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**Australian Transport Safety Bureau**

**ATSB TRANSPORT SAFETY REPORT**  
Road Safety Research and Analysis Report  
CR 226

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Peter Cairney and Anthony Germanchev  
ARRB Consulting

March 2006





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*Office location:* 15 Mort Street, Canberra City, Australian Capital Territory  
*Telephone:* 1800 621 372; from overseas + 61 2 6274 6590  
*Facsimile:* 02 6274 6474; from overseas + 61 2 6274 6474  
*E-mail:* [atsbinfo@atsb.gov.au](mailto:atsbinfo@atsb.gov.au)  
*Internet:* [www.atsb.gov.au](http://www.atsb.gov.au)

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### Author(s)

Peter Cairney and Anthony Germanchev

ARRB Consulting

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### Performing Organisation

ARRB Consulting

ABN 68 004 620 651

ARRB Group Ltd

500 Burwood Highway

Vermont South VIC 3133

[www.arrb.com.au](http://www.arrb.com.au)

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### Available from

Australian Transport Safety Bureau

PO Box 967, Civic Square

ACT 2608 Australia

[www.atsb.gov.au](http://www.atsb.gov.au)

Project Officer Marcus Matthews

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### Abstract

This pilot study was undertaken to investigate whether presently available methods were capable of generating useful information on the relative contribution of microtexture and macrotexture to stopping distance at different speeds. All trials were conducted using the same late model Holden Commodore Station Wagon fitted with anti-lock braking (ABS), a Global Positioning System (GPS), an accelerometer and a computer. Testing was carried out at four sites with different combinations of macrotexture and skid resistance. Data were analysed using a full factorial Analysis of Variance (ANOVA) design, i.e. four levels of site x four levels of speed x two levels of conditions, with five replications at each site. Significant effects were found for all speed variables, all two way interactions and the three way interaction. However, it was clear that by far the largest effect was speed, based on the mean squares and the Partial Eta Squared statistic. The next largest effect was the three way site x speed x condition interaction, which is probably due to the large increases in stopping distance in wet conditions at site 3, which only occurred at higher speeds. Site 3 had low macrotexture and was the only site to have low skid resistance. It may have been possible to obtain better combinations of skid resistance and macrotexture for testing purposes if the minimum length specified for sites (300 metres) had been shorter. The test results suggest that 80 metres of road with consistent surface characteristic would be sufficient. Further investigation of the relation between crash occurrence and road surface characteristics, taking into account geometric characteristics and travel would seem to be the most productive direction for the immediate future.

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### Keywords

Surface texture, braking distance, test.

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### Notes

- (1) ATSB reports are disseminated in the interest of information exchange.
  - (2) The views expressed are those of the author(s) and do not necessarily represent those of the Australian Government.
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# EXECUTIVE SUMMARY

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## Background

The condition of road surfaces affects crash risk primarily through its impact on stopping distance. The relevant parameters of road surface condition are microtexture (surface irregularities less than 0.5 mm in depth) and macrotexture (surface irregularities between 0.5 mm and 50 mm). Macrotexture can now be measured very easily and inexpensively compared to other methods available for assessing the state of road surfaces. A surfacing management system based on macrotexture may therefore have considerable advantages. This pilot study was undertaken to investigate whether presently available methods were capable of generating useful information on the relative contribution of microtexture and macrotexture to stopping distance at different speeds.

## Method

All trials were conducted using the same late model Holden Commodore Station Wagon fitted with anti-lock braking (ABS), equipped with a Global Positioning System (GPS), an accelerometer to monitor the vehicle's longitudinal (i.e. forward) acceleration, and a computer to capture the output from the GPS and the accelerometer. The same driver was used throughout the trials to minimise inconsistencies in achieving the set speed, in selecting the starting point for braking and in the force applied to the brake pedal.

Testing was carried out at four sites along Princes Highway West, Victoria, selected to be flat and straight and safe for conducting the tests. The surface characteristics were:

- Site 1, macrotexture > 0.7 mm SMTD, British Pendulum Number (BPN) = 68
- Site 2, macrotexture < 0.4 mm SMTD, British Pendulum Number (BPN) = 64
- Site 3, macrotexture < 0.4 mm SMTD, British Pendulum Number (BPN) = 50
- Site 4, macrotexture > 0.7 mm SMTD, British Pendulum Number (BPN) = 74

Traffic controllers were used to ensure safe operation and prevent interruption to the test procedure. At each site, trials with a dry road were conducted first. A braking trial at 40 km/h was followed by one at 60, then one at 80, and finally one at 100. This sequence was repeated until five trials at each speed were completed. The procedure was repeated with a wet pavement, a water tanker was used to wet the road prior to each run.

There was a clear progression of stopping distance with increasing speed, from around 10 m at 40 km/h to between 40 and 50 m at 100 km/h. There was relatively little difference in stopping distance among the sites. Under dry conditions, Site 1 had lower stopping distances at 40 km/h. This may have been due its being the first site to be tested, when the driver tended to use an aggressive braking style before he relaxed into a more consistent braking style with practice. Site 4 tended to have slightly longer stopping distances.

At 40 km/h and 60 km/h, the wet pavement did not appear to affect stopping distance. However, at 80 km/h, a slight increase in stopping distance at Site 3 is evident, which becomes much more pronounced at 100 km/h.

The data were analysed using a full factorial Analysis of Variance (ANOVA) design, i.e. four levels of site × four levels of speed × two levels of conditions, with five replications at each site. Significant effects were found for all speed variables, all two way interactions and the three way



interaction. However, it was clear that by far the largest effect was speed, based on the mean squares and the Partial Eta Squared statistic. The next largest effect was the three way site  $\times$  speed  $\times$  condition interaction, which is probably due to the large increases in stopping distance in wet conditions at site 3, which only occurred at higher speeds.

Apart from the effect of speed, the only effect that was large enough to have practical significance was the interaction of site, speed and condition. In wet conditions at higher speeds, stopping distances were noticeably greater at the site which had low skid resistance as measured by the British pendulum tester.

Although Condition emerged as a significant factor, inspection of the results revealed no consistent differences between wet and dry conditions for sites, other than for Site 3 in the wet at higher speeds. This is consistent with the view that the mechanism of hysteresis is the more important factor in determining stopping distance, and that it is unaffected by surface wetness.

## Discussion

The study was unable to come up with any clear findings relating macrotexture to stopping distance. At the two sites with low macrotexture, dry stopping distances were similar to stopping distances at Sites 1 and 4 for the same speeds. Only with the wet pavement testing did stopping distance increase at Site 3.

From the investigators' observations while driving to and from the test sites, there appeared to be other sections which had low macrotexture, but they were probably too short to meet the criteria for the present study which required a 300 m length of consistently low or high macrotexture. With the benefit of hindsight, this requirement could be relaxed to 100 m or even less, as stopping distances at 100 km/h did not exceed 50 m. This would allow many more options for testing.

The closest comparable work on the stopping distance of current vehicles appears to that of Bullen and Ruller (1997). Their results agree well with the present study at lower speeds, but found longer stopping distances at higher speeds.

When new macrotexture survey data becomes available, it would be worth investigating whether any really low macrotexture sections can be identified. If suitable sites are available, it would be worth running another study to determine whether differences in stopping distance can be demonstrated. However, modern condition surveys and asset management standards make it increasingly difficult to find low-standard surfacing on which to conduct such tests.

In the meantime, the higher crash rates associated with low macrotexture appears to be a robust phenomenon. Combining geometric survey, condition, traffic and crash data to build up a more comprehensive picture of crash rates and to understand what combinations of features might give rise to increased crash risk in association with low macrotexture would appear to be the most productive direction for the immediate future.



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# 1 INTRODUCTION

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The condition of road surfaces affects crash risk primarily through its impact on stopping distance. The relevant parameters of road surface condition are microtexture (surface irregularities less than 0.5 mm in depth) and macrotexture (surface irregularities between 0.5 mm and 50 mm). While microtexture is thought to affect stopping distance solely by adhesive friction, macrotexture is believed to exert an effect through the mechanical deformation of the tyre (hysteresis) and through the prevention of a water film across the road.

Road surfaces have traditionally been assessed by measuring their skid resistance, which is a combination of microtexture and macrotexture. There are a large number of devices for measuring skid resistance. The British pendulum tester is a simple, flexible device but labour intensive and unsuitable for network surveys. Most devices for network testing are either towed or require dedicated vehicles. They tend to be relatively expensive to operate, and require close attention to calibration. Because the microtexture component of skid resistance is responsive to seasonal changes, frequent surveys are required to provide accurate assessment of the state of the network.

With the development of laser equipment for measuring road surface condition, it has become possible to measure macrotexture reliably and at much lower cost than skid resistance. Macrotexture surveys are generally carried out as part of a comprehensive survey of road condition which measures roughness and rutting using a multi-laser profilometer (MLP). The surveys may also include video surveys of road and shoulder width, sign and marking assets, and clear zones as well. Macrotexture appears not to be greatly affected by seasonal change.

Work carried out more than 10 years ago in the UK demonstrated that the distribution of macrotexture and skid resistance were unrelated (Roe et al. 1991), and that low macrotexture was related to increased crash risk. Similar findings emerged from work in France carried out about the same time (Gothie 1993). Recent Australian work also confirms these findings. Cairney and Styles (2005) found closely matching results from the Great Eastern Highway (GEH), WA and the Princes Highway West (PHW), Victoria. Crash rates increased once macrotexture fell below a sensor-measured texture depth (SMTD) of 0.3 or 0.4 mm.

A subsequent study on the Princes Highway West confirmed these results (Cairney, Styles and Bennett 2005). The focus of this second study was to investigate the relationship between rutting and crashes. Princes Highway West was selected for this study as it was believed to have a higher level of rutting than other major routes in Victoria. The study design included examining the relationship between rutting and other surface characteristics, including macrotexture, and the relationship between these characteristics and crashes. A second macrotexture survey was also available for this study, allowing more precise matching of crash dates and survey dates. Crash data for the years 1999 and 2000 were matched with macrotexture data from a survey carried out in 2000, and crash data from 2001-2003 were matched with a survey carried out in 2002.

Sites with an SMTD of 0.4 mm or less accounted for 53% of crash sites and 37% of other sites. Compared to the average, the risk of crashing at a site with SMTD of 0.4 mm or less is  $53/37 = 1.43$  times, or 43% greater, than the average risk for the road. Since the risk of crashing with an SMTD of more than 0.4 mm is  $47/63 = 0.75$ , i.e. less than the average, the relative risk of crashing at a site with an SMTD of 0.4 mm or less compared to a site with an SMTD of greater than 0.4 mm is  $1.43/0.75 = 1.91$ , or just over 90% greater.

One important feature of this second study was that it was possible to obtain estimates of traffic flow broken down in sufficiently fine detail to produce meaningful estimates of crash rates in relation to macrotexture. Crashes per million vehicle km travelled was approximately 80% higher when macrotexture fell to an SMTD of 0.4 mm or less.

There therefore seems to be a consistent body of data which demonstrates that crash rate increases considerably when macrotexture falls below a SMTD of 0.4 or 0.3 mm.

A recent laboratory study measured the skid resistance of briquettes of road surfacing material using a British pendulum tester (Bazlamit and Reza 2005). The experimenters were primarily interested in how skid number varied with temperature. The investigation involved measuring adhesion and hysteresis independently at different temperatures. This was achieved by treating normal wet surface measurements as representing the effects of hysteresis and adhesion, and assuming that a water and liquid soap application was sufficient to minimise or eliminate adhesion. Skid resistance measurements obtained when the soap was applied were assumed to represent the effects of hysteresis alone; subtracting these measurements from the values obtained when water only was used gives an estimate of the contribution of adhesion. Although the relative contribution of hysteresis and adhesion varied across the temperature range, hysteresis was always the dominant factor, contributing between 70 and 80% of combined friction. Unfortunately, this work does not tell us how the relative contribution of the two factors is likely to vary with speed.

At present, there appears to be no published data which relate stopping distance to macrotexture and microtexture. Past Australian work has related stopping distance to skid resistance as measured by the Sideways Force Coefficient Routine Investigation Machine (SCRIM, see Bullen and Ruller 1997; also see RTA/VicRoads 1995 for details of SCRIM). As explained earlier, SCRIM measurements rely on a combination of macrotexture and microtexture effects.

Better understanding of the effects of macrotexture and microtexture on stopping distance is important for three reasons:

- Convincing evidence of a clear relationship between stopping distance and macrotexture (or lack of it) would help decide how important it is to pursue studies of the relationship between macrotexture, crashes and other surface characteristics, and would give added credibility to these studies. Recent technical developments in the area of road survey instrumentation, GPS and GIS have made this type of research feasible.
- The question is of considerable theoretical interest, and has direct practical applications. The flexibility of modern vehicle tyres, in particular their capacities to absorb energy through the mechanism of hysteresis, means that classic friction models of the stopping process are inadequate. There is a reasonable chance of developing a robust, readily-understandable model of the braking process in the course of this research, which has the potential to influence the design of road surfaces in different operating environments, and to influence the type of road survey information collected to support maintenance regimes in different speed environments.
- This knowledge may have the potential to improve the accuracy of crash investigations. More detailed knowledge of the relationship between stopping distance and surface characteristics can only improve the accuracy of the determination of vehicle speed. At present, such determinations are based on skid resistance, which is a relatively unstable measure (being sensitive to rainfall), and which depends on both macrotexture and microtexture.

The present study was undertaken to investigate whether presently available methods were capable of generating useful information on the relative contribution of microtexture and macrotexture to stopping distance at different speeds.

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## 2 METHOD

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### 2.1 Vehicle and sites

#### 2.1.1 Vehicle

All trials were conducted using the same late model Holden Commodore Station Wagon fitted with anti-lock braking (ABS). The vehicle had a mass of 1,640 kg. Three tyres were inflated<sup>1</sup> to 2 kg per cm<sup>2</sup> and one was marginally lower at 1.9 kg per cm<sup>2</sup>.

The vehicle was equipped with the following:

- a Global Positioning System (GPS) which provided real-time tracking of the vehicle's position
- a switch on the brake pedal
- an accelerometer to monitor the vehicle's longitudinal (i.e. forward) acceleration
- a computer to capture the output from the GPS and the accelerometer.

The GPS system was a *microsat global positioning sensor* with 0.5% accuracy and 10 mm resolution when measuring distance with a 20 Hz update rate. This device provided the vehicle stopping distance metric for this study. The switch on the brake pedal was connected to the GPS data logging system to provide a time marker when the pedal was pressed.

The same driver was used throughout the trials to minimise inconsistencies in achieving the set speed, in selecting the starting point for braking and in the force applied to the brake pedal.

#### 2.1.2 Sites

Testing was carried out at four sites along Princes Highway West, Victoria. This route was familiar to the team as it was used in the earlier study of macrotexture and crashes (Cairney and Styles 2005) and a subsequent study on rutting, macrotexture and crashes carried out for VicRoads (Cairney, Styles and Bennett 2005). The most recent VicRoads macrotexture survey data was used to select possible test sites for further consideration. A three stage site selection process was used. Firstly sites were selected from the macrotexture and geometric survey records, with the following characteristics:

- 300 m of continuous SMTD values of less than 0.4 mm or greater than 0.7 mm
- gradient less than 1% and curvature less than 0.1 mm.

This enabled sections with high and low macrotexture to be identified, and where geometry was not likely to interfere with testing. The second stage in the selection was to measure the skid resistance at each site, using a British pendulum tester. This testing was carried out by an experienced

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<sup>1</sup> Readers may be more familiar with tyre pressures in lbs per square inch, i.e. 28 and 27 lbs per square inch respectively.

technician who had a traffic controller present for all tests, along with associated signage. This was an attempt to identify sites which would have suitable combinations of low and high macrotexture. This stage was not entirely successful as it proved difficult to find sites with low macrotexture.

The third stage in selection was an inspection by the project leader to ensure the characteristics appeared to be as described, and that there were no other features of the sites which would compromise the safe and efficient conduct of the tests. Two potential sites were eliminated on this basis.

The characteristics of the sites were as follows:

- Site 1, macrotexture > 0.7 mm SMTD, British Pendulum Number (BPN) = 68
- Site 2, macrotexture < 0.4 mm SMTD, British Pendulum Number (BPN) = 64
- Site 3, macrotexture < 0.4 mm SMTD, British Pendulum Number (BPN) = 50
- Site 4, macrotexture > 0.7 mm SMTD, British Pendulum Number (BPN) = 74

## **2.2 Conduct of testing and data collected**

### **2.2.1 Traffic control**

Advance signing, 'Prepare to Stop' signing and a traffic controller were provided at each end of the site. Traffic controllers were in visual and radio contact with each other at all times. Traffic was stopped at each end of the site just before each trial began, and remained stopped until the trial and any measurements outside the vehicle were concluded, and the test vehicle was on its way back to the start point. In the case of wet road trials, traffic was stopped before the tanker wet the road surface.

### **2.2.2 Procedure**

At each site, the trials with the dry surface were always conducted before the trials with the wet surface. The first dry surface trial was conducted at 40 km/h, the second at 60 km/h, the third at 80 km/h and the fourth at 100 km/h. This sequence was repeated until five trials had been conducted at each speed. The sequence of trials was repeated for the wet surface trials.

On each trial, the driver of the test vehicle had approximately 150-200 m to bring the vehicle up to the required speed before reaching the braking point, indicated by a traffic cone. The driver held the vehicle at as steady a speed as possible and attempted to brake when exactly aligned with the cone. The driver attempted to brake as hard as possible on each occasion. Once the vehicle came to a stop, the driver left the vehicle in that position for a few seconds so that the stopped condition would be clearly registered on the vehicle's logging system, and then turned the vehicle round to return to the start point. The experimenter then reset the logging equipment ready for the next trial.

For the wet surface trials, the tanker passed along the test section immediately prior to the test vehicle, the driver beginning the test run as soon as the tanker had completed its run and pulled into the side. The tanker driver commenced spraying a few metres in advance of the braking marker, and continued spraying until he was well clear of the area in which braking took place, a distance of approximately 80 m. It was not possible to accurately measure the water dispersion, but calculations based on the tanker's capacity, the proportion of water used, the length of the site, width of the

spray bar and number of runs indicates a dispersal rate of approximately 0.7 litres per m<sup>2</sup> on each run.

Turning the vehicle around, re-setting the data logger, stopping traffic and, during the wet-surface trials, wetting the road, took up a few minutes between successive trials. There was no set time between trials. From time to time, immediately at the conclusion of 100 km/h stopping trials, all the test vehicle tyres and wheels were inspected and checked by hand for signs of brakes running hot. In no case was this detected.

### **2.2.3 Data collected**

Trials proceeded smoothly, but a few had to be repeated for various reasons. On one occasion, the trial was terminated to avoid a collision with a swooping kestrel which had been hovering for some time above a large pool by the roadside. The most usual reason for a trial to be repeated was that the driver had not maintained a sufficiently steady speed on the approach to the braking point. Surprisingly, this was more difficult at the lowest speed. Inspection of the results suggests reasonably consistent approach speeds and stopping distances, especially for the higher-speed trials.

Unfortunately, one of the logging system's characteristics was that data tended to get over-written, especially when runs had to be repeated. The team was not always aware that this had happened, and as a result, a small amount of data is missing, namely:

Site 2: 1 trial at 100 km/h

Site 3: 1 trial at 40 km/h

Site 4; 1 trial at 40 km/h, and 1 trial at 100 km/h.

All missing trials are under dry road conditions. The missing data represent 5% of all dry trials and are dispersed across the sites. In all cases where there is missing data, estimates of stopping distance for that site and speed combination will be based on four trials rather than five. The statistical analysis method takes account of the missing trials.

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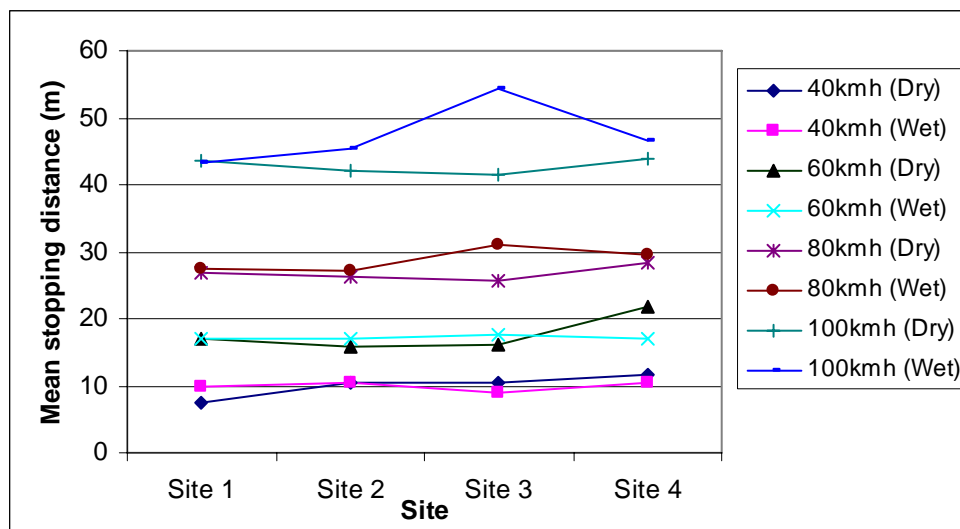
## 3 RESULTS

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### 3.1 Overall results

The mean stopping distance at each test site at each speed, under wet and dry conditions, is shown in Figure 1. Table 1 presents the means, along with the standard deviation for each of these means, estimated from five trials<sup>2</sup> at each site.

**Figure 1: Mean stopping distance at each site at different speeds, wet and dry conditions**



There is a clear progression of stopping distance with increasing speed, from around 10 m at 40 km/h to between 40 and 50 m at 100 km/h. There is relatively little difference in stopping distance among the sites. Under dry conditions, Site 1 had lower stopping distances at 40 km/h. This may have been due its being the first site to be tested, when the driver tended to use an aggressive braking style before he relaxed into a more consistent braking style with practice. Site 4 tended to have slightly longer stopping distances.

At 40 km/h and 60 km/h, the wet pavement did not appear to affect stopping distance. However, at 80 km/h, a slight increase in stopping distance at Site 3 is evident, which becomes much more pronounced at 100 km/h.

The standard deviation is an indication of the consistency of the stopping distances. Inspection of Table 1 shows that in general, standard deviations lay in the range of 1-3 m. With an average stopping distance of 10 m or so for a speed of 20 km/h, the standard deviation is between 10 and

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<sup>2</sup> Except for the four occasions on which a trial was inadvertently omitted, in which case the mean was estimated over four trials.



30% of the mean. With a stopping distance of more than 40 m for speeds of 100 km/h, the standard deviation is generally between 2 and 3 m, or between 5 and 7% of the mean.

**Table 1: Mean and standard deviations of stopping distance**

		Stopping distance (m)					
Speed (km/h)	Site	Condition					
		Dry			Wet		
		Mean	SD	<i>n</i>	Mean	SD	<i>n</i>
40	1	7.48	0.554	5	9.90	2.604	5
	2	10.50	2.724	5	10.45	0.922	5
	3	10.33	1.945	4	8.93	1.130	5
	4	11.73	2.231	5	10.49	1.442	5
	<b>Total</b>	<b>9.99</b>	<b>2.480</b>	<b>19</b>	<b>9.94</b>	<b>1.654</b>	<b>20</b>
60	1	16.99	1.152	5	17.06	1.302	5
	2	15.70	1.009	5	17.14	2.795	5
	3	15.99	1.822	5	17.50	0.862	5
	4	21.65	4.527	5	16.93	1.774	5
	<b>Total</b>	<b>17.58</b>	<b>3.400</b>	<b>20</b>	<b>17.16</b>	<b>1.694</b>	<b>20</b>
80	1	26.75	1.540	5	27.50	0.786	5
	2	26.22	1.039	5	27.16	2.047	5
	3	25.56	1.282	5	31.00	2.198	5
	4	28.27	2.721	5	29.69	2.698	5
	<b>Total</b>	<b>26.70</b>	<b>1.919</b>	<b>20</b>	<b>28.84</b>	<b>2.489</b>	<b>20</b>
100	1	43.47	3.102	5	43.33	5.001	5
	2	42.18	0.947	4	45.52	3.595	5
	3	41.44	1.491	5	54.28	2.679	5
	4	43.99	2.818	4	46.66	2.718	5
	<b>Total</b>	<b>42.74</b>	<b>2.333</b>	<b>18</b>	<b>47.45</b>	<b>5.378</b>	<b>20</b>

### 3.2 Statistical analysis - overall results

Levene's test for the homogeneity of variance, applied at the 0.01 level due to its high sensitivity, indicated that assumptions about the homogeneity of variance were not violated ( $F(31,125) = 1.652$ ,  $p > .01$ ). However there are large differences in the variance associated with the different speeds, and although ANOVA is generally regarded as a robust technique, this large difference violates its basic assumptions. The precaution has therefore been taken of conducting a separate ANOVA for each speed (see Section 3.3).

The data were analysed using a full factorial Analysis of Variance (ANOVA) design, i.e. four levels of site  $\times$  four levels of speed  $\times$  two levels of conditions, with five replications at each site. The results of the ANOVA are shown in Table 2.

The effects of all main factors and interactions in the full analysis were large in relation to the error mean square. Significant effects were found for all speed variables, all two way interactions and the three way interaction. However, it is clear that by far the largest effect was speed, based on the mean squares and the Partial Eta Squared statistic. The next largest effect was the three way site  $\times$  speed  $\times$  condition interaction, which is probably due to the large increases in stopping distance in wet conditions at site 3, which only occurred at higher speeds.

**Table 2: Results of ANOVA of stopping distances**

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Observed Power(a)
Corrected Model	27835.273(b)	31	897.912	168.543	.000	.977	1.000
Intercept	98149.746	1	98149.746	18423.196	.000	.993	1.000
Site	119.880	3	39.960	7.501	.000	.153	.984
Speed	26610.529	3	8870.176	1664.976	.000	.976	1.000
Condition	97.828	1	97.828	18.363	.000	.128	.989
Site * Speed	113.759	9	12.640	2.373	.016	.146	.903
Site * Condition	135.595	3	45.198	8.484	.000	.169	.993
Speed * Condition	159.923	3	53.308	10.006	.000	.194	.998
Site * Speed * Condition	218.434	9	24.270	4.556	.000	.247	.998
Error	665.939	125	5.328				
Total	126002.207	157					
Corrected Total	28501.212	156					

a Computed using alpha = .05; b R squared = .977 (adjusted R squared = .971)

### 3.3 Analysis of stopping distance at different speeds

In view of the clear differentiation of stopping distance at different speeds, and the different relations between variables at different speeds, further ANOVAs were carried out for each speed level. This resulted in each case with a two-way ANOVA, 4 sites  $\times$  2 conditions, with five replications for each combination of site and condition, with the exception of the inadvertent omissions noted earlier.

The full ANOVA tables for the analysis at each speed are presented in Appendix A. Summary results are presented in Table 3, in which results for the four ANOVAs have been grouped together, so that the results relating to Site are all grouped together, as are the results for Condition, and the results for the interaction.

In all cases, the Sites factor was significant, but the Condition factor was significant only for the 80 and 100 km/h conditions. The Site  $\times$  Condition interaction was significant for the 60, 80 and

100 km/h conditions. Note that in all cases where there is no significant effect, i.e. the Condition factor at 40 and 60 km/h and the Site × Condition interaction at 40 km/h, the power of the comparison is extremely low. The appropriate interpretation therefore is that there is insufficient data to test for differences in these cases, rather than that there is no difference under these conditions.

**Table 3: Summary of results of ANOVAs carried out for each speed**

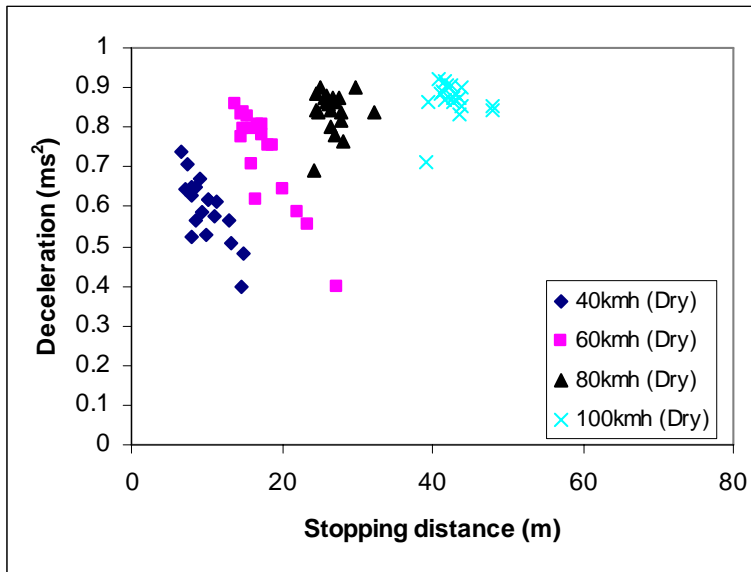
Factor	Speed	F	Significance	Partial Eta <sup>2</sup>	Power
Site	40	3.219	.036	.237	.684
	60	3.463	.028	.244	.718
	80	2.992	.045	.219	.651
	100	4.207	.013	.296	.807
Condition	40	0.12	.913	.000	.051
	60	0.365	.550	.011	.090
	80	12.454	.001	.280	.928
	100	21.772	.000	.421	.995
Site × condition	40	2.232	.104	.178	.511
	60	4.371	.011	.291	.826
	80	3.347	.031	.239	.705
	100	8.350	.000	.455	.985

### 3.4 Stopping distance and average deceleration

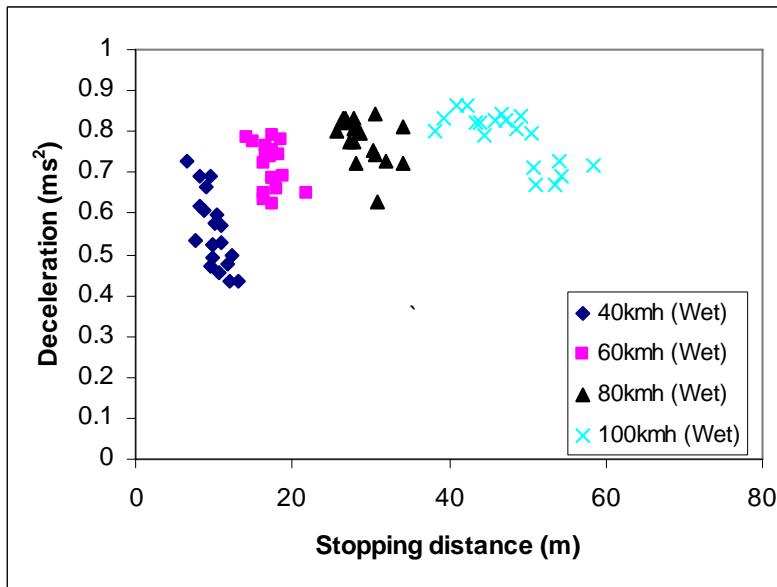
Stopping distance is the product of average deceleration rate and time. The average deceleration rate depends on the speed at which the vehicle was travelling prior to braking and the time over which the deceleration took place, i.e. the time before the application of the brakes and the vehicle coming to a complete stop.

The relationship of stopping distance to average deceleration is shown for dry and wet conditions in Figures 2 and 3 respectively.

**Figure 2: Relation between deceleration and stopping distance, dry conditions**

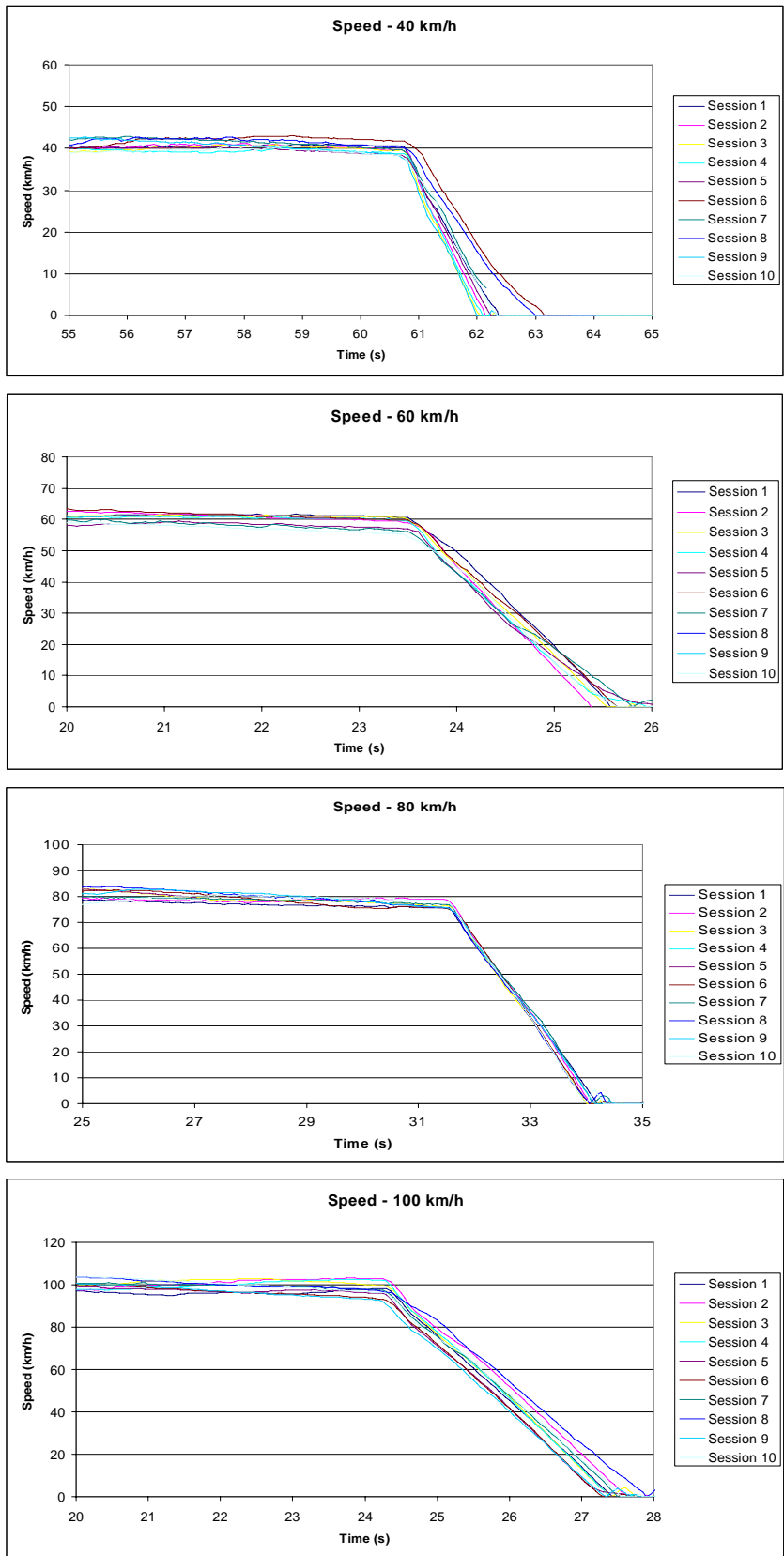


**Figure 3: Relation between deceleration and stopping distance, wet conditions**



Speeds on each session are shown for each block of trials in Figure 4. It can be seen that mean vehicle speeds fell within a narrow range throughout the investigation. Variability was particularly low at 80 km/h.

**Figure 4: Mean speeds for each block of trials**



The mean deceleration achieved on each block of trials is shown in Table 4. It can be seen that the mean deceleration for wet trials is similar to dry trials for 40 km/h and 60 km/h, but this increases slightly for 80 km/h and more definitely for 100 km/h. Inspection of Table 4 shows that the difference at Site 3 is considerably greater than at any other site for the 100 km/h and the 80 km/h sites. At 60 km/h, there also a substantial difference, but the results at that speed are very inconsistent across sites.

**Table 4: Mean and standard deviation deceleration**

		Deceleration (m/s <sup>2</sup> )					
Speed	Site	Condition					
		Dry			Wet		
		Mean	SD	<i>n</i>	Mean	SD	<i>n</i>
40	1	0.67	0.05	5	0.54	0.12	5
	2	0.53	0.04	5	0.49	0.04	5
	3	0.60	0.04	4	0.64	0.07	5
	4	0.56	0.11	5	0.56	0.05	5
	<b>Total</b>	<b>0.59</b>	<b>0.08</b>	<b>19</b>	<b>0.56</b>	<b>0.09</b>	<b>20</b>
60	1	0.73	0.07	5	0.69	0.07	5
	2	0.82	0.02	5	0.72	0.07	5
	3	0.80	0.04	4	0.70	0.02	5
	4	0.60	0.14	5	0.77	0.02	4
	<b>Total</b>	<b>0.73</b>	<b>0.12</b>	<b>19</b>	<b>0.72</b>	<b>0.06</b>	<b>19</b>
80	1	0.78	0.06	5	0.80	0.02	5
	2	0.86	0.01	5	0.78	0.09	5
	3	0.86	0.03	5	0.73	0.01	5
	4	0.86	0.04	5	0.82	0.02	5
	<b>Total</b>	<b>0.84</b>	<b>0.05</b>	<b>20</b>	<b>0.79</b>	<b>0.05</b>	<b>20</b>
100	1	0.83	0.07	5	0.79	0.05	5
	2	0.88	0.01	4	0.83	0.02	5
	3	0.88	0.04	5	0.70	0.03	5
	4	0.89	0.03	4	0.83	0.02	4
	<b>Total</b>	<b>0.87</b>	<b>0.05</b>	<b>18</b>	<b>0.79</b>	<b>0.06</b>	<b>19</b>

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## **4 DISCUSSION**

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### **4.1 Summary of findings**

The target initial speeds were adequately maintained throughout the experiment. This is shown in the narrow band of speeds on different blocks evident in Figure 4.

Braking performance appears to show little variability in relation to the main effects of speed, site and conditions being manipulated in the study, as shown by the results of the main ANOVA, and the subsequent ANOVAs carried out for each speed. Speed had a much greater impact on stopping distance than the other variables. Site and Condition both had a significant effect.

Apart from the effect of speed, the only effect that was large enough to have practical significance was the interaction of site, speed and condition. In wet conditions, at higher speeds, stopping distances were noticeably greater at the site which had low skid resistance as measured by the British pendulum tester.

There was less variation in the mean deceleration than in the stopping distance as it is limited by physical factors and applies for longer periods at higher speeds. However, lower deceleration was evident on trials with a longer stopping distance.

### **4.2 The effects of wet surface**

Although Condition emerged as a significant factor, inspection of the results in Tables 1 and 4 reveals no consistent differences between wet and dry conditions for sites, other than for Site 3 in the wet at higher speeds. This is consistent with the view that the mechanism of hysteresis is the more important factor in determining stopping distance, and that it is unaffected by surface wetness.

The effects of surface wetness were evident at Site 3, but only at higher speeds. This is probably because there is relatively more variability in the data at lower speeds.

### **4.3 Relation of stopping distance to macrotexture**

The study was unable to come up with any clear findings relating macrotexture to stopping distance. At the two sites (Sites 2 and 3) with low macrotexture, dry stopping distances were similar to stopping distances at Sites 1 and 4 for the same speeds. Only with the wet pavement testing did stopping distance increase at Site 3.

Site 3 was certainly among the sites with low macrotexture which were available for testing along the road. From the investigators' observations while driving to and from the test sites, there appeared to be other sections which appeared to have low macrotexture, but they were probably too short to meet the criteria for the present study which required a 300 m length of consistently low or high macrotexture. With the benefit of hindsight, this requirement could be relaxed to 100 m or even less, as stopping distances at 100 km/h did not exceed 50 m. This would allow a lot more options for testing, and may identify some sites with lower macrotexture.

## 4.4 Relation to other work on stopping distance

The closest comparable work on the stopping distance of current vehicles appears to be a body of work by Bullen and Ruller (1997) which is focussed principally on the validation of techniques used in crash investigation. In one of their earlier papers (Bullen and Ruller 1992), they used different techniques to estimate the stopping distance of a typical vehicle. The comparison of their results and those of the present study is shown in Table 5. Although stopping distances show reasonable agreement at lower speed, there is a substantial discrepancy at higher speed.

**Table 5: Comparison of stopping distances with other work**

	Stopping distance (m)		
	40 km/h	60 km/h	80 km/h
Bullen and Ruller 1992	7-10	15-25	35-45
Present study	9.99	17.58	26.70

## 4.5 Further work

While it has been demonstrated that the instrumentation package used in the present study is sufficiently sensitive to pick up differences in stopping distance related to surface characteristics, it has not been possible to demonstrate that it can detect differences relating specifically to macrotexture. This may be because the study did not use sites with sufficiently low macrotexture to give rise to changes in stopping distance.

When new macrotexture survey data becomes available, it would be worth investigating whether any really low macrotexture sections can be identified, based on the shorter road lengths discussed in Section 4.3. If they can, then it would be worth running another study to determine whether differences in stopping distance can be demonstrated. However, modern condition surveys and asset management standards make it increasingly difficult to find low-standard surfacing on which to conduct such tests.

In the meantime, as was shown in Section 1, the higher crash rates associated with low macrotexture appears to be a robust phenomenon. Combining geometric survey, condition, traffic and crash data to build up a more comprehensive picture of crash rates and to understand what combinations of features might give rise to increased crash risk in association with low macrotexture would appear to be the most productive direction.



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## 5 REFERENCES

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## 6 APPENDIX: ANOVA TABLES

### Stopping distance: 40 km/hr

Homogeneity of variance is improved for this test ( $F(7, 31) = 1.881, p > .05$ ). There is a statistically significant main effect of site ( $F(3, 31) = 11.017, p < .05$ ). Post-hoc comparisons (Tukey's HSD) reveal a statistically significant difference between sites 1 and 4 (Tukey's HSD = 2.423,  $p < .05$ ). The effect of condition is not statistically significant, and it is worth noting that the power for this observation is particularly low. Although the interaction between site and pavement condition is not significant, it is approaching significance, with a moderate effect size and moderate power.

#### Tests of between-subjects effects

Dependent variable: stopping distance

Source	Type III sum of squares	df	Mean square	F	Sig.	Partial Eta squared	Observed power(a)
Corrected model	56.540(b)	7	8.077	2.360	.047	.348	.763
Intercept	3861.111	1	3861.111	1127.957	.000	.973	1.000
Site	33.052	3	11.017	3.219	.036	.237	.684
Condition	.041	1	0.041	0.012	.913	.000	.051
Site * condition	22.921	3	7.640	2.232	.104	.178	.511
Error	106.116	31	3.423				
Total	4037.896	39					
Corrected total	162.656	38					

(a) Computed using alpha = 0.05

(b) R squared = 0.348 (adjusted R squared = 0.200)

## Stopping distance: 60 km/hr

Homogeneity of variance is satisfied, ( $F(7,32)=2.017, p>.05$ ). There is a statistically significant main effect of site ( $F(3,32)=50.977, p<.05$ ). Condition does not have a statistically significant effect, but there is a statistically significant interaction between site and condition ( $F(3, 32) =21.616, p<.05$ ).

### Tests of between-subjects effects

Dependent variable: stopping distance

Source	Type III sum of squares	df	Mean square	F	Sig.	Partial Eta squared	Observed power(a)
Corrected model	117.633(b)	7	16.805	3.398	.008	.426	.916
Intercept	12067.981	1	12067.981	2440.283	.000	.987	1.000
Site	50.977	3	16.992	3.436	.028	.244	.718
Condition	1.806	1	1.806	.365	.550	.011	.090
Site * condition	64.849	3	21.616	4.371	.011	.291	.826
Error	158.250	32	4.945				
Total	12343.864	40					
Corrected total	275.883	39					

(a) Computed using alpha = 0.05

(b) R squared = 0.348 (adjusted R squared = 0.200)

## Stopping distance: 80 km/hr

Homogeneity of variance is satisfied ( $F(7,32)=1.735, p>.05$ ). There is a statistically significant main effect of both site ( $F(3,32)=33.012, p<.05$ ) and condition ( $F(1,32)=45.796, p<.05$ ). There is also a statistically significant interaction between site and condition ( $F(3,32)=36.926, p<.05$ ).

### Tests of between-subjects effects

Dependent variable: stopping distance

Source	Type III sum of squares	df	Mean square	F	Sig.	Partial Eta squared	Observed power(a)
Corrected model	115.733(b)	7	16.533	4.496	.001	.496	.976
Intercept	30844.694	1	30844.694	8387.782	.000	.996	1.000
Site	33.012	3	11.004	2.992	.045	.219	.651
Condition	45.796	1	45.796	12.454	.001	.280	.928
Site * condition	36.926	3	12.309	3.347	.031	.239	.705
Error	117.675	32	3.677				
Total	31078.103	40					
Corrected total	233.408	39					

(a) Computed using alpha = 0.05

(b) R squared = 0.348 (adjusted R squared = 0.200)

## Stopping distance: 100 km/hr

Homogeneity of variance is satisfied ( $F(7, 30) = 1.130, p > .05$ ). There is a statistically significant main effect of both site and condition ( $F[3, 30] = 119.440, p < .05$ , and  $F[1, 30] = 206.30, p < .05$ ). There is also a significant interaction between site and condition ( $F(3, 30) = 237.066, p < .05$ ).

### Tests of between-subjects effects

Dependent variable: stopping distance

Source	Type III sum of squares	df	Mean square	F	Sig.	Partial Eta squared	Observed power(a)
Corrected model	568.678(b)	7	81.240	8.585	.000	.667	1.000
Intercept	76605.484	1	76605.484	8095.050	.000	.996	1.000
Site	119.440	3	39.813	4.207	.013	.296	.807
Condition	206.030	1	206.030	21.772	.000	.421	.995
Site * condition	237.066	3	79.022	8.350	.000	.455	.985
Error	283.898	30	9.463				
Total	78542.345	38					
Corrected total	852.575	37					

(a) Computed using alpha = 0.05

(b) R squared = 0.348 (adjusted R squared = 0.200)