JARI	Japanese Automobile Research Institute
JSAE	Japanese Society of Automotive Engineers
LED	Light Emitting Diode
MIRA	Motor Industry Research Association
MRC	Moment Reference Centre
PC	Personal Computer
PTFE	Polytetrafluorethylene
RAM	Random Access Memory
SAE	Society of Automotive Engineers
SERC	Science and Engineering Research Council

Notation

A	reference area (m ²)
C	duplex tunnel area (m ²)
C _D	drag coefficient
C _L	lift coefficient
C _M	pitching moment coefficient
C _N	yawing moment coefficient
C _R	rolling moment coefficient
C _Y	sideforce coefficient
D	drag (N)
L	lift (N)
M	pitching moment (Nm)
N	yawing moment (Nm)
R	rolling moment (Nm)
Re	Reynolds number
S	model plus mirror image frontal area (m ²)
U	local flow velocity (m/s)
U _∞	freestream or resultant flow velocity (m/s)
U _F	flow velocity due to vehicle forward speed (m/s)
U _L	resultant local flow velocity (m/s)
U _R	local flow velocity due to model rotation (m/s)
U _W	flow velocity due to ambient wind (m/s)
X	distance from gust entry (m)
X _{DYN}	peak-to-peak dynamic signal
X _{QS}	change in quasi-static signal
Y	sideforce (N)
α	aerofoil angle of incidence (°)
β	yaw angle (°)
ΔC _N	difference between dynamic and quasi-static yawing moment coefficient at a given yaw angle
ω	angular velocity (rad/s)

a	intersection of line with y-axis
b	slope of line
c	chord length of aerofoil (m)
f	frequency of oscillation (Hz)
k	reduced frequency ($\omega c/2U_\infty$)
l	vehicle length (m)
n	Number of samples
q	freestream dynamic pressure (Pa)
q_c	dynamic pressure corrected for blockage (Pa)
t	time (s)
w	reference length (m)
x	sample mean

Chapter 1

Introduction

The work detailed in this thesis is concerned with the assessment of transient crosswind effects on simplified models of passenger cars. A primary objective was to establish at Cranfield University (then the Institute of Technology) an experimental rig to measure the aerodynamic forces and moments on model cars propelled across a simulated crosswind gust. The research was part of a collaborative project between two SERC Research Grant Programmes. Amongst the participants were Cranfield University, Rover Group, the University of Nottingham and British Rail.

1.1 The Importance of Transient Aerodynamics

Static tests demonstrate that, with regard to lateral forces and moments, most vehicles are aerodynamically unstable, however, it must be noted that the lateral stability of a vehicle subjected to a crosswind is not dependent upon aerodynamic forces alone. The vehicle's centre of gravity position and neutral steer point (the centre of tyre forces) both have a strong influence upon overall crosswind performance. It is quite possible for an aerodynamically sensitive design to be made acceptable to the driver by incorporating a forward centre of gravity position and a neutral steer point close to the aerodynamic centre (achieved by adjusting the cornering stiffness of the tyres), though this in no way precludes aerodynamic research as an important part in achieving satisfactory vehicle crosswind performance. Ideally all aspects of vehicle dynamics should be fine tuned for optimum lateral stability characteristics.

Over the last decade, a greater emphasis has been placed upon reducing the aerodynamic drag of motor cars; a move driven largely by the desire to reduce fuel consumption. Unfortunately, low drag configurations often exhibit poor lateral aerodynamic characteristics, particularly when travelling at high speed. It is probable that future developments will also see a reduction in vehicle mass and hence a corresponding decrease in the vehicle's ability to safely react any aerodynamic inputs. Wind tunnel testing of models will remain an important part of vehicle development though there is some doubt as to whether conventional techniques alone will be adequate to assess all the

implications of vehicle aerodynamics.

The aerodynamic forces and moments that act upon any motor vehicle in motion are due to the combined effects of vehicle forward speed and atmospheric wind. It is obvious that the atmospheric environment is subject to frequent variations, which in turn are likely to create changes in the vehicle's flowfield structure. Research conducted on cars through use of conventional wind tunnel equipment will usually produce information on only "quasi-static" forces and moments, however, from the relatively small amount of dynamic tests undertaken to date it is apparent that transient aerodynamic characteristics can be strongly detrimental to vehicle stability.

1.2 Aims of the Research

The object of this work was to undertake an investigation of transient lateral aerodynamic effects on ground vehicles, with particular emphasis being placed upon the relatively small yaw angles ($\leq 30^\circ$) that correspond to flow conditions likely to be encountered whilst travelling at high speed along a motorway. The following two non-standard wind tunnel techniques were employed:

1) A test track facility was constructed and subsequently commissioned to assess the effects of an impulsive crosswind gust. Measurements were made of the aerodynamic forces and moments acting on vehicle models as they were propelled along the track and encountered a gust simulated by the Boundary Layer Wind Tunnel (BLWT).

2) The College of Aeronautics' "Oscillatory Facility" (see Garry and Cooper, 1986, ref.19) was used to conduct dynamic yaw experiments. During these tests models were fixed to a turn-table in the working section of the 0.91 x 0.91 m wind tunnel. With the tunnel running the turntable was moved at various rates, over stipulated yaw angle ranges, while force and moment measurements were made.

In addition to dynamic testing, quasi-static experiments were conducted for comparison. These involved both force and moment measurements and flow visualization studies.

Chapter 2

Literature Review

2.1. The Nature of the Problem

It is widely known that the aerodynamic stability of ground vehicles (including cars, commercial vehicles and trains) can be adversely affected by the presence of a crosswind.

The poor crosswind handling of one production model led directly to an accident where the passenger was killed. This example is used by Jacobson 1985 (ref.1) to illustrate how critical vehicle crosswind performance can be. Jacobson concludes that some manufacturers allow such poor designs to be produced partly because they are proven in regions where the prevailing wind speeds are much lower than the extreme cases that the model is likely to encounter.

To support this idea, Figure 2.1, reproduced from Bitzl, 1961 (ref.2) gives the frequency of strong winds in various parts of Germany. In such areas as the Dutch coast, wind speeds are likely to be twenty five percent greater than in Northern Germany. The geography of the UK has forced roads to be aligned so that crosswinds often constitute a large problem. Average wind speeds of between 45 and 55 m.p.h. (20.1-24.6 m/s) and of at least one or two hours duration have been recorded near Nottingham (Jacobson, 1985 ref.1).

There is a trend in the automotive industry towards low-drag configurations and it is probable that the future will also see a general reduction in vehicle weight. These two factors can contribute to handling problems at exposed sites during windy periods and as a direct consequence of this, motor manufacturers are now more concerned about the crosswind stability of their vehicles.

It is usual to establish the crosswind aerodynamic loads of a vehicle by testing a scale model in a wind tunnel. The model is aligned at an angle of yaw

(β) to the freestream flow in order to simulate the situation that a full scale car would experience when driven in a crosswind (see figure 2.2).

The way in which steady state crosswind instability arises was demonstrated by Barth, 1960 (ref.3) who analysed pressure distribution about a scale model vehicle. Typical surface static pressures (at two horizontal levels) around a car subjected to a 20 degree steady crosswind are depicted in figure 2.3. From this it is clear that aerodynamic sideforce results from a pressure differential between the vehicle's windward and leeward sides. On the leeward side considerable negative pressure stems from high local velocities at the leading edge. On the windward side a small positive pressure exists up to approximately the midpoint of the wheelbase. Over the rear half of the vehicle, steadily increasing negative pressure is observed. The pressures acting on the body lead to a sideforce directed leeward and to a yawing moment which generally acts to turn the vehicle's nose away from the crosswind. The term "adverse yaw" is sometimes used to describe the action of the yawing moment. This alludes to the fact that cars are usually statically unstable in yaw. Variations of both steady state yawing moment and sideforce, with respect to crosswind angle, have a linear relationship over small values of β . When the relative crosswind angle is increased so that the flow is fully separated at the leeward front wing, then the sideforce is reduced and so too is the yawing moment. This is analogous to the behaviour of an aerofoil at high incidence, where the stall leads to loss of lift and a small pitching moment.

In the interests of steady state crosswind stability it is advantageous to incorporate separated flow at the leeward corner of the vehicle. Unfortunately, the drag penalty incurred from such a flow is generally unacceptable to the vehicle designer. One solution may be to employ a front end device which causes flow separation at crosswind angles greater than approximately 10 degrees. This would preserve low drag characteristics at small yaw angles and also limit the suction peak at larger values of β . Figure 2.4, from Hucho, 1981 (ref.4) shows two ideas for the front planform of a car, designed to induce leeward separation at large yaw angles.

Conventional static wind tunnel testing permits investigation of steady state aerodynamic stability, that is, vehicles travelling at constant velocity

subjected to a constant crosswind. However, this type of wind tunnel testing does not indicate the importance of the following:

- (i) Road/vehicle relative motion
- (ii) The twisted resultant flow produced by the effects of shear in a natural crosswind (see figure 2.5 for an illustration of this)
- (iii) The transient nature of the wind caused by such things as overtaking situations, the topography of surrounding land and atmospheric gusts.

Smith, 1972 (ref.9) carried out full scale tests to determine the general properties of atmospheric crosswinds. A car was equipped with specially calibrated anemometers and other instrumentation to allow the lateral and longitudinal components of the relative wind velocity to be recorded continuously while the car was driven on public roads. It was found that the form of most gusts depends upon the topography (both natural and man-made) adjacent to the road. An example of a wind-gust profile for a cutting is given in figure 2.6. It is interesting to note for such a land feature the lateral wind speed can actually reverse direction.

The limited number of dynamic tests carried out to date demonstrate that transient effects may be considerable. Investigations conducted by Beauvais, 1967 (ref.6) show that dynamic sideforce and yawing moment coefficients may initially exceed static values. Although the dynamic inputs eventually return to the expected steady state condition, the initial "overshoot" characteristic is clearly detrimental to vehicle aerodynamic stability. To investigate the detrimental effects of transient crosswinds it was decided to construct a model test track facility at Cranfield University. A full account of this facility is given in chapter three.

To continue this literature survey, the following section considers the various techniques (both static and dynamic) that have been employed to assess the aerodynamic stability of vehicles.

2.2 Methods of Testing Vehicles for Crosswind Stability and Related Work to date

Three different approaches are considered within this section. These are as follows:

- 2.2.1. Scale model static wind tunnel tests
- 2.2.2. Scale model dynamic wind tunnel tests
- 2.2.3. Full scale tests

For the purposes of this thesis static testing will be taken to include those tests in which the model is positioned in the wind tunnel at a constant yaw angle, (whether a moving ground plane is used or not). In contrast, dynamic tests seek to simulate the transient nature of crosswinds by various moving model, or displaced flow techniques. In the following each method is considered in turn.

2.2.1. Static Wind Tunnel Testing of Model Vehicles

It has been apparent for some time that certain styling features can cause considerable instability in crosswinds. Consequently, static wind tunnel testing of model vehicles has been taking place for several decades.

A variety of model car shapes were tested by Barth, 1960 (ref.3), at yaw in the 1.5 x 1 metre tunnel at the Vehicle and Engine Research Institute, Stuttgart. One of the aims of Barth's work was to obtain data which could be taken into account during the early stages of car body design. The report demonstrates that Barth understood how significant the adverse yawing moment was with regard to vehicle crosswind stability.

Tests were conducted using 3/8 scale models in the wind tunnel by Tustin and Carr, 1963 (ref.7), on behalf of the Ford motor company, in order to determine the aerodynamic effects of certain modifications to the basic form of a small passenger vehicle. A summary of their findings is as follows:

- i) A steeply sloping fastback gave a greater adverse yawing moment.
- ii) The side forces and yawing moments were strongly influenced by the position of the "canopy" (that is, the glazed area of the passenger compartment) and the rear most location, which corresponded to a van or estate car, produced the best characteristics.
- iii) Vertical stabilizing fins were found to be an effective means of reducing the adverse yawing moments common to most cars but are somewhat impractical due to their necessary size.
- iv) A reverse angle rear window (reminiscent of the Ford Anglia) produces less lift and slightly smaller yawing moments.

More than twenty years later Gilhaus and Renn, 1986 (ref.8) also tested 3/8 scale basic car shapes, in the Ford wind tunnel at Koln. The models were of modular construction and their work details how certain styling practices can reduce vehicle crosswind stability. It is concluded that optimising the forebody for low drag does not have such a detrimental effect on stability as optimising the rear-body for low drag. This stems from the fact that many fundamental styling changes aimed at reducing drag also cause sideforce reduction in the presence of a crosswind. A smaller front sideforce will aid vehicle stability by reducing the adverse yawing moment while a smaller rear sideforce will be detrimental to vehicle stability because it will tend to increase the adverse yawing moment.

Some of the crosswind characteristics discovered by Gilhaus and Renn are as follows:

- i) By rounding the front vertical edges of the wings a low static pressure zone is encouraged on the leeward side of the car leading to an increase in the adverse yawing moment.
- ii) If a low bonnet with rounded edges and a raked back windscreen are incorporated into a design then the frontal sideforce and hence the yawing moment are reduced due to the smaller projected side area.
- iii) Body tapering towards the roof reduces the total sideforce on the car, while plan view tapering towards the rear (known as boat tailing) reduces only the rear sideforce and hence increases the yawing moment.

When Gilhaus and Renn consider the effect that rear body styling has on steady state crosswind stability their findings are contrary to those of Emmelmann, 1981 (ref.10) and Kohri and Kataoka, 1989 (ref.11). Gilhaus and Renn state that a smaller projected rear side area reduces the rear side-force and hence increases the adverse yawing moment. This is perhaps a little misleading as it leads one to conclude that the notch-back, with its relatively small rear side area, suffers from the highest yawing moment. In contrast, the three references mentioned above all list the fast-back configuration as possessing the greatest yawing moment and smallest side force. The general hierarchy of the sideforce and yawing moment curves for different vehicle configurations is illustrated in figure 2.7.

These findings suggest that projected side area is not a dominant factor in determining the magnitude of the yawing moment, indeed, Kohri and Kataoka, 1989 (ref.11) state that there is virtually no correlation between rear side area (i.e. the projected side aft of the centre of the wheel-base) and yawing moment coefficient (C_N).

Kohri's tests were performed on 1/5th scale model cars held at yaw to the freestream flow in the Mitsubishi Motor Corporation's small scale wind tunnel. Force and surface static pressure measurements were recorded together with surface flow visualization in order to examine the aerodynamic properties of each model configuration in steady crosswinds. The models were once again of modular construction, providing greater variety in the shapes under test. The authors findings can be summarized as follows:

- i) For a car subjected to a steady crosswind there usually exists a corner vortex, that is, a three dimensional separation pattern appears downstream of the "C"-pillar (as shown in figure 2.8). When the magnitude of this vortex grows the pressure in the region immediately upstream of the "C" pillar decreases due to the local flow accelerations induced.
- ii) As the slope of the notch back's rear window is brought closer to that of the fastback, the area influenced by the vortex is increased resulting in an even greater yawing moment (see figure 2.9).
- iii) The radius of the "C"-pillar is often increased in an attempt to reduce the vehicle's overall drag. Unfortunately this also reduces the pressure at

the windward "C"-pillar and thereby increases the yawing moment.

iv) Only with the estate type configuration is the rear side area a dominant factor. The small positive pressure on the rear of this configuration tends to reduce the yawing moment.

Wind tunnel tests on 1/4 scale models cars are described by Davis, 1987 (ref.12). The models were evaluated for steady crosswind stability in the 4.5 ft. x 4 ft. (1.2m x 1.4 m) wind tunnel at Imperial College, London. This facility has a moving ground plane that can be aligned at an angle of yaw to the free stream flow. Unfortunately, due to technical problems, Davis was unable to undertake lateral force and moment measurements, however, he discovered that the presence of rotating wheels considerably alters the flow around the model. For the type of sports car tested a moving ground plane did not appear to have a significant effect on the measured forces. However, when the model's wheels were rotated (by making contact with the moving ground) there were considerable differences in the measured forces and large changes in the surface static pressure distribution. With the wheels rotating there is no net change in lift when the model is yawed but there is a considerable shift in the lift force towards the front. Davis states that this forward shift "will result in an unstable feel to the car". His use of the word "feel" in this context is subtle, yet important. By it he is predicting a drivers qualitative assessment of such a vehicle. In reality a forward shift of the lift force increases stability and reduces steering response.

2.2.2. Dynamic Wind Tunnel Testing of Model Vehicles

One method of dynamic crosswind testing involves propelling models along a track mounted orthogonally to a wind tunnel/ crosswind generator. Beauvais, 1967 (ref.6) employed this approach in research for the Ford Motor Company, using the University of Michigan's 5 ft. x 7 ft. (1.5m x 2.1m) low speed wind tunnel. It was discovered that, when compared with steady state tests, the moving model experiments demonstrated larger yawing moments as the car entered the simulated gust. After travelling approximately three car lengths, the forces and moments experienced by the model correlated well with the steady state tests.

The crosswind test track of Brown, 1973 (ref.13) was a larger and more sophisticated system than that used by Beauvais. It not only incorporated a crosswind generator but also included twin adjustable parallel tracks so that the effects of vehicle spacing in various passing situations could be analysed. The presence of a crosswind proved to be a significant feature in simulated overtaking situations. Brown discovered that the wake of a vehicle would extend downstream at approximately the same angle as the relative wind. Other vehicles disturbed by this wake tended to experience lower sideforce results, compared to the nil crosswind case.

At the Japanese Automobile Research Institute (JARI) Yoshida, 1977 (ref.14) used a crosswind test track to investigate the forces experienced by a vehicle/trailer combination while traversing a simulated crosswind gust. Not surprisingly it was found that forces acting upon this configuration were different to those acting upon the vehicle alone. It was concluded that the airflow around the tractor (towing vehicle) was greatly influenced by the body of the trailer. In his tests Yoshida also experimented with the track aligned at various yaw angles, relative to the crosswind generator. It was found that the same results could be obtained by fixing the track perpendicular to the crosswind generator and varying the relative vehicle/ crosswind speeds to produce the desired crosswind angle. Yoshida suggests that transient effects of wind gusts appear to indicate front body shape is still an important consideration when designing a vehicle with good crosswind stability.

Moving model tests were conducted by Stewart, 1977 (ref.15) using a crosswind test track which was developed at the Motor Industry Research Association (M.I.R.A.). Car and commercial vehicle models of 1/4 and 1/10th scale, respectively, were tested through simulated gusts of varying horizontal and vertical profiles. Accurate boundary layer simulation was impossible with the scale of models used (turbulence scale was estimated at between 1/50 and 1/80 of that occurring in natural gusts). Results are presented for the transient side force, yawing moment, lift force, pitching moment and rolling moment recorded as the models traverse the crosswind simulator. However, passenger car handling investigations would benefit from relative crosswind angles less than the approximate value of 30 degrees used by Stewart. Errors were also encountered, due to the inertia effects of the models. The first car models designed for use on Stewart's track weighed 5.5 kg (including balance support

structure). This was subsequently reduced to 1.6 kg by adopting model aircraft construction techniques. However, the natural frequencies of the models were still in a band around the "cut-off" filter frequency and therefore inertia effects were still present in varying degrees.

Howell, 1983 (ref.16) developed a crosswind test track at Warwick University in order to investigate the aerodynamic forces and moments experienced by models of contactless-suspension high speed trains. It was found that the side force due to the gust developed quickly, with the majority of the peak load achieved within a gust whose width was 80 % of the model length. The lift force took considerably longer to develop. In terms of steady state stability, results obtained by holding the train model at yaw to the free stream flow were seen to be conservative. In both the values of side force and lift, static tunnel results were greater than those obtained in the gust.

Tests on Advanced Passenger Train (A.P.T.) models are reported by Baker, 1986 (ref.17). A 1/50th scale model was propelled across a wind tunnel in which an atmospheric boundary layer had been simulated and the aerodynamic forces and moments were recorded. The force and moment coefficients were seen to rise within 1.5 carriage lengths from the edge of the gust. In a similar way to Howell, 1983 (ref.15), the results for the side force coefficient were compared with values measured in static low turbulence experiments and were observed to be well below the latter values. There were differences in the results obtained with level ground and embankment situations and the use of shielding devices referred to as "wind fences" substantially reduce the force and moment coefficients.

A moving model rig for testing aerodynamic effects on trains is also employed by British Rail Research at Derby. The facility consists of three straight 150m long tracks and is designed to accommodate trains at 1/25th scale. The trains are catapulted down the track at speeds of up to 125 mph (56 m/s) and the test section incorporates a simple crosswind generator. Investigations conducted by BR have included an analysis of slipstream airflows in the presence of a crosswind. The research concluded that a crosswind can significantly increase the peak air velocities within the slipstream.

Kobayashi and Yamada, 1988 (ref.18) identified "one box" type vehicles such as the Toyota Space Cruiser as being particularly susceptible to a loss of stability when entering a region of crosswind. A 1/10th scale "one box" type model was tested on a track, in conjunction with a crosswind generator. Flow visualization and a measurement of the pressure distributions was undertaken in order to establish the cause of the phenomenon. Forces and moments were also measured, although only a resultant crosswind angle of 30 degrees was considered. Results indicated that the yawing moment attains a peak value when the vehicle is 1.3 times its own length into the crosswind region ($X/l=1.3$). After this the yawing moment decreases and becomes constant at about $X/l=4.0$. The cause of the yawing moment peak is identified as being the negative pressure resulting from a vortex occurring on the lee side immediately aft of the front end. This peak was reduced by modification of the vehicle shape, particularly by raking back the windscreen.

The crosswind track facility is only one approach to testing model vehicles for transient aerodynamic effects. Another method was employed Garry and Cooper, 1986 (ref.19) who tested simple commercial type models by taking force and moment measurements while the models were rotating about their vertical centre line axis in smooth, uniform flow. This was designed to simulate a constantly changing incident flow and the results were compared with more conventional wind tunnel tests, where the model is held at several fixed yaw angles and measurements taken for each position. It was observed that the magnitude of drag and yawing moment coefficients did not change considerably (when data from the two methods is compared), even at rotational speeds as high as 64 degrees per second. However the dynamic coefficient versus yaw angle curves are displaced relative to the yaw axis. The magnitude and sign of this "phase shift" are dependent on both yaw rate and model geometry and can be observed at rotational rates as low as 0.25 degrees per second.

The rotating model technique, however, does not accurately simulate a gust caused by topographical features as Watkins 1992 (ref.29) illustrates. Due to the effect of model rotation superimposed upon a freestream flow, local yaw angle varies along the length of the model. This variation in fact simulates the impossible situation where a vehicle exits a tunnel (for instance) into a crosswind and the rear of the vehicle "sees" the disturbance first. Watkins

suggests that one solution is to consider rotation and translation of the vehicle via a force balance platform that can be moved accordingly in the tunnel.

An innovative method for dynamic crosswind testing of vehicle models was employed by Dominy 1991 (ref.30). A 1/10th scale car was mounted in a conventional open section wind tunnel. Gusts were produced by flow ducted from a plenum and controlled by means of a shutter. Though the research was limited in scope (forming the basis of an undergraduate project) a strong case is put forward for the benefits of the technique as follows:

- i) A standard wind tunnel facility and instrumentation can be used.
- ii) It is possible to simulate certain aspects of the atmospheric boundary layer.
- iii) A standard rolling road technique can be incorporated.
- vi) Risk of "mechanical noise" is reduced when compared with moving model techniques.

Dominy was able to demonstrate the test method to be successful at measuring transient sideforce and yawing moment, however, during the course of research the following problems were encountered.

- i) In order to simulate correctly the "jet" effect of a gust between two buildings the shutter needs to move at the same velocity as the main wind tunnel flow. In practise this was not achieved and so the simulation was more closely related to a gust between two slow moving lorries.
- ii) The model support and shutter mechanism used the same mounting frame hence mechanical "noise" was induced as the shutter moved.
- iii) Non-zero results for C_N and C_Y were experienced at zero degrees yaw due to the asymmetric blockage produced by the shutter.

These problems are peculiar to the test programme detailed and could be rectified with further development. A more fundamental limitation of the technique is the fact that flow separations corresponding to a gust emerging from between two buildings are not accurately modelled. The blockage presented by the shutter encourages axial flows that alter the nature of any flow separation. Dominy somewhat improved this situation by employing a dummy wall fixed to the shutter.

A relatively simple approach to crosswind testing was employed by Mullarkey, 1990 (ref. 31) who used a fixed model and a pair of oscillating aerofoils to produce a sinusoidal transverse gust superimposed upon mean wind tunnel flow. Gust wavelengths of 2 to 20 model lengths and peak angles (β) of $\pm 8^\circ$ were investigated. Though simple, the test technique again has certain deficiencies, principally:

- a) the generation of non-uniform flows and
- b) transient aerodynamic effects associated with the motion of the vanes.

Dynamic sideforce and yawing moment admittance functions were calculated by Mullarkey to compare transient and static results for the same model configuration; an aerodynamic admittance of unity corresponding to steady state behaviour. Even at the longer gust wavelengths the aerodynamic admittance function did not tend to unity and Mullarkey concluded that there was probably insufficient time for the dynamic flows to establish the quasi-static state. The fact that static forces and moments were slightly greater than dynamic values is used by Mullarkey to put forward the argument that steady state results are a reasonable engineering estimate of unsteady lateral forces.

Although not directly related to the crosswind performance of vehicles Kobayashi and Sasaki, 1987 (ref.5) investigated the transient aerodynamic effects of an overtaking H.G.V. upon a car/trailer combination. Since the relative velocity between the models is small, a simple traversing mechanism was used to move an H.G.V. model past a car/trailer model over a ground board in an open section wind tunnel. Kobayashi found that the flow displaced by a truck can create large yawing moments on any other vehicle overtaking it, or being overtaken by it. From the results of the work simple add-on aerodynamic devices were devised to stabilize the combination when under the influence of airflow around an H.G.V.

2.2.3. Full Scale Testing

The reason for employing full-scale tests is outlined by Watkins et al, 1984 (ref.20). Although measurements conducted on models in the wind tunnel produce a clear picture of the aerodynamic performance ranking of various vehicle configurations it is not always possible to translate these results directly

to the full scale case, (due mainly to the effects of wind turbulence). Watkins concludes that the obvious solution is to conduct full scale experiments, guided by the findings of model tests.

In order to obtain information on how vehicle body shape affects the aerodynamic disturbances experienced from a crosswind, Takanami, 1976 (ref.21) developed test equipment to measure aerodynamic yawing moment and side force on a full scale body. The facility was driven in front of a crosswind generator while the values of aerodynamic yawing moment, side force and crosswind vector were recorded. Both transient and steady state aerodynamics were considered. The problems inherent in this approach are outlined as follows:

- i) "Noise" can be generated from the road surface.
- ii) Atmospheric wind can influence the results.
- iii) Data may be affected by the motion of the test rig.

However, Takanami was able to show that his theoretical methods for predicting aerodynamic disturbances and the results from the full scale tests gave similar findings.

Both Yoshida, 1977 (ref.14) and Kobayashi, 1988 (ref.18) used full scale test results to compare with data from the moving model experiments (previously described in section 2.2.) It was found that moving model tests and full scale tests gave similar results for the side force measured, however, the yawing moment results were different because there was a change of the yaw angle in the full scale case. This occurred at the moment of penetration into the crosswind. The effect was not apparent in model experiments because the cars in this case were restricted in their movement by the track.

In his moving model work (as described in section 2.2.2) Kobayashi, 1988 (ref.18) reached the conclusion that the adverse yawing moment on a "one box" type vehicle could be reduced by "raking back" the vehicle's wind screen. In order to verify this, full scale tests were conducted where the angle of inclination of the wind screen was altered and the yaw rate was measured while the vehicle passed in front of a crosswind generator 45m long. It was found that as the angle of windscreen inclination was brought nearer to the horizontal both

the change in yaw rate ($\partial C_N / \partial \beta$) and yaw rate peak are reduced, thereby endorsing the moving model tests.

Extensive full scale tests have been undertaken by van den Hemel et al, 1990 (ref.22) at Volvo BV in Holland. Eight configurations of road going cars were tested, incorporating differences in weight, suspension and aerodynamics. Objective measurements and subjective ratings made in natural and artificial crosswinds and were found to correlate reasonably well. Van den Hemel concludes that future research in this field should concentrate on the pulse value of the yaw velocity (defined in figure 2.10), which appears to be the most relevant value for crosswind sensitivity.

2.3. Theoretical Methods

Theoretical methods are an important component of the research into vehicle crosswind performance. In some instances theoretical methods are used to reduce the amount of testing required since this can be a costly and time consuming process. On the other hand, theoretical methods are used to augment the results from both model and full scale tests and produce values for accident risk levels from measured aerodynamic forces and moments.

Hucho and Emmelmann, 1973 (ref.23) used slender body theory, converted from aircraft aerodynamics to the aerodynamics of ground vehicles to calculate the side force and yawing moment of a vehicle in a crosswind gust. Later the effects of the transient nature of wind gusts was incorporated and shown to give considerably higher values for the derivatives than the static results. This is in good agreement with results from earlier moving model tests.

Emmelmann, 1981 (ref.10) states that no general definition exists for the crosswind sensitivity of vehicles and of course the effects of side winds on vehicles have, in large, been established from test results. In order to investigate crosswind sensitivity completely it would be necessary to fully understand the relationship between driver and vehicle. However it is very difficult to describe the vehicle/ driver system because of the many unknowns with regard to driver adaptability.

It is true to say that vehicle development relies upon simple evaluation methods. Fixed control conditions are usually assumed and the degree of safety for each crosswind situation is calculated, dependant upon the vehicles lateral deviation over a set time period.

Baker, 1985 (ref.24) developed a method to predict accident wind speeds for different accident types. To use this approach it is necessary to have detailed information on the aerodynamic coefficients of the vehicle in question. In the analysis an accident is said to have taken place when one of the following occurs:

- i) One wheel reaction falls to zero.
- ii) Lateral deflection exceeds 0.5m.
- iii) The angular deflection is greater than 0.2 rads (measured after a period of 0.5 seconds, following a crosswind disturbance).

The assumptions made are that the vehicle is a four wheeled single mass on a straight level road and that the crosswind gust is a step input wind from zero. It is apparent that further work is required in investigating ways of relaxing some of the more limiting assumptions.

In a later paper Baker, 1987 (ref.25) developed the above theory for accident wind speeds, by including a simplified model for driver behaviour. The same paper contained a study which predicted those parameters most likely to precipitate wind induced accidents on high sided articulated road vehicles. Although the model of driver behaviour is simple it did appear to produce realistic results. However, full scale verification would be required before the predictions can be believed with confidence.

2.4 Summary

The nature of vehicle aerodynamic stability has been addressed and techniques, employed by various authors, to assess vehicle crosswind performance have been considered. Static tests provide useful information on vehicle performance though they give no indication of the importance of transient effects. The limited number of dynamic tests conducted to date have shown that these effects can be considerable.

For the purposes of vehicle design, the automotive engineer needs to be sure that satisfactory crosswind performance is achieved in all conditions. In the initial design stages the relatively simple and cost effective static wind tunnel test can eliminate configurations that are obviously problematic, however, as the concept is refined, the designer will require an accurate tool for assessing the impact of transient aerodynamic situations. The current research is concerned with the design and commissioning of just such a tool, that is, a dynamic test facility capable of simulating the atmospheric wind.

The following dynamic model tests have been considered in this literature survey:

- i) Dynamic yaw tests in a conventional tunnel
- ii) Oscillating aerofoils upstream of a model in a conventional wind tunnel
- iii) An impulsive gust generated by a shutter controlled nozzle venting obliquely towards a model in a conventional open section wind tunnel.
- vi) A test track sited orthogonally to a crosswind generator.

As previously stated, dynamic yaw tests are adversely affected by the fact that a yawing motion superimposed upon uniform flow produces an unrealistic variation in local β . In addition the atmospheric boundary layer cannot be realistically simulated in such a test.

Oscillating aerofoil techniques can suffer the non-uniformity of the flow at the model location and secondary/transient aerodynamic effects associated with the vanes themselves. As with the dynamic yaw technique it is not possible to simulate a realistic atmospheric boundary layer.

An impulsive gust from a shutter controlled nozzle is considered to be the most promising dynamic test to use a conventional wind tunnel. However, the technique is not perfect since it does not accurately simulate the local flow separations involved as a gust issues between two buildings, for instance. Once again simulation of an atmospheric boundary layer would be relatively difficult when compared to the performance of a boundary layer wind tunnel facility.

It can be argued that a crosswind track, in conjunction with a boundary layer wind tunnel, offers the best representation of the full-size situation. Transient features are accurately modelled, road vehicle relative motion is reproduced and a choice of both gust profile and atmospheric boundary layer is possible. The technique was chosen for the current research project and the design and manufacture of the new Cranfield facility is detailed in chapter three.

Chapter 3

Test Facilities

3.1 Introduction

The main aim of this research was to design and commission a model test facility capable of assessing vehicle response to transient crosswinds. A "crosswind track" was manufactured for the task. This approach was considered to be superior to all other dynamic techniques, being able to accurately simulate the full scale situation.

The Cranfield Crosswind Test Track facility consists of a rail, approximately 17m in length, aligned orthogonally to the flow direction in the College's Boundary Layer Wind Tunnel (BLWT) (figure 3.1). Model cars of approximately 1/6th scale, fitted with an internal strain gauge balance (figure 3.2) are fired along a track at speeds of up to 20m/s and encounter a sharp-edged gust as they pass through the working section of the tunnel. In this way both road/vehicle relative motion and the transient nature of the full-scale situation are accurately reproduced. Changes in the resultant yaw angle are achieved by varying the flow velocity. Although an important aspect of the crosswind track facility is the large "fetch" of the wind tunnel that permits various atmospheric boundary layers to be modelled, the major effects of the boundary layer were eliminated during the current research for reasons detailed in section 3.2.7.

Much time was spent in assessing the best approach to creating the Cranfield Test Track facility. Decisions were made only after the findings of previous researchers had been taken into account. Section 3.2 considers each aspect of track design in detail, appraising the features of other facilities and commenting on how they influenced the final design solution for the new Cranfield facility.

In addition to crosswind track experiments dynamic yaw tests were also conducted, where models were moved at various rates, through stipulated yaw

angle ranges, while force and moment measurements were taken. This work was conducted within the college's existing "Oscillatory Facility" (detailed in section 3.3).

It was hoped that a comparison could be made between the Crosswind Track and Oscillatory Facility by testing the same model configurations in both. In the event this comparison was not possible (for reasons given in chapter six), though the dynamic yaw tests did provide useful information on vehicle dynamic response.

Finally, quasi-static experiments (outlined in section 3.4) were conducted on all dynamic test models to assess the implications of dynamic simulation.

3.2 The Design of the Cranfield Test Track Facility

The following concerns the design of each aspect of the new Cranfield facility, after taking into account the methodology of previous researchers.

3.2.1 The Track and Model Carriage System

The test track employed by Beauvais, 1967 (ref.6) used extruded aluminium rails mounted on a plywood base, 25ft. long (7.6m). Brown, 1973 (ref.13) used two tracks each of 225ft. (68.6m) in length in order to simulate highway passing situations, while Yoshida, 1977 (ref.14) had to use an 8.5m long test track due to the limited size of the laboratory. Stewart, 1977 (ref.15) offers considerable detail on the 24m track used in conjunction with the Motor Industry Research Association (M.I.R.A.) crosswind simulator. This is very similar to the arrangement used by Beauvais in that it consists of parallel aluminium channel section rails mounted on a block board base. The test track used by Howell, 1983 (ref.16) was also 24m in length, being fabricated from aluminium angle extrusions bolted to steel support frames, mounted in the vertical sense.

A horizontal plate type track is described by Baker, 1986 (ref.17). The system was employed by British Rail Research at Cranfield University (then the Cranfield Institute of Technology) and used the College of Aeronautics' Boundary Layer wind tunnel for crosswind simulation. The track has now been reassembled at the University of Nottingham. The horizontal plate used was a commercially available "Hepco Guideway" mounted on an accurately levelled I-beam, which in turn was fixed to large concrete blocks. Great care was taken to ensure that all mechanical vibrations were at frequencies above 50 Hz. Consequently, by using a low pass filter with a cut-off at 50 Hz only the aerodynamically induced vibrations were analysed and hence an assessment of the unsteady forces and moments could be undertaken to obtain coefficients corresponding to extreme gusts.

The plate type track was chosen for the new Cranfield facility because of its simplicity, however, instead of being orientated horizontally, the plate was designed in the vertical sense (similar to the layout of Howell) to give the model carriage (figure 3.3) a large side area for easy mounting of (and access

to) the strain gauge amplifiers, data recorder and ni-cad packs.

The new Cranfield track (figure 3.4) is made up of five steel plates bolted together, end to end and held by eighteen support arms. The plates cross-sectional dimensions are 3/8" x 6" (.01 x .15m). The support arms are welded to the three span-wise steel box sections that run the length of the facility and these are in turn welded to the nine upright support pillars. This simple arrangement ensured that during construction accurate levelling of the track was relatively straight forward. To restrict mechanical inputs to a minimum, there are no track joints in the vicinity of the test section. A photograph of a test model on the track is presented in figure 3.5.

The model carriage (figure 3.3) runs on four main bearings with eight side bearings to maintain it's correct position on the track. Considerable effort was taken to keep the mass of the model carriage and associated equipment as small as possible.

3.2.2 Force Balance

Most researchers undertook to measure the forces and moments on their models via a conventional strain gauge balance and this too was the approach adopted for the Cranfield facility.

The test models are mounted above the carriage (figure 3.2) on a strut 3/4 inch (.019m) wide (there is a corresponding slot in the tunnel floor). The strut supports the internal strain gauge balance (figure 3.6) which is capable of measuring lift, pitching moment, rolling moment, side-force and yawing moment. This balance is effectively an aluminium tube which has been machined so that its cross section at six distinct points is reduced to four slender webs. These are the active elements of the balance. Strain gauges are fitted to the webs and wired together in a "Wheatstone Bridge" arrangement. The orientation of each group of webs will dictate the level of strain that they experience from a given force or moment. Hence, each active element predominantly responds to one force or moment and the balance is calibrated by applying numerous test loads. When installed in the model, the two ends of the balance are secured to the floor-pan, while the centre section (balance earth) is clamped to the top of the support strut.

The signals from the balance are amplified before being recorded. The electronic trigger which initiates data recording is also incorporated into the amplifier circuit board.

3.2.3 Model Propulsion and Braking system

A 20 hp. electric motor was incorporated into Brown's, 1973 (ref.13) test track. The motor drove models via steel cables, contained within guideways. The acceleration and deceleration were controlled by the slippage of a magnetically actuated friction clutch and brake, respectively. The complexity of the system was justified for the work in question because it allowed two models to pass each other at an accurately predetermined point in order to simulate a highway passing situation.

A falling weight propelled the 1/10 scale models used by Kobayashi, 1988 (ref.18). The weight was attached to the model carriage by a cable which passed over two pulleys. The model was accelerated over a distance of 5m to a speed of 7m/s. This system works well for models travelling at relatively low speeds but there would be considerable technical difficulties in using this method to achieve higher rates of acceleration. Gravity was also employed to decelerate Kobayashi's models, with the track being inclined upwards after the wind tunnel mouth.

Bungee cords were successfully used by Beauvais, 1967 (ref.6), Stewart, 1977 (ref.15), Howell, 1983 (ref.16) and Baker, 1986 (ref.17) to propel model vehicles ranging from 1/4 scale cars to 1/50 scale trains with masses in the region of 2 kg (including the carriage and support). Baker shows that this method also gives good repeatability ($\pm 2\%$) of model speed in the test section.

An electric motor system similar to that of Brown, 1973 (ref.13) was considered unnecessarily complicated and costly for Cranfield's application. Likewise, the use of a hydraulic ram could not be justified due to its size and complexity.

The bungee propulsion system was adopted and has proven to be a simple, reliable, cost effective approach with excellent repeatability of model

velocity ($\pm 1.5\%$). A schematic diagram of the bungee system is shown in figure 3.7. One 10m cotton-covered bungee cord of 9mm diameter passes through a towing eye on the underside of the propulsion carriage and its two ends are anchored to the floor at the braking end of the track. The propulsion carriage runs on four PTFE blocks as these are better than conventional bearings at withstanding the high acceleration and braking loads imposed upon them. The propulsion carriage sits on the track behind the model carriage, while a third "firing" carriage completes the propulsion system. The three carriages are "coupled" together and drawn back by a 450 kg winch and steel cable to the start of the track. Once the remote firing button is depressed, a solenoid switch is activated in the firing carriage which releases the propulsion and model carriages. After travelling approximately 6m the propulsion carriage is stopped by two arrester posts and the model carriage disconnects, to coast through the working section at constant velocity before it exits to engage the braking system.

The braking system is a composite one, made up of twin steel friction strips (each 4.4m in length) and three arrester bungees. As the model carriage enters the braking area a friction pad on the carriage begins to rub between the two strips. When the model is approximately half way along the deceleration region, an arrester hook engages the three bungees. The friction strips are freed by the use of release levers.

The main advantage of a composite braking system is that the retarding force is closer to being constant. The acceleration force of the propulsion bungees, on the other hand, is very high at first but decreases rapidly as the carriages progress along the track. This initial "kick" produces a large inertia signal that is not experienced in the braking section. In view of this situation it was considered wise to record the force balance's zero readings immediately after braking instead of immediately before launch.

Despite the simplicity and reliability of the bungee propulsion system, two cautionary notes must be added relating to their use. The bungee must be pre-tensioned by a small amount when at rest. This will substantially reduce its "whipping" action when the model is fired. Secondly, in order to maintain a high level of model speed repeatability, the bungee must be released shortly after it has been tensioned (that is, within a few seconds). If the bungee is

extended for any long period then there is a noticeable reduction in the force that it produces. This situation is a time dependant phenomena known as stress relaxation. It is a visco-elastic effect, which unlike creep in metals (a plastic flow) does not produce any permanent damage.

3.2.4 Data Acquisition System

Trailing communications cables were used to relay data by Brown, 1973 (ref.13), Beauvais, 1967 (ref.6), Yoshida, 1977 (ref.14) Stewart, 1977 (ref.15) and Baker, 1986 (ref.17). Brown discounted the use of a radio transmitter on board the model carriage to send information to a remote receiver because of doubts in the reliability of such equipment at that time. With improvements in modern electronic equipment this approach is probably now viable. The B.R. test facility at Derby (previously sited at Mickleover) overcomes the potential pitfalls of trailing wires and radio transmitters by incorporating a compact on-board data recorder into the model carriage.

In the light of current technology it was decided to follow British Rail's lead and use a battery powered on-board data recorder mounted on the model carriage. A commercially available unit, the Polycorder PC-704 (figure 3.8), manufactured by Omnidata USA, was selected. The machine offers 12 bit resolution and is capable of recording the five analogue data channels from the balance at a rate of 400 Hz per channel, while the digital signal that triggers the start of recording and monitors the model position is sampled at 2000 Hz. The data collected is down-loaded to a PC, via a temporary RS 232 communications lead, at the end of every run.

3.2.5 Model Speed Measuring Device

The model carriage is fitted with two phototransistors which respond to the output of infra-red LEDs. Triggering one phototransistor will cause the digital signal sent to the Polycorder to go "high", while triggering the other will send it "low". There are five LEDs mounted on brackets along the track. The first one merely ensures that the digital signal is at it's correct state for firing when the model is winched back. The second LED initiates data recording, while subsequent LEDs mark the start, middle and end of the test section respectively. The model's position is accurately assessed by the transition of the

digital signal between the high and low states.

3.2.6 Testing Technique

Due to the nature of dynamic testing, the recorded forces and moments will contain both aerodynamic and inertia signals. In order to isolate the inertia inputs, it is possible to enclose the model in a box, which in no place touches it and thereby shield it from any aerodynamic influence. In the case of the Cranfield test track this would be an extremely difficult operation. The shroud would be large and therefore subject to a high aerodynamic drag, nevertheless, the greatest problem would be in fitting it to the model support strut, given the limited clearance between model and ground board. Howell, 1983 (ref.16) utilized a technique based upon Brown, 1973 (ref.13) where accelerometers were used to isolate inertia and track induced signals from the aerodynamic data. To avoid the unnecessary complications of incorporating accelerometers into the Cranfield facility a different technique is employed where the vehicle model is substituted with a system incorporating two wooden plates that link the extreme ends of the balance as they would in the model. The plates are weighted to simulate the model's mass and centre of gravity position. A much smaller aerodynamic shroud (figure 3.9) is then needed to shield the balance. Tests conducted in this manner are termed "wind-off" tests.

3.2.7 Crosswind Simulation

The current research is concerned primarily with the response of vehicles to a change in the external flow field and an exact simulation of that flow is not necessary. It is for this reason that the major effects of the boundary layer are eliminated to produce a resultant flow velocity distribution similar to that achieved in a conventional wind tunnel test. This in turn allows a more meaningful comparison between dynamic and static wind tunnel test results. It is expected that the additional effects of shear will be assessed in future research.

The major effects of shear were removed by the introduction of a ground-board approximately 4 inches (.1 m) above the tunnel floor (figure 3.10). The low energy boundary layer is essentially drawn off beneath the

ground board. The effectiveness of this technique can be seen from the boundary layer profiles in figure 3.11. Freestream longitudinal turbulence intensity on the centreline of the BLWT is in the range 0.5 - 0.8%. (Refer to appendix A for an investigation of flow quality in the vicinity of the Crosswind Track).

3.2.8 Test Models

Two types of model were used during tests. The first, a basic saloon car, had interchangeable estate, notch-back, square-edged fastback and rounded fastback configurations (figures 3.12 and 3.14). The second model, a simple bluff-body, used extensively by Rover Group for fundamental aerodynamic research was employed solely to investigate the effects of backlight angle (figures 3.13 and 3.15). Ground clearance for the bluff body model was 33 mm, while the gap between the basic saloon's fixed wheels and the ground board was 2 - 3mm. Both dynamic test models (fabricated and supplied by Rover Group) were of relatively lightweight construction to try and minimize their inertia effects.

Bluff-body model = 1.0kg

Basic saloon = 0.39kg

Unfortunately the higher mass of the bluff-body was sufficient to produce large inertia effects. The results obtained were heavily contaminated with "noise" and were impossible to redeem through signal processing. Therefore only results for the basic saloon are discussed in chapter five (the chapter concerned with Crosswind Track tests).

3.3 Oscillatory Facility

This section details the second test facility used to assess transient aerodynamic effects on model ground vehicles. Known as the Oscillatory Facility a main feature is its ability to produce periodic model motion. Nevertheless, tests conducted using this equipment concentrated exclusively upon subjecting models to a transient (not oscillatory) motion. The simulation of a constant change in incident flow between two extreme yaw angles (referred to as dynamic yaw) is quite distinct from the impulsive crosswind gust of the test track system. The oscillatory equipment was devised by Garry, 1986 (ref.19) and was further developed during the course of this current research.

The Bluff-body model provided the basis for oscillatory experiments. The model sits above a turntable (figure 3.16), let into the full-span ground board, in the 0.91 x 0.91 m closed working section, open-return wind tunnel of the College of Aeronautics. The rotating turntable is driven by a stepper motor/gearbox with both rate of movement and yaw angle range defined by the operator.

The tunnel working section flow velocity (U_{∞}) is measured using a Pitot-static probe mounted .18 m ahead of and .27 m above the model. Flow angularity on the model centreline is $< 0.2^{\circ}$ at $U_{\infty\max} = 24\text{m/s}$. Freestream longitudinal turbulence intensity on the centreline of the tunnel is 0.9%. The adjustable trailing edge flap is set to produce zero circulation around the ground-board/model combination. This is assessed by means of two static tappings, one above and one below the ground board at its leading edge.

3.3.1 Force Balance

A schematic diagram of the equipment incorporated into the oscillatory facility is given in figure 3.17.

Model mounting is via an aluminium frame which forms part of the strain gauge balance. The purpose built, three-component balance system consists of four strain gauged multi-webbed supports linking a rotating turntable to the aluminium frame (within the model). The four supports incorporate extension pieces to produce the desired model ground clearance of

33 mm. Electrical signals from the strain gauge bridges are amplified and fed to a conditioning unit that converts the four channel input into a three channel output. The balance measures drag, side-force and yawing moment and is calibrated by the application of test loads.

3.3.2 Turn Table Control

An IBM compatible PC was implemented to control the turn table movement via its "IEEE 488" interface. A BASIC programme ("TURNT5.BAS"), written to perform the task of setting rotational rates, and yaw angle ranges was also used to control the acceleration and deceleration ramps. The level of acceleration/deceleration is chosen to be as high as is practical, so that a constant yaw rate can be achieved as soon as possible. The characteristics of the facility place an upper limit on the level of acceleration/deceleration. If this level is too great then the model initially achieves an angular velocity larger than required, before it settles down to the correct rate of rotation. In addition the model will overshoot its rest position upon retardation. This situation is illustrated in figure 3.18a, while figure 3.18b shows the same steady state rate of rotation, this time with a more appropriate acceleration/deceleration ramp.

3.3.3 Data Acquisition

The data recorder is that from the track facility, and in a similar manner it is used to record five analogue channels (the three force balance channels, flow dynamic pressure and model position). The relatively high sample rate of 400 Hz per channel is essential so that the three balance outputs are recorded near simultaneously. The data recorder also triggers the turntable control, after a set period of recording. In this way, the start of model movement always occurs within the same time period of each data file.

3.4 Quasi-Static Tests

In addition to dynamic force measurements, quasi-static tests were carried out (in both the Oscillatory Facility and the BLWT) where test models were held at a constant yaw angle to the freestream flow. These tests used exactly the same equipment as their respective dynamic tests, with the exception of the data recording device employed. Where the dynamic tests used a high speed data recorder, the quasi-static tests used an Apricot computer and A/D converter.

Flow visualisation tests were also conducted in one of the College's open section wind tunnels and exact copies of the dynamic test models were fabricated especially for these studies. The models, shown in figures 3.14 and 3.15 had surface finishes ideally suited to the various flow visualization techniques employed.

Chapter 4

Quasi-Static Tests

4.1 Introduction

Vehicle rear end configuration was of primary interest during the course of research as this had been shown by previous authors to cause a significant variation in vehicle crosswind stability characteristics.

Quasi-static testing was performed to provide a data base of force and moment coefficients to compare with dynamic tests. The term "quasi-static" is used because the results obtained may be dependent upon the history of the flow field. In addition to force and moment measurements specially fabricated reproductions (1:1 scale) of the basic saloon and bluff-body model (figures 3.14 to 3.15) were subjected to several flow-visualization techniques. These tests are considered first.

4.2 Flow Visualization Studies

During flow-visualization studies the models were mounted above a fixed ground-plane in the College of Aeronautics' "1B" open-section/closed-return wind tunnel. The following flow visualization methods were utilized:

- i) Smoke filaments introduced into the flow upstream of the model.
- ii) Nylon-tufts attached to the windward side and upper surface of the test vehicle.
- iii) A wool-tuft grid sited at various stations within the vehicle wake.
- iv) Oil flow-visualization on the upper surfaces of the model.

Oil flow-visualization involved the use of a paraffin-based "paste", with titanium dioxide acting as a tracer. The paste was applied to the test model immediately before the wind tunnel flow was commenced. The freestream flow direction, for all photographs of oil flow-visualization, is left to right. Certain

flow features consisted of highly structured separation regions containing a large quantity of flow-visualization paste. When the tunnel flow ceased the paste would run, under the influence of gravity and the structures would be lost. For this reason all photographs were taken "wind-on", with separation patterns intact. All photographs of oil flow-visualization experiments are presented with accompanying sketches of the salient flow features.

All test models employ free transition, however, the leading edge roughness varies considerably between the models used for flow visualization and dynamic tests. The transition region for all models was ascertained by monitoring the change in boundary layer acoustic signal. At test Re values transition for both types of dynamic model (at zero degrees yaw) occurred within the first 50mm from the leading edge of the "bonnet". Re for the flow visualization tests was increased to bring transition to the same point. For the bluff-body model $Re = 12.0 \times 10^5$ (based on a model length of 0.69m). For the basic saloon $Re = 10.9 \times 10^5$ (based on a model length of 0.60m).

Flow studies were carried out on all configurations of bluff-body and basic saloon model. A yaw angle range of 0 to 30 degrees was investigated at 5 degree intervals from $\beta = 0$. For each yaw angle, the model was positioned before initiating the flow. This is different to the procedure for force and moment measurements, where models were moved to the next yaw case while the wind tunnel was operating.

The following analysis of flow characteristics considers yaw angle cases that illustrate important flow features. For this reason, the range of β discussed varies from model to model.

4.2.1 Flow Visualization for the Basic Saloon Car Model

Smoke flow visualization gives an appreciation of the general extent of each vehicle wake (figures 4.1 to 4.4). Two yaw angles are illustrated for each model configuration ($\beta=10^\circ$ and $\beta=25^\circ$). As expected, the larger yaw angle causes gross flow separation and an extensive wake flow for all but the rounded fastback configuration. The generous radius of curvature to the "C-pillar of this configuration presents less of an adverse pressure gradient and therefore reduces the degree of flow separation (figure 4.2b). At $\beta=10^\circ$ both the square

and rounded fastback models experience "C-pillar" vortex flows that reattach themselves to the backlight surface (figures 4.1a and 4.2a). (note: refer to figure 2.3 for the definition of "A" and "C-pillars").

Oil flow studies for the basic saloon are presented in figures 4.5 to 4.10 inclusive.

The estate model flowfield (not depicted here), exhibits largely attached flow throughout the yaw angle range. Flow separations occur mainly at the trailing edges of the vehicle.

Considering the square-edged fastback, flow attachment is the dominant feature at small angles of yaw. Two attached "C-pillar" vortices that originated as a symmetrical flow structure at $\beta=0^\circ$ (not depicted) are still evident in an asymmetric form at $\beta=10^\circ$ (figure 4.5a). Local flow separations are apparent at the leading edge of the bonnet and roof and particularly at the Trailing edge of the roof. At $\beta=15^\circ$ separation at the junction of the roofline and windward "C-pillar" is evident (figure 4.5b), though the leeward "C-pillar" vortex is still attached. At $\beta=20^\circ$ the region of flow separation is extensive (figure 4.5c), the leeward vortex fails to attach and local flow separation is observed at the top of the windward front wing, adjacent to the "A-pillar".

Despite poor quality surface flow pictures for the rounded fastback (figure 4.7) local flow separations are clear at all yaw angles. At $\beta=20^\circ$ (figure 4.7b) there is an attached vortex upon the backlight surface which causes separation of the flow immediately above it (as the photograph is viewed). At $\beta=30^\circ$ (figure 4.7c) there is a considerable region of separated flow on the backlight surface.

The notch-back configuration at $\beta=0^\circ$ demonstrates the complex separation structure that exists on the rear window surface (figure 4.9a). The major flow characteristics are virtually identical to those reported by Chometon, 1988 (ref.26), who precisely mapped the wake flow for a Renault 21 notch-back. The flow pattern produced over the rear window area also shows features similar to the leading edge separation bubble occurring on a low aspect ratio wing at incidence (see figure 4.11 from Werle, 1986, ref. 27). For the notch-back vehicle, the "leading edge" is represented by the top of the rear

window. At $\beta > 0^\circ$ the flow pattern is seen to become asymmetric. The general form of the surface flow structure changes little with increasing β . Local flow separations occur at positions similar to previous cases.

4.2.2 Flow Visualization for the Bluff Body Model

The yaw angle range of particular interest for the bluff-body model is $\beta = 0$ to 20° , as this corresponds to values of β over which forces and moment were measured.

Surface flow over the forebody region of the square-back model is well illustrated in figure 4.12. Local flow separation is observed at the leading edge of the roof at $\beta = 0^\circ$ (figure 4.12a). The characteristic "herring-bone" pattern of an attached vortex is very clear at $\beta = 20^\circ$ (figure 4.12b), the vortex being attached to the surface of the roof.

There are two attached vortices on the backlight of the 10 degree bluff-body at $\beta = 0^\circ$ (figures 4.14a), though their form is not particularly clear in the photograph. At $\beta = 10^\circ$ the attached roof vortex interacts with the windward backlight vortex (figure 4.14b). The interaction appears to be the cause of vortex breakdown at $\beta = 15^\circ$ (figure 4.14c).

The increase of backlight angle to 20 degrees causes local flow separations at the trailing edge of the roof in addition to the existing local separation at the leading edge of the roof (figure 4.16a). Attached vortices are present on the backlight surface at $\beta = 0^\circ$, though once again these are not particularly clear in the photograph. At $\beta = 10^\circ$ (figure 4.16b) there is no longer an attached leeward vortex, however, the windward backlight vortex and roof vortex are well defined. Again there is interaction between these vortices and the consequence is vortex breakdown at $\beta = 20^\circ$ (figure 4.16c).

A highly structured flow separation pattern is observed on the backlight of the 30 degree model at $\beta = 0^\circ$ (figure 4.18a). In addition, there are two well defined attached vortices that persist throughout the yaw angle range (figures 4.18b and 4.18c). Whereas the flow in the previous cases was dominated by the roof vortex it appears that the strength of the backlight vortices on the 30 degree model are sufficient to make them the major influence upon the flow.

The behaviour of the windward backlight vortex in the case of all bluff-body configurations is influenced by its interaction with the roof vortex. The existence and form of the roof vortex is, in turn, dependent upon model geometry (figure 3.15 gives a good idea of the bluff-body geometry). The implication is that when considering a practical vehicle, vortices could be generated from any number of body components. The behaviour of the vehicle flowfield is certain to be governed by the way in which the fundamental flow features interact.

In the case of the forty degree model, flow is completely separated over the backlight surface at all yaw angles under test (figure 4.20). The attached roof vortex is present at $\beta > 0^\circ$.

4.3 Force and Moment Measurements

For all tests, two extreme yaw angles were chosen (relative to the freestream flow direction). If these extreme values are called $+\beta$ and $-\beta$ then the yaw angle ranges through which each test model was rotated can be written as follows:

- i) $-\beta$ to $+\beta$
- ii) $+\beta$ to $-\beta$
- iii) 0 to $+\beta$
- iv) 0 to $-\beta$

For each test the model was moved to its start position and the wind tunnel flow initiated. Following this the vehicle was moved slowly through the yaw angle range, being stopped at selected yaw angle values while force and moment data was recorded. The majority of configurations appear to be unaffected by the flowfield history and the results in these cases are presented for model rotation from 0 to $+\beta$.

The reference point for all moment coefficients (the moment reference centre - MRC) is sited at the centre of each force balance. This position is given for both test models in figures 3.12 and 3.13. The force and moment sign convention employed for all tests (both quasi-static and dynamic) is illustrated in figure 4.22. All coefficients are measured with respect to body axes. To simplify the presentation of results each of the two test models is examined separately.

4.3.1 Force and Moment Measurements for the Basic Saloon

The basic saloon car model (figure 3.12) was tested in the CoA Boundary Layer Wind Tunnel (BLWT). The same measuring equipment employed during Crosswind Track dynamic tests was also used during quasi-static testing. This included the strain-gauge force balance (able to measure all components with the exception of drag) and signal conditioning unit. The only difference between the two tests lay in how the data was recorded. Dynamic tests used a high speed data recorder, while quasi-static tests used a PC.

With a blockage ratio of 1.3% for the model at $\beta=0^\circ$ it was decided to use the results with no correction for blockage.

The Reynolds number for quasi-static tests on the basic saloon was $Re = 7.8 \times 10^5$, (based on a model length of 0.60m). These tests were designed to match the model speed attained on the Crosswind Track. Unfortunately when the dynamic tests were conducted it became necessary to propel models at a lower speed, resulting in a difference in Re between dynamic and quasi-static tests (Re for the dynamic tests was 5.8×10^5). Variation of the quasi-static transition point with Re was minimal, possibly due to the beneficial effect of model surface roughness. In any case it is not expected that Re effects will have a significant influence on force and moment measurements at the two Re values.

The acceptable level of data repeatability is illustrated in figure 4.23, where the results from two runs are over-plotted. Initial tests highlighted a problem in measurement of the yawing moment. For model movement from β to 0° , the results would show an upward shift of the curve, as if a significant yawing moment was still being applied at $\beta = 0^\circ$. The problem was found to lie in the model mounting system and changes in the mounting plate and locating studs succeeded in curing the problem.

The results for the coefficients of lift, pitching moment, rolling moment side-force and yawing moment versus yaw angle are given in figures 4.24 to 4.28.

The form of the lift coefficient curves (figure 4.24) is as expected for this type of body, with a general increase in lift as yaw angle increases. The high lift value for the square edged fast-back can be attributed to the attached "C"-pillar vortices, which represent a considerable region of low pressure. As the yaw angle increases, the windward vortex, for this configuration, grows in strength. At a critical yaw angle (between 10 and twelve degrees), failure of the windward "C"-pillar vortex to attach creates a sudden decrease in the lift coefficient. The rounded fast-back on the other hand experiences high lift values over a wide range of yaw angles.

In general the pitching moment values (figure 4.25) increase with yaw angle. Once more the behaviour of the "C"-pillar vortices dictate the performance of the square-edged fast-back. Initially, the presence of the low pressure region created by the vortices causes a pitching moment of zero. As yaw angle increases from zero, a relatively small positive pitching moment develops, followed by a larger rate of increase as the windward corner vortex is no longer attached.

The rolling moment coefficients are relatively small and virtually linear over yaw angle ranges close to zero (figure 4.26). The results show little variation with changing configuration, however, their sign and magnitude indicates that the aerodynamic centre of pressure is a short distance below the moment reference centre (MRC).

Sideforce and yawing moment coefficients are closely related. The estate configuration experiences the largest sideforce (figure 4.27), as expected, since it is one of the few configurations for which physical side area is the dominant factor. The presence of the windward "C"-pillar corner vortex is responsible for the reduced side-force experienced by the rounded fast-back. Since this vortex represents an area of low pressure, flow along the rear windward side of the vehicle is caused to accelerate, thereby creating an extensive low pressure region which in turn diminishes the side-force. This region of low pressure, combined with the low pressure peak usually found over the leeward front corner of the vehicle, is also responsible for the high yawing moment values of the rounded fast-back model (figure 4.28).

With the exception of the square-edged fastback, all results repeat well, no matter which direction of movement or yaw angle range is considered. Although the square-edged fast back performance does repeat, the results for this configuration are shown to be dependent upon flowfield history. This performance is illustrated in figure 4.29. Lift and sideforce results are presented for two directions of model movement, (as depicted by the arrows). Differences in force measurement cause a hysteresis loop over the approximate range $\beta = 5$ to 12° . This indicates a bi-stable flow structure, that is, a region where either of two flowfield solutions can exist. The likelihood of any one particular flow structure existing depends upon the flowfield history.

Referring back to the flow visualisation studies it can be seen that the above yaw angle range is associated with the change from attached vortex flow to separated flow (or vice versa). Once flow separation has occurred the model must be moved back towards $\beta=0^\circ$ by several degrees before the attached vortex will re-establish.

4.3.2 Force and Moment Measurements for the Bluff-Body Model

Quasi-static aerodynamic tests were conducted on the bluff-body model in the College's Oscillatory Facility. This is capable of measuring drag as well as side-force and yawing moment. The blockage ratio for this model/tunnel combination was approximately 6% at $\beta=0^\circ$ and the continuity method of blockage correction was applied to the results (see appendix B).

The same equipment used during dynamic yaw tests was used for the quasi-static measurements, with the exception of the high speed data recorder which was replaced by a PC.

While the balance initially gave good repeatability of drag measurements it was soon discovered that repeatability was adversely affected when the model was derigged between tests. In this way the data for drag could vary by $\pm 7\%$. Tests were conducted upon a simple prismatic model to ascertain whether the problem was model related. The same situation was encountered. Despite further investigation no solution to the problem could be found and eventually it was decided to work with only sideforce and yawing moment results, which in any case are the components of greatest interest with regard to crosswind stability. The good repeatability of sideforce and yawing moment data is illustrated in figure 4.30, where the results for two consecutive runs are over-plotted.

The Reynolds number for quasi-static tests conducted in the Oscillatory Facility was $Re=8.6 \times 10^5$, based upon a model length of 0.69m. The flow velocity in the Oscillatory Facility, close to the top speed of the tunnel, was dictated by the largest signal that the force balance (and related instrumentation) could measure.

The sideforce results (figure 4.31) are of the expected form for a body of this sort. The square-back experiences the largest sideforce, while the 20 degree backlight generally has the lowest. The other configurations have intermediate values for the yaw angle range under test, with the exception of the 30 degree backlight which exhibits the lowest sideforce at $\beta=15^\circ$ and above.

Yawing moment results are presented in figure 4.32. As expected, configurations that exhibit large sideforce coefficients also experience the lowest yawing moment values. The 20 degree backlight has the highest yawing moment, though this is equalled by the 30 degree backlight at $\beta=15^\circ$ and above.

For all configurations except the 30 degree backlight all forces and moments repeat well, no matter which sense the model is yawed. Like the square-edged fastback basic saloon the results for the 30 degree backlight show a hysteresis loop, though this time the yaw angle range covered is more extensive, extending from $\beta=0^\circ$ to $\beta=15^\circ$ (figure 4.33). Once again this shows an existence of bi-stable flow, that is a yaw angle range over which either one of two flow solutions is possible. The flow structure established is dictated by the flowfield history. If the test model is first positioned at any yaw angle above $\beta=0^\circ$ and then the wind tunnel flow is initiated, the force and moment results recorded correspond to the dashed lines in figure 4.33. This means that for the flow visualization study only results at $\beta=0^\circ$ gives an indication of the flow structure governing the solid lines in figure 4.33. The important aspect of this flow (figure 4.18a) is clearly a highly structured separation region whose intricate pattern, once disturbed will not be achieved again until the model returns to $\beta=0^\circ$.

4.4 Discussion

Quasi-static tests conducted in two separate facilities and on two distinctly different families of basic vehicle model have shown one configuration in each test to be governed by a region of bi-stable flow. Within this region the flow solution is determined by flowfield history, that is, the direction from which the region of bi-stable flow is approached.

The two models in question were the square-edged fastback version of the basic saloon and the bluff-body model with thirty degree backlight. Bi-stability for the square-edged fastback, is associated with the attachment or separation of the "C-pillar" vortex. In the case of the 30 degree backlight bluff-body the flow appears to be influenced by the existence of a highly regimented area of flow separation, whose exact structure is difficult to determine.

Chapter 5

Crosswind-Track Tests

5.1 Introduction

This chapter commences with a brief discussion of important development work that took place after construction of the Crosswind Track Facility. The quality of aerodynamic information obtained was very much dependent upon the characteristics of the equipment, therefore, this is considered in 5.3, while track results are discussed in section 5.4.

5.2 Development of the Facility

Initial proving of the system presented several technical difficulties. The first, was failure of the propulsion carriage's main bearings. Of similar design to the model carriage the propulsion carriage is fitted with a towing "eye" on its lower surface. The position of the eye, dictated by the bungee propulsion system, caused significant pitching moments at both launch and arrest, which in turn lead to premature (and often spectacular) failure of the bearings.

The solution was to use machined blocks of PTFE in place of the conventional bearings. PTFE is a particularly "slippery" type of plastic and works well in this application. For the same degree of bungee extension there was no significant reduction in model speed. In addition, each block incorporates a depth adjustment, reset every fifty runs or so, to account for wear and thereby maintain its correct tolerance.

The propulsion bungee itself also caused difficulties. Despite steps being taken to keep the bungee system as far from the model carriage as possible interference between the two was experienced on one occasion, leading to sudden carriage deceleration.

A high-speed video analysis of track behaviour successfully identified

the problem. With a "dummy" balance installed within the test model multiple runs were undertaken while video equipment recorded the performance of the facility. From this study, it became clear that the bungees experience a significant amount of movement, or "whipping", shortly after model release. The bungees, which were only lightly tensioned before the propulsion carriage was drawn back, were then pre-tensioned by approximately 5% of their relaxed length. This measure succeeded in substantially reducing bungee movement upon release and thereby eliminated the problem. The high speed video material also demonstrated acceptable model release and braking performance.

Model mass had a large effect on the quality of aerodynamic data. Unwanted inertia inputs were large, particularly for the bluff-body model. In certain situations inertia inputs were large enough to cause "cropping" of the data, that is, the signals exceeded the recording range of acquisition equipment.

Measures taken to minimize the mass of the bluff-body model included the use of wooden balance-mounting-blocks (aluminium ones had been used for the basic saloon model). Unfortunately, the wooden blocks were unable to withstand the dynamic loads imposed by track testing and failure of the forward mounting point during the course of a run caused severe damage to the model. There is no doubt that the future requirement is for a low-mass body shell and mounting blocks of suitable tensile strength.

Signal conditioning was also a source of error. The problem manifested itself as a large balance response-time to near instantaneous inputs. Though this presented few difficulties in quasi-static experiments, where the results are time-averaged, the situation was completely unacceptable for dynamic measurements. Eventually the cause was identified as being unsuitable components within the conditioning unit. This was rectified and the resulting response time following the instantaneous release of a load proved to be excellent (within 1 ms - figure 5.1).

In the interests of safety and efficiency the following check list was devised for operating the crosswind track:

1. Remove the track covers.
2. Clean the track using spray oil.
3. Disconnect the data recorder's battery charger (if in use).
4. Check the charge level of all ni-cads.
5. Remove the external power supply to balance and fit ni-cads.
6. Fit the ni-cad cover-plate, ensuring that bolts are well tightened.
7. When the amplifiers have warmed up (approximately 5 minutes)
check the balance for correct operation, then zero all signals.
8. Switch on the trigger L.E.D.s.
9. Place the safety warning sign in position.
10. Check the wear of the propulsion, winch and braking bungees, winch cable,
coupling rope and propulsion carriage runners.
11. Check the condition of the towing eye, the arrester hook, model
carriage and firing carriage bearings, shackles and anchor points.
12. Switch on the winch.
13. Remove the safety pin from the firing carriage.

5.3 Characteristics of the Track Facility

During the course of research three types of test were conducted:

- i) Crosswind tests. Models are fired along the track as the Boundary Layer Wind Tunnel simulates an impulsive crosswind gust.
- ii) Zero degree yaw-angle tests. Here models are fired along the track without the Boundary Layer tunnel operating.
- iii) Wind-off tests. In these tests the model is substituted by a system of wooden plates and ballast weights that reproduce the model's mass and centre of gravity position. The plates connect the active ends of the balance in the same manner as in the model. The whole system is then covered with an aerodynamic shroud and fired along the test track.

It is clear that the aim of data processing is to obtain, as near as possible, results that give purely aerodynamic information. Equally apparent is the fact that any moving model technique is almost certain to induce mechanical "signal noise". It has already been stated that the quality of the aerodynamic data is closely related to the characteristics of the track. This section uses data obtained from dynamic tests on the basic saloon model to illustrate the performance of the track facility.

The high level of model speed repeatability ($\pm 1.5\%$) permits accurate synchronisation of selected data files (to within 2.5 ms). This is imperative since the intended analysis technique relied heavily upon the removal of mechanical noise by subtracting wind-off signals from the crosswind results. Zero yaw tests were also conducted to provide additional "wind-off" data for lateral components. This technique was considered acceptable because sideforce, yawing moment and rolling moment are all nominally zero at zero degrees yaw.

5.3.1 Resonance of the Combined Force Balance/Mounting System

With regard to dynamic experiments, the resonant frequencies of the balance and model support system were identified as being an important consideration early in the project. Unfortunately, conflicting goals caused the stiffness of certain components to be below their ideal values.

From here on, the combined model, balance and support assembly will be referred to as the balance system.

The balance system's resonant frequencies were investigated for both the model installation and the wind-off apparatus. Resonance was assessed by the following method. The model carriage was fired along the track and data was logged as it progressed through the working section and into the brake. Held at rest by the friction strips, the unit continued to vibrate. Free from external inputs, the oscillations were purely the decaying resonant frequencies of the system. Taking this information and performing a Fast Fourier Transform (FFT) analysis, the resonant frequencies of the balance system were assessed for all recorded force and moment coefficients.

Considering the model installation first, natural oscillations for lift and pitching moment cover a large frequency range. In contrast, all lateral coefficients exhibit distinct resonant frequencies and in particular, sideforce has a large amplitude component of approximately 18 Hz (figure 5.2. - note that the frequency range 0 - 200 Hz is the maximum according to the Nyquist sampling theory; also the resolution is 2 Hz, given by $1/T$ where T is the sample time).

It is immediately apparent that the resonant frequencies of the balance system are very close to the frequency range of likely aerodynamic inputs. The system behaves in a similar manner to a tuning fork. The impulse of model launch is analogous to the tap of a tuning fork on a table top. Irrespective of subsequent external forces, the balance system will tend to "sing" at its resonant frequency as it progresses along the test track. More importantly, should external inputs, whether aerodynamic or mechanical, occur at the natural frequency of the system, they will be amplified out of all proportion. This would present major problems during subsequent data reduction.

For the wind-off installation the amplitudes of all free oscillations are significantly reduced. (This is illustrated for sideforce and yawing moment in figure 5.3).

It is highly probable that the wooden plates, employed in wind-off tests, (described in section 3.2.6) are responsible for reducing the amplitude of certain signals. Whilst static loads measured by the balance remain constant, irrespective of mounting system employed, the reduced amplitude of wind-off free oscillations is certain to influence dynamic measurements. There will be differences in the mechanical "noise" recorded by wind-off and crosswind tests which invalidates the method of subtracting the wind-off signal as a means of noise elimination.

5.3.2 Measured Force and Moment Coefficients

Typical coefficients produced from a single crosswind test appear in figure 5.4 (note that the Y-axis scale for the forces is different to that for the moments). The digital trace gives an indication of model position, relative to the tunnel's test section and also demonstrates that model velocity is constant within this area. No attempt has been made to remove mechanical signals and indeed the level of noise is considerable.

5.3.3 Spectral Analysis of Force and Moment Coefficients

An FFT spectral analysis of the crosswind data (from figure 5.4) showed the sideforce coefficient to have a broad frequency range and a spike at 18 Hz, of similar magnitude to the free-oscillation (given in figure 5.2). This suggests there are no external inputs, either aerodynamic or mechanical, at this frequency. The 18 Hz component is merely the oscillation following the impulse of launch, however, it is still an important component because the amplitude is significant and its frequency is within the likely range for aerodynamic components.

During the track tests both rolling moment and yawing moment were excited at their resonant frequencies. This is evident from the FFT analysis of Crosswind Track data (see figure 5.5). The amplitude of the forced oscillation in yawing moment is particularly large. This is more significant than the

sideforce free-oscillation because the aerodynamic yawing moment coefficient is significantly smaller than the aerodynamic sideforce coefficient.

Figure 5.6 presents the yawing moment results for two consecutive runs. The constant phase relationship between the two signals strongly suggests that the 41 Hz input is a mechanically induced "track signature".

5.3.4 The Influence of signal "noise"

The dynamic results were compared with quasi-static ones for the same model at the same yaw angle (estate at 20° yaw). The dynamic results contain information on the changing aerodynamic signal as the model progresses from $\beta=0$ to the crosswind value. For this reason, the quasi-static coefficients used for comparison are formulated by subtracting zero yaw figures from the coefficient values at 20° yaw. The quasi-static coefficients are expressed as a percentage of the maximum peak to peak dynamic signal to illustrate the level of influence of signal noise (figure 5.8 - the method of calculation is given in figure 5.7). In addition to showing the influence of signal noise, the results of figure 5.8 are also affected by moving model simulation, transient aerodynamics and Reynolds number effects, though it is believed that mechanical noise has the largest effect. Note that the "Y-axis" in figure 5.8 only extends to 40%. This shows that the level of signal noise is high, particularly for lift and pitching moment coefficients.

5.3.5 Data Repeatability

As discussed in section 5.3.1, the fundamental difference between crosswind and wind-off signals excludes simple subtraction of wind-off data as a means of removing mechanical inputs. This was verified by further analysis, which showed the technique allowed significant mechanical noise to remain within what should be purely aerodynamic data. An alternative method was to use zero yaw signals for information on mechanical inputs, subtracting these from the crosswind files. This approach much improved matters, though a certain level of noise remained within the results. The reason for this was poor data repeatability.

Repeatability of the "raw" signals was closely scrutinised. All types of data file were considered; crosswind tests, wind-off tests and zero yaw tests. If the repeatability of the data is good then synchronised signals recorded during two identical runs should, if subtracted, one from the other, produce a nominal zero value. In reality, significant variations in signal amplitude were observed. To quantify this the following technique (illustrated in figure 5.9) was employed. The variance of the difference between two signals from two consecutive runs was expressed as a percentage of the average variance of the original two signals. This method was repeated for data from similar runs and averaged to produce the final figure for percentage variance of the raw data.

Channels one and two together respond to lift and pitching moment, channel three to rolling moment and channels four and five to sideforce and yawing moment.

Immediately apparent is the fact that percentage variance of signal amplitude can be large (from approximately 7% to 50%). The results for crosswind and zero yaw tests are similar in magnitude, while the wind-off runs give a somewhat higher signal percentage variance.

5.3.6 Limitations of Data Processing

Since the data repeatability was generally poor, the mean of three synchronised zero yaw files was subtracted from each crosswind data file. This succeeded once again in improving matters, though mechanically induced signals were still clearly present (note that because zero yaw files were not originally intended to be the primary source of mechanical information fewer tests were conducted and as a result only three files on average gave good enough synchronisation to be used). Further data processing considered the use of a digital filter (notes on digital filter design are given in appendix B).

Filter design needs careful consideration for the current application simply because the data contains high levels of noise and all frequency components are relatively close together; making it difficult to separate them. The most demanding case would be if the test model's aerodynamic admittance for a high frequency gust (that is a short duration gust input) was unity. Sideforce response would then approximate to a step input. Filter response to

such an input is an important feature and an illustration of this is given in figure 5.11. Ideally both response time and settling time should be as short as possible and this is generally achieved by increasing the number of filter coefficients employed, however, because the demands upon the filter are already so stringent, it is impossible to reconcile all requirements. No matter how the filter is designed, information on model response to gust entry is distorted.

Eventually it was decided to implement a simple smoothing algorithm (a 25-point moving average) because of its ease of implementation and the fact that it gives a clear presentation of the steady-state region during the model's immersion in the gust. Figure 5.12 compares the performance of a 10 Hz lowpass filter with that of the 25-point moving average.

5.4 Track Results

Tests on all model configurations were undertaken at resultant yaw angles of 10, 15, 20, 25 and 30 degrees. Additional test results are contained within appendix D (figures D1 to D8).

As previously stated, the significant problems associated with signal "noise", that limit the amount of useful aerodynamic data, are compounded by the bluff-body model's greater physical size and mass. These shortcomings made it impossible to extract any meaningful information for this model. As a result, only data from the basic saloon warrants analysis.

The Reynolds number for the tests on the basic saloon model, based upon zero yaw angle resultant flow and the length of the test model (.6m) was approximately $Re = 5.8 \times 10^5$.

Analysis concentrates upon the sideforce coefficient since this is an important feature of vehicle stability. Moreover, all other coefficients contain a large amount of noise that is impossible to eliminate to any satisfactory degree.

The level of noise incurred in C_Y is clearly appreciated when the smoothed signal is plotted over the unprocessed data (figure 5.13). With the positions of model-tail gust-entry and nose-exit superimposed upon the data it is apparent that the smoothing algorithm distorts the sideforce response to the gust. On the other hand these positions match the "raw" coefficient response fairly closely. Considering the unprocessed coefficient, there is a peak in C_Y observed immediately before tail entry. Shortly after nose exit C_Y begins to decrease. Note that the mechanical input from the brake makes the sideforce appear to reverse direction shortly after nose exit. Despite its limitations the smoothing algorithm does produce a reliable assessment of the "steady state" period while the model is immersed in the gust.

Yawing moment coefficient smoothed by the same algorithm illustrates the problem of residual noise for this component (figure 5.14). Though yawing moment is heavily contaminated it appears to be a general rule that all configurations first "overshoot" the quasi-static result before returning towards it. This is in good agreement with the findings of Beauvais, 1967 (ref.6).

The sideforce time histories for a yaw angle of 30 degrees (figure 5.15) provide large aerodynamic signals that clearly demonstrate the same hierarchy of configurations as the quasi-static tests, however, as previously mentioned, the effects of model entry into the gust are distorted due to the smoothing function. As a consequence of this the model appears to anticipate both gust entry and exit. In addition, smoothing also makes it difficult to assess the exact number of model lengths travelled from nose entry to the steady state condition. It is only possible to deduce that steady state is reached within a certain value.

A comparison of quasi-static results (given in chapter four) with the steady-state section of dynamic data again illustrates that the general hierarchy of model configurations is the same for both tests (figure 5.16 and 5.17). In addition, the dynamic results are consistently lower than the quasi-static values. Figure 5.18 demonstrates the point by plotting quasi-static C_Y alongside dynamic C_Y for the two extreme configurations (estate and rounded fastback). This is in good agreement with the results of Howell, 1983 (ref.16) though the phenomenon is not fully understood.

With reference to the sideforce response it appears that the side-load takes longer to develop in the case of the square-edged fastback (see figure 5.15). This ties in with quasi-static observations of a bi-stable flow-structure (see chapter four). The model will experience a change from one flow condition to the other (that is, from an attached "C-pillar" vortex to a separated one) as it moves from zero degrees yaw ahead of the gust to 30° immersed in it. The delay in reaching steady-state is therefore linked to the slow development of the viscous side-load component associated with the second flow structure.

Such conclusions only bear weight if the results are proved to be repeatable. Only two "wind-on" runs were conducted per configuration and these are over-plotted for both the rounded and square fastback models in figures 5.19 and 5.20. These illustrate the acceptable level of repeatability of aerodynamic coefficients (once the influence of mechanical signals has been removed). This then demonstrates the reliability of the crosswind track technique.

5.5 Discussion

Tests conducted on the Crosswind track facility have been adversely affected by unwanted mechanical inputs. The effect was compounded by resonant frequencies of associated equipment existing within the frequency range of interest. Model mass also had a critical influence upon signal quality.

Analysis concentrated upon C_Y ; the least contaminated of all coefficients measured. A simple smoothing algorithm was applied to the data, to allow assessment of the steady-state region within the gust. The general hierarchy of the results agrees well with quasi-static measurements, though the actual values are less than the quasi-static result.

The bi-stable flow structure that affects the square-edged fastback was seen to influence the dynamic results. The time for this configuration to reach steady-state was longer than any other. The reason for this lies in the change from one fundamental flow structure to another and the slow build up of the viscous side-load associated with the second flow regime.

The crosswind track has proved to be a reliable facility that can produce repeatable aerodynamic data. With further refinement it will no doubt prove to be a useful research tool.

Chapter 6

Dynamic Yaw Tests

6.1. Introduction

In this chapter the results obtained from dynamic yaw tests are presented and discussed. Though the equipment employed is known as the "Oscillatory Facility" it is important to note that the experiments described here are of a transient nature and not oscillatory.

Initially the intention was to use the bluff-body model to collate data from dynamic yaw tests and crosswind track experiments. Unfortunately, this was not possible because, as previously discussed, the general quality of test track data is poor, especially in the case of the relatively heavy bluff-body model.

Based upon the quasi-static tests and preliminary dynamic yaw research three bluff body model configurations were selected for testing as follows:

- i) The square-back configuration. This model experiences the greatest C_Y and the lowest C_N . When the model is at yaw a single attached vortex exists on the surface of the roof.
- ii) The 20 degree backlight configuration. This model generally experiences the lowest C_Y and greatest C_N . When the model is at yaw there is vortex interaction between its roof and backlight vortices.
- iii) The 30 degree backlight configuration. This model is influenced by a bi-stable flow-field that causes its force and moment response to switch between values close to those of the square-back and values similar to those of the 20 degree backlight. The model is influenced by highly structured separation on the backlight surface and a well defined pair of "C-pillar" vortices.

6.2 Development of the Facility

Development of the facility included the implementation of new data acquisition equipment, a PC to control the turntable and the re-siting of minor controls to permit one-person operation. Problems relating to the model's inertia were encountered during the dynamic yaw tests, however, these effects only tend to influence C_N results and are far less serious than similar problems on the crosswind track.

6.3 Characteristics of the Oscillatory Facility

Tests investigated the effects of five different yaw rates (20,30,40,50 and 60 degrees per second). The models were moved about their centres through two yaw angle ranges ($0 - 10^\circ$ and $0 - 15^\circ$) in both clockwise and anticlockwise directions (i.e. $0 - 10^\circ$ and $10 - 0^\circ$).

To obtain aerodynamic data from the oscillatory facility the principle is to run two tests for each configuration, one with the model moving and wind-tunnel running ("wind-on" test) and one with the model moving alone ("wind-off" test). The wind-off signal is subtracted from the wind-on and this should remove any mechanical contamination within the aerodynamic data, however, as with the track tests, the nature of the facility makes matters a little more complicated than this. It is therefore necessary to look closely at the characteristics of the oscillatory facility to obtain the best from the aerodynamic information.

6.3.1 Resonance of the Combined Force-Balance/Mounting System

The method employed for assessing the resonant frequencies of the balance system was similar to the approach used for the crosswind track.

A "wind-off" test was conducted, that is, the model was moved in yaw with the wind tunnel itself not operating. After model arrest the balance system continues to freely oscillate. As in chapter five fast fourier transform (FFT) analysis is performed on the section of data containing the free oscillations. The only significant oscillations (found to be in yaw) occurred at approximately 14

Hz. The FFT analysis for this component is presented in figure 6.1. Compare this with the FFT analysis of free oscillations in yaw for the track facility, given in figure 5.2 (note that there is a considerable difference in the scales of the two figures). Of course, the significant difference in signal amplitude is largely due to the fact that model launch and arrest on the track produce a greater impulse than the corresponding phases of the relatively simple dynamic yaw tests discussed in this chapter.

6.3.2 Measured Force and Moment Coefficients

Typical coefficients measured during a single wind-on run appear in figure 6.2. Sideforce and yawing moment signals are presented with no attempt to remove mechanical "contamination". (Note the difference in y-scale for the two coefficients).

As discussed in chapter four drag measurements produced some unexplained discrepancies when the model was de-rigged between test runs. For this reason it is impossible to deduce what implications simulation of a transient situation has for C_D . Fortunately sideforce and yawing moment, which are of primary importance with regard to vehicle stability, demonstrate excellent repeatability. The following discussion will centre upon C_Y and C_N .

Consulting figure 6.2 once more, comparison of the quasi-static and dynamic results shows that for the configuration under scrutiny (20° backlight moving at 20 deg/sec from 0° to 15° angle of yaw) transient effects are insignificant in sideforce. More importantly, signal "noise" in sideforce is negligible. This is a characteristic of all sideforce results and greatly simplifies the process of data analysis for this component. On the other hand there are differences between the quasi-static and dynamic results for yawing moment coefficient which appear to be largely due to mechanical inputs. It is of little surprise that the yawing motion of the dynamic test induces mechanical "noise" in the recorded aerodynamic yawing moment.

6.3.3 Spectral Analysis of Force and Moment Coefficients

An FFT spectral analysis of the transient wind-on phase reveals a significant frequency peak in yawing moment only (figure 6.3). This occurs at the resonant frequency of 14 Hz and the same frequency is found within wind-off data (shown as a dotted line). From this it is clear that there are yawing moment inputs at the resonant frequency.

6.3.4 Data Repeatability

Since the level of repeatability is good the best way of illustrating it is to over-plot the data from a sequence of runs (figure 6.4).

6.3.5 Limitations of Data Processing

The dynamic yaw results for C_Y are of good quality and present no problem with analysis. No form of digital filtering or smoothing is necessary for this force component.

C_N suffers from mechanical inputs which are not wholly removed by subtraction of the wind-off signal. The reason for this is complex and is discussed further in appendix D, however, one point is worth mentioning here.

One reason for the existence of mechanical contamination is the fact that at higher rotational rates the large inertia signals at model launch and arrest do not line up within respective wind-on and wind-off data files. This is because the aerodynamic yawing moment experienced during wind-on tests is large enough to actually influence the movement of the turntable, either speeding it up or slowing it down. Figure 6.5 shows the difference between programmed yaw rate and achieved yaw rate.

As with the data from the crosswind track, the only recourse was to use some form of filter, following subtraction of the wind-off data (see appendix B).

For future research, the only real solution to the problem of mechanical contamination of C_N is to simultaneously reduce the mass of the test model and

increase the resonant frequencies of the balance system. Dynamic yaw tests conducted by the author (Cairns, 1992 ref.28) have shown that mass reduction pays dividends in terms of reducing the wind-off signal. Figure 6.6 demonstrates this by comparing raw wind-off data-files for balance channel 3 (the channel that responds most strongly to yawing moment).

6.4 Test Results

The results for sideforce and yawing moment are considered individually. As previously stated, the signal to noise ratio for sideforce is high, and as a consequence C_Y requires no digital filtering. Yawing moment on the other hand is improved by the application of a simple smoothing algorithm; in this case an eight point moving average.

The Reynolds number for tests on the bluff-body model, based upon freestream flow velocity and model length (0.69m) was $Re = 8.6 \times 10^5$. Additional test results are contained within appendix D (figures D9 to D16).

6.4.1 Sideforce Results

For the majority of cases quasi-static and dynamic sideforce results are near-identical irrespective of yaw angle range or yaw rate. An illustration of typical quasi-static and dynamic data is presented in figure 6.7.

The only result that shows a difference between the quasi-static and dynamic cases is the 30 degree backlight configuration. Even so, variations between the two types of data only occur in the yaw angle range $\beta = 0 - 15^\circ$. C_Y first overshoots its steady-state value before returning to it. The overshoot (ΔC_Y) is always the same magnitude, though the time to return to the quasi-static value can vary considerably (figure 6.8).

As explained in chapter four, the 30 degree backlight is governed by a bi-stable flowfield structure. The overshoot witnessed in dynamic tests is a consequence of the flow pattern that exists at small yaw angles remaining beyond its normal "cut-off" yaw angle. At this extreme yaw angle the flow structure is very "fragile". Small fluctuations in the wind tunnel flow are

enough to cause it to breakdown. The precise time at which this occurs is dependent upon fluctuations of the wind tunnel flow.

Certain similarities can be observed between the dynamic behaviour of the 30 degree backlight and that of an oscillating aerofoil. In this case aerofoil incidence (α) is analogous to vehicle yaw angle (β). A comparison of static and dynamic normal force acting on an aerofoil is shown in figure 6.9 from Carr *et al*, 1977 (ref. 32). Static forces coincide with dynamic forces as α increases. With a fundamental change in the static flow structure (in this case gross separation of the upper surface flow) the two results diverge and the dynamic forces "overshoot" the static ones. This behaviour is similar to the sideforce response of the 30 degree backlight. The physics of dynamic aerofoil stall are well documented and the following considers the dynamic stall of a NACA 0012 aerofoil.

Initially as the aerofoil exceeds the static stall angle the boundary layer remains thin and there is no sign of flow reversal at the surface. As α increases flow reversal appears at the rear of the aerofoil. Large eddies appear in the boundary layer and move down the aerofoil. Flow reversal spreads over the aerofoil chord and at $\alpha = 23.4^\circ$ the boundary layer at the front of the aerofoil abruptly separates and a vortex forms travelling at 35 - 40 percent of the freestream velocity. The first effect of dynamic stall is that normal force rises more rapidly with increasing incidence (opposite to the steady state stall). With the vortex at approximately mid chord the normal force decreases sharply. After the dynamic-stall vortex has left the aerofoil the flow experiences some lower amplitude oscillations before settling down as a fully separated flow similar to that observed on aerofoils experiencing steady state stall.

6.4.2 Yawing Moment Results

As with sideforce, the dynamic yawing moment for the 30⁰ backlight shows a difference with quasi-static results in the range $\beta = 0$ to 15 degrees. The results undershoot by a constant magnitude and the time taken for them to return to the quasi-static value is very much the same as in the sideforce case. Figure 6.10 shows the quasi static data with the overshoot marked on for both C_Y and C_N . The way in which each overshoot matches the quasi-static curves for the initial flow structure support the idea that dynamic yaw tests are briefly

maintaining the flow structure at a yaw angle were it would not normally exist.

Dynamic yawing moment results are similar to quasi-static values except that all dynamic data exhibits a "lag" with respect to the direction of model movement (figure 6.11). That is, if quasi-static yawing moment is increasing then dynamic yawing moment will be lower, at any given model position. Conversely, with decreasing quasi-static yawing moment the dynamic result will be greater. The lag can be measured in terms of ΔC_N , the difference in quasi-static and dynamic measurements of C_N , assessed at various values of β . The result for the 20 degree backlight moved from $\beta = 0$ to 15° at 3 different yaw rates, is given in figure 6.12.

It is observed that the lag generally increases with increasing yaw rate. Also there appears to be a peak in the results, after which the lag tends to reduce as the yawing motion continues. The case for 20 deg/sec appears to exhibit an "advance" at $\beta = 4^\circ$. This is not a true aerodynamic advance but merely a result influenced by mechanical "noise".

In all probability the effect of the lag is at least partly due to peculiarities of the test technique. As the model rotates there is an effective change in local yaw angle. This change ($\Delta\beta$) is illustrated at the nose and tail of the model in figure 6.13. This will alter the yawing moment and hence tend to produce a lag with respect to the quasi-static signal. The rotating air mass effectively acting upon the model during wind-off tests could be expected to cause a yawing moment in the same sense as the above case, however, this effect is possibly less than the effect of $\Delta\beta$.

Watkins 1992, (ref.29) considered local velocity vectors along the centre-line of a rotating model. Figure 6.14 uses this approach to show how local yaw angle changes with model movement. It has been seen that the "lag" increases with increasing yaw rate and to make the situation more apparent, a rotational rate is presented that is ten times the highest value tested. The figure helps one to visualize the reason why dynamic yawing moment differs from the quasi-static result.

Though no correlation was observed between model configuration and the magnitude of the lag it may be possible that certain changes in

configuration could either:

- a) reduce the degree of lag
- b) cause the quasi-static and dynamic results to coincide or even
- c) produce an "advance"

To illustrate this idea, a model moving with increasing β is considered. In this case one of the above conditions might be witnessed if the increase in local yaw angle at the rear of the model (see figure 6.13) induces flow accelerations that in turn create a region of relative low pressure acting to increase quasi-static yawing moment and sufficient in magnitude to overcome the effects of reduced local yaw angle at the front of the vehicle.

6.5 Discussion

Tests conducted within the Oscillatory Facility have produced good quality aerodynamic information regarding dynamic yaw situations.

Some mechanical signals remained in the yawing moment results and the facility could be improved further by minimizing the mass of test models employed and increasing the resonant frequencies of the facility.

Yawing moment demonstrates a lag, with respect to quasi-static results. This lag increases in magnitude with increasing yaw rate and is due, at least in part to the characteristics of the simulation.

Dynamic sideforce is seen to be virtually identical to the quasi-static result, except for the case of the 30 degree backlight model, moving from $\beta = 0$ to 15° . This configuration is dominated by a bi-stable flow. The implications of dynamic testing for this configuration are that the initial flow, experienced at small yaw angles, will be maintained briefly at higher yaw angles where it would not normally exist. This of course causes deviation from the quasi-static results. For the 30 degree backlight, sideforce overshoots the quasi-static results, while yawing moment undershoots them.

Conclusions

A test track facility for measuring dynamic loads on vehicles in gusts has been designed and constructed. After development and commissioning tests the facility is seen to produce repeatable data, but difficulties in isolating the aerodynamic and mechanically induced loads remain.

A basic saloon car model with interchangeable estate, notch-back, rounded and square-edged fastback configurations was tested on the track facility. Transient loads were measured as the model passed through a gust of variable resultant yaw angle. Time histories for aerodynamic sideforce demonstrate that the general hierarchy, with respect to model configuration, agrees well with quasi-static measurements. Sideforce develops quickly, mostly within one vehicle length of gust entry. Steady-state sideforce within the gust is generally lower than its quasi-static equivalent. This is in good agreement with the findings of Howell, 1983 (ref.16).

Mechanical inputs in yawing moment induce considerable signal noise, therefore, the processing of this coefficient presented the most demanding analysis task. This was unfortunate as yawing moment is arguably the most important coefficient with regard to motor car aerodynamic stability. A simplistic filtering technique makes some data analysis possible and results suggest that aerodynamic yawing moment for all configurations, overshoots quasi-static values upon gust entry. However, further development of the facility and data processing techniques is required.

The CoA Oscillatory Facility received development and has subsequently been used to undertake dynamic yaw experiments on a bluff-body model, fitted with various backlight angles.

Both crosswind-track and dynamic yaw experiments produce mechanical noise at the resonant frequency of test equipment, however the amplitude of such signals is significantly greater for the crosswind-track.

Quasi-static experiments have demonstrated how two of the test model configurations are each influenced by two distinct flow structures; one at low yaw angles, the other at high yaw angles. For both configurations there is an intermediate region where the flow is bi-stable, that is, either of the two structures can exist. The likelihood of any one particular flow structure existing is governed by the flowfield history - essentially the direction in which the model is yawed.

Both crosswind track and dynamic yaw tests indicate that bi-stable flow phenomenon, witnessed in quasi-static tests, have implications in dynamic simulation. The flow structures associated with this bi-stability are viscous-dominated and the slow development of viscous loads can be an important feature.

It is possible that various vehicle configurations could induce bi-stable flow. If such flow behaviour is apparent then quasi-static force and moment measurements will not provide an adequate engineering estimate of the transient aerodynamic loads. In this event it is imperative that the automotive engineer conducts investigations into the vehicle's dynamic performance.

Chapter 8

Recommendations for Further Work

The single most important objective is finding a method to increase the resonant frequencies of the Crosswind-Track. Success in this matter would facilitate isolation of aerodynamic data in future experiments. It is worth emphasising once again that the quality of data is also closely linked to model mass. Keeping this to a minimum is a prerequisite. These factors also apply, to a lesser extent, to the Oscillatory Facility.

A relatively minor, though nevertheless beneficial, operation would be to reposition the model-release and braking areas. Originally the release point was sited close to the BLWT, to avoid noticeable model deceleration prior to gust entry. The brake was fitted adjacent to the tunnel because braking performance was viewed with caution. Neither situation is as limiting as was first thought, therefore, moving the release and arrest points further from the working section is now a realistic option. This will extend the effective test area and increase the amount of usable data before and after the gust (Note - ground-board extensions would be required in the new region).

Initially it would be advisable to conduct tests with boundary layer effects eliminated, for the reason expressed in section 3.2.7. Once a suitable data base had been compiled, further tests could be undertaken to assess the implications of shear. By suitable adjustments within the BLWT it should be possible to modify both vertical shear (boundary layer profile) and horizontal shear (gust profile).

Future development of the Oscillatory Facility could benefit from an investigation of balance performance, with respect to drag measurement, to discover why this component should produce such poor repeatability.

Track experiments during the current course of research have not endeavoured to simulate the effects of rotating wheels. Since this has been shown by certain researchers to have a significant effect on vehicle flowfield it would be advantageous to incorporate this feature into the crosswind track. The engineering required to produce this need not be complicated as figure 8.1 illustrates. A mounting plate is fitted to the top of the model carriage upon which two axle supports are mounted. These supports pass through the slot in the ground board designed for the balance strut. At the top of each axle support is a spring and damper unit to ensure wheel contact is maintained. It should be possible to choose a suitable coil and damper from the large number now sold for use in radio controlled racing cars. The axle is mounted on a pivot to allow movement in roll due to small imperfections in the ground board surface. The wheels should be lightweight and fitted with a suitable bearing. At no point do the axles or wheels touch the model shell.

The ground board for the rotating wheel case would need to be the complete length of the test track. Wheel arch cavities can be represented in the model and this will, in turn reduce the risk of interference between wheel and body. One of the greatest problems in preparing the existing crosswind track, was setting the gap between fixed wheel and ground board, so that it was as small as possible, while remaining clear of the "road" for the complete length of the test section. More importantly, the gap generates an unrealistic low pressure region beneath the wheel. The rotating wheel technique eliminates both of these problems. While the aerodynamic loads on the wheels themselves are not measured, the main emphasis is upon the effects of body styling changes and for this reason it is considered more important to accurately simulate the complete vehicle flowfield.

Once reliable aerodynamic force and moment results are being obtained a mathematical model could be implemented to assess accident risk levels. Such a model has been developed by Baker, 1985 and 1987 (refs. 24 and 25). In addition, Howell 1989 (ref.33) has produced satisfactory predictions, of vehicle lateral displacement through a controlled crosswind gust, by using a simple two degree of freedom model along with wind tunnel data and crude assumptions regarding tyre and suspension properties. The technique has proved adequate for initial assessment of vehicle behaviour in a crosswind.

References

1. Jacobson M.A. (1985) *Accident Avoidance - The Crosswind Sensitivity of Some Streamlined Cars*, The Tenth International Technical Conference on Experimental Safety Vehicles.
2. Bitzl F. (1961) *Die Einwirkung von Seitenwindkraften auf den Strassenverkehr*. Zeitschrift für Verkehrssicherheit, no.3, 1961, and no.2, 1962. Dr. Arthur Tetzlaff-Verlag, Frankfurt/M.
3. Barth R. (1960) *Effect of Unsymmetrical Wind Incidence on Aerodynamic Forces Acting on Vehicle Models and Similar Bodies*, M.I.R.A. Translation no.15/60.
4. Hucho W.H. (1981) *Aerodynamics of Road Vehicles* (English version 1987 Butterworths and Co ISBN 0408014229). page 219
5. Kobayashi N. and Sasaki Y. (1987) *Aerodynamic Effects of an Overtaking Articulated Heavy Goods Vehicle on Car-Trailer - An Analysis to Improve Controllability*, S.A.E. paper 871919.
6. Beauvais F.N. (1967) *Transient Nature of Wind Gust Effects on an Automobile*, S.A.E. paper 670608.
7. Tustin R.C. and Carr G.W. (1963) *Aerodynamics of Basic Shapes for Small Saloon Cars*, M.I.R.A. report.
8. Gilhaus A.M. and Renn V.E. (1986) *Drag and Driving-Stability Related Aerodynamic Forces and Their Interdependence - Results of Measurements on 3/8 scale Basic Car Shapes*, S.A.E. paper 860211.

9. Smith J.P. (1972) *Wind Gusts Measured on High-Speed Roads*.
MIRA Research report no. 1972/7
10. Emmelmann H.J. (1981) *Driving Stability in Side Winds*, - from
the publication *Aerodynamics of Road Vehicles*,
edited by Wolf Heinrich Hucho. English edition
Butterworths and Co. 1987.
11. Kohri I. and Kataoka T. (1989) *Research on Improvement of
Crosswind Properties of Passenger Vehicles*,
J.S.A.E. Review, July 1989.
12. Davis J.P. (1987) *Cross Wind Stability of High Performance Road
Cars*, S.A.E. paper 870724.
13. Brown G.J. (1973) *Aerodynamic Disturbances Encountered in
Highway Passing Situations*, S.A.E. paper 730234.
14. Yoshida Y. *et al* (1977) *Transient Aerodynamic Forces and Moments
on Models of Vehicles Passing Through a Cross-Wind*,
S.A.E. paper 770391.
15. Stewart M.J. (1977) *Transient Aerodynamic Forces on Simple Road
Vehicle Shapes in Simulated Cross-Wind Gusts*,
M.I.R.A. Research Report no.1977/5.
16. Howell J.P. (1983) *The Response of High Speed Ground Vehicles to
Crosswind Gusts*, Ph.D. Thesis, Warwick University.
17. Baker C.J. (1986) *Train Aerodynamic Forces and Moments from
Moving model Experiments*, Journal of Wind
Engineering and Industrial Aerodynamics, no.24,
pages 227 to 251.

18. Kobayashi N. and Yamada M. (1988) *Stability of one box type vehicle in a Cross-Wind - An Analysis of Transient Aerodynamic Forces and Moments*, S.A.E. paper 881878

19. Garry K.P. and Cooper K.R. (1986) *Comparison of Quasi-Static and Dynamic Wind Tunnel Measurements on Simplified Tractor -Trailer Models*, Journal of Wind Engineering and Industrial Aerodynamics, no.22, pages 185 to 194

20. Watkins S., Gibson K. and Saunders J.W. (1984) *Wind Tunnel Tests on a One-Tenth Scale Tipper Truck with Various Drag Reducing Devices*, Melbourne Institute of Technology Report no. WTR1034.

21. Takanami K. *et al* (1976) *Conversion from Wind Vector into Aerodynamic Inputs Acting on Vehicle Body in Side Wind Gusts*, FISITA Sixteenth Congress, Tokyo.

22. Van den Hemel H.J.M., Elink Schuurman R., Riemersma J.B.J. and Blaauw G.J. (1990) *The Way was Long, the Wind was Cold*, Journal of Automotive Technology International, pages 411 to 415.

23. Hucho H.W. and Emmelmann H.J. (1973) *Aerodynamic Derivatives of a Vehicle in Cross Wind Gusts*, S.A.E. paper 730232.

24. Baker C.J. (1985) *A Simplified Analysis of Various Types of Wind -Induced Road Vehicle Accident*, Journal of Wind Engineering and Industrial Aerodynamics, no.22, pages 69 to 85.

25. Baker C.J. (1987) *High Sided Articulated Vehicles in Strong Cross Winds*, Journal of Wind Engineering and Industrial Aerodynamics, no.31, pages 67 to 85.

26. Chometon F. (1988) *Simultaneous Use of Oil-Flow Patterns and Total Pressure Tomographies for a More Complete Understanding of Flow Structures Around a Car*, S.A.E. paper 885137.

27. Werle H. (1986) *Structures des Decollement sur des Ailes Cylindriques*.
La Recherche Aerospatiale, No.3, pages 221-242

28. Cairns R.S. (1992) *Quasi-Static and Dynamic Wind Tunnel Testing of Configurations Relevant to the "E-Auto" Project*, International Ecotechnology Research Centre report, Cranfield, (restricted circulation).

29. Watkins S. *et al* (1992) *On the Generation of Turbulence for Road Vehicles*. Paper 2E-4 pp.223-226, 11th Australian Fluid Mechanics Conference, University of Tasmania, Australia

30. Dominy R.G. (1991) *A Technique for the Investigation of Transient Aerodynamic Forces on Road Vehicles in Crosswinds*.
Proc. of the Inst. of Mech. Engineers Vol 205, pp 245-250

31. Mullarkey S. (1990) *Aerodynamic Stability of Road Vehicles in Side Winds and Gusts*. PhD Thesis, Imperial College.

32. Carr L. *et al* (1977) *Analysis of the Development of Dynamic Stall Based on Oscillating Aerofoil Experiments* NASA TN D-8382

33. Howell J.P. (1989) *Crosswind Response of Cars*. Autotech 89, IMechE C399/3

Appendix A

Flow Characteristics of the Boundary Layer Wind Tunnel

Vehicle model tests during the course of this research were undertaken with the effects of the atmospheric shear layer largely eliminated. This approach was adopted in order to facilitate the assessment of purely dynamic characteristics, when the moving model experiments were compared with more conventional quasi-static test results.

The Cross Wind Track facility was built to use the boundary layer wind tunnel of the College of Aeronautics. This Tunnel allows accurate simulation of atmospheric boundary layer characteristics, by the use of such devices as roughness elements upstream of the test model. However, the very nature of the working section with its large "Fetch", ensures that the floor boundary layer is indeed extensive, even when the tunnel is completely "clean".

For the current research, a ground-board, raised above the tunnel floor, was installed. The model cars travel above this new ground plane as the tunnel's low energy boundary layer is effectively drawn off beneath it. Before the ground-board was fitted, the wind tunnel was calibrated at various flow velocities by traversing a Pitot-static probe across it at different heights above the floor. The results of this calibration are illustrated in figure A1 (the freestream flow velocity (U_∞) is used as a reference to non-dimensionalize the results). From this information, it was decided that a ground-board height of 10 cm would sufficiently reduce the effects of shear.

The second tunnel calibration produced the horizontal velocity contours above the new ground-board shown in figure A2. These illustrate the beneficial modification of shear effects, particularly at the higher freestream flow velocities. In the interests of clarity only a selected few velocity contours are presented here. Lateral position for the velocity contours was measured from

the control room side of the tunnel, that is, from the opposite side to model entry, therefore, the model crosses the contours from right to left.

When calibrating the tunnel, freestream flow velocities were selected to correspond to yaw angles of 20 and 30 degrees, based upon estimations of what the likely model speed would be. As can be seen from figures A1 and A2 the freestream flow velocities differ for the two sets of contours. Initially it was anticipated that model speeds of up to 25 ms^{-1} would be achieved. The second calibration was conducted after early model tests had shown 18 ms^{-1} to be a more realistic value, however, the actual model speed eventually selected was closer to 14 ms^{-1} . This figure gives a resultant yaw angle of approximately 25° at a freestream velocity of 6.4 ms^{-1} .

A qualitative assessment of tunnel flow was conducted by the introduction of smoke filaments into the flow at various positions, to ensure that no adverse characteristics existed.

The calibrations previously detailed do not give information concerning flow velocities close to the ground board. This is because the static tappings on the conventional Pitot-static probe used could suffer from interference effects when in close proximity to a surface. For the third calibration, boundary layer profiles were measured at five different stations across the tunnel. These positions are illustrated in figure A3. The probe used was a fine scale Pitot tube with a static probe mounted 64 mm directly above it. The dynamic pressure measurements for all calibrations were taken 14cm upstream of the model support arm slot. This corresponds approximately to the position of the windward side of the test model.

Figure A4 gives a comparison of the boundary layers produced above the tunnel floor and ground-board respectively. The fuller profile above the elevated ground-plane is immediately apparent. Figures A5a to A5e show the boundary layers above the ground board at the five stations across the wind tunnel. Extreme profiles are illustrated and where there is a large difference in their values, an intermediate profile is also included.

Appendix B

Data Acquisition and Processing

The following material concerning data acquisition and analysis is divided into three sections as follows:

- i) Quasi-static tests
- ii) Track tests
- iii) Dynamic Yaw tests

Force balances and pressure transducers used were all calibrated before testing, with additional checks performed afterwards.

B.1 Quasi-Static Tests

Voltage readings from the force balance were sampled by a personal computer, via a GPIB known as an "IEEE 488" interface. However, before this could be achieved the signals were passed through an analogue-to-digital converter.

A BASIC programme (CX1.EXE) was used to control the data acquisition, logging all forces, moments and freestream dynamic pressure along with the user-defined yaw angle. The programme read all channels simultaneously and averaged them over one hundred readings. The data obtained was then processed by a second BASIC programme (BLWTQS.BAS in the case of the Boundary Layer Wind Tunnel and OFQS.BAS in the case of the Oscillatory Facility) which subtracted any zero offsets and calculated the force and moment coefficients, ready for plotting by a separate software package.

Zero values were recorded immediately before and after each run. In the

case of the quasi-static tests conducted in the oscillatory facility, the zero figures constitute the first and last lines of the data file. However, the results from the boundary layer tunnel have separate zero files. This system ensured that no files were left open for long periods, a problem that could have easily arisen since the boundary layer tunnel takes longer to prepare for quasi-static tests than the oscillatory facility.

Freestream dynamic pressure was recorded in both wind tunnels by the use of a Pitot-static probe in the working section. The blockage ratio for the basic saloon model in the boundary layer tunnel is 1.3% and therefore results can be used confidently, with no correction for blockage. For the oscillatory facility however, the blockage ratio for the bluff-body model is in excess of 6% and hence a correction is applied to the dynamic pressure.

The reference dynamic pressure is derived from a calibration of the Pitot-static probe (used during tests) against a second Pitot-static probe positioned at what would be the centre of model volume in the working section. Correction for blockage is achieved by applying the continuity equation. This is a relatively simple approach which assumes that the interference velocity increase is uniformly distributed over the wind tunnel cross section. The equation for corrected dynamic pressure is as follows:

$$(q_c/q) = (1-S/C)^{-2}$$

Where q_c = corrected dynamic pressure

q = reference dynamic pressure

C = duplex tunnel area.

S = model plus mirror image frontal area.

The reference dimensions for all tests were taken as the projected frontal area of the model and the wheelbase (or nominal wheelbase) length.

B.2 Track Tests

A portable data recorder mounted on the model carriage logs, sequentially, two seconds of force and moment data from five balance channels, as the model traverses the simulated crosswind gust. Normally, sampling frequency is set at least twice as high as the greatest frequency of interest (the minimum condition according to the Nyquist sampling theory). For our purposes it is advantageous to sample at as high a frequency as possible for reasons other than just anti-aliasing.

The Polycorder is only equipped with one analogue-to-digital converter. This makes it an order of magnitude less expensive than a unit with an A/D for each channel but means simultaneous sampling is impossible. Some machines produce near-simultaneous sampling by employing what is known as a burst mode, though this is still a relatively expensive feature. Near simultaneous sampling is important because certain channels have to be combined to produce the force and moment results. The low level of balance interactions means that no more than two channels need be combined to produce any given force or moment value.

For a single input channel the Polycorder can sample at around 72 kHz. If more than one channel is used then this figure drops dramatically to a channel to channel scan rate of just 2000 Hz. The machine was purchased on the understanding that its software would be rewritten to increase the total scan rate to 8000 Hz; considered to be an acceptable value. Unfortunately the software modifications caused large errors in the recorded signals and after much correspondence with both the manufacturers and distributors this software had to be abandoned. The maximum sample rate of 2000 Hz was used (giving 400 Hz effective sample rate per channel).

Light emitting diodes are placed at intervals along the track. When one of two corresponding photo-transistors, mounted on the model carriage passes an LED, a digital signal is triggered. The state of the digital signal (either "high" or "low") depends upon which photo-transistor is affected. By arranging the system so that each photo-transistor is activated by alternate LEDs, the model's passage can be traced from the changing digital signal. The digital signal is logged by the data recorder and is also used to trigger the recording

sequence. Since no analogue-to-digital converter is required, the digital signal can be recorded at a full 2000 Hz and therefore allow accurate placement of the model to within .5 milliseconds.

Three types of test were conducted:

- i) Cross-wind tests. Models are fired along the track as the Boundary Layer Wind Tunnel simulates an impulsive crosswind gust.
- ii) Zero degree yaw-angle tests. Here models are fired along the track without the Boundary Layer tunnel operating.
- iii) Wind-off tests. In these tests the model is substituted by a system of wooden plates and ballast weights that reproduce the model's mass and centre of gravity position. The plates connect the active ends of the balance in the same manner as in the model. The whole system is then covered with an aerodynamic shroud and fired along the test track.

Multiple wind-off runs were undertaken to obtain a spread of model speed. The resulting choice would permit selection of wind-off files to give a near perfect alignment with crosswind results. For each configuration two crosswind tests were conducted. The data was downloaded to a personal computer after each run and converted from binary form to an ASCII file through use of the data recorder's own "Polytools" software.

A BASIC programme "PD4.BAS" was written to subtract zero offsets, to print out information on the vehicles progress through the tunnel, synchronise the signals with respect to nose entry into the gust and configure the data so that further processing could take place within a commercial graphical spreadsheet package (called "DADiSP").

The force and moment coefficients are all based upon resultant crosswind dynamic pressure (derived from the combination of model velocity and wind tunnel flow velocity), model projected frontal area and model wheelbase (see figure 3.12).

Digital filtering techniques were investigated as a tool to eliminate mechanical signals that remained within the aerodynamic data after initial processing. Of the four categories of digital filter (lowpass, bandpass, bandstop and highpass) the lowpass filter was chosen, since the likely aerodynamic component is of a relatively low frequency, while mechanically induced noise essentially occurs at higher frequencies.

For processing multi-frequency signals, the non-recursive filter also known as the Finite Impulse Response (FIR) filter, offers the advantage that it can be made phase-linear. This guarantees the absence of phase related amplitude errors in the resulting output signal. For this reason, the FIR filter routine within the DADiSP software was used. DADiSP employs the Remez Exchange algorithm (a standard polynomial method) to generate the filter series.

Aspects that must be considered during the design of a filter are best covered with reference to the response curve in figure B.1 (a 50 Hz lowpass filter). Firstly the transition width should be narrow, to permit accurate separation of the passband and stopband frequencies. Secondly there should be no "ripple" in the passband as this would result in distortion of the output signal.

A high attenuation in the stopband is desirable because this enhances elimination of the unwanted frequencies. Finally a minimum number of coefficients in the filter series reduces computing time. Unfortunately even if an infinite number of coefficients are allowed it is not possible to build a filter that is optimised with respect to all of the other three conditions. Sharp transition and a large stopband attenuation are only achieved by paying the price of passband ripple. Filter design is therefore a compromise which must be dictated by the properties of the data under analysis. It must be stressed that digital filters can only be expected to enhance information that is already of a reasonable quality. They cannot be used to redeem heavily contaminated data.

B.3 Dynamic Yaw Tests

The same data recorder used for track tests was employed during dynamic yaw experiments. Once again 5 analogue channels were sampled at a total of 2000 Hz (effectively 400 Hz per channel), for a duration of 2 seconds. This time no digital signal was recorded, though the three force balance channels were logged along with flow dynamic pressure and turntable position (given by the output of a belt-driven potentiometer).

The turntable is controlled by a BASIC programme (TURNT5.BAS) that operates through an IEEE 488 interface. Movement of the turntable is triggered by the data recorder, after a set period of recording "steady state" signals. This ensures that the transient phase is at approximately the same position within each data file, and hence simplifies analysis.

Three types of data file were recorded as follows:

- i) Zero offsets (model stationary, wind tunnel off).
- ii) wind-off data (model moving, wind tunnel off).
- iii) wind-on readings (model moving, wind tunnel running).

Mean zero offsets were calculated from the first file type in the list using a BASIC programme. The results were printed out as a visual check and if any significant "drift" was witnessed then the preceding data would be discarded and the test repeated.

The turntable position signal is used to determine the period of model movement for each test. Although the noise level of the signal is low, it is still difficult to judge the exact points at which model motion begins and ends. In order to obtain an accurate value for the start and stop times a linear regression technique is employed and the signal is substituted by two horizontal straight lines (the periods during which the model is stationary) and one straight line of a known gradient (the transient period). The two intersection points of these lines then give the start and stop times (figure B2). The variation of start position is small, however, the data for each test run is shifted in time to improve alignment of respective start points (to within 2.5 ms). Start time is double checked by considering the time at which channel 3 is first seen to respond (this channel is sensitive to yaw and clearly illustrates commencement

of the transient phase).

A second BASIC programme (PDD3.BAS) takes the wind off and wind-on files, subtracts the relevant zero offsets from both, aligns the signals (using the method previously described) and configures the data for further analysis within the "DADiSP" software package.

Within "DADiSP" the wind-off signals are then subtracted from wind-on values and aerodynamic coefficients are calculated using the same method for dynamic pressure correction as used in the quasi-static tests.

Due to the influence of aerodynamic effects the length of the transient phase within respective wind-off and wind-on files can differ, on average, by up to three percent. The largest mechanical signal appears at the first moment of model movement and because all signals are aligned with respect to this instant, its effect is removed by subtracting wind-off signals from the wind-on data. However, because of the difference in signal length, mechanical inputs are still evident at the end portion of the resulting aerodynamic coefficients. Spectra calculated for all channels of the raw wind-off data show that the dominant frequencies are low, with nothing above 20 Hz. The usual approach to removing the mechanical signal would be to filter the resulting signal, but because the aerodynamic data is also predominantly a low frequency phenomenon, it is impossible to employ any type of pass-band filter without affecting the aerodynamic results. A simple method to eliminate the majority of unwanted mechanical inputs, while preserving the aerodynamics, is achieved through the use of an 8 point moving average. The resulting data is then ready for plotting.

Special Software

The following gives a brief survey of the software used during the course of research. It is not intended as a user's manual but merely describes the important features of each programme/software package.

C.1 Standard Packages

A number of standard software packages were implemented to assist the development of software, perform processing of data and facilitate presentation of the work. A brief list of the main packages follows. For further information the reader is referred to the relevant user manuals.

WORD FOR WINDOWS version 2.0 (Microsoft Corp.). Word processor.

DADISP version 1.05B (DSP Development Corp.). A digital signal analysis package in the form of a graphic spreadsheet. Signals can be analysed using various functions such as Fourier analysis, Convolution, etc. This package was used to process all dynamic force and moment measurements.

DADISP version 3.0 (DSP Development Corp.). A development of the above software, this version incorporated the additional feature of digital filtering. Designs (of the FIR variety) are generated by a Remez Exchange algorithm. Unfortunately this software contained one serious flaw associated with its use of extended Random Access Memory (RAM). The "DOS-Extender" code, associated with use of additional RAM, was "third party" software, not written by the DSP Development Corporation themselves. It proved to contain several "bugs", the most frustrating of which was being returned to the system when

the data disk was full. This invariably lead to loss of the data within the current worksheet. For this reason, DADiSP 3.0 was used only to generate filter designs. These were then imported into the earlier version of the software for evaluation in final processing.

QUICKBASIC version 4.5 (Microsoft Corp.). Used to develop software for controlling test equipment and processing data.

FREELANCE version 3.01 (Lotus Development Corp.). Drawing and graph plotting package.

POLYTOOLS version 2.0 (Omnidata Corp.). Used for data transfer/formatting and writing of acquisition software. The package contains both a standard editing environment and an automatic routine for programme creation. To generate a high speed data acquisition file the user merely inputs the desired parameters, such as the channel to channel scan rate, number of signals etc. All dynamic measurements are stored in binary format and Polytools is used to convert these files to ASCII code, compatible with processing software.

C.2 CoA software developments

CX1.EXE Quasi-static data acquisition. The user defined parameters include number of channels and signal range. Multiple readings are taken and averaged for each test configuration.

TURNT5.BAS Controls turntable movement and triggers data acquisition during dynamic yaw tests. The user specifies direction, range and speed of turntable movement. In addition, changes can be made to the rate of acceleration and deceleration to and from the desired turntable speed. The format of the command string that controls the turntable is:

X -400 @ 1200 ^5 \$

This states that the x-axis is to be moved a total of 400 motor steps at a rate of 1200 steps per second (note that 40 motor steps give one degree of movement of the turntable). There are sixteen available acceleration rates, with

corresponding hexadecimal code numbers from 0 to F (refer to the "Digiplan 1185-101" manual for details of each acceleration rate).

C.3 Software Written by the Author

Software Development was undertaken following the guidelines of good programming practise. Particular emphasis was placed upon source code readability (to ease the task of "de-bugging") and program extensibility (to allow incorporation of additional programme tasks as testing progressed).

BLWTQS.BAS Takes raw data from BLWT Quasi-static tests, calculates aerodynamic coefficients and configures each file for plotting within "Freelance".

OFQS.BAS Takes raw data from Quasi-static tests conducted in the Oscillatory Facility, calculates aerodynamic coefficients and configures each file for plotting within "Freelance"

PD4.BAS Processes crosswind-track data files exported from "Polytools" and configures them for further analysis within "DADiSP".

PDD3.BAS Processes dynamic-yaw data files exported from "Polytools" and configures them for further analysis within "DADiSP". To assess the period of model movement the programme uses linear regression on the transient phase of the position trace (see also figure B2):

$$\begin{array}{ll} a n + b \sum x = \sum y & \text{where: } a = \text{y-axis intersection} \\ a \sum x + b \sum x^2 = \sum xy & b = \text{slope of the line} \end{array}$$

DA2FL.BAS Configures data exported from "DADiSP" to a format suitable for plotting in "Freelance".

Appendix D

Additional Dynamic Test Results

The time histories of dynamic C_Y and C_N , contained within this appendix augment the results of chapters five and six (chapters concerned with transient testing).

Commissioning tests on the Crosswind Track were undertaken using a basic saloon car model with interchangeable modules giving estate, notch-back, square and rounded fastback configurations (figures 3.14). Further Crosswind Track experiments were also conducted on a bluff-body research model (figures 3.15), though inertia effects proved to be at a level that made subsequent isolation of aerodynamic signals impossible. (The mass of the bluff-body is 2.5 times greater than that of the basic saloon).

Aerodynamic information was obtained for the bluff-body model during dynamic yaw experiments, model mass being less critical for this test technique.

D.1 Track tests (figures D1 to D8)

C_Y and C_N measurements, from Crosswind Track tests of the Basic Saloon car are processed by a simple smoothing algorithm. C_L , C_M and C_R were subject to extreme levels of mechanical contamination and as a result no useful aerodynamic information can be derived from them.

In some respects smoothing distorts the data. Steady state regions can be assessed with confidence, but the algorithm makes the model appear to anticipate gust entry and exit. No accurate assessment of initial gust response can be made, though it is obvious that the majority of the sideforce is attained within one vehicle length of gust entry.

The hierarchy of steady state C_Y is identical to that of quasi-static measurements. At a resultant yaw angle (β) of 10 degrees all configurations quickly reach a steady state condition (figure D1). At $\beta = 15$ degrees and above, the square-edged fastback takes longer than any other configuration to achieve steady state. This is an extremely repeatable result (see figures 5.19 and 5.20), governed by the slow development of viscous-dominated loads associated with a fundamental change in flow structure.

For C_N the mechanical inputs are considerable. Only the extreme condition $\beta = 30$ degrees is presented (figures D6 to D8) as the aerodynamic inputs for this case are of sufficient magnitude to allow broad conclusions to be drawn. C_N values for all configurations overshoot the steady state condition on gust entry. As in the case of C_Y , the general hierarchy of results agrees with quasi-static data. The precise value of steady state C_N is difficult to assess, though most configurations appear to reach some sort of steady-state condition. C_N for the square-edged fastback, however, continues to decrease as the model traverses the gust. This correlates with the slow build up of viscous-dominated rear side-load whose effect is witnessed in the sideforce results.

D.2 Dynamic Yaw tests (figures D9 to D16)

Problems associated with unwanted mechanical inputs also influence the Oscillatory Facility, though, the scale of the effect is much reduced. Sideforce results are used confidently with no further processing. Yawing moment, on the other hand requires the use of a smoothing algorithm to produce results suitable for analysis.

Dynamic C_Y and C_N are presented for the two extreme yaw rates tested (20 deg/sec and 60 deg/sec) over the yaw angle ranges $\beta = 0$ to 15 degrees and $\beta = 15$ to 0 degrees.

Generally, identical results are achieved for quasi-static and dynamic C_Y (figures D9 to D12). The exception is the 30 degree backlight moving from $\beta = 0$ to 15° . Quasi-Static results have shown that the flowfield around the 30 degree backlight undergoes a fundamental change in the region $12^\circ < \beta < 15^\circ$. It is important to note that this effect is dependent upon flowfield history.

During dynamic tests the initial flowfield structure continues to exist at $\beta = 15^\circ$ degrees (see figures D9 and D10) and this causes the dynamic C_Y measurements to overshoot quasi-static results. The initial flow structure is very "fragile" at $\beta = 15^\circ$ and eventually the second flowfield establishes itself. The time taken for this to occur appears to depend upon fluctuations in wind tunnel flow. Once the change in flow structure has started, the second regime takes approximately 0.3 seconds to form.

Quasi-static tests on the 30° backlight bluff-body model have demonstrated a large hysteresis loop in force measurements. The model must return to $\beta = 0^\circ$ before the initial flow structure will re-establish. For this reason there are no unusual dynamic effect for rotation of the model from $\beta = 15$ to 0° .

At high yaw rates (50 deg/sec. and above) models moved from $\beta = 15$ to 0° will overshoot their rest position of $\beta = 0^\circ$. Initially, the turntable stepper motor exerts a considerable force to overcome the aerodynamic yawing moment acting against model movement. The magnitude of aerodynamic yawing moment decreases with yaw angle, but because the yaw rate is high, the stepper motor has insufficient time compensate and so overshoots its rest position before returning to it.

All dynamic C_N measurements exhibit a "lag", when compared with quasi-static results. The magnitude of the "lag" increases with increasing yaw rate.

C_N measurements for the 30 degree backlight also show a reliance upon dynamic effects. However, rather than an overshoot of quasi-static results C_N demonstrates an undershoot in the range $\beta = 0$ to 15° (see figures D13 and D14).

Mechanically induced oscillations are evident within C_N results. For each particular type of test, the form of the mechanical signal is the same, no matter which model configuration is used. Close inspection of wind-on and wind-off signals has highlighted several effects that govern the form of mechanical "noise". Within each signal there is always a large peak at model "launch". This phenomenon is constant for all data files. Subtraction of the

wind-off signal from the wind-on results removes the peak from aerodynamic data.

There are significant mechanical signals experienced during the initial transient phase, shortly after model launch. These do not tend to repeat and are the main cause of oscillations within C_N results, such as those found in figures D13 and D15. At model arrest, there is another significant peak in the inertia signal. This is removed at low yaw rates by subtraction of the wind-off data. Model movement at high rates of yaw is influenced by the aerodynamic yawing moment. This causes a difference between programmed and attained yaw rate (figure 6.5). The result is significant mis-alignment of the "stopping impulse" for rates in excess of 30 deg/sec.

The inertia signal at model arrest is apparent in figure D14. Expanding or contracting the wind-off signal, through interpolation, succeeds in aligning the stopping impulse within respective wind-on and wind-off files. Unfortunately, there are additional, very repeatable, mechanical oscillations present within the transient phase. These oscillations occur at the resonant frequency of the balance system and are a time dependant phenomenon. Interpolation of the data, aimed at aligning the stopping impulse (a position dependant phenomenon) also succeeds in distorting the oscillations at the resonant frequency.

Mechanical inputs are complex and vary depending upon the type of test conducted. For this reason it is important that future work concentrates on reducing mechanical "noise" by minimizing the mass of test models and increasing the resonant frequency of the balance system.

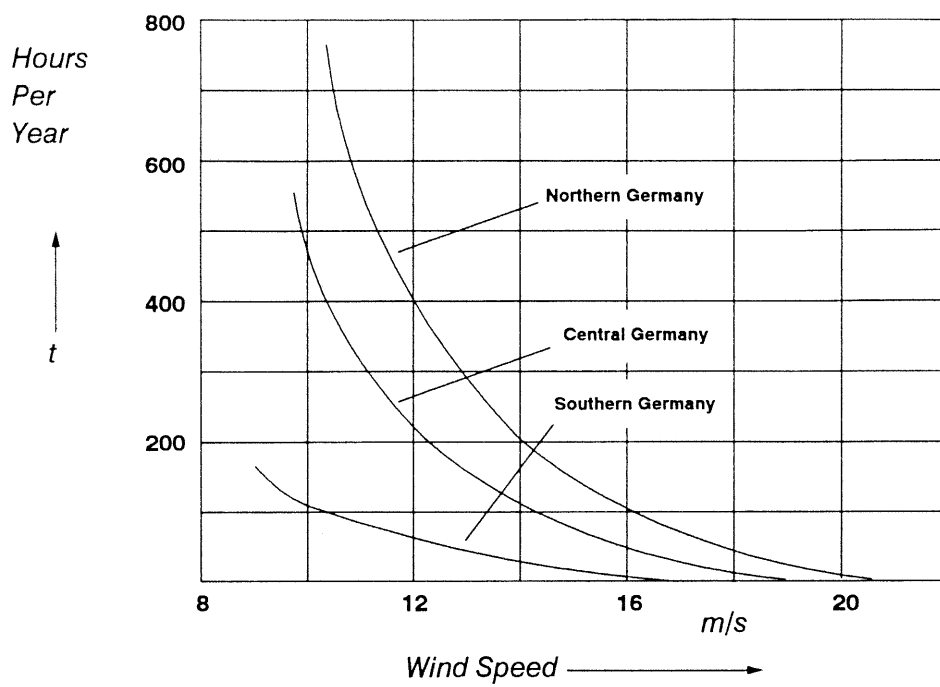


**Figure 2 . 1 The Frequency of Strong Winds in Various Regions of Germany
- Bitzl (1961)**

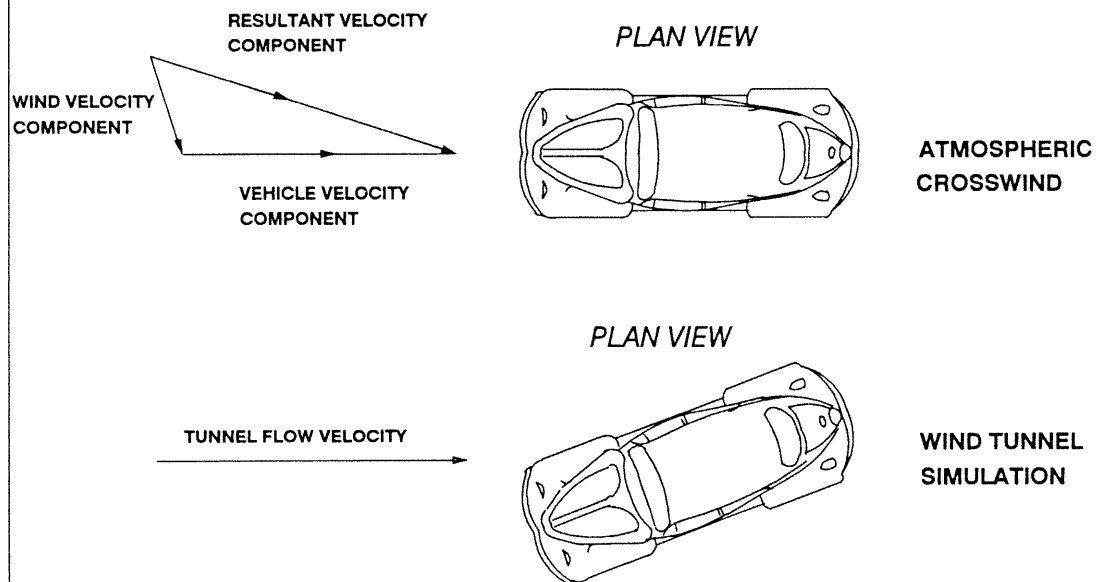


Figure 2 . 2 Conventional Simulation of a Crosswind in a Wind Tunnel

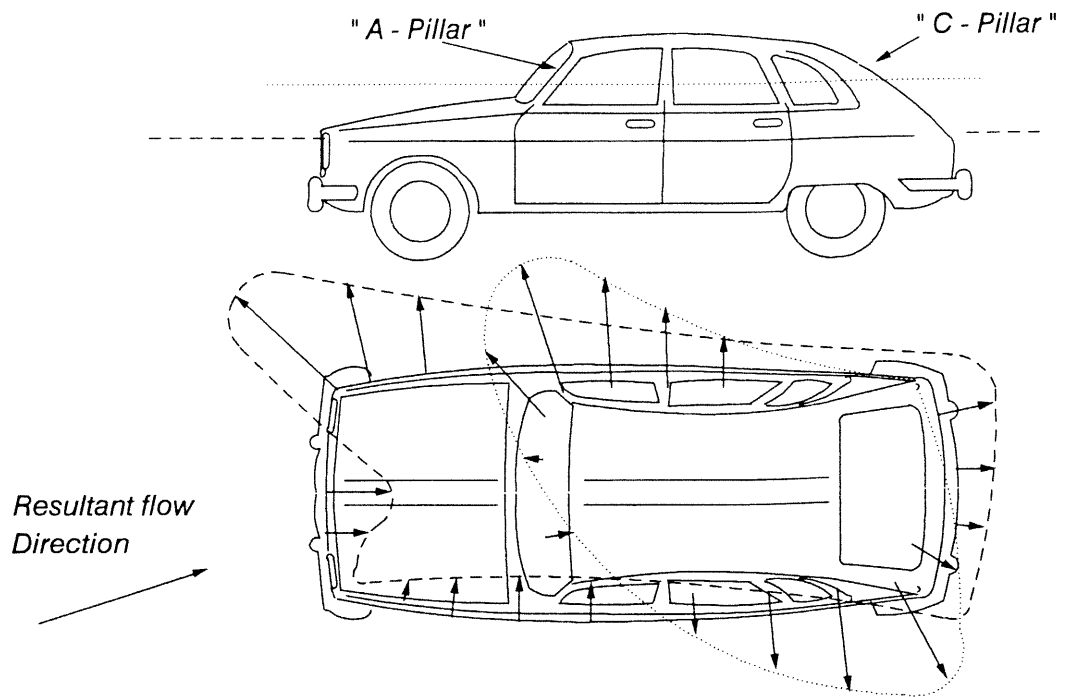


Figure 2 . 3 Schematic Diagram of the Surface Static Pressure Distribution Around a Typical Car Subjected to a Steady Crosswind

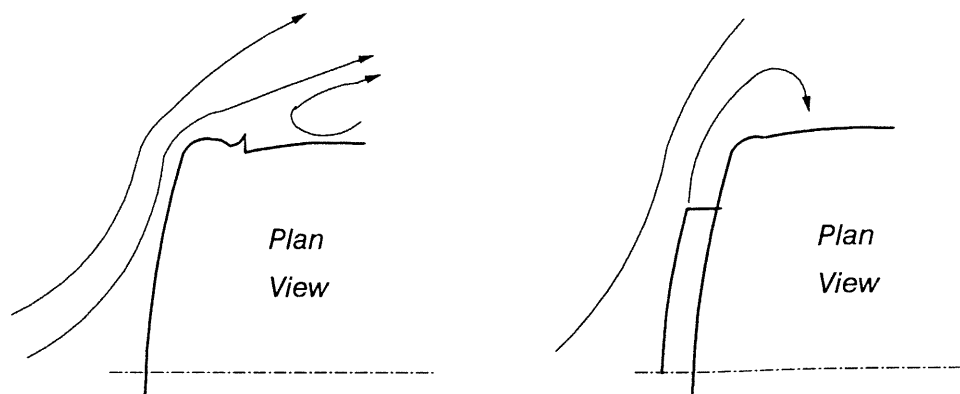


Figure 2 . 4 Devices for Controlled Separation at the Leeward Front Corner of a Vehicle - Hucho (1981)

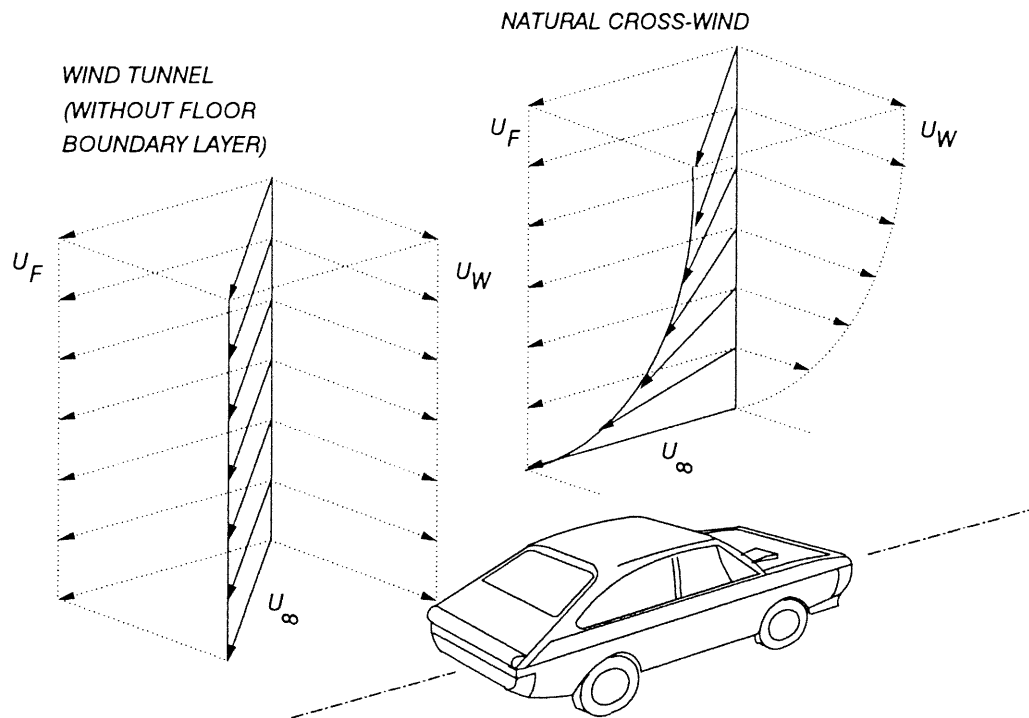


Figure 2 . 5 A Comparison of Crosswind Profiles

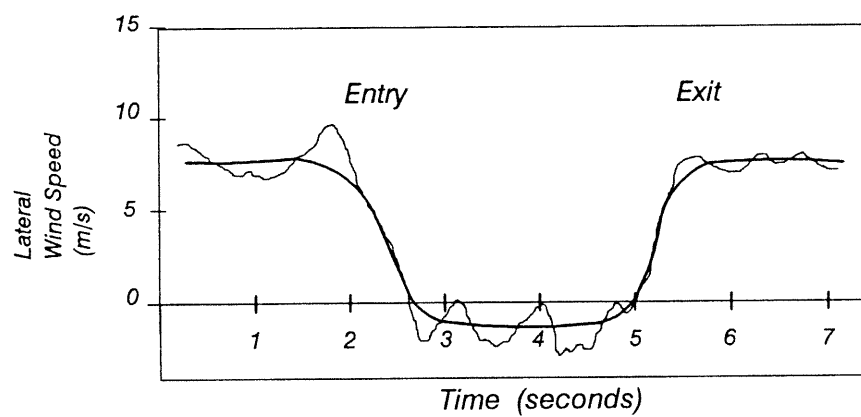


Figure 2 . 6 A Typical Crosswind Profile for a Car Passing Through a Cutting - Smith (1972)

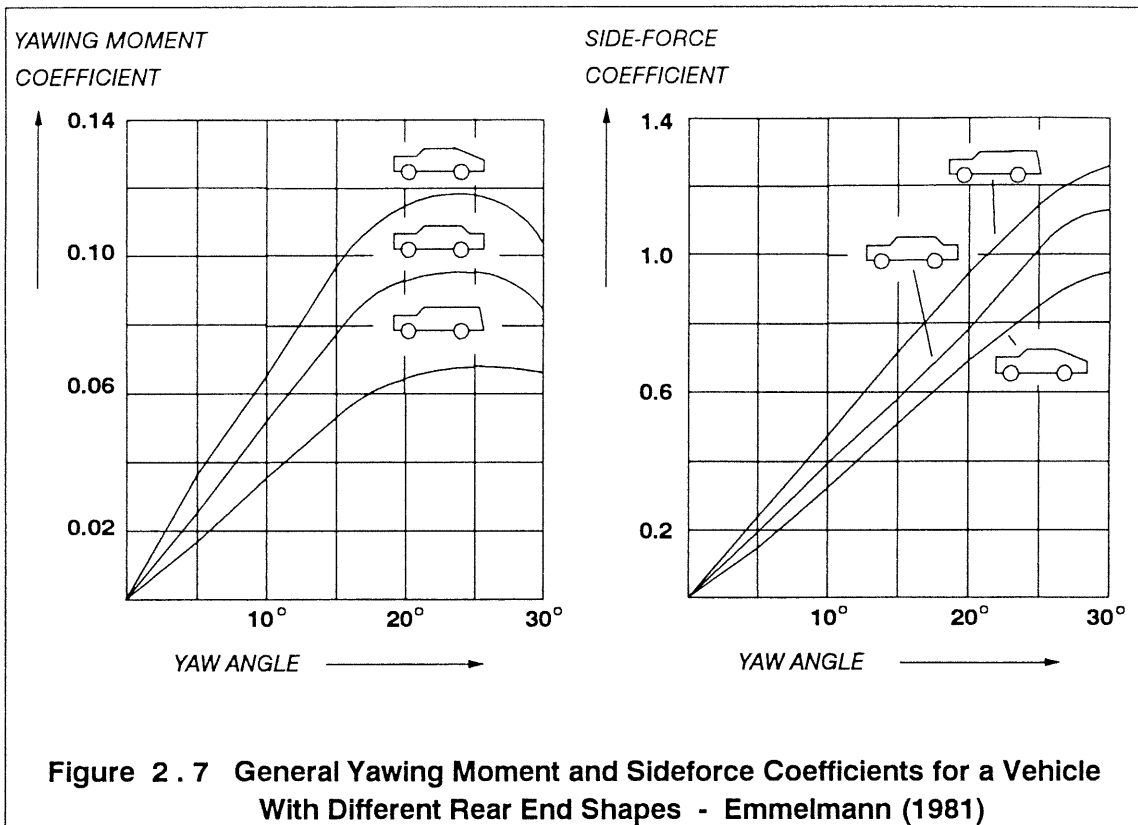
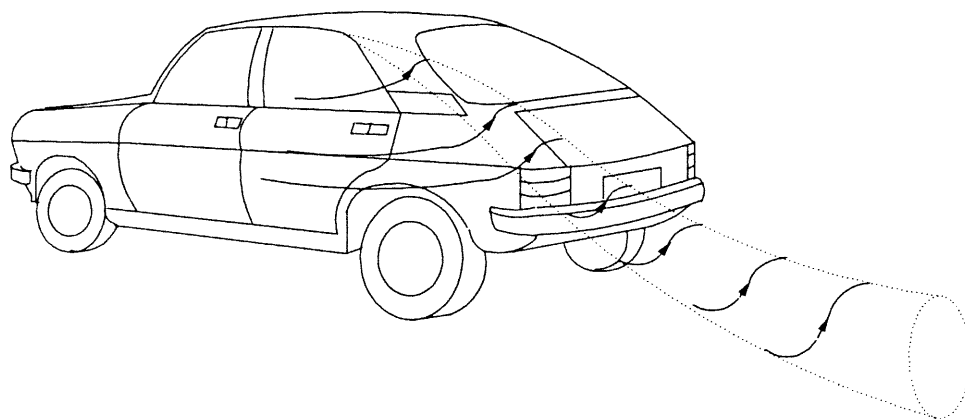
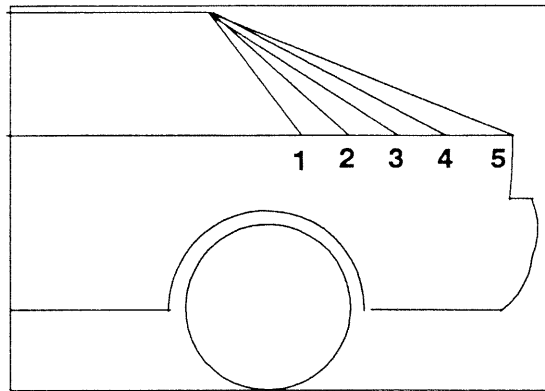


Figure 2.8 Schematic Diagram of the "C - Pillar " Vortex



*Yawing Moment
Coefficient*

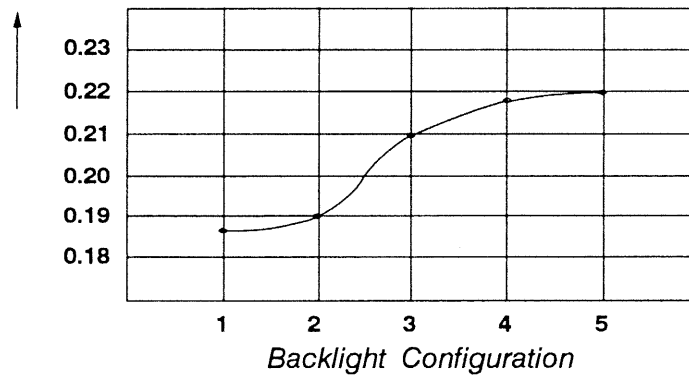
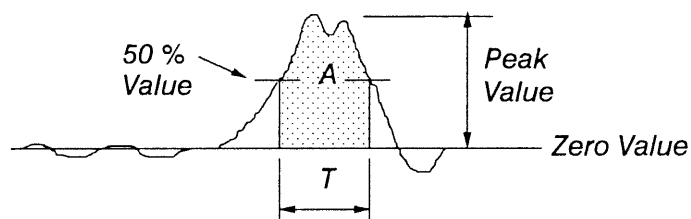


**Figure 2 . 9 Relationship Between Backlight Angle and Yawing Moment
(20 degrees resultant yaw angle) - Kohri (1989)**



$$\frac{\text{Area } A}{\text{Time } T} = \text{Pulse Value}$$

Figure 2 . 10 Method for Calculating the Pulse Value of Yaw Velocity

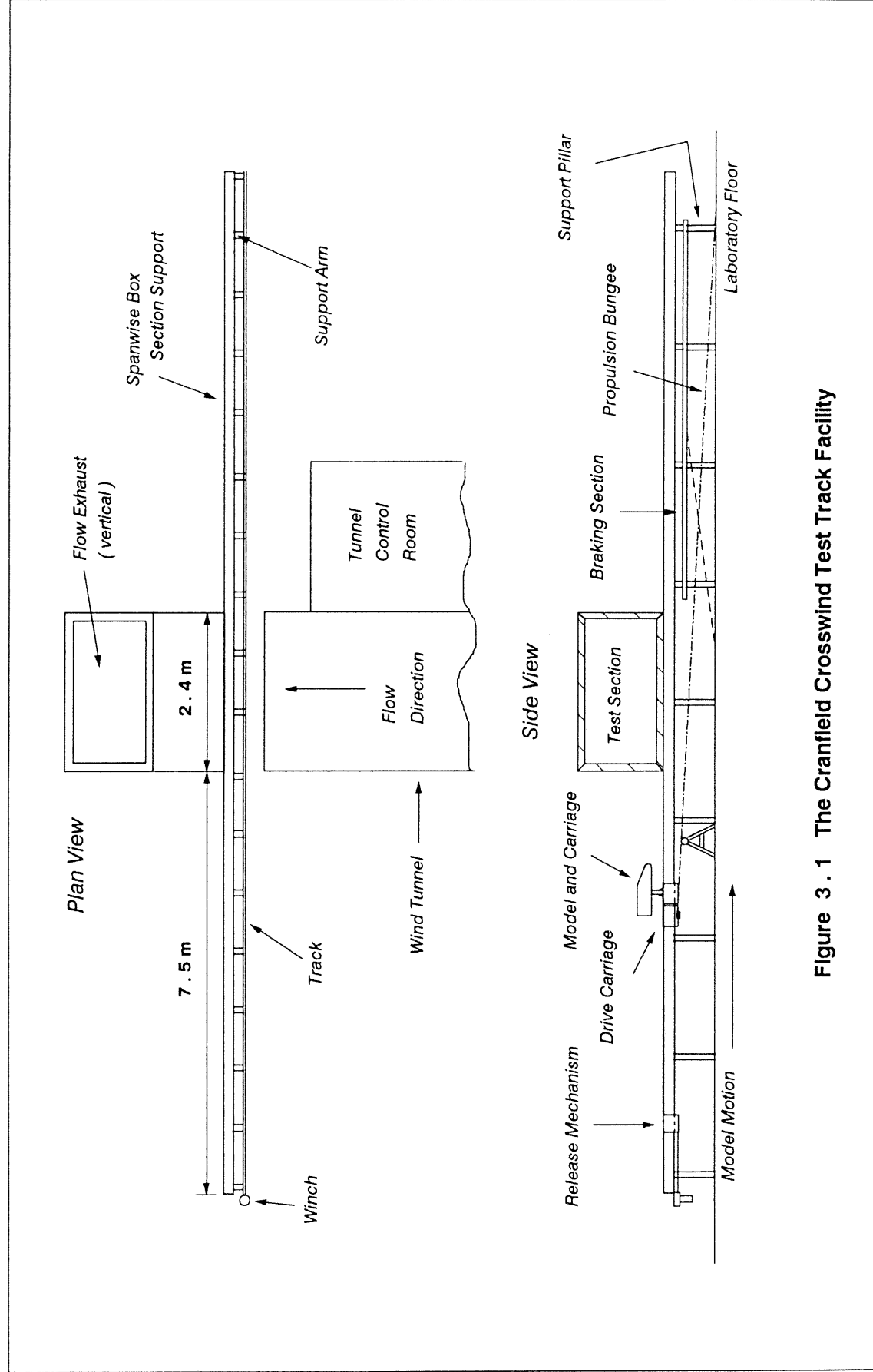


Figure 3.1 The Cranfield Crosswind Test Track Facility

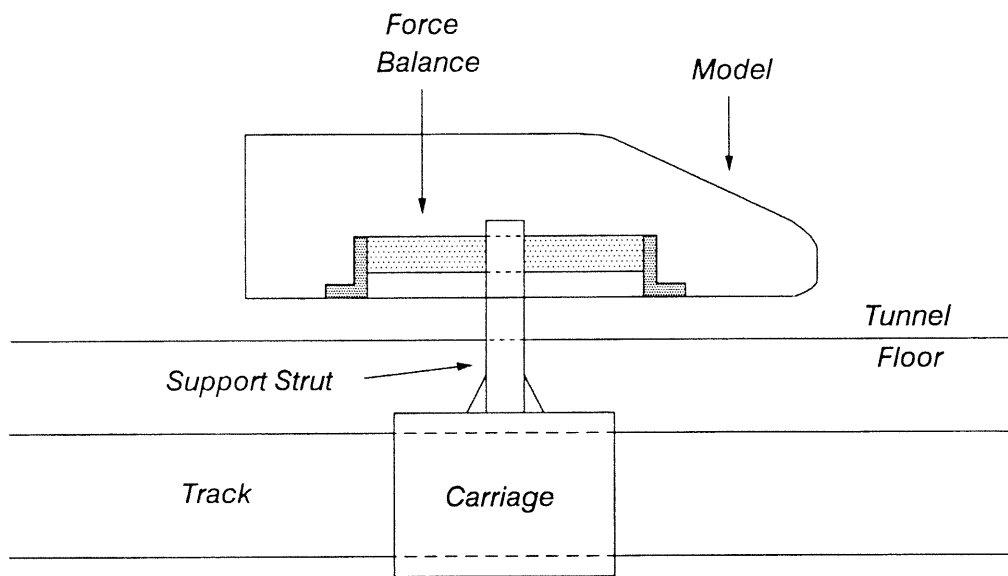


Figure 3 . 2 Schematic Diagram of Model and Related Equipment

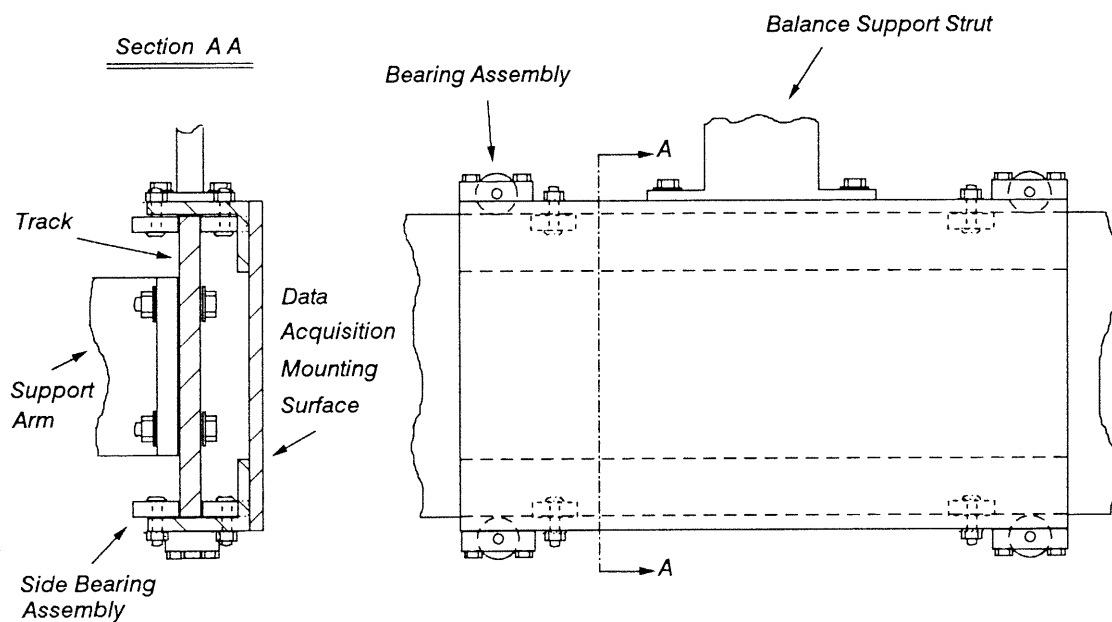


Figure 3 . 3 The Model Carriage

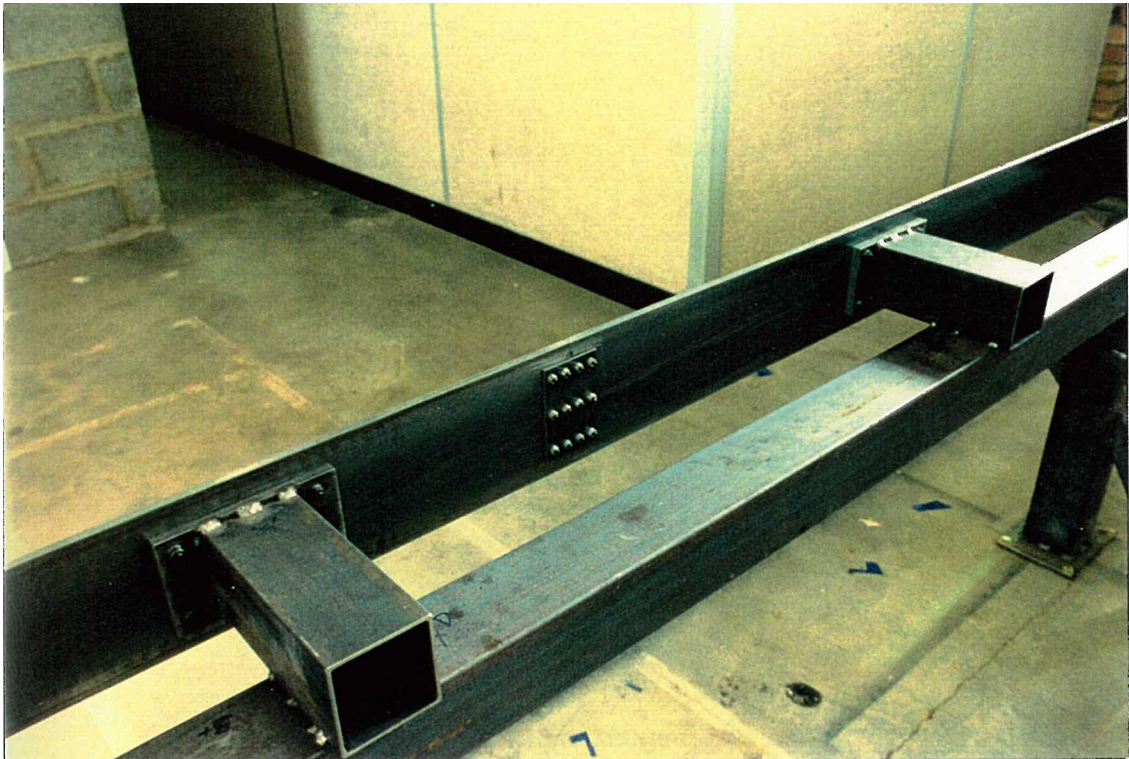


Figure 3 . 4 The Vertical-Plate Track

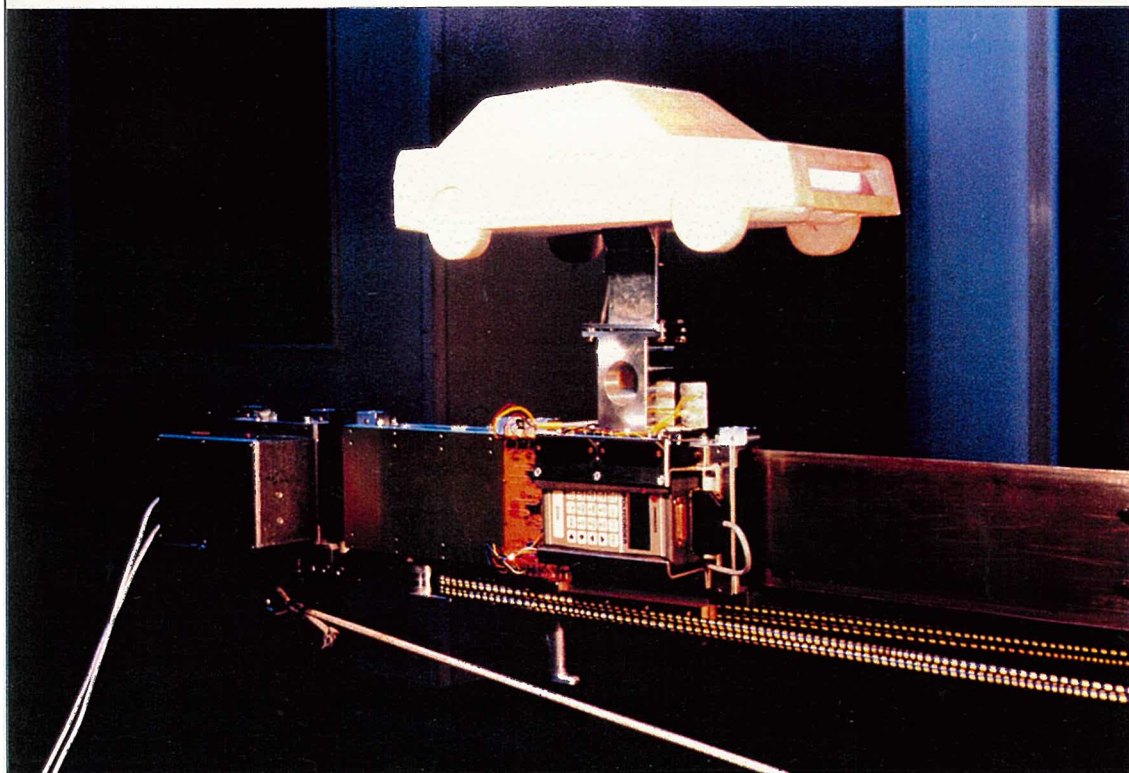


Figure 3 . 5 The Basic Saloon Test Model on the Track

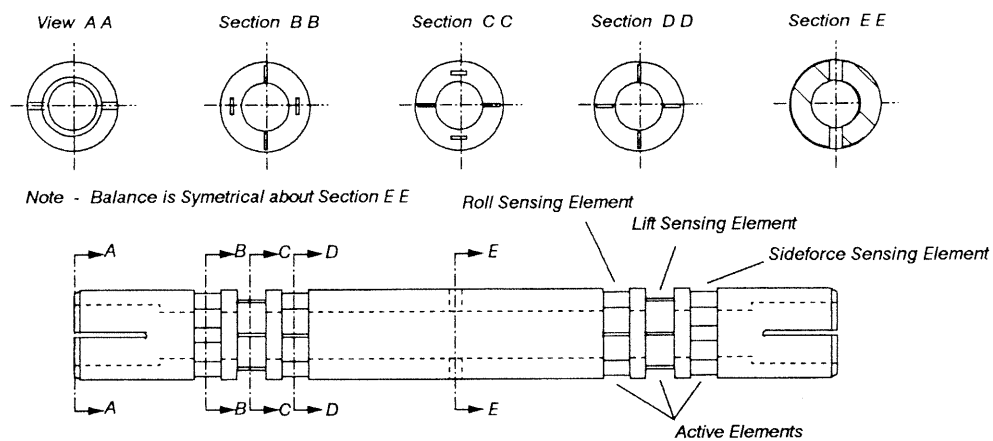


Figure 3 . 6 The Strain Gauge Force Balance

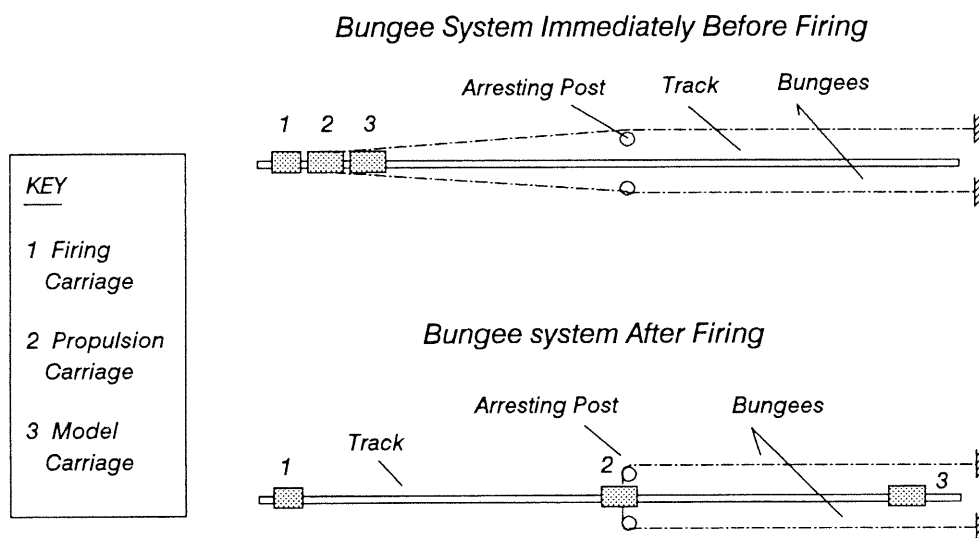


Figure 3 . 7 The Bungee Propulsion System

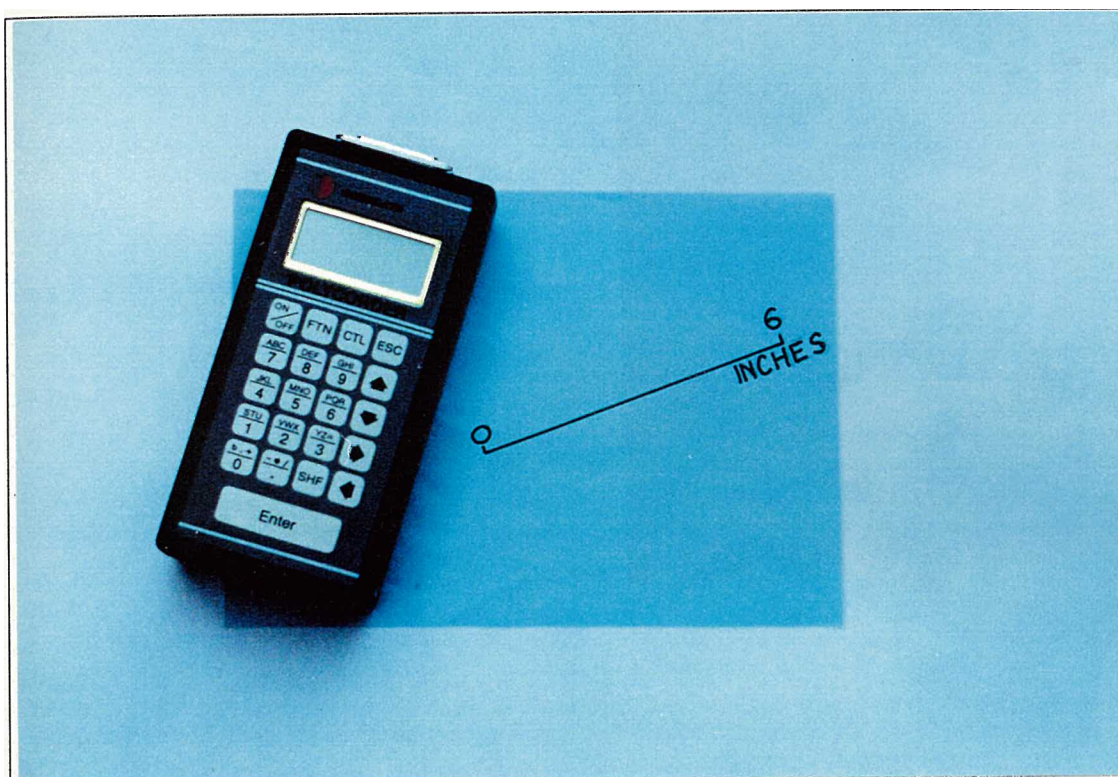


Figure 3 . 8 The On-Board Data Recorder

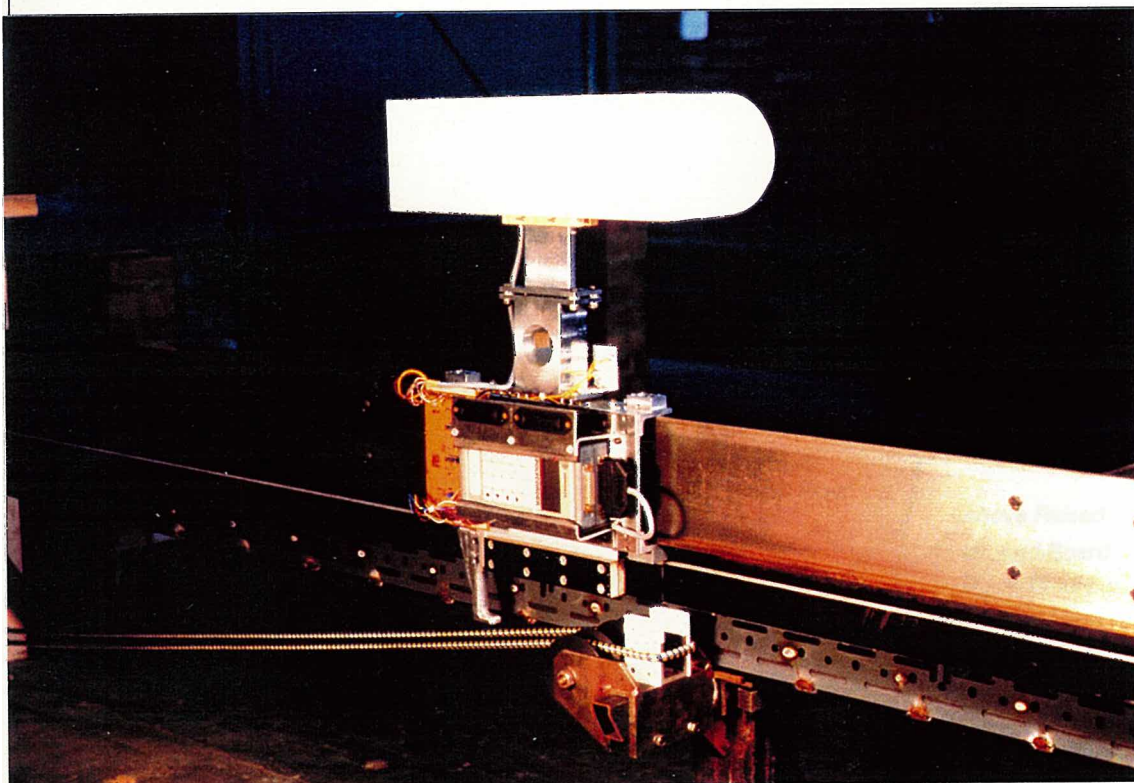


Figure 3 . 9 The Aerodynamic Shroud

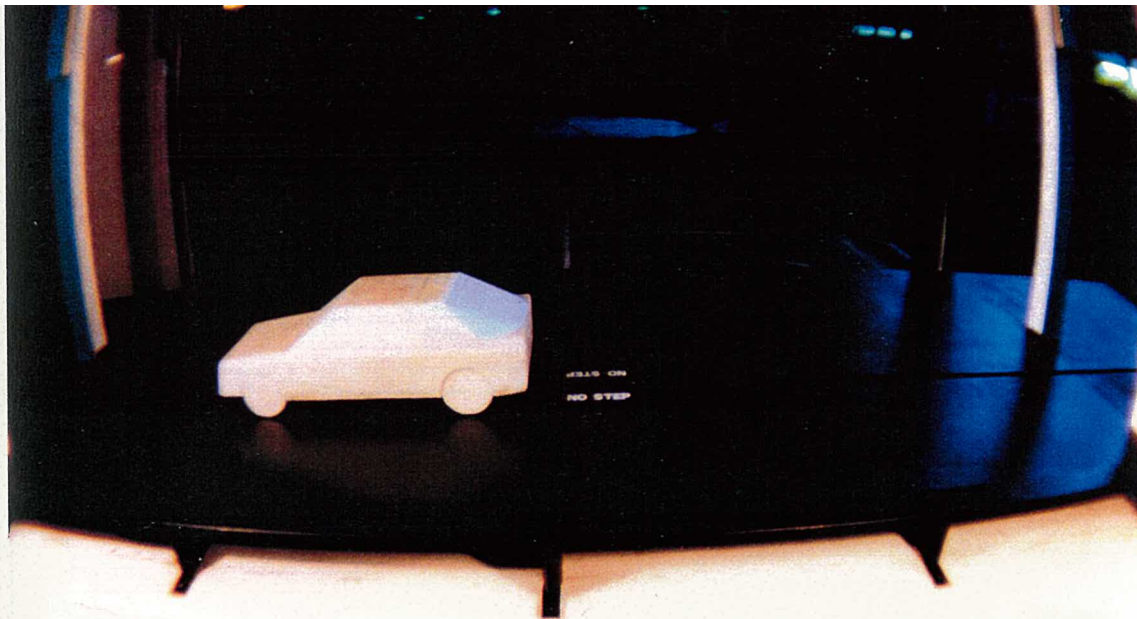


Figure 3.12 Basic Nelson Car Test Model Including Additional
Exterior and Interior Configurations

Figure 3.10 The Raised Ground Board

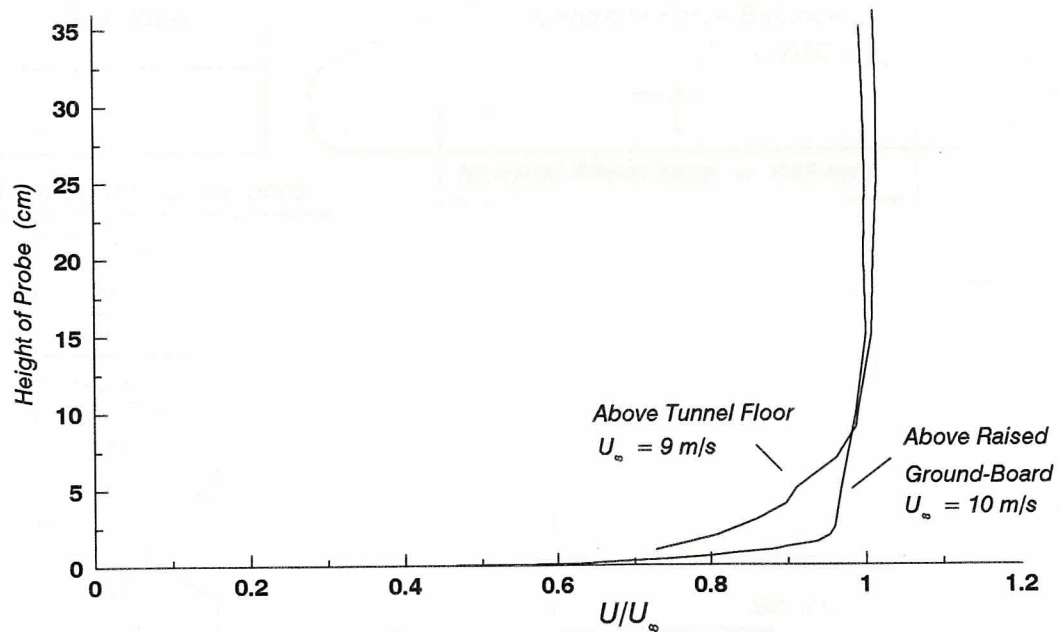


Figure 3.11 Boundary Layer Profiles Before and After
Ground Board Installation

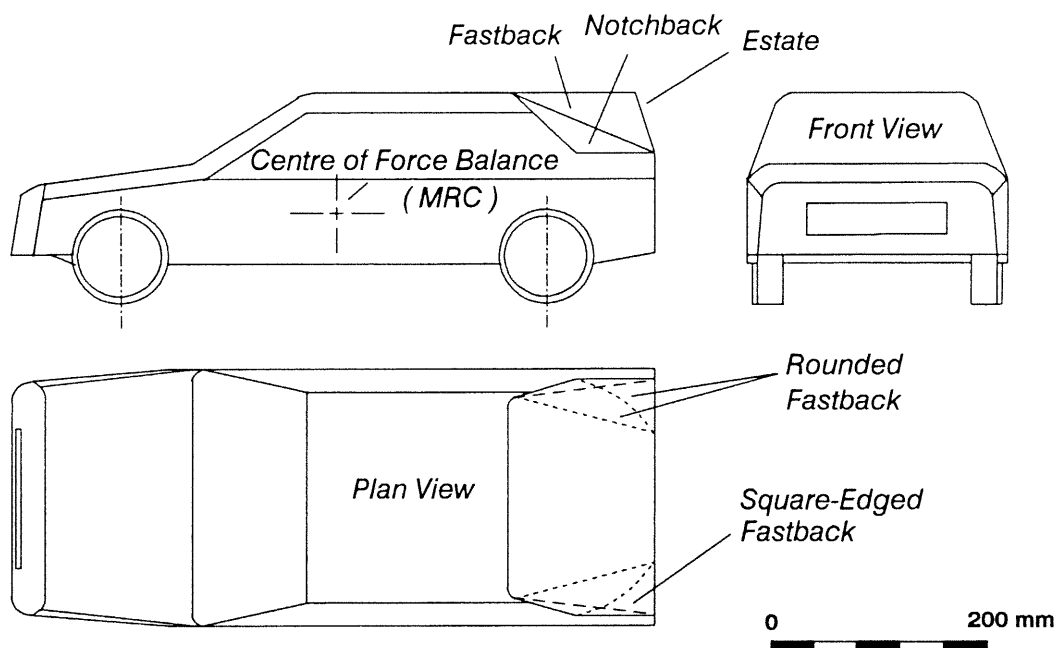


Figure 3 . 12 Basic Saloon Car Test Model Including Additional Estate and Fastback Configuration

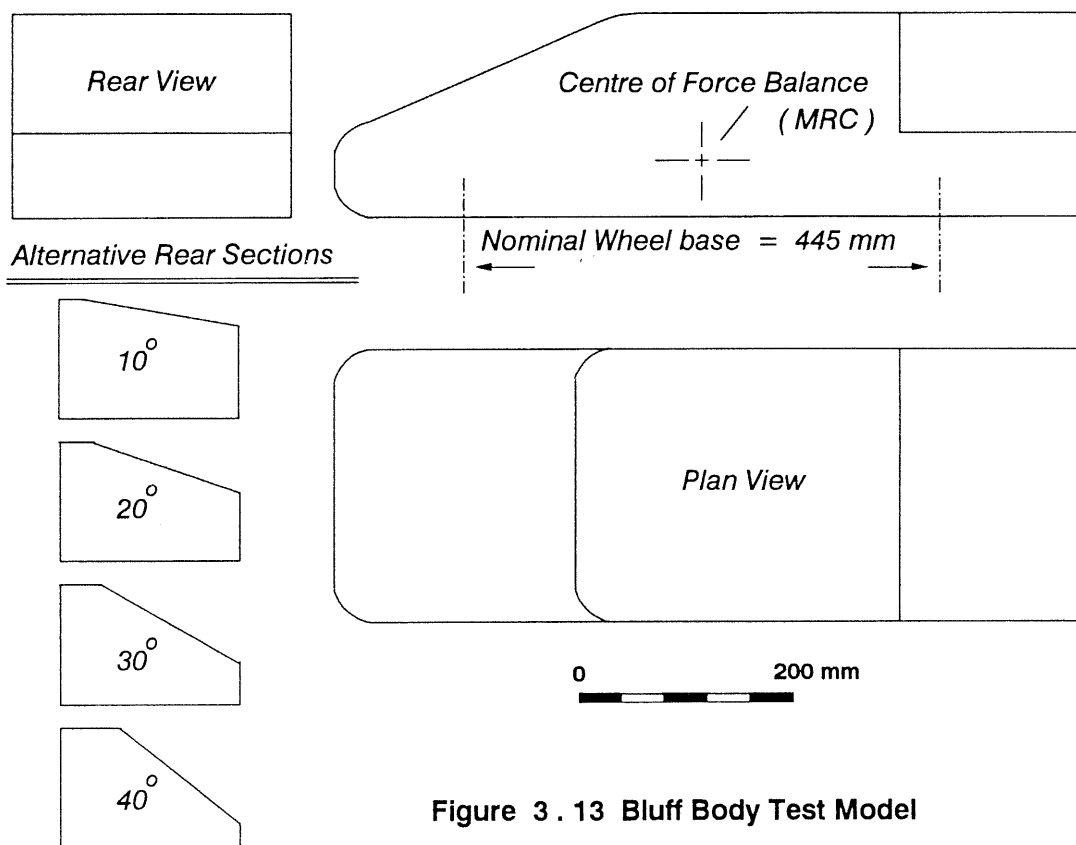


Figure 3 . 13 Bluff Body Test Model

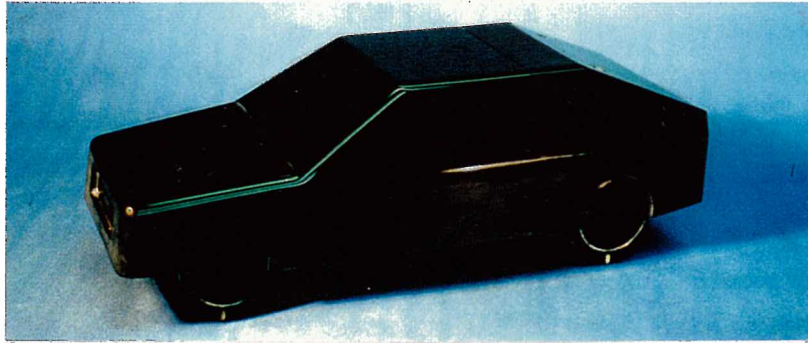
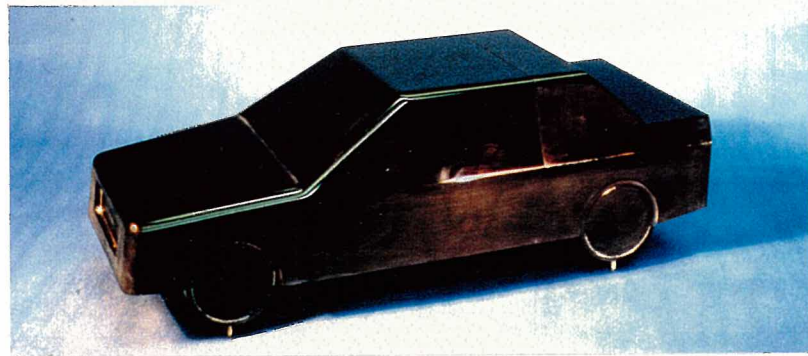
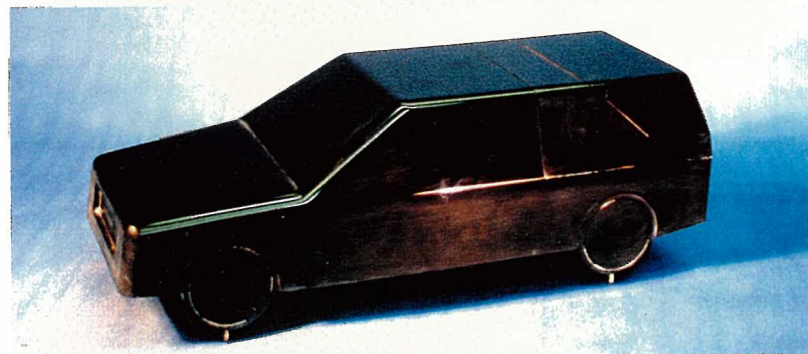


Figure 3 . 14 Basic Saloon Car Test Model with (From Top) Square and Rounded Fastback, Notchback and Estate Configurations

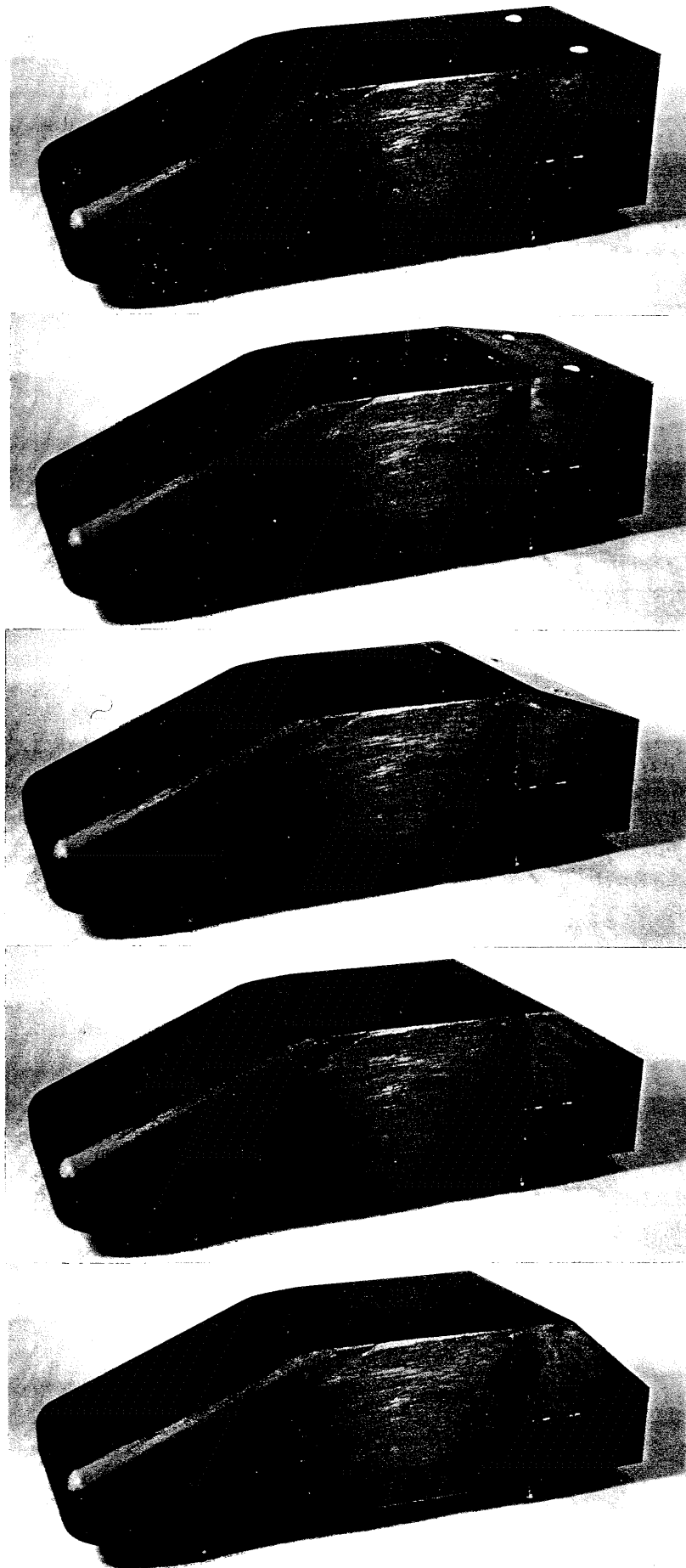


Figure 3 . 15 Bluff-Body Test Model with (From Top)
Square, 10, 20, 30 and 40 Degree Backlights

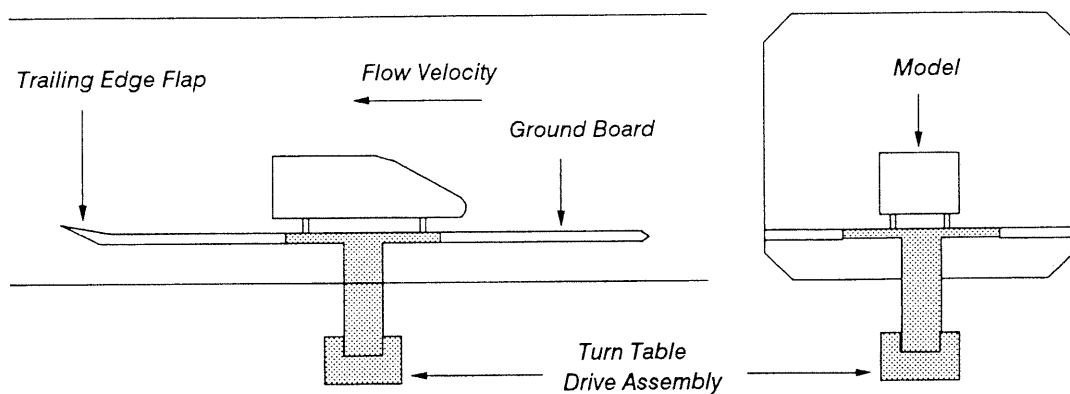


Figure 3 . 16 Layout of the Oscillatory Facility

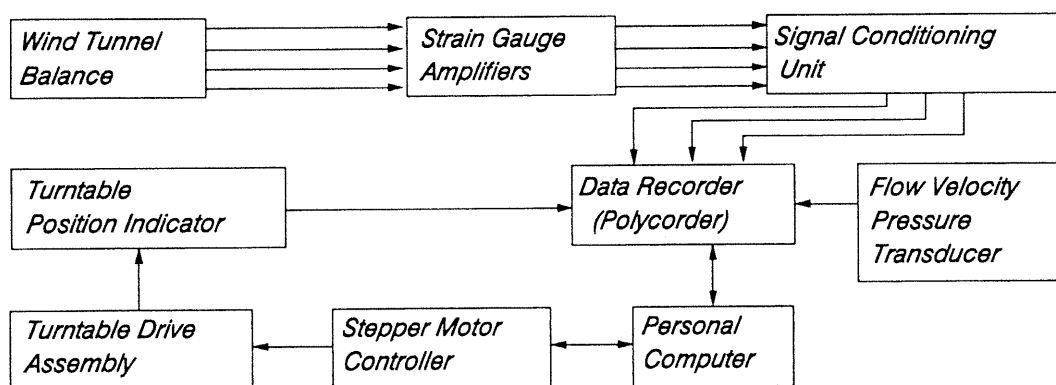


Figure 3 . 17 Schematic Diagram of Experimental Equipment Employed During Dynamic Yaw Tests (Oscillatory Facility)

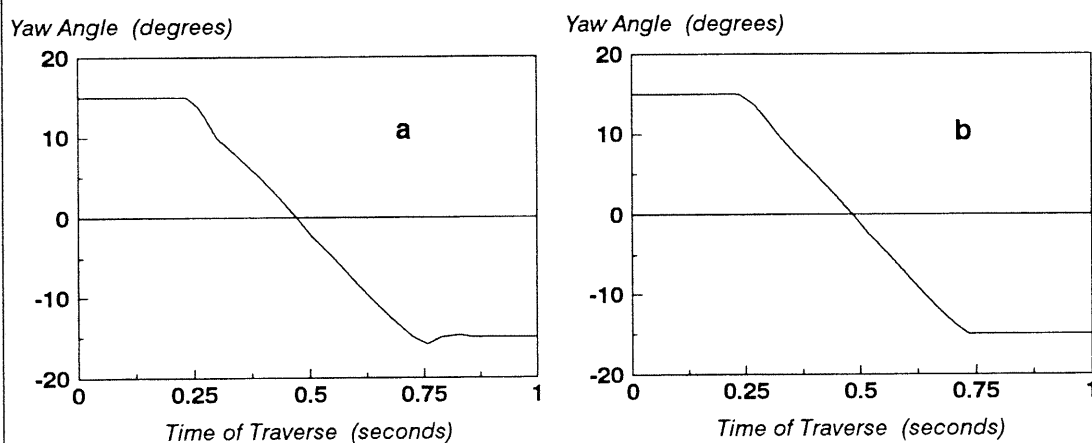


**Figure 3 . 18 Movement of Model Turntable (50 degrees per second)
With a) High and b) medium Initial Acceleration Rate**



**Figure 4 . 1 a Smoke Flow Visualization for the Basic Saloon
(Square-Edged Fastback Configuration at 10 Degrees Yaw)**

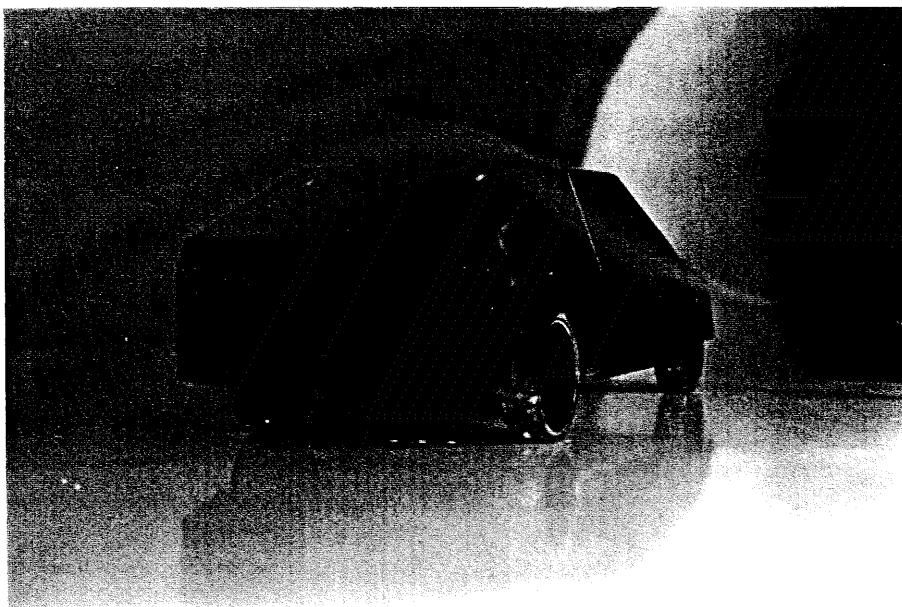


**Figure 4 . 1 b Smoke Flow Visualization for the Basic Saloon
(Square-Edged Fastback Configuration at 25 Degrees Yaw)**

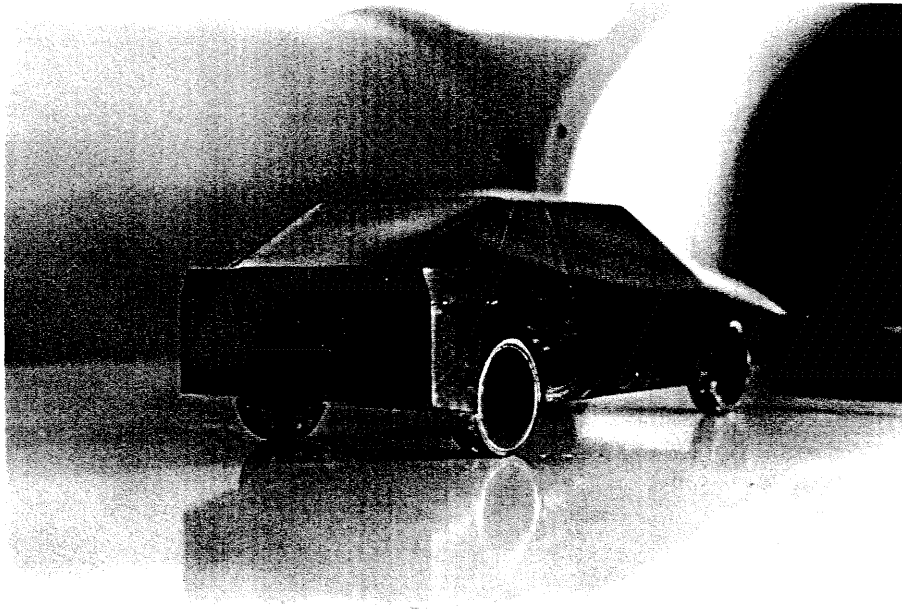


**Figure 4 . 2 a Smoke Flow Visualization for the Basic Saloon
(Rounded Fastback Configuration at 10 Degrees Yaw)**

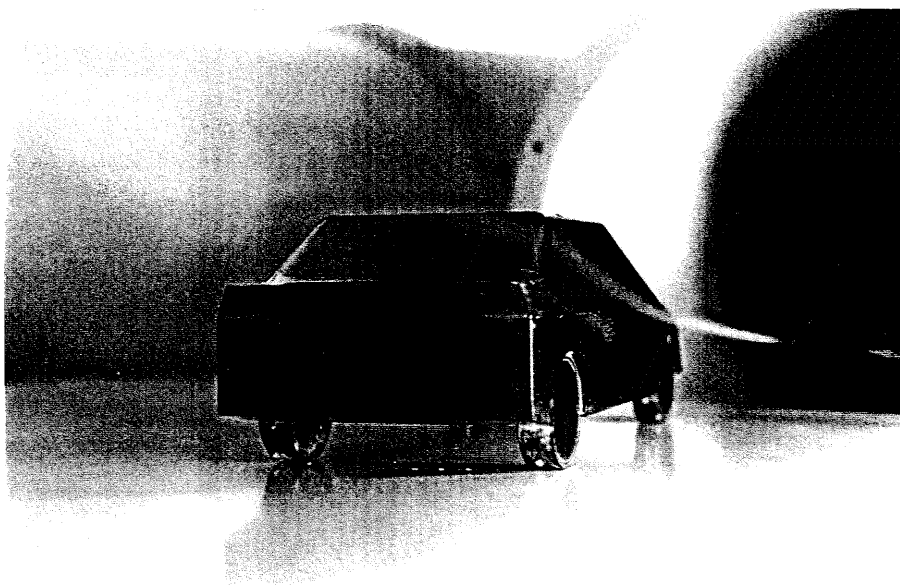


**Figure 4 . 2 b Smoke Flow Visualization for the Basic Saloon
(Rounded Fastback Configuration at 25 Degrees Yaw)**

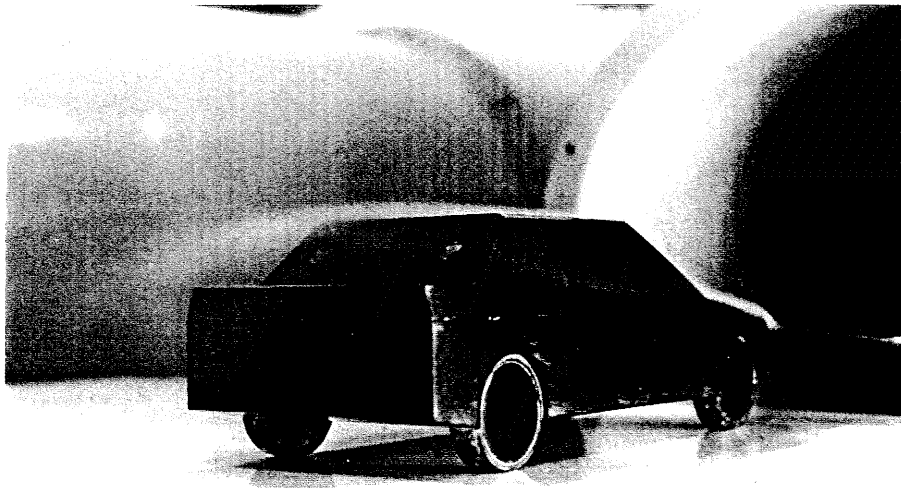


**Figure 4 . 3 a Smoke Flow Visualization for the Basic Saloon
(Notchback Configuration at 10 Degrees Yaw)**

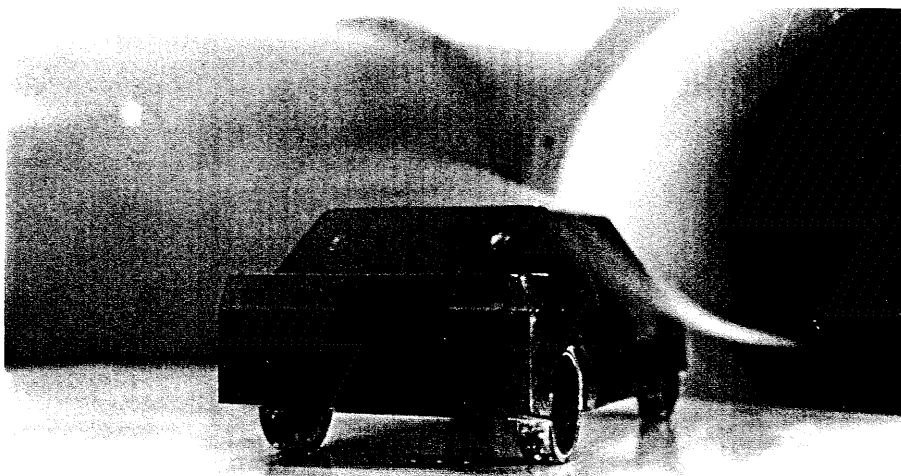


**Figure 4 . 3 b Smoke Flow Visualization for the Basic Saloon
(Notchback Configuration at 25 Degrees Yaw)**

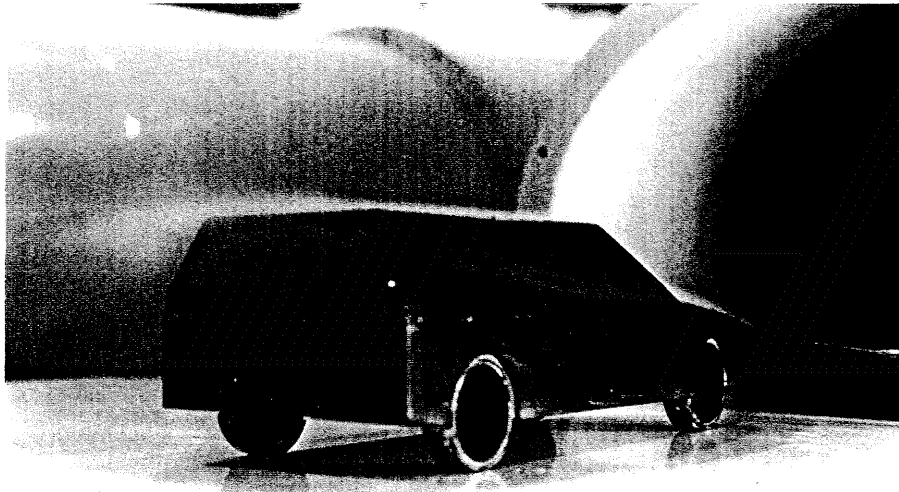


**Figure 4 . 4 a Smoke Flow Visualization for the Basic Saloon
(Estate Configuration at 10 Degrees Yaw)**

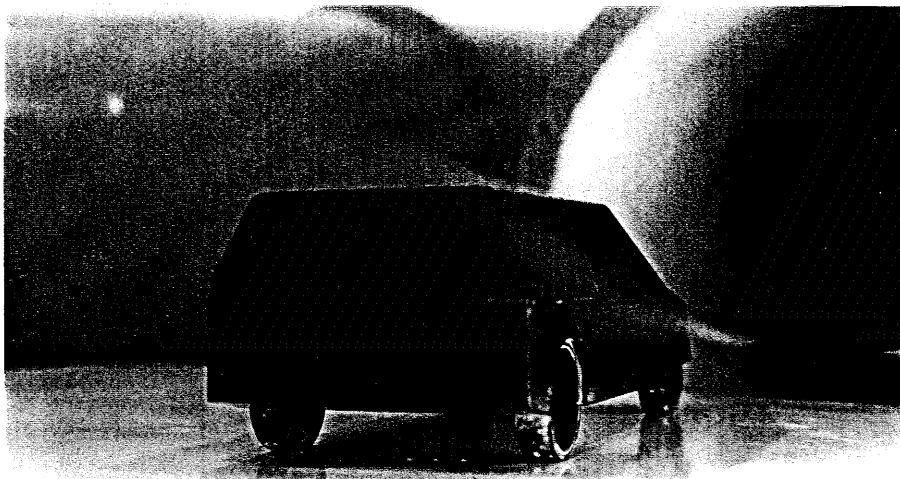


**Figure 4 . 4 b Smoke Flow Visualization for the Basic Saloon
(Estate Configuration at 25 Degrees Yaw)**

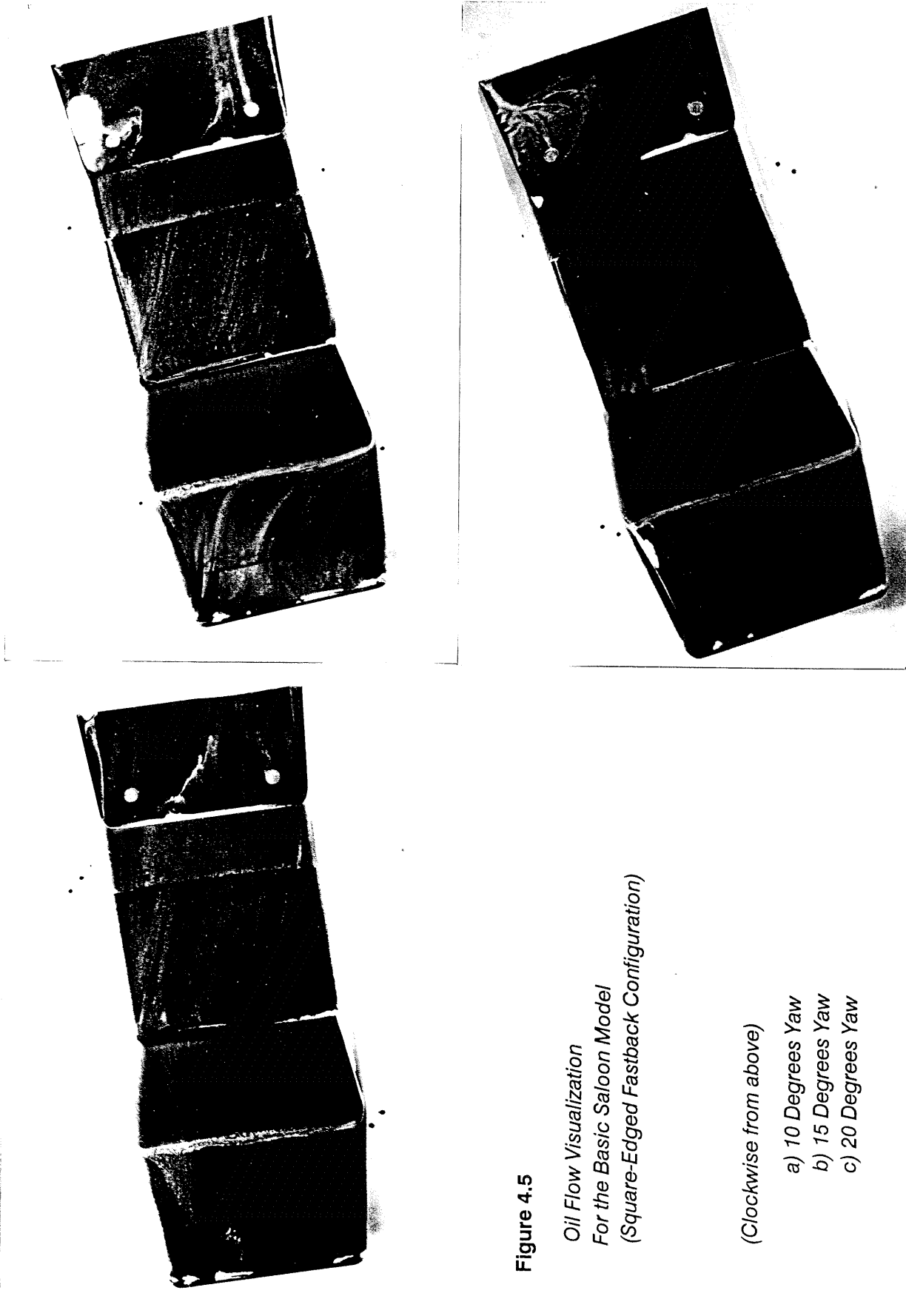
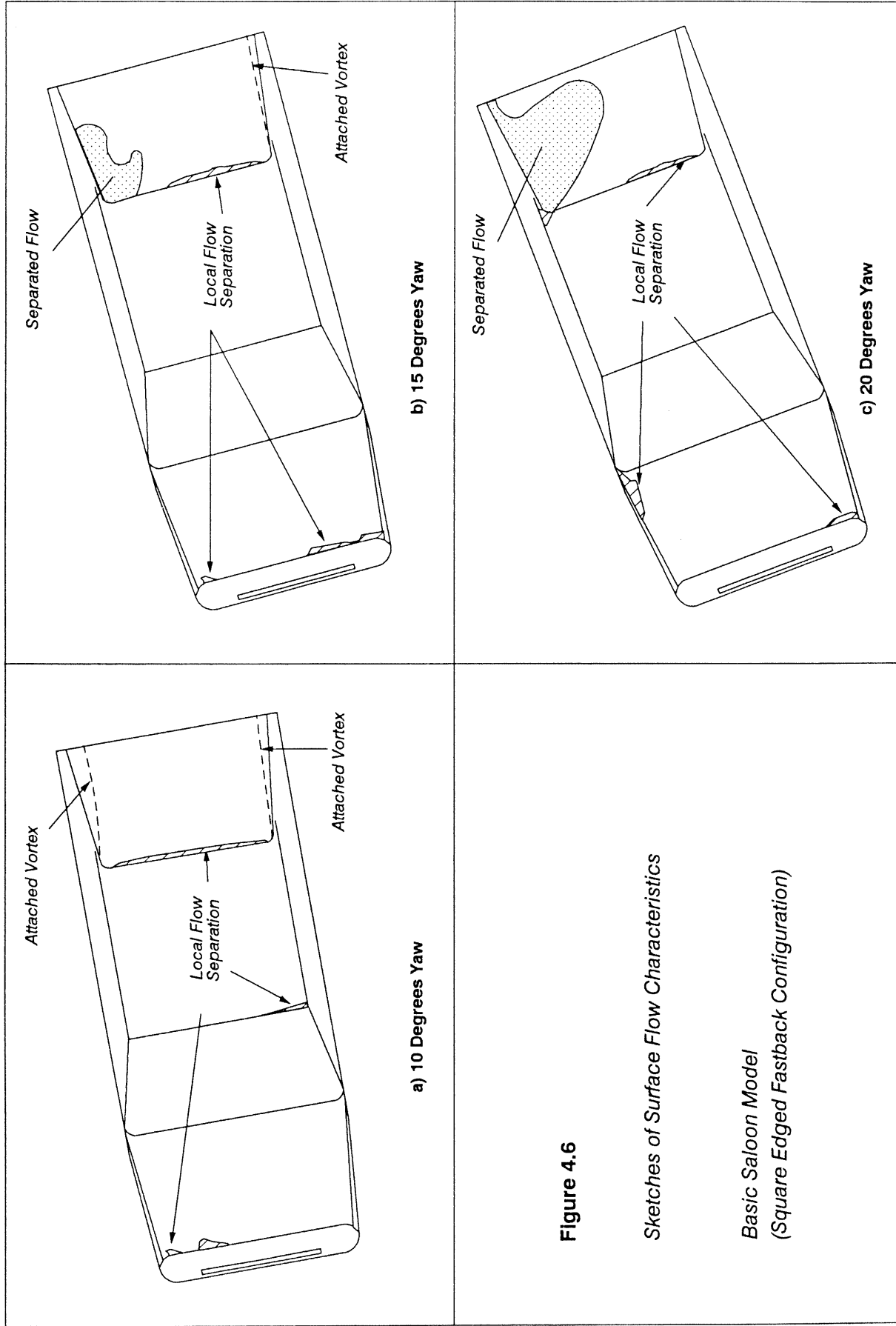


Figure 4.5

*Oil Flow Visualization
For the Basic Saloon Model
(Square-Edged Fastback Configuration)*

(Clockwise from above)

- a) 10 Degrees Yaw
- b) 15 Degrees Yaw
- c) 20 Degrees Yaw



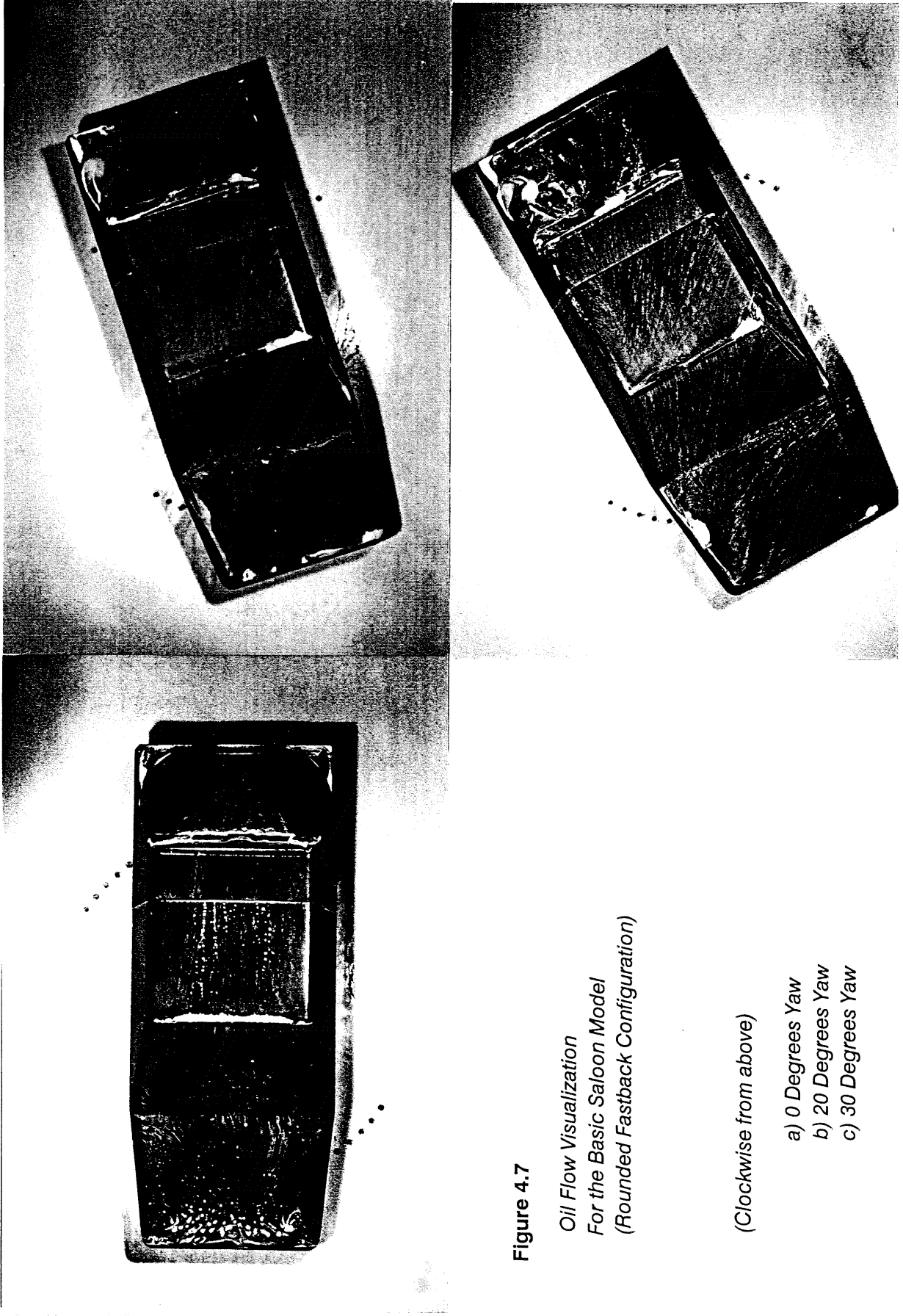
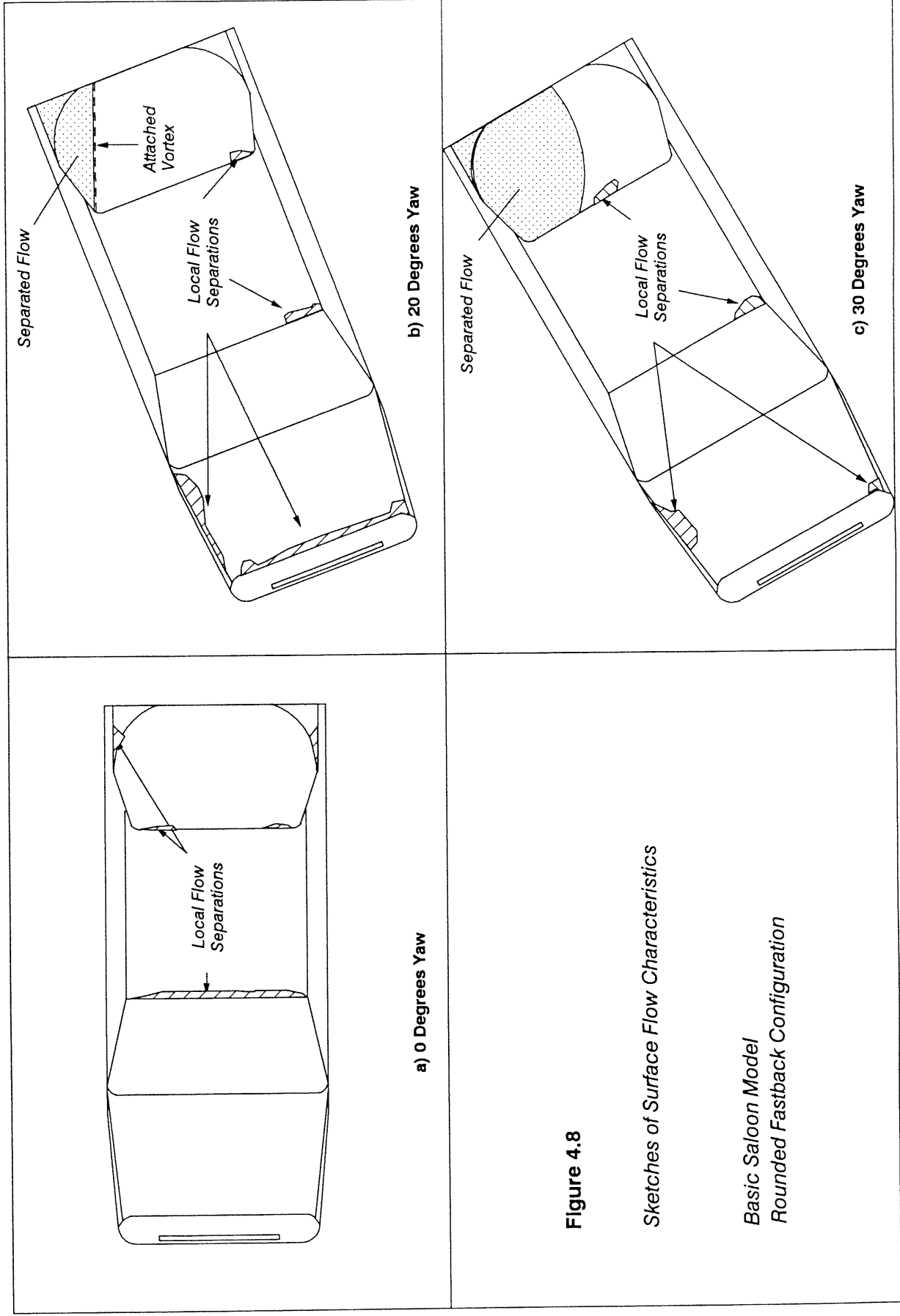


Figure 4.7

*Oil Flow Visualization
For the Basic Saloon Model
(Rounded Fastback Configuration)*

(Clockwise from above)

- a) 0 Degrees Yaw
- b) 20 Degrees Yaw
- c) 30 Degrees Yaw



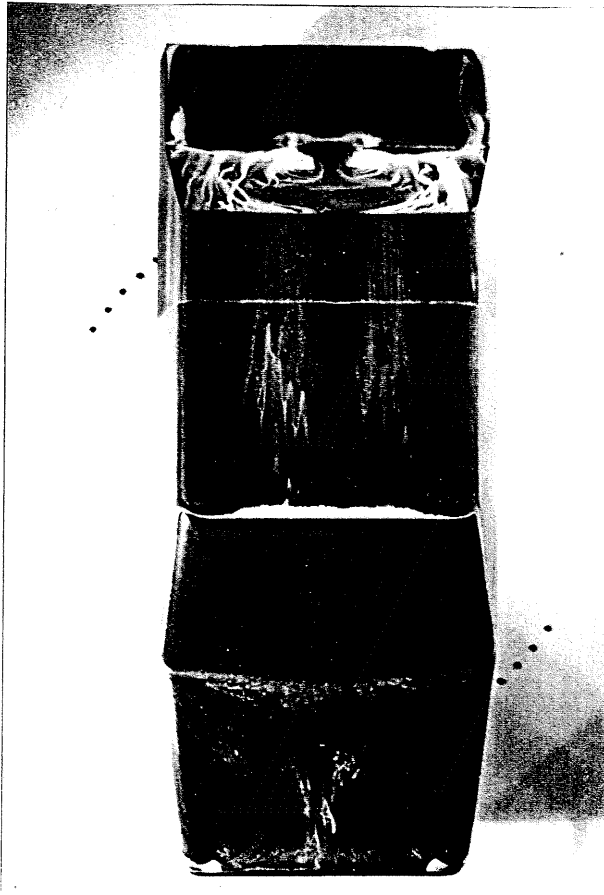
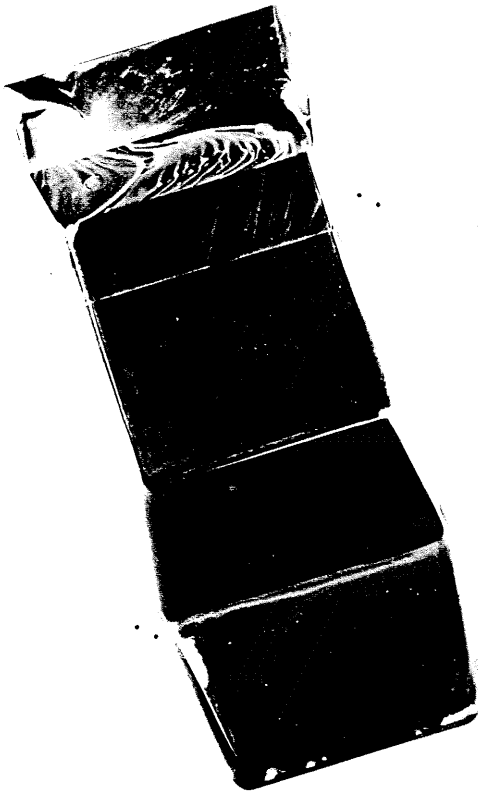
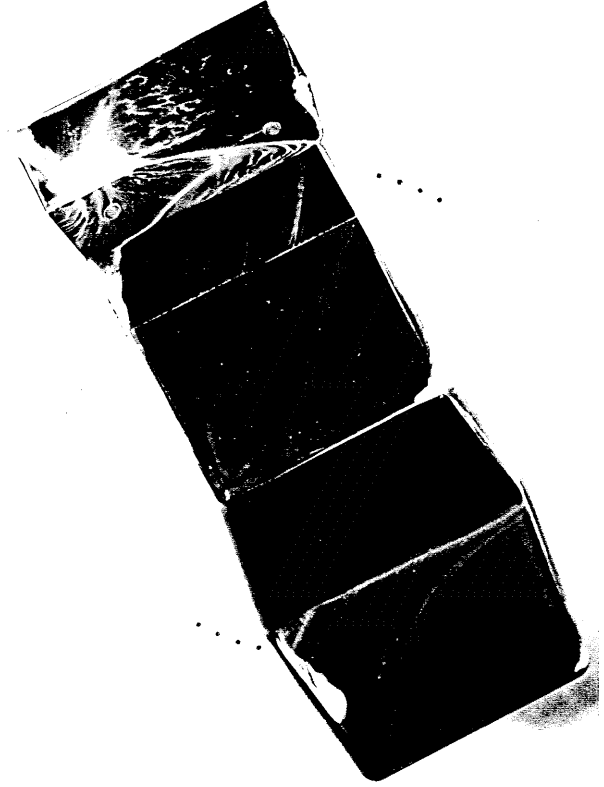
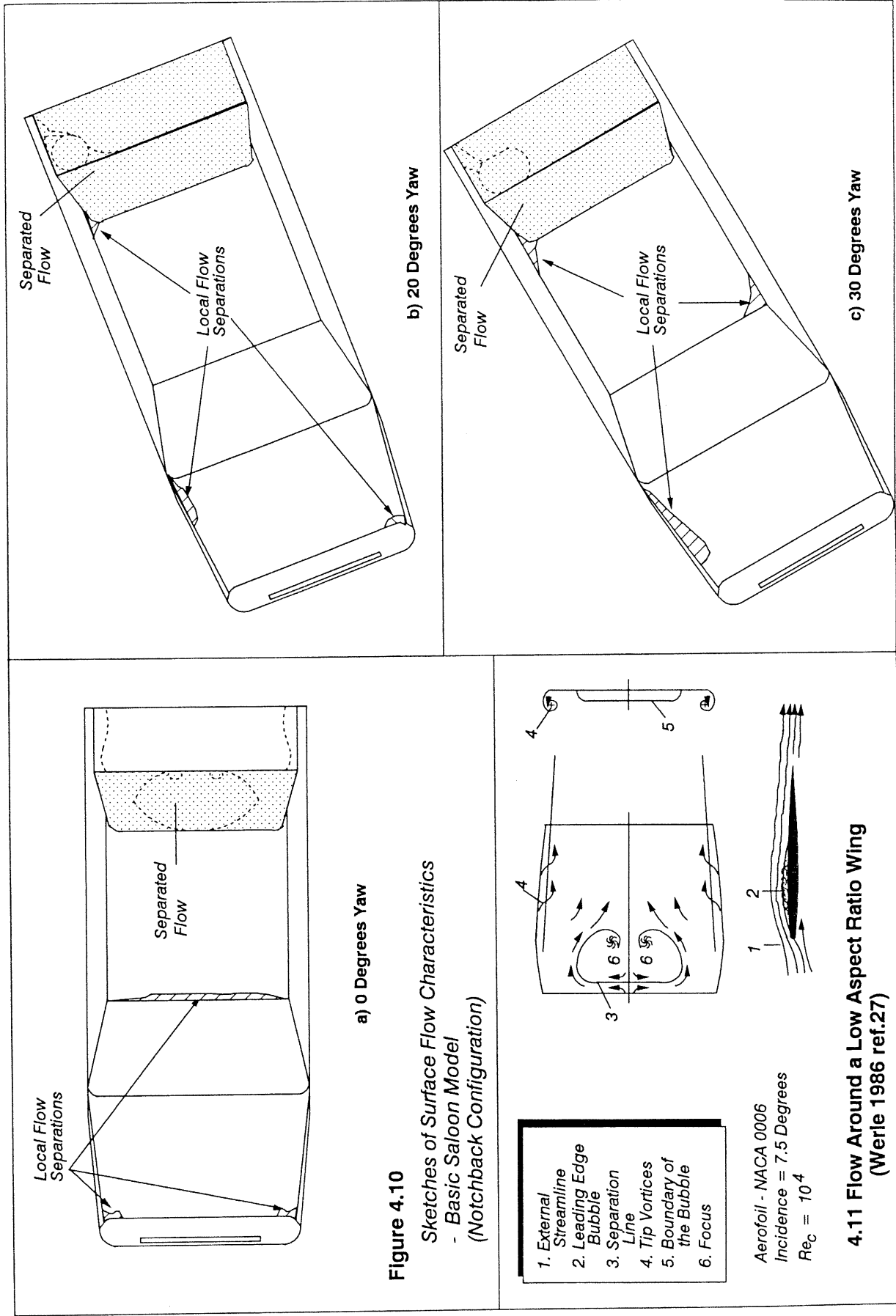


Figure 4.9

*Oil Flow Visualization
For the Basic Saloon Model
(Notchback Configuration)*

(Clockwise from above)

- a) 0 Degrees Yaw
- b) 20 Degrees Yaw
- c) 30 Degrees Yaw



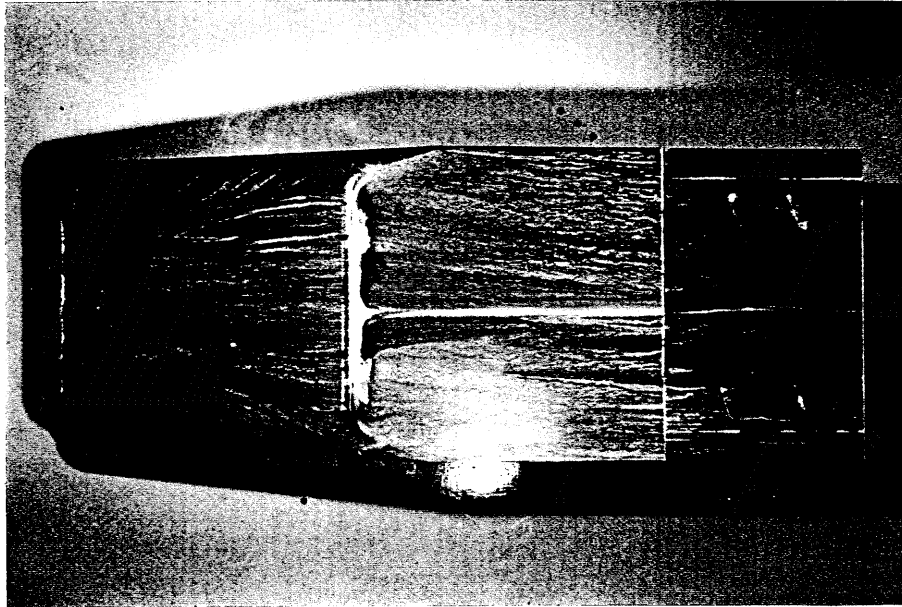


**Figure 4 . 12 a Oil Flow Visualization for the Bluff-Body Model
(Square-back Model at 0 Degrees Yaw)**

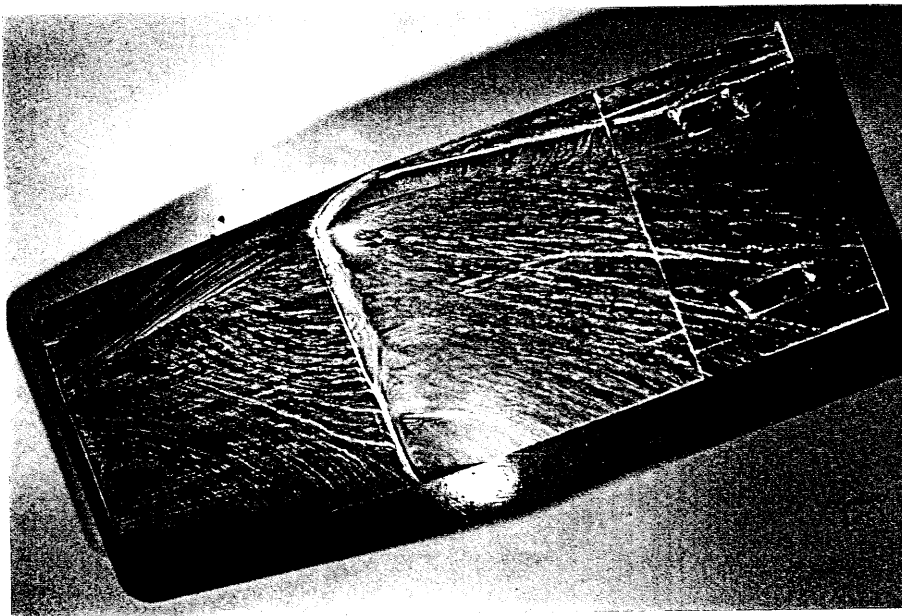
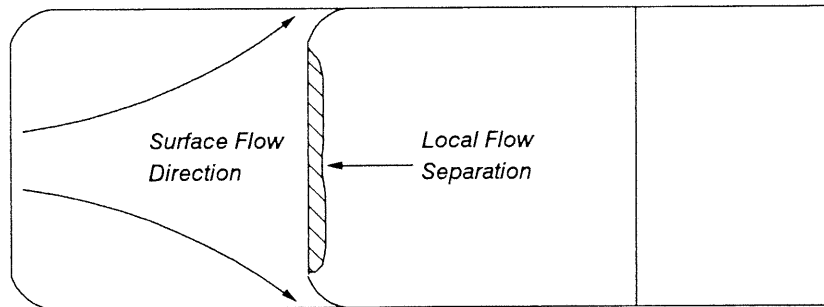
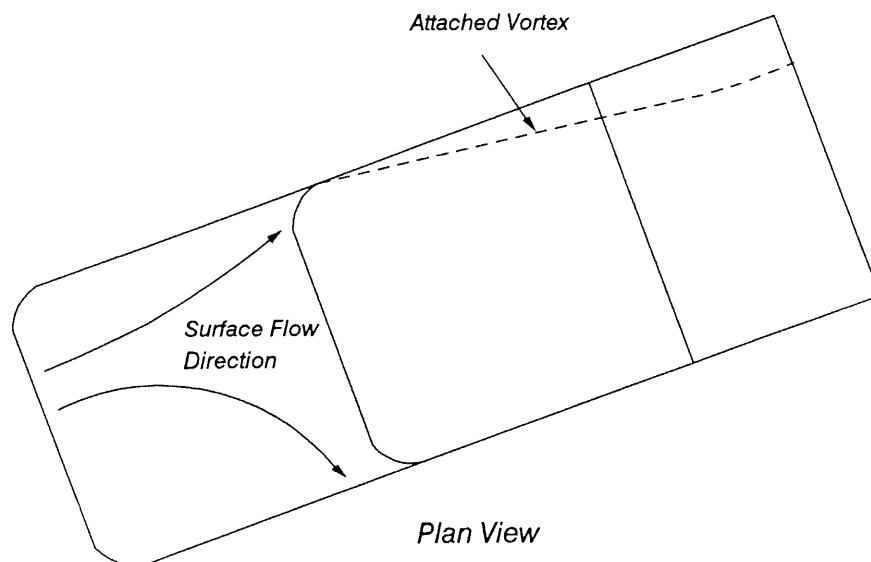


**Figure 4 . 12 b Oil Flow Visualization for the Bluff-Body Model
(Square-back Model at 20 Degrees Yaw)**



Plan View

**Figure 4 . 13 a Sketch of Surface Flow Characteristics for the Bluff-Body Model
(Square-back Model at 0 Degrees Yaw)**



Plan View

**Figure 4 . 13 b Sketch of Surface Flow Characteristics for the Bluff-Body Model
(Square-back Model at 20 Degrees Yaw)**

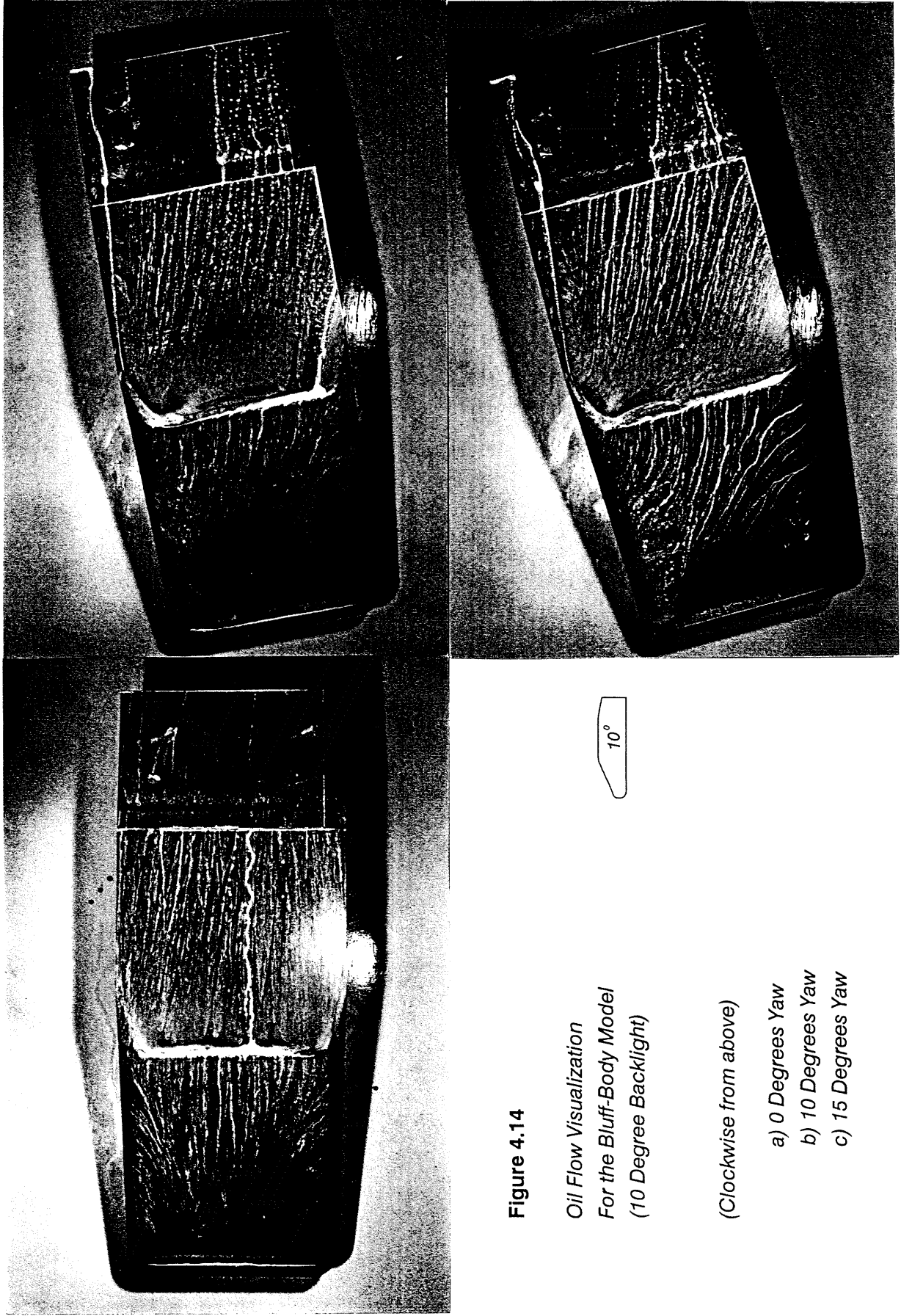


Figure 4.14

*Oil Flow Visualization
For the Bluff-Body Model
(10 Degree Backlight)*

(Clockwise from above)

- a) 0 Degrees Yaw
- b) 10 Degrees Yaw
- c) 15 Degrees Yaw

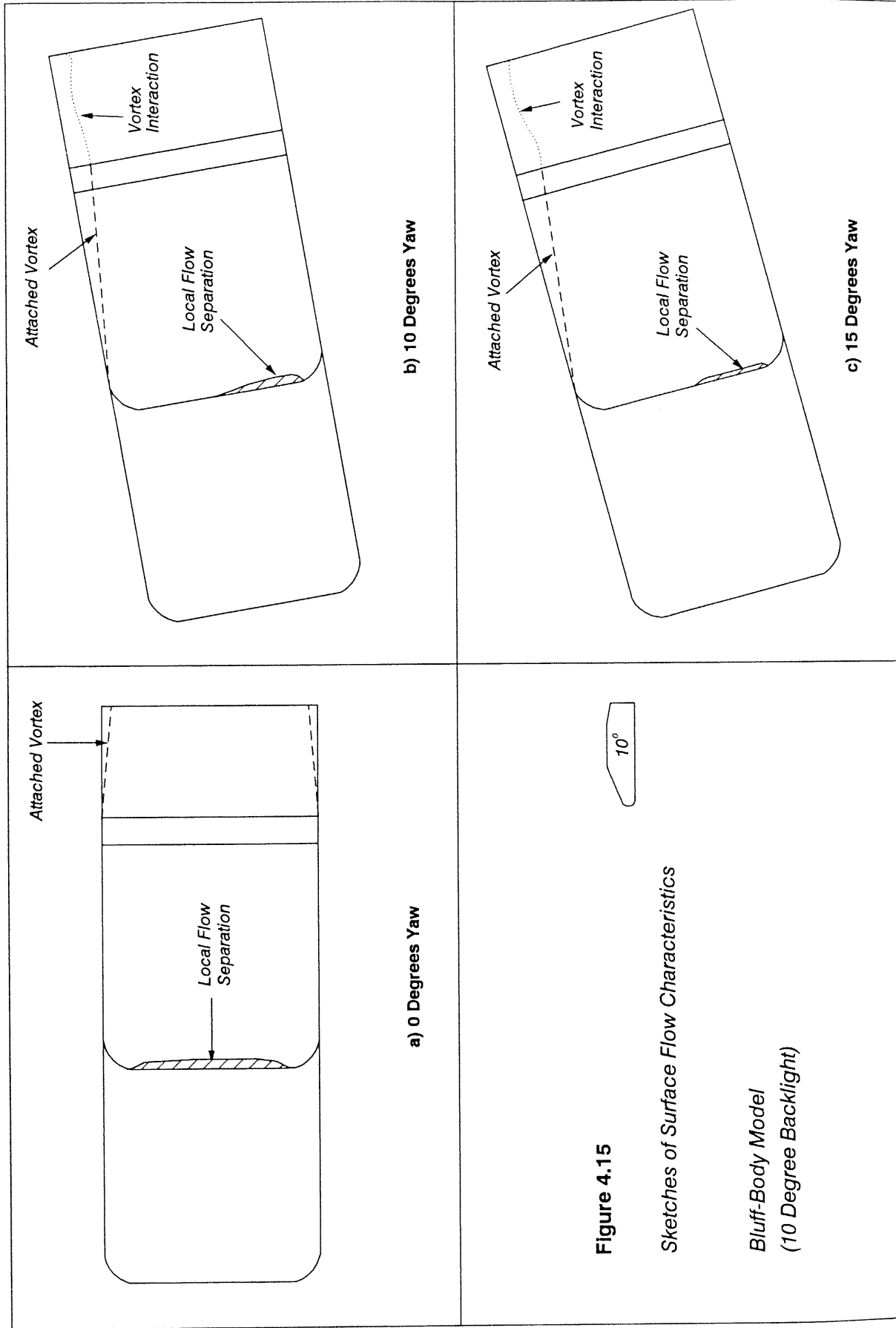
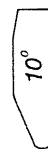


Figure 4.15

Sketches of Surface Flow Characteristics

Bluff-Body Model
(10 Degree Backlight)



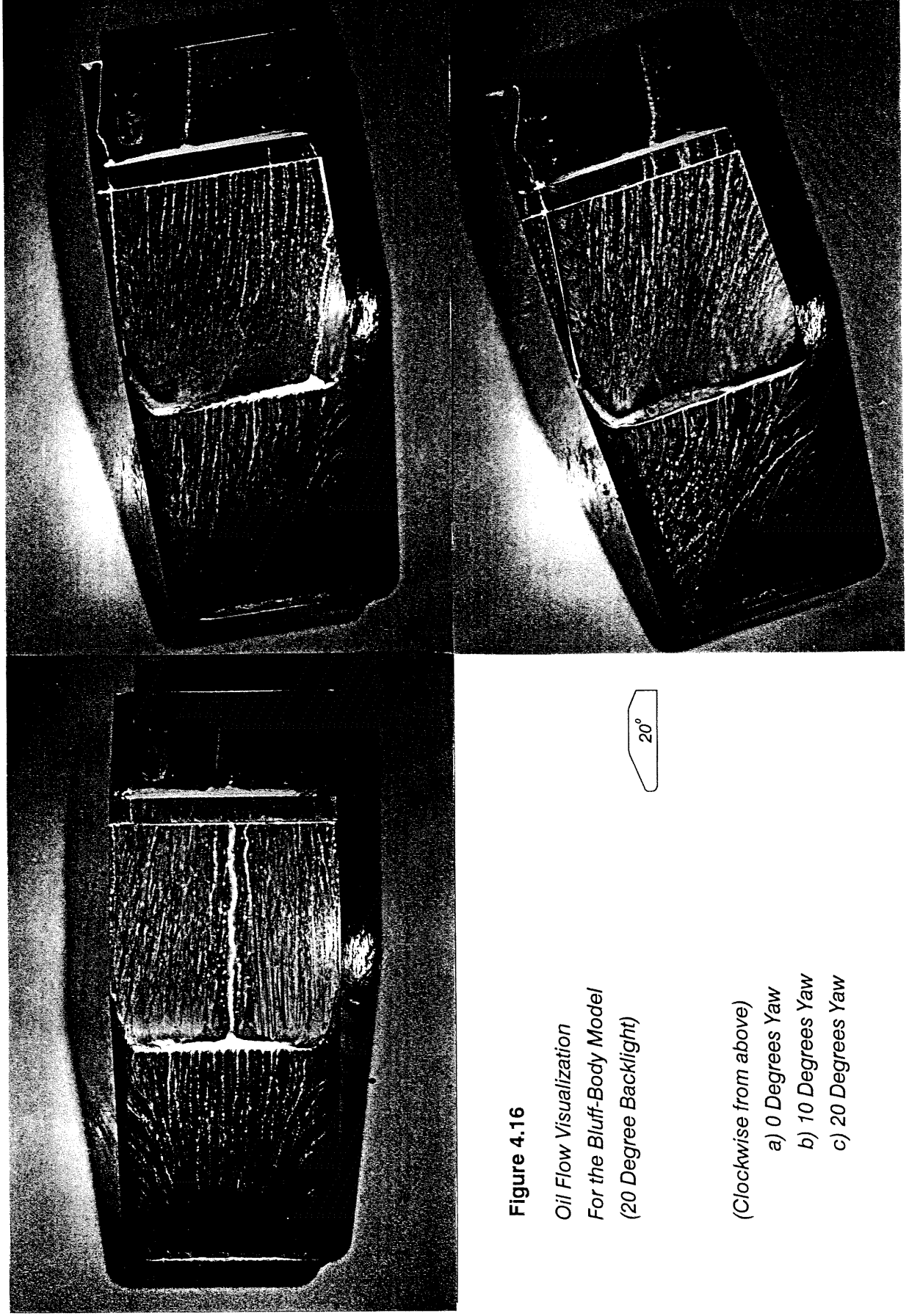
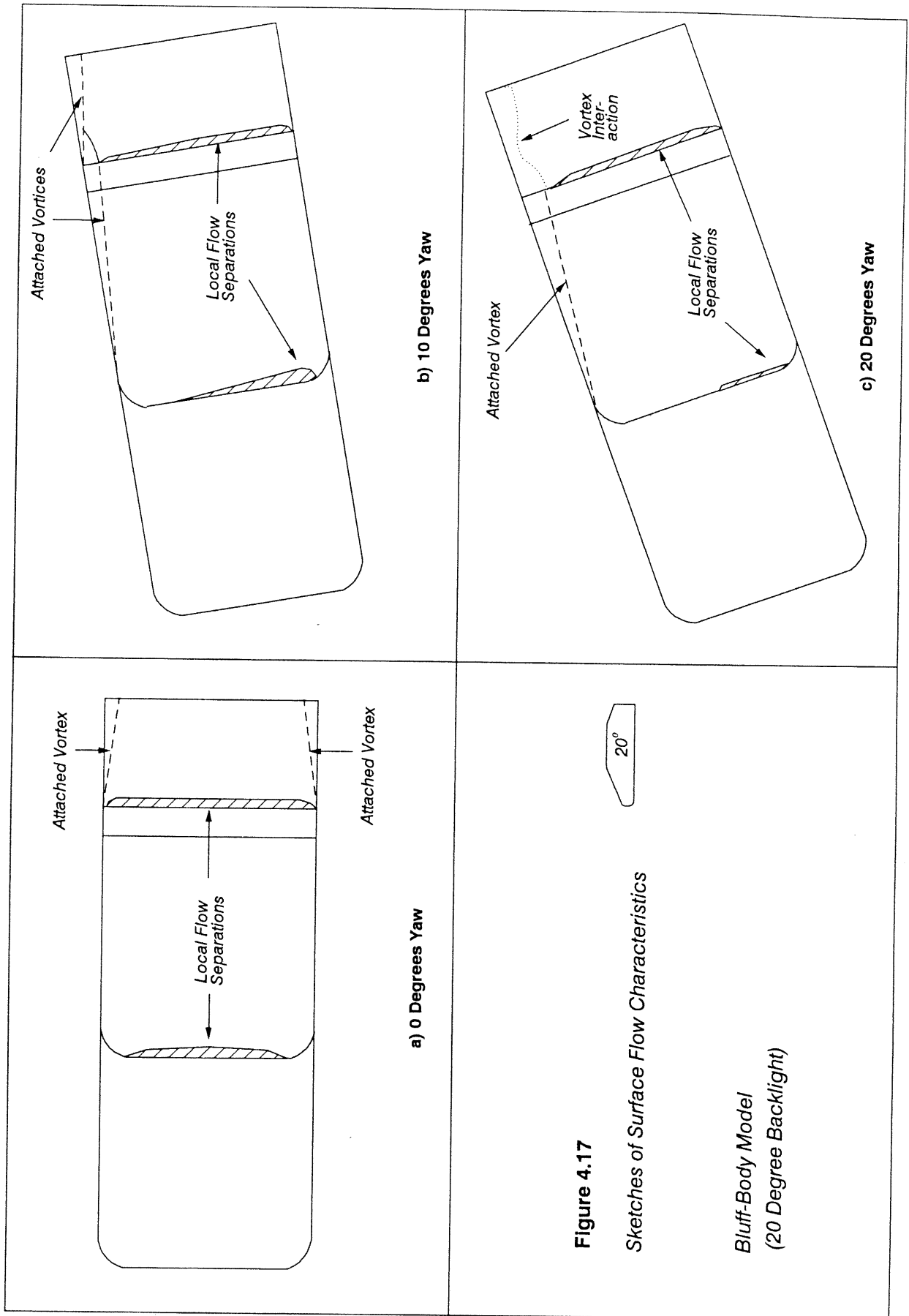


Figure 4.16

*Oil Flow Visualization
For the Bluff-Body Model
(20 Degree Backlight)*

(Clockwise from above)
a) 0 Degrees Yaw
b) 10 Degrees Yaw
c) 20 Degrees Yaw



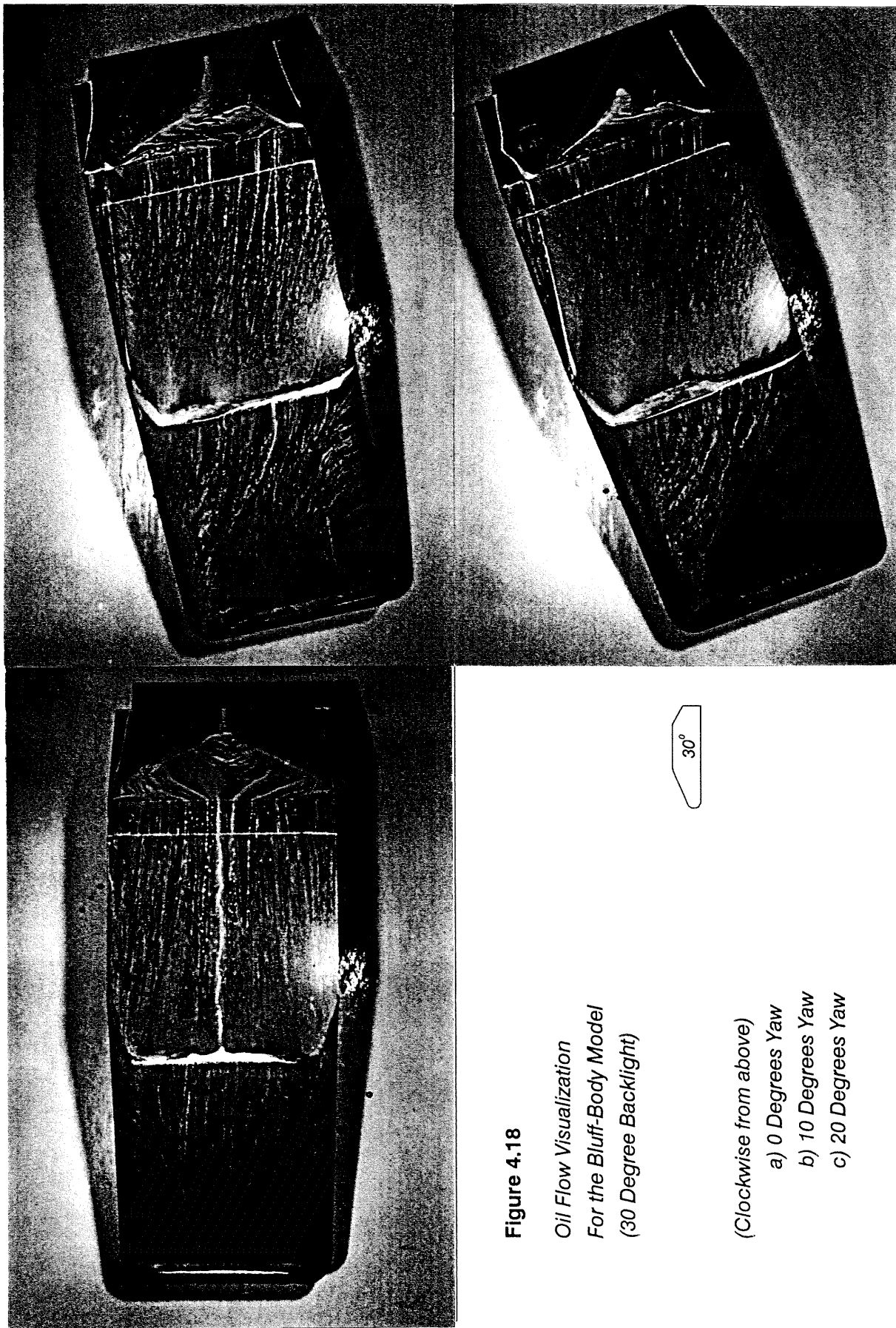
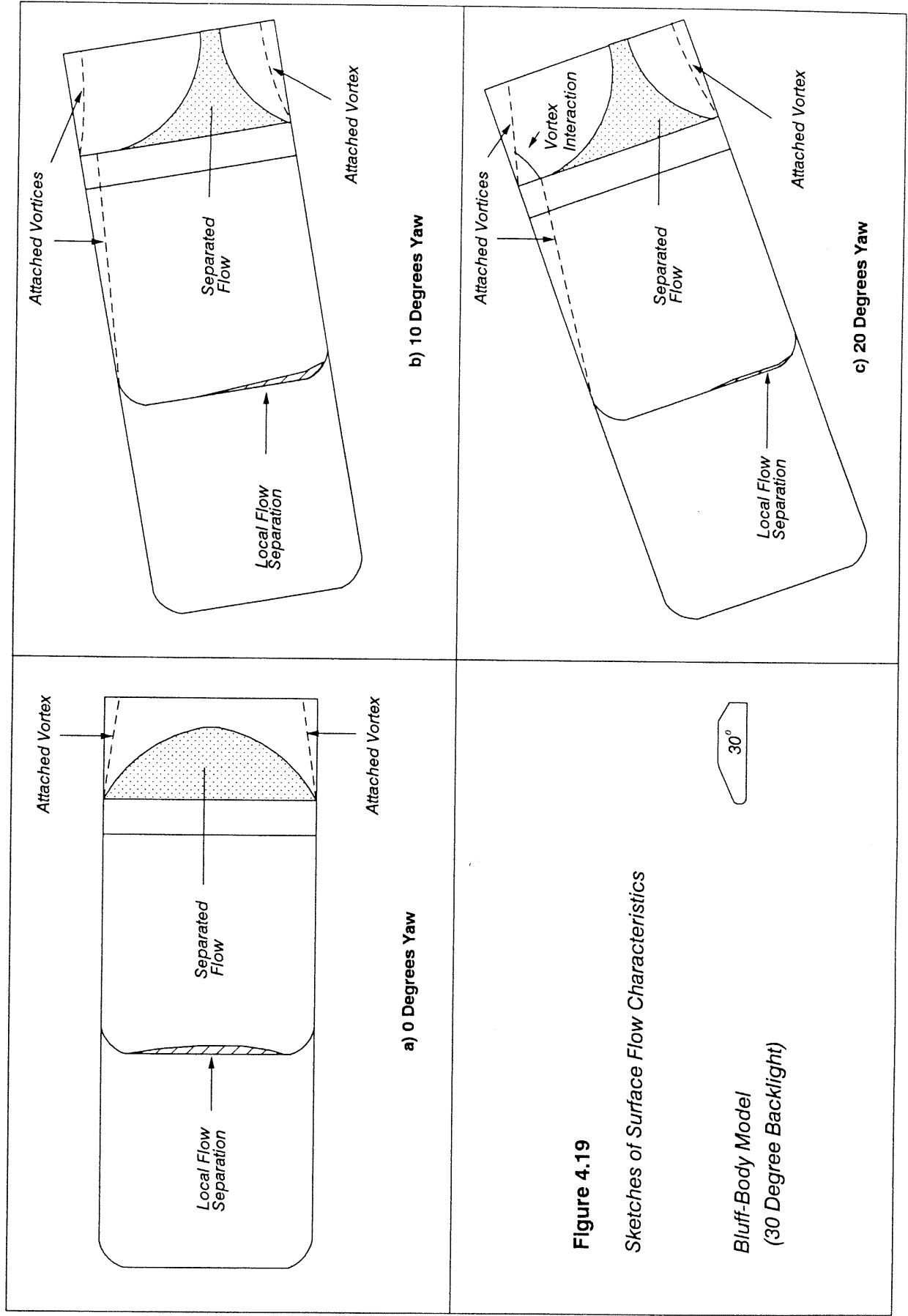


Figure 4.18

*Oil Flow Visualization
For the Bluff-Body Model
(30 Degree Backlight)*

(Clockwise from above)
a) 0 Degrees Yaw
b) 10 Degrees Yaw
c) 20 Degrees Yaw



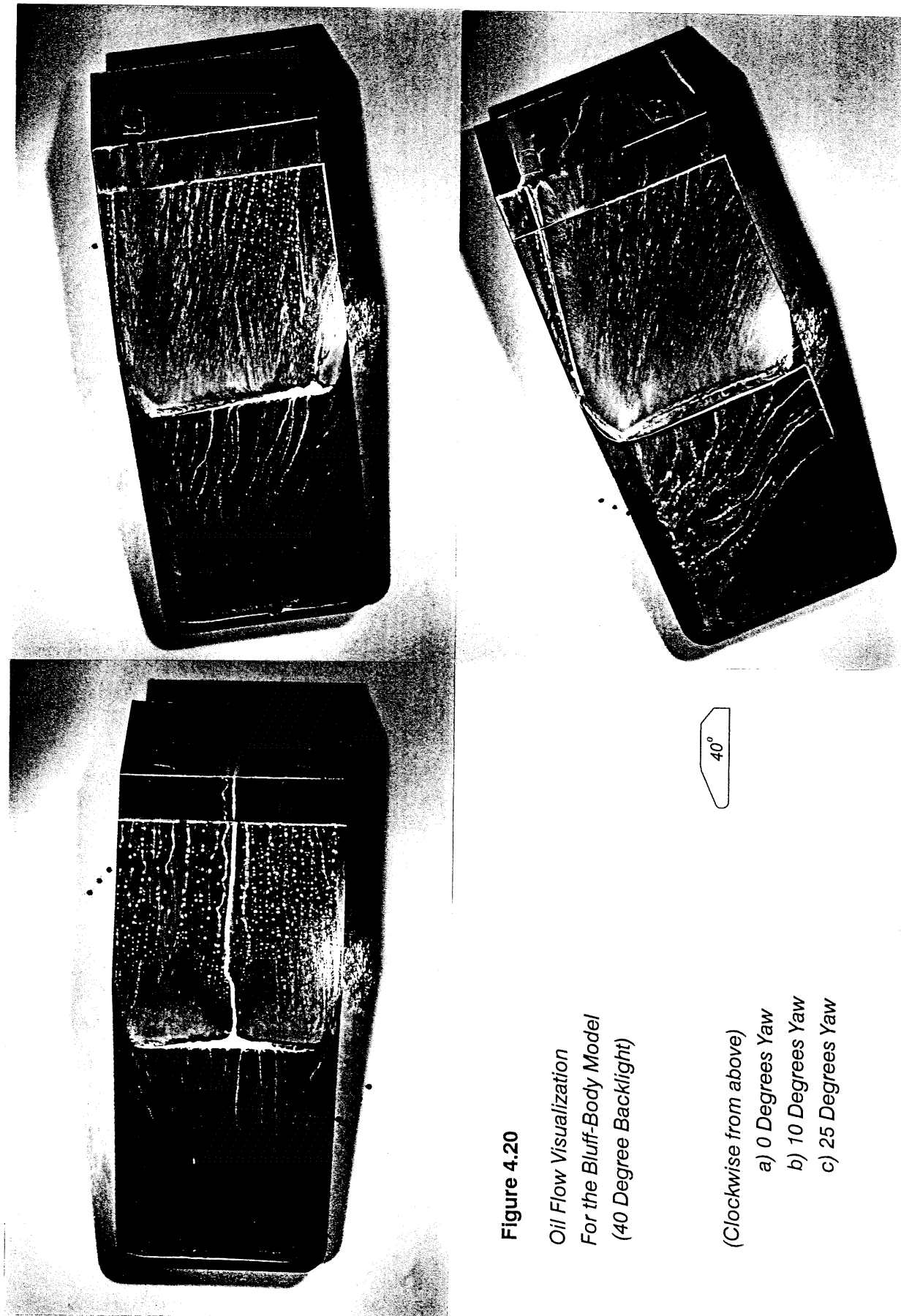


Figure 4.20

*Oil Flow Visualization
For the Bluff-Body Model
(40 Degree Backlight)*

(Clockwise from above)

- a) 0 Degrees Yaw*
- b) 10 Degrees Yaw*
- c) 25 Degrees Yaw*

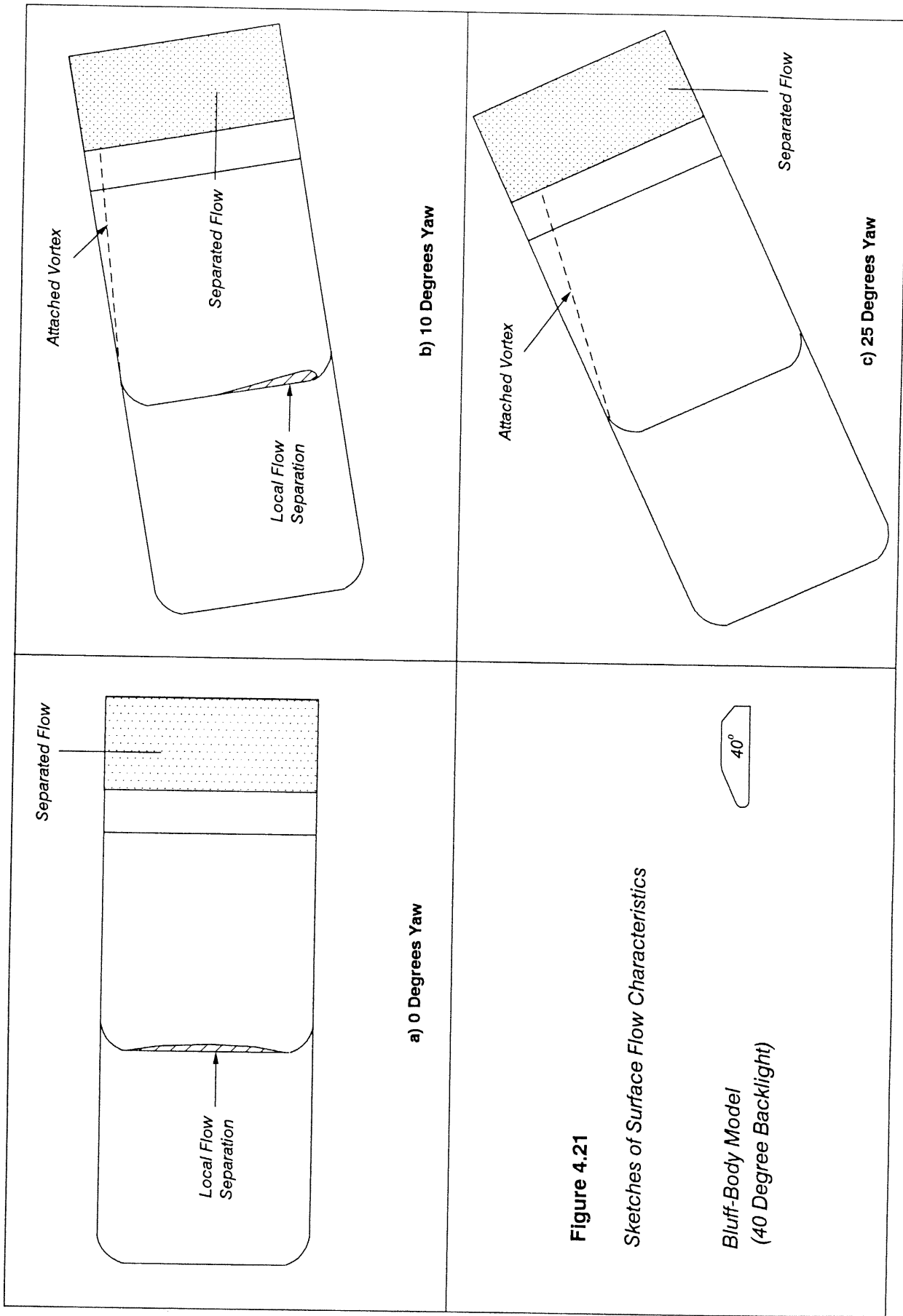


Figure 4.21

Sketches of Surface Flow Characteristics

*Bluff-Body Model
(40 Degree Backlight)*

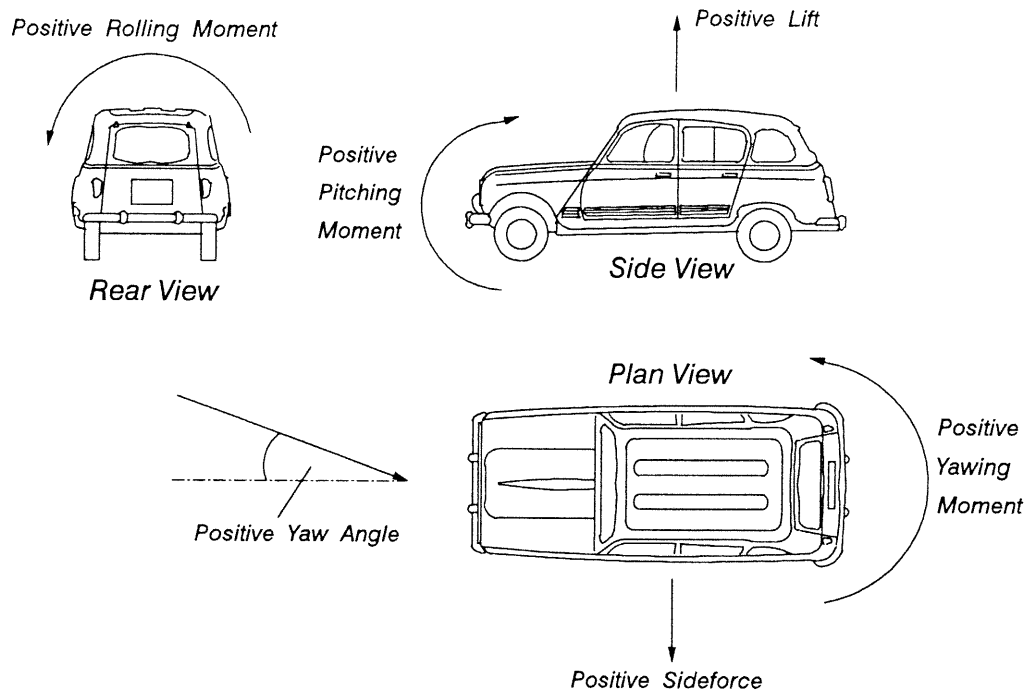


Figure 4 . 22 Force and Moment Sign Convention

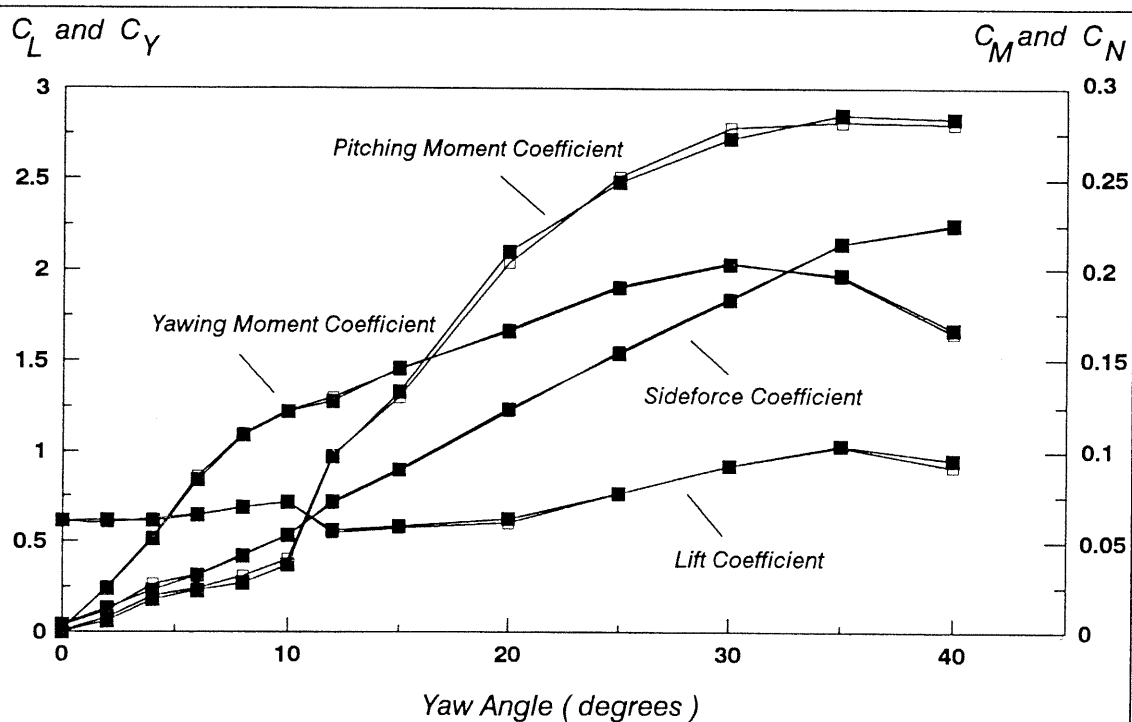


Figure 4 . 23 An Illustration of Data Repeatability for the Basic Saloon Model (Square-Edged Fastback Configuration - Two Runs Over-Plotted)

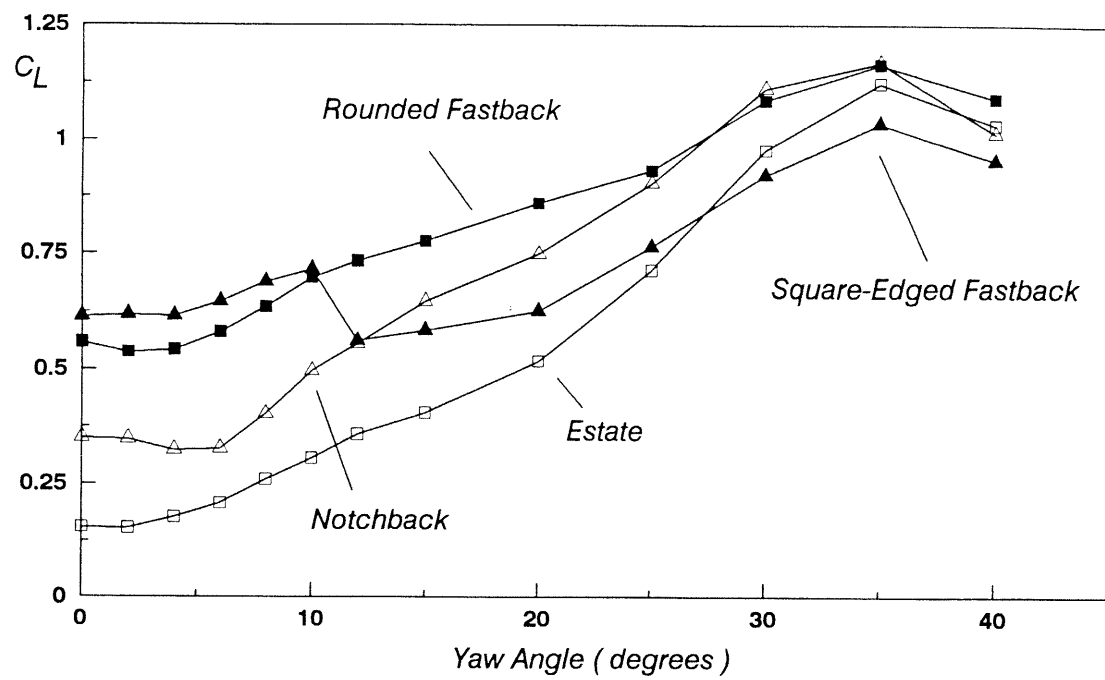


Figure 4 . 24 Quasi-Static Lift Coefficients for the Basic Saloon Model

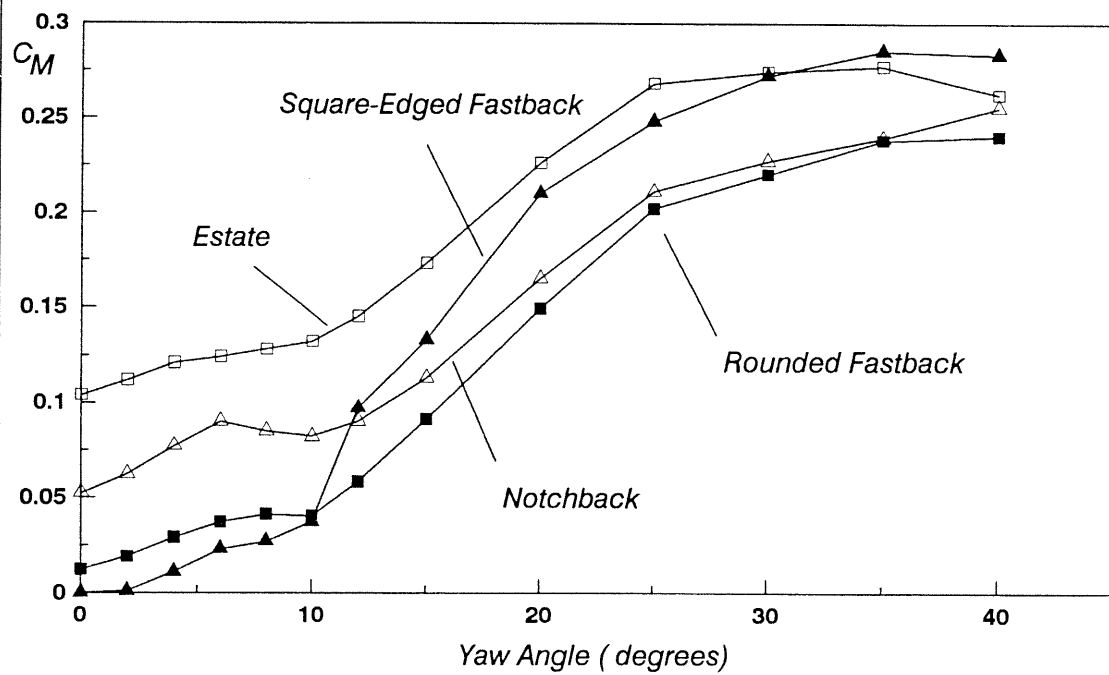


Figure 4 . 25 Quasi-Static Pitching Moment Coefficients for the Basic Saloon Car Model

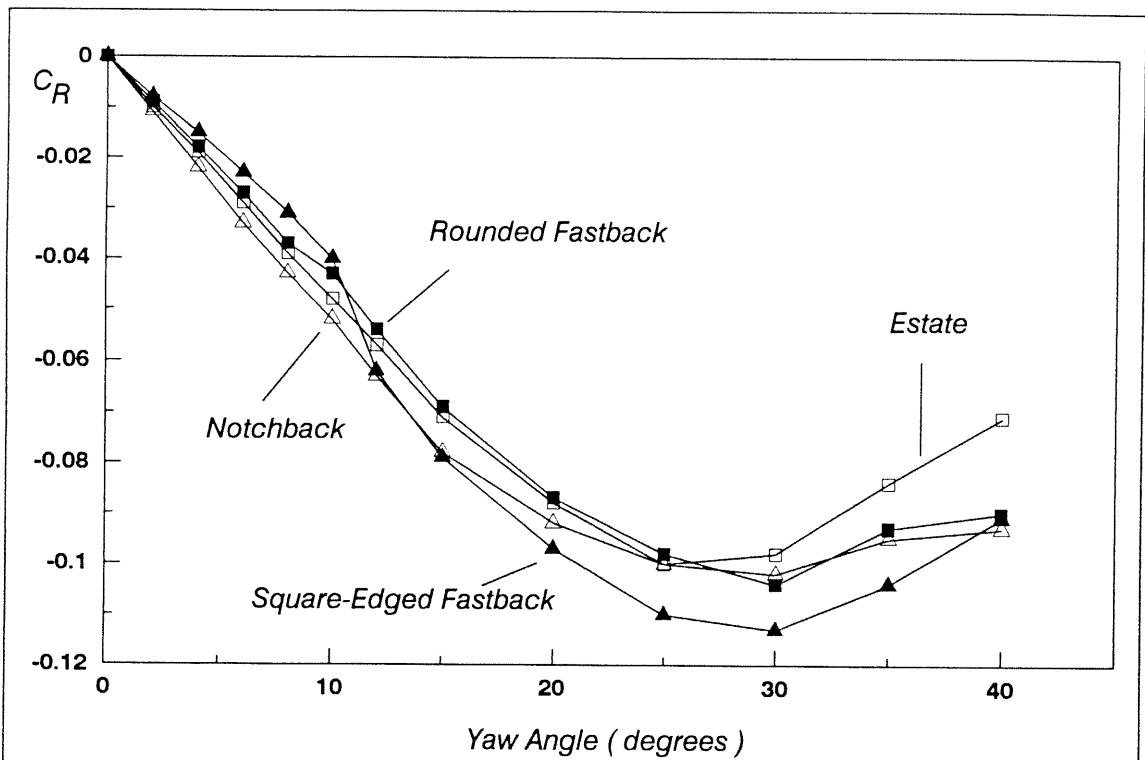


Figure 4 . 26 Quasi-Static Rolling Moment Coefficients for the Basic Saloon Model

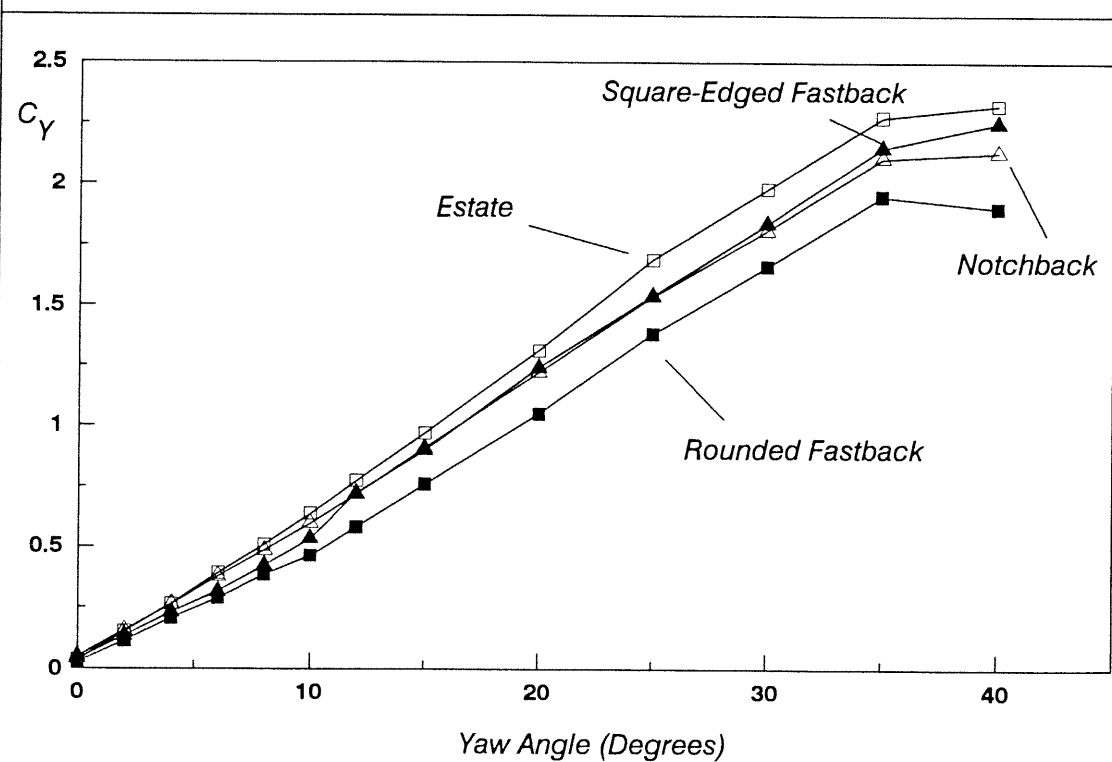


Figure 4 . 27 Quasi-Static Sideforce Coefficients for the Basic Saloon

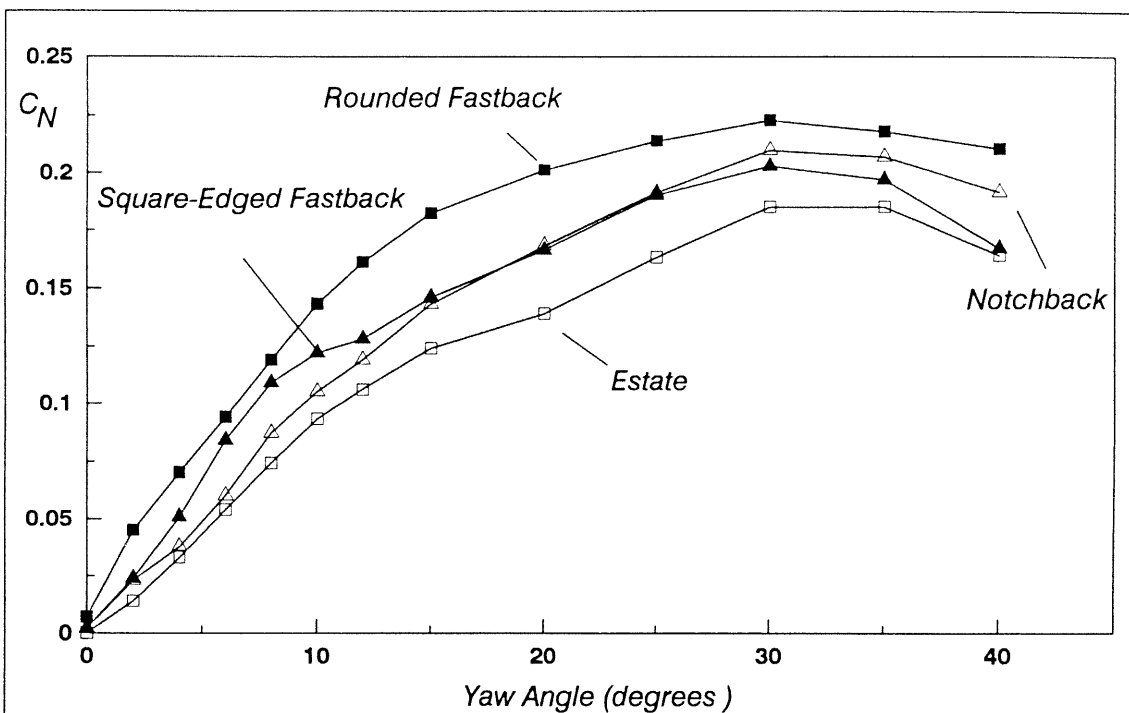


Figure 4 . 28 Quasi-Static Yawing Moment Coefficients for the Basic Saloon

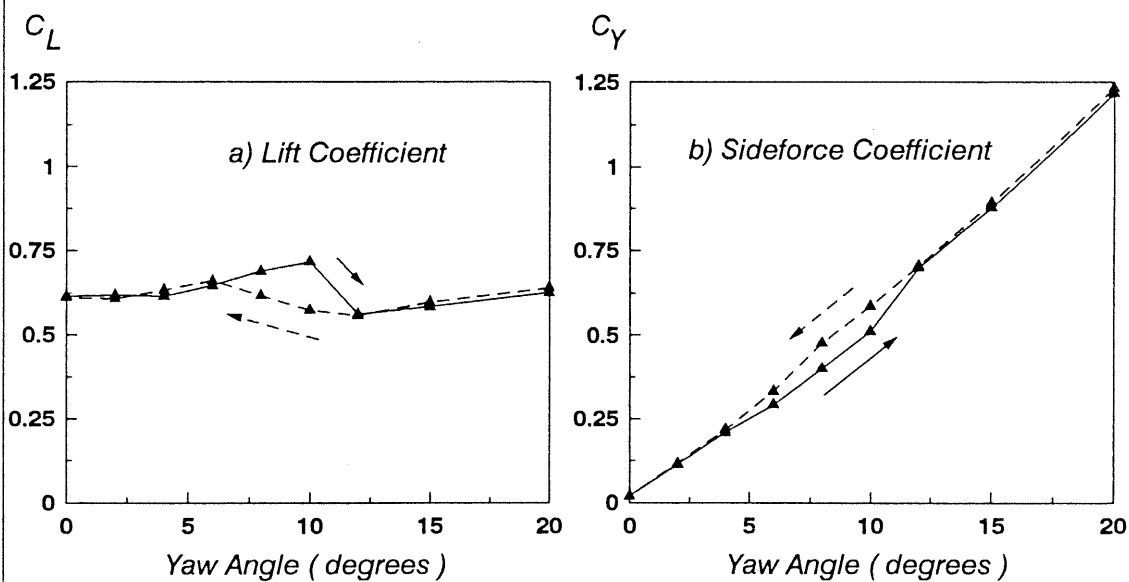


Figure 4 . 29 The Dependence of Coefficient Results for the Square-Edged Fastback upon Flowfield History - Manifested as a "Hysteresis Loop"

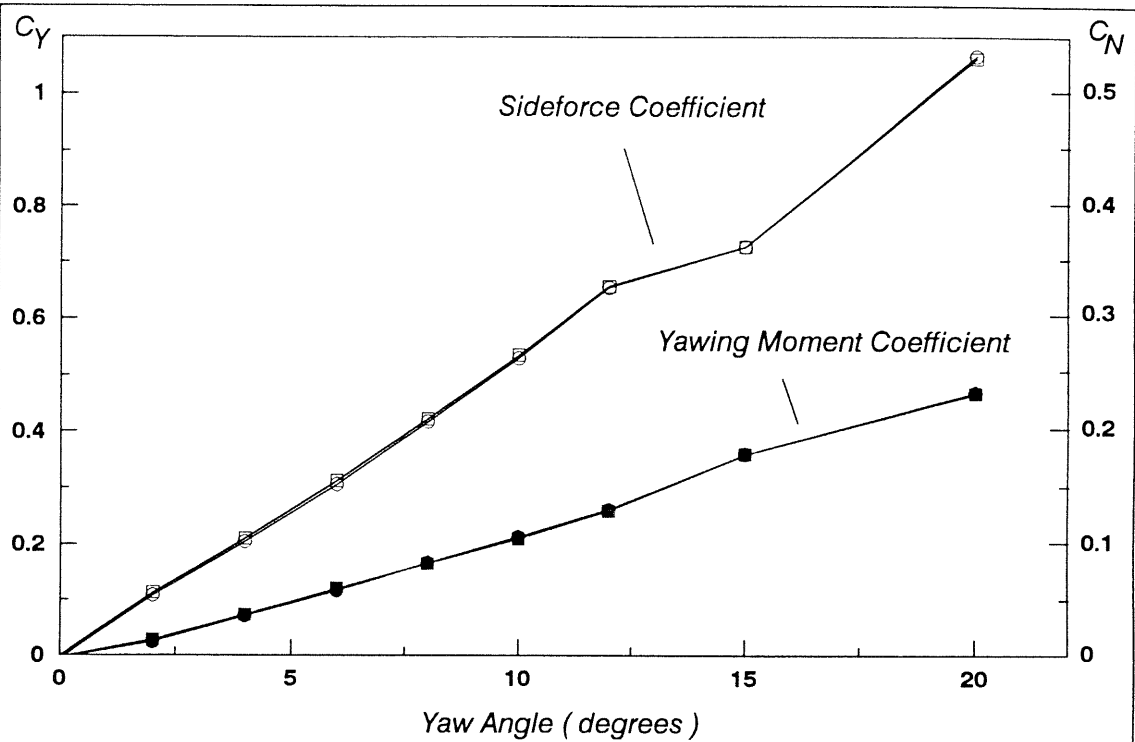


Figure 4 . 30 An Illustration of Data Repeatability for the Bluff-Body Model
(30 Degree Backlight) (Two Runs Over-Plotted for each Coefficient)

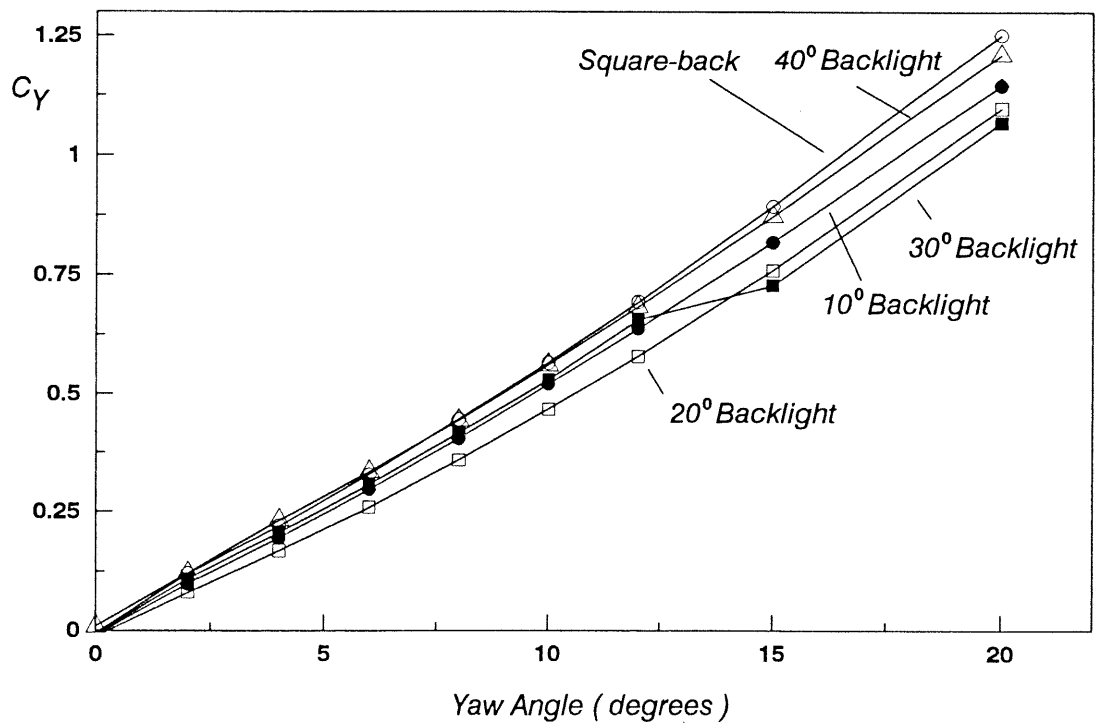


Figure 4 . 31 Quasi-Static Sideforce Coefficients for the Bluff-Body Model

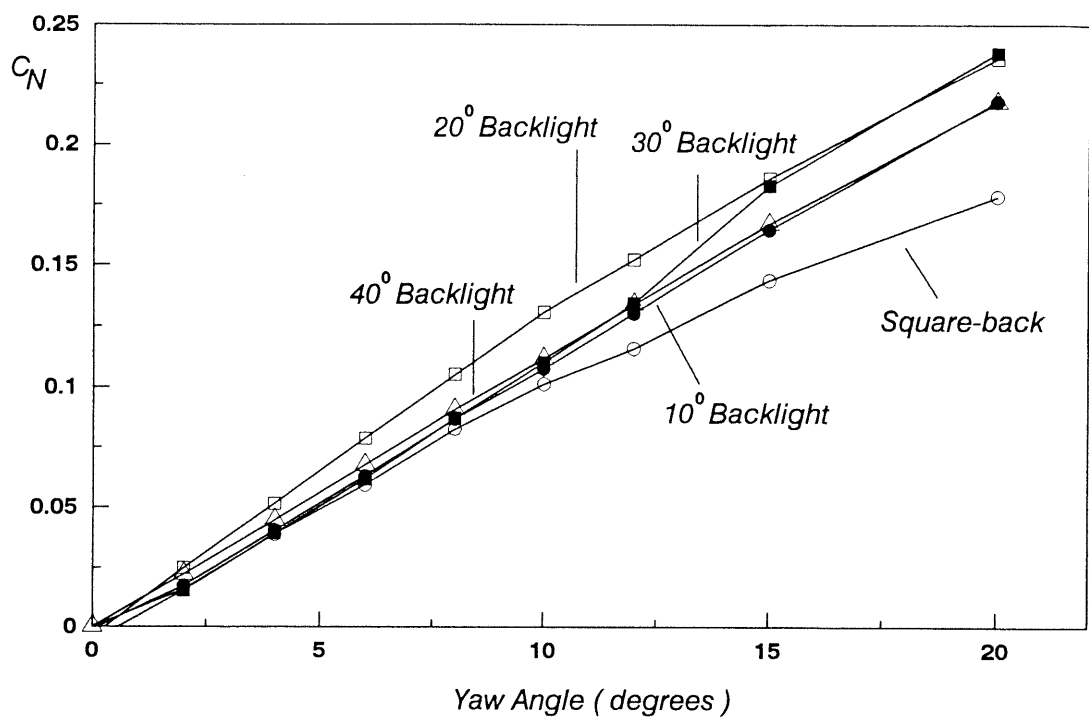


Figure 4.32 Quasi-Static Yawing Moment Coefficients for the Bluff-Body Model

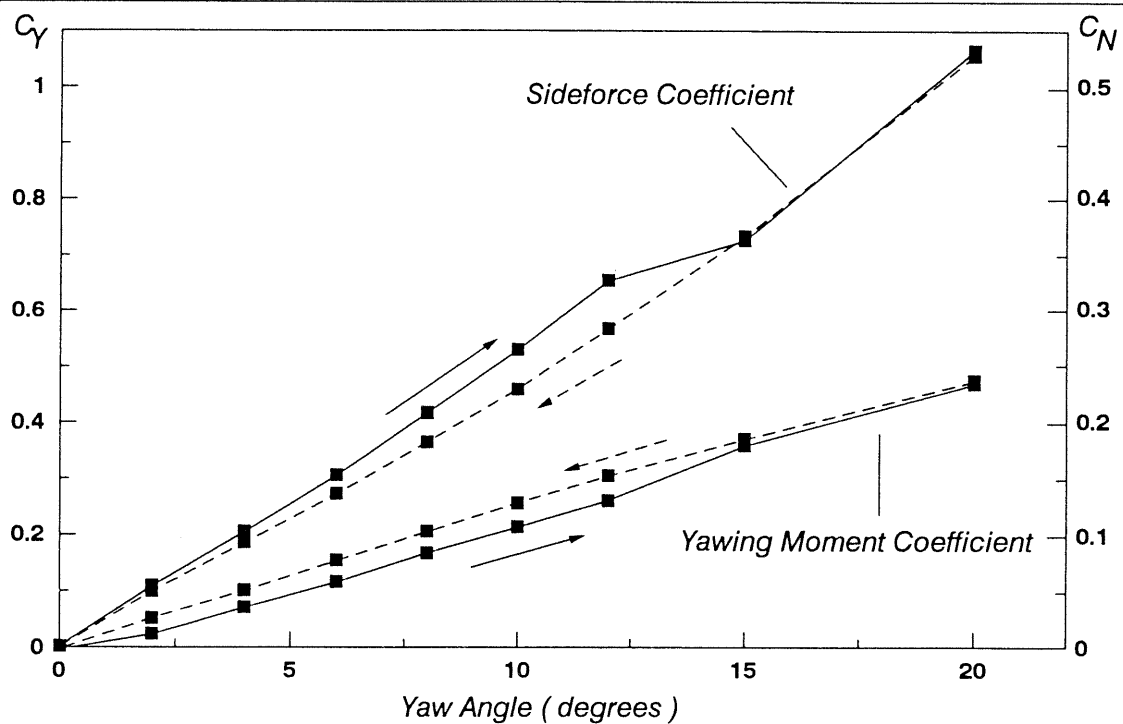


Figure 4.33 The Dependence of Coefficient Results for the 30 Degree Backlight Bluff-Body Model upon Flowfield History - Manifested as a "Hysteresis Loop"

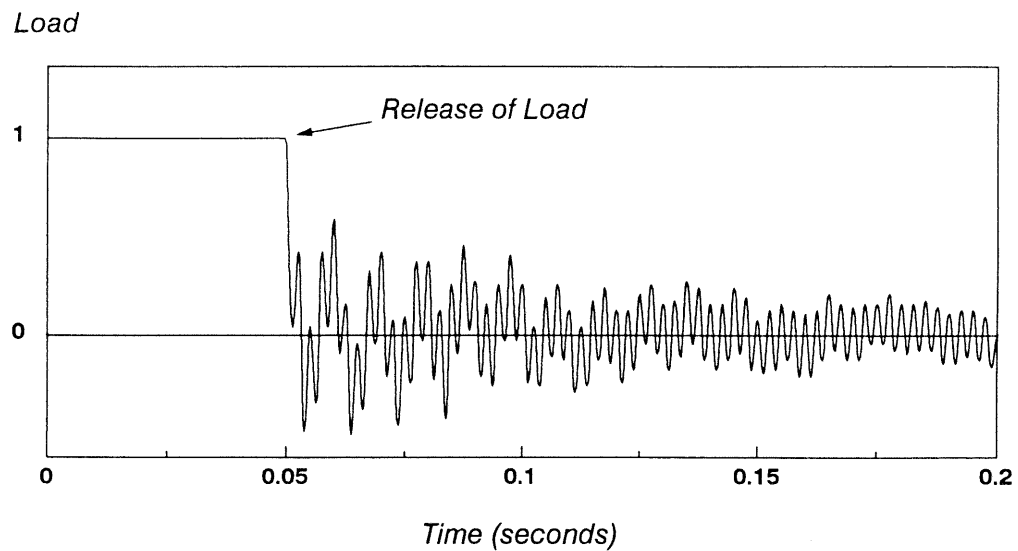


**Figure 5 . 1 Balance Response to an Instantaneous Release of Load
- (channel one)**

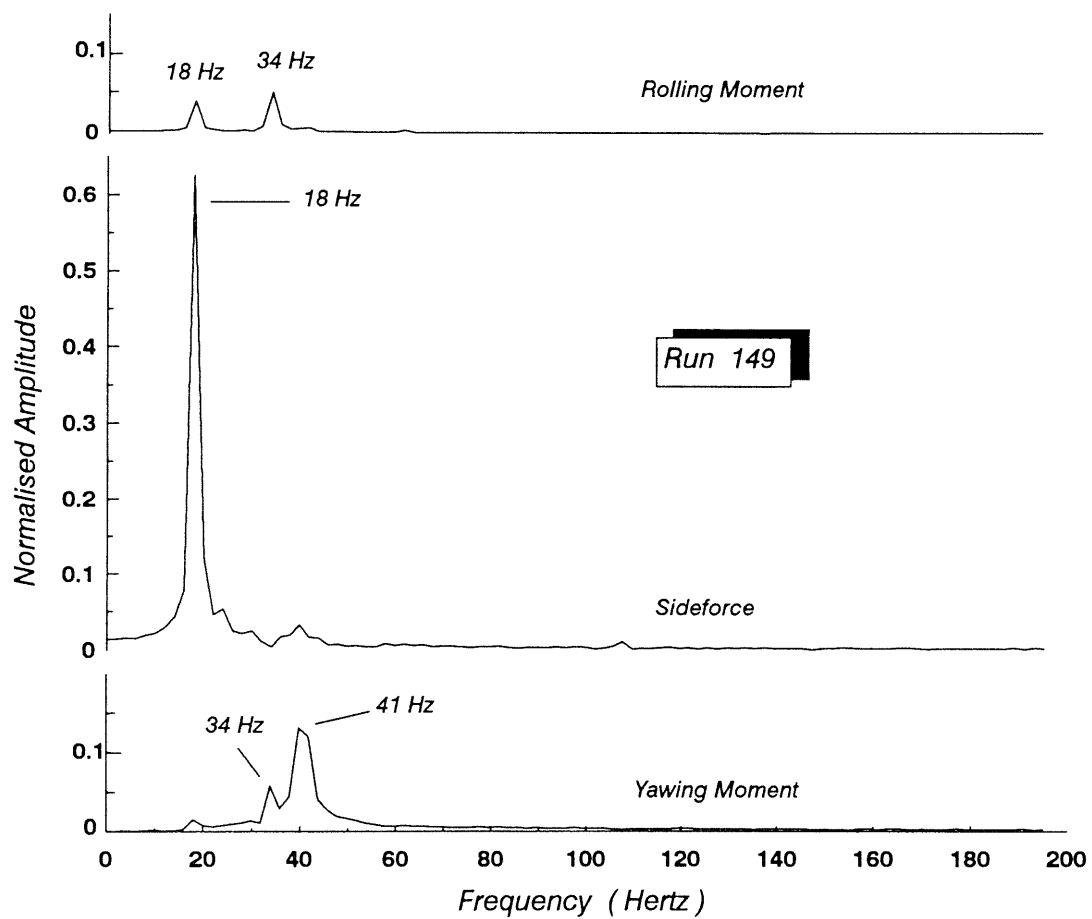


**Figure 5 . 2 FFT Spectral Analysis Illustrating Resonant Frequencies for
Lateral Coefficients. (Force Balance With Model Fitted)**

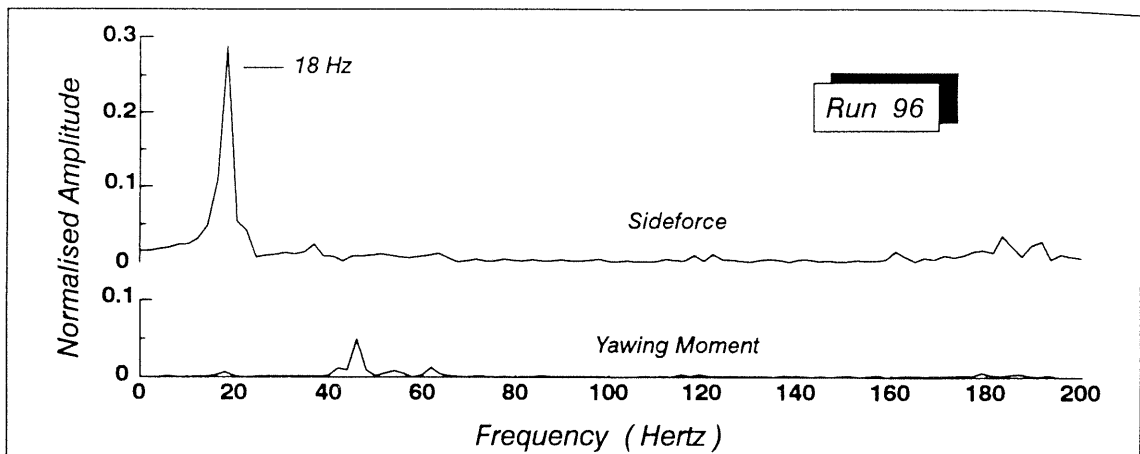


Figure 5.3 FFT Spectral Analysis Illustrating Resonant Frequencies for Lateral Coefficients. (Force Balance Fitted with Wind-off Equipment)

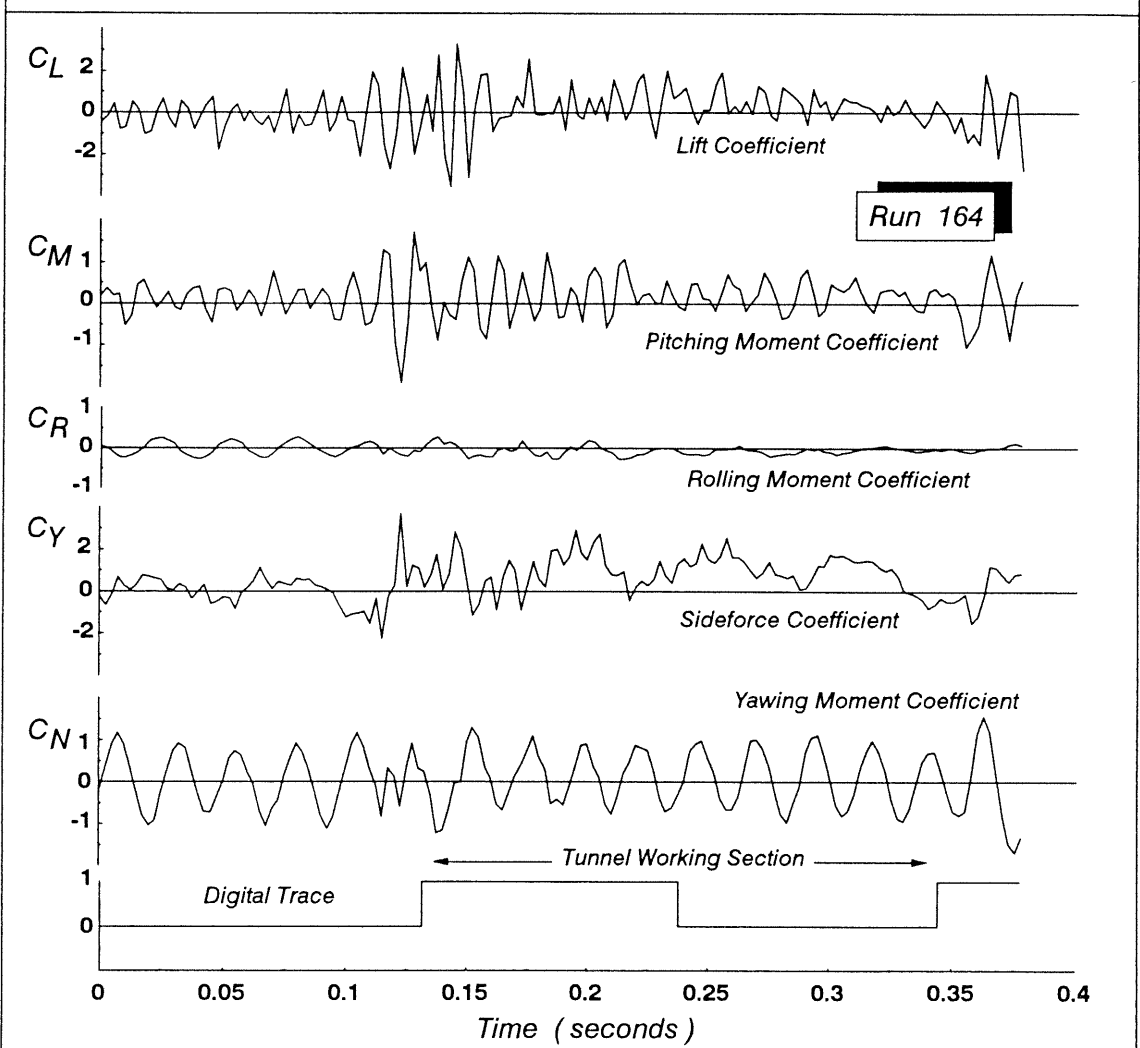


Figure 5.4 Time Histories of Force and Moment Coefficients Derived from a Single Crosswind Test. (Estate model at 20 degrees yaw)

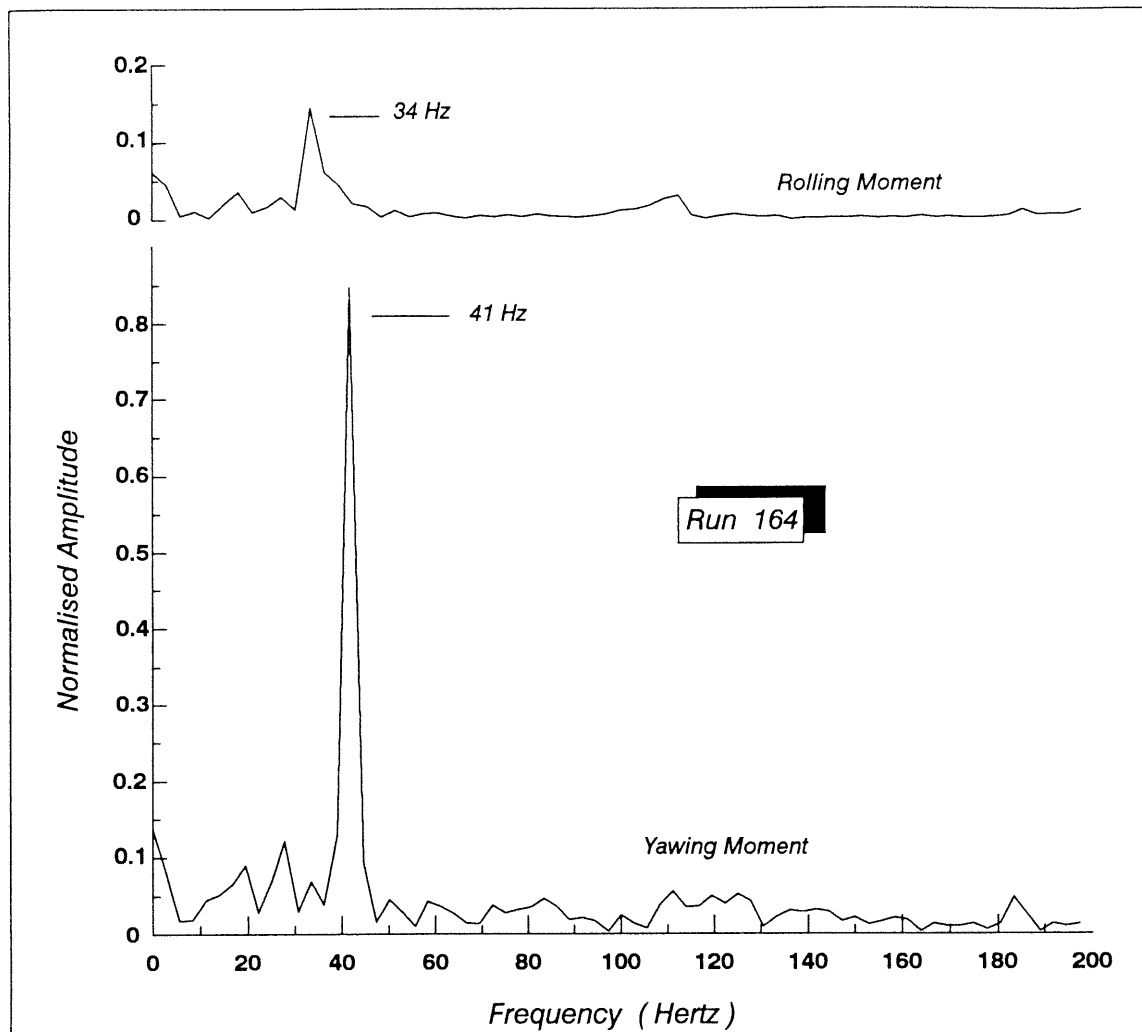


Figure 5.5 FFT Spectral Analysis of Coefficients Measured During a Crosswind Test (Estate Model at 20 Degrees Yaw when Immersed in Gust)

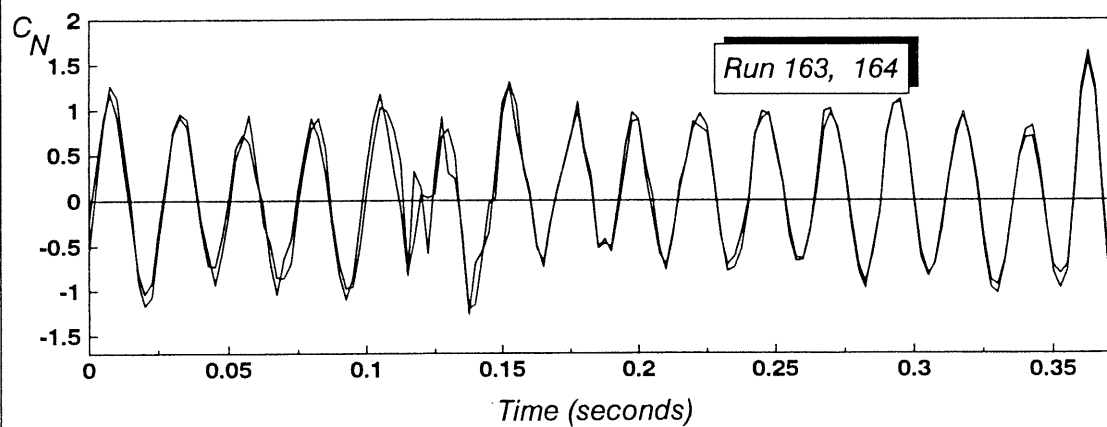


Figure 5.6 Time Histories for Yawing Moment Coefficients, Derived by Over-Plotting the Results from Two Consecutive Runs (Estate Model at 20 Degrees Yaw)

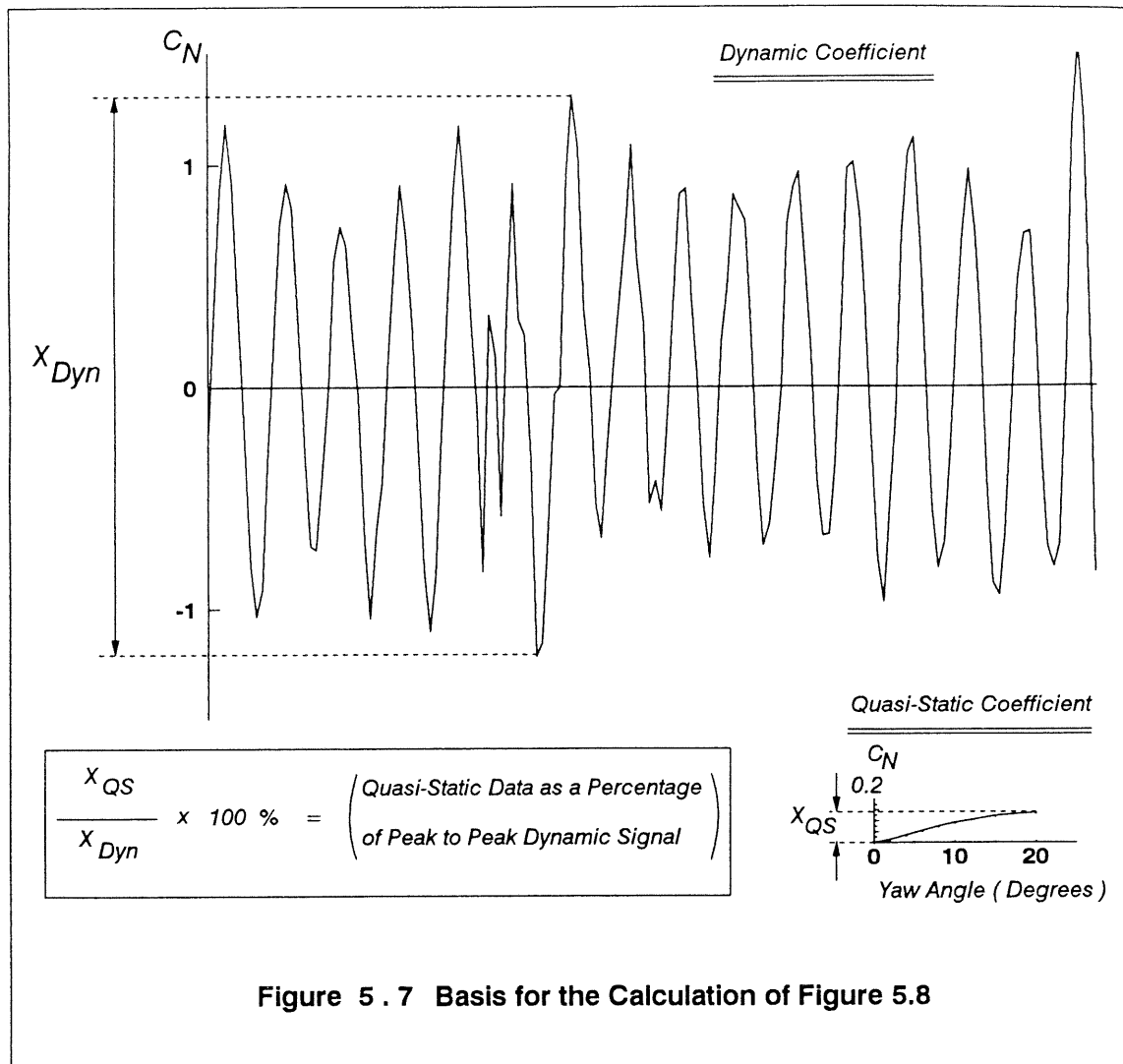


Figure 5 . 7 Basis for the Calculation of Figure 5.8

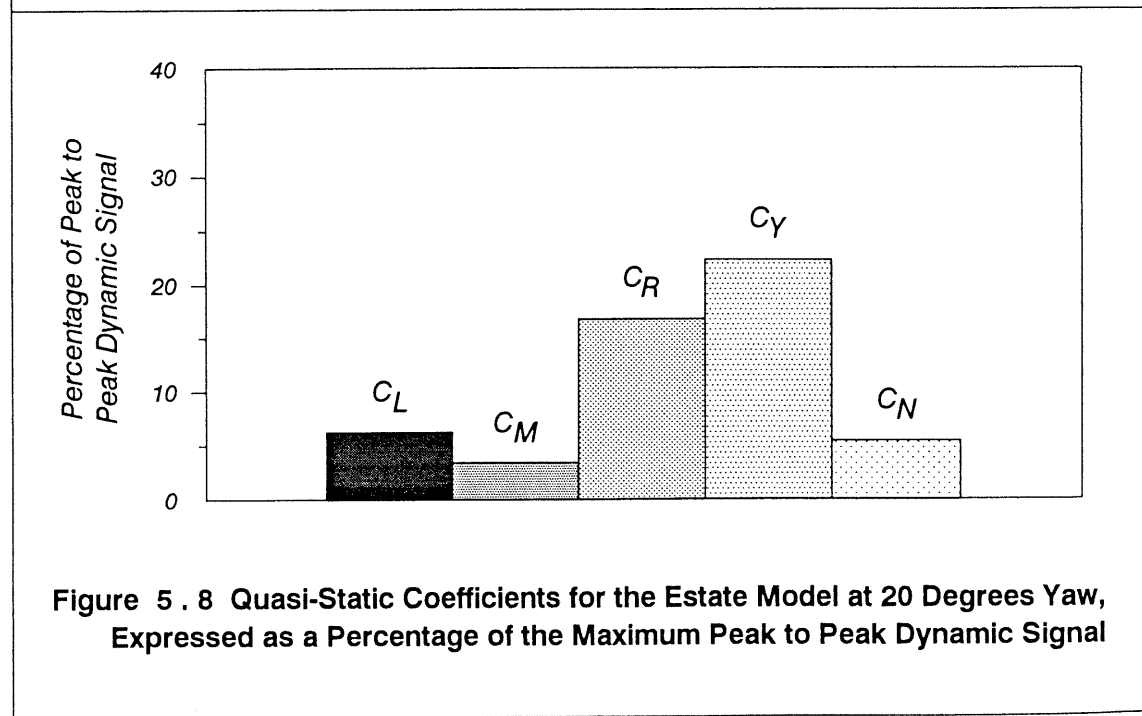


Figure 5 . 8 Quasi-Static Coefficients for the Estate Model at 20 Degrees Yaw, Expressed as a Percentage of the Maximum Peak to Peak Dynamic Signal

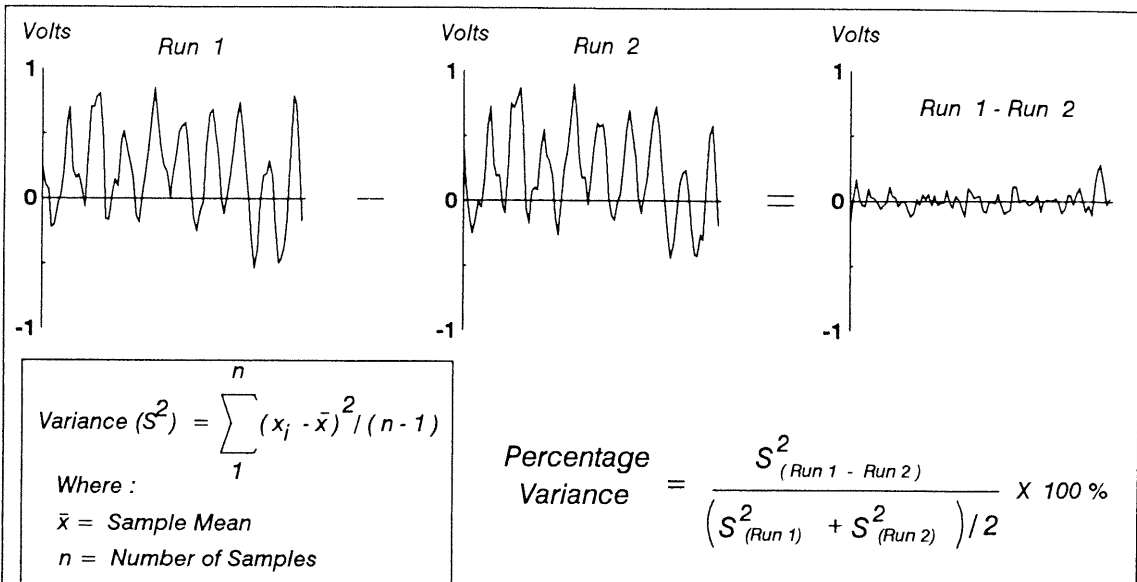


Figure 5.9 Basis for Calculating Figure 5.10

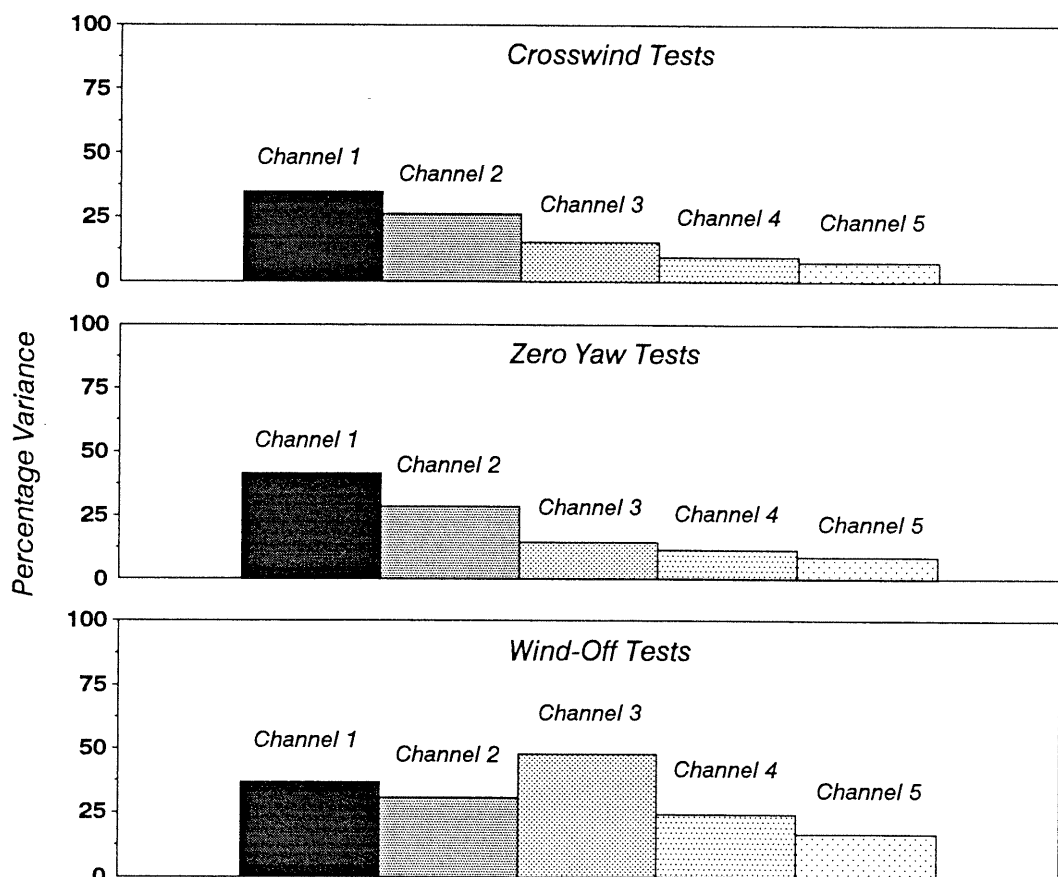


Figure 5.10 An Illustration of Raw Data Repeatability, Expressed as a Percentage Variance of the Difference Between Two Signals (from two identical tests)

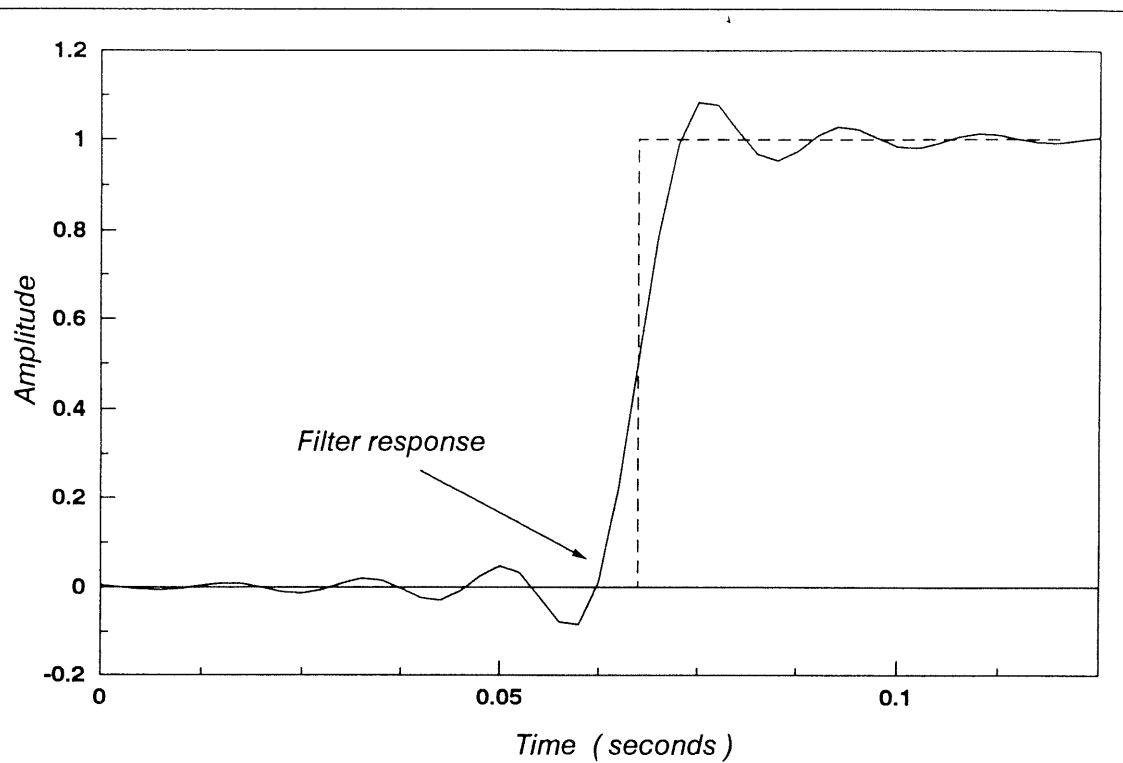


Figure 5 . 11 Response of a 50 Hz Lowpass Filter to a Unit Step - Input

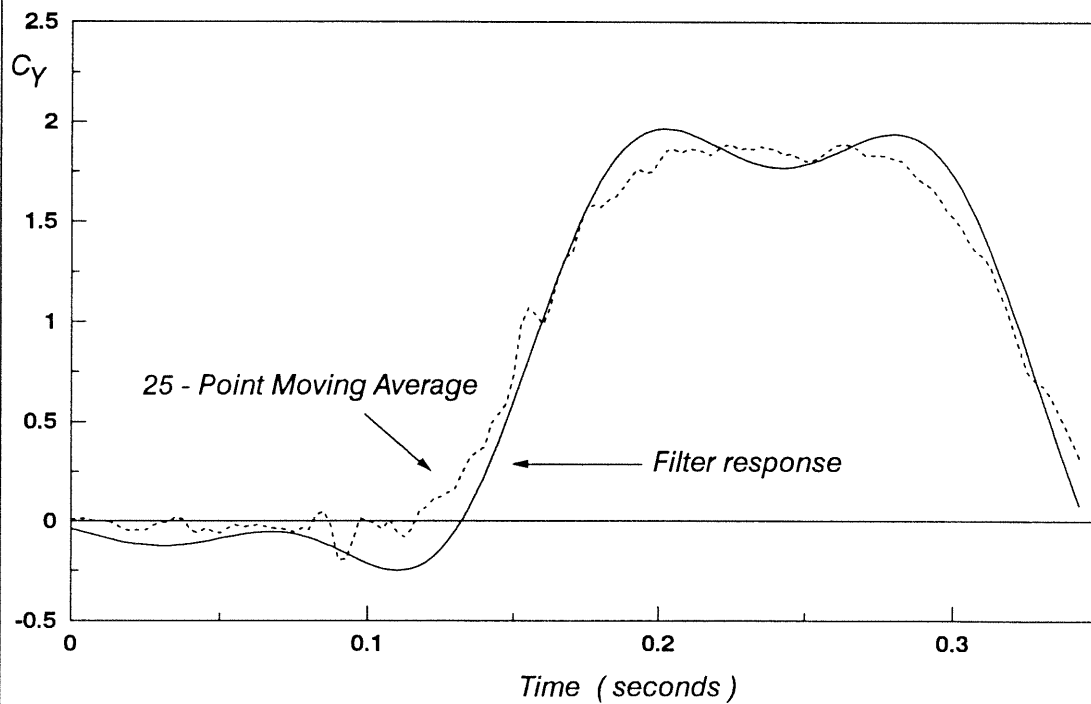


**Figure 5 .12 Comparison of a Lowpass Filter with a 25 - Point Moving Average,
Applied to Sideforce Coefficient Data (Estate model at 30 degrees yaw)**

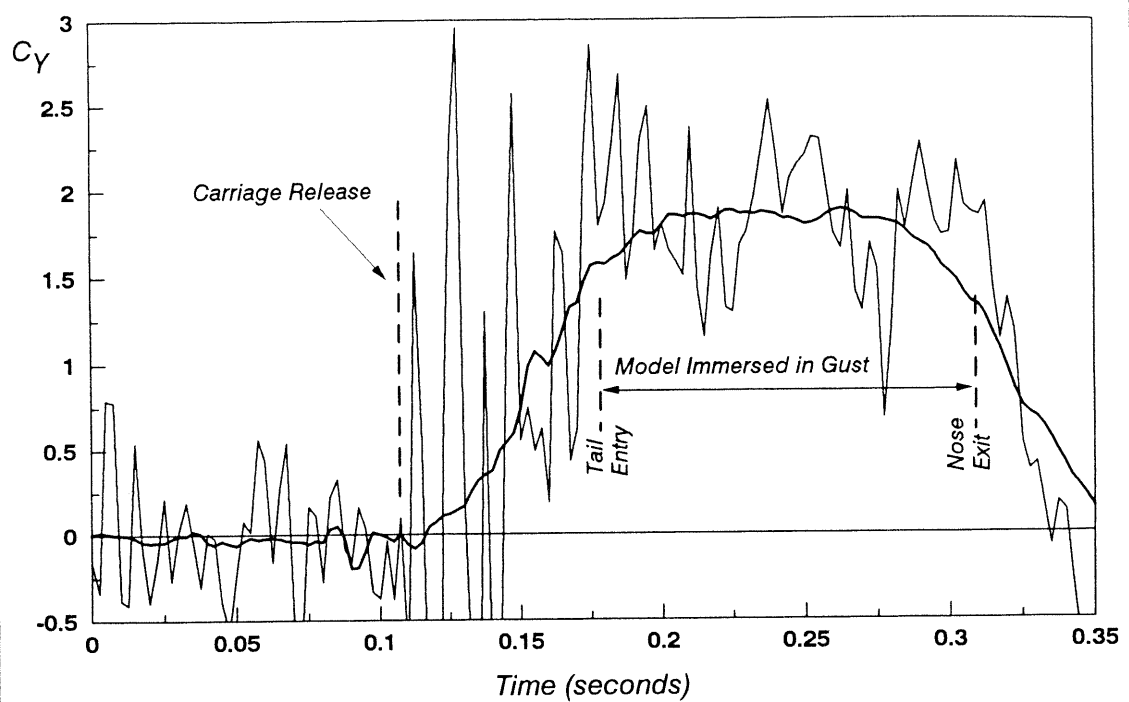


Figure 5.13 Recorded Sideforce Coefficient with a 25 - Point Moving Average Over - Plotted (Estate Model at 30 degrees yaw)

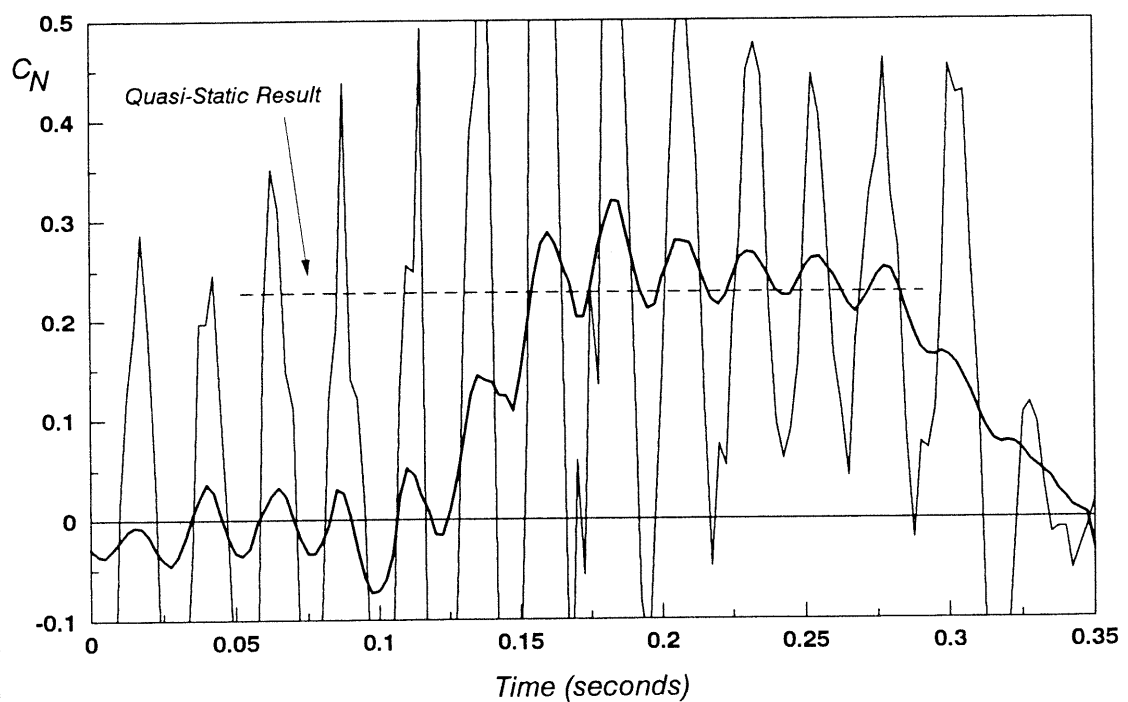


Figure 5.14 Recorded Yawing Moment Coefficient with a 25-Point Moving-Average Over-Plotted (Rounded fastback model at 30 degrees yaw)

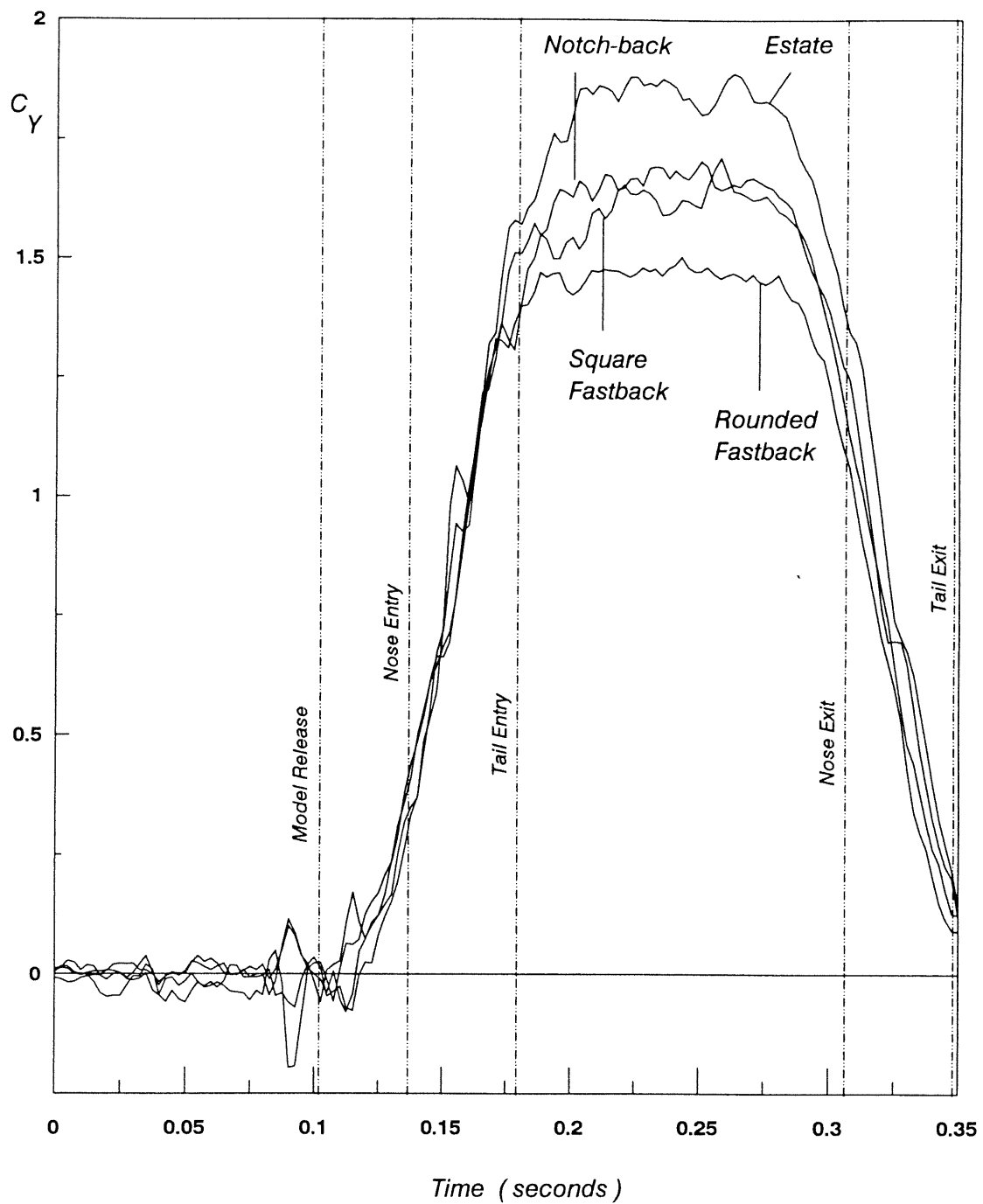


Figure 5 . 15 Typical Time Histories of Sideforce Coefficient for a Range of Vehicle Shapes Traversing a Simulated 30 Degree Crosswind Gust

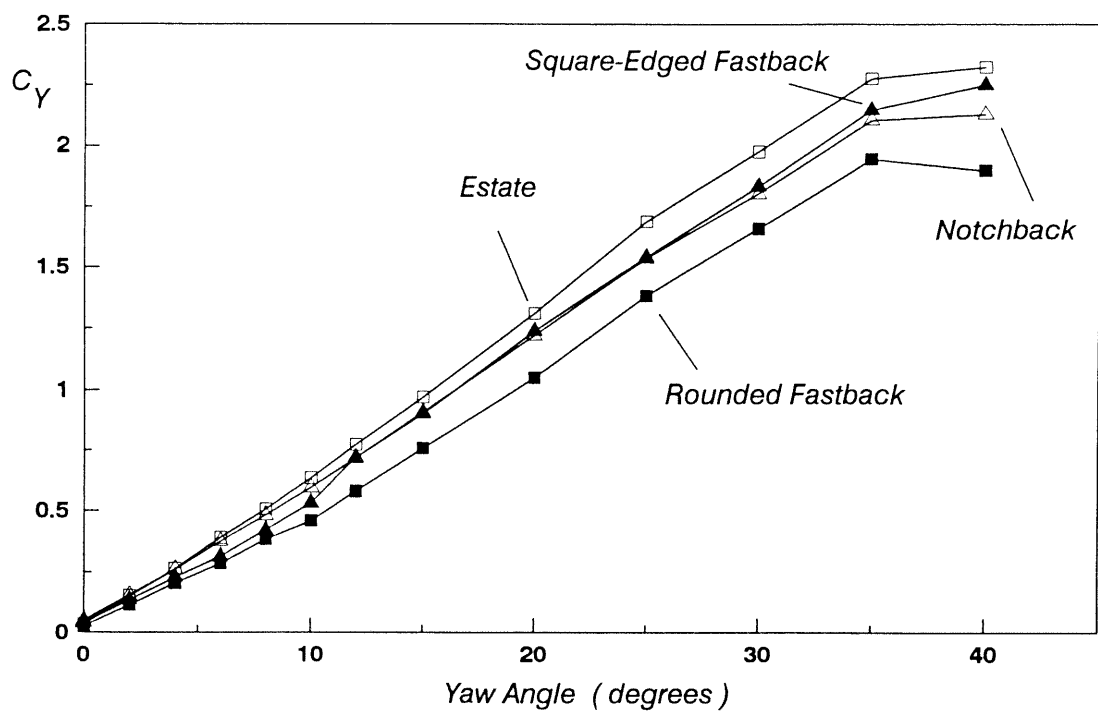


Figure 5.16 Quasi-Static Sideforce Coefficients for Various Basic Saloon Car Configurations

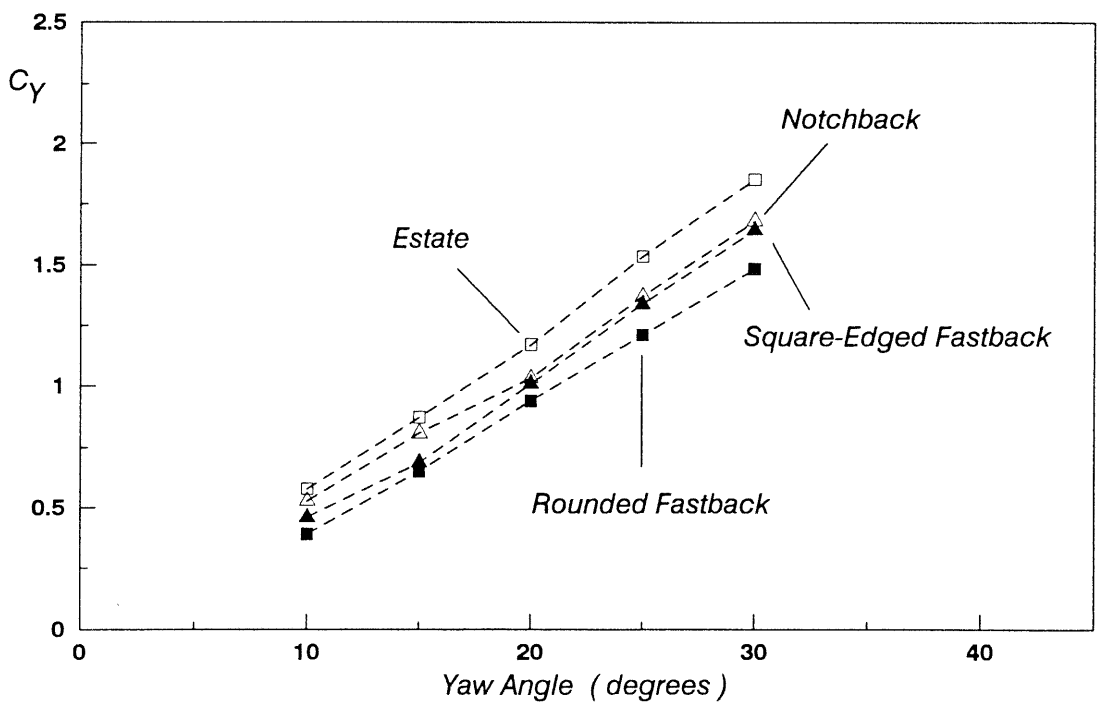


Figure 5.17 Mean Sideforce Coefficients Measured During the Steady-State Phase of Dynamic Tests

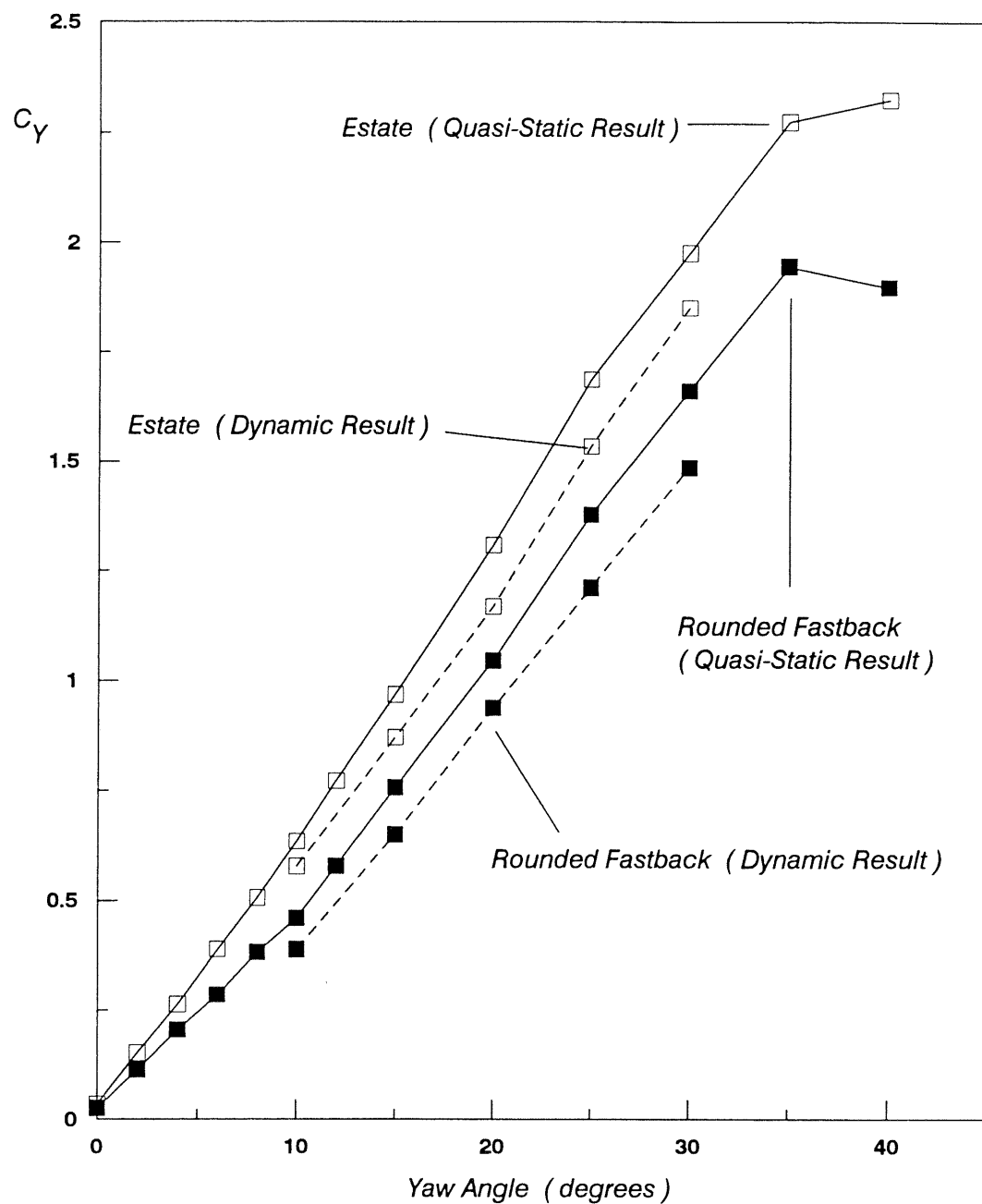


Figure 5 . 18 Selected Test Results Plotted to Illustrate the Level of Agreement Between Quasi-Static and Dynamic Sideforce Measurements

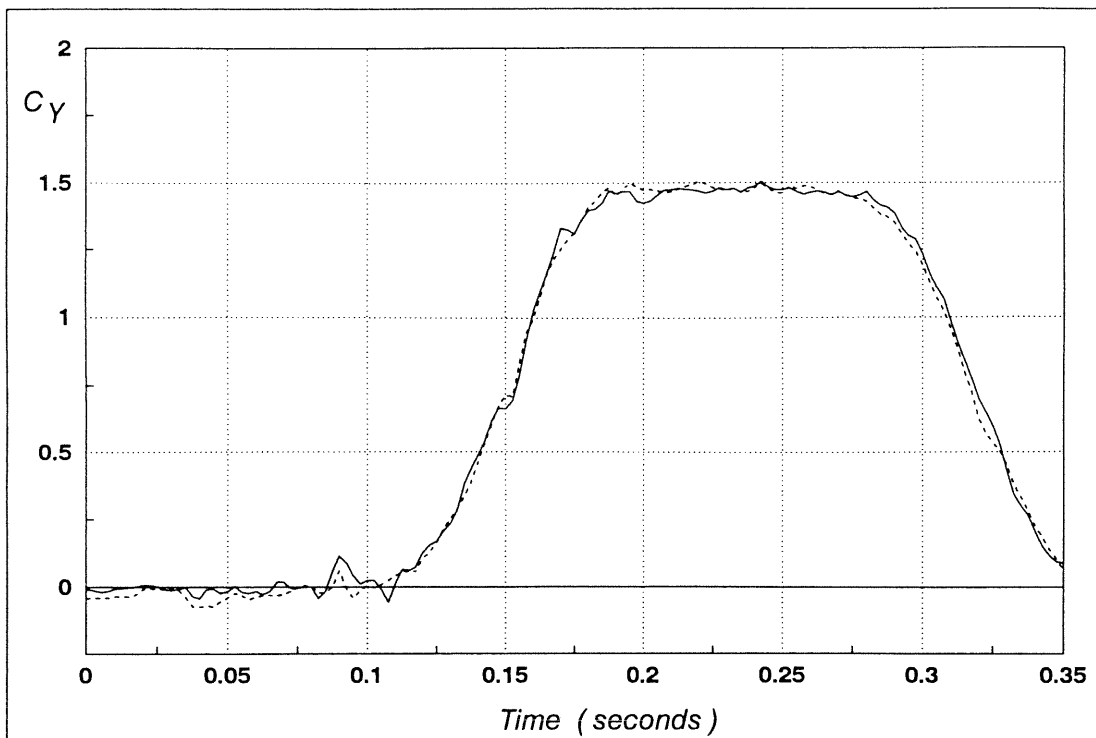


**Figure 5.19 A Demonstration of Sideforce Repeatability
(Rounded fastback at 30 degree yaw)**

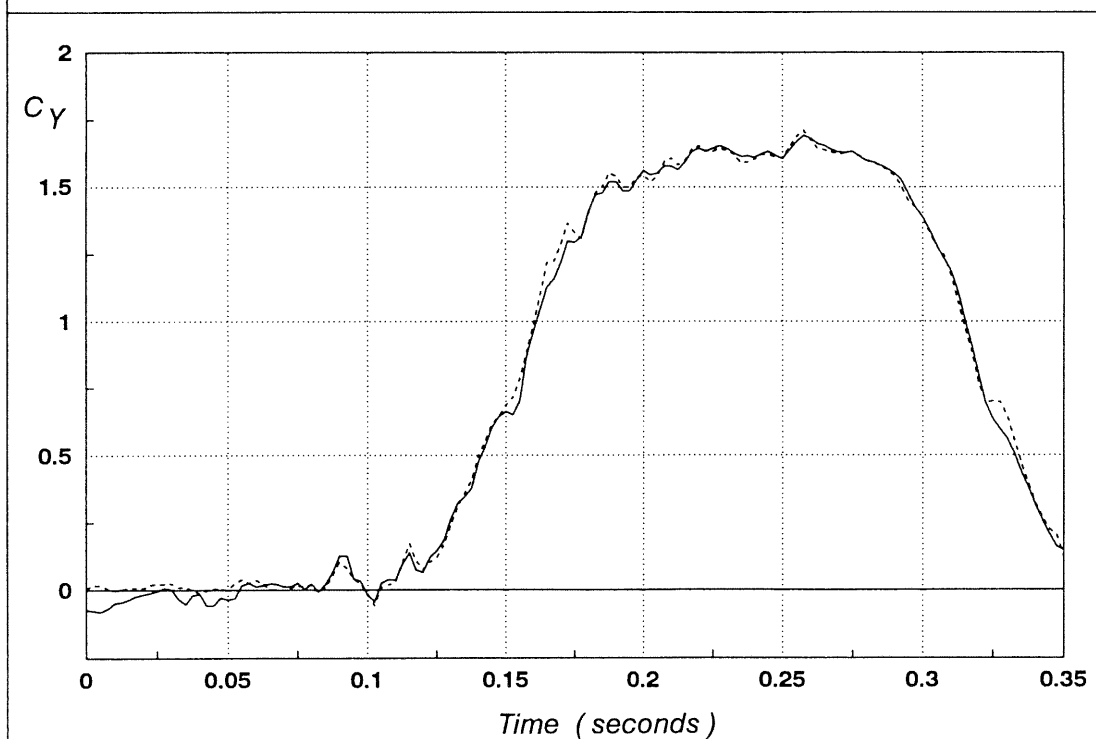


**Figure 5.20 A Demonstration of Sideforce Repeatability
(Square-edged fastback model at 30 degrees yaw)**

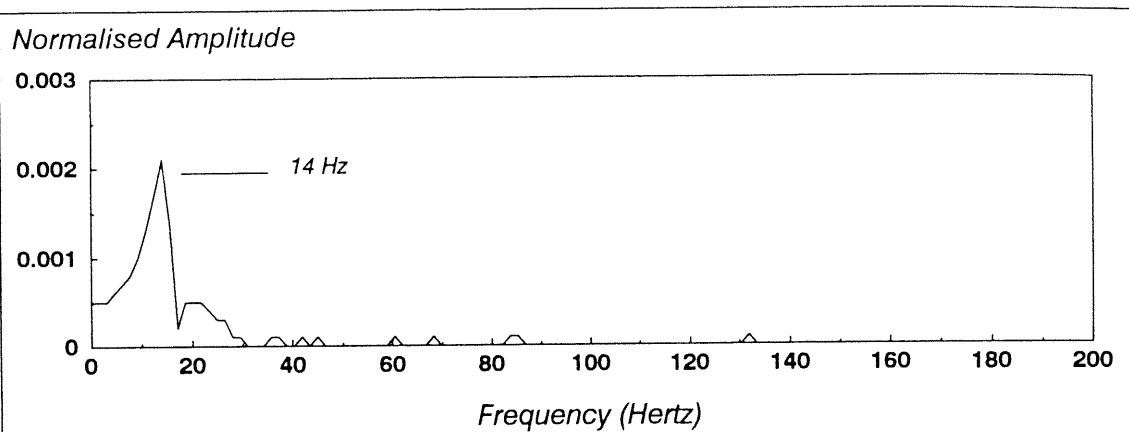


Figure 6.1 FFT Spectral Analysis Illustrating the Resonant Frequency for Yawing Moment Coefficient (Force balance with model fitted)

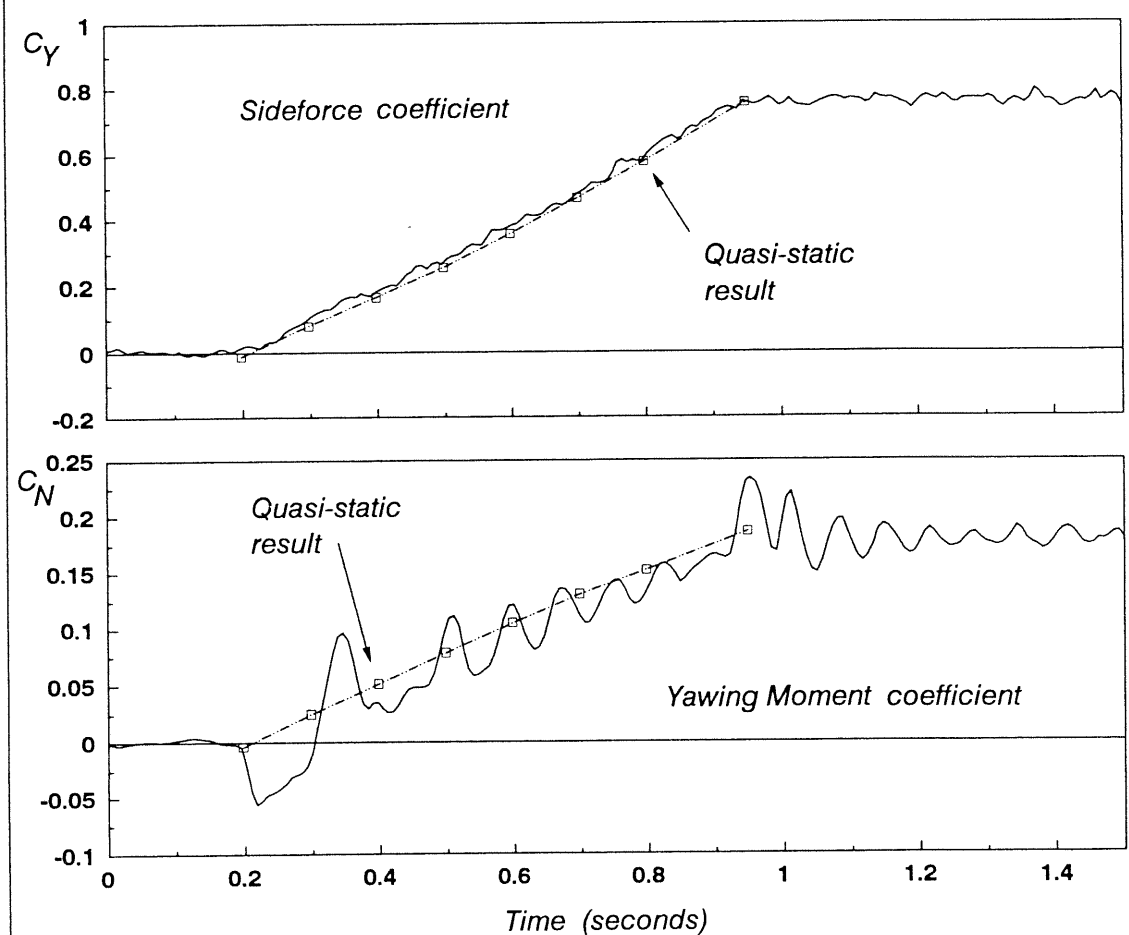


Figure 6.2 Quasi-Static Results Plotted over Dynamic Time Histories of Sideforce and Yawing Moment (Bluff-body model with 20 degree backlight)
(The dynamic signals are the result of a single test conducted at a yaw rate of 20 degrees per second from 0 to 15 degrees)

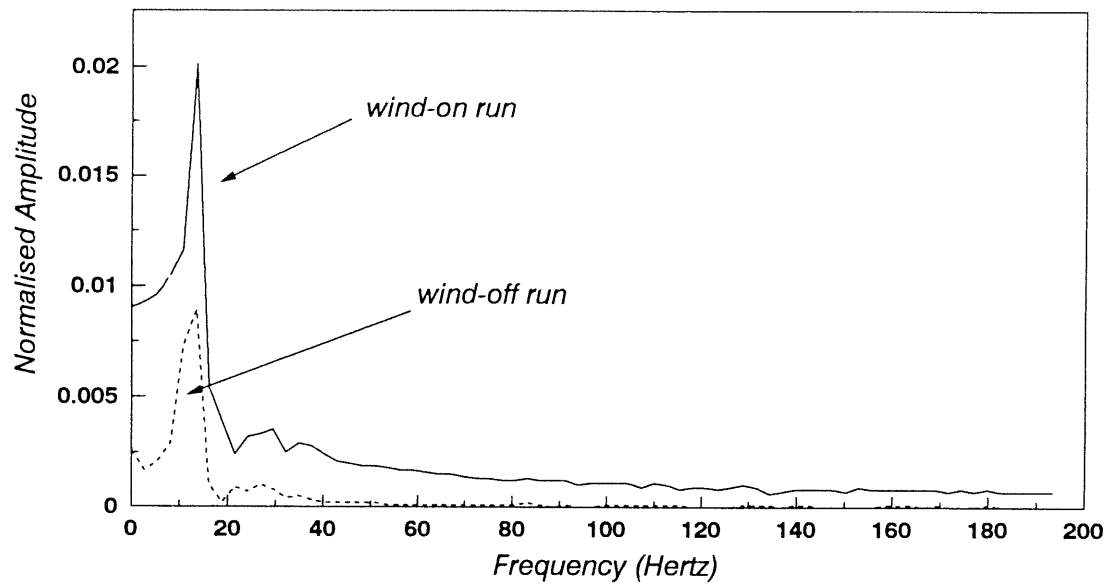


Figure 6.3 FFT Spectral Analysis of the Transient Phase for Both Wind-On and Wind-Off Yawing Moment Coefficients

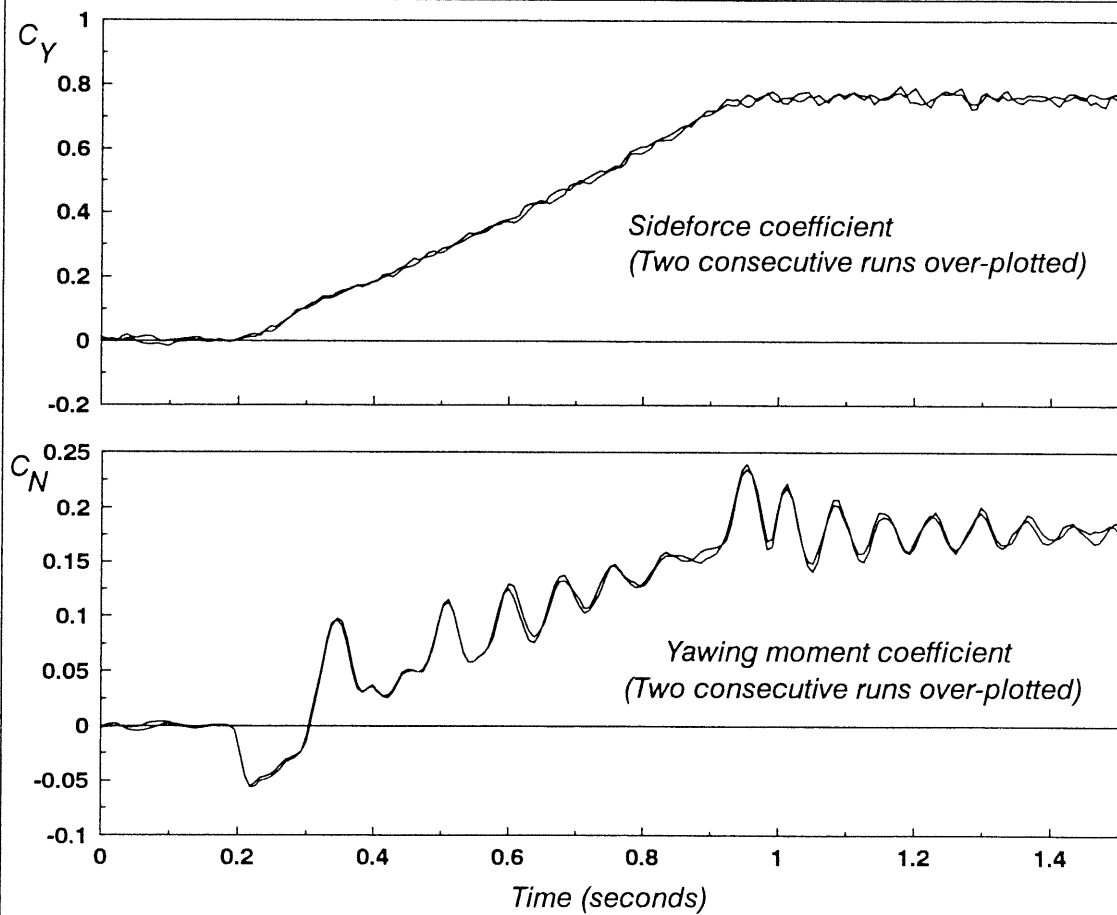


Figure 6.4 A Demonstration of Data Repeatability (Bluff-body model with 20 degree backlight, moved from 0 to 15 degrees at 20 degrees per second)

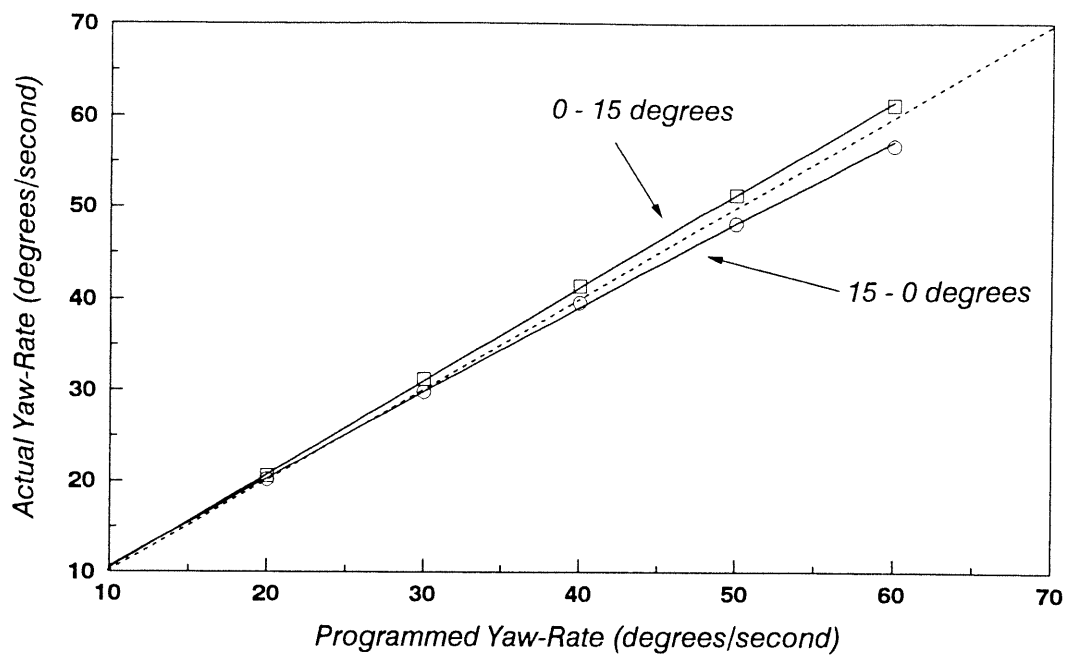


Figure 6 . 5 Deviation from the Programmed Yaw Rate, Caused by the Influence of the Aerodynamic Yawing Moment

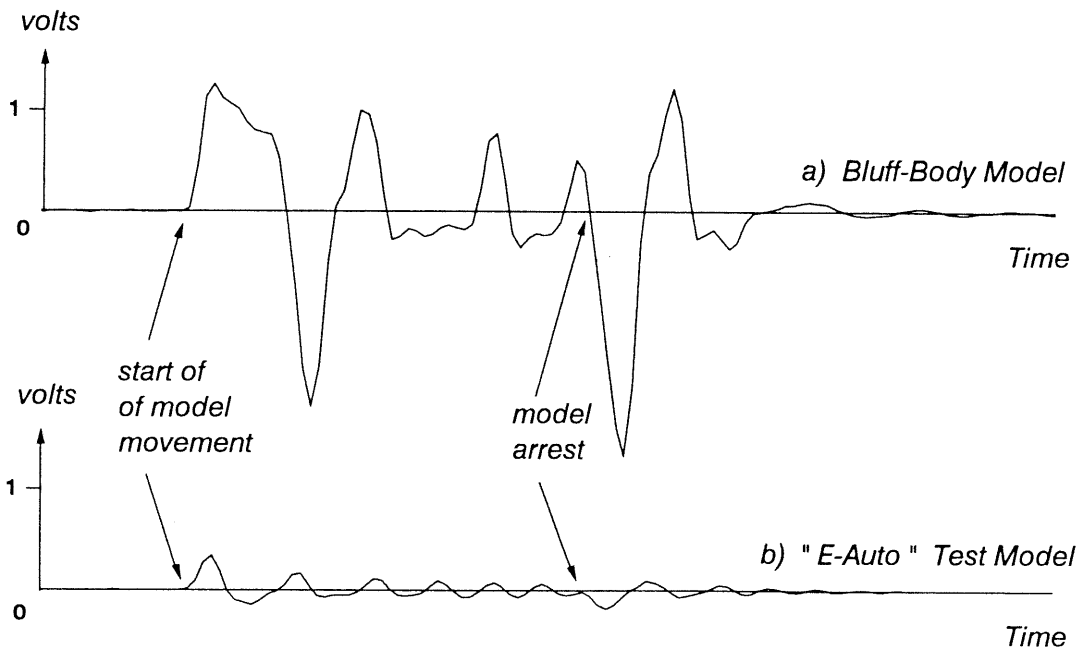


Figure 6 . 6 Decrease of the "Wind-Off" Signal Through Model Mass Reduction. For Both Models Raw Data is Presented from Channel 3 (yawing moment sensitive)

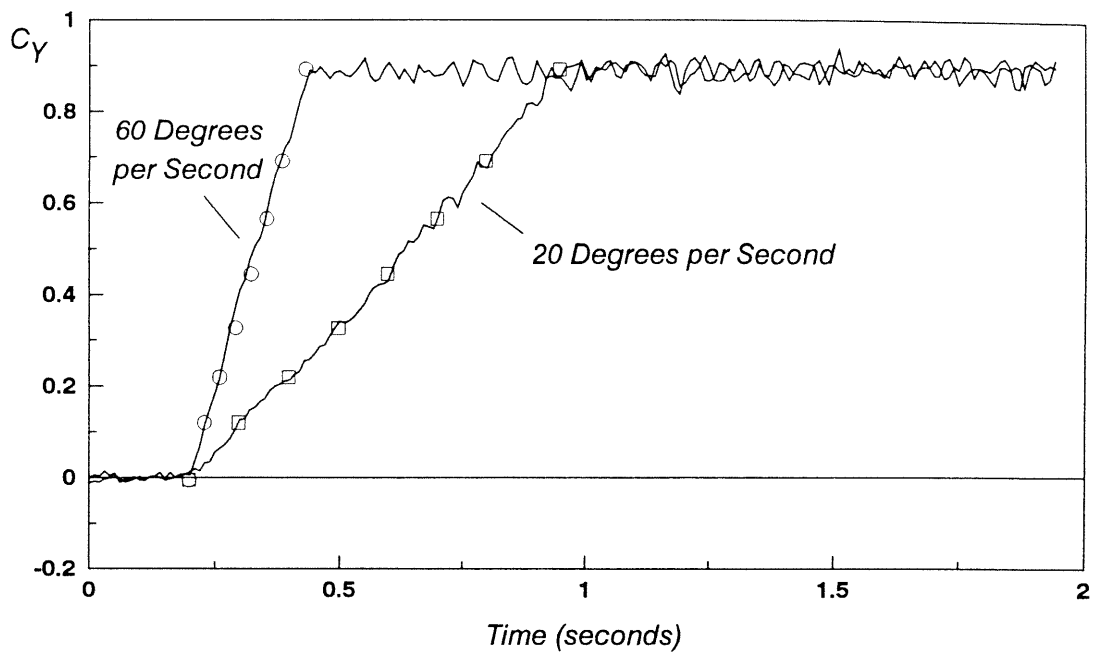


Figure 6.7 Quasi-Static Results Plotted over Dynamic Time Histories
Illustrates the Good Agreement of Sideforce for the Two
Types of Test (Bluff-body model with square backlight
moved through the yaw angle range 0 to 15 degrees)

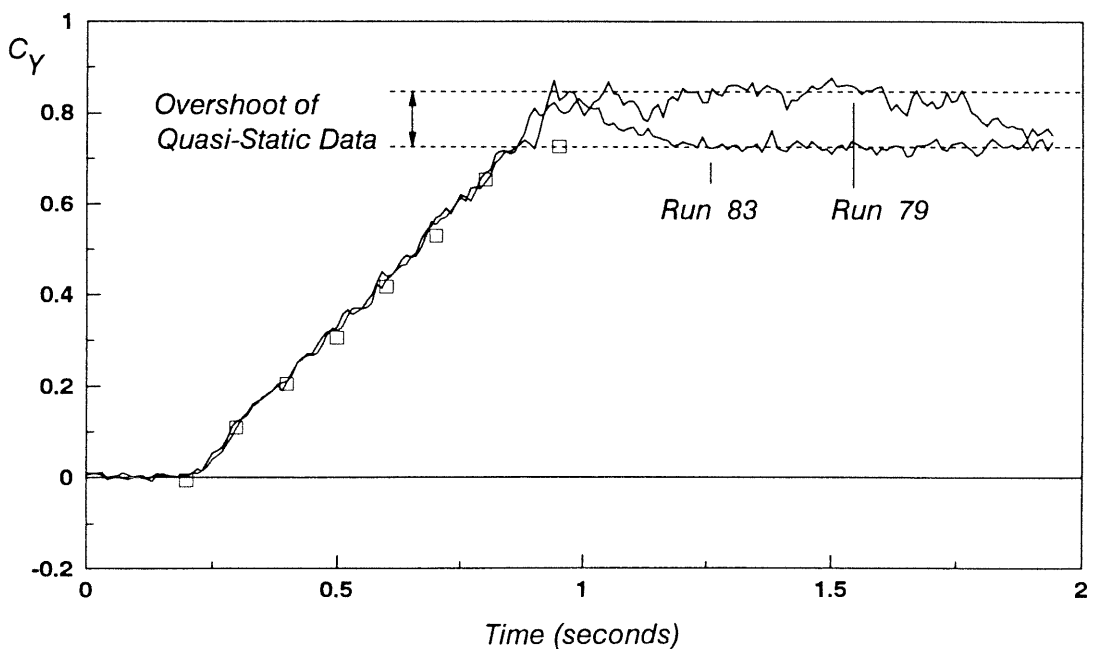


Figure 6.8 The Presence of a Bi-Stable Flow Structure Can Cause
Differences Between the Quasi-Static and Dynamic Results
(Bluff-body model moved at 20 degrees per second from
0 to 15 degrees)

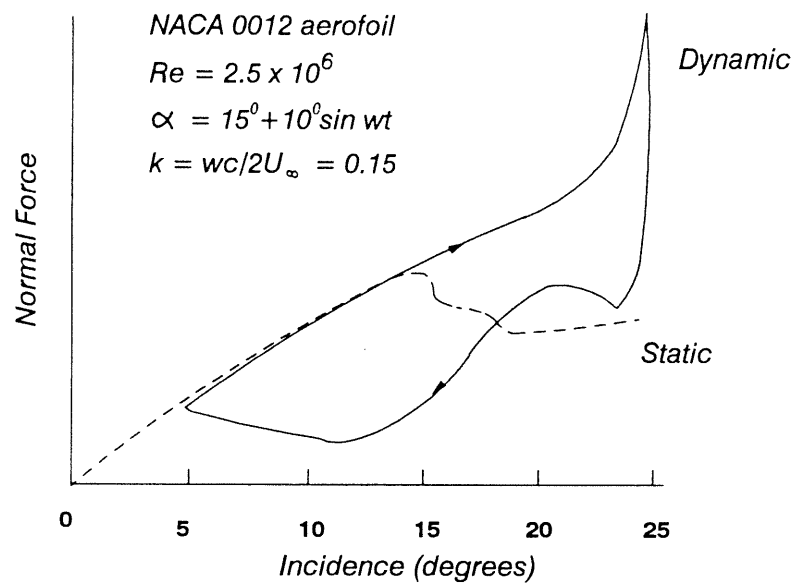


Figure 6.9 Normal Force on an Oscillating Aerofoil
 - Carr et al, 1977 ref.32

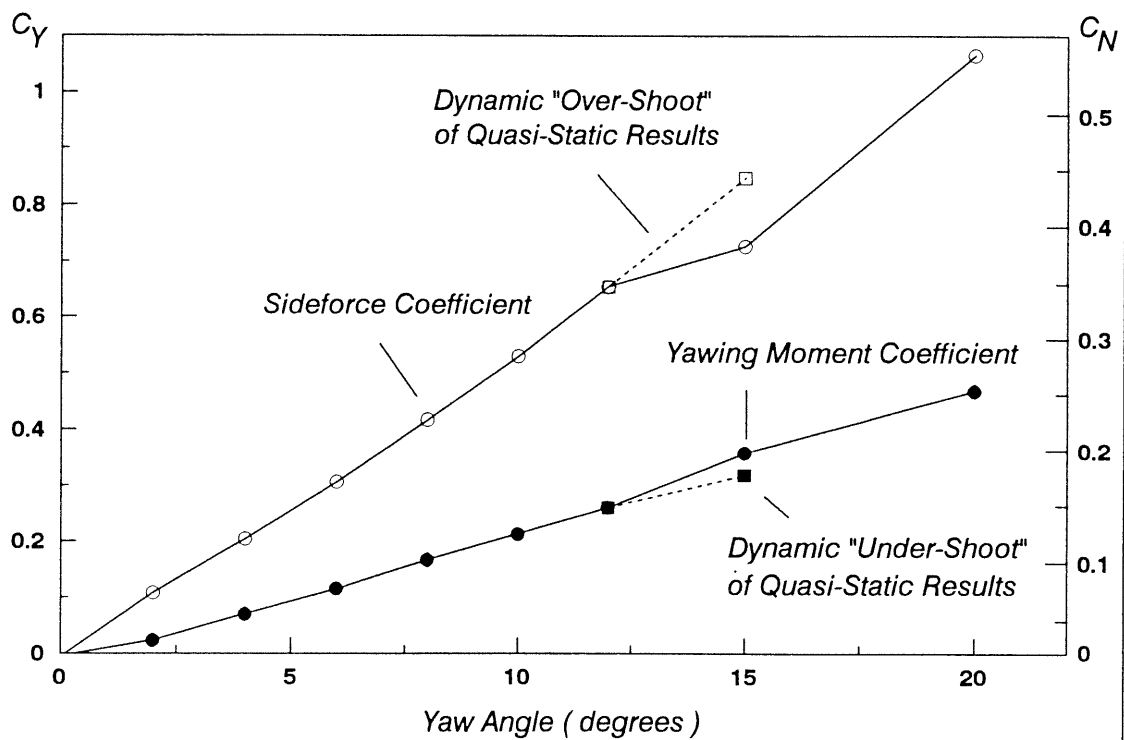


Figure 6.10 Quasi-Static Results for the Bluff-Body Model with 30 Degree Backlight
 The Dynamic Over-Shoot and Under-Shoot are Illustrated as Dotted Lines

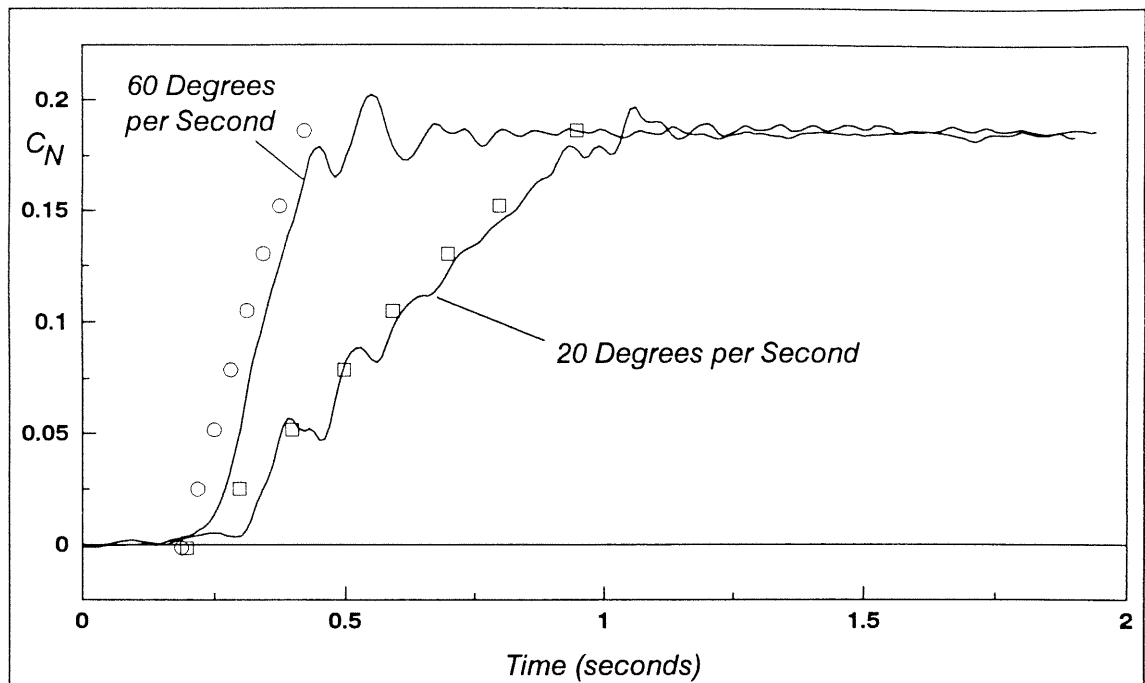


Figure 6.11 Quasi-Static Results Plotted over Dynamic Time Histories Illustrate the "Lag" of the Dynamic Coefficients, Particularly at the Higher Yaw Rates. (Bluff-body model with 20 degree backlight) (Yaw angle range 0 to 15 degrees)

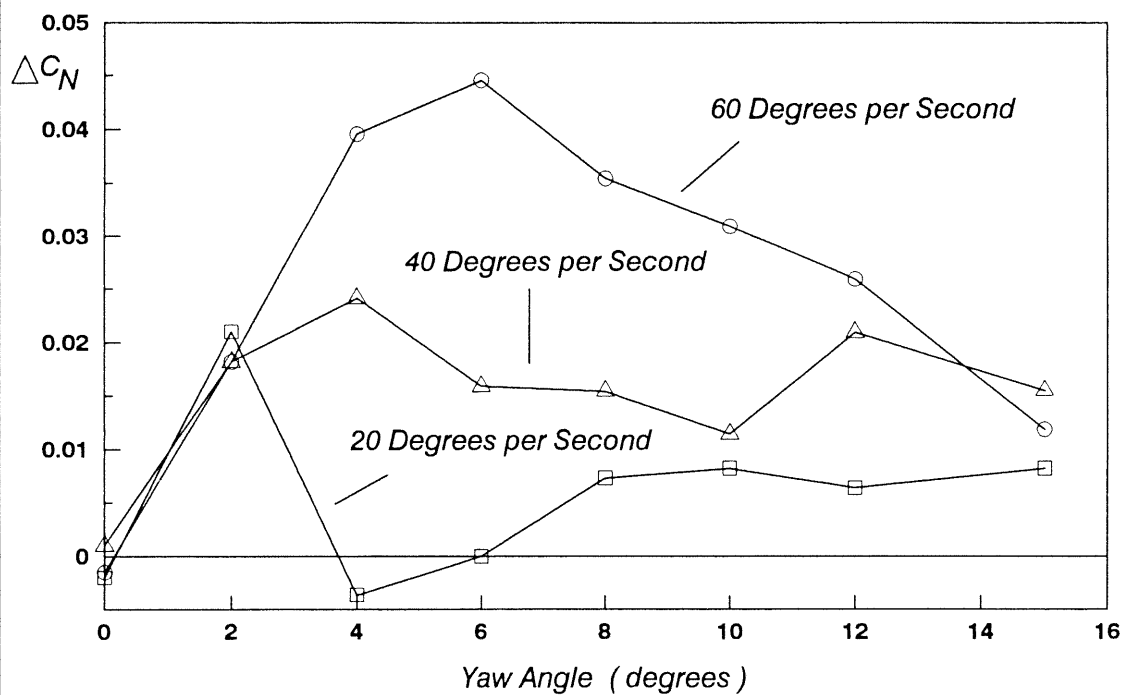


Figure 6.12 Influence of Yaw Rate on Yawing Moment Coefficient for Bluff-Body Model with 20 Degree Backlight

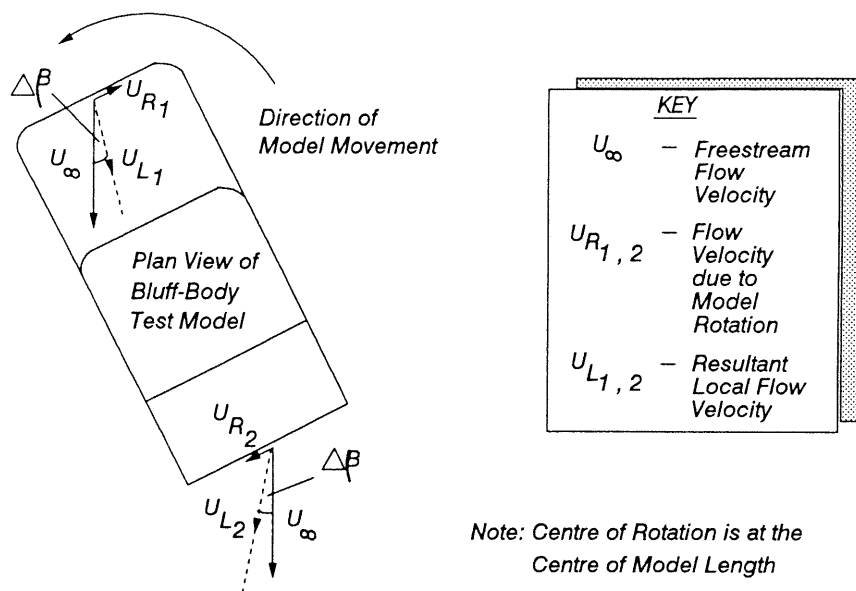


Figure 6 . 13 How Local Yaw Angle is Influenced by Model Rotation During Transient Tests

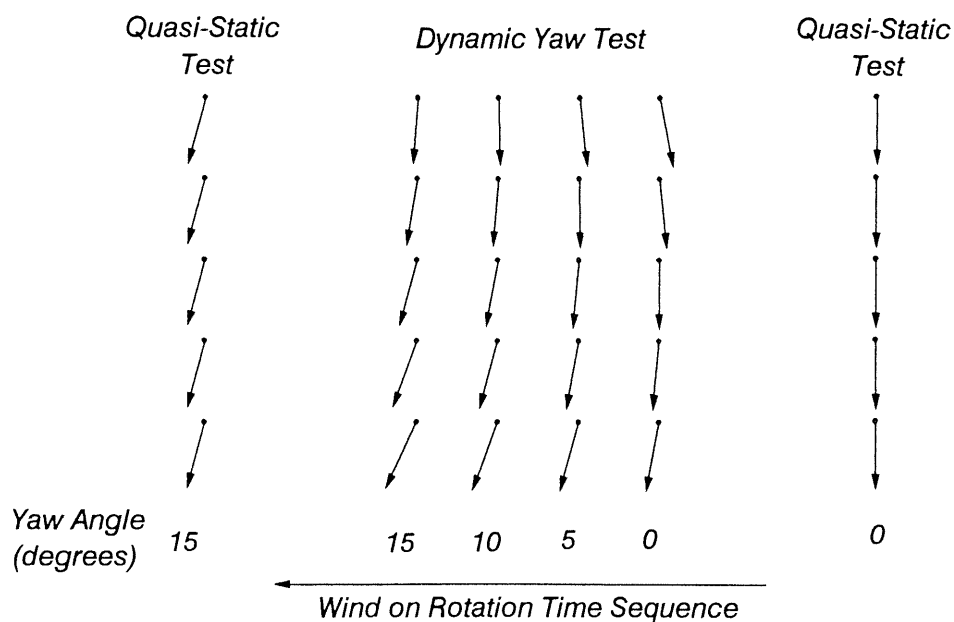
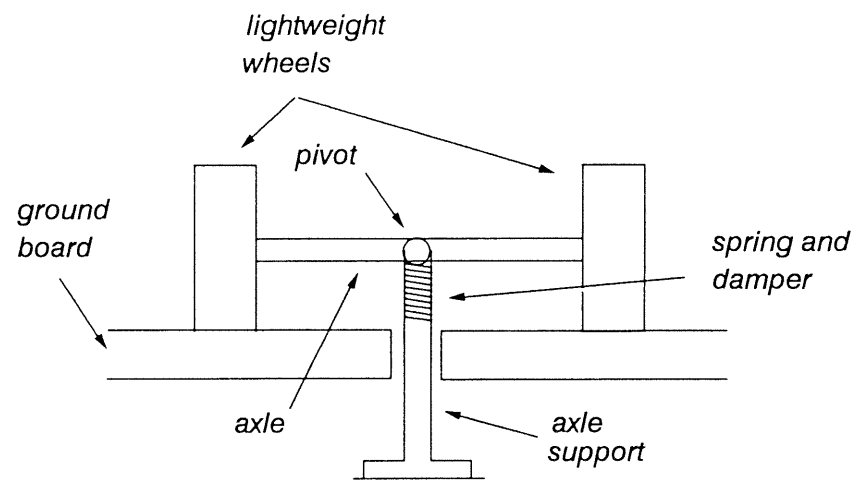
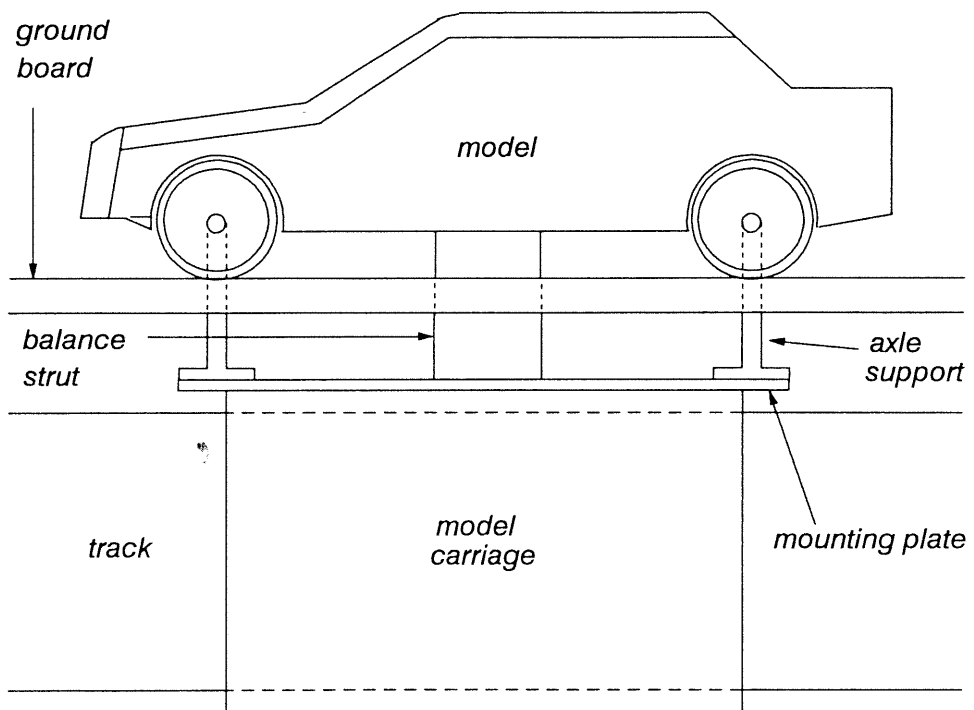


Figure 6 . 14 Local Flow Velocity Vectors Along the Centre Line of a Vehicle Rotated in the Wind Tunnel. (Based on Watkins, 1992 ref.29)
 $U_{\infty} = 19 \text{ m/s}$ $\dot{\beta} = 600 \text{ degrees per second}$

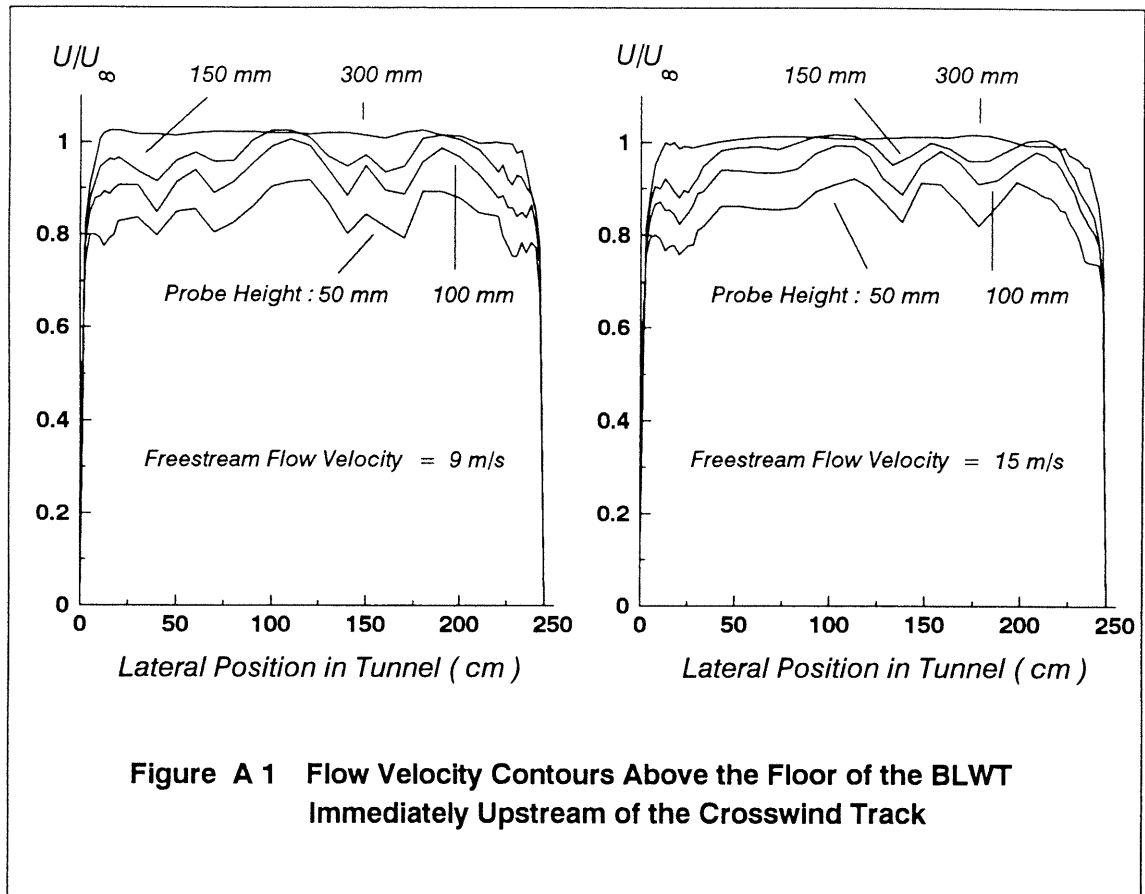
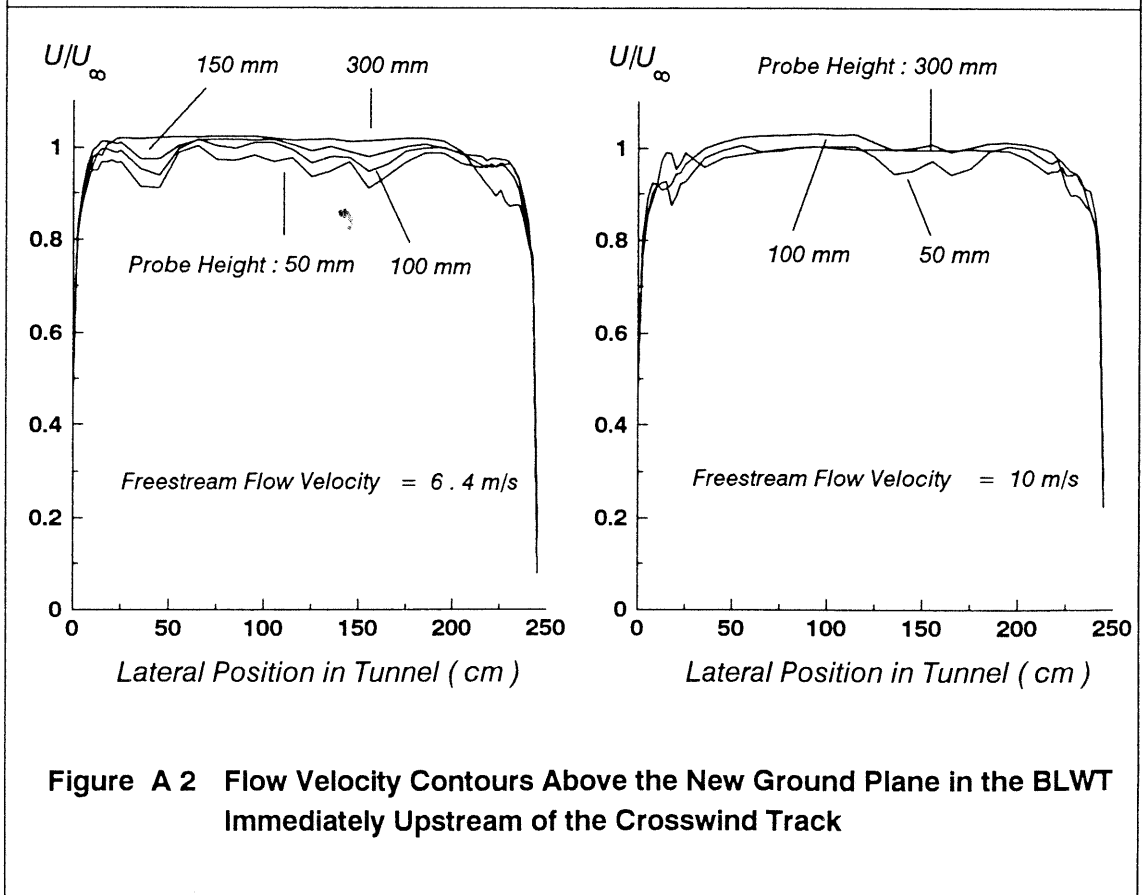


DETAILED END ELEVATION



SIDE ELEVATION

Figure 8 . 1 Modification to the Crosswind Track System to Incorporate Rotating Wheels



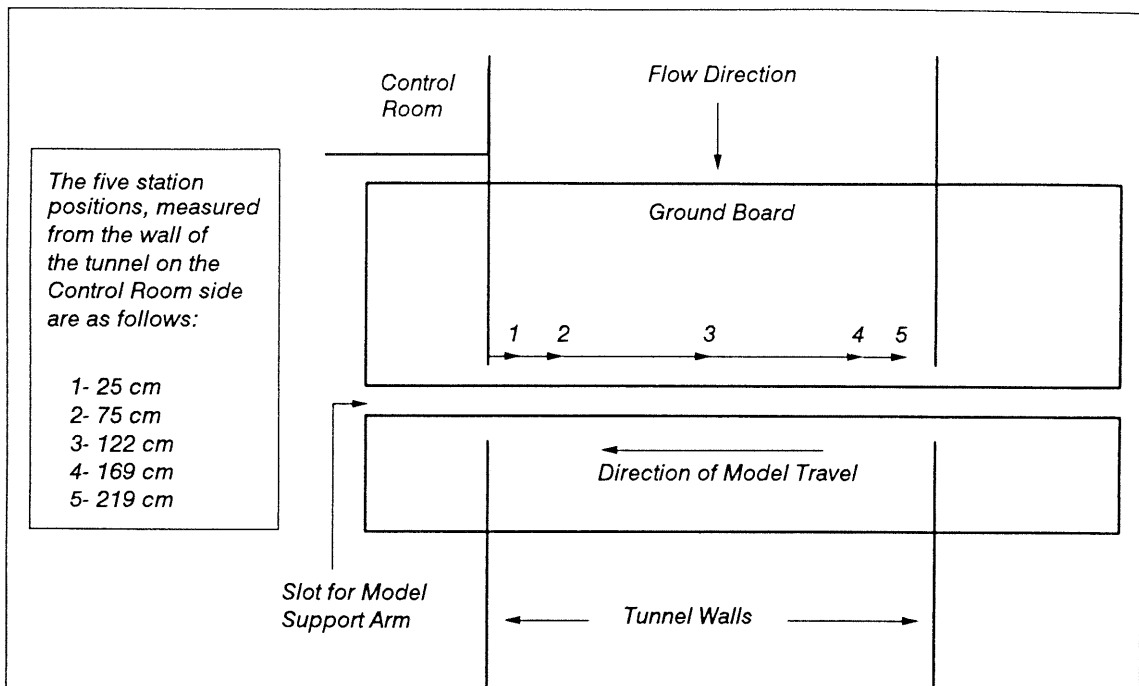


Figure A 3 Schematic Plan of the BLWT in the Vicinity of the Crosswind Test Track, Illustrating the Stations at which Boundary Layer Profiles were Measured

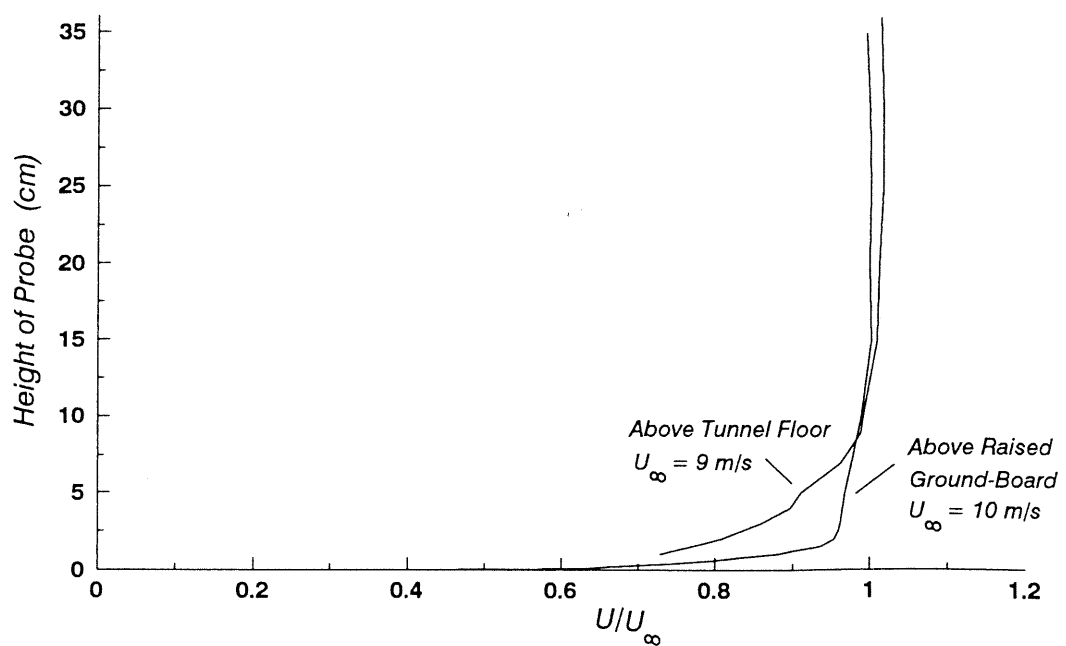


Figure A 4 Boundary Layer Profiles at Station 3 Before and After Ground Board Installation

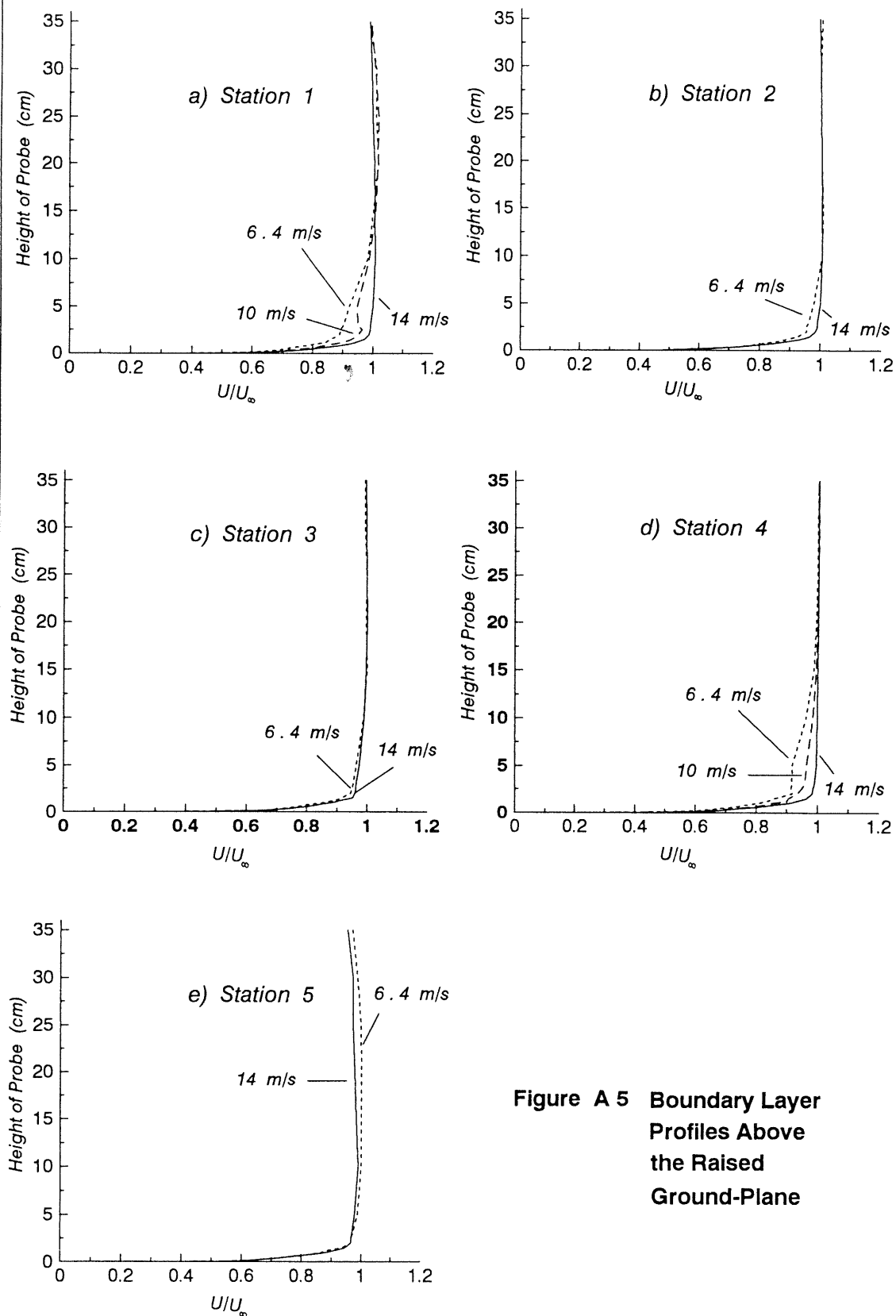


Figure A 5 Boundary Layer Profiles Above the Raised Ground-Plane

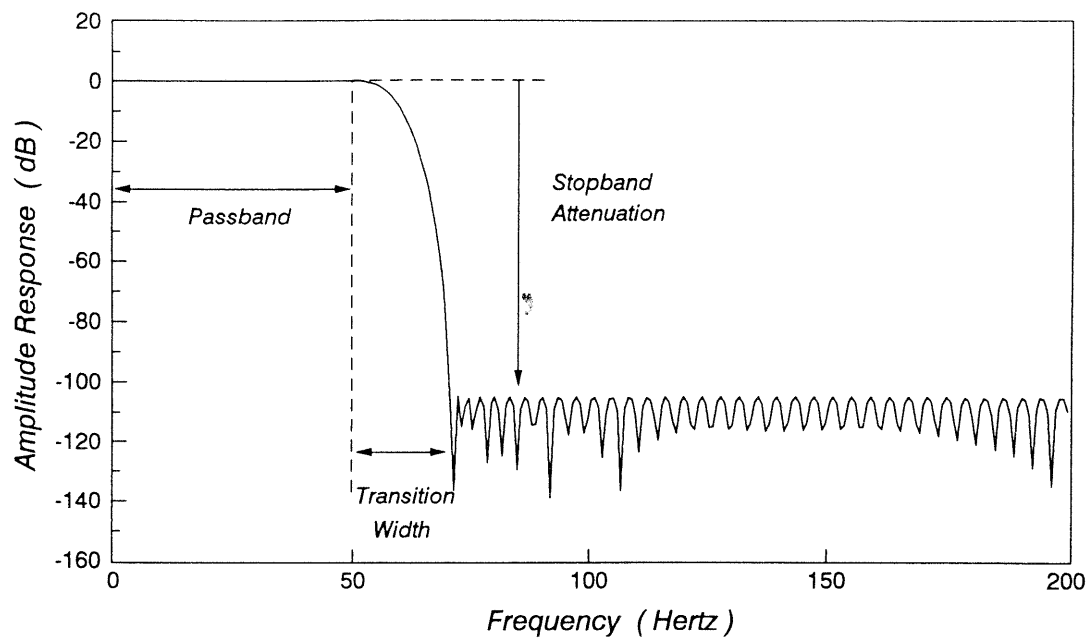


Figure B 1 Response Curve for a 50 Hz Lowpass Filter

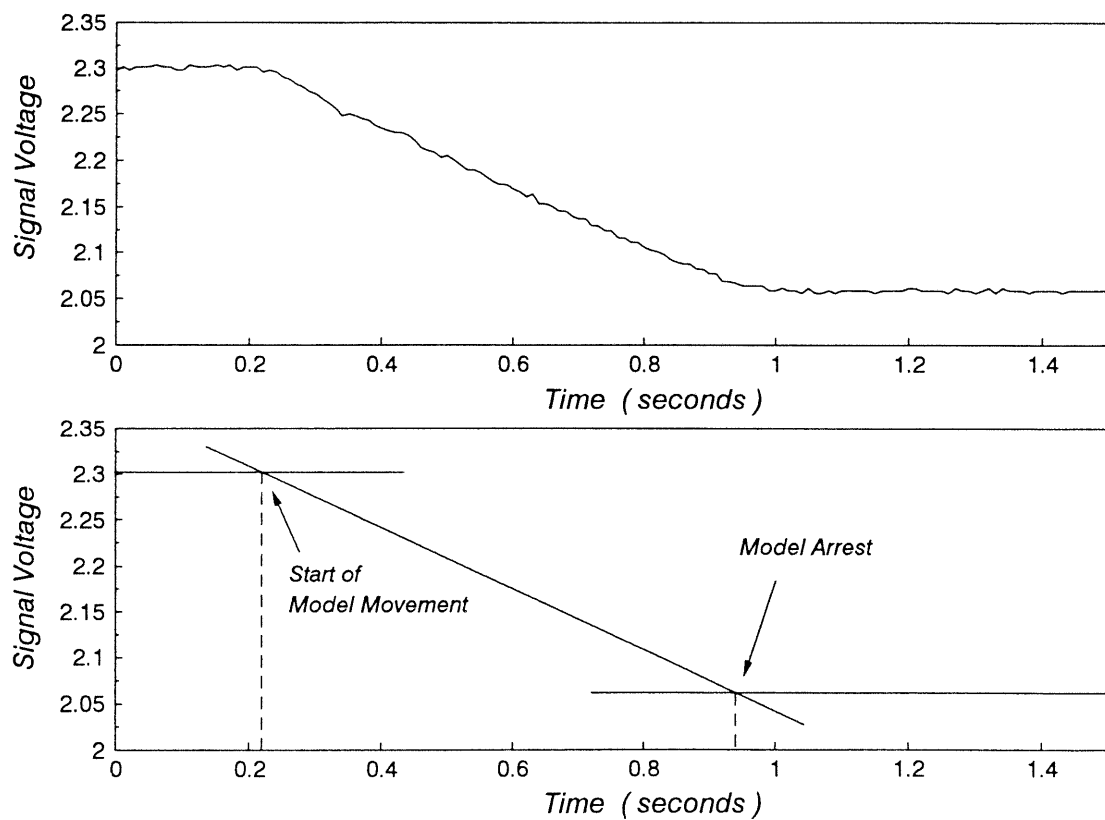


Figure B 2 The Position Signal and Linear Regression Technique Employed to Identify the Period of Model Movement

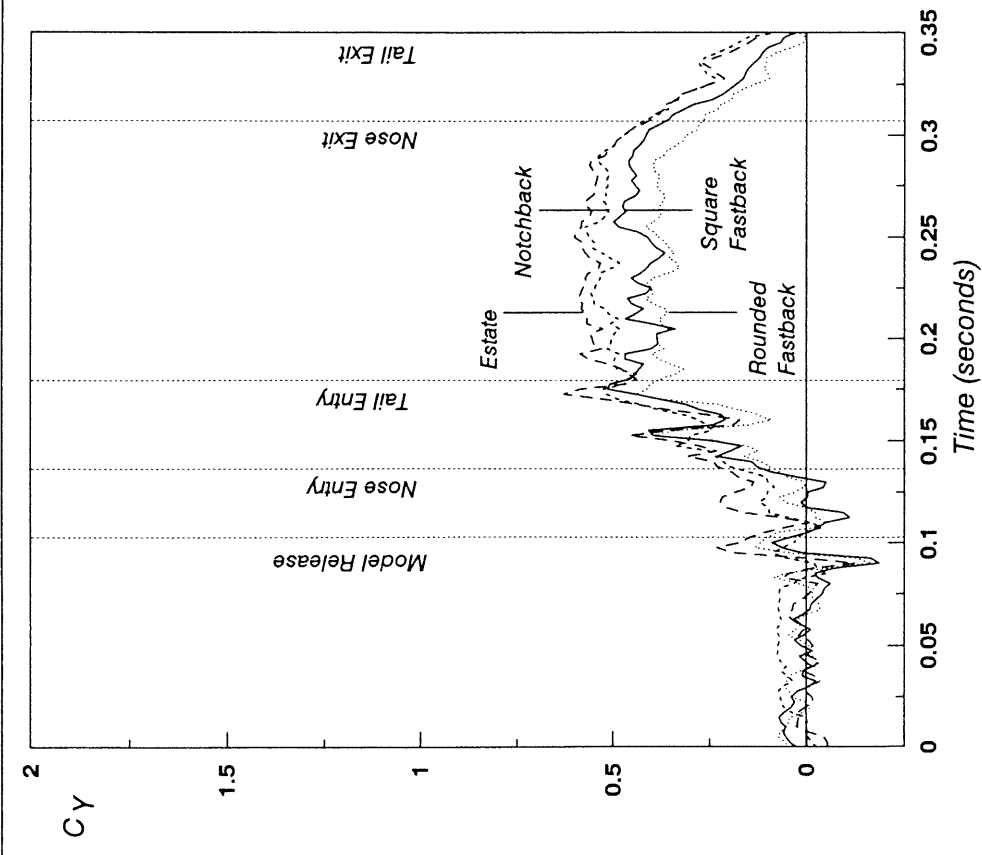


Figure D 1 Sideforce Time Histories for Models Traversing a Simulated Crosswind Gust (Basic saloon configurations at a yaw angle of 10 degrees)

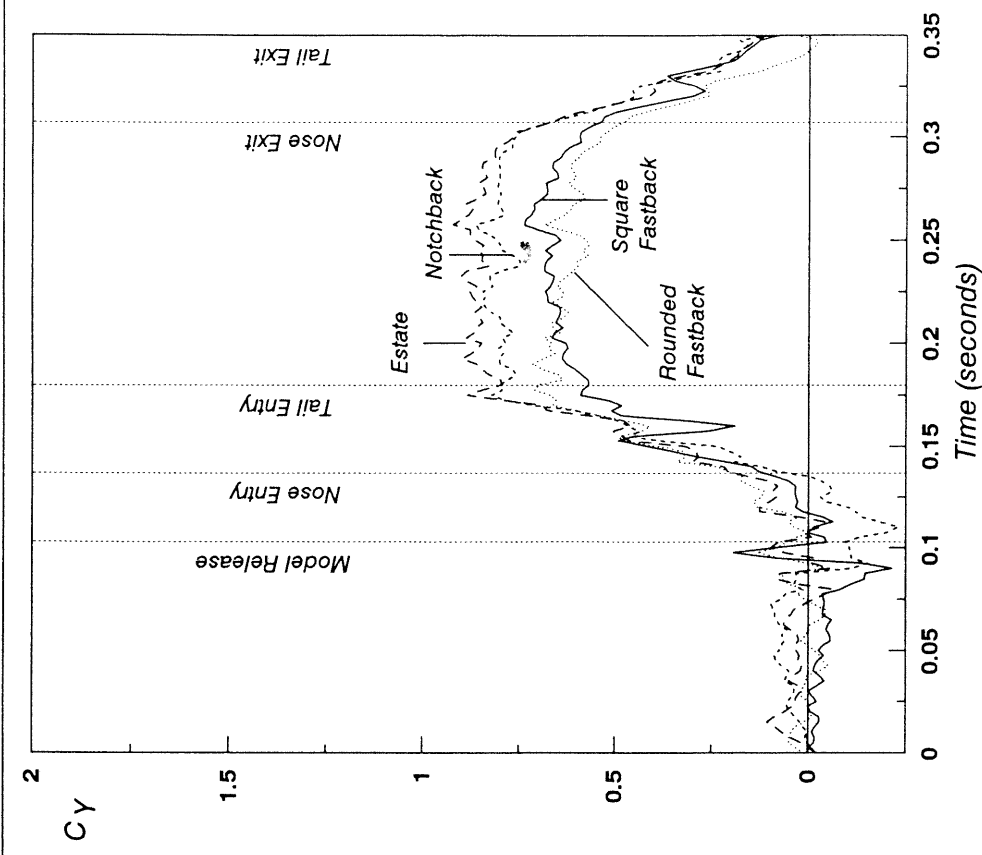


Figure D 2 Sideforce Time Histories for Models Traversing a Simulated Crosswind Gust (Basic saloon configurations at a yaw angle of 15 degrees)

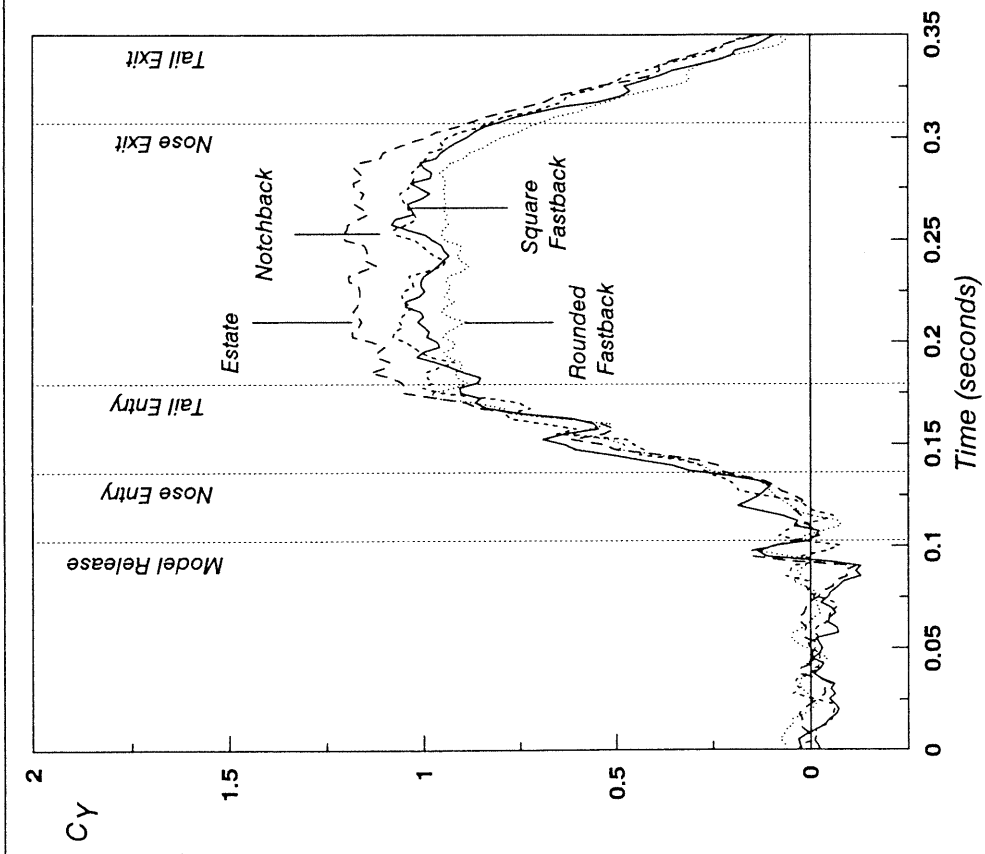


Figure D 3 Sideforce Time Histories for Models Traversing a Simulated Crosswind Gust (Basic saloon configurations at a yaw angle of 20 degrees)

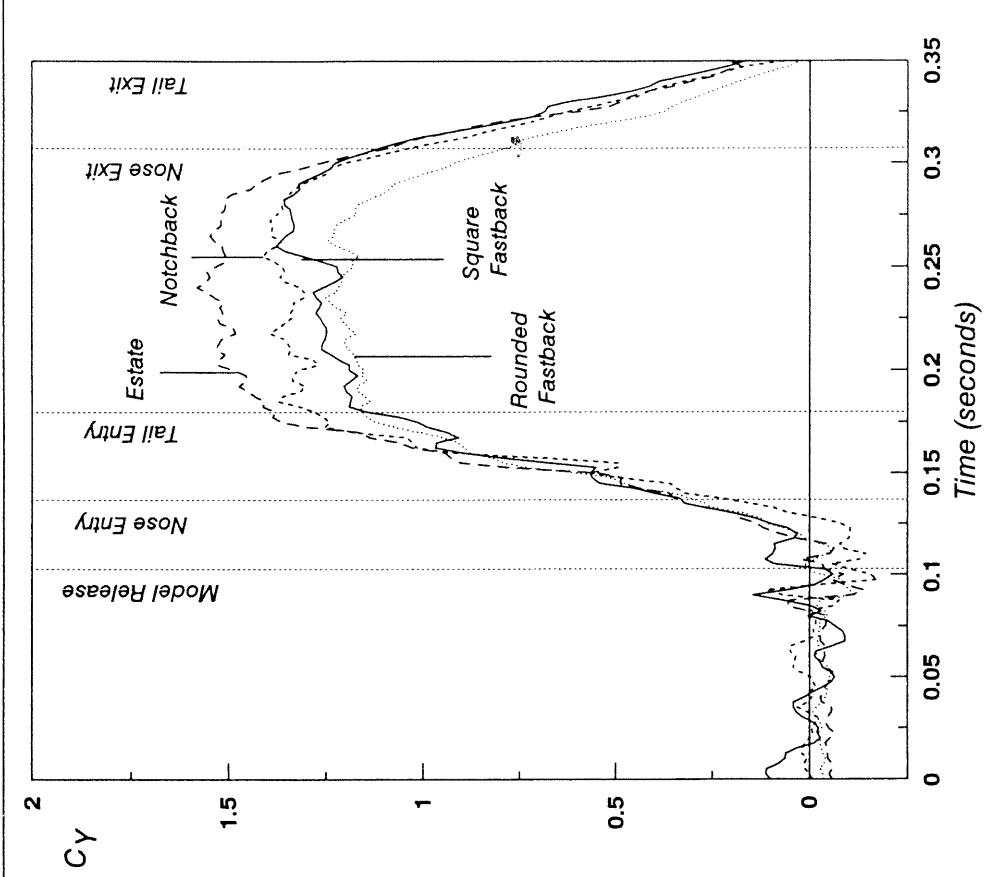


Figure D 4 Sideforce Time Histories for Models Traversing a Simulated Crosswind Gust (Basic saloon configurations at a yaw angle of 25 degrees)

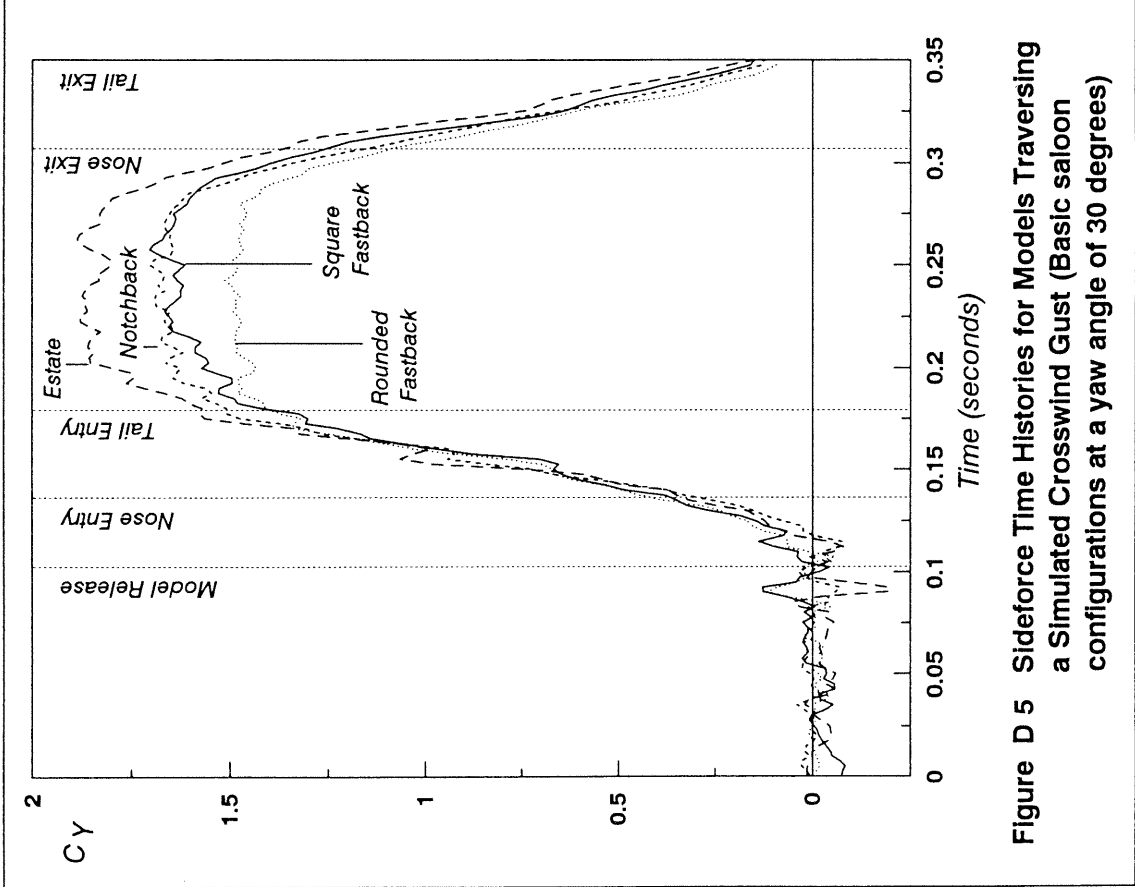


Figure D 5 Sideforce Time Histories for Models Traversing a Simulated Crosswind Gust (Basic saloon configurations at a yaw angle of 30 degrees)

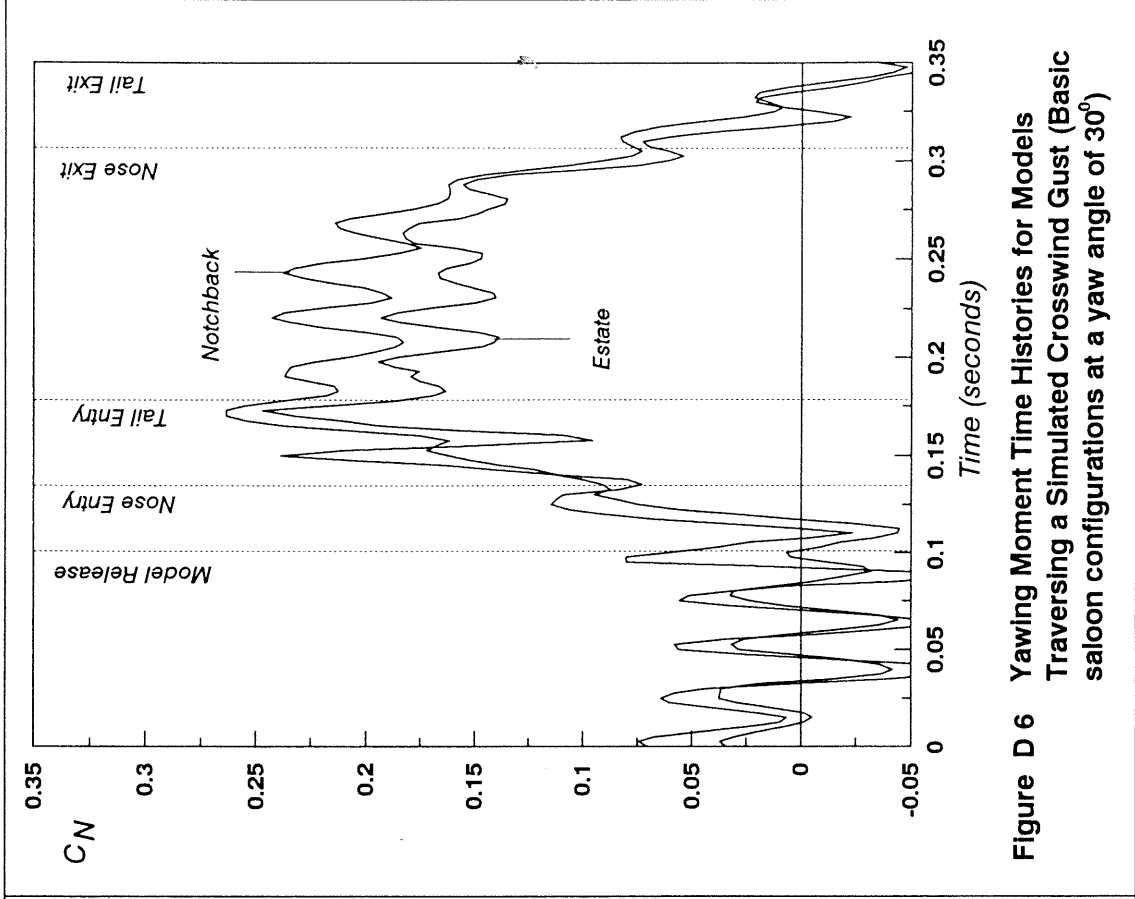


Figure D 6 Yawing Moment Time Histories for Models Traversing a Simulated Crosswind Gust (Basic saloon configurations at a yaw angle of 30°)

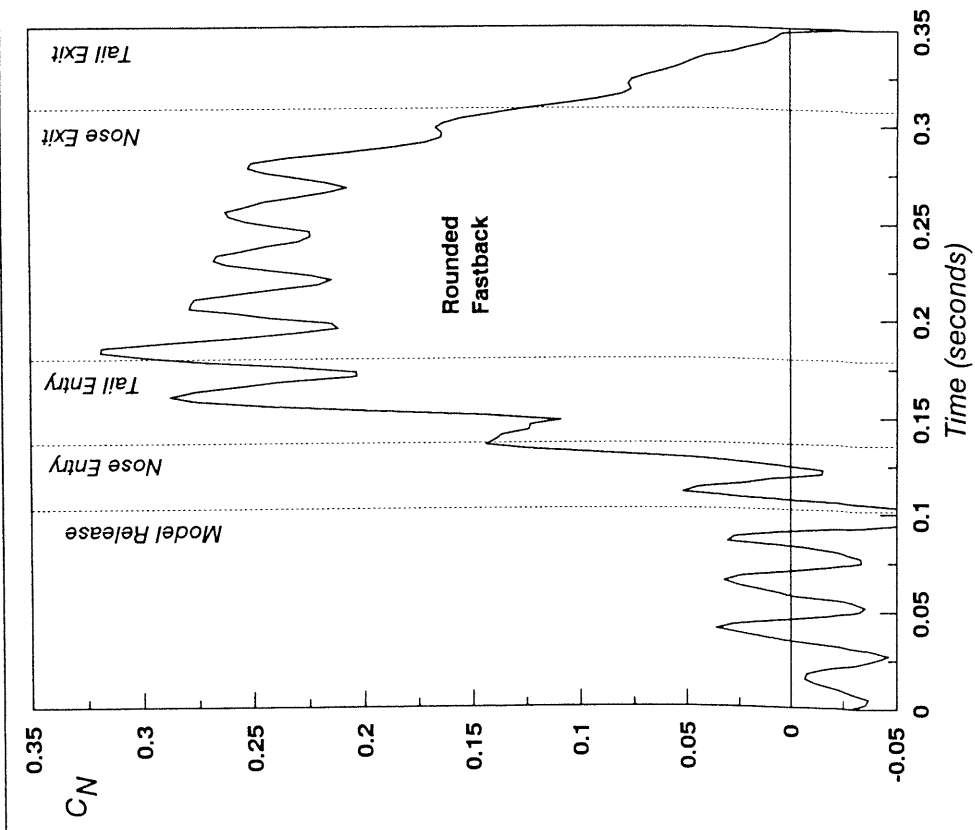


Figure D 7 Yawing Moment Time History for the Rounded Fastback Model Traversing a Simulated Gust (Resultant yaw angle = 30 degrees)

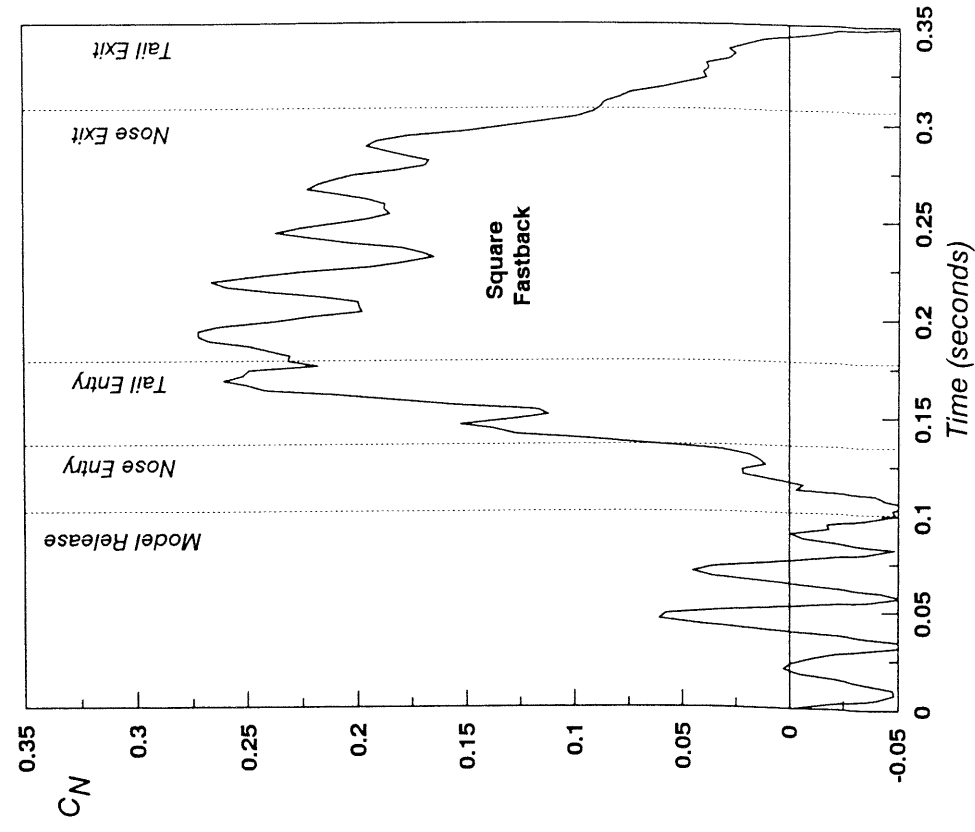


Figure D 8 Yawing Moment Time History for the Square-Edged Fastback Model Traversing a Simulated Gust (Resultant yaw angle = 30 degrees)

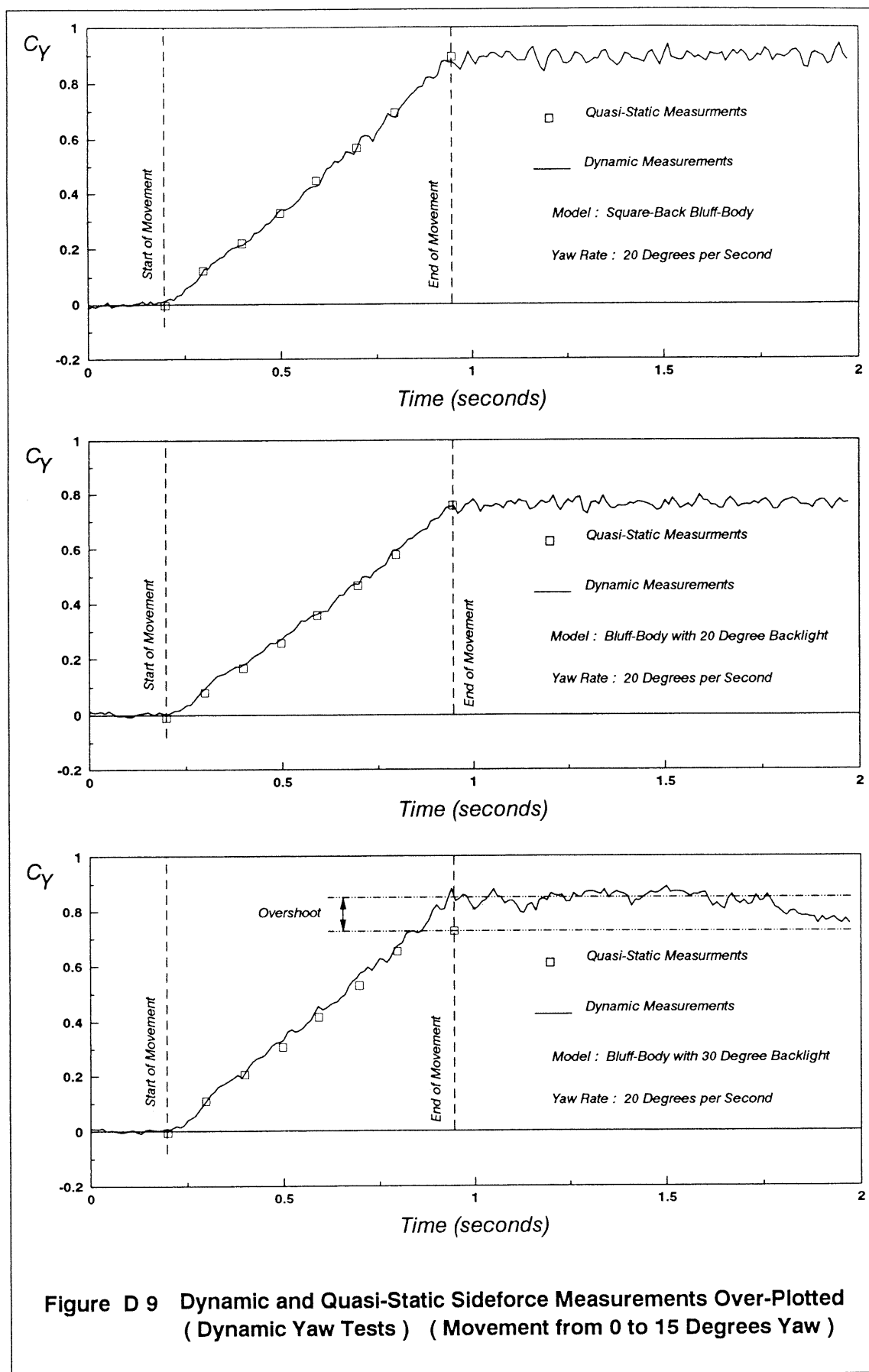
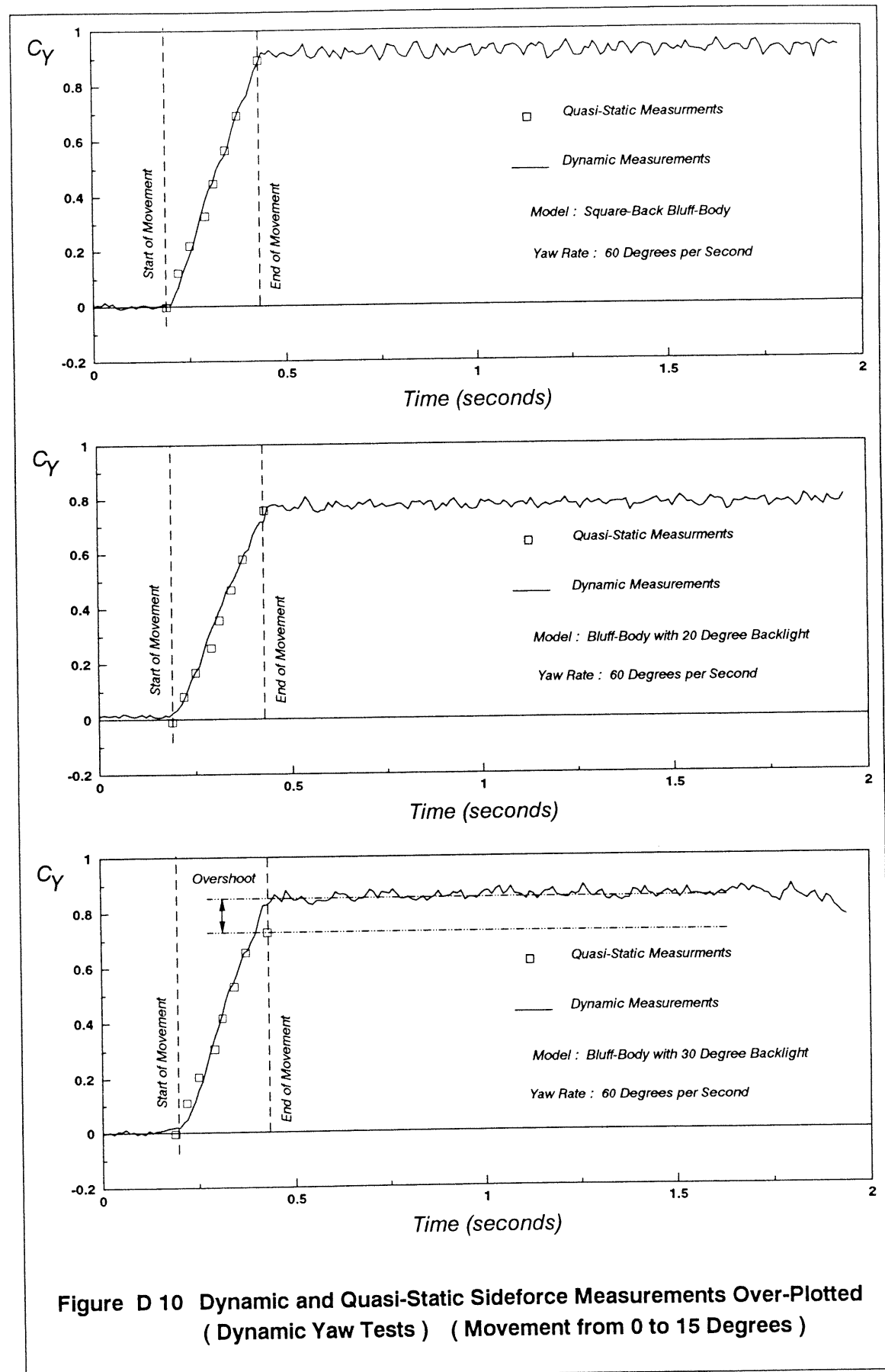


Figure D 9 Dynamic and Quasi-Static Sideforce Measurements Over-Plotted (Dynamic Yaw Tests) (Movement from 0 to 15 Degrees Yaw)



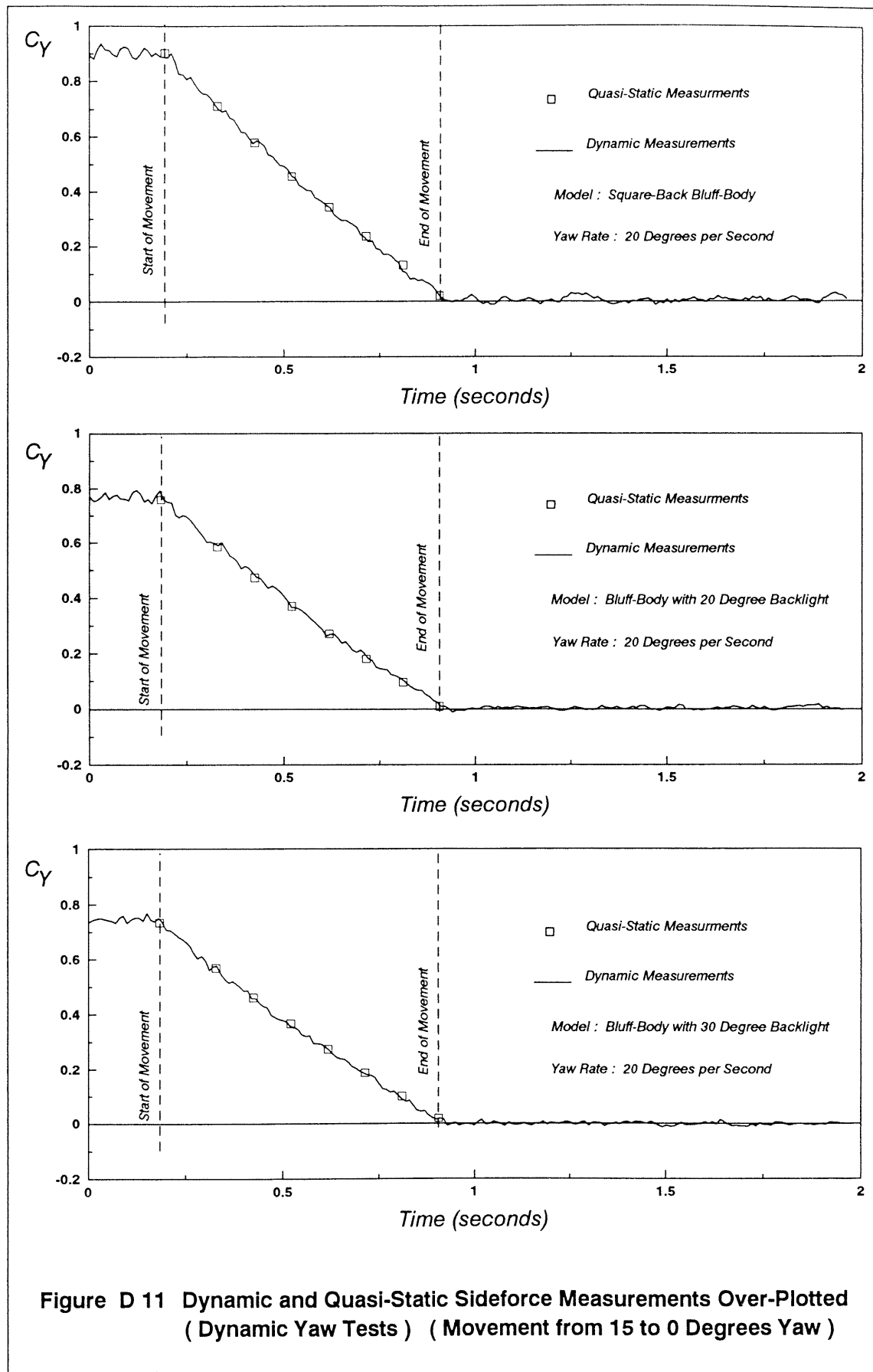
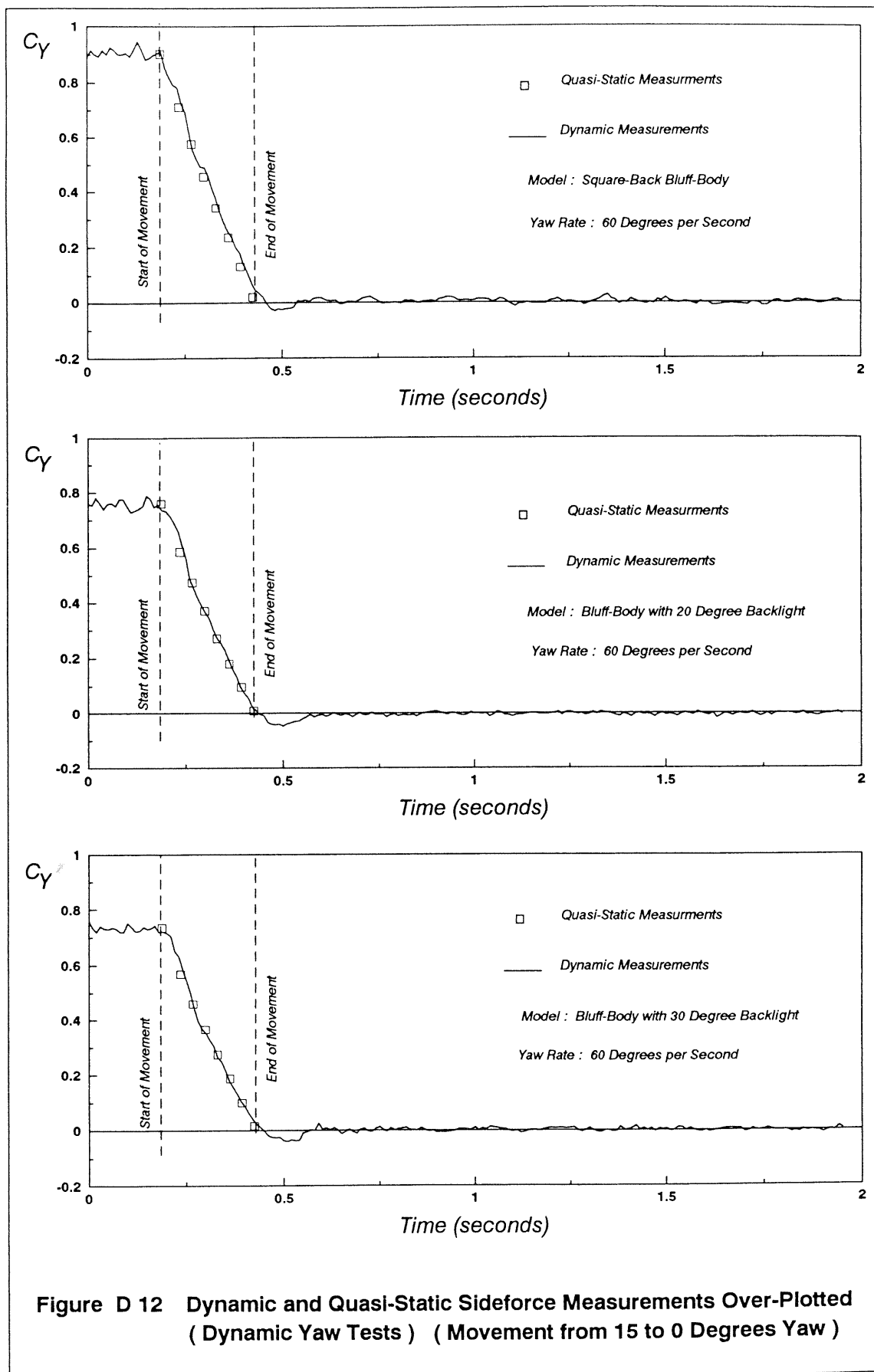


Figure D 11 Dynamic and Quasi-Static Sideforce Measurements Over-Plotted (Dynamic Yaw Tests) (Movement from 15 to 0 Degrees Yaw)



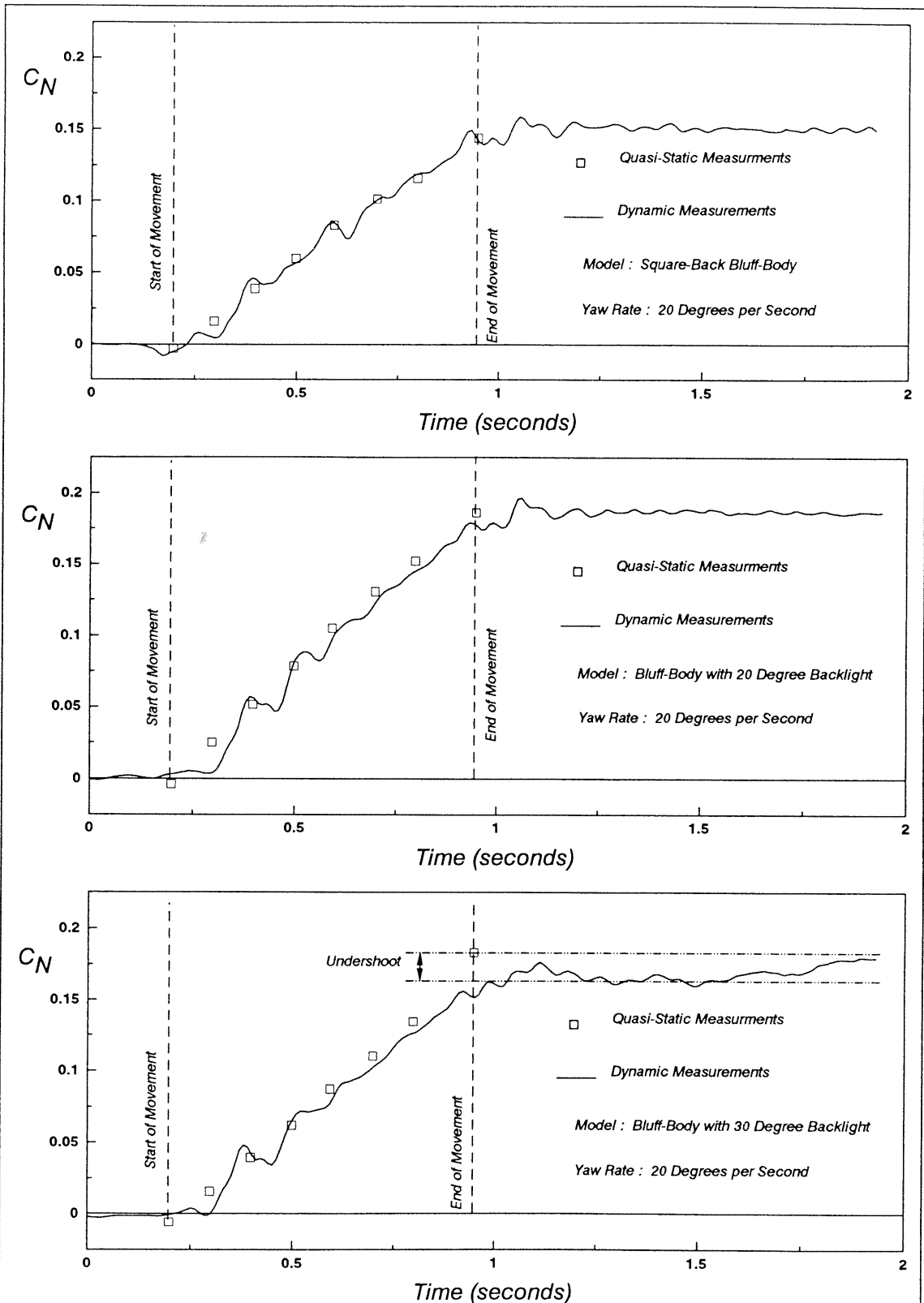


Figure D 13 Dynamic and Quasi-Static Yawing Moment Measurements Over-Plotted (Dynamic Yaw Tests) (Movement from 0 to 15 Degrees Yaw)

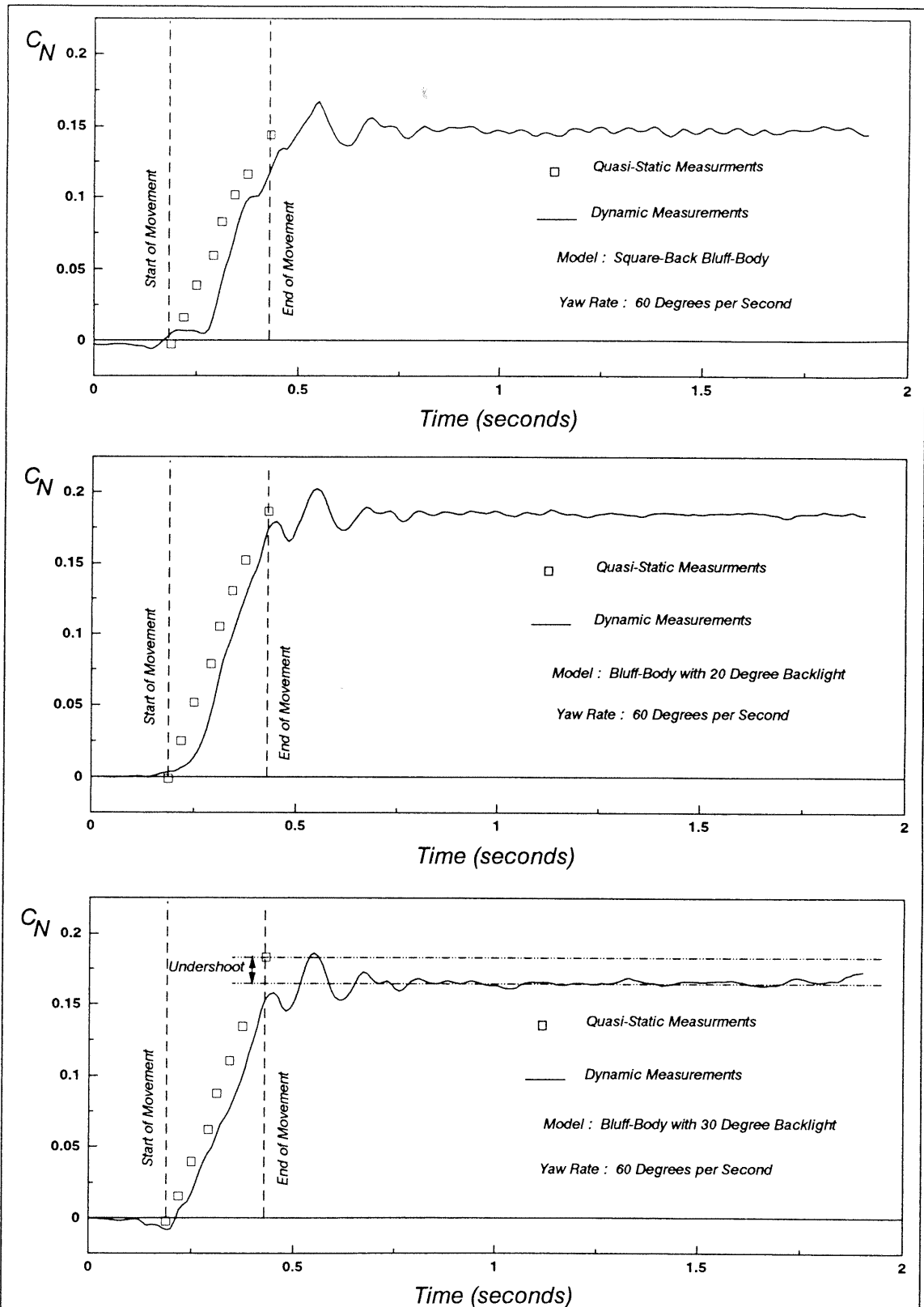


Figure D 14 Dynamic and Quasi-Static Yawing Moment Measurements Over-Plotted (Dynamic Yaw Tests) (Movement from 0 to 15 Degrees Yaw)

