Differential Friction and Primary NCAP

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ABSTRACT

This paper will briefly introduce the concept of differential friction, as it occurs in practice on road networks, before looking at the development of test procedures in the UK for the assessment of the primary safety performance of new vehicles. Draft protocols for a range of tests involving braking manoeuvres have been developed to evaluate the likely in-service performance and benefits of new car stability and control systems. In particular, this paper will examine the results from a number of straight line braking tests. The tests involve a series of rapid braking manoeuvres on a road surface with a high level of differential friction, i.e. one wheel path on a surface with a low level of friction and the other wheel path on a surface with a high level of friction. The response of each test vehicle has been assessed in terms of stopping distance and yaw stability during deceleration. It is considered that, if such tests were adopted as part of a routine testing regime, then the trends that emerge are likely to become of great interest to those professions with an interest in the concepts of differential friction, such as crash reconstructionists, road network asset managers and researchers.

1. INTRODUCTION

The initial idea for the production of this paper arose from the work of TRL as lead consultants on the Austroads technical document, AP-G83/05 – Guidelines for the Management of Road Surface Skid Resistance, which was published in January 2005. The document aims to provide useful guidelines to assist road authorities in developing local strategies for managing road network skid resistance in their area or region[1]. The document is not intended to be a comprehensive textbook on skid resistance. However, it does collate and provide useful background information on various key underlying concepts and issues.

One of the issues where considerable debate was found to remain is with "differential friction", which is taken to mean any situation where the level of friction available to a vehicle is greater in one wheel path than the other. Such a scenario frequently occurs in practice due to a number of complex and often interrelating factors; such that it is rare for the level of friction available to a motorist to be the same in both left and right wheel paths.

Logic suggests that differential friction must have the potential to adversely affect vehicle handling and stability in some way. However, it is difficult to quantify these effects in "real world" terms given the inherent variability of differential friction on road networks and that loss of control events leading to collisions / injury are relatively rare when considered against the number of kilometres travelled by road users. This then prompts practitioners to consider investigation of differential friction levels at which risk becomes greatest for a given manoeuvre (such as cornering or braking). Investigating differential friction is further complicated by the fact that loss of control incidents which do not result in a collision are rarely reported and that modern vehicles are becoming more forgiving of road conditions through the introduction of systems such as Anti-lock Braking Systems (ABS).

Research into differential friction has typically focused on braking and / or cornering manoeuvres. However, the available research is not conclusive in determining whether: (1) differential friction has greatest potential adverse affects in straight line braking scenarios or cornering scenarios; (2) how different vehicles and vehicle stability systems respond to differential friction; and perhaps more practically, (3) what level of differential has to be reached before remedial action to the road surface needs to be considered.

This paper adds to the debate by introducing some of the latest information on differential friction emerging from the development of testing protocols in the UK that have been proposed as candidates for the European New Car Assessment Programme (EuroNCAP) board to consider. The draft protocols include straight line braking tests on a laterally split coefficient of friction surface, i.e. one uniform high friction surface and one uniform low friction surface. The emerging trends are considered to be of interest to practitioners with an interest in differential friction, its effects and the way in which the systems on modern vehicles cope with such a scenario.

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[1] Note: the document relates only to sealed (i.e. bituminous and concrete) road surfaces

2. MEASURING ROAD SURFACE FRICTION

There are a range of factors which can lead to a differential friction situation developing on a road surface. Chapters 2, 4 and 6 of Austroads Guidelines AP-G83/05 provide discussion on these factors.

Road asset management professionals are encouraged to routinely measure road surface friction to monitor the condition of the pavements across their network and use the data obtained to help prioritise and initiate remedial measures. However, where this is done, measurements are often only taken in the nearside (left) wheel path of Lane 1. Measuring in such a way means that the engineer does not routinely obtain a measure of the level of differential friction between left and right wheel paths at a location.

This methodology has emerged due to the left wheel path of Lane 1 being found to provide the lowest levels of in-service skid resistance due to factors such as the typical crossfall of roads and the propensity for heavy, slow moving vehicles to travel in Lane 1. This worst case scenario enables the engineer to compare 'defective' (below Investigatory Level) sites across the road network and to prioritise them for remedial action. Accordingly, the vast majority of test devices used to measure skid resistance are equipped to provide measurement from a single wheelpath.

It is only on the rare occasion, when a conscious decision has been made to equip a test device with both left and right test pods, that a level of differential friction can be calculated from two concurrently obtained test values. The authors are aware of a limited number of Sideways-force Coefficient Routine Investigation Machines (SCRIMs) fitted with two (left and right) test pods.

Where test devices with two test pods are used, there also remains an inconsistent approach to the calculation and usage of the differential friction values obtained. One known approach has been to set investigatory levels for differential friction (typically based on the speed limit for a road) which are used to identify sites requiring further detailed investigation. A second known approach is to only use the measured differential skid resistance value as a secondary screening tool, becoming one of a number of parameters to be assessed during a site investigation. In this case, the site investigation itself is usually triggered by the investigatory levels associated with the left wheel path result. The authors are also aware of a third approach, whereby the results obtained from the left and right wheel paths are averaged to give a single value which can then be assessed against a pre-set investigatory level. With this third approach, the differential friction is calculated, but only used as a secondary screening tool during the site investigation process.

3. PRIMARY NCAP

The UK Department for Transport (DfT) commissioned TRL to lead a consortium of companies in the development of test procedures aimed at assessing the primary safety features of passenger cars. These protocols could potentially be used to develop a routine assessment programme with the results from new vehicle primary safety assessments being made available to consumers, in a similar manner to the star rating system already being used for crash tests carried out as part of the European New Car Assessment Programme (EuroNCAP). The Australian and New Zealand version of this programme is known as ANCAP (Australian New Car Assessment Program).

In short, the UK Primary NCAP research project aims to follow the success of the EuroNCAP programme which has been highly successful in encouraging manufacturers to improve vehicle crashworthiness. The focus of existing new car assessment programmes is to improve the impact protection of vehicles. While this approach tends to reduce the incidence and severity of injuries, it has no real effect on reducing the actual frequency of crashes. Primary NCAP is based on the premise that a reduction in the number of crashes can reasonably be expected through improvements in those features of vehicle design that relate to primary safety.

Proposed test methods have been evaluated for a range of primary vehicle safety categories including:

- Braking;
- Handling;
- Visibility;
- Lighting; and
- Ergonomics.

The UK Primary NCAP project began in August 2000. Since that date, TRL has developed draft protocols for straight line braking, braking in a turn, ergonomics and field of view. These proposals have been submitted to the UK DfT and to EuroNCAP for their consideration. However, neither organisation has yet made any commitment to including the proposals as part of a routine testing regime.

3.1 BRAKING TEST PROTOCOLS

TRL has assessed a range of test methods for determining vehicle response during straight line braking manoeuvres. These tests were carried out using nine different cars and a range of different test surfaces.

The braking test methods evaluated by TRL have been refined to form a series of draft test protocols. Some of the test methods, and associated test results, discussed in this paper form part of the initial evaluation process and have not necessarily been adopted as protocol.

3.1.1 Test Surfaces

Braking tests were conducted on uniform high, medium and low friction surfaces and a combined surface which provided a level of differential friction. For tests on the uniform medium-coefficient surface, the uniform low-coefficient surface and the differential friction surface the test track was wetted using a spray bar system with the water depth maintained at 1.5mm ±1mm.

The differential friction surface comprised basalt tiles as the low friction surface, with an average coefficient of friction of 0.25g, and an adjacent concrete surface which had an average coefficient of friction of 0.75g. Braking tests were conducted such that the left side of the test vehicle travelled on the low friction surface and the right side travelled on the high friction surface.

3.1.2 General Test Method

For each straight line braking test the vehicle was driven towards the test surface in a straight line and at constant velocity. The positions of the steering wheel and accelerator were consciously held (as far as possible) in the initial state prior to commencement of the braking manoeuvre.

Both open-loop and closed-loop braking manoeuvres were considered. For the open-loop manoeuvres the steering wheel was held fixed after the braking manoeuvre commenced. Whereas, the closed-loop manoeuvres allowed the driver to adjust his inputs, which is more representative of a real world situation in which a driver is likely to react to the situation.

The open-loop tests on the differential friction surface were carried out at speeds ranging from 10mile/h (16 kph) to 50mile/h (80 kph). The closed-loop tests were carried out at speeds ranging from 10mile/h (16 kph) to 70mile/h (112 kph).

The points in time used to analyse each test are illustrated in **Figure 1** and include:

- ***Start of observation*** t_0***-2*** - the time interval over which measurements are made commences at least two seconds before the accelerator is released;
- ***Time of accelerator release*** t_0 - the moment when the accelerator pedal is released;
- ***Time of brake pedal actuation*** t_1 - the time at which the centre of the brake pedal has been depressed 6mm from its initial position;
- ***Reference point in time*** t_2 - the time at which the brake pedal force reaches 500N. This point is used to calculate the rise rate of the brake pedal;
- ***Reference point in time*** t_3 - the time when the brake pedal force reaches an initial peak value above the minimum value of 500N;
- ***Reference point in time*** t_n - a point in time 2 seconds after t_3, unless the vehicle has already become stationary, in which case the time shall be when the vehicle speed has fallen to 5mile/h ;
- ***Reference point in time*** t_f - the time at which vehicle becomes stationary.

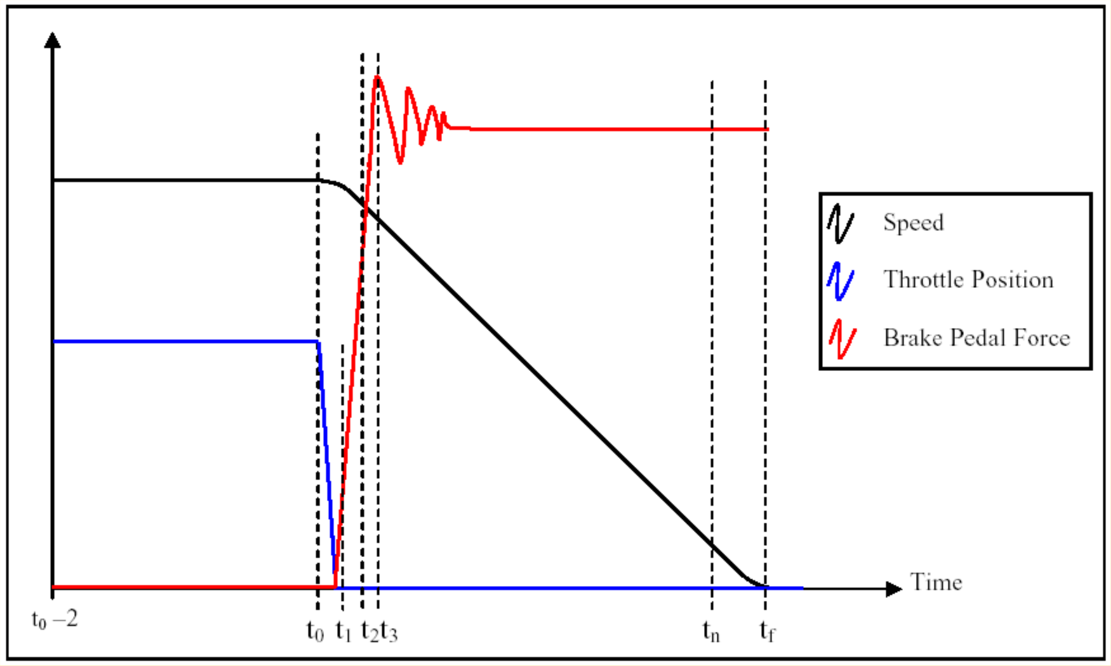

Figure 1 – Description of Test Period

To ensure the deceleration rate obtained during each braking test was representative of a rapid braking manoeuvre the following conditions needed to be met:

- the reaction time (t_0 - t_1) must not exceed 0.5 second;
- the delay time (t_0 - t_3) must not exceed 1.0 second;
- the brake pedal rise rate (t_1 - t_2) must be such that a brake pedal force of 500N is achieved in not more than 0.2 second;
- the mean brake pedal force between t_3 and t_n must be greater than 500N.

Braking tests were also carried out at positions on the test track where the vehicle passed longitudinally from one uniform friction surface to another uniform friction surface in a straight line under braking, i.e. friction jump tests.

While test methods for braking in a turn have been developed, physical testing to date has only been carried out on uniform surfaces, i.e. no testing has been carried out for braking in a turn manoeuvres on a differential friction surface.

3.2 PRIMARY NCAP RESULTS

All the vehicle stopping distances have been corrected for variation in entry speed. This was achieved by calculating an average deceleration for each test based upon the recorded entry speed and stopping distance. This value of average deceleration was then used to calculate a "corrected stopping distance" from the precise nominal speed.

3.2.1 Differential Friction (Open-Loop)

For the open-loop manoeuvres the steering wheel was held fixed after the braking manoeuvre commenced. All vehicles except vehicle 3 were equipped with an Anti-lock Braking System (ABS).

Figure 2 shows a comparison of the mean corrected stopping distance at each test speed for the open-loop tests on the differential friction surface.

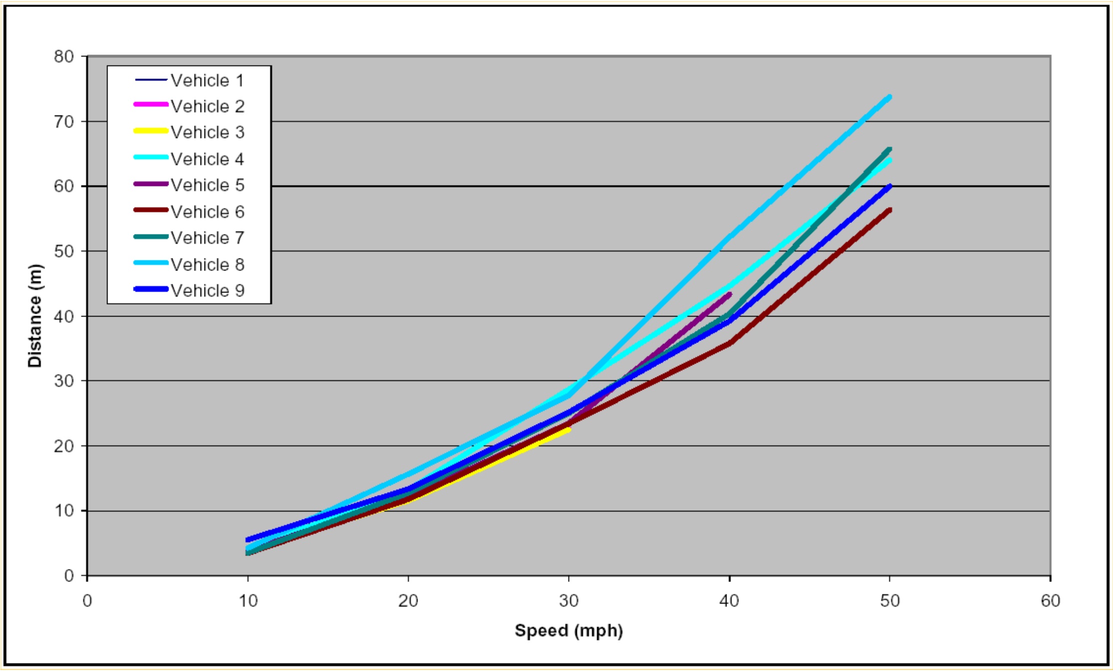

Figure 2 – Comparison of mean corrected stopping distance (open-loop tests on differential friction surface)

Vehicle 5 could only be tested up to 40mile/h (64 kph) because it repeatedly spun at this speed. At a test speed of 30mile/h (48 kph) the vehicles with ABS followed a similar path under braking, as shown by the overhead views in **Figure 3**. At higher test speeds the ABS equipped vehicles exhibited greater variation in response under braking. Vehicle 3 deviated much further than the other vehicles because it consistently spun approximately 90 degrees at 30mile/h (48 kph).

Figure 3 shows how, with the nearside (left) of the vehicle travelling on the low friction surface, this type of braking manoeuvre causes the vehicle to deviate towards the right. In a “real world” situation the vehicle would be travelling towards the opposing traffic lane with significant potential for a head on collision.

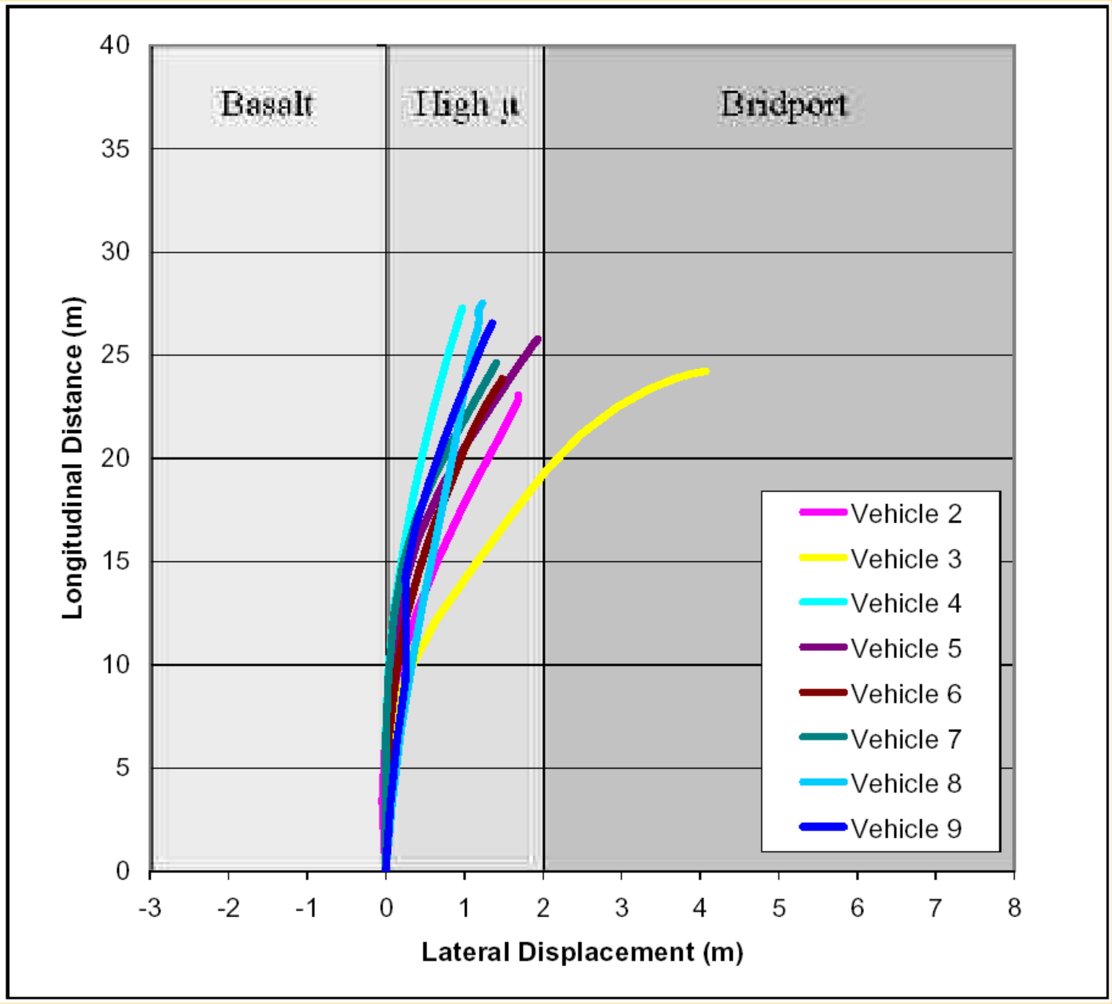

Figure 3 – Overhead plots of test vehicle paths at 30mile/h (open-loop tests on differential friction surface)

Figure 4 shows an example time history of yaw rate for each vehicle at a test speed of 30 mile/h (48 kph).

It can be seen from **Figures 3 and 4** that the vehicles with the smallest lateral deviation also had the lowest levels of yaw rate. The time history for vehicle 3 shows that it rotated around the Z-axis for just over two seconds at which point the vehicle had turned enough for both rear wheels to be on the low friction surface. This caused a sudden increase in the yaw rate.

Vehicles 4, 5 and 7 are fitted with an Electronic Stability Programme (ESP) which automatically adjusts the brake force at each wheel, introducing yaw moments to counter the instability being experienced by the vehicle. Vehicle 4 appears to be very stable with low levels of yaw rate and minimal lateral deviation. Vehicles 5 and 7 show similar values of yaw rate and lateral deviation to the non-ESP vehicles.

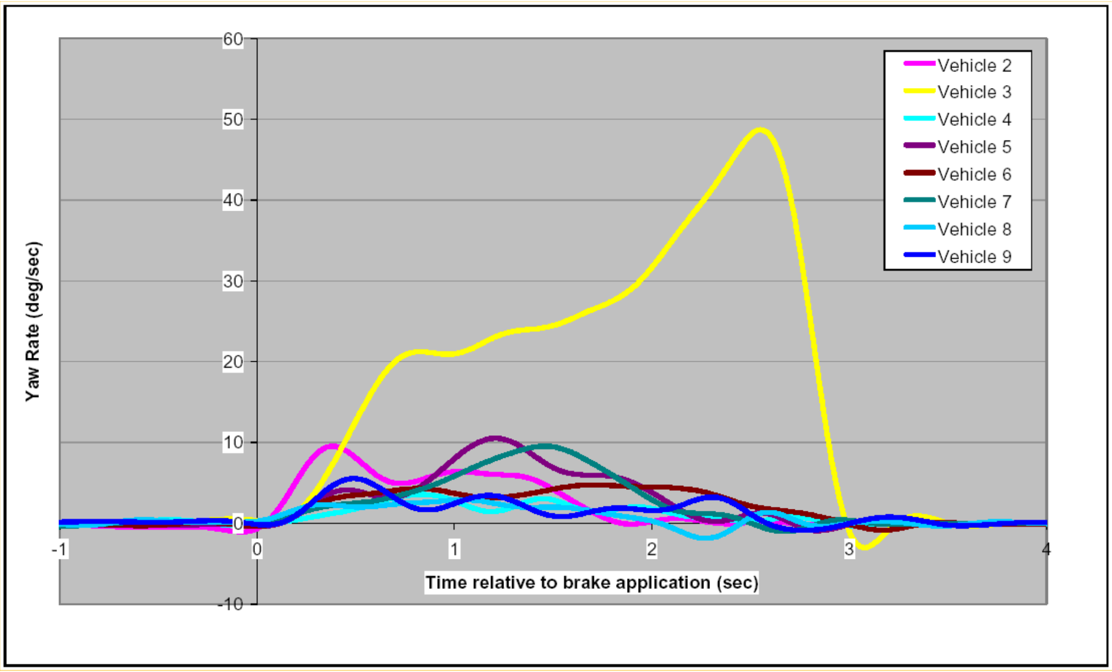

Figure 4 – Time histories of yaw rate at 30mile/h (open-loop tests on differential friction surface)

A statistical analysis of the lateral deviation and yaw rates showed that there were significant statistical differences between the vehicles. The statistical analysis was carried out using a Tukey's honestly significant difference test with a confidence level of 95%. As shown in Figures 3 and 4, vehicle 3 (the non-ABS vehicle), displayed very large differences in behaviour to the ABS-equipped vehicles.

3.2.2 Differential Friction (Closed-Loop)

For the closed-loop manoeuvres the driver was allowed to adjust his inputs.

Figure 5 shows a comparison of the mean corrected stopping distance at each test speed for the closed-loop tests on the differential friction surface.

Based upon the mean corrected stopping distance the comparative performance of each vehicle is similar to that observed during the equivalent open-loop tests. However, the stopping distances recorded are longer than for the open-loop tests because the driver's steering input helps to keep the vehicle in a straight line and therefore maintains the differential friction condition throughout the test.

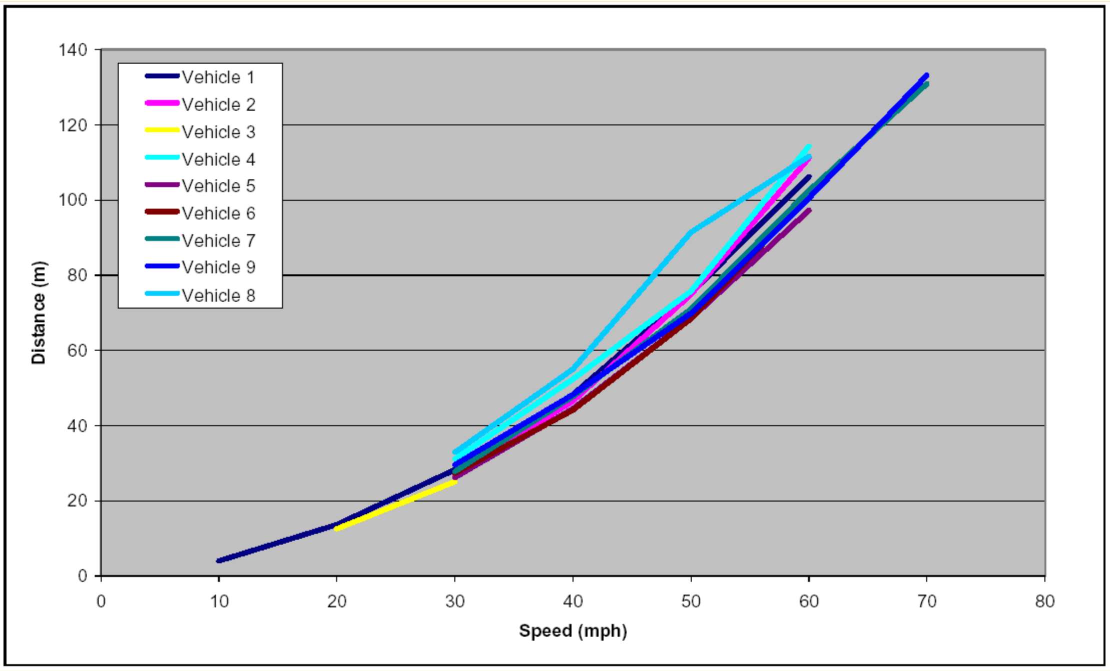

Figure 6 – Comparison of mean corrected stopping distance (closed-loop tests on differential friction surface)

Figure 7 shows the amount of corrective steering used by the test driver in each during a series of tests carried out at 30mile/h (48 kph).

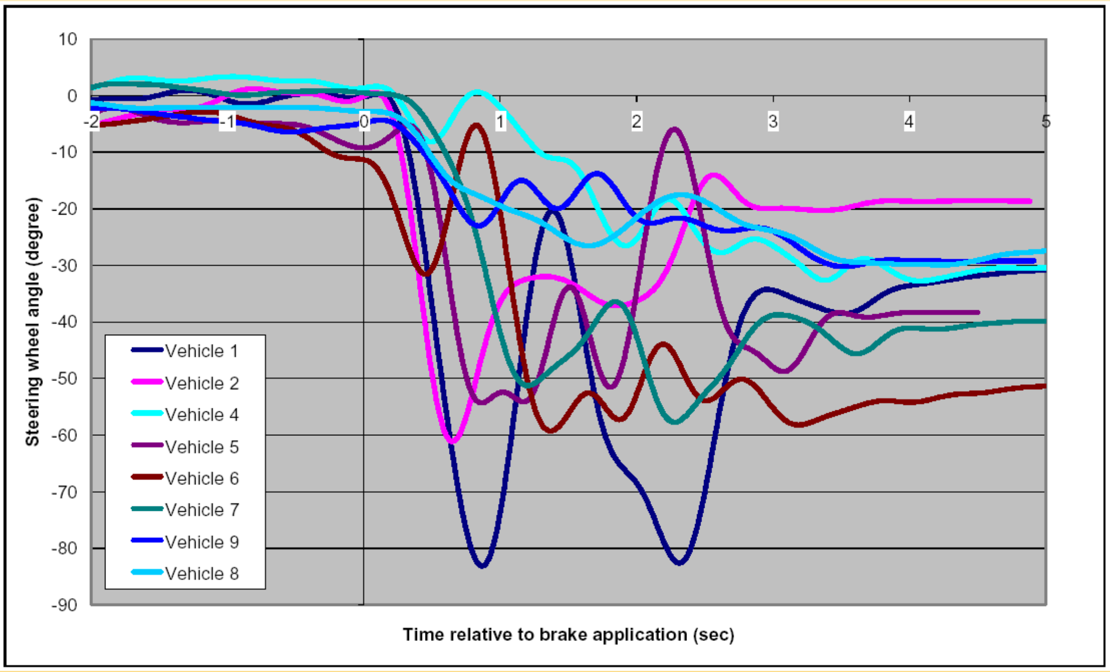

Figure 7 – Steering wheel angle during tests at 30mile/h (closed-loop tests on differential friction surface)

Figure 8 shows that the lateral deviation of the test vehicles at 30mile/h (48 kph) is small enough to keep the left hand wheel path on the low friction surface for the duration of the stop thus reducing the friction available and increasing the stopping distance when compared to the open-loop tests.

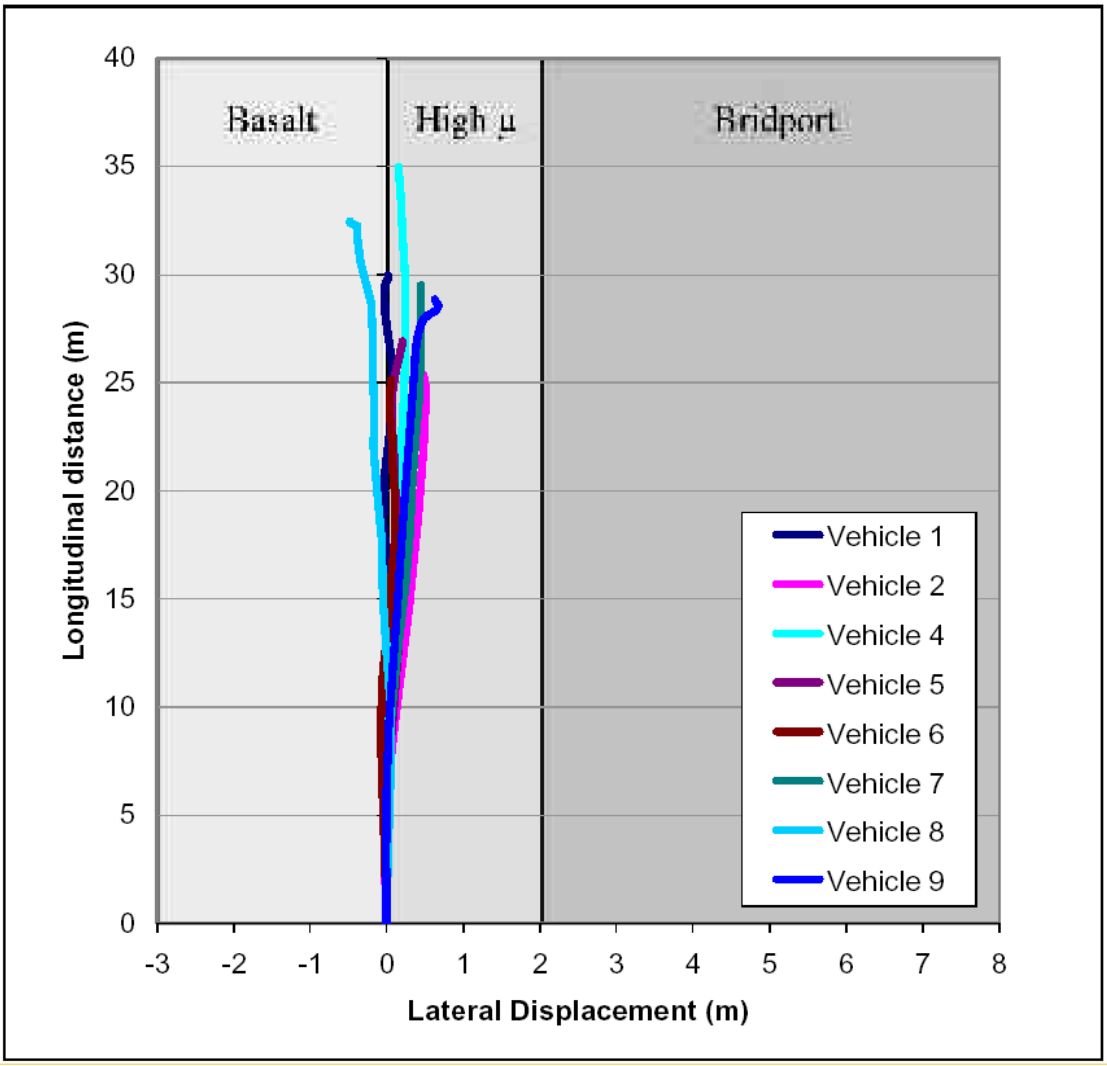

Figure 8 – Overhead plots of test vehicle paths at 30mile/h (closed-loop tests on differential friction surface)

Whilst the lateral deviation is shown to be less than for the open-loop tests, a statistical analysis reveals that differences can still be seen between some of the vehicles.

Figure 9 shows the typical levels of yaw rate observed during the closed-loop tests at 30mile/h (48 kph).

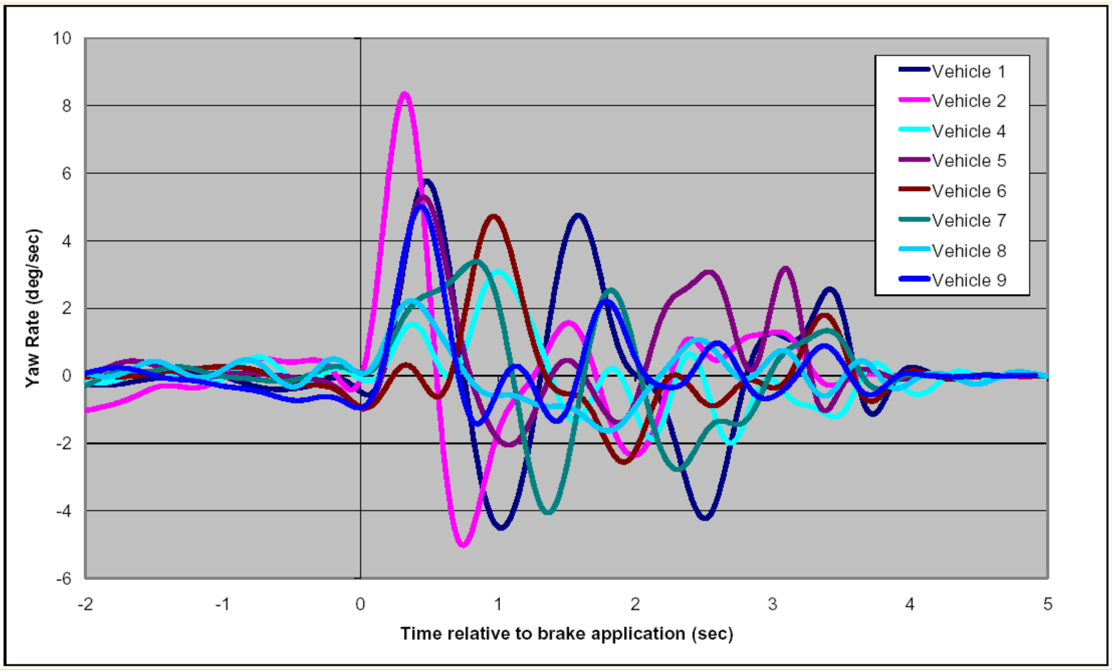

Figure 9 – Time histories of yaw rate at 30mile/h (closed-loop tests on differential friction surface)

The yaw rates recorded during the closed loop tests were slightly lower than those found during the open-loop tests. Results for vehicle 3 have not been included due to the vehicle spinning approximately 90 degrees during the test at this speed, i.e. at 30mile/h (48 kph).

The vehicles that exhibited the highest levels of yaw rate also required the greatest amount of steering to keep the vehicle straight. **Figures 8 and 9** show that vehicles 1 and 2 had the greatest yaw rate and also the greatest amount of steering. Vehicles 4 and 8 exhibited some of the lowest levels of yaw rate and required the least amount of corrective steering.

3.2.3 Longitudinal Changes in Friction

This test is intended to evaluate the ability of a vehicle to respond quickly as it travels from one surface to another, both with differing levels of friction, without suffering directional instability in a straight line braking manoeuvre. The test vehicles were subjected to tests where the vehicle traversed from a surface with a uniform high level of friction to one with a uniform low level of friction, and vice versa (low to high).

Figure 10 shows a comparison of yaw rate for the vehicles equipped with ABS when changing from a high to low coefficient surface. The time scale on the graph is zeroed at a point where the surface friction changes and shows that the change in friction does not cause any substantial yaw instability for any of the vehicles tested.

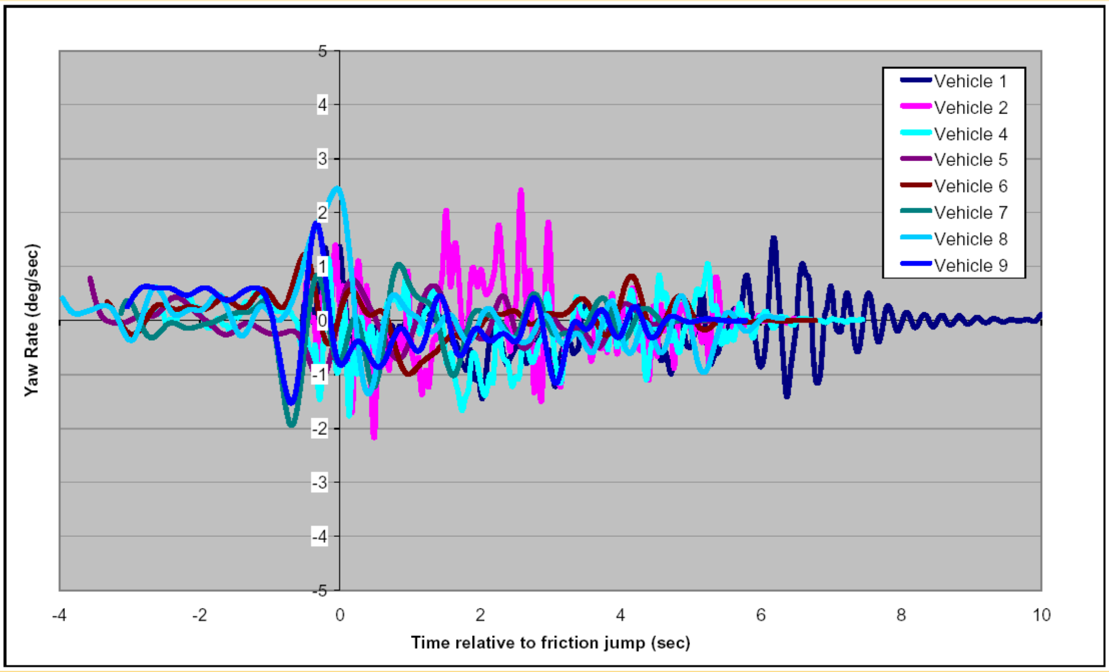

Figure 10 – Yaw rate for ABS vehicles
(longitudinal change in friction – high to low coefficient)

Vehicle 3 (the non-ABS vehicle) spun when completely on the low friction surface. However, it did not start to spin until it had been on the low friction surface for just over four seconds, appearing to indicate that it was not the actual change in friction that caused the problem.

Yaw rates from the low to high friction tests are shown in **Figure 11**.

Although the results shown in **Figures 10 and 11** do not suggest any substantial instability during the tests, a statistical analysis of the yaw rates indicated that there was some difference in the performance of each vehicle.

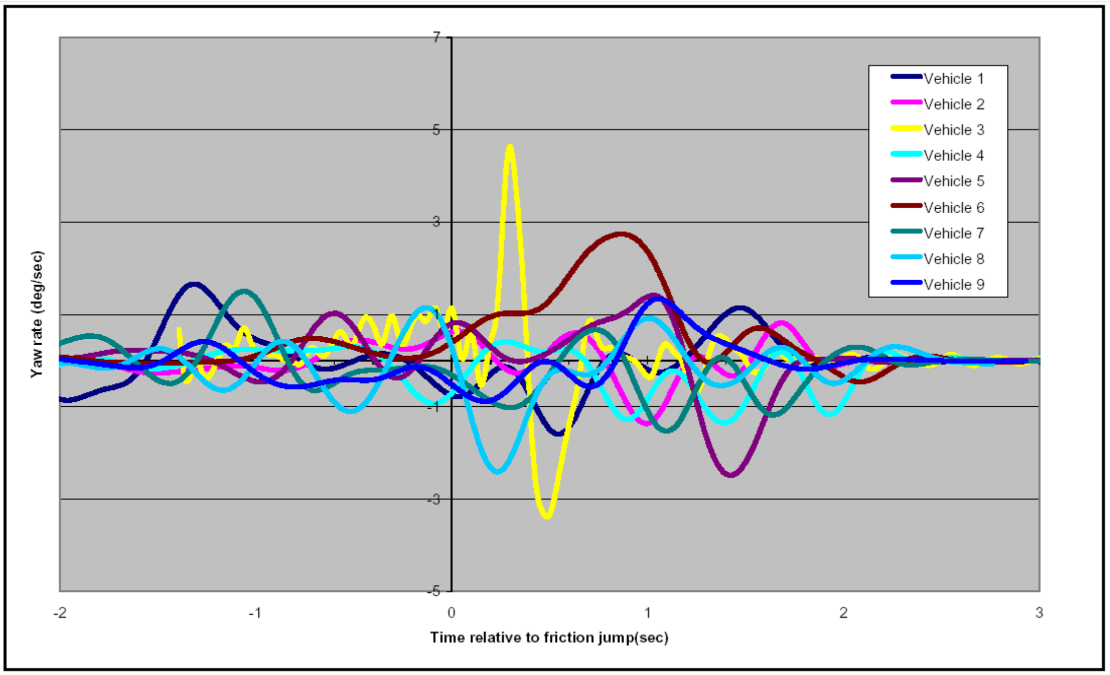

Figure 11 – Yaw rate for ABS vehicles
(longitudinal change in friction – low to high coefficient)

4. DISCUSSION

The brake tests on the uniform high and medium friction surfaces showed no evidence of yaw instability. Whereas, tests on the uniform low friction surface suggested that there was greater potential for instability due to the lower level of grip. In this test the non-ABS vehicle consistently suffered from yaw instability even at low test speeds of 30mile/h (48 kph) and 40mile/h (64 kph). This clearly discriminates between vehicles with ABS, and those without ABS, and seems to reflect the effectiveness of ABS on low grip surfaces. However, vehicle 2 showed signs of instability at 60mile/h (96 kph) and suffered a full spin at 70mile/h (112 kph), demonstrating that not all ABS-equipped vehicles are necessarily stable in all such conditions.

The results of the differential friction tests (open-loop) showed significant differences between the vehicles in terms of both stopping distance and stability. Again, the stability performance of the non-ABS vehicle was much lower than that of the ABS-equipped vehicles, but there were also significant differences between the ABS-equipped vehicles. The tests highlighted the compromise between stopping distance and stability. Those vehicles with the lower levels of lateral deviation also tended to have longer stopping distances.

The results of the open-loop differential friction tests showed a greater differentiation between vehicles in terms of stopping distance at higher speeds, i.e. at 50mile/h (80 kph) compared to 30mile/h (48 kph). The lateral deviation of the vehicles was much greater at 50mile/h (80 kph) compared to 30mile/h (48 kph) and was, in fact, found to be much greater than one lane width (3.5 metres) for most vehicles.

Closed-loop differential friction tests were also considered. The advantages of such tests are that they can be carried out at higher speeds and that the reaction of the driver is more accurately represented. The main disadvantage of this test is that the repeatability is largely dependant on the driver's skill and consistency.

The yaw rates observed in the closed-loop tests were lower than those in the open-loop tests because of the corrective steering input made by the driver. The tests showed that, where driver control is permitted, most ABS-equipped cars can be controlled such that they remain stable, even up to 70 mile/h. However, a high degree of skill is required. Even the manoeuvres carried out during these tests, with the high level of expectancy involved, required a high level of skill from the driver.

The steering input by the driver tended to follow the yaw motion as a response to it, rather than the cause of it. A difference in the amount of corrective steering applied for each vehicle was observed which generally related to the magnitude of the yaw. However, it is also important to note that the amount of steering applied at the wheel is also influenced by the steering ratio, which will differ between vehicles.

The tests involving a longitudinal change in surface friction demonstrate that the ABS-equipped vehicles maintained directional stability when traversing two uniform surfaces with different coefficients of friction. Only one of the vehicles tested showed any stability problems in this test and that was the non-ABS vehicle when passing from high to low friction. Analysis of the results showed that the instability occurred some time after the surface transition and was in fact related to braking on a uniform low friction surface.

The road surfaces used in the differential friction tests provided a friction ratio of about three to one, i.e. the high and low friction surfaces had a coefficient of about 0.75g and 0.25g, respectively. The results of these tests provide no objective basis for estimating the severity of response where the friction ratio between the wheel paths is less than three to one, suffice to say that intuitively, the severity is likely to be less. However, it should be noted that although the low friction surface used in these tests is considered to represent icy conditions, measurements have shown that comparable coefficients of friction can be recorded in a range of other conditions on public roads. For example, measurements recently obtained on a UK motorway have been shown to have a coefficient as low as 0.2g in wet conditions at high speed.

As indicated earlier in the paper, test methods for braking in a turn have also been produced as part of the Primary NCAP research programme. However, testing to date has only been carried out on uniform surfaces. Preliminary results have shown that braking in a turn can generate significant yaw instability, even on a uniform surface. Although the effects associated with a differential friction surface have not been investigated in detail for this type of manoeuvre, there is the obvious possibility that vehicle instability could be exacerbated. TRL is currently considering investigating further the various issues associated with differential friction on bends through the use of sophisticated and well validated computer models.

Such research would assist in providing greater understanding of: (1) the significance of differential friction in straight line braking versus cornering scenarios; and (2) how different vehicles and vehicle stability systems respond to differential friction. It is envisaged that addressing these issues will ultimately assist road asset management practitioners in establishing, with greater understanding, appropriate investigatory intervention levels associated with differential friction.