

**New and improved accident reconstruction techniques
for modern vehicles equipped with ESC systems**

by R F Lambourn, P W Jennings, I Knight and T Brightman

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**NEW AND IMPROVED ACCIDENT RECONSTRUCTION
TECHNIQUES FOR MODERN VEHICLES EQUIPPED WITH ESC
SYSTEMS**

Version: Final

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Techniques for Modern Vehicles and Safety Systems**

**Client: Transport Research Foundation
(Prof. Rod Kimber)**

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Executive summary

The advent of several modern safety technologies has raised many questions as to their effect on the evidence which will present itself to an investigator at the scene of a road accident. Accident investigation techniques rely heavily on the interpretation of tyre skid and scuff marks, and the knowledge which on-scene investigators apply has been largely unchanged for 20 or more years. Improved knowledge would be of the greatest use to investigators working as part of the legal process, while road safety researchers would benefit if they were able to find evidence that a particular safety technology had come into action, and perhaps altered the outcome of an incident. Because of this TRL proposed a project, to be funded by the Transport Research Foundation (TRF), to investigate safety technologies in place, to be followed by a small pilot study of one particular technology as part of the experimental programme of investigation.

The review of current safety technologies which was conducted covered modern tyre design, anti-lock brake systems, brake-assist, electronic stability programs, active steering and “black box” data recorders. Following this it was decided to carry out a programme of experiments with a car fitted with an electronic stability control (ESC) system. The particular interest was to find what tyre marks would be laid on the ground, to discover whether they displayed any features which could be taken as an indication that an ESC system was active, and whether an established method of speed calculation based on the curvature of the tyre marks and the friction between the tyres and the road could be employed. This car was fully instrumented and had an arrangement whereby the ESC system could be turned off.

Four different manoeuvres were chosen for the investigation: an asymmetric sine-steer, in which the car, in neutral, was steered first in one direction and then more sharply in the other, before straightening up; a similar manoeuvre in which the driver held the steering on until the vehicle had come to a halt; a step steer, in which the car was suddenly steered sharply to one side; and a step steer in a turn with “lift off”, in which the car was driven fast in a circle, and then steered harder in the same direction while releasing the throttle at the same moment.

In each of these manoeuvres curved tyre marks were produced, displaying some lateral striations of scratches indicative of a side-slipping of the tyres. However, the nature of the two surfaces on the TRL track which were used for the experimentation was not such as to show the marks and any detail within them very clearly.

The angle of these striations across the tyre marks is known to have some correlation with the amount of braking applied to a wheel; however, in the various runs no particular feature could be found which would enable an investigator to say that the vehicle making them had been subject to ESC intervention. In those runs where it was *known* that the ESC system had been activated, the angle of the striations and the degree of yaw could be matched to the operation of the ESC, but, had the ESC activity been unknown, these features could equally have been due to the manner in which the vehicle was being driven.

However, the authors are aware that, while the car they were using was a “family” saloon, more “sporty” cars have ESC systems which only become active when the vehicle is subject to a greater amount of yaw. Such cars might, therefore, produce detectable features in their tyre marks when the ESC activates later in the manoeuvre.

The calculation of the speed of the car from the curvature of its tyre marks was found to be unaffected by the operation of the ESC. However, it was noted that overall, the result was a significant underestimate when the coefficient of friction of a sliding tyre was used, and that when the peak coefficient of friction was used, a much more accurate result was obtained.

The rate of loss of speed of the car during its manoeuvres was also noted. This is a quantity which has been little investigated, even though it is of considerable interest to the accident investigator, and the values found in this experimentation where hard steering had been applied were surprisingly high, at around 0.3g.

The conclusions of this pilot study may be summarised as follows:

1. With the particular car used in this experimentation, on the two particular surfaces, nothing could be found in the tyre marks which would enable an investigator to determine whether or not an ESC system had been activated.
2. Further investigations with a vehicle with a more “sporty” ESC system, which activates at a greater level of yaw, and therefore further into a potential loss of control situation, would be of benefit.
3. The activation of an ESC system, at least in the vehicle tested, does not have an effect on the validity of the calculation of speed from the curvature of the tyre marks. However, our experimentation has tended to support the belief among some investigators that the use of the sliding coefficient of friction may lead to too low a speed being calculated, and that it would be more appropriate to use the peak coefficient of friction. Since this calculation is widely carried out for the benefit of the courts, a deeper investigation of this question would be of considerable value.
4. The rate of loss of speed of the car along its tyre marks, of up to around 0.3g, has proved higher than expected. Here too, more thorough research on this point would be of benefit.

1 Introduction

Traditional techniques in accident investigation and reconstruction rely on the identification of evidence at the incident scene from the road and vehicles, and the interpretation of this evidence using basic physical laws. In particular, the correct identification of tyre marks is crucial to the reconstruction process.

Many techniques in road traffic accident investigation require investigators to make assumptions and to simplify their analyses, such that vehicle movements become treated in an idealised manner. For example, in calculating speed from vehicle yaw marks the traditional approach is to measure the geometry of the marks and to check this against criteria described by Lambourn in 1989. If the geometry of the marks meets the criteria then it is possible to calculate the speed of a vehicle based on the 'critical speed' which will cause a vehicle to slide sideways whilst travelling a particular curved path on a particular surface. If the marks do not meet the criteria then, on our present understanding, they cannot always be used to reliably calculate speed, although, with caution, some estimate may still be possible.

These criteria have not been improved upon in the intervening years, and have, for example, been reproduced in a recently published SAE handbook (Brach & Brach, 2005).

The above method is necessarily limited in its application, and hence it does not provide investigators with a fully effective tool for addressing non-standard situations. Other methods are similarly restrictive and do not provide effective tools for investigating the variety of situations which drivers can encounter (and fail to deal with) which contribute to many road traffic accidents. Since the electronic braking and handling systems fitted to many modern vehicles act to assist drivers to retain control in extreme circumstances, the action of these systems calls into question whether many traditional assumptions actually remain valid for these vehicles.

The present investigation is intended to inform investigators and safety researchers as to the suitability of existing techniques and to provide information which could be crucial to the proper interpretation of physical evidence from modern crash scenes. In focusing on the marks generated by modern vehicles in limit manoeuvres, and by providing detailed measurements of vehicle behaviour, it is hoped that this experimental programme will provide up-to-date data and information to investigators and safety researchers to assist their assessments of vehicle speed in individual incidents.

2 Background

2.1 Tyre marks and accident reconstruction

When a manoeuvre is sufficiently severe to cause a substantial amount of slip between a vehicle's tyres and a dry road surface, tyre marks will usually be left on the road, and the understanding and interpretation of these marks is an important part of the skills employed by the accident investigator.

A guide to the identification of tyre marks in general has been given by Baker (1986). In locked wheel braking any features within them (due to the tread pattern or material caught beneath the wheel) will run along the marks in the direction of travel of the vehicle. It is unusual for ABS braking to produce tyre marks, but they are occasionally found as faint and usually continuous marks, again with any features appearing as longitudinal "stripes" within them. Lambourn (1994) has investigated the appearance of such ABS marks.

When the manoeuvre causing tyre slip is due to steering, with or without braking, the tyre marks have the distinguishing feature within them of lateral lines or stripes or striations. The presence of the lateral striations, when they appear in extreme manoeuvres, is largely due to the buckling of the tread area under high sideways forces, and the mechanism for this has been described by Yamazaki and Akasaka (1988). Under pure sideways force the striations should run across the tyre mark at 90°, but it is generally found that the angle is less, ranging from something close to 90° to 45° or less. The angle appears to be related to the amount of longitudinal force being applied to the wheel in question, either as accelerating power or, more commonly, braking action. This effect is described by Cooper and Fricke (1990), who indicate that, if they are regarded as running from the inside to the outside edge of the tyre mark, the striations will be angled forward if the vehicle has been under braking and backwards if it was under power. In experiments where cornering was combined with braking or accelerating, Hague et al. (1997) were able to detect some relationship between the angle and the braking or accelerating force.

Figure 1 below (taken from the present investigations) shows a typical tyre mark in close-up.

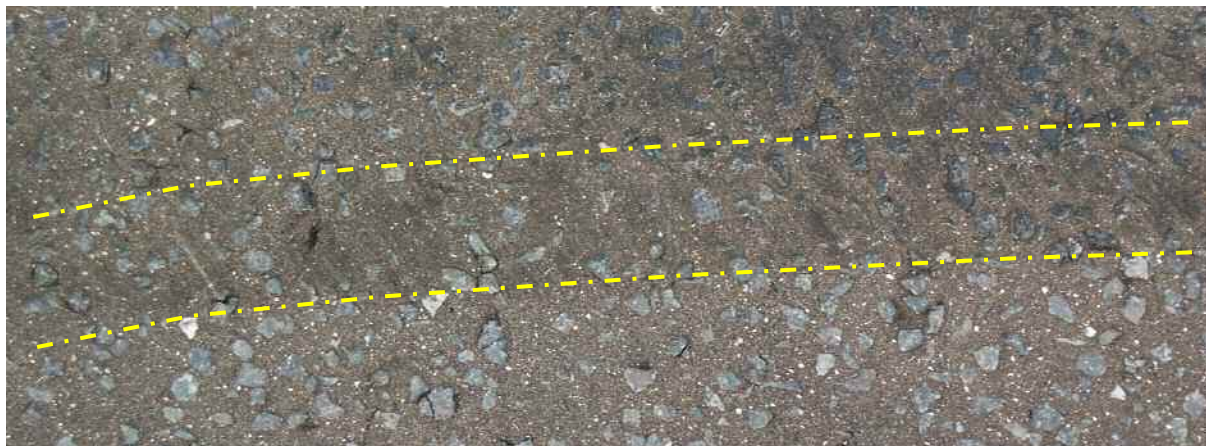


Figure 1. Striated cornering tyre mark

2.2 Modern tyre technology and tyre pressure

Tyre technology has advanced over the last 10 to 20 years and the types of wheels and tyres fitted to passenger cars has also changed. In general, the trend has been for the tyre width and diameter to increase but for the profile to decrease. This can result in an increase in the stiffness of the sidewall of the tyre. These changed characteristics have the potential to change the nature of the tyre marks left during emergency manoeuvres and no research has been identified that aims to quantify this effect.

Tyre pressures are often found to vary from the manufacturer's recommended value in ordinary service. Where low or high tyre pressures are found after a loss of control accident they are frequently cited as a contributory factor in the accident, or even the main cause of the accident, even if the variation is relatively small. However, many investigators believe that the magnitude of the effects attributed to small changes in tyre pressures is too great. Research on this subject does exist (for example, Hulme, 2004) but is usually small scale experiments with minimum instrumentation aimed at investigating specific accidents rather than a scientific quantification of effects for a range of tyres/vehicles in a range of conditions.

Various systems have been developed to monitor tyre pressure, and provide a warning when it falls below a certain level. These use various methods to detect pressure loss in tyres and supply a range of responses, from dashboard warning lights to adjusting the intervention of an ABS system to adapt to the change in tyre performance (Continental Automotive Systems, 2005). There is little to suggest that a tyre pressure monitoring system will individually affect the evidence available at an accident scene, unless the activation of the warning light on the dashboard is recorded electronically and can be interrogated later in order to establish whether or not tyres were adequately inflated.

In addition to systems to monitor tyre pressures, some cars are now equipped with "run flat" tyres. These are tyres that are claimed to be capable of maintaining adequate levels of comfort and grip even when a puncture has occurred. These have the potential to affect accident reconstruction by changing the nature of the tyre marks left at the scene, and potentially, by changing the appropriate values of friction that should be applied in reconstruction calculation. There is little published research on the potential effects on the handling of a car if it is driven with a mixture of 'normal' and 'run flat' tyres.

2.3 Antilock Braking Systems (ABS)

Antilock braking systems have become the standard fit in the European automotive market, car manufacturers having agreed a commitment which has led to all new cars sold in Europe being fitted with ABS.

An ABS works primarily to ensure that the driver maintains steering control of the vehicle under heavy braking. This is achieved by preventing the tyres from locking during heavy braking. Another benefit of these systems is that they may reduce stopping distances, by keeping the tyre-road slippage at an optimum value for maximum braking.

These systems are now very sophisticated but are still subject to further development to increase efficiency. A variety of future improvements may become commonplace in coming years, and include roadside to vehicle control, fuzzy logic methods for controlling ABS, and analysis of vehicle/wheel/road resonance systems to predict the slip condition of the road surface, to aid in maintaining braking force at a maximum (Austin & Morrey, 2000; Sugai et al. 1999).

ABS reduces the exposure to accidents that a vehicle undergoes in most circumstances. Although it is difficult to place exact numbers on the reduction or increase in certain categories of accidents that ABS equipped cars undergo (for instance, the driver of an ABS equipped car may choose to steer off the road instead of hitting a pedestrian, and so ABS cars may have increased incidences of leaving the road) it does seem that there is a significantly reduced chance of accidents for cars equipped with ABS. The greatest reduction in risk found was 42%, for frontal crashes in unfavourable road conditions (Hertz et al., 1998). Another study notes reductions of 9-11% on overall accident rates and 16-17% reductions to accident rates on wet roads (Padmanaban & Lau, 1996).

In considering the effect of ABS on accidents, it is also important to take into account the effect that occurs when some vehicles are ABS equipped and others are not. The shorter stopping distance of an ABS equipped car is such that although some studies have found that being equipped with ABS reduces the risk of shunting another vehicle on wet roads by 32%, it was found to increase the risk of being shunted by another vehicle by 30% in similar conditions (Evans, 1998).

ABS allows steering while under emergency braking, and also affects stopping distance on some surfaces. Although the usual effect is to shorten stopping distances, especially on wet or icy roads, on

loose surfaces such as gravel, stopping distance increases by an average 27.2 percent (Forkenbrock et al., 1998). On a non ABS equipped car a mound of gravel will build up in front of a locked wheel, significantly adding to the retarding forces applied to the car. This additional braking effect is lost when a car is fitted with ABS. This potential problem may be reduced or eliminated by systems which detect that a car is travelling on such a surface and instruct the ABS system to act appropriately, to improve its performance to match that of a non ABS car on loose aggregate (McManus et al., 2003). The lack of this ploughing effect at an accident scene on an unbound surface is likely to provide good evidence that an ABS was present, assuming heavy braking took place, and also as evidence that the car did not stop as quickly as it would have were the ABS not present.

By preventing the wheel from skidding, an ABS is likely to reduce or eliminate the physical evidence of marks on the road, depending on the exact conditions at the tyre road interface. In practice, ABS equipped cars do leave lighter intermittent marks on the road under heavy braking in some circumstances. These could be used to produce estimates of vehicle speed in a similar way to skidmarks, bearing in mind that a higher value of μ should be used, compared with those derived from traditional skid tests, because the ABS system will maintain braking closer to an optimal value than a skidding car (Linsey, 1994). It was also noted that ABS provides different levels of advantage in terms of braking force at different speed. One study noted the ratio between locked-wheel and peak friction fell from approximately 70% at 20 km/h, to 50% at 110km/h (Viner et al., 2000). This suggests that any attempt to adjust speed estimation methods for vehicles with ABS must not only take into account the increased advantage of such systems on slippery road surfaces, but also the speed the vehicle was travelling at at each stage of its braking. Early studies (Robinson & Riley, 1991) also showed some variability between the ABS systems fitted to different cars, although it is expected that this variability will be progressively reduced as electronic control becomes more sophisticated, enabling deceleration rates to move asymptotically towards the theoretical maximum value set by value of peak friction.

There are some problems with ABS noted in the literature. One problem that is widely noted is the negation of much of the value of ABS by drivers who are not aware of the correct braking behaviour in an ABS car, or who are unable to act on such awareness in the moments immediately preceding a collision. A tendency to come off the brake pedal when the effect of ABS is felt, or to continue the old braking technique of “pumping” the brake reduces the braking force on the car, and can extend stopping distance significantly. It is found that failure to apply the brakes correctly is reasonably commonplace among untrained drivers, and it might be expected that evidence of this could be found at accident scenes (Mollenhauer et al., 1997).

It has been noted that ABS enables the driver to steer while emergency braking. At some accident scenes curved and intermittent marks have been left by a vehicle taking avoiding action while emergency braking. In this condition, the laws of physics dictate that the longitudinal deceleration achieved must decrease because part of the available friction is being used to generate the cornering forces. In those circumstances where curved striated tyre marks are found, it has been shown that the established method of calculation of the vehicle’s speed from the curvature of the marks remains valid (Lambourn, 1994).

2.4 Brake Assist Systems (BAS)

Brake assist systems work by recognising emergency braking behaviour, and applying appropriate braking responses. This counteracts the common tendency for drivers to brake progressively, even in emergency situations, and so increase braking distance. By recognising characteristics such as the speed with which the brake pedal is depressed the system recognises the intention of an emergency brake application and immediately applies an increased braking force compared with the actual demand of the driver, thus reducing stopping distance (Hara et al., 1998).

The effect of Brake Assist Systems is to more rapidly apply full braking in an emergency braking situation. As such, it is likely that the physical evidence present at the scene will not differ between a car with such a system and one without such a system where the driver applied maximum braking

force promptly at the start of emergency braking. Such a system would tend to decrease the amount of braking that occurs before the appearance of any tyre mark, such that typical drivers without BAS would have been travelling faster than the reconstructed minimum speed whereas the predictions for those with BAS might be more accurate. However, no research was identified that attempted to quantify this effect and any findings would be difficult to apply reliably in accident reconstruction because the actions of the driver in this respect are likely to be unknown.

2.5 Electronic Stability Control (ESC)

ESC systems sense parameters such as yaw rate, steering wheel angle and lateral acceleration in order to detect differences between the intended and actual path of the vehicle. The system is then linked to the ABS and engine management system in order to differentially apply the brakes and/or reduce the engine power to individual wheels, thus generating yaw moments to correct the vehicles path. These systems are known by a variety of other proprietary names such as Vehicle Dynamic Controller (VDC) and Vehicle Stability Control (VSC) but are referred to generically as ESC in this report.

Market penetration of ESC systems was estimated at 27% in Europe in 2002, and is expected to reach 50% in Europe by 2007 (Reed Electronics Research, 2003). Previous research indicates that ESC significantly reduced instability in test manoeuvres where substantial instability was encountered. It also suggests that ESC does not influence vehicle behaviour when a driver attempts to operate outside the physical limits of the vehicle. No significant disbenefits of ESC systems were found, and clear evidence of positive influence on safety and accident reduction was cited (Grover & Knight, 2005). ESC is also now “strongly recommended” to all consumers by the EuroNCAP organisation (EuroNCAP, 2005).

It is suggested that ESC must work to constrain vehicle behaviour to that expected by normal human driving behaviour. It does this either by producing similar vehicle behaviour under both normal and extreme conditions, or by avoiding situations where the behaviour of the vehicle suddenly changes (van Zanten et al., 1995). Van Zanten et al. summarise design rules for ESC systems as follows:

- when nearing its physical limit a vehicle should show predictable behaviour;
- on slippery roads deviations from normal handling should be small;
- vehicle load variations should not greatly affect vehicle behaviour;
- disturbances should have little influence on vehicle motion (e.g. side wind);
- steering behaviour should be kept in an optimal area.

The effect of ESC on reducing accident risk is estimated by a Swedish study at an effectiveness of 22.1% over all accidents, though it is worth noting that the 95%-ile bands are $\pm 21\%$. This increased to 31.5% on wet roads, and further increased to 38.2% on roads covered in ice and snow (Lie et al., 2003). A similar study in the US estimated that ESC reduced single vehicle accident risk by approximately 41% (Farmer, 2004).

There are a number of ESC systems which do not necessarily work in all conditions, and do not always work to the same level of effectiveness. ESC systems may turn off in banked turn conditions when a large lateral slope is detected, unless the car is under full braking. However, this condition is unlikely to be found on public roads, and is of more relevance during track driving. The systems may also shut off when the car is reversing.

The performance of ESC systems relies upon them having accurate data on the physical and performance dimensions of the vehicle. One researcher has claimed that because of this the performance can vary quite widely with factors such as tyre wear (van Zanten, 2000).

Although extensive information was found regarding the operation, performance and effectiveness of ESC, no literature could be found assessing whether the presence of an operational ESC system could be detected from tyre marks left at accident scenes or whether the operation of ESC affected the

speeds predicted from traditional reconstruction of critical speed tyre marks, as described by Lambourn (1989).

2.6 Active Steering

Active steering systems automatically adjust the steering ratio according to the speed that the vehicle is travelling at. This exaggerates steering input at slow speeds to facilitate easy manoeuvring, and applies a slight counter-steer at high speeds, to ensure drivability and directional stability (Krenn & Richter, 2004).

As noted above, Active Steering maintains a mechanical link between the steering wheel and the front road wheels, but adjusts the ratio of this steering depending on the speed that the vehicle is travelling at. This not only means less steering input is required when travelling at low speed, but also means that at high speed a driver is less likely to lose control of the car through excessive steering input. The total effect is to provide a steering behaviour closer to the expected behaviour for a given steering input (Krenn & Richter, 2004). There was no evidence in the literature to show the preventative effect of Active Steering on accident risk, and though it might intuitively be expected to reduce accidents caused by loss of control when a driver over steers at high speed, no literature assessing this possibility has been found.

Preceding sections have shown that critical speed tyre marks are generated by lateral slip between the tyre and the road. The intervention of active steering would not be expected to change this evidence in any way and should not affect accident reconstruction in most cases. Difficulties may arise if allegations were made that the active steering behaved inappropriately and, thus, contributed to the accident because it would not be possible to tell whether the tyre marks were left because of the driver inputs or the actions of the system. In this type of case investigations would have to focus on the function of the system and any electronic fault recording capability.

2.7 “Black Box” Accident Data Recorders

“Black box” has been used in this report as a generic term for a variety of information gathering and recording systems in modern vehicles. Although dedicated journey and/or accident information recorders are still relatively rare in passenger cars, several safety subsystems collect data as part of their operation, and in some cases it can be made available after the collision (Gilman, 1999). Black boxes are likely to become more widespread and “pay as you drive” insurance is a recent innovation that will hasten their penetration of the vehicle fleet (Norwich Union, 2006). Although it is clear that logging of data does not immediately affect an accident, there is potential for an accident investigator to be able to download incident data from a vehicle. In theory, it is possible to record quite detailed information about the behaviour of the vehicle before and during any incident (Ueyama et al., 1998). However, there are a range of factors that could potentially affect the use that accident investigators put this data to:

- legal issues regarding ownership of the data and rights to privacy;
- the accuracy of the system and tolerances that should be applied to conclusions drawn from the data;
- the relationship between conclusions derived from recorded data and those derived from tyre marks and how to resolve any conflict between the two.

Considerable literature already exists in relation to these data recorders and some of these issues have been quantified. However, TRL is not aware of any conclusive and accepted guidelines for the use of the devices in expert evidence.

2.8 Discussion

Studies of advanced safety systems seem to agree that they can have a significant impact on accident rates, and that the impact for a given system often varies quite widely depending on the accident circumstances and the type of accident being discussed. This suggests that any techniques developed for interpreting data from accidents involving vehicles equipped with these systems must be developed with a range of performance conditions in mind.

The review focussed on changes and new technology that have already been applied to passenger cars. The following areas were identified.

- Tyre technology
- ABS
- BAS
- ESC
- Active Steering
- “Black Box” data recorders.

Of these, BAS and Active Steering were considered to have the least effect on accident reconstruction, although each of them did have some potential issues. ABS was found to have a very substantial effect but research describing this effect was already available and little could be done to overcome the problems. ESC, tyre technology and black box data recorders were considered to have the most potential effect on reconstruction, coupled with the least research investigating the issues. It was, therefore, concluded that this initial feasibility project should focus on research and experimentation to see whether the presence of ESC could be detected from tyre marks and whether its operation affected critical speed calculations. Future work could be aimed at investigating modern tyre technology, tyre pressure and black boxes and could also be expanded to cover different vehicle types.

3 Experimental programme

3.1 Instrumented vehicle

The car used in the experimental programme was a medium sized front wheel drive four-door saloon (a Volkswagen Passat). It was instrumented in the same way as the vehicle used by Grover and Knight in their investigation into ESC, as follows:

- instrumented steering wheel to measure steering wheel angle, angular rate and torque;
- optical sensor to measure longitudinal speed, distance and slip angle;
- inertial platform to measure angular rate and acceleration of the vehicle in three orthogonal axes (pitch, roll, yaw, x, y, z);
- string potentiometers to measure the position and rate of change of position of the throttle and brake pedals;
- load cell to measure the force applied to the brake pedal;
- four pressure transducers to measure the hydraulic pressure applied to each brake calliper;
- data logger to record the output of the various transducers;
- display unit to provide visual information to the driver.

3.2 Surfaces used for the programme

The programme was carried out on two parts of the central area of the TRL research track: an area of hot rolled asphalt (HRA) and a circle and wider area of stone mastic asphalt (SMA).

Both surfaces had been laid for some time, and, while not traffic polished, were well weathered. The HRA surface was also jointed and somewhat irregular.

Locked-wheel skid tests were performed on them with the car, to find their sliding tyre/road coefficient of friction. The car was braked hard to a halt (with the ABS disabled) from about 50 km/h, and data were taken from the recorded longitudinal acceleration, which gave figures of:

HRA: peak friction 1.02, slide friction 0.77

SMA: peak friction 0.96, slide friction 0.75

3.3 Experimental manoeuvres

The experimental manoeuvres were based on some of those which had previously been used by Grover and Knight, being:

3.3.1 *Asymmetric sine steer*

This manoeuvre involved a straight line approach at 50 mile/h, where the driver first steered quite hard to the right and then much harder back to the left. Before the first steering action the throttle was released and neutral was selected. Although it essentially copied the manoeuvre described by Grover and Knight (2005) (and with the same driver), the exact rates and amplitudes of steer were not necessarily identical to those used in the earlier research.

3.3.2 *Asymmetric sine steer without removing final steer*

This manoeuvre was not used by Grover and Knight. It is the same as the asymmetric sine steer, except that in the second steering action the steering is then held at its maximum amplitude. This is intended to emulate the action of a driver who has, in the second steer, lost control of his vehicle and continues to steer until it crashes.

These first two manoeuvres were performed on the HRA surface.

3.3.3 *Step steer*

The vehicle was driven at a steady speed (about 40 mile/h) in a straight line on the SMA surface, and the steering was then suddenly increased by an angle of about 180°.

3.3.4 *Step steer in a turn with lift off*

Here the vehicle was driven at a steady speed (about 55 mile/h) on the 100 metre radius SMA circle, which meant that it was cornering steadily at about 0.6g. The steering was then suddenly increased by about 40°, with the throttle being released at the same moment.

In the first, second and fourth manoeuvres, investigations were made with and without the ESC in operation. In the third, they were only made with the ESC active.

3.4 Recording of tyre marks

The paths of the tyre marks were recorded with a laser scanning device which measures the three-dimensional coordinates of each point from which it receives a reflection. To enhance their visibility, reflectors and small cones were placed along the tyre marks at intervals of about 5 metres. Figure 2 below shows the scanner and the tyre marks from the first of the asymmetric steer runs (see 4.1.1 below).



Figure 2. The laser scanner in operation

The striations, if any, were identified along the tyre marks, and their angles were measured with a protractor. The angles were recorded relative to the local line of the tyre mark. This takes no account of the vehicle yaw angle if any is present.

A limited amount of still photography was also undertaken.

4 Experimental results

For each of the experimental runs which are described below two figures showing the results are presented: a plot of the tyre marks and a graph showing certain of the recorded data. In the plots, the front tyre marks are shown in red and the rear tyre marks in green; the crosses on the plots indicate the positions of the cones and reflectors; and on each plot the radius of curvature of the first part of the front right tyre mark is indicated for two or three arc lengths, the lengths being 10 metres (shown in magenta), 15 metres (cyan) and 20 metres (blue). The data plotted on the graphs are the yaw rate (Z_{rate}), the hydraulic pressure at each brake, the slip angle, and the lateral acceleration.

4.1 Asymmetric sine steer

Five asymmetric sine steer runs were performed, three with the ESC system on, two with it off. Descriptions of the individual runs follow, which include figures showing the plots of the tyre marks generated during the second steering action, when the car was turned to the left. In each of the figures the car is travelling from right to left. Table 1 at the end of this section summarises the runs.

4.1.1 Run 1, ESC on

In the first run the ESC system was active. Full steering – about 210° – was applied. Figure 3 shows the plot of the tyre marks, which were from the right (offside) wheels only.

Figure 4 shows the data recorded for various quantities. The start of the tyre marks occurred at 3.4 seconds, and they ended at 4.5 seconds. Over their length the speed fell from 47 mile/h to 39 mile/h. The data included in Figure 4 are the yaw rate, the four brake line pressures, the slip angle and the lateral acceleration. Looking at the brake line pressures, it can be seen that the ESC system activated the two right brakes, increasing and then reducing them again along the length of the tyre marks.

No striations could be seen in the tyre marks but a few diagonal scratches, from small stone particles on the track, were present in the mid section of the front wheel mark. The angles of these, measured against the line of the mark, were 45° , 35° , 55° and 70° .

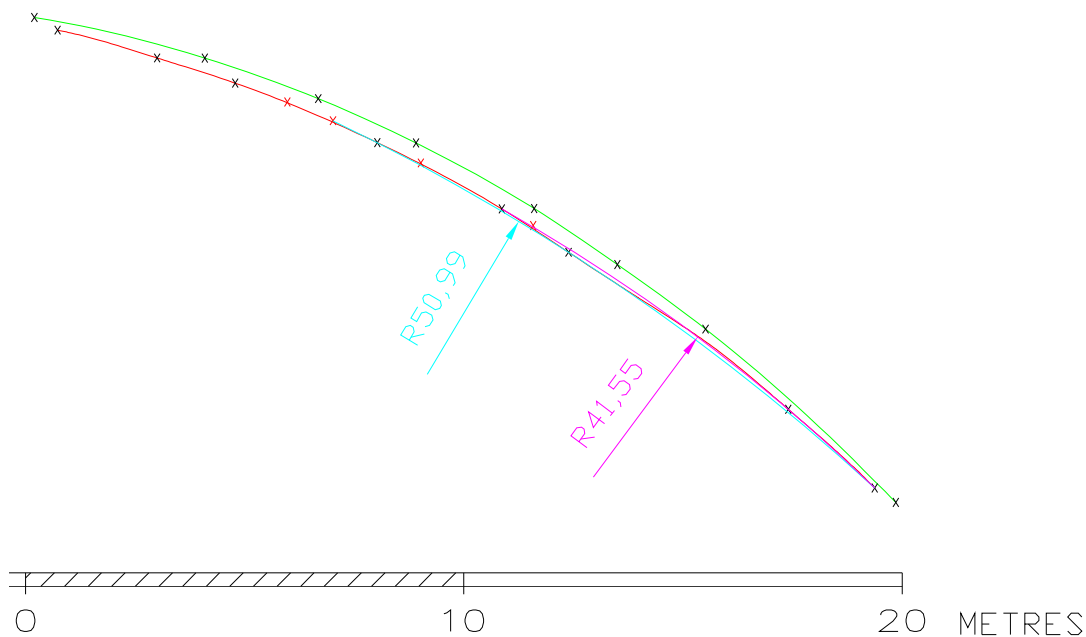


Figure 3. Asymmetric sine steer run 1, ESC on

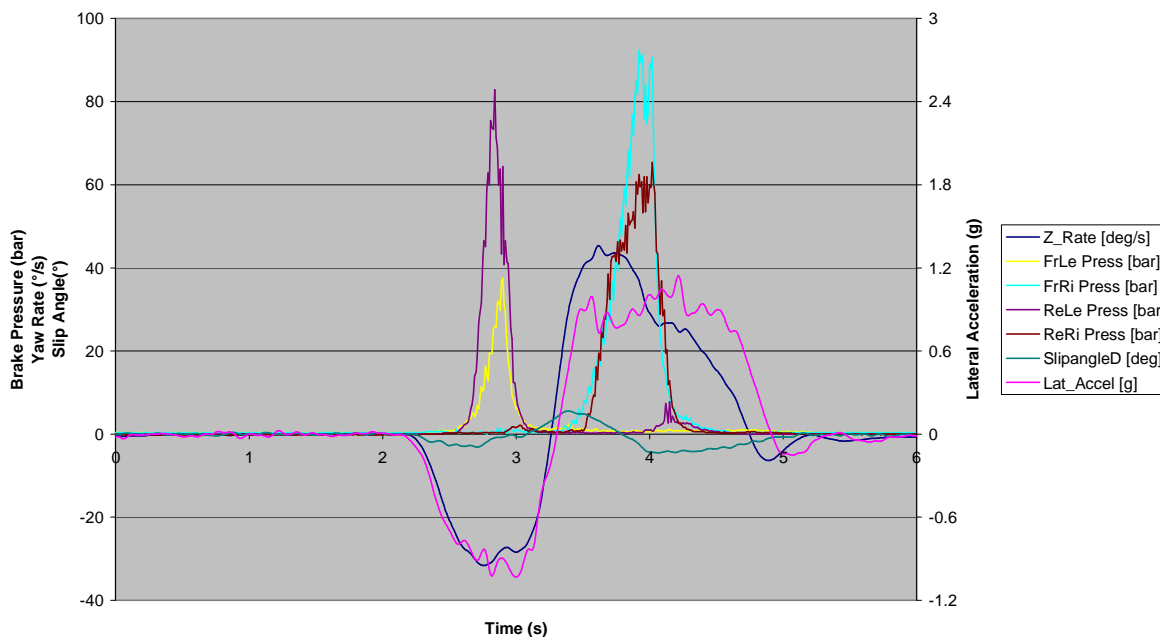


Figure 4. Data from asymmetric sine steer run 1, ESC on

4.1.2 Run 2, ESC on

In the second run a little less steering – about 195° – was applied. Figure 5 shows the plot of the tyre marks, and Figure 6 shows the data. Again, there were marks from the right wheels only, and the start of the front wheel mark occurred at 3.3 seconds and ended at 4.1 seconds, and the speed fell from 47 mile/h to 42 mile/h.

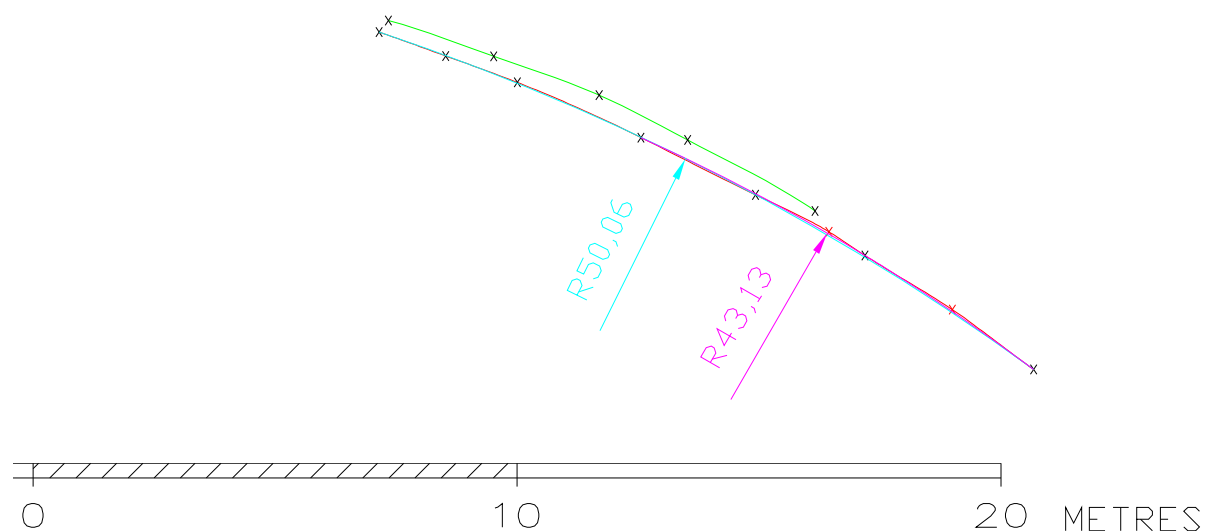


Figure 5. Asymmetric sine steer run 2, ESC on

As in the first run, the ESC system activated the two right brakes, increasing and then reducing the pressure over the length of the marks.

Little in the way of lateral markings could be seen: only an early striation at about 70° and a lateral scratch soon after at about 50°. The early striation marks were, significantly, found where there was a patch of excess bitumen on the surface due to over-banding.

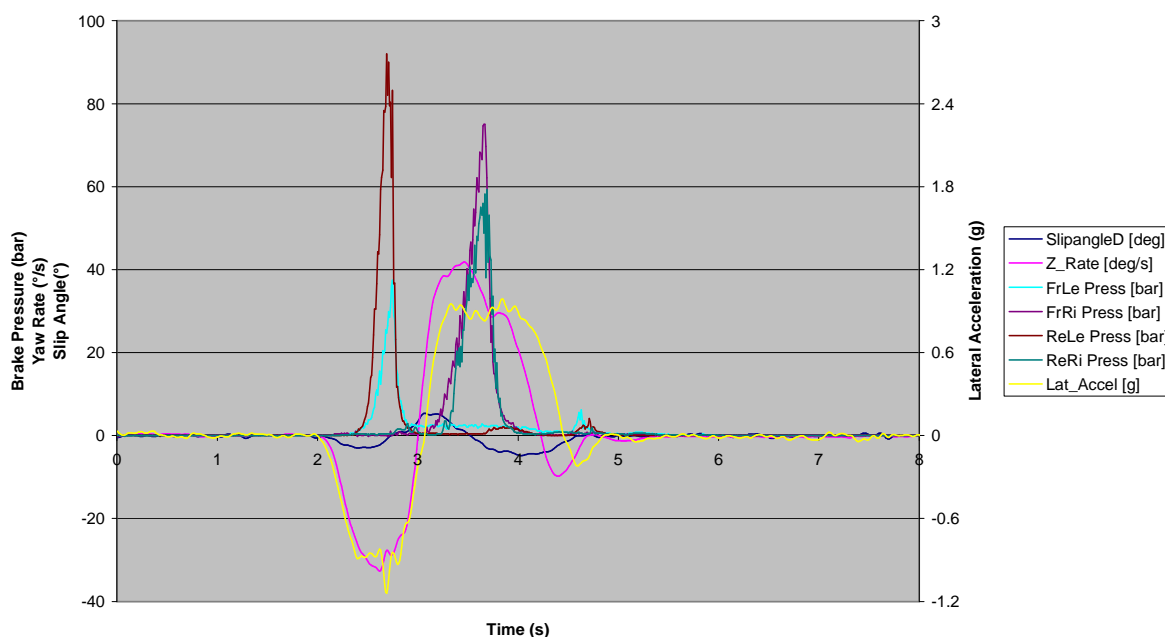


Figure 6. Data from asymmetric sine steer run 2, ESC on

4.1.3 Run 3, ESC on

For the third run, about 210° of steering was applied, as in the first run. Figure 7 shows the plot of the tyre marks, and Figure 8 shows the data. Again, there were marks from the right wheels only, and the start of the front wheel mark occurred at 3.2 seconds and ended at 4.2 seconds. The speed fell from 47 mile/h to 40 mile/h. As before, the ESC system activated the two right brakes, increasing and then reducing the pressure over the length of the marks.

Here there were scratches and striations in both marks. In the rear wheel mark they were found in the latter half, with angles between 60° and 75°. In the front wheel mark they were found at several points along its length, the sequence of angles being 65°, 70°, 50°, 50°, 80° and 60°. There may be an indication here that, in the front wheel at least, the angle of scratches or striations decreases as the ESC activates.

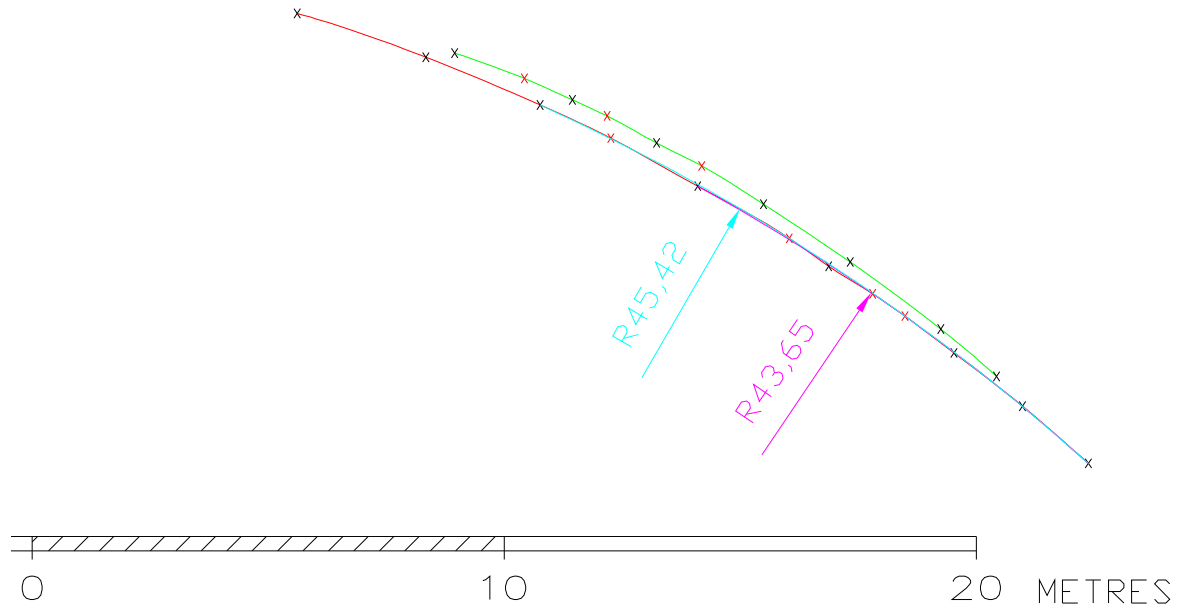


Figure 7. Asymmetric sine steer run 3, ESC on

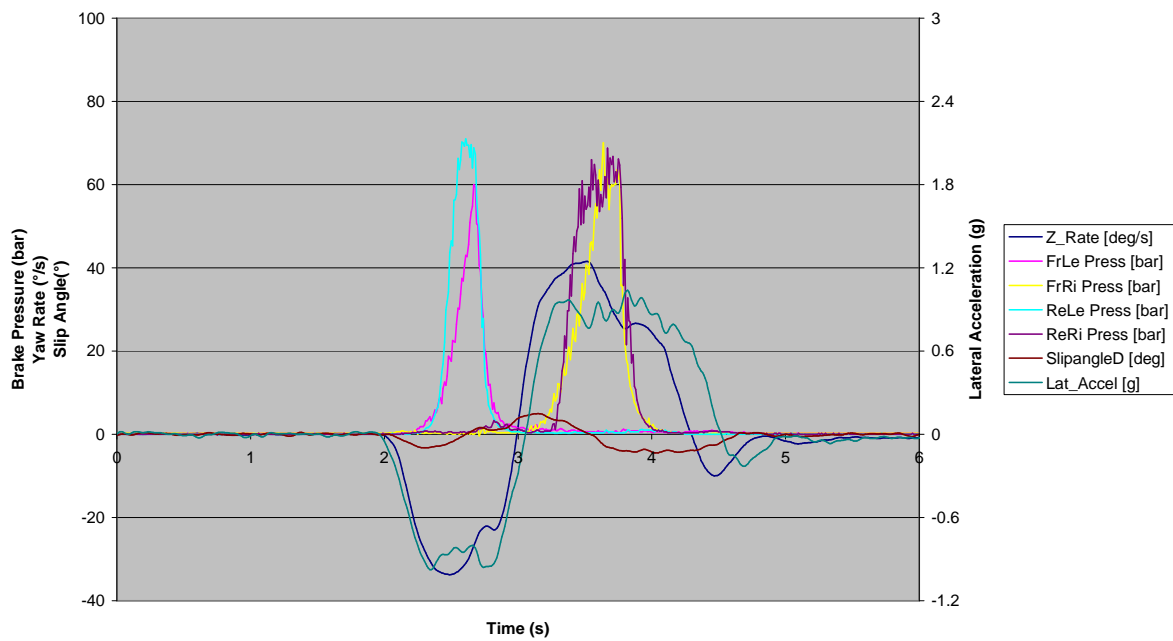


Figure 8. Data from asymmetric sine steer run 3, ESC on

4.1.4 Run 4, ESC off

For the fourth and fifth runs the ESC was turned off. For the fourth run the steering was turned through no more than 185°. Figure 9 shows the plot of the tyre marks, and Figure 10 shows the data for the fourth run. Once again, there were marks from the right wheels only: the start of the front wheel mark occurred at 3.6 seconds and ended at 4.8 seconds. The speed fell from 48 mile/h to 41 mile/h. The brake line pressures remain, of course, at zero, or very nearly so, throughout.

Very few scratches or striations were found: at two points close together in the middle of the front wheel mark a striation at 75° and a scratch at 50° were found, while early in the rear mark a scratch at 80° was found.

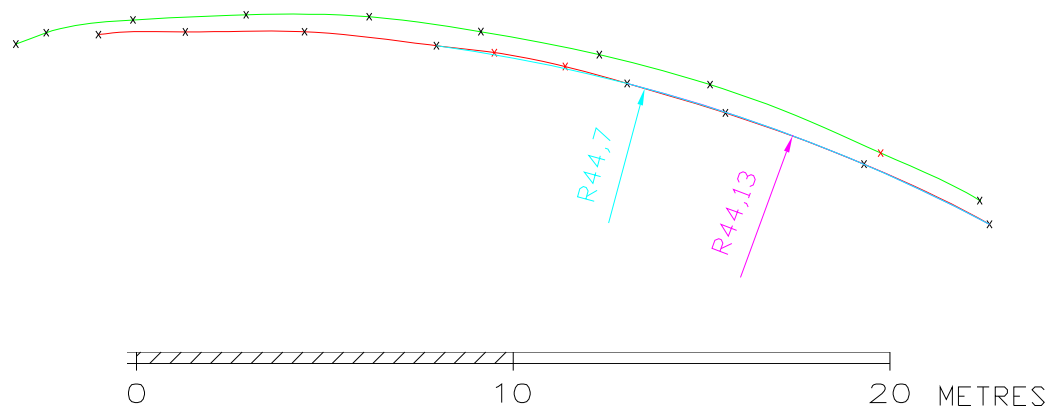


Figure 9. Asymmetric sine steer run 4, ESC off

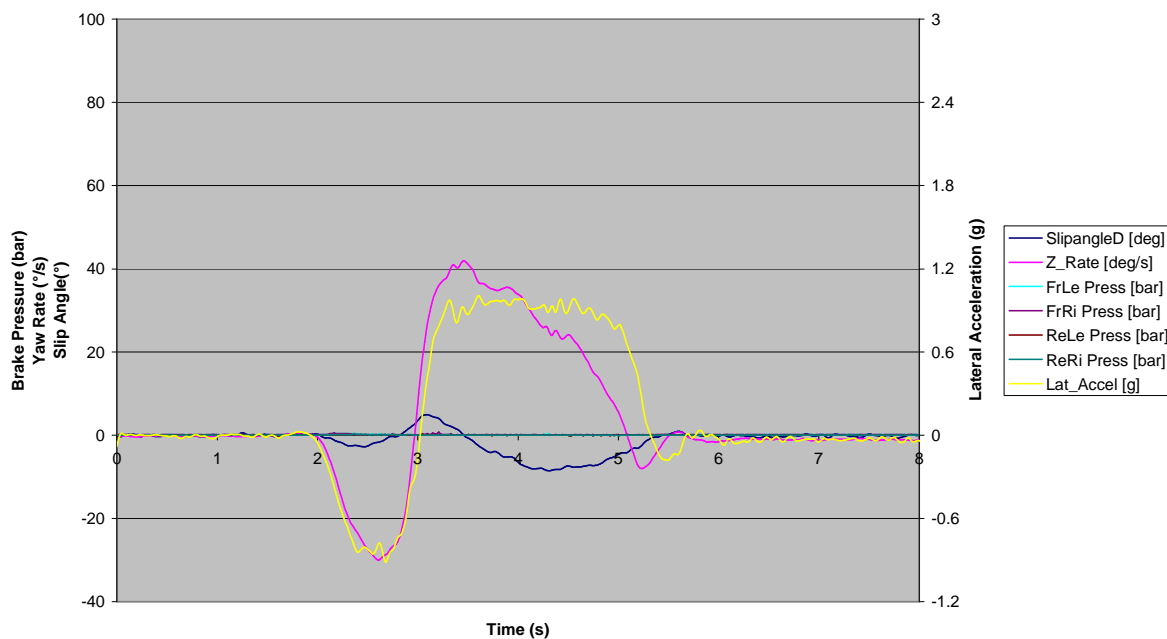


Figure 10. Data from asymmetric sine steer run 4, ESC off

4.1.5 Run 5, ESC off

In the fifth run, with the ESC off, “very hard” steering was applied, up to 205°. Figure 11 shows the plot of the tyre marks, and Figure 12 shows the data. Three tyre marks were observed, the third coming from the front left wheel. The start of the front right tyre mark occurred at 3.1 seconds, when the speed was 47 mile/h, and as the car progressed it developed a considerable yaw. Our measurement of the tyre marks was ended after the car had travelled about 44 metres: this occurred at a time of 5.5 seconds, at which point the vehicle had yawed through about 20° and was travelling at 31 mile/h.

Quite clear striations were visible throughout these marks, particularly where the wheels crossed the overbanding. Their angle for most of the length of the front right mark was about 70°, reducing to 60° close to the end. In the rear right mark it varied between 75° and 60° throughout.

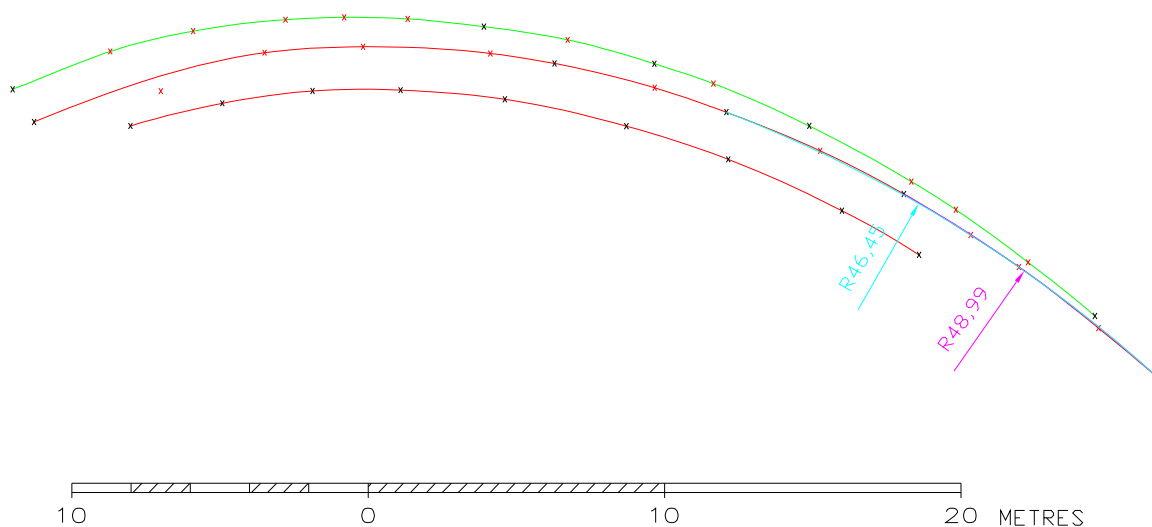


Figure 11. Asymmetric sine steer run 5, ESC off

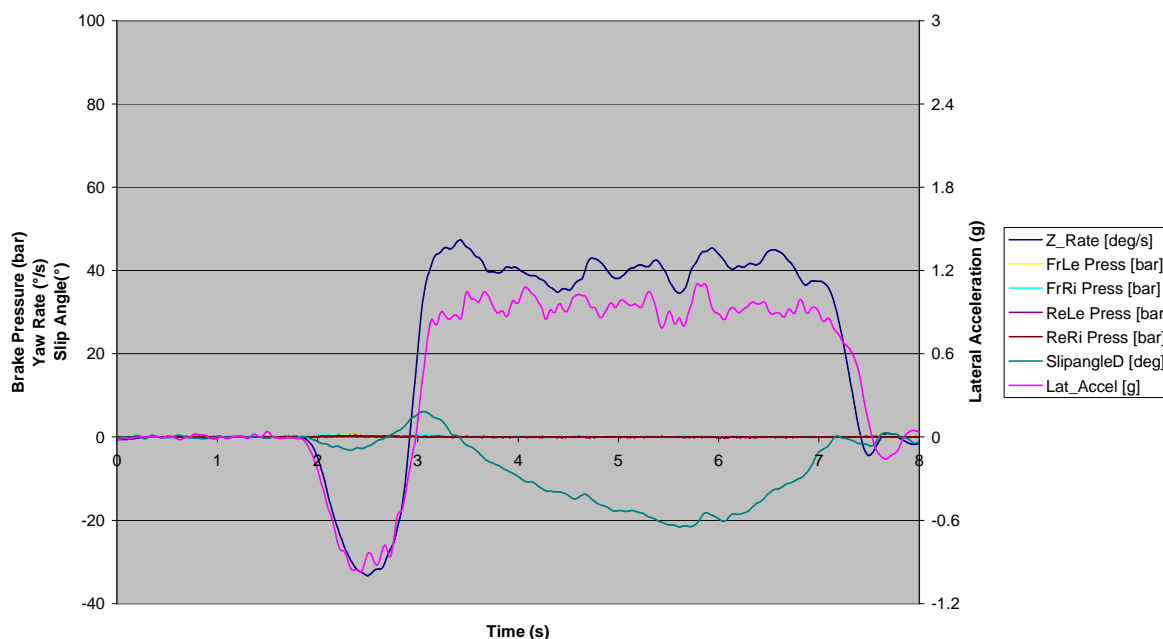


Figure 12. Data from asymmetric sine steer run 5, ESC off

4.1.6 The appearance of the tyre marks

Quite clear curved tyre marks from two or three wheels were found from the second steering action, and lateral striations or scratches could be seen along their lengths. Although not measured, faint tyre marks could also be seen from the first steering action.

There was nothing striking in the appearance of these tyre marks which could be used to indicate that the ESC was active. There are features which, with the knowledge that an ESC system was present and activated, could be attributed to it, namely the possibly smaller angle of the striations when the system was active (run 3), or the smaller amount of yaw when the driver was steering very hard (compare runs 1 and 3 with run 5). However, the smaller angle of the striations could equally have been caused by the driver himself applying the brakes, while in a real incident one would never be able to say whether a small amount of yaw was due to the intervention of ESC or to the driver applying less than the full amount of steering.

4.1.7 Speeds calculated from tyre marks

Table 1 below gives the figures which are found when the speed of the car is calculated from the curvature of the tyre marks. This uses the established method which was explored by Lambourn (1989), of calculating the radius of curvature of the first 15 metres approximately of the front outside tyre mark (the front right mark in these runs) from the positions of three points on the arc, and then calculating a speed based on the sliding tyre/road coefficient of friction μ using the simple relationship,

$$v = \sqrt{(\mu \cdot g \cdot r)}$$

This calculation procedure is frequently called the “critical speed” calculation. In addition, the speed has been calculated using the peak coefficient of friction (1.02, in these runs), and also for a shorter length of tyre mark, of approximately 10 metres. The radii have been calculated in each instance by fitting arcs through three selected marker cones and reflectors in the scanner plots.

Table 1. Speed calculations from tyre marks, asymmetric sine steer

run no. & ESC	approx. arc, metres	radius, metres	actual speed at start of arc, mile/h	actual speed at end of arc, mile/h	calculated speed, $\mu=0.77$	calculated speed, $\mu=1.02$
1: ON	10	41.6	47.0	44.2	40	46
	15	51.0	47.0	40.4	44	51
2: ON	10	43.1	47.1	42.6	40	47
	15	50.1	47.1	41.8	44	50
3: ON	10	43.7	47.6	44.1	41	47
	15	45.4	47.6	41.3	41	48
4: OFF	10	44.1	47.5	44.8	41	47
	15	44.7	47.5	43.6	41	47
5: OFF	10	49.0	47.6	45.5	43	50
	15	46.5	47.6	43.7	42	48

Several observations arise from these figures. Firstly, the smaller radii found for the 10 metre arc as compared to the 15 metre arc in the first three runs are improbable, since when the vehicle is being steered hard in this way, and not under power, the radius would decrease as it progresses: these

figures may be the result of insufficiently careful placing of the marker cones. (The difference in the fourth run is insignificant.)

Secondly, the critical speed calculation, which is generally regarded as giving a figure for the speed of the vehicle at the *start* of the marks, plus-or-minus 10%, has consistently underestimated that figure, frequently by an amount which is more than 10%, whereas a calculation based on the peak friction gives much better results. And thirdly, there is no discernable difference between the ESC-on and ESC-off conditions.

4.2 Asymmetric sine steer without removing final steer

Four further asymmetric sine steer runs were made in which the driver held the second (leftward) steering action until the car had slowed almost to a stop. In the first and fourth runs the ESC system was on, in the second and third it was off.

4.2.1 Run 1, ESC on

In the first run the steering was turned left through about 175° and then held. Figures 13 and 14 show the plots of the tyre marks and the data. Here, and in all four of these runs, three tyre marks were visible: from the front and rear right wheels and from the front left wheel. In Figure 13 the radius of the front right tyre mark is calculated for approximate arc lengths of 10, 15 and 20 metres.

In this run the start of the tyre marks occurred at 3.6 seconds, and our recording of them ended at 5.7 seconds, and over their length the speed fell from 46 mile/h to 36 mile/h.

In Figure 14 it can be seen that, as in the first asymmetric sine steer runs, the two right brakes were applied and then released by the ESC system, after which, starting at about 4.1 seconds there was some lesser activity from the left brakes.

Some striations were noted throughout the tyre marks, varying between 60° and 70° throughout, with 75° measured at the very end. It was also noted that the separation of the front and rear right marks increased at first to about 25 cm, but then reduced and stabilised at about 15 cm.

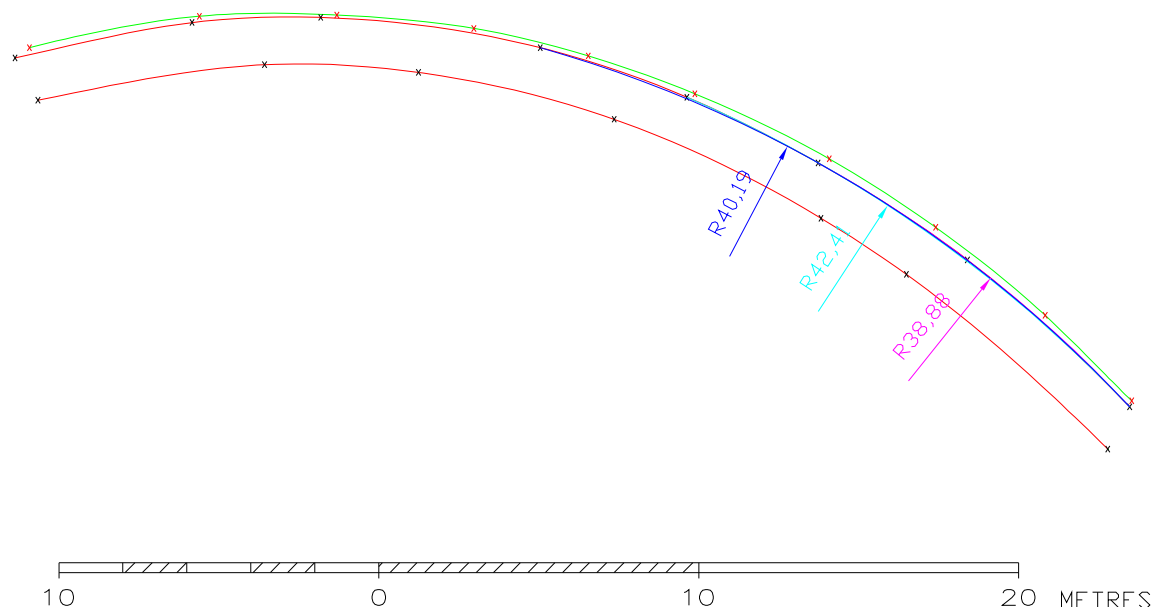


Figure 13. Asymmetric sine steer with steering held, run 1, ESC on

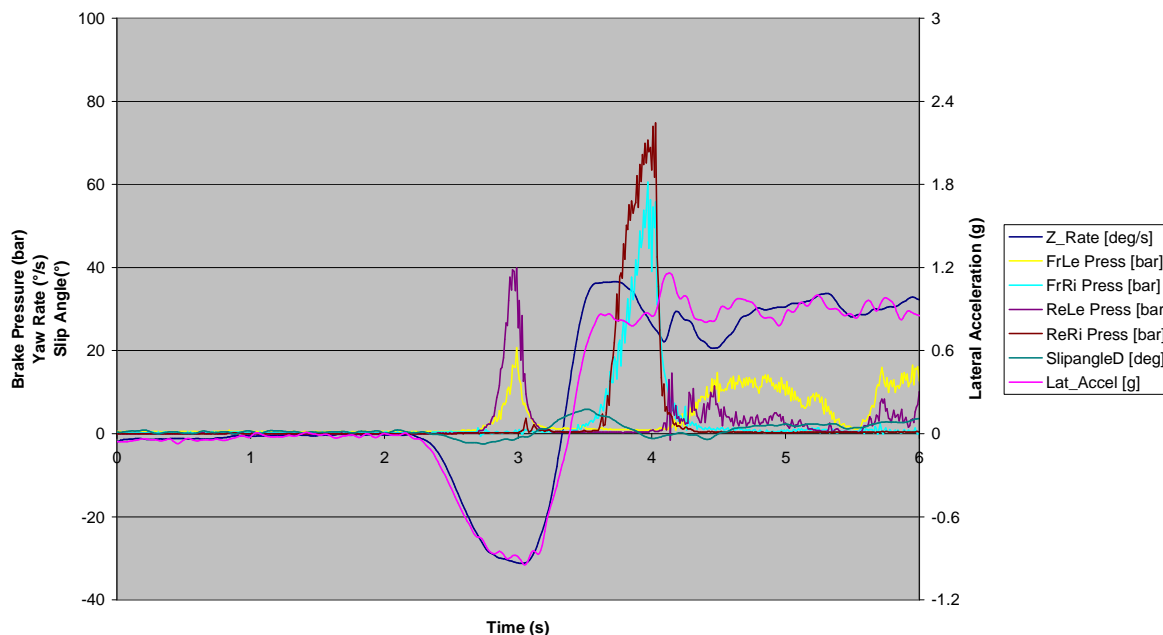


Figure 14. Data from asymmetric sine steer with steering held, run 1, ESC on

4.2.2 Run 2, ESC off

In the second run, where the ESC was turned off, the steering was turned through about 170°. Figures 15 and 16 show the plots of the tyre marks and the data. Here again three tyre marks were visible: from the front and rear right wheels and from the front left wheel. In this run the start of the tyre marks occurred at 3.4 seconds, and our recording of them ended at 5.7 seconds, and over their length the speed fell from 48 mile/h to 36 mile/h.

The angles of the striations which could be seen were a little shallower, varying between 50° and 70°, but were not strikingly different to those in run 1. The separation of the front and rear marks was greater than in run 1, progressing to about 46 cm, but then reducing again as speed was lost.

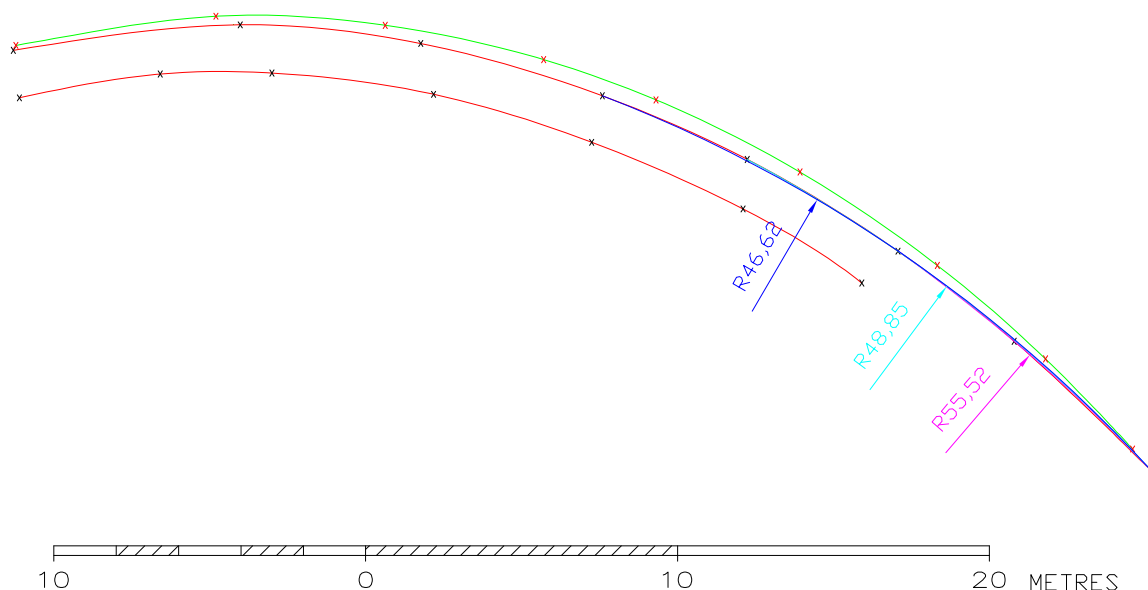


Figure 15. Asymmetric sine steer with steering held, run 2, ESC off

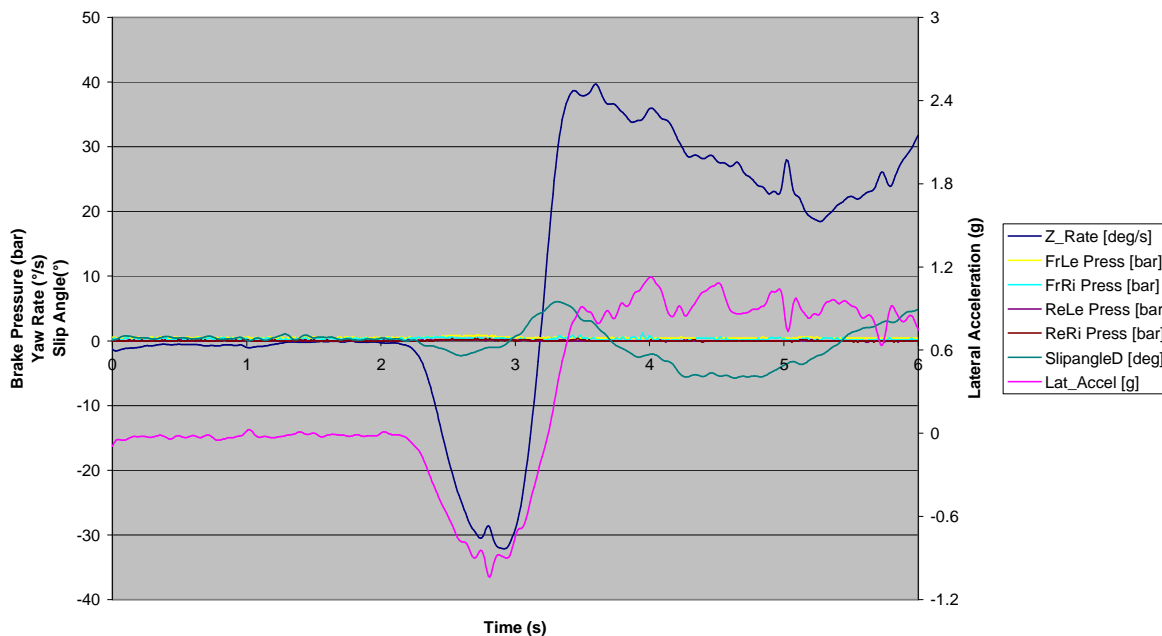


Figure 16. Data from asymmetric sine steer with steering held, run 2, ESC off

4.2.3 Run 3, ESC off

For run 3 the ESC was again switched off, but harder steering was applied, with the wheel turned to about 215°. Figures 17 and 18 show the plots of the tyre marks and the data. Three tyre marks were visible, from the front and rear right wheels and from the front left wheel, and in this run the start of the tyre marks occurred at 3.4 seconds, and our recording of them ended at 5.9 seconds; over their length the speed fell from 49 mile/h to 28 mile/h.

A more substantial yaw was produced, with the separation of the front and rear marks reaching nearly 100 cm two-thirds of the way through the recorded length, before reducing to about 70 cm at the end. The striations, however, remained in the region 65° to 75° throughout.

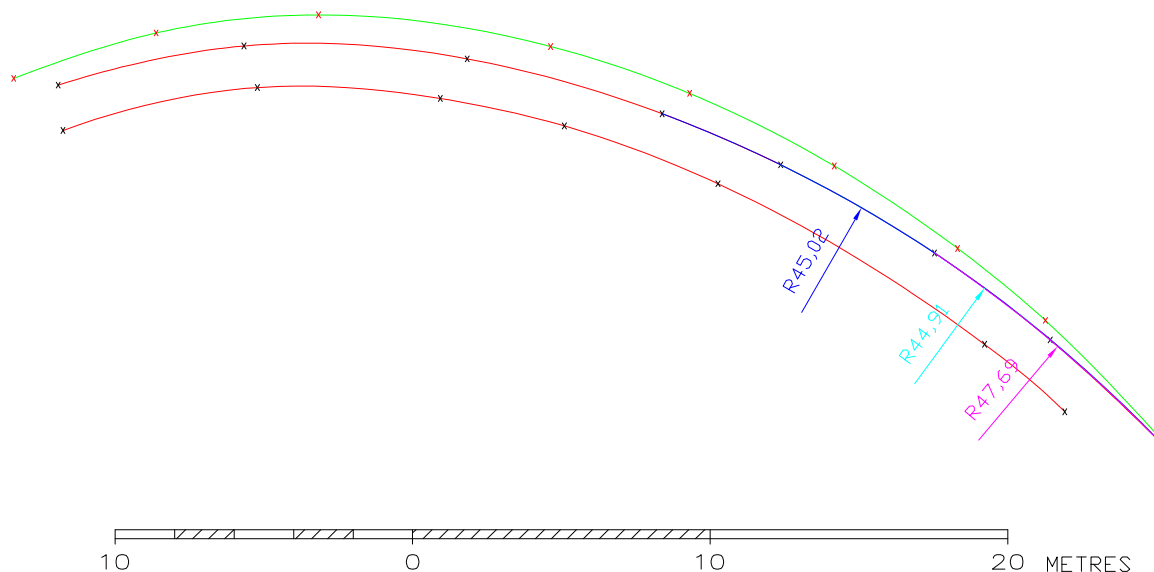


Figure 17. Asymmetric sine steer with steering held, run 3, ESC off

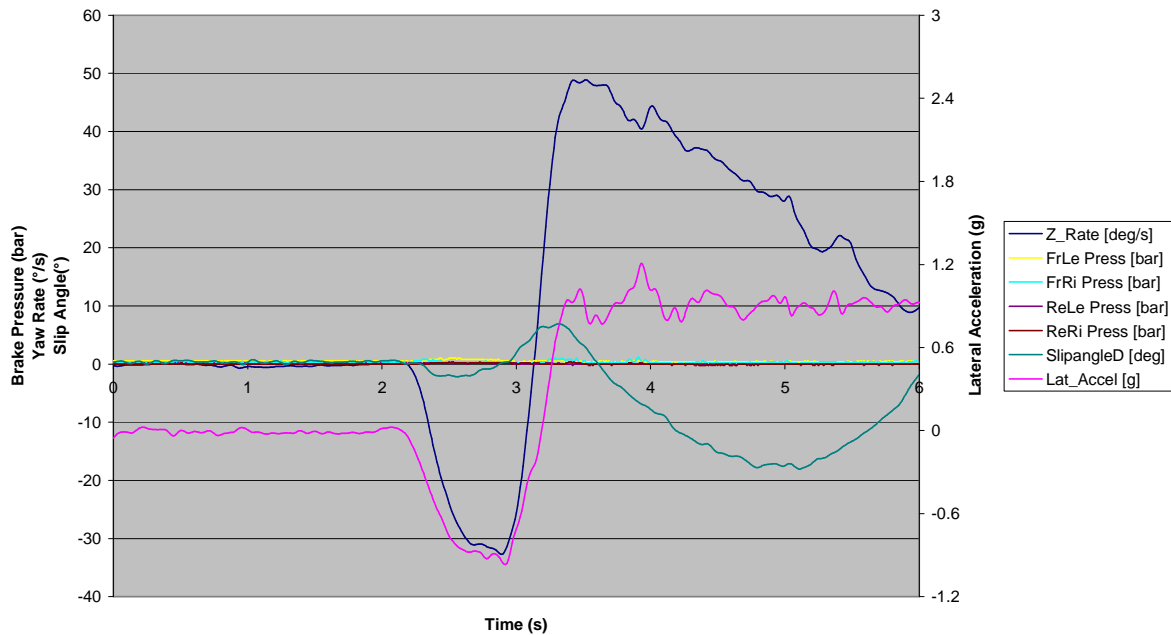


Figure 18. Data from asymmetric sine steer with steering held, run 3, ESC off

4.2.4 Run 4, ESC on

The ESC was turned back on for the last of this set of runs. The steering was turned through about 180°, and Figures 19 and 20 show the plots of the tyre marks and the data. The start of the tyre marks occurred at 3.4 seconds, and our recording of them ended at 5.7 seconds; over their length the speed fell from 47 mile/h to 35 mile/h.

As in the first run, it can be seen in Figure 20 that the two right brakes were applied and then released by the ESC system, after which, starting at about 4.0 seconds there was some lesser activity from the left brakes.

Also as in the first run, some striations were noted throughout the tyre marks, varying between 65° and 70° throughout. Here the separation of the front and rear right marks increased at first to about 33 cm, but then reduced and stabilised at about 13 cm.

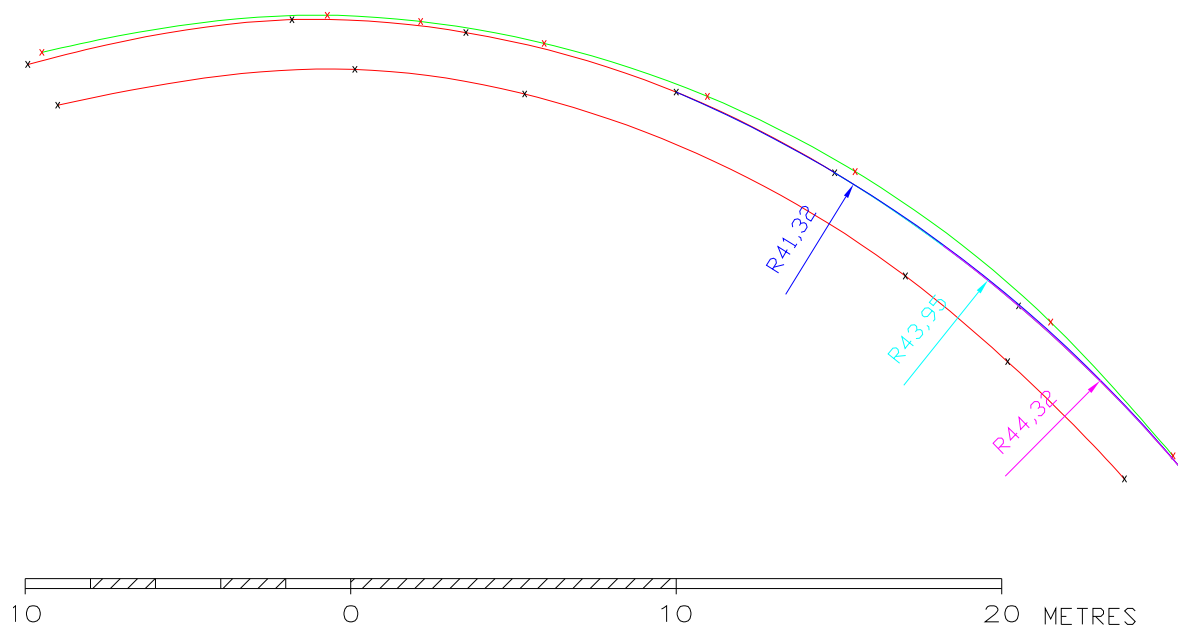


Figure 19. Asymmetric sine steer with steering held, run 4, ESC on

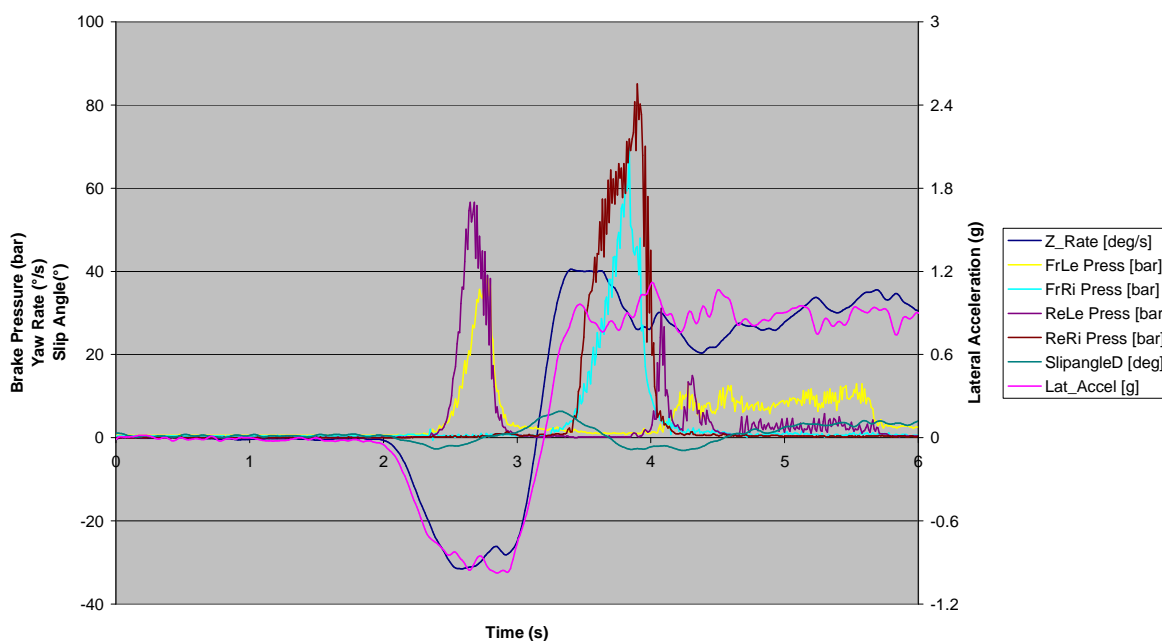


Figure 20. Data from asymmetric sine steer with steering held, run 4, ESC on

4.2.5 The appearance of the tyre marks

As with the first set of runs (where the steering was removed at the end of the second half sine), there was nothing striking in these tyre marks which would indicate that ESC was active. The only noticeable difference between the two conditions was, not unexpectedly, that without the ESC the car developed a considerable yaw, whereas with it active, the yaw was controlled and indeed reduced somewhat once the steering was held steady.

4.2.6 Speeds calculated from tyre marks

Table 2 below shows the calculation of speed from the first 10, 15 and 20 metres of the front right tyre marks.

Table 2. Speed calculations from tyre marks, asymmetric sine steer with steering held

run no. & ESC	approx. arc, metres	radius, metres	actual speed at start of arc, mile/h	actual speed at end of arc, mile/h	calculated speed, $\mu=0.77$	calculated speed, $\mu=1.02$
1: ON	10	38.9	45.7	42.2	38	44
	15	42.4	45.7	40.8	40	46
	20	40.2	45.7	39.6	39	45
2: OFF	10	55.5	48.5	46.4	46	53
	15	48.9	48.5	44.8	43	49
	20	46.6	48.5	43.4	42	48
3: OFF	10	47.7	49.7	46.2	42	49
	15	44.9	49.7	44.2	41	47
	20	45.0	49.7	42.5	41	47
4: ON	10	44.3	47.4	43.6	41	47
	15	44.0	47.4	40.5	41	47
	20	41.3	47.4	39.2	40	45

These calculations of speed show the same tendency as was noted in Table 1, that the results based on the sliding coefficient are consistently below the starting speed by a substantial amount, whereas the results found from using the peak friction are very much closer to the correct figure.

4.3 Step steer

Two step steer turns were performed, both with the ESC turned on. Sharper steering was employed in the second turn than in the first.

4.3.1 Run 1

For the first runs the steering was turned sharply through 170°. Figures 21 and 22 show the tyre marks and the data. Three tyre marks were found, from the front and rear right wheels and the front left wheel. In Figure 21 the radius of the front right mark is calculated for approximate arc lengths of 10, 15 and 20 metres.

In this run the start of the tyre marks occurred at 4.4 seconds, and our recording of them ended at 7.9 seconds, and over their length the speed fell from 44 to 37 mile/h.

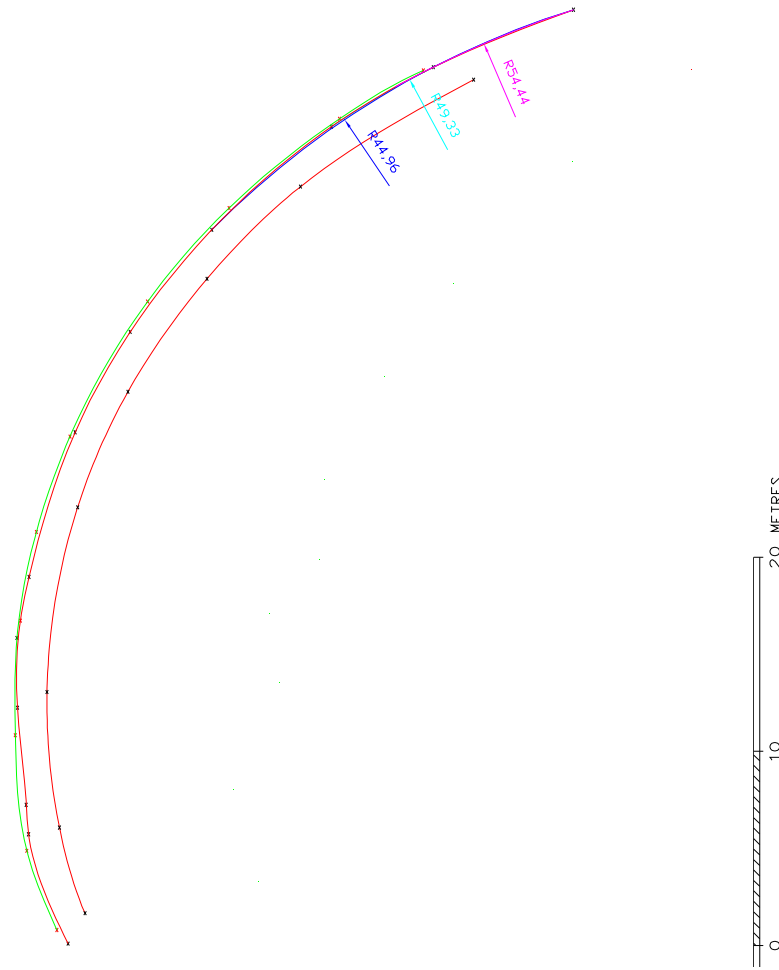


Figure 21. Step steer run 1, ESC on

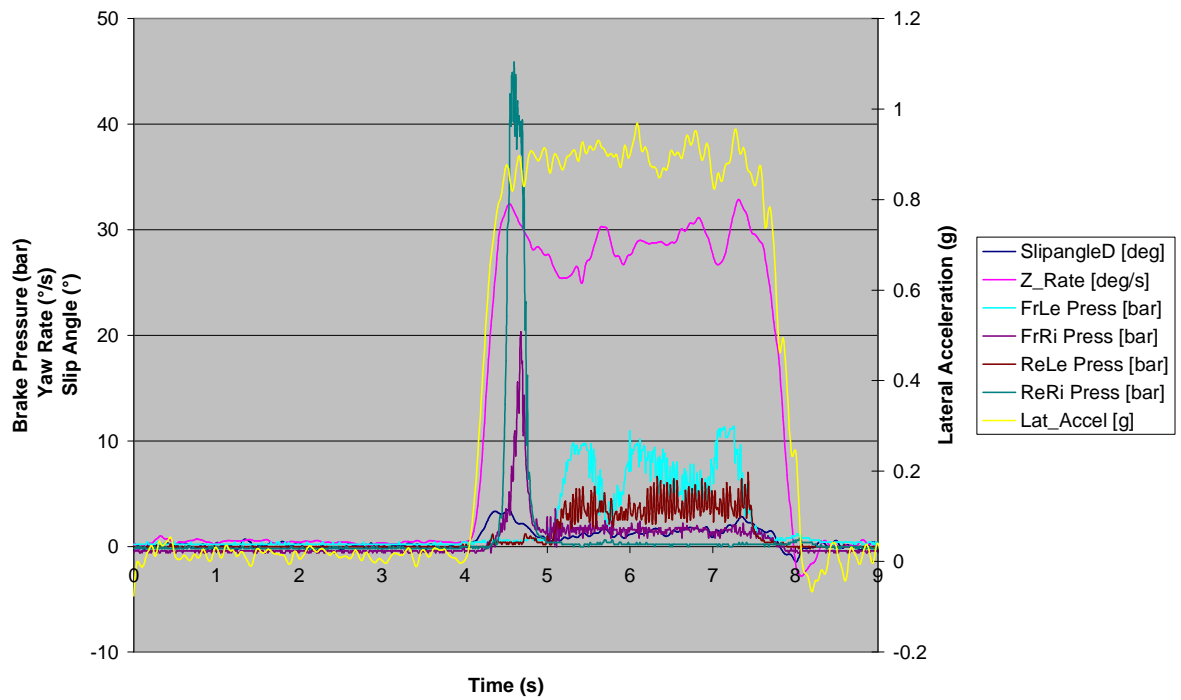


Figure 22. Data from step steer run 1, ESC on

In Figure 22 it can be seen that at first the rear right brake was applied with about half the pressure observed in the asymmetric sine runs (45 as against around 80 bar), while the front right brake was activated at only about 20 bar. But after a half second the right braking becomes very small, and it is the left brakes which are active, albeit at quite a low level.

Very little in the way of striations could be seen in the tyre marks, but some scuffing could be seen at an angle of about 70° . There was a steady separation of the front and rear marks of about 13 cm.

4.3.2 Run 2

For run 2 more steering – about 205° - was applied. The tyre marks started at 3.8 seconds, when the speed was 47 mile/h, and our recording of them ended at 7.7 seconds, when the speed was 36 mile/h. Figure 23 shows the plot of the tyre marks: in them the front left mark was very faint.

In Figure 24 shows the data. However, the measurement of the lateral acceleration malfunctioned during this run, and only the brake pressures and the slip angle have been plotted. It will be seen that with the higher speed and steering, more pressure was applied to the right brakes in the earlier part of this run.

As in the first run there was very little in the way of striations. The offset progressed to about 19 cm over the first 10 cm and then reduced to a steady amount of about 12 cm.

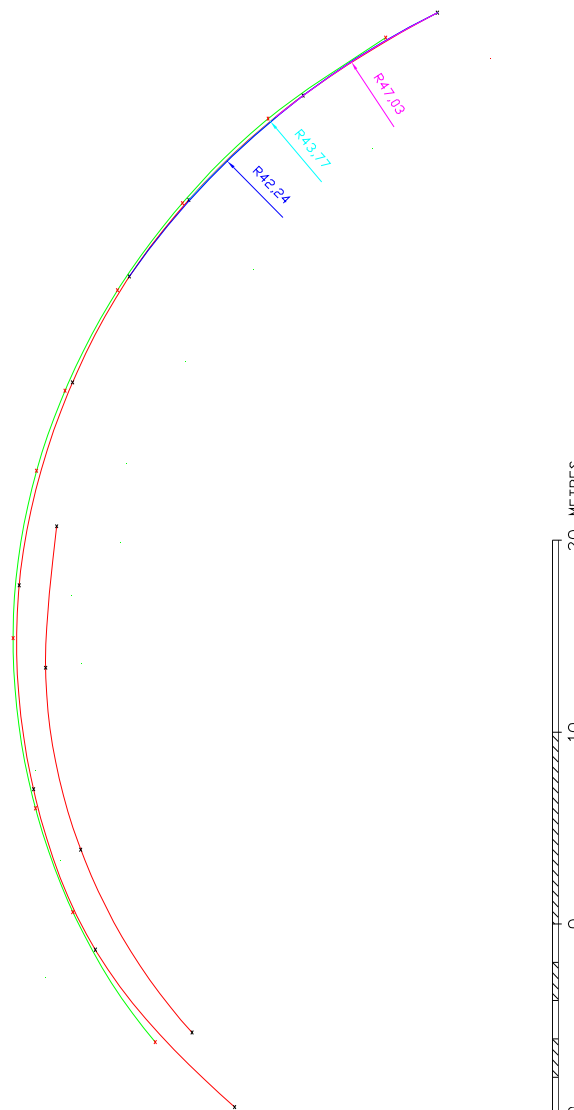


Figure 23. Step steer run 2, ESC on

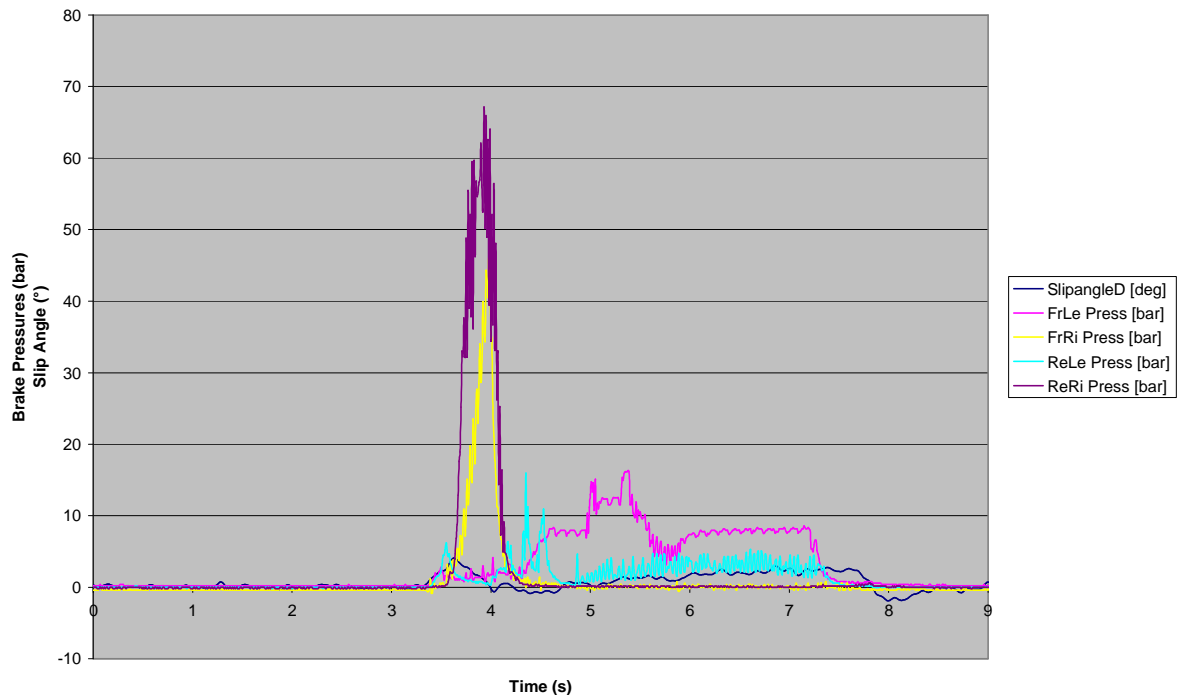


Figure 24. Data from step steer run 2, ESC on

4.3.3 *The appearance of the tyre marks*

In these two runs the appearance of the tyre marks was unremarkable. While the relatively small offset and, in the second run, the reduction in the offset, can be attributed to the action of the ESC, they might equally be due to the particular actions of the driver. The lack of clear striations has meant that little in the way of interpretation of them could be carried out: this is considered further in the Discussion section of this report.

4.3.4 *Speeds calculated from tyre marks*

Table 3 below shows the calculation of speed from the first 10, 15 and 20 metres of the front right tyre marks.

Table 3. Speed calculations from tyre marks, step steer

run no. & ESC	approx. arc, metres	radius, metres	actual speed at start of arc, mile/h	actual speed at end of arc, mile/h	calculated speed, $\mu=0.75$	calculated speed, $\mu=0.96$
1: ON	10	54.4	44.4	43.0	45	51
	15	49.3	44.4	42.5	46	48
	20	45.0	44.4	42.0	41	46
2: ON	10	47.0	46.9	43.4	42	47
	15	43.8	46.9	42.6	40	45
	20	42.2	46.9	41.6	39	45

Here again, the speeds calculated from the peak coefficient are rather better than those found with the sliding coefficient, apart from that found from the 10 metre arc in Run 1.

4.4 Step steer in turn with lift off

Four step steer turns with lift-off were performed. In the first and fourth the ESC was turned off; in the second and third it was turned on.

4.4.1 Run 1, ESC off

For the first run the ESC was turned off. Figures 25 and 26 show the tyre mark plots and the data.

The car approached the run area travelling on the 100 metre radius curve at 55 mile/h, at which time it was experiencing a lateral acceleration of 0.6g. Its steering at this stage was turned through 70°. The steering was then turned to about 160° at 2.7 seconds. Tyre marks were evident at 2.9 seconds, when the speed was 55 mile/h. Our recording of them ended at 5.6 seconds, when the speed was 41 mile/h.

Two tyre marks were found, from the front and rear right wheels, for most of the recorded distance. Faint striations were visible at angles between 70° and 80°. The separation between the tyre marks quickly increased to about 36 cm and remained close to that value.

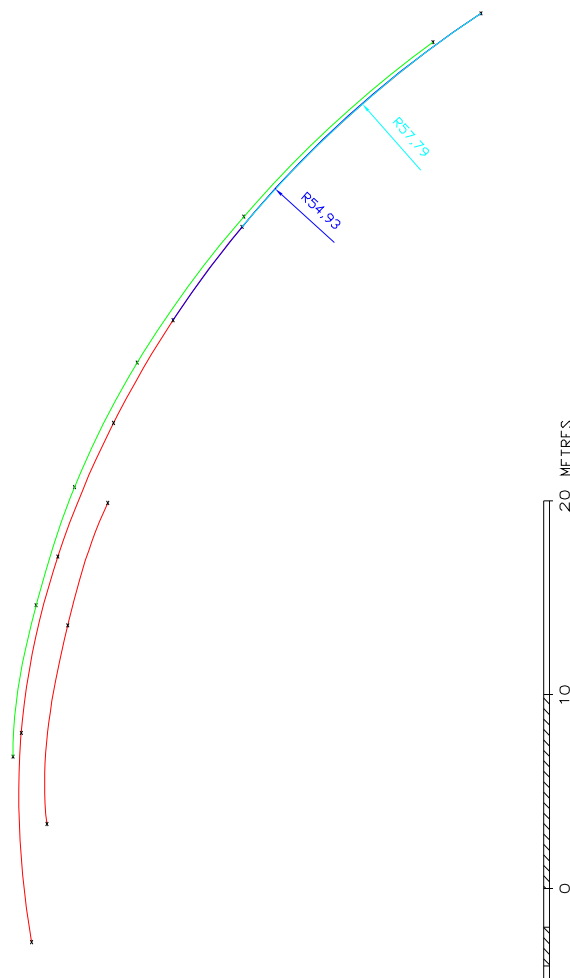


Figure 25. Step steer in turn with lift off, run 1, ESC off

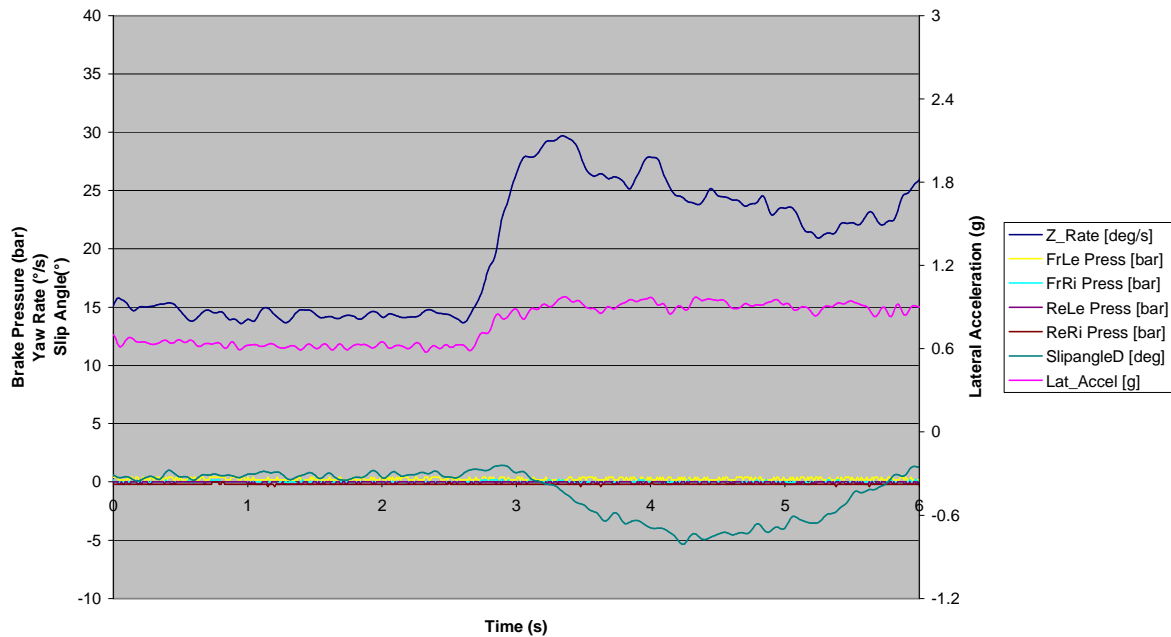


Figure 26. Data from step steer in turn with lift off, run 1, ESC off

4.4.2 Run 2, ESC on

Run 2, with the ESC on, followed the same approach conditions as run 1. Figures 27 and 28 show the tyre plots and run data.

The steering was increased from 70° to 155° at about 2.8 seconds, and the tyre marks began at 3.0 seconds, when the speed was 56 mile/h. Our recording of the tyre marks ended at 7.2 seconds, when the speed was 35 mile/h.

Although three tyre marks were eventually visible, the third – front left – mark only became visible some way into the turn. Any striations were very faint and at about 70° . The front and rear marks separated early on to about 35 cm and then came together with a separation of about 12 cm.

Interestingly, the right brakes were activated early in the turn, released, and then reactivated, with the rear brake being applied more strongly than the front.

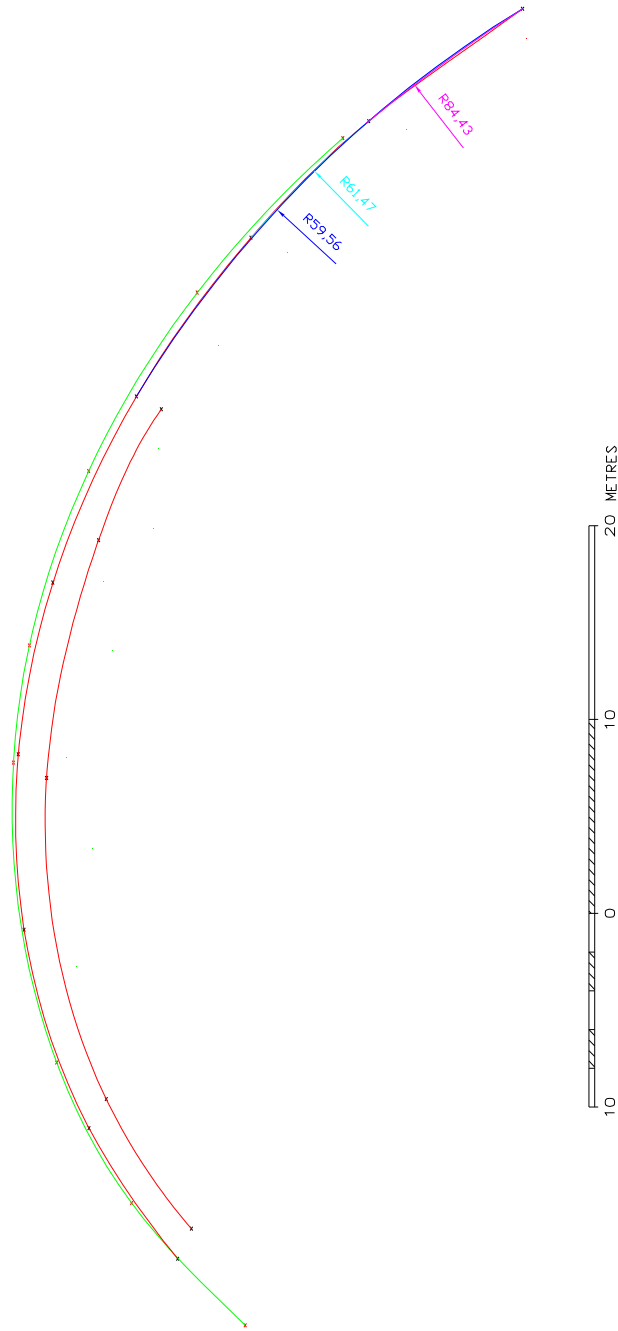


Figure 27. Step steer in turn with lift off, run 2, ESC on

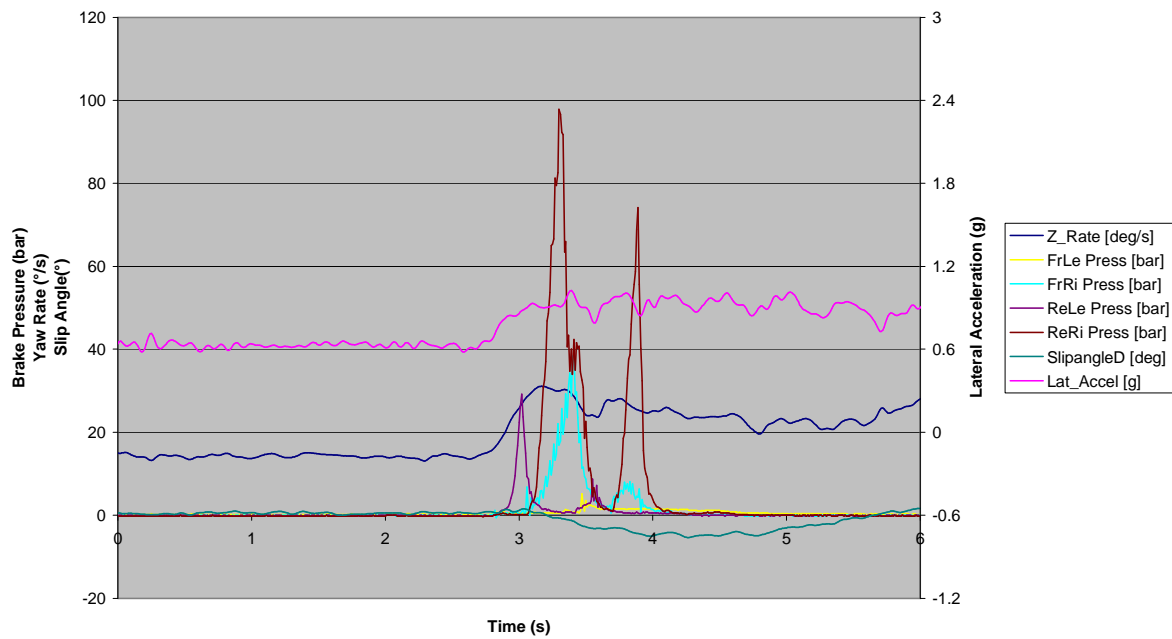


Figure 28. Data from step steer in turn with lift off, run 2, ESC on

4.4.3 Run 3, ESC on

Run 3 was essentially the same as run 2. Figures 29 and 30 show the tyre plots and the data. The steering was increased from 70° to 155° at about 2.8 seconds, and the tyre marks appeared at 3.3 seconds, when the speed was 55 mile/h. Our recording of the tyre marks ended at 7.3 seconds, when the speed was 37 mile/h.

Although the third (front left) tyre mark was visible throughout, the striations were again faint and at about 70° . As before, the separation of the marks increased to about 34 cm and then reduced to settle at about 13 cm. Likewise, two applications of the right brakes are apparent in the data.

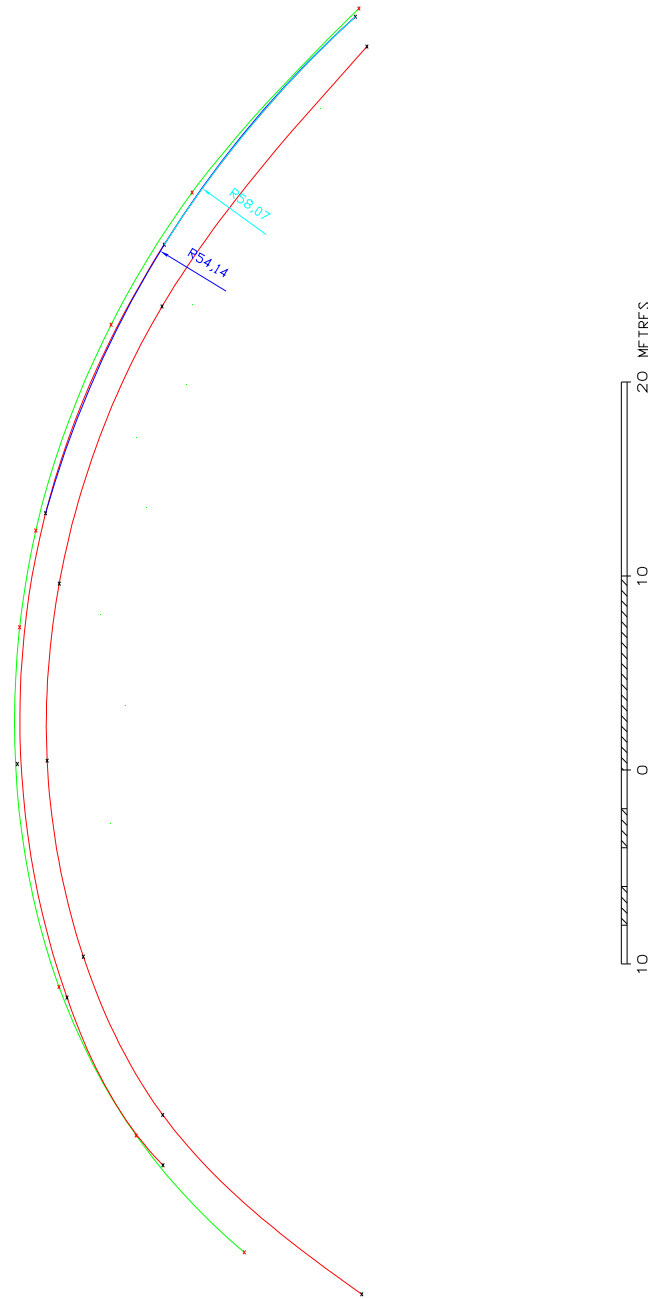


Figure 29. Step steer in turn with lift off, run 3, ESC on

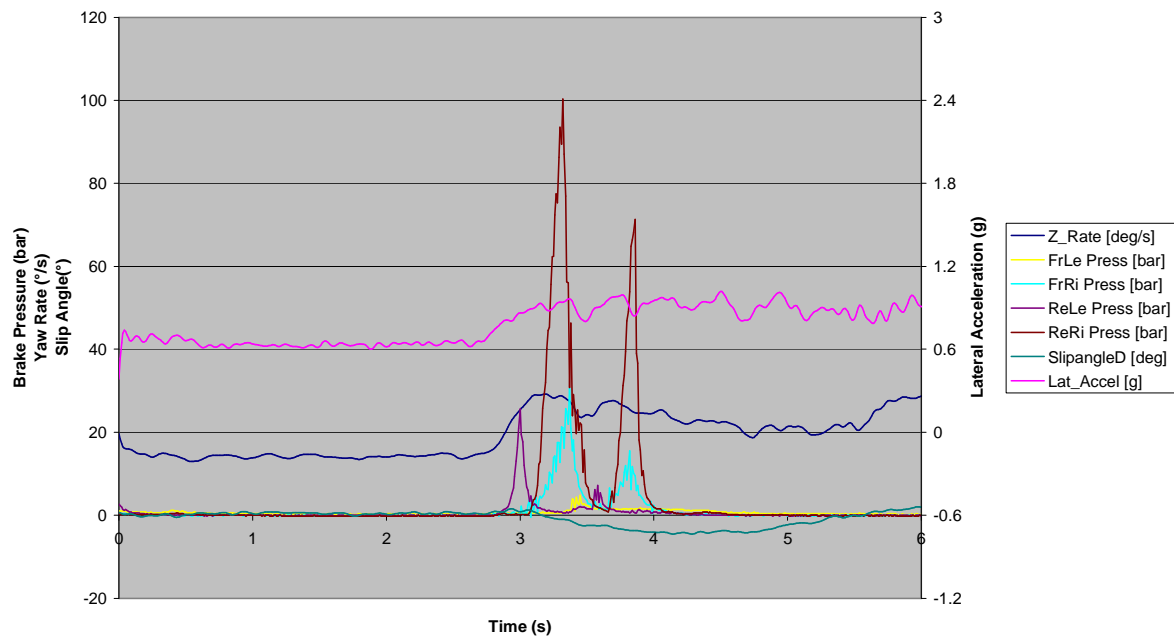


Figure 30. Data from step steer in turn with lift off, run 3, ESC on

4.4.4 Run 4, ESC off

For the fourth run, the ESC was turned off. Figures 31 and 32 show the tyre plots and the data. The steering was increased from 65° to 150° at about 3.6 seconds, and the tyre marks appeared at 3.9 seconds, when the speed was 55 mile/h.

Again, faint striations were visible, at angles between 60° and 70° , but even though the ESC was off, the separation of the tyre marks increased at first to 31 cm, but then reduced to around 13 cm.

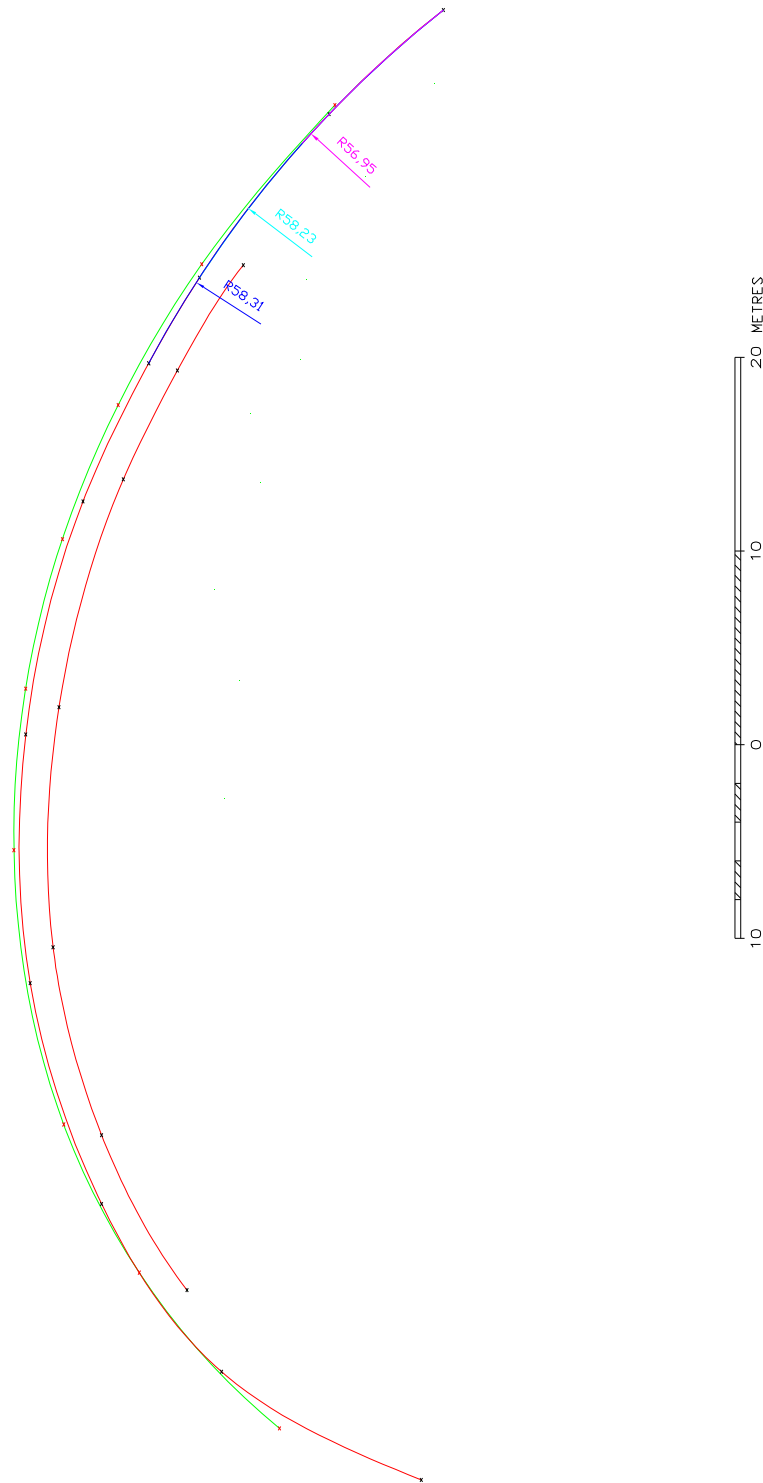


Figure 31. Step steer in turn with lift off, run 4, ESC off

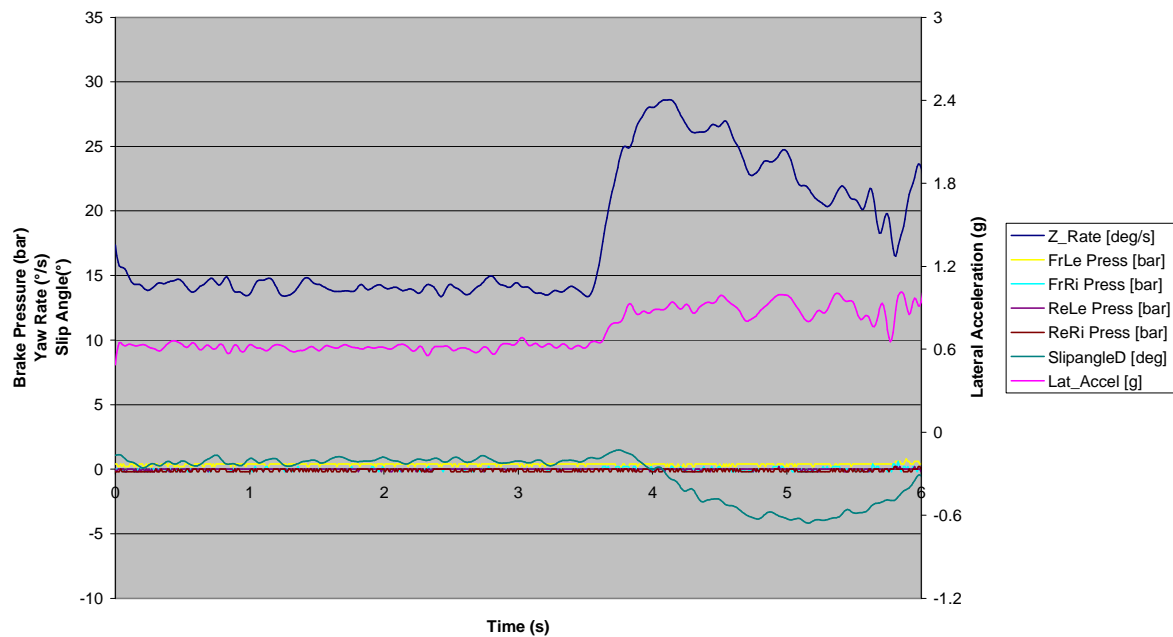


Figure 32. Data from step steer in turn with lift off, run 4, ESC off

4.4.5 Appearance of tyre marks

Again, in these runs the appearance of the tyre marks was unremarkable. While the reduction in the offset in the second and third runs may be attributed to the action of the ESC, a similar reduction was observed in the last run, so that in any given instance this could equally be due to the particular actions of the driver. As before, the lack of clear striations has meant that little in the way of interpretation of them could be carried out.

4.4.6 Speeds calculated from tyre marks

Table 4 below shows the calculation of speed from the first 10, 15 and 20 metres of the front right tyre marks. (A 10 metre arc could not reliably be taken from the scan data from runs 1 and 3.)

Table 4. Speed calculations from tyre marks, step steer in turn with lift off

run no. & ESC	approx. arc, metres	radius, metres	actual speed at start of arc, mile/h	actual speed at end of arc, mile/h	calculated speed, $\mu=0.75$	calculated speed, $\mu=0.96$
1: OFF	15	57.8	55.1	52.5	46	52
	20	54.9	55.1	51.8	45	51
2: ON	10	84.4	56.2	53.7	56	63
	15	61.5	56.2	52.4	48	54
	20	59.6	56.2	50.6	47	53
3: ON	15	58.1	55.5	51.0	46	52
	20	54.1	55.5	49.7	45	51
4: OFF	10	57.0	54.9	53.0	46	52
	15	58.2	54.9	51.8	46	52
	20	58.3	54.9	50.6	46	52

Once again, the speeds calculated from the peak coefficient are rather better than those found with the sliding coefficient, apart from that found from the 10 metre arc in Run 2.

5 Discussion

The first object of this programme of experiments was to find whether there would be any features in a set of curved tyre marks which would enable an investigator to determine whether an ESC system had been activated. The conclusion we have come to, for the particular vehicle we have used on the particular surfaces, is that there are not. However, to a significant extent our investigations were hampered by the lack of clarity of the tyre marks on the TRL research track. It is our experience from real accident investigations that public roads, particularly when the surface has been recently laid, often show tyre marks and features such as striations within them very much more clearly. On the most readily marked surfaces it can also occur that thin “sub-critical” marks are seen before the fully developed striated “critical” speed marks. It might therefore be the case that with a more clearly-marking surface it would have been possible to see greater detail in the overall pattern of the marks and also the striations, and in particular to detect any variation in them which could be correlated with the activation of the brakes by the ESC system. As it was, no correlation could be detected.

There were features in the pattern of the marks, such as a reduced yaw or striations at a lesser angle, which we could ascribe to the operation of ESC simply because it was known that the system had activated. But in the absence of such knowledge it would not have been possible to say whether it was the ESC or the direct actions of the driver which had caused them.

Another important matter to be borne in mind is the actual programming of the ESC system fitted to the experimental vehicle. An ESC system can be tuned to the car, and whilst the detailed settings in our vehicle will be a matter of commercial confidentiality, we believe that the threshold for ESC intervention will be a little lower on a family car such as a Volkswagen Passat than on a car which is marketed on its “sporty” image. Investigations with a car with a higher threshold, i.e. where the ESC will only intervene once a larger yaw angle has developed, may reveal clearer evidence of ESC activity in the tyre marks. Furthermore it is understood that in some cars, switching off the ESC does not truly switch it off, but instead raises the threshold for intervention. It may therefore be fruitful to investigate whether there is any variation in the marks between the high and low thresholds in circumstances where all other parameters (car, road surface, experimental method) are unchanged. We are aware that in one model of “sporty” car, the driver can choose between the “normal” threshold, a “sporty” threshold, or switch it off entirely.

The second object of this investigation was to find whether the established method of calculating speed from the curvature of the tyre marks would remain valid when an ESC system was active. The results showed that in the measuring procedure we used, a short arc of about 10 metres was insufficient to produce a reliable result. For longer arcs, of 15 or 20 metres, the speeds calculated with the sliding coefficient of friction tended to underestimate the speed by an amount which often exceeded 10%, whereas when the peak coefficient was used the errors were much smaller.

In the established technique the procedure is to use the sliding coefficient and quote the result to be an indication of the speed at the start of the clear tyre marks, $\pm 10\%$ (Lambourn, 1989). However, the instrumentation used in that investigation was, by present standards, quite crude, and more recent work (for example Cliff et al., 2004) has been coming to the conclusion that, overall, the sliding coefficient tends to underestimate speed by a rather greater amount, whereas the peak coefficient tends to overestimate it, but by a much smaller amount. However it was noted during our experiments that it was difficult to generate visible marks, and those that were generated were fainter on the surface used than on some runway surfaces used in the past. In particular, tests previously reported (Lambourn 1989) included tyre prints which were generated at lateral acceleration levels corresponding to less than the slide friction value, and striated tyre marks commencing when the vehicle was cornering at a level corresponding to the slide friction value. It appears that the surfaces used at TRL will only generate visible marks when the vehicle is cornered at a level virtually at the peak friction. Further experiments must be conducted on a variety of surfaces before generalising the conclusions drawn from this project to tyre marks found on other road surfaces.

An interesting observation which can be made from the data we have gathered is the rate of loss of speed along the length of the marks. It is often asserted in accident investigations that when a car is undergoing hard cornering it will lose speed, although the actual rate is a matter of estimation. In our

present experimentation it emerges that where the steering has been quite hard, a surprisingly high speed loss of about 0.3g was experienced, with or without the action of ESC. Where only moderate steering was used, notably in the runs at 4.2.2 and 4.3.1 above, the deceleration was around 0.1g.

6 Conclusions and recommendations

1. With the particular car used in this experimentation, on the two particular surfaces, nothing could be found in the tyre marks which would enable an investigator to determine whether or not an ESC system had been activated.
2. Further investigations with a vehicle with a more “sporty” ESC system, which activates at a greater level of yaw, and therefore further into a potential loss of control situation, would be of benefit, particularly as incidents involving such vehicles tend to be more contentious for the accident investigator.
3. The activation of an ESC system, at least in the vehicle tested, does not have an effect on the validity of the calculation of speed from the curvature of the tyre marks. However, our experimentation has tended to support the belief among some investigators that the use of the sliding coefficient of friction may lead to too low a speed being calculated, and that it would be more appropriate to use the peak coefficient of friction. Since this calculation is widely carried out for the benefit of the courts, a deeper investigation of this question would be of considerable value. Any such investigation would be better carried out on a surface which shows tyre marks readily, rather than on those parts of the TRL track which we have used here.
4. The rate of loss of speed of the car along its tyre marks, of up to around 0.3g, has proved somewhat higher than expected, and is a useful finding for the accident investigator. Here too more thorough research on this point would be of benefit.

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