Investigating the effect of inflation pressure on our ability to conceptually reconstruct accidents

by C Grover, L Walter, T L Smith and R F Lambourn

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INVESTIGATING THE EFFECT OF INFLATION PRESSURE ON OUR ABILITY TO CONCEPTUALLY RECONSTRUCT ACCIDENTS

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Executive summary

Established methods in accident investigation and reconstruction rely on the identification and interpretation of physical evidence from the scene and from the vehicles, using basic physical laws. Such techniques require investigators to make some assumptions and to simplify their analyses such that vehicle movements become treated in an idealised manner. These methods do not, therefore, provide investigators with fully effective procedures for addressing the non-standard situations which drivers encounter, which contribute to many road traffic accidents. In the course of investigations work, many examples arise where the conclusions of expert reports are limited by the absence of supporting test data. In particular, incorrect tyre pressure is often cited as a contributory or even main cause of an accident in the absence of independent knowledge of the effects of such incorrect tyre pressures.

Tyre manufacturers are increasingly developing new tyre technology. Many manufacturers are producing tyres that may be temporarily driven on after a partial or total loss of pressure, commonly referred to as *run flats*. These tyres are constructed with reinforced sidewalls that support the vehicle weight and are resistant to bending in comparison with traditional tyres in which the inflation pressure alone maintains the structural stiffness.

This report documents a programme of experimentation for the benefit of accident investigators who have the task of reconstructing road traffic accidents. This experimental programme focused on investigating the effects of modern tyre technology on the tyre/pavement friction (low profile and run flat) and vehicle braking performance and handling characteristics (run flat). The components of the experimental programme combine to build up an understanding of the effect of inflation pressure for a range of modern tyre types and operating conditions, so providing the accident investigator with a source of data relating to the performance of modern tyres.

The research concludes that there are some statistically significant differences between under-inflated tyres and those inflated to recommended pressure. For example, the peak lateral acceleration achieved during the step steer test was greatest for the correctly inflated tyres and reduced as the tyres were under-inflated. However, whilst under-inflation may have profound effects on the nature of vehicle control (and this bears strongly on accident probability), its effect on the reliability of conceptual accident reconstruction *given physical* data (tyre marks on the road etc) is small. The most significant differences *for accident reconstruction purposes* were found when a run-flat tyre is completely deflated. In one experiment the complete deflation resulted in a loss of vehicle control.

1 Introduction

This report documents a programme of experimentation primarily for the benefit of accident investigators who have the task of reconstructing road accidents from the physical evidence found at the scene and on, or in, the vehicles. The programme focused on investigating the effects of modern tyre technology (low profile, run flat) on the tyre/pavement friction and vehicle braking performance and handling characteristics.

Established methods in accident investigation and reconstruction rely on the identification and interpretation of physical evidence from the scene and from the vehicles using basic physical laws. Such techniques require investigators to make some assumptions and to simplify their analyses such that vehicle movements become treated in an idealised manner. These methods do not, therefore, provide investigators with fully effective tools for addressing the non-standard situations which drivers encounter, which contribute to many road traffic accidents. In the course of investigations many examples arise where the conclusions of expert reports are limited by the absence of supporting test data. In the absence of independent knowledge of the effects of incorrect tyre pressures, under-inflation of tyres is often cited as a contributory or even main cause of an accident.

The components of the experimental programme combine to build up an understanding of the effect of inflation pressure for a range of modern tyre types and operating conditions, providing the accident investigator with a source of data relating to the performance of modern tyres.

The structural stability of a tyre is maintained by the internal pressure, which also provides for retention on the wheel. Greater inflation pressure increases the mechanical stiffness while reducing the area of the contact patch for a given normal load. Under-inflation increases the area of the contact patch but reduces the stiffness of the tyre. This results in more energy being dissipated in the tyre wall as heat, which can ultimately lead to tyre failure.

Tyre manufacturers are increasingly developing new tyre technologies. Many manufacturers are producing tyres that may be temporarily driven on after a partial or total loss of pressure, commonly referred to as “run flats”. These tyres are constructed with reinforced sidewalls that support the vehicle’s weight and are resistant to bending in comparison to traditional tyres, in which the inflation pressure maintains the structural stiffness. Run flat tyres are designed to allow normal acceleration, braking and steering for short distances at moderate speeds, typically 50 miles at a maximum speed of 50mile/h (Dunlop Tyres, 2006). A vehicle equipped with run flat tyres as original equipment must also be equipped with a tyre pressure monitoring system to alert the driver to a loss of pressure.

A search of recent publications (2000-2006) was carried out to identify if any previous research had considered the effect of under-inflation on the tyre/pavement friction, vehicle braking and vehicle handling characteristics.

The Derbyshire Constabulary (Bailey, 2000) investigated whether incorrect tyre pressure affected the stopping distance of a car in emergency locked-wheel braking. All tyres were at the same pressure in each test, and pressures ranged from 50% under inflation to 70% over inflation. The weight of the vehicle was also increased by 14% from its usual “operational” amount for some of the tests. The average deceleration was found to be in the region of 0.75-0.80g throughout, and the author concluded that there was no identifiable trend to suggest that tyre pressure or vehicle load influence the results. However, inspection of the graphs of their results does suggest a small decline in deceleration with increasing pressure, of the order of 0.04g over the whole range.

More recent testing on a car carried out by Merseyside Police (Hulme, 2004) investigated matters further. Tests were carried out with different variations of over- or under-inflated tyres (±50%) on front or back; comparison was made with the anti-lock braking system (ABS) enabled or disabled; then similar tests were made using tyres designed to allow the driver to continue the journey on a flat tyre at reduced speed (run flat tyres). The vehicle remained generally stable. Use of the ABS produced increased stopping ability. It again appeared that the variations in tyre pressure caused no increase in stopping distance in emergency braking conditions.

Arndt and Arndt (2006) tested two vehicles, an SUV fitted with normal tyres and then with a temporary use spare tyre in place of a normal tyre, and a saloon car fitted with normal tyres and then run-flat tyres all round. Steady state cornering tests and 180° step steer tests (J-turn) at target speeds of either 30 or 35 mile/h were carried out to investigate the effects of various tyre conditions on the vehicles' handling performance.

All tests with the SUV were conducted with the tyres inflated to the recommended pressure. The research concluded that with the fitment of a temporary use spare tyre on the rear right position, the vehicle maintained a safe understeer characteristic up to the limit of tyre friction for turns in both directions, similar to that achieved with normal tyres fitted all round. In the left turn step steer tests the vehicle did not spin out with either tyre configuration. However, the for the same test inputs, the peak yaw rate was 11% higher and the peak body slip angle was 35% greater when the temporary use spare tyre was fitted. The author commented this may lead to loss of control at higher speeds. Once steady state was achieved the results with the normal tyres and the temporary use spare were very similar.

Tests with the saloon car were carried out with both the normal and run flat tyres fitted and correctly inflated except for the following conditions:

- Rear right deflated and unmodified;
- Rear right inflated and modified, involving the removal of the tread and outer steel belt, simulating a complete tread-belt separation.

At low lateral accelerations below 0.3g the saloon maintained a safe understeer characteristic with both normal and run-flat tyres fitted for all tyre conditions. At higher lateral accelerations the overall characteristic was one of oversteer for conditions that involved a deflated or modified tyre on the outside of the turn. Deflated or modified tyres also reduced the ultimate lateral acceleration achievable. Both the normal and run-flat tyres were dislodged from the rim when they were located on the outside of the turn when the vehicle was approaching the limit of lateral acceleration.

In the step steer tests a loss of control was only experienced when a deflated or modified tyre was on the outside of the turn. Peak yaw rates were substantially higher when deflated or modified tyres were used compared to correctly inflated tyres for both tyre types. However the extent to which they were higher cannot be quantified because of limitations of the instrumentation. Both types of modified tyres produced a measurably higher peak yaw rate immediately after the steering input when compared to deflated tyres.

2 Experimental programme: Pavement Friction Tester (PFT)

2.1 Aims and objectives

The literature review did not identify any published literature describing the effect that tyre inflation pressure and type have on the longitudinal friction measurement between the tyre and pavement for modern tyre types. Some literature was identified that compared stopping distances and handling performance.

Therefore the aims of this element of experimental programme were to:

- investigate the effects that tyre type, surface condition, inflation pressure and speed have on the peak and locked wheel friction between the tyre and pavement;
- investigate the effects that tyre type and inflation pressure have on the locked wheel tyre marks left on a dry surface;
- contribute to the definition of the vehicle experimental programme to be carried out later in the project by identifying areas of interest and extreme results for further investigation.

2.2 Experimental equipment

The Pavement Friction Tester (PFT), operated by TRL on behalf of the Highways Agency (HA), was used to conduct the experimentation. The PFT was ballasted such that the axle weight was 930kg, equivalent to the static unladen front axle weight of the vehicle that was used subsequently in the vehicle experimental programme.

PFT operation was nominally in accordance with ASTM E274-06 (SAE, 2006), albeit with modified parameters including the tyres used, test speed and surface condition. This method utilizes a measurement representing the steady-state friction force on a locked wheel as it is dragged over a pavement surface under constant load and at a constant speed with the wheel aligned parallel to the direction of motion and perpendicular to the pavement. The average locked wheel friction number (equivalent to the coefficient of friction between the tyre and pavement multiplied by 100) was then determined from the measurements for each run. The rolling wheel peak friction number occurring prior to wheel lock was also determined.

Experimentation was carried out on the TRL Research Track on a both a wetted and dry stone mastic asphalt (SMA) surface, which complies with the requirements of Appendix A of TRL Report 314 together with the following requirements:

- Polished stone value of the course aggregate is not less than 65;
- The texture depth of the surfacing after compaction was in accordance with the requirements of Clause 921 of the Specification for Highway Works (Highways Agency, 2004);
- The texture depth, as measured by the sand patch method in accordance with BS598: Part 105, (BSI, 1990) was 1.5mm when the track was laid.

Experimentation was carried out using three modern tyres, classified as the following for the purposes of then investigation:

- Normal (205/55R16);
- Low profile (195/40R16);
- Run flat (195/55R16).

The normal tyre was the same size (rim diameter, width and profile) as that fitted by the vehicle manufacturer as original equipment on the vehicle which was used in the vehicle experimental programme subsequently in the project, and representative of the size of tyres commonly found on modern cars. To minimise the effects of additional variables:

- All tyres used were from the same manufacturer;
- A 16” rim size was maintained throughout the experimentation;
- Tyre widths were matched as closely as possible; however not all tyres were available in the same width hence there was some slight variation;
- The normal and low profile tyre were of the same model;
- The size of the normal and run flat tyres were matched as closely as possible.

All experimentation on a wetted surface was carried out before commencing that on a dry surface so as to minimise the effects of tyre wear. All tests for each tyre type were carried out with a single tyre.

Ambient conditions (surface temperature, air temperature and relative humidity) were monitored and recorded during experimentation to ensure consistency, as was the tyre temperature due to the potential for heat build up when operating in an under-inflated condition.

2.3 Experimental procedure

For the normal tyre the effects that inflation pressure, speed and surface condition had on the friction between the tyre and pavement were investigated. For the low profile and run flat tyres all runs were carried out at the same speed. Only the effects of inflation pressure and surface condition were investigated.

The reference tyre pressure used for all tyres was that for the unladen front axle of the vehicle that was used in the vehicle experimental programme subsequently in the project, namely 2.30bar. Experimentation was carried out at this pressure and ±10% increments up to values of ±30%. Experimentation with the run flat tyre was also carried out with the tyre fully deflated.

The conditions (inflation pressure, speed and surface condition) under which experimentation was carried out for the normal, low profile and run flat tyres are shown in Table 1, Table 2 and Table 3 respectively. The number of runs carried out under each condition is shown.

Table 1. Normal tyre experimental matrix

Surface condition	Speed (mile/h)	Inflation condition (relative to normal)						
		-30%	-20%	-10%	Normal	+10%	+20%	+30%
Wet	20	10			10			10
	40	10	10	10	10	10	10	10
	60	10			10			10
Dry	20							
	40	6			6			6
	60							

Table 2. Low profile tyre experimental matrix

Surface condition	Speed (mile/h)	Inflation condition (relative to normal)						
		-30%	**-20%**	**-10%**	**Normal**	**+10%**	**+20%**	**+30%**
Wet	20							
	40	10	10	10	10	10	10	10
	60							
Dry	20							
	40	6			6			6
	60							

Table 3. Run flat tyre experimental matrix

Surface condition	Speed (mile/h)	Inflation condition (relative to normal)							
		-100%	**-30%**	**-20%**	**-10%**	**Normal**	**+10%**	**+20%**	**+30%**
Wet	20								
	40	10	10	10	10	10	10	10	10
	60								
Dry	20								
	40	6	6			6			6
	60								

Examples of the tyres inflated at various pressures are shown in Table 4.

Table 4. Tyres at each inflation condition

Inflation Condition (relative to normal)	Normal	Low profile	Run flat
+30%			
Normal			
-30%			
-100%			

To facilitate statistical analysis a total of ten runs was completed for each unique condition when experimenting on a wetted surface. Experimentation on a dry surface caused substantial tyre wear, hence the number of conditions investigated was reduced and only six runs were carried out for each condition. Photographic evidence and measurements describing the tyre marks left when experimenting on a dry surface were also recorded.

2.4 Results and analysis

The results were compiled and an ANOVA analysis performed to identify statistically significant differences at the 95% confidence level between the locked wheel friction numbers and rolling wheel peak friction numbers for the experimental conditions evaluated. This section describes the results and the key statistically significant findings.

2.4.1 *Normal tyre*

The results obtained for the normal tyre are shown in Table 5. The figures shown in brackets are the lower and upper 95% confidence limits about the mean.

Table 5. Normal tyre mean rolling wheel peak and locked wheel friction numbers

Inflation condition	Surface condition							
	Wetted						Dry	
	Speed (mile/h)							
	20		40		60		40	
	Mean friction number							
	Rolling peak	Locked	Rolling peak	Locked	Rolling peak	Locked	Rolling peak	Locked
-30%	98.9 (96.1, 101.6)	58.4 (57.2, 59.7)	96.2 (94.4, 98.0)	43.0 (41.8, 44.2)	89.1 (87.1, 91.2)	38.9 (37.6, 40.2)	121.8 (120.1, 123.5)	64.7 (61.9, 67.5)
-20%	-	-	97.6 (95.8, 99.3)	44.6 (43.4, 45.9)	-	-	-	-
-10%	-	-	97.4 (95.6, 99.2)	43.5 (42.2, 44.7)	-	-	-	-
Normal	95.8 (93.1, 98.6)	59.6 (58.4, 60.9)	97.1 (95.3, 98.9)	47.4 (46.2, 48.7)	94.7 (92.7, 96.8)	45.3 (44.0, 46.6)	113.4 (111.7, 115.1)	68.3 (65.5, 71.1)
+10%	-	-	96.7 (95.0, 98.5)	42.6 (41.3, 43.8)	-	-	-	-
+20%	-	-	96.6 (94.8, 98.3)	42.8 (41.5, 44.0)	-	-	-	-
+30%	97.3 (94.5, 100.0)	54.2 (53.0, 55.5)	92.7 (91.0, 94.5)	41.5 (40.3, 42.8)	89.6 (87.5, 91.6)	36.3 (35.0, 37.6)	116.6 (114.9, 118.3)	65.7 (62.9, 68.5)

The normal tyre locked wheel friction number and rolling wheel peak friction number results are shown in Figure 2.1 and Figure 2.2 respectively.

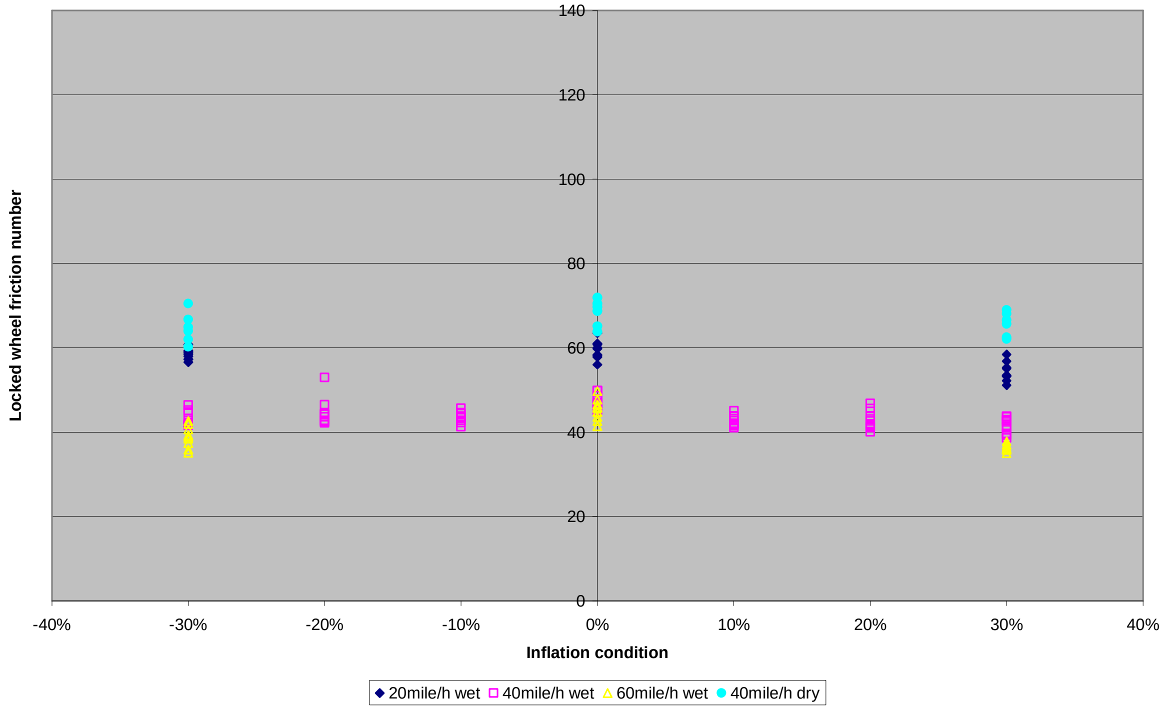


Figure 2.1. Normal tyre locked wheel friction number

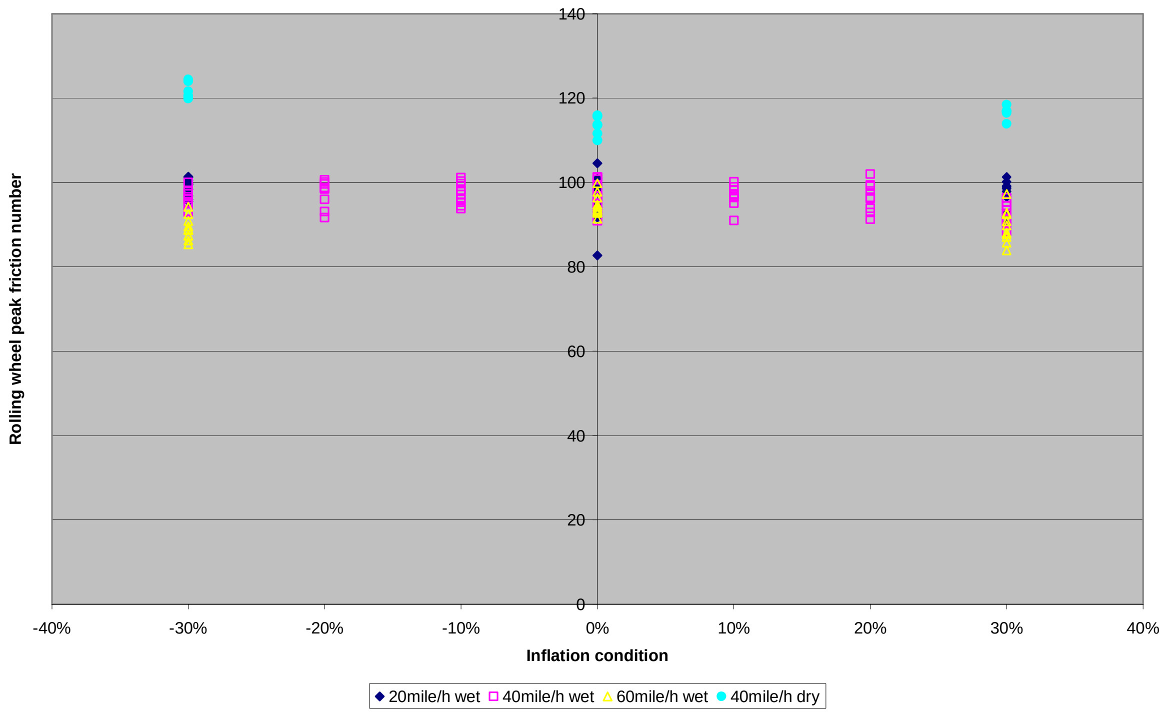


Figure 2.2. Normal tyre rolling wheel peak friction number

Analysis of the results obtained for the locked wheel friction number and rolling wheel peak friction number for the normal tyre on a wetted surface yielded:

- At 20mile/h:

    - There was a statistically significant difference between the locked wheel friction number obtained for +30% inflation compared to the other inflation conditions, between which there were no statistically significant differences. The locked wheel friction number reduced at +30% inflation.
    - The mean rolling wheel peak friction number was slightly lower for the normal pressure than the -30% or +30% inflation. However there were no statistically significant differences.
- At 40mile/h:
    - The highest mean locked wheel friction number was obtained for normal inflation. The only statistically significant difference identified was between the locked wheel friction number for normal inflation and all other inflations, between which there were no statistically significant differences;
    - The mean rolling wheel peak friction number results were similar for all inflation conditions, the only statistically significant difference being that the rolling wheel peak friction number for +30% inflation is less than that for all other inflation conditions.
- At 60mile/h:
    - The highest mean locked wheel friction number was obtained for normal inflation, the lowest for +30% inflation, -30% lying in between. Statistically significant differences were identified between the results obtained for all inflation pressures.
    - The mean rolling wheel peak friction number was greater at normal inflation than +30% and -30% inflation. A statistically significant difference was identified between the results obtained for normal inflation and all other inflations.

Analysis of the results obtained for the locked wheel friction number and rolling wheel peak friction number for the normal tyre on a dry surface (Table 5) yielded:

- At 40mile/h there were no statistically significant differences between the locked wheel friction numbers obtained; although the sample mean locked wheel friction number for normal inflation was slightly greater than those for +30% and -30% inflation.
- The mean rolling wheel peak friction number was lowest at the normal inflation pressure and greatest at -30% inflation. Statistically significant differences were identified between the results obtained for all inflation pressures.

2.4.2 Low profile tyre

The results obtained for the low profile tyre are shown in Table 6. The figures shown in brackets are the lower and upper 95% confidence limits about the mean.

Table 6. Low profile tyre mean rolling wheel peak and locked wheel friction numbers

Inflation condition	Surface condition			
	Wetted		Dry	
	Speed (mile/h)			
	40			
	Mean friction number			
	Rolling peak	Locked	Rolling peak	Locked
-30%	81.6 (78.0, 85.1)	31.1 (29.1, 33.0)	115.9 (114.8, 117.1)	78.5 (76.1, 80.8),)
-20%	83.6 (80.0, 87.1)	31.8 (29.9, 33.8)	-	-
-10%	81.7 (78.2, 85.3)	32.0 (30.1, 34.0)	-	-
Normal	81.0 (77.4, 84.6)	28.8 (26.9, 30.8)	115.0 (113.9, 116.2)	70.3 (67.9, 72.6)
+10%	79.4 (75.8, 83.0)	31.3 (29.4, 33.3)	-	-
+20%	88.6 (85.0, 92.1)	36.6 (34.7, 38.5)	-	-
+30%	90.1 (86.5, 93.7)	39.1 (37.1, 41.0)	117.0 (115.9, 118.2)	73.0 (70.7, 75.3)

The low profile tyre locked wheel friction number and rolling wheel peak friction number results are shown in Figure 2.3 and Figure 2.4 respectively.

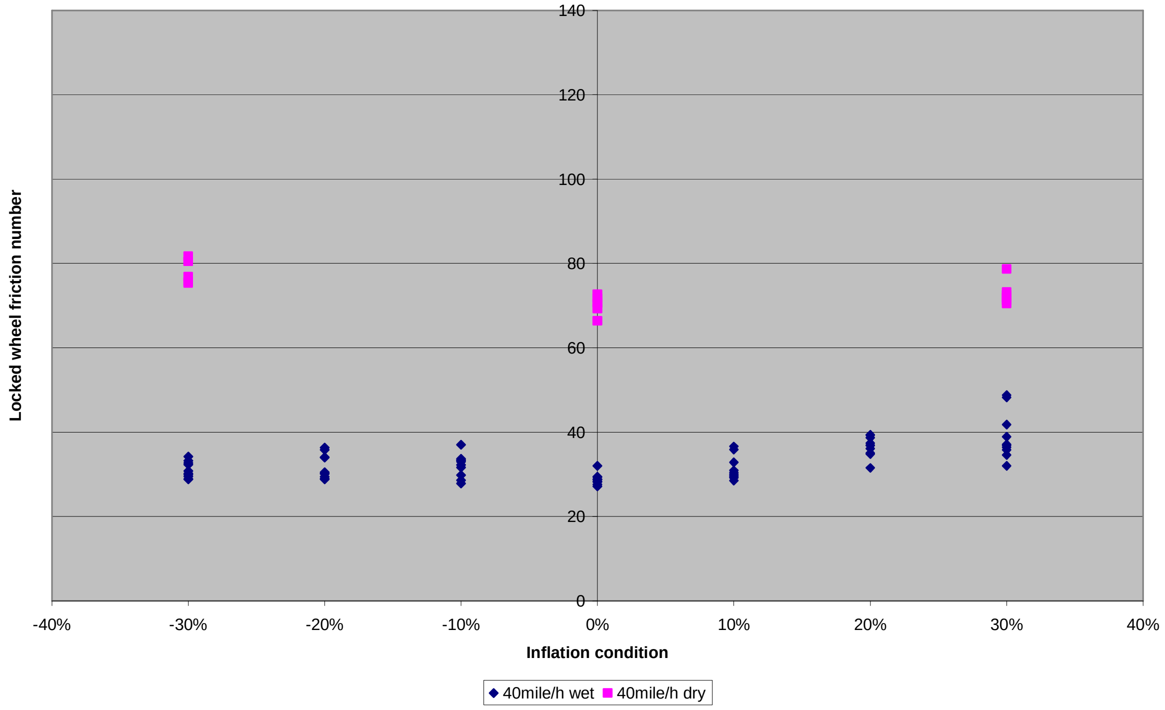


Figure 2.3. Low profile tyre locked wheel friction number

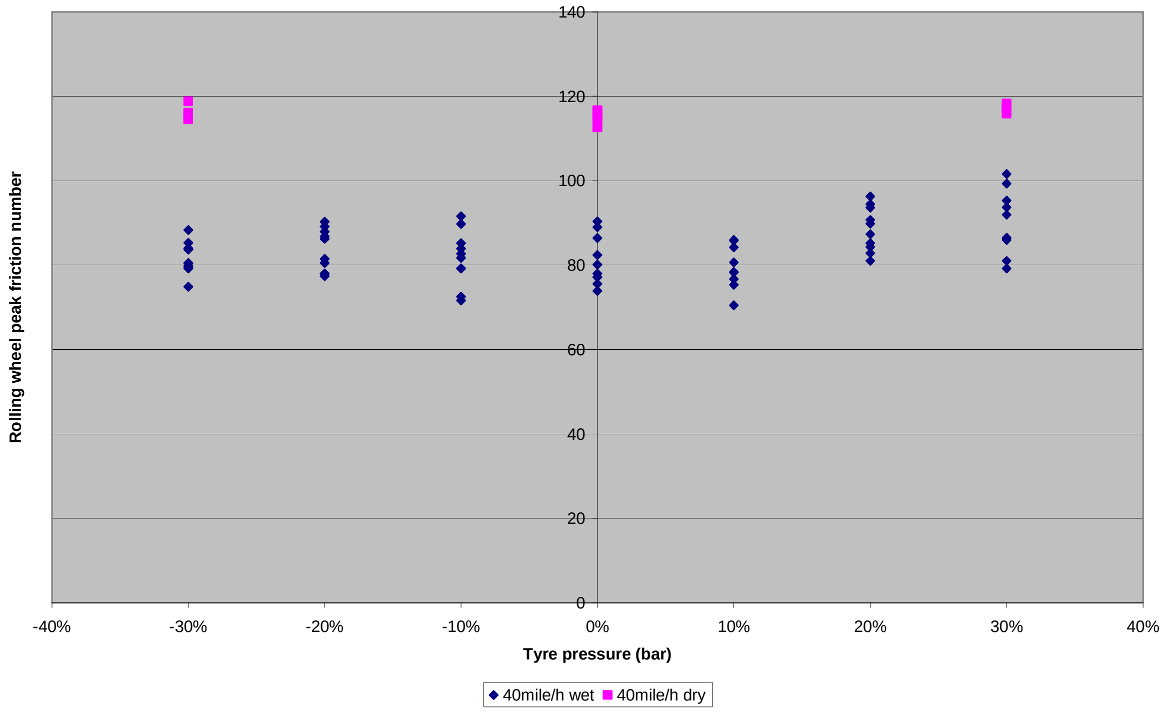


Figure 2.4. Low profile tyre rolling wheel peak friction number

Analysis of the results obtained for the locked wheel friction number and rolling wheel peak friction number for the low profile tyre on a wetted surface yielded:

- The mean locked wheel friction number was lowest for normal inflation, and similar for all other inflation pressures except for +20% and +30% inflation where the friction number increased slightly. A statistically significant difference was identified between the results obtained for the +20% and +30% inflation together and all other inflations.
- The mean rolling wheel peak friction number was similar for the normal and -10%, -20% and -30% inflations, with greater values obtained for +10%, +20% and +30%. A statistically significant difference was identified between the +30% inflation and all other inflation pressures.

Analysis of the results obtained for the locked wheel friction number and rolling wheel peak friction number for the low profile tyre on a dry surface yielded:

- The mean locked wheel friction number was lowest for normal inflation and greatest at -30% inflation. A statistically significant difference was identified between -30% inflation and the other inflations.
- The mean rolling wheel peak friction number was similar for all inflations. No statistically significant differences were identified.

Statistical analyses comparing the locked wheel friction number and rolling wheel peak friction number for the normal and low profile tyre were not performed. However, comparing the means on a wetted surface yields:

- The locked wheel friction number for the low profile tyre is lower by 11.2 to 12.8 for inflations of -30% to +10%, except for at normal inflation where the difference is 18.6. The difference reduces to 6.2 at +20% inflation and 2.5 at +30%.
- The rolling wheel peak friction number for the low profile tyre is lower by 14.0 to 17.3 at inflations of -30% to +10%. The difference reduces to 8.0 at +20% inflation and 2.6 at +30%.

Comparing the means on a dry surface yields:

- The low profile tyre locked wheel friction number is 5.9 less than that of the low profile tyre at -30% inflation. At normal and +30% inflation the values obtained are similar for both tyre types.
- At normal inflation the low profile tyre rolling wheel peak friction number is 2.0 greater than that of the normal tyre. At +30% inflation the difference is 7.3, and at -30% it is 13.7.

2.4.3 Run flat tyre

The results obtained for the run flat tyre are shown in Table 7. The figures shown in brackets are the lower and upper 95% confidence limits about the mean.

Table 7. Run flat tyre mean rolling wheel peak and locked wheel friction numbers

Inflation condition	Surface condition			
	Wetted		Dry	
	Speed (mile/h)			
	40			
	Mean friction number			
	Rolling peak	Locked	Rolling peak	Locked
-100%	70.1 (67.3, 72.8)	27.9 (25.8, 30.0)	97.2 (95.7, 98.7)	45.7 (44.0, 47.4)
-30%	88.1 (85.4, 90.9)	38.8 (36.7, 41.0)	119.8 (118.3, 121.2)	62.0 (60.2, 63.7)
-20%	90.6 (87.9, 90.9)	40.8 (38.6, 42.9)	-	-
-10%	90.4 (87.6, 93.1)	38.1 (36.0, 40.3)	-	-
Normal	85.4 (82.7, 88.2)	32.3 (30.2, 34.4)	115.0 (113.5, 116.4)	59.0 (57.3, 60.7)
+10%	90.6 (87.8, 93.3)	35.2 (33.1, 37.4)	-	-
+20%	92.3 (89.6, 95.1)	35.6 (33.5, 37.8)	-	-
+30%	90.0 (87.2, 92.7)	35.0 (32.9, 37.1)	116.1 (114.6, 117.5)	57.7 (56.0, 59.4)

The run flat tyre locked wheel friction number and rolling wheel peak friction number results are shown in Figure 2.5 and Figure 2.6 respectively.

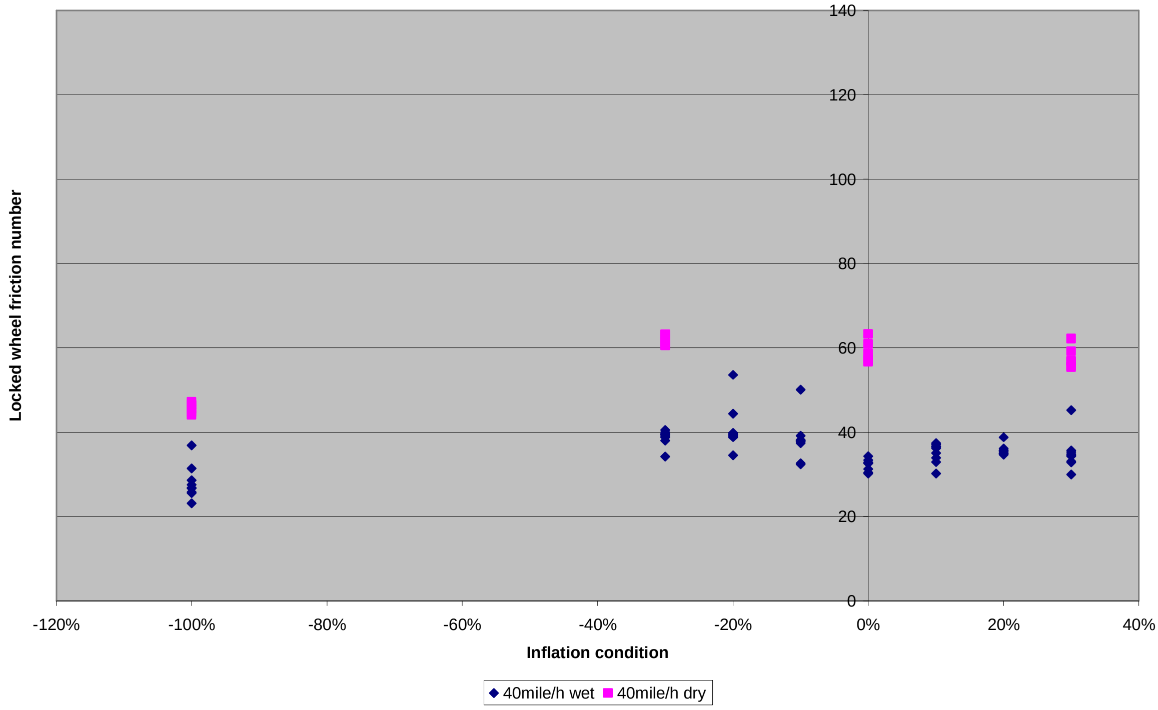


Figure 2.5. Run flat tyre locked wheel friction number

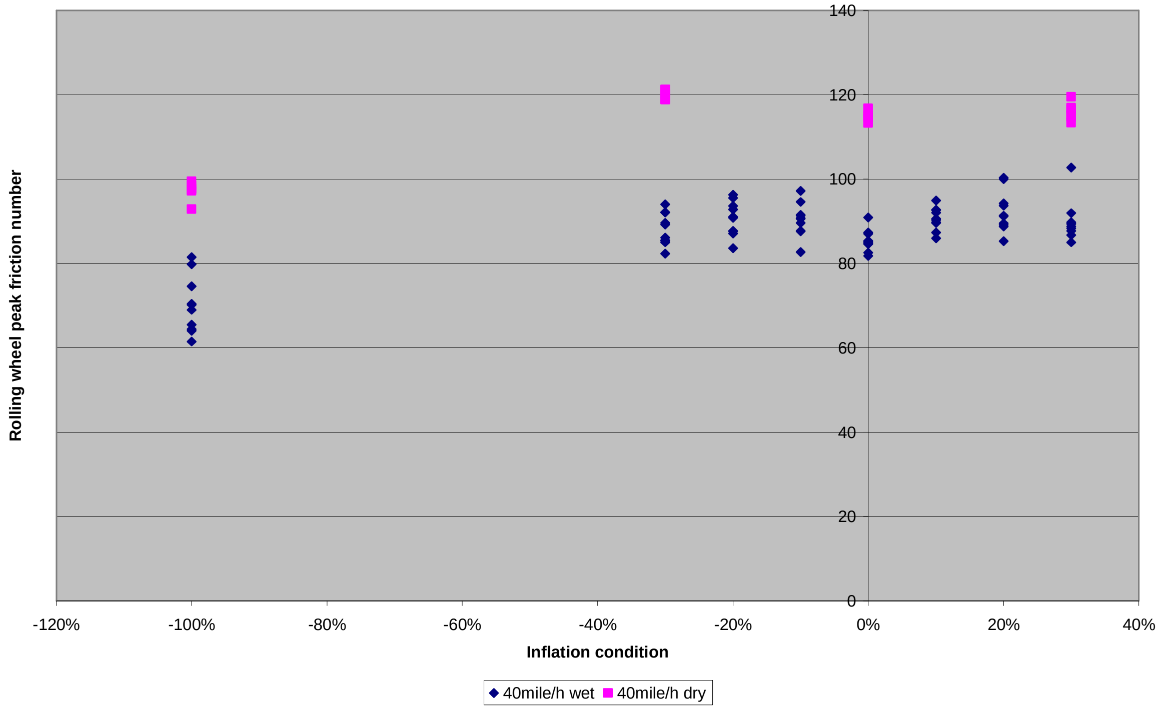


Figure 2.6. Run flat tyre rolling wheel peak friction number

Analysis of the results obtained for the locked wheel friction number and rolling wheel peak friction number for the run flat tyre on a wetted surface yielded:

- The mean locked wheel friction number obtained for -100% inflation was substantially lower than that for all other inflations and the mean locked wheel friction number for normal inflation was lower than that for all other inflated conditions. A statistically significant difference was identified between -100% inflation and all other inflations except for normal inflation.
- The mean rolling wheel peak friction number was substantially lower for -100% inflation than all other inflations, and the mean rolling wheel peak friction number was lower than that for all other inflated conditions, the remaining pressures providing similar results. A statistically significant difference was identified between -100% inflation and all other inflations.

Analysis of the results obtained for the locked wheel friction number and rolling wheel peak friction number for the run flat tyre on a dry surface yielded:

- The mean locked wheel friction number obtained for -100% inflation was substantially lower than that for all other inflations. A statistically significant difference was identified between -100% inflation and all other inflations
- The mean rolling wheel peak friction number obtained for -100% inflation was substantially lower than that for all other inflations. A statistically significant difference was identified between -100% inflation and all other inflations.

Statistical analyses comparing the locked wheel friction number and rolling wheel peak friction number for the normal and run flat tyre were not performed. However, comparing the means on a wetted surface yields:

- The locked wheel friction number for the run flat tyre is lower by 14.0 to 17.3 at -30% to +10% inflation. The difference reduces to 8.0 at +20% inflation and 2.6 at +30%.
- The rolling wheel peak friction number for the run flat tyre is lower by 5.8 to 15.1 for inflations of -30% to +30%, except for at -10% inflation where the difference is 2.7.

Comparing the means on a dry surface yields:

- The locked wheel friction number for the run flat tyre is lower by 2.8 at -30% inflation, 9.3 at normal inflation and 8.0 at +30% inflation.
- The rolling wheel peak friction numbers for the run flat tyre are similar to those of rthe normal tyre, varying by a maximum of 2.1 at -30% inflation.

Comparing the means for the run flat and low profile tyres on a wetted surface yields:

- The locked wheel friction number for the run flat tyre is greater by 3.8 to 11.2 at -30% to +20% inflation. The values at +30% inflation are similar.
- The rolling wheel peak friction number for the run flat tyre is greater by 3.5 to 8.9 for inflations of -30% to +10%. At +20% the values are similar and at +30% the run flat value is less than the low profile value by 4.1.

Comparing the means for the run flat and low profile tyres on a dry surface yields:

- The locked wheel friction number for the run flat tyre is greater by 11.3 to 16.5 at -30% to +30% inflation.
- The rolling wheel peak friction numbers for the run flat and low profile tyres are similar. The greatest difference is at -30% inflation where the run flat value is greater by 3.8.

2.4.4 Tyre marks

The tyre marks made in the dry condition were photographed and any distinctive features were noted.

2.4.4.1 Normal tyre

There was little if anything to distinguish the marks made at normal and +30% inflation pressures. In both, the five ribs of the tread were clearly visible, as is shown in Figure 2.7.

Figure 2.7. Normal tyre, normal pressure (left – showing the marks from two successive runs) and +30% pressure (right):

Figure 2.8 shows that at -30% inflation, the mark was not dissimilar, although it had noticeably sharper edges.

Figure 2.8. Normal tyre, -30% pressure

2.4.4.2 Low profile tyre

Figure 2.9 shows the tyre marks from the low profile tyre at normal pressure and at +30% pressure.

Figure 2.9. Low profile tyre, normal pressure (left) and +30% pressure (right)

At normal pressure, the sharp edge of the tyre mark makes it very similar in appearance to the normal tyre at normal pressure. At +30% the mark had less sharp edges and was noticeably narrower, at about 14.5cm compared with 16.5cm under normal inflation.

Figure 2.10 shows that at -30% pressure the mark from the low profile tyre was clearly wider and sharper edged.

Figure 2.10.Low profile tyre, -30% pressure

2.4.4.3 Run flat tyre

The mark at normal pressure is shown in Figure 2.11, its width is 15 cm.

Figure 2.11. Run flat tyre, normal pressure

Figure 2.12 shows that at inflations of +30% and -30% the mark was very similar in appearance, being slightly narrower in the first case and slightly wider in the second by about 0.5cm.

Figure 2.12. Run flat tyre, +30% pressure (left) and -30% pressure (right)

With full deflation, the mark from the run flat tyre shows a dramatic difference, as can be seen in Figure 2.13.

Figure 2.13. Run flat tyre, fully deflated

The mark becomes a pair of “tram lines”, with a width of 17cm, and is clearly made by the shoulders of the tread area only. Figure 2.14 shows the worn patch on one shoulder after these runs.

Figure 2.14. Run flat tyre with wear to shoulder after fully deflated runs

3 Experimental programme: Vehicle

A series of full vehicle experiments was carried out to determine how the vehicle would behave with a combination of different tyre pressures for two different types of tyre, normal and run flat. The experiments were carried out in two parts, straight line braking and vehicle handling.

3.1 Experimental equipment

A medium sized, front wheel drive four door saloon equipped with anti-lock brakes (ABS), electronic brake force distribution (EBD). The vehicle was also fitted with electronic stability control (ESC), but this was switched off for all experimentation.

For all experimentation carried out the vehicle was in its kerb weight condition with an allowance of 150kg for the instrumentation and driver. The vehicle was fitted with the following instrumentation:

- 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 Straight line braking

3.2.1 Experimental procedures

The objective of this manoeuvre was to determine the braking performance and directional behaviour of the experimental vehicle during a straight line braking manoeuvre on a road surface having a high coefficient of friction. Experimentation was carried out on the same stone mastic asphalt (SMA) surface on the TRL Research Track as was used for the PFT experimental programme.

The manoeuvre was performed nominally in accordance with the procedure developed for the PNCAP braking protocol (Dodd, 2003). In this manoeuvre the steady state linear motion of the experimental vehicle travelling at a constant velocity of 40mile/h was disturbed by a rapid brake application. Prior to braking, the throttle was released and the transmission put into neutral. The brake pedal was pressed as quickly as possible to achieve a brake pedal force greater than 500N, which was then held constant for the duration of the stop. The steering wheel position was fixed throughout the manoeuvre. The experimental results were collected from straight line braking tests for the tyre conditions described in Table 8 and Table 9. Six replicates for each set of tyre pressures were completed.

Ambient conditions (surface temperature, air temperature and relative humidity) were monitored and recorded during experimentation to ensure consistency, as was tyre temperature due to the potential for heat build up when operating in an under-inflated condition.

Table 8. Tyre pressures and affected tyre in experimental order – normal tyres

Order	Inflation (relative to normal pressure)	Tyres affected
1	-30%	Front
2	0%	All
3	-60%	Front
4	-60%	Side
5	-30%	All
6	-60%	All
7	-30%	Side

Table 9. Tyre pressures and affected tyre in experimental order – run flat tyres

Order	Inflation (relative to normal pressure)	Tyres affected
1	-30%	All
2	-100%	All
3	-100%	Front
4	0%	All
5	-60%	All
6	-100%	Side

The outcome variables from the experiments were Stopping Distance (m) and mean full developed deceleration (g) (MFDD). These results were the basis of the statistical investigation which aimed to determine any differences in results for different inflations (detailed in Table 8 and Table 9 above).

Within the investigation, it has been necessary to add some variables as covariates in the model. Possible covariates are Entry Speed, Mean Initial Speed, Change in Initial Speed, Initial Steering Angle, Overall Steering Angle, Average Brake Force, Reaction Time, Rise Rate, Delay Time, Mean Acceleration, and Peak Acceleration. A regression procedure is followed for each model in order to determine which covariates are required.

3.2.2 Results and analysis

Table 10 and Table 11 summarise the data for MFDD and stopping distance for the different inflation conditions for the normal and run flat tyres. For each condition, there were six replicates. Although the entry speed for the tests were restricted to 40mile/hr ±2mile/hr, entry speed is necessary as a covariate in the model for mean stopping distance to account for the remaining variation in entry speed.

Table 10. MFDD and unadjusted and adjusted mean stopping distance for each tyre inflation group – normal tyres

Inflation	MFDD (g)			Stopping Distance (m)			
	Mean	Std. Deviation	Rank	Mean	Std. Deviation	Rank	Adjusted Mean
-30% F	1.14	0.016	3	18.34	0.634	1	19.02
Normal	1.11	0.026	6	19.43	0.363	7	18.85
-60% F	1.07	0.098	7	18.86	0.655	4	19.04
-60% S	1.17	0.020	1	18.94	0.540	5	18.53
-30% A	1.13	0.056	5	19.39	0.742	6	19.05
-60% A	1.14	0.096	4	18.80	0.827	3	18.94
-30% S	1.14	0.046	2	18.45	0.945	2	18.78

Table 11. MFDD and unadjusted and adjusted mean stopping distance for each tyre inflation group – run flat tyres

Inflation	MFDD (g)			Stopping Distance (m)			
	Mean	Std. Deviation	Rank	Mean	Std. Deviation	Rank	Adjusted Mean
-30% A	1.02	0.025	3	19.18	0.025	3	19.42
-100% A	0.89	0.083	5	21.59	0.083	5	21.36
-100% F	0.88	0.043	6	21.56	0.043	6	22.09
Normal	1.04	0.026	1	19.12	0.026	1	18.90
-60% A	1.03	0.042	2	18.54	0.042	2	19.32
-100% S	0.90	0.035	4	24.41	0.035	4	21.30

Figure 3.1 and Figure 3.2 compare the values of MFDD and stopping distance for the different tyre inflations for both the normal and run flat tyres.

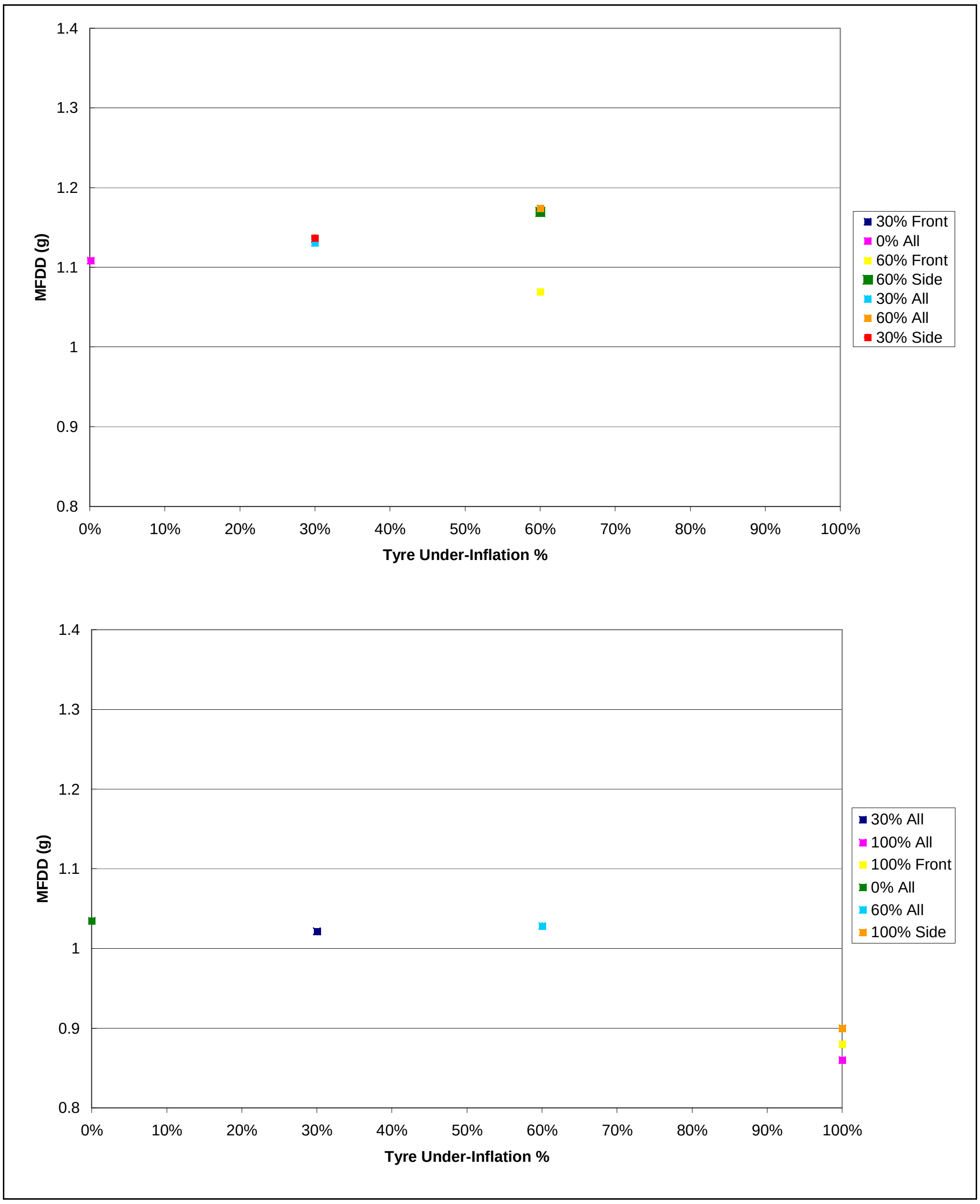


Figure 3.1. Average value of MFDD for normal tyres (top) and run flat tyres (bottom)

For normal tyres there appears to be a slight but insignificant increase in MFDD as the tyre pressure is reduced with the exception of the 60% under-inflated front tyres. For run flat tyres, the variation in MFDD is smaller than for the normal tyres at up to 60% under-inflation. When the run flat tyres were under-inflated by 100% there was a significant decrease in MFDD.

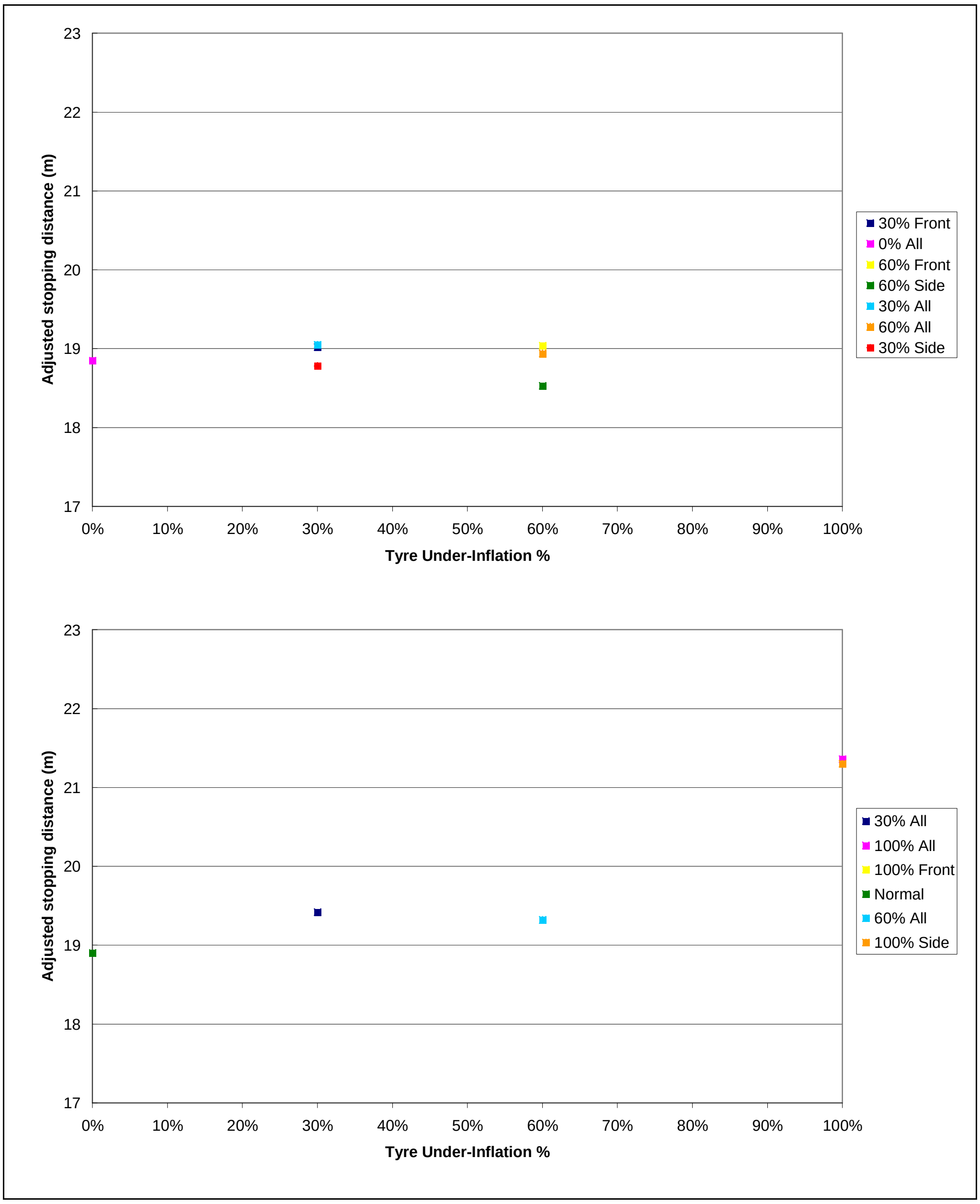


Figure 3.2. Comparison of average value of adjusted stopping distance between normal tyres (top) and run flat tyres (bottom)

For normal tyres, there is a reduction in stopping distance as the tyres are deflated from 30% to 60% under-inflation on all tyres. 60% under-inflation on only one side of the vehicle reduced the stopping distance by the largest amount, although this was less than 0.5m. However, significant differences were detected between 60% deflation on only one side and all conditions in the following group: 30% deflation on front tyres, 60% deflation on the front tyres, 30% deflation on all the tyres and 60% deflation on all tyres.

For the run flat tyres under-inflation by 30% or 60% had a small, but insignificant effect on stopping distance, with a mean stopping distance within 0.5m of the stopping distance achieved with the recommended pressures. Where the tyres were 100% under-inflated on all tyres, the front tyres or only one side of the car, the stopping distance increased by more than 2m from the baseline. This was statistically significantly different from all other inflation conditions.

A detailed statistical analysis of the straight line braking experiments can be found in Appendix A

3.3 Handling

3.3.1 Experimental procedure

3.3.1.1 Step steer

The objective of this manoeuvre was to investigate the handling performance and stability of the experimental vehicle during a step steer manoeuvre on a road surface having a high coefficient of friction. Experimentation was carried out on a hot rolled asphalt (HRA) surface on the TRL Research Track.

The step steer manoeuvre was performed nominally in accordance with the lateral transient response experimental methods for road vehicles (BSI, 1989). In this manoeuvre the steady state linear motion of the experimental vehicle travelling at a constant velocity of 50 mile/h was disturbed by a steering input that was applied as rapidly as possible to a predetermined value and maintained at that value. The accelerator pedal position was fixed for the duration of the initial period and maintained after the steering input was initiated.

The magnitude of the steering input was determined by requiring a steady state motion at 50 mile/h on a circular path, the radius of which gave the required lateral acceleration. The procedure recommends experimentation at a lateral acceleration of 0.4g; however for the purposes of this investigation, experimentation was carried out at the maximum lateral acceleration that the experimental vehicle could achieve, limited by the tyre-pavement friction. The procedure also states that both left and right turns shall be considered. This is intended to ensure the vehicle behaviour is symmetrical, which was not relevant to this investigation, and manoeuvres were carried out in one direction only. Experimental results were collected from step steer tests for the tyre conditions described in Table 12 and Table 13. Six replicates for each set of tyre pressures were completed. The pressure was reduced on the tyres loaded during the manoeuvre, namely the left tyres when carrying out a right step steer.

Table 12. Tyre pressures and affected tyre in experimental order – normal tyres

Order	Inflation (relative to normal pressure)	Tyres affected
1	-30%	Side
2	-50%	Side
3	0%	All
4	-30%	Front
5	-50%	Front

Table 13. Tyre pressures and affected tyre in experimental order – run flat tyres

Order	Inflation (relative to normal pressure)	Tyres affected
1	-100%	Front
2	-30%	Side
3	-50%	Side
4	0%	All
5	-50%	Front
6	-100%	Side
7	-30%	Front

Ambient conditions (surface temperature, air temperature and relative humidity) were monitored and recorded during experimentation to ensure consistency, as was tyre temperature due to the potential for heat build up when operating in an under-inflated condition.

The outcome variables from the experiments were lateral acceleration, yaw rate and slip angle. Analysis of each of these variables was performed in accordance with the method specified in the lateral transient response experimental methods for road vehicles (BSI, 1989), investigating:

- Response time (time taken for a vehicle transient response to achieve 90% of the new steady state value);
- Peak response time (time taken for a vehicle transient response to achieve its peak value);
- Peak value achieved (for lateral acceleration, yaw rate and slip angle);
- Steady state value (for lateral acceleration, yaw rate and slip angle).

3.3.1.2 Step steer in turn

The objective of this manoeuvre was to investigate the handling performance and stability of the experimental vehicle during a step steer manoeuvre whilst already undergoing cornering on a road surface having a high coefficient of friction. This manoeuvre was designed to reflect a possible accident situation where a driver negotiates a bend that suddenly tightens part way through, where the driver has selected his entry speed based on the initial larger radius of turn. Experimentation was carried out on a stone mastic asphalt (SMA) surface on the TRL Research Track.

In this manoeuvre the steady state circular motion of the experimental vehicle travelling at a constant velocity on a circular path of radius 100m with a lateral acceleration of 0.6g was disturbed by an additional steering input that doubled the steering wheel angle applied as rapidly as possible and maintained the value. The accelerator pedal position was fixed for the duration of the initial period and then released at the same time as the steering manoeuvre was initiated to maximise the potential vehicle instability. Experimental results were collected from step steer in turn tests for the tyre conditions described in Table 14 and Table 15. Six replicates for each set of tyre pressures were completed. The pressure was reduced on the tyre loaded during the manoeuvre, namely the right tyre when carrying out a left step steer in turn test.

Table 14. Tyre pressures and affected tyre in experimental order – normal tyres

Order	Inflation (relative to normal pressure)	Tyre affected
1	0%	Rear
2	-30%	Rear
3	-50%	Rear

Table 15. Tyre pressures and affected tyre in experimental order – run flat tyres

Order	Inflation (relative to normal pressure)	Tyre affected
1	0%	Rear
2	-30%	Rear
3	-50%	Rear
4	-100%	Rear

The outcome variables from the experiments were lateral acceleration, yaw rate and slip angle. Analysis of each of these variables was performed nominally in accordance with the method specified in the lateral transient response experimental methods for road vehicles (BSI, 1989) for a normal step steer test. However because of the nature of the manoeuvre, specifically the effect of the released accelerator and increased tyre scrub from the additional steering input which caused the vehicle to slow down rather than achieve a steady state situation, only the peak values for the variables were analysed.

Ambient conditions (surface temperature, air temperature and relative humidity) were monitored and recorded during experimentation to ensure consistency, as was tyre temperature due to the potential for heat build up when operating in an under-inflated condition.

3.3.2 Results and analysis

3.3.2.1 Step steer

Table 16 and Table 17 summarise the data for peak and steady state lateral acceleration, yaw rate and slip angle values, and the 90% and peak response times for each variable, for the different inflation pressures for the normal and run flat tyres.

Table 16. Mean lateral acceleration, yaw rate and slip angle response times and values for each tyre inflation group – normal tyre

Tyre under-inflation	Lateral acceleration				Yaw rate				Slip angle			
	Response time (s)		Peak (g)	Steady state (g)	Response time (s)		Peak (°/s)	Steady state (°/s)	Response time (s)		Peak (°)	Steady state (°)
	Peak	90%			Peak	90%			Peak	90%		
-30% Side	0.38 (0.37, 0.40)	0.18 (0.18, 0.19)	27.13 (26.31, 27.94)	21.70 (21.26, 22.14)	0.75 (0.65, 0.86)	0.30 (0.29, 0.31)	0.96 (0.94, 0.98)	0.80 (0.78, 0.82)	0.21 (0.18, 0.23)	0.08 (0.07, 0.10)	2.67 (2.54, 2.81)	1.58 (1.44, 1.71)
-50% Side	0.41 (0.37, 0.44)	0.18 (0.17, 0.18)	26.21 (25.62, 26.8)	20.75 (20.53, 20.98)	0.83 (0.62, 1.04)	0.28 (0.27, 0.29)	0.91 (0.89, 0.92)	0.75 (0.74, 0.76)	0.96 (-0.52, 2.44)	0.08 (0.06, 0.09)	2.50 (2.40, 2.61)	1.61 (1.45, 1.78)
Normal	0.44 (0.40, 0.48)	0.18 (0.17, 0.18)	29.52 (28.87, 30.17)	23.15 (22.84, 23.45)	0.70 (0.57, 0.82)	0.29 (0.28, 0.31)	1.00 (0.98, 1.01)	0.84 (0.82, 0.85)	0.20 (0.19, 0.21)	0.08 (0.06, 0.09)	2.95 (2.85, 3.05)	1.82 (1.63, 20.00)
-30% Front	0.44 (0.38, 0.50)	0.18 (0.17, 0.19)	26.96 (26.17, 27.74)	21.86 (21.47, 22.24)	0.71 (0.59, 0.84)	0.29 (0.27, 0.31)	0.96 (0.94, 0.97)	0.80 (0.79, 0.82)	0.21 (0.20, 0.22)	0.08 (0.07, 0.09)	2.80 (2.68, 2.91)	1.72 (1.66, 1.78)
-50% Front	0.41 (0.37, 0.45)	0.18 (0.18, 0.18)	25.45 (24.56, 26.33)	20.57 (20.26, 20.88)	0.59 (0.56, 0.61)	0.28 (0.26, 0.30)	0.93 (0.91, 0.95)	0.76 (0.74, 0.77)	1.05 (-0.62, 2.71)	0.09 (0.09, 0.10)	2.60 (2.53, 2.68)	1.79 (1.64, 1.94)

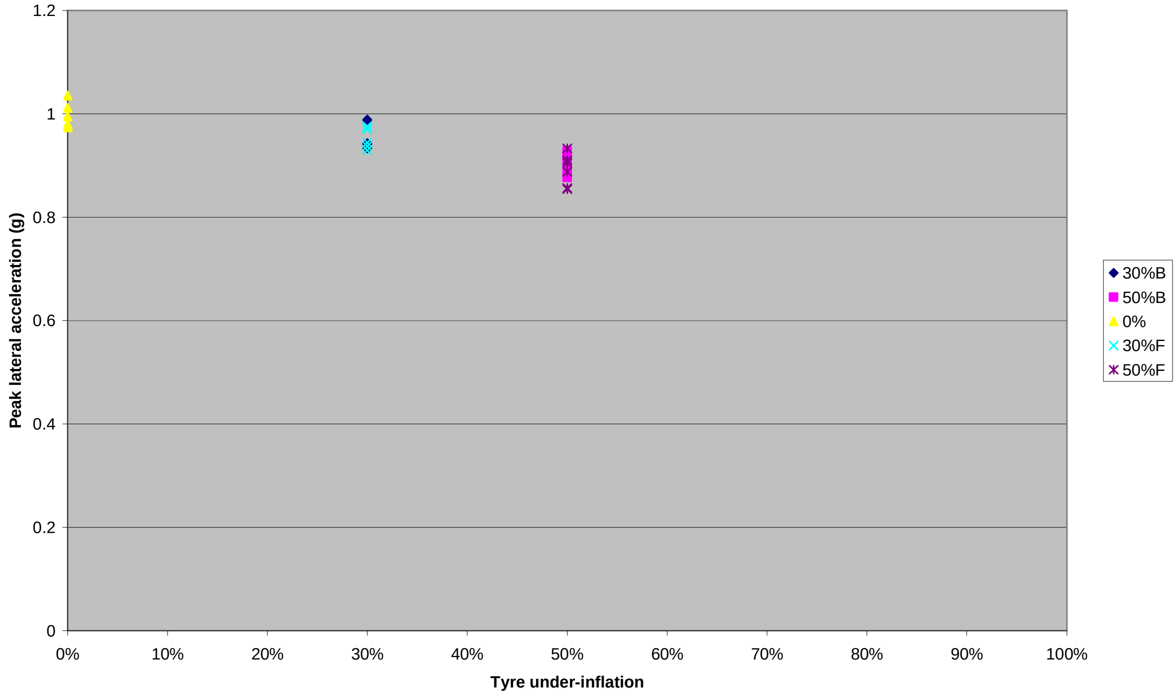
Table 17. Mean lateral acceleration, yaw rate and slip angle response times and values for each tyre inflation group – run flat tyre

Tyre under-inflation	Lateral acceleration				Yaw rate				Slip angle			
	Response time (s)		Peak (g)	Steady state (g)	Response time (s)		Peak (°/s)	Steady state (°/s)	Response time (s)		Peak (°)	Steady state (°)
	Peak	90%			Peak	90%			Peak	90%		
-100% Front	0.34 (0.29, 0.39)	0.14 (0.14, 0.15)	18.37 (17.71, 19.03)	14.53 (14.23, 14.82)	0.60 (0.56, 0.63)	0.21 (0.20, 0.23)	0.65 (0.64, 0.66)	0.53 (0.51, 0.54)	3.03 (0.51, 5.54)	0.10 (0.09, 0.10)	1.98 (1.88, 2.09)	1.35 (1.23, 1.46)
-30% Side	0.45 (0.40, 0.50)	0.17 (0.16, 0.17)	27.3 (26.78, 27.83)	21.19 (20.99, 21.39)	0.58 (0.53, 0.63)	0.30 (0.26, 0.34)	0.93 (0.91, 0.95)	0.77 (0.76, 0.78)	0.20 (0.19, 0.21)	0.08 (0.06, 0.09)	2.58 (2.47, 2.69)	1.32 (1.23, 1.41)
-50% Side	0.48 (0.44, 0.51)	0.17 (0.16, 0.18)	26.44 (25.9, 26.98)	20.70 (20.22, 21.17)	0.65 (0.56, 0.73)	0.28 (0.26, 0.29)	0.90 (0.89, 0.91)	0.75 (0.74, 0.75)	0.20 (0.17, 0.22)	0.08 (0.07, 0.09)	2.53 (2.43, 2.63)	1.26 (1.11, 1.40)
Normal	0.50 (0.46, 0.54)	0.17 (0.17, 0.18)	28.88 (28.44, 29.31)	22.70 (22.30, 23.09)	0.60 (0.57, 0.64)	0.29 (0.27, 0.31)	1.02 (1.00, 1.03)	0.82 (0.81, 0.83)	0.21 (0.20, 0.22)	0.07 (0.06, 0.08)	2.62 (2.46, 2.79)	1.22 (1.00, 1.44)
-50% Front	0.45 (0.42, 0.48)	0.17 (0.17, 0.17)	27.01 (26.41, 27.62)	21.23 (21.08, 21.39)	0.59 (0.56, 0.61)	0.28 (0.26, 0.30)	0.93 (0.91, 0.95)	0.76 (0.74, 0.77)	1.15 (-0.71, 3.01)	0.09 (0.07, 0.10)	2.68 (2.49, 2.87)	1.48 (1.25, 1.71)
-100% Side	0.41 (0.36, 0.47)	0.15 (0.14, 0.15)	21.16 (20.19, 22.12)	14.27 (13.7, 14.84)	0.67 (0.52, 0.81)	0.24 (0.22, 0.26)	0.65 (0.62, 0.67)	0.65 (0.62, 0.67)	0.18 (0.17, 0.20)	0.05 (0.04, 0.06)	1.86 (1.71, 2.00)	0.76 (0.60, 0.91)
-30% Front	0.48 (0.44, 0.52)	0.17 (0.17, 0.17)	28.19 (27.12, 29.25)	21.76 (21.44, 22.07)	0.63 (0.60, 0.67)	0.28 (0.25, 0.30)	0.95 (0.93, 0.97)	0.78 (0.78, 0.79)	0.19 (0.19, 0.20)	0.07 (0.06, 0.08)	2.58 (2.40, 2.75)	1.29 (1.05, 1.53)

The 90% and peak response times were very similar, and in fact no significant differences were found, for all variables for the normal tyre at the various inflation pressures. The greatest difference was in the lateral acceleration peak response time, where the fastest response was achieved with the tyres inflated correctly. Similarly, for the run flat tyre there was little variation in the response times when the tyres were inflated to some extent. However, when the tyres were 100% under-inflated there were some significant differences discovered (see Table 29, Table 30, Table 33 and Table 36). The lateral acceleration 90% response time, yaw rate 90% and peak response and slip angle 90% response time was quicker for 100% under-inflation compared to all other inflation pressures. This was a significant difference for lateral acceleration 90% reponse time between 100% deflation (front and all) and all other inflation levels (Table 30). For yaw rate 90%, significant differences were found between 100% deflation on front tyres and all inflations of 50% or less (Table 33). For slip angle 90% response time (Table 36) significant differences were found between 100% deflation on all tyres and all inflations of 50% or less.

However, for all lateral accelerations and yaw rates, the peak or steady state value achieved when the tyres were 100% under-inflated was significantly lower than that achieved with all other inflation conditions. However statistically significant differences in steady state slip angle were only identified between the conditions of 100% deflation on all the tyres and all other inflation conditions of up to 50% under-inflation.

Figure 3.3, Figure 3.4, Figure 3.5 and Figure 3.6 compare the peak and steady state values of lateral acceleration and yaw rate angle for each replicate for the different tyre inflations for both the normal and run flat tyres.



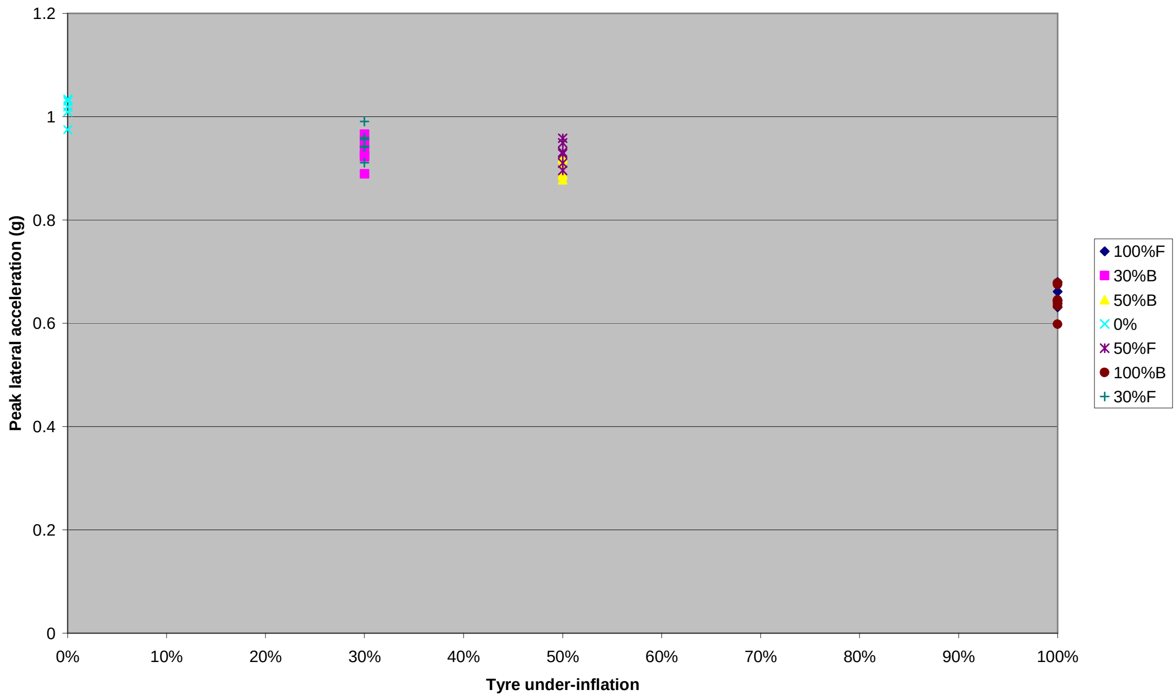
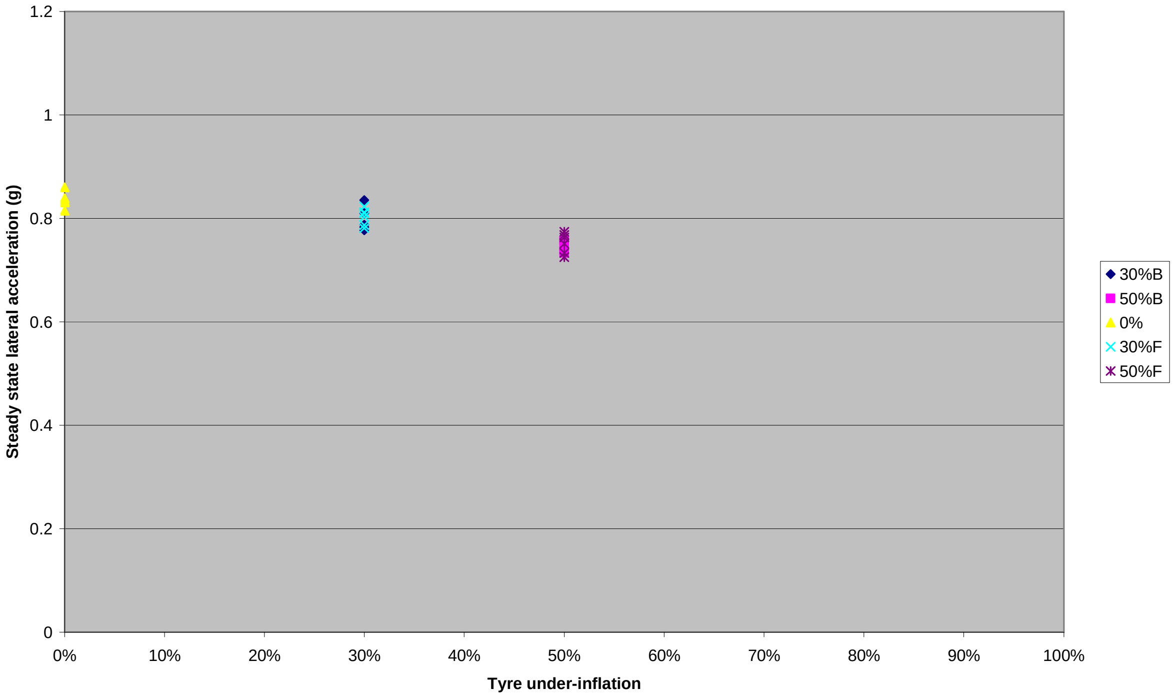


Figure 3.3. Comparison of variation in peak lateral acceleration between normal tyres (top) and run flat tyres (bottom)

The peak lateral accelerations achieved for the normal tyres were similar, but exhibiting a downwards trend as the inflation reduced. Significant differences were detected here between the average for normal inflation (yellow triangle) and all other averages, and also differences between 50% inflation on the front tyres (purple cross) and 30% deflation on all tyres (blue diamond). For run-flats, a similar trend is evident, however more significant differences were found here (see Table 31). For both tyre types the peak lateral acceleration achieved reduced with further under-inflation, and reduced significantly when the run flat tyre was 100% under-inflated. Experimentation carried out with only the front tyre pressure altered, or both the front and rear tyre pressures altered, yielded similar responses.



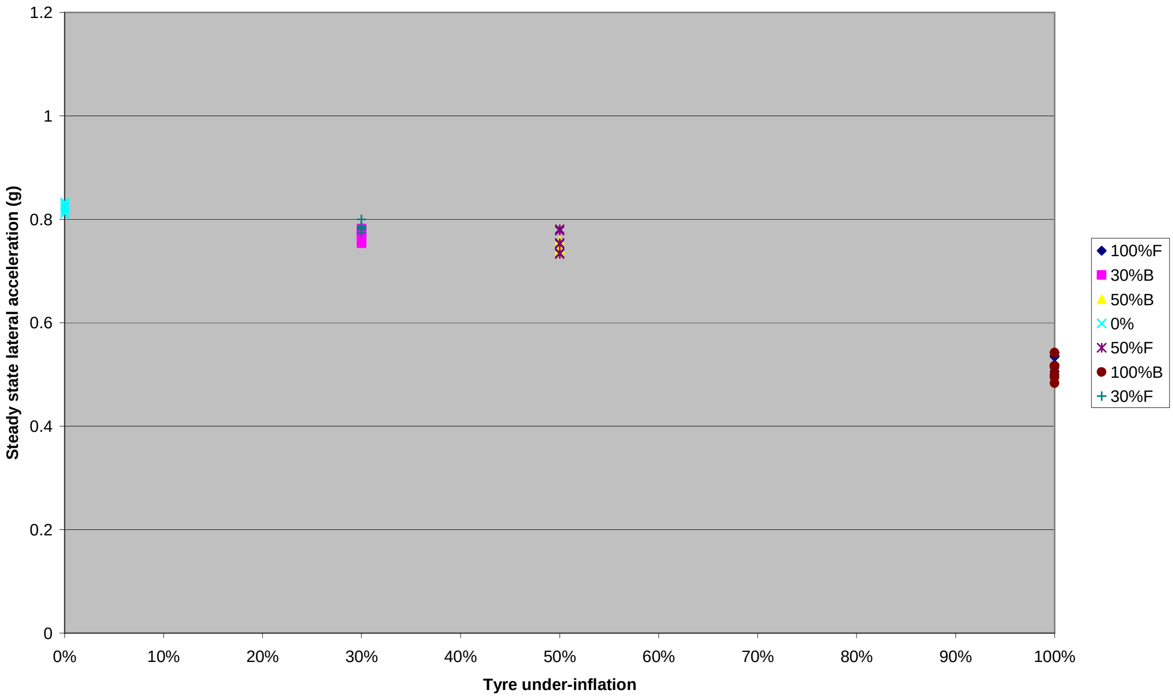
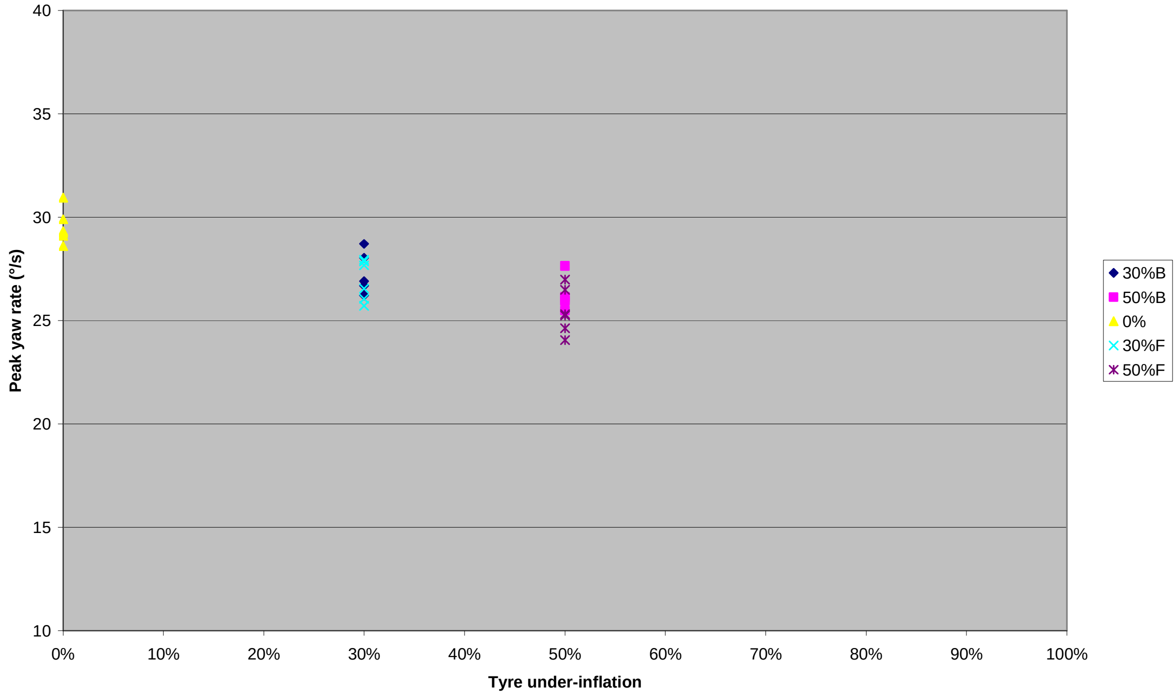


Figure 3.4. Comparison of variation in steady state lateral acceleration between normal tyres (top) and run flat tyres (bottom)

The findings for the effect of inflation pressure on the steady state lateral acceleration achieved mirror those for the peak lateral acceleration. Steady state values are lower than the peak values, but display similar trends of a reduction with further under-inflation.



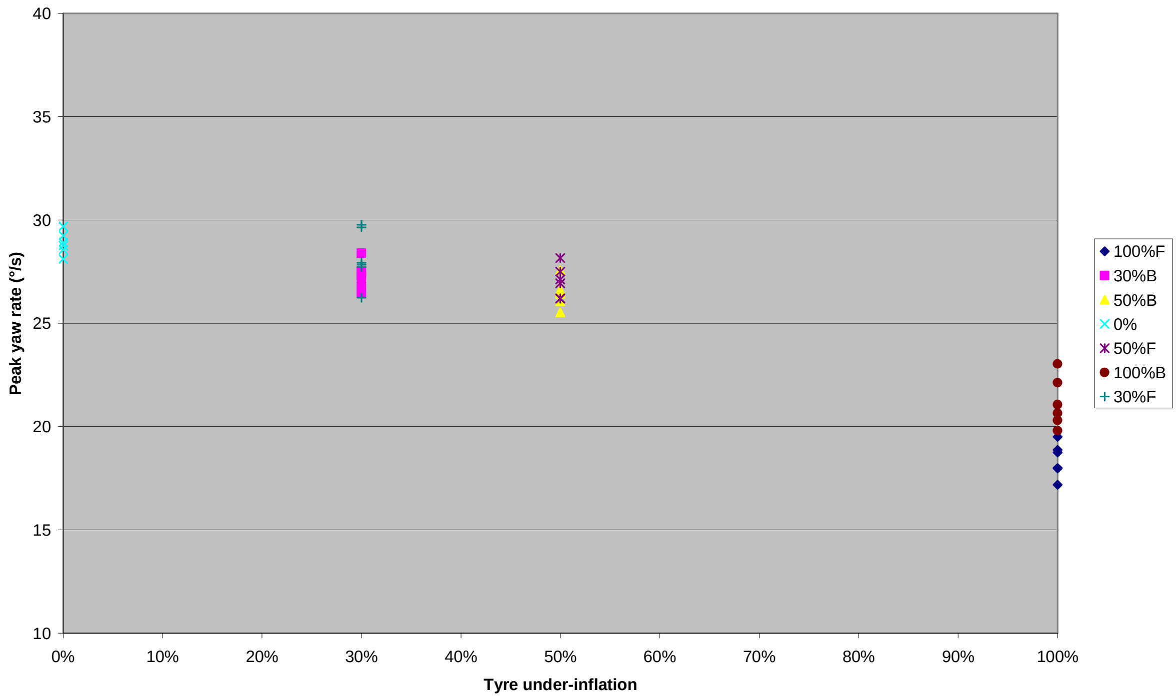
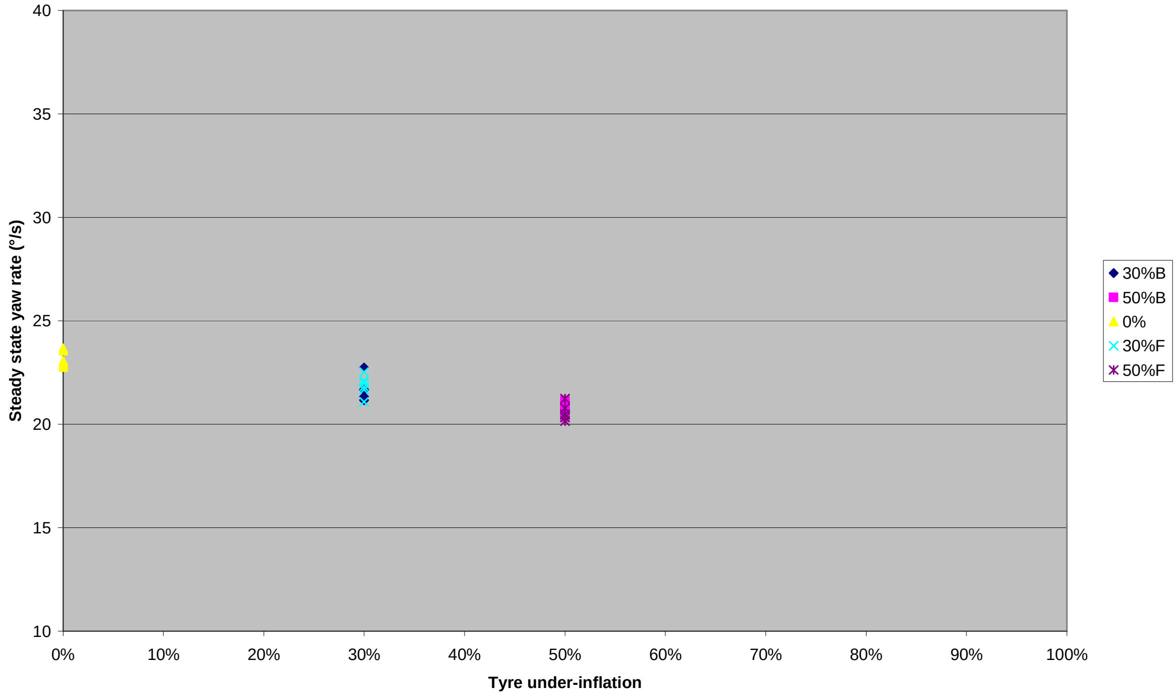


Figure 3.5. Comparison of variation in peak yaw rate between normal tyres (top) and run flat tyres (bottom)

The peak yaw rate achieved for both the normal and run flat tyres was similar at normal inflation, approximately 29deg/s, the greatest value being achieved when the tyres were correctly inflated. This yaw rate is commensurate with the vehicle responding in a stable manner to the applied steering input. No directional instability occurred in any of the under-inflated tyre conditions for either tyre type. Similarly to the lateral acceleration, the peak values achieved reduced with further under-inflation, and reduced significantly when the run flat tyre was 100% under-inflated.



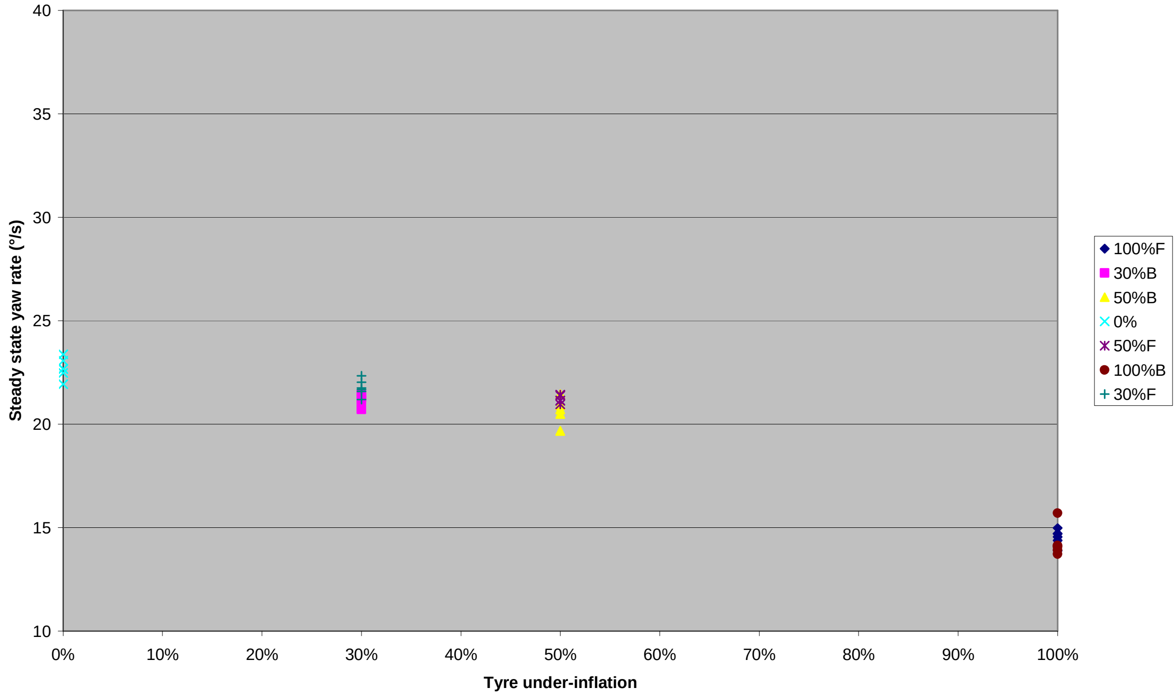


Figure 3.6. Comparison of variation in steady state yaw rate between normal tyres (top) and run flat tyres (bottom)

The findings for the effect of inflation pressure on the steady state yaw rate achieved mirror those for the peak yaw rate. Steady state values are lower than the peak values, but display similar trends of a reduction with further under-inflation.

Directional stability was maintained during all step steer manoeuvres carried out with the various inflation pressures for both the normal and run flat tyre. Peak slip angles were of similar magnitude to those typically achieved during normal driving.

To illustrate the effect that the tyre inflation pressure had on the vehicle response to the step steer input the vehicle paths for various front tyre inflation pressures for the normal and run flat tyre are shown in Figure 3.7. The origin is located at the point at which the steering input was applied in the manoeuvres.

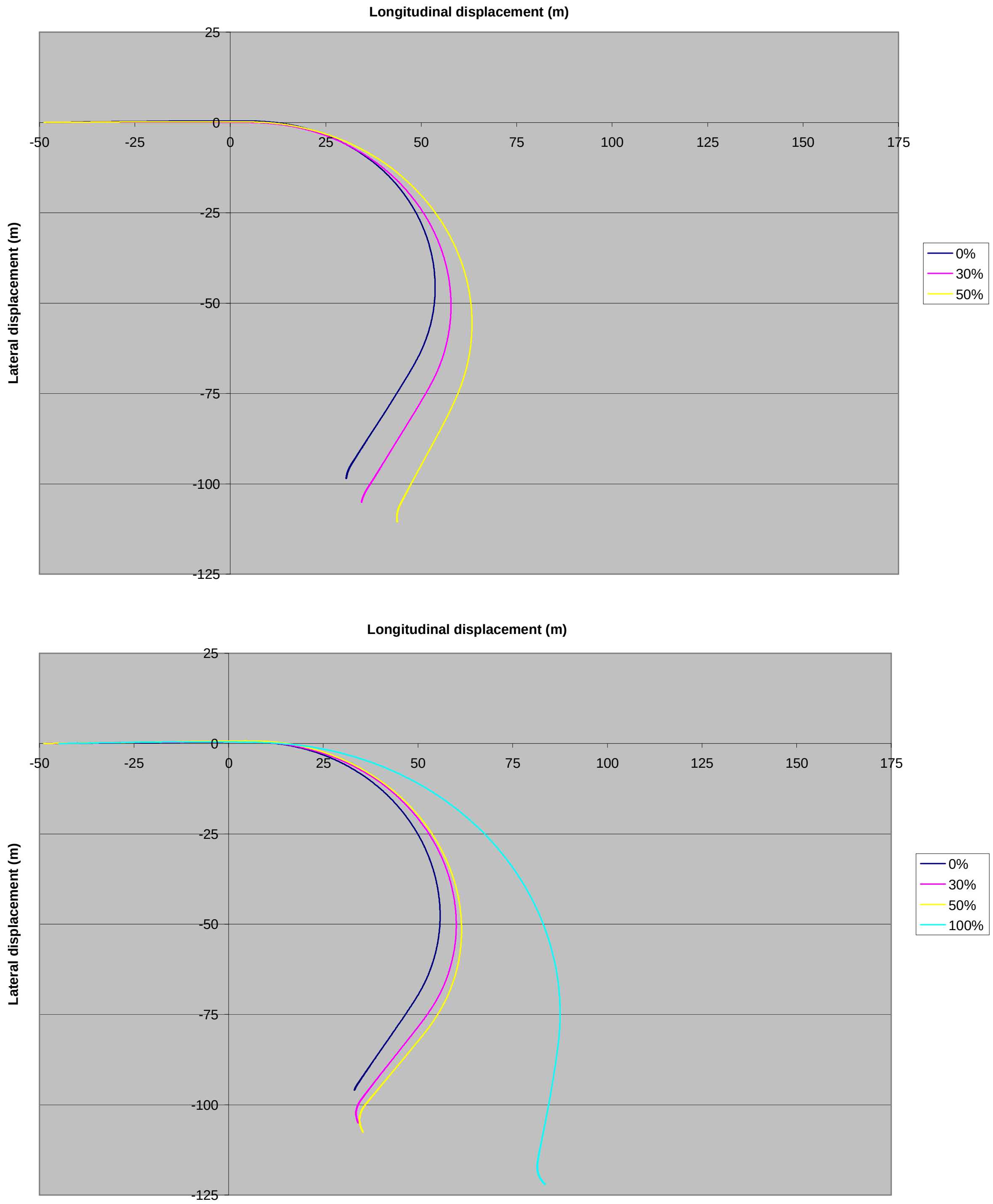


Figure 3.7. Comparison of vehicle path during step steer tests with normal (top) and run flat (bottom) front tyre pressure altered

The tightest turn (maximum vehicle response) is achieved with the tyre correctly inflated for both the normal and run flat tyre. This corresponds with the maximum lateral acceleration and yaw rate values occurring with the tyres correctly inflated. Under-inflation reduces the vehicle response and results in a larger radius of turn, however the vehicle still responds in a stable manner and follows a wider path, the most notable difference being for the run flat tyre when 100% under-inflated.

For the normal tyre statistically significant differences were identified for both the peak and steady state values for lateral acceleration and yaw rate between the normal inflation pressure and all the other inflation pressure combinations investigated. The maximum vehicle response was obtained when the tyres were correctly inflated, and a significant, albeit slight, degradation was identified for the other inflation pressures.

For the run flat tyre statistically significant differences were identified between the correct inflation pressure and all other inflation pressures for the steady state lateral acceleration and the peak and steady state yaw rate. Statistically significant differences were also identified in the peak lateral acceleration between the correctly inflated run flat tyre and all other inflation pressures except for the 30% under-inflation of the front tyre only. Again the maximum vehicle response was obtained when the tyres were correctly inflated, and a significant, albeit slight, degradation was identified for the other inflation pressures. 100% under-inflation resulted in a more substantial (and significant) degradation in vehicle response.

3.3.2.2 Step steer in turn

Table 18 and Table 19 summarise the data for mean peak lateral acceleration, yaw rate and slip angle for the different inflation conditions for the normal and run flat tyres. Experimentation with the run flat tyre 100% under-inflated revealed substantial vehicle instability such that a manoeuvre comparable to that carried out for the other tyre inflation conditions could not be safely executed. The results of this experimentation were not suitable for direct comparison with those from the other tyre inflation conditions therefore they are reported separately.

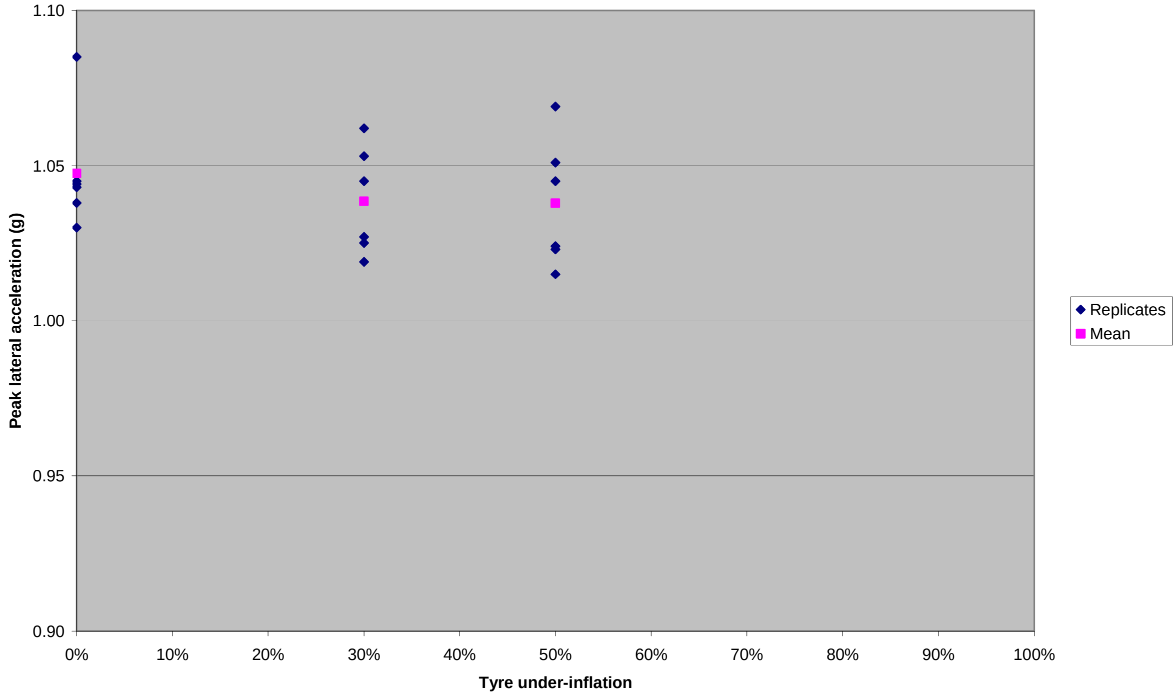
Table 18. Mean peak lateral acceleration, yaw rate and slip angle for each tyre inflation group – normal tyres

Tyre under-inflation	Mean peak lateral acceleration (g)	Mean peak yaw rate (°/s)	Mean peak slip angle (°)
0%	1.05 (1.03, 1.06)	29.4 (28.6, 30.2)	4.3 (2.8, 5.9)
-30%	1.04 (1.02, 1.05)	29.8 (29.2, 30.3)	7.2 (5.9, 8.5)
-50%	1.04 (1.02, 1.05)	30.0 (29.4, 30.7)	8.3 (6.9, 9.6)

Table 19. Mean peak lateral acceleration, yaw rate and slip angle for each tyre inflation group – run flat tyres

Tyre under-inflation	Mean peak lateral acceleration (g)	Mean peak yaw rate (°/s)	Mean peak slip angle (°)
0%	1.03 (1.02, 1.04)	29.6 (29.2, 30.0)	6.0 (4.5, 7.4)
-30%	1.02 (1.01, 1.04)	32.6 (31.7, 33.5)	13.5 (11.0, 16.0)
-50%	1.04 (1.03, 1.05)	32.8 (32.3, 33.3)	11.3 (10.1, 12.5)

Figure 3.8, Figure 3.9 and Figure 3.10 compare the peak values of lateral acceleration, yaw rate and slip angle for each replicate for the different tyre inflations for both the normal and run flat tyres to illustrate the spread in the data. The mean of the peak values is also included for comparison.



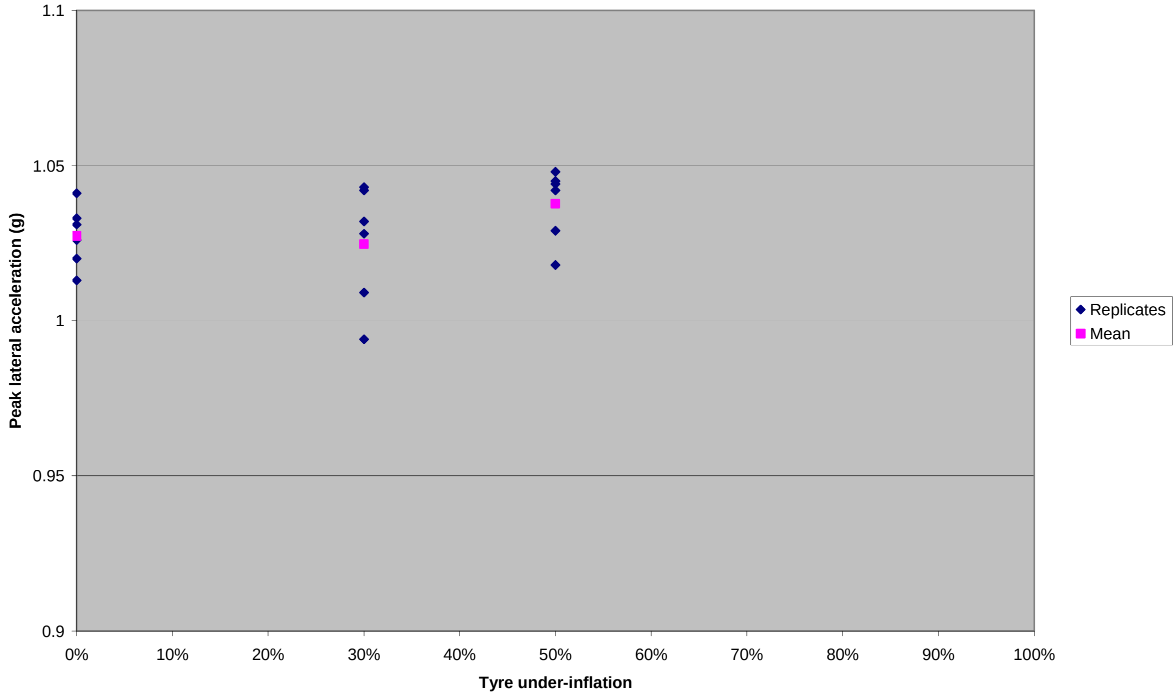
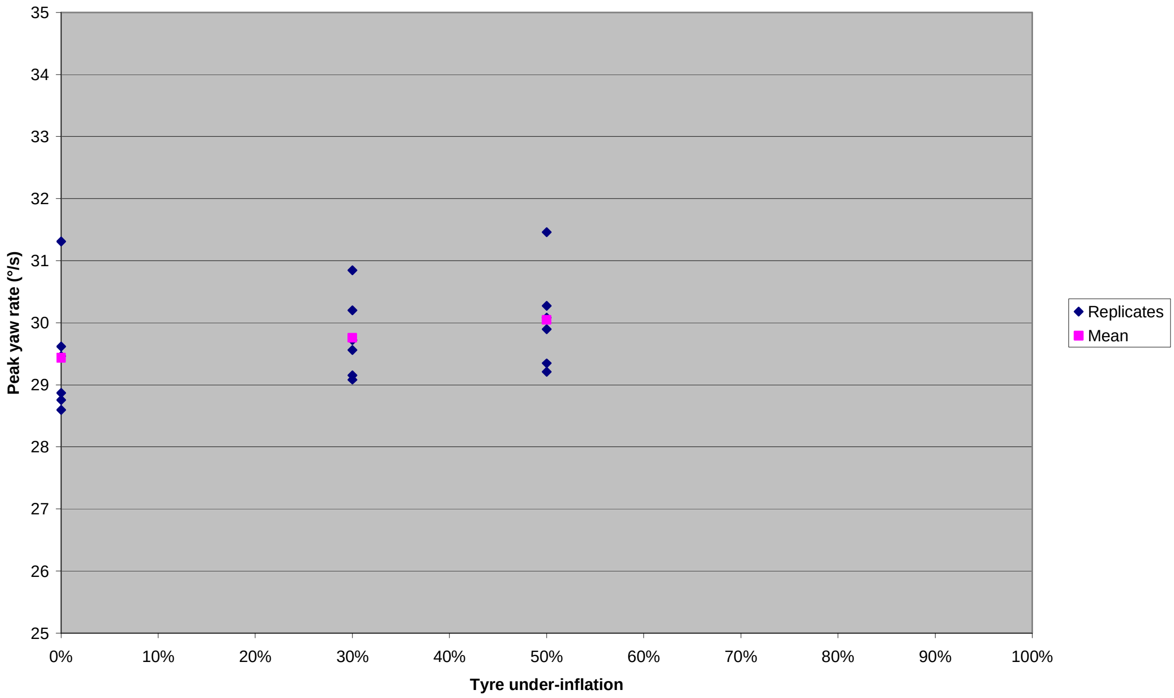


Figure 3.8. Comparison of variation in peak lateral acceleration between normal tyres (top) and run flat tyres (bottom)

The peak lateral acceleration achieved for both the normal and run flat tyres in the various inflation conditions was similar, and no significant differences were found.



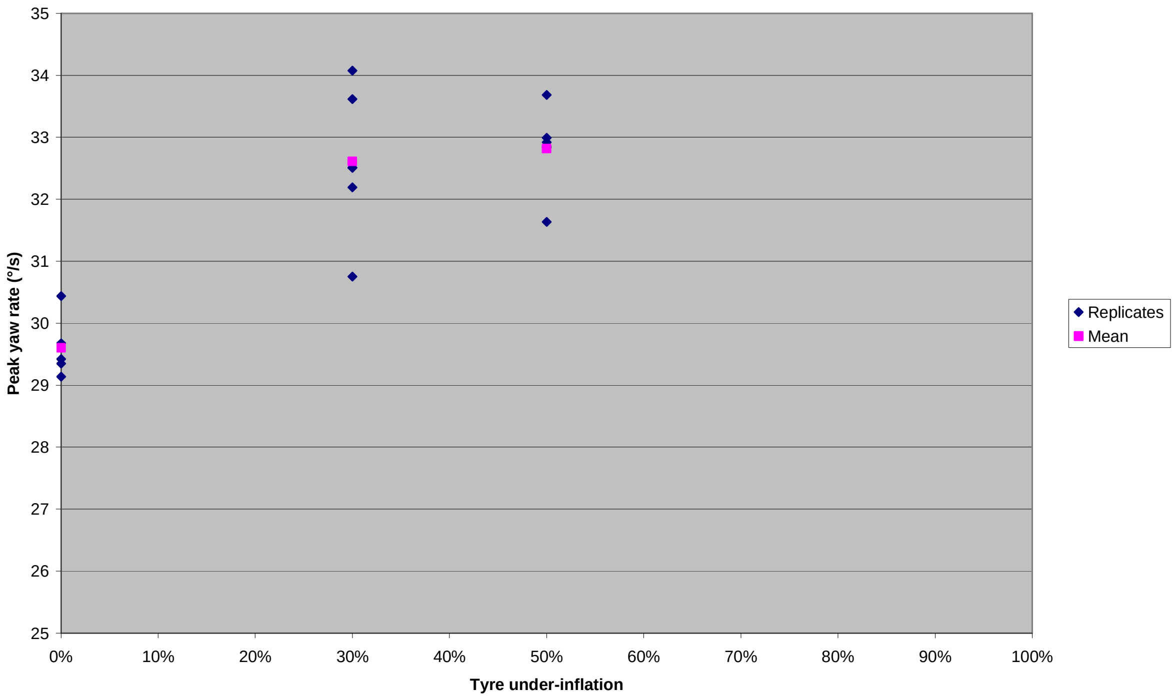
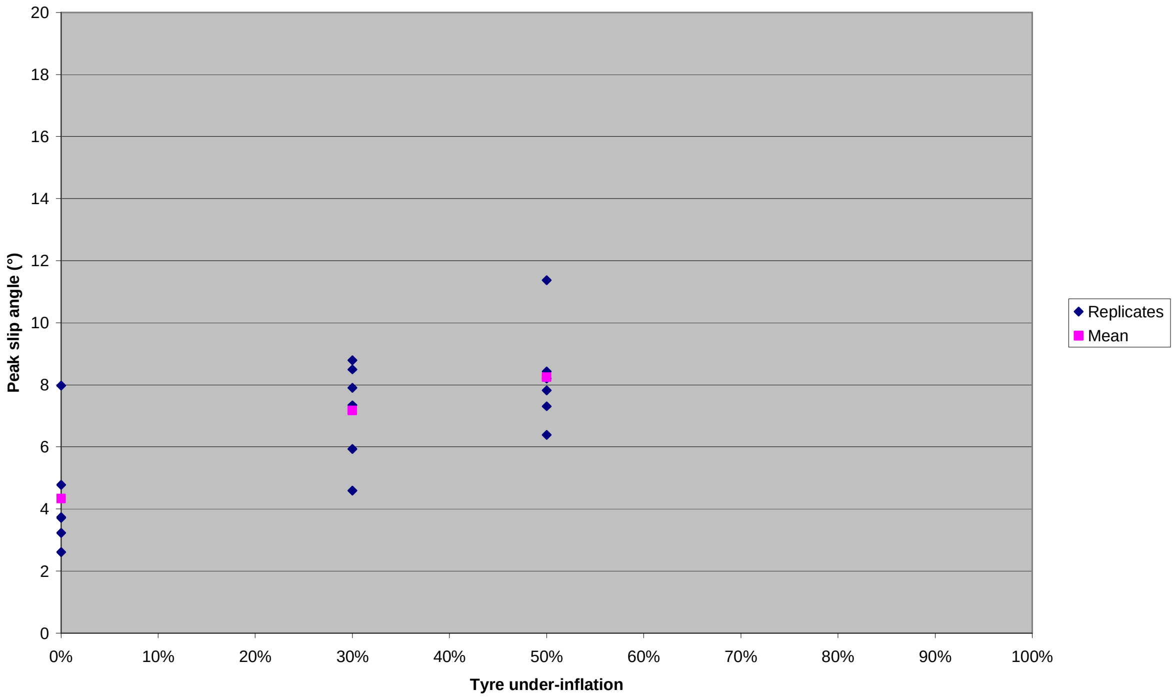


Figure 3.9. Comparison of variation in peak yaw rate between normal tyres (top) and run flat tyres (bottom)

The peak yaw rate achieved with the normal tyre inflated in various conditions was similar, indicating a weak trend for the peak yaw rate to increase with further tyre under-inflation. Peak yaw rates were similar for both the normal and run flat tyre correctly inflated. The run flat tyre showed a stronger trend for the peak yaw rate to increase with additional tyre under-inflation. Statistically significant differences were found between normal and under-inflations for run flat tyres only.



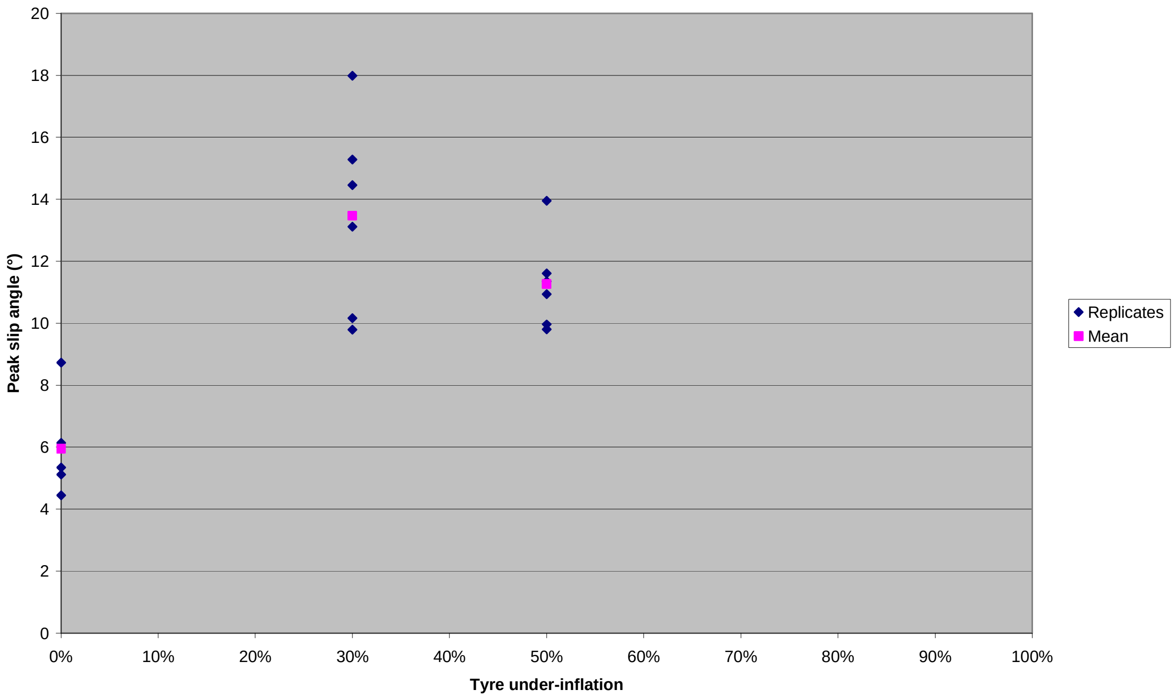


Figure 3.10. Comparison of variation in peak slip angle between normal tyres (top) and run flat tyres (bottom)

The peak slip angles were significantly smaller for both the normal and run flat tyre when the tyres were inflated at the correct pressure than those under-inflated. For all inflation conditions the peak slip angles were greater for the run flat tyre than the normal tyre. Under-inflation for both tyre types resulted in greater peak slip angles. At 50% under-inflation the peak slip angles were approximately double those achieved at the correct inflation for both tyre types.

Directional stability was maintained in all step steer in a turn manoeuvres with up to 50% under-inflation for both the normal and run flat tyres. Experimentation carried out with the run flat tyre 100% under-inflated revealed substantial vehicle instability such that maintaining the steady state circular motion established prior to the application of the step steering input proved difficult. To investigate the effect a step steer in turn manoeuvre similar to that performed for all the other inflation conditions was undertaken, albeit with a lower initial lateral acceleration of nominally 0.3g. Figure 3.11, Figure 3.12 and Figure 3.13 show time histories of the lateral acceleration, yaw rate and slip angle respectively for an example of this manoeuvre. Time histories from a manoeuvre carried out with correctly inflated run flat tyres with an initial lateral acceleration of nominally 0.6g are also included for comparison.

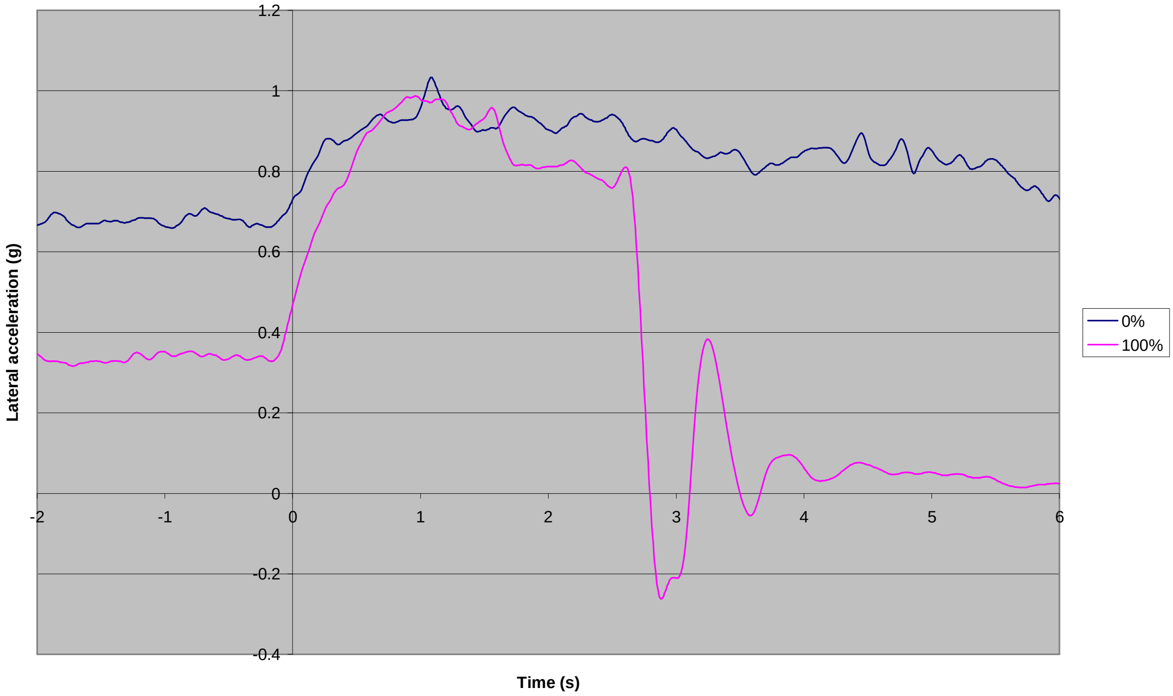


Figure 3.11. Comparison of lateral acceleration between manoeuvres with correctly inflated and 100% under-inflated run flat tyre

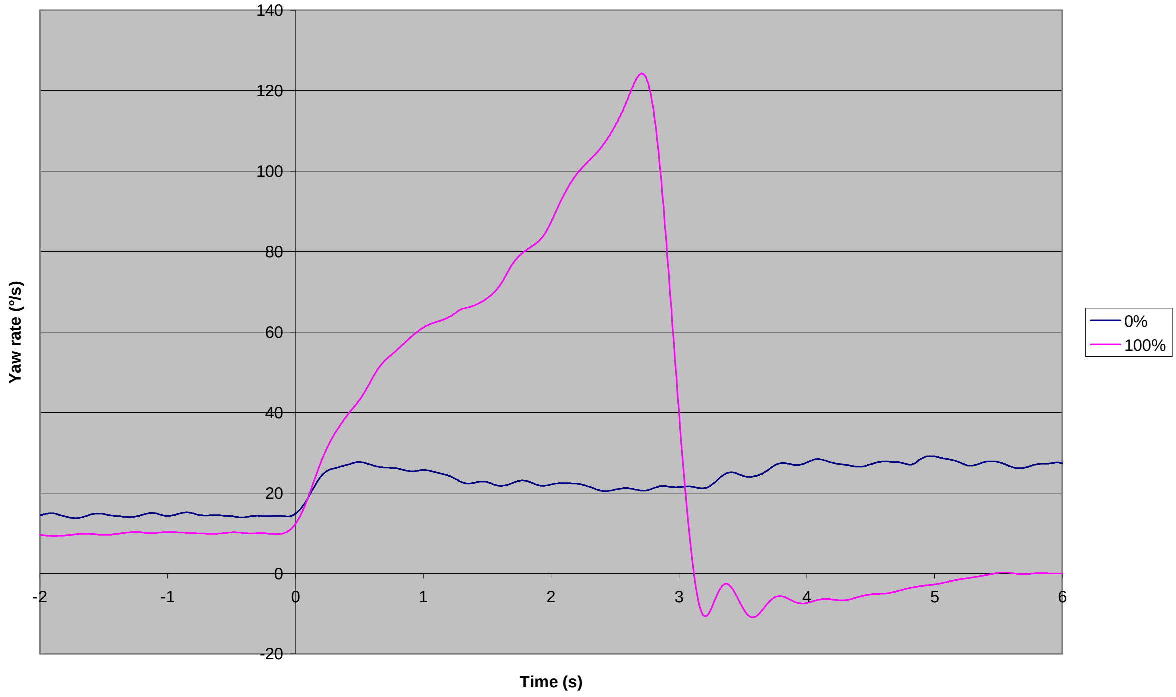


Figure 3.12. Comparison of yaw rate between manoeuvres with correctly inflated and 100% under-inflated run flat tyre

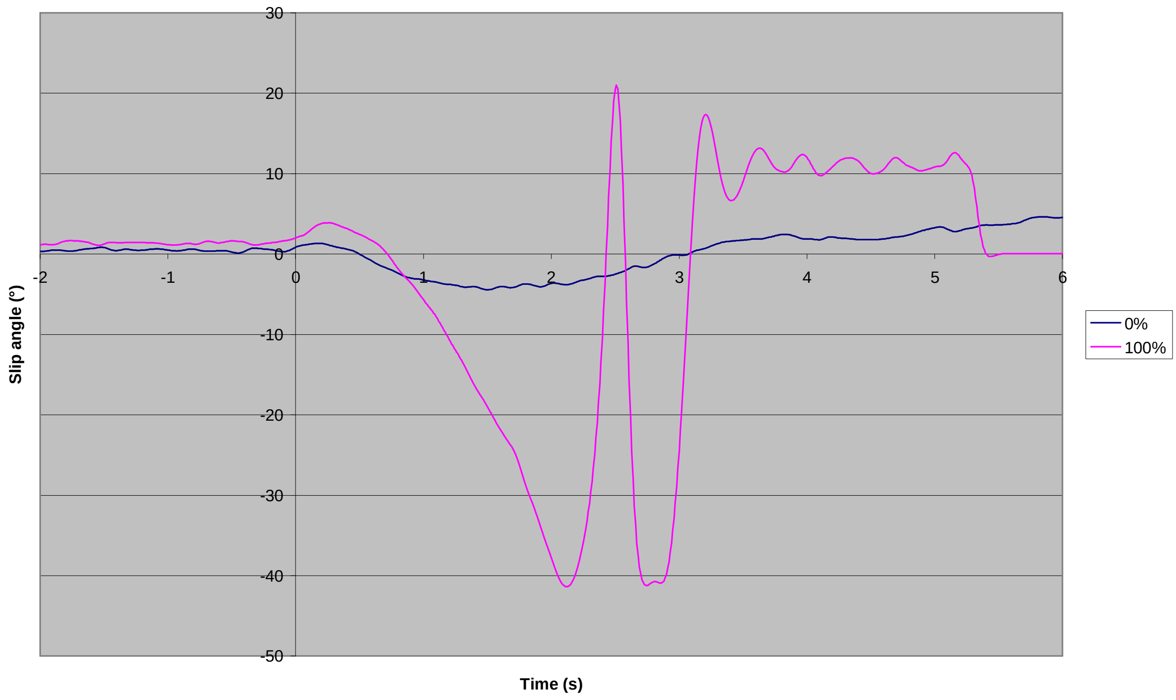


Figure 3.13. Comparison of slip angle between manoeuvres with correctly inflated and 100% under-inflated run flat tyre

During the manoeuvre carried out with the correctly inflated tyre, the yaw rate increased from the steady state value of 15deg/s to an initial peak of 28deg/s immediately after the steering input was applied. The yaw rate then stabilised. When the tyre was 100% under-inflated the yaw rate increased almost linearly to a peak of 124deg/s after the steering input because directional instability occured and the vehicle spun. A peak slip angle of 41° further highlights the instability, since a peak value of 4° was achieved with correctly inflated tyres. In these runs the outer wall of the deflated tyre also had a tendency to become unseated from the wheel rim.

4 Discussion

The purpose of this experimentation has been to find how far tyre inflation pressures, and in particular inflation pressures which differ substantially from the correct or recommended values, can affect the conclusions which an accident investigator might come to when reconstructing a particular incident. Particular issues are whether incorrect tyre pressure should be a consideration in the calculation of speed from braking marks or from curved steering marks, or whether it might be a plausible explanation for the loss of control of a vehicle.

Both the PFT and straight line vehicle braking experiments measured quantities which are related to the friction between the tyres and the ground. With the PFT, rolling wheel peak and locked wheel friction were measured and expressed as a “friction number” which is 100 times the coefficient of friction. With the car, the MFDD under anti-lock braking was measured, together with the overall stopping distance. While rolling wheel peak friction is rarely used by accident investigators, the locked wheel friction and the MFDD are of considerable interest in the calculation of speed from braking marks using equation 1.

$$u = \sqrt{v^2 + 2\mu gs} \qquad (1)$$

where :

u = initial speed (m/s)

v = final speed (m/s)

μ = coefficient of friction

g = acceleratation due to gravity (9.81 m/s^2)

s = distance (m) (taken from braking marks).

The calculation therefore uses the square root of the coefficient of friction (or the MFDD), and because of this any examination of variations in this quantity due to inflation pressure should concentrate on the square roots of their values.

On a dry road it is generally accepted that there will be an uncertainty of ±5% in a speed calculated from a braking distance. This figure takes into account variation in the friction of the different tyres normally fitted to cars and random errors in the measuring process. On a wet surface (where in any case braking marks are rarely discovered) the uncertainty is less readily quantified because of the greater variability in the qualities of tyres and surfaces in this condition, but it will certainly be more than 5%, and a figure of ±10% would not be unreasonable.

4.1 Pavement Friction Tester (PFT) results

These experiments measured the peak and locked-wheel friction of the three tyres on a particular surface when wet and dry. The summarised results are in Tables 5, 6 and 7.

The overall results from the PFT show the well known difference between wet and dry conditions, and also, on the wet surface, the drop in friction which occurs with increasing speed.

Considering the results for all three tyres on the dry surface, the “normal” 205/55ZR16 tyre showed a locked wheel friction number of about 66, with no statistically significant difference in the values over the range of plus and minus 30% of the correct inflation pressure, although there was some indication of a slightly higher friction at normal pressure than at both + and -30%.

With the low profile 195/40ZR16 tyre, there was no significant difference in the mean locked wheel friction number between normal and +30% pressure, the value being about 72. At -30% pressure the mean friction number was 78.5, a difference from the normal value of 8.2. When the square roots of the figures are considered, the value at -30% pressure exceeds the others by about 4.4%: this means that (putting aside any other sources of error), if the speed of a car with tyres under-inflated by this amount were to be calculated on the basis of the friction measured with a correctly inflated tyre, the figure found would be an underestimate of about 4.4%.

With the run flat 195/55R16 tyre there was again no significant difference between normal and +30% pressure, with a value of about 58. At -30% the mean friction number was 62.0, which differs from the normal pressure figure of 59.0 by a barely significant amount: taking the square roots, the excess is 2.5%.

However, when the run flat tyre was fully deflated both the peak and locked wheel friction was substantially less than in the inflated state. The locked wheel friction number was 45.7, 13.3 less than the normally inflated value and an excess in the square root values of 13.6%.

Of as much interest as the variation in the locked wheel friction due to pressure change of the individual tyres is the difference between the three tyres. Bringing together the values at normal pressure, they were: normal tyre, 68.3; low profile tyre, 70.3; run flat tyre, 59.0. The difference in the first two is barely significant, but the friction of the run flat tyre is substantially less than that of the other two: taking the square root values, it is 8 to 9%. By contrast, the differences in the peak values are insignificant, these being 113.4, 115.0 and 115.0 respectively.

Summing up these results, a moderate degree of under-inflation (i.e. of 30%) appears to increase the locked wheel friction amount by an amount which is comparable to the ±5% error which may be expected when calculating speed using these calculations. An appropriate conclusion by an investigator making a calculation in such a circumstance (remembering that the under-inflation would have to be present in all four tyres of the car), is that any error in his result is likely to be one of slight underestimate of the speed.

However, the complete deflation of the run flat tyre takes the friction the other way, and would lead to an overestimate of speed of more than 10% (when all four tyres were deflated).

But of greater importance in the case of run flat tyres is that, even when correctly inflated, the locked wheel friction measured for the tyre in this study was significantly less than that of the normal tyres. This means that in any accident investigation it would be best if the friction were measured with tyres of the type in question: failing that, it would probably be appropriate to reduce the calculated speed by 10 to 15%.

Turning to the results in wet conditions, with the normal tyre, the mean locked wheel friction number at 40 mile/h varied between 41.5 at +30% pressure and 47.4 at normal pressure, with the -30% figure (43.0) lying between them. The difference between the square roots of the higher value and the lower is 6.9%.

With the low-profile tyre, at 40 mile/h on the wet surface the maximum mean friction was 39.1 at +30% pressure and the minimum was 28.8 at normal pressure. The difference in the square rooted figures is 16.5%. What is seen here is, firstly, a reversal of the maximum/minimum characteristics seen with the normal tyre with the friction number being higher at -30% pressure than the friction number at normal pressure; secondly, a much lower friction number than for the normal tyre; and thirdly a much greater variation across the inflation pressures.

Finally the run-flat 195/55R16 tyre: excluding for the moment the -100% inflation figures. In the wet condition the maximum mean friction number occurred at -20% (40.8), with the minimum at normal pressure (32.3) and a square root difference of 12.4%. The -100% figures were substantially less at 27.9, a difference of 21% in the square roots.

Here again there is a difference in the pattern of variation in the ±30% inflation range, and over all three tyres there is no clear trend of the friction becoming higher or lower as the pressure is changed from -30% to +30%: rather, there is some variation which is significant statistically (i.e. it does not appear to be due to chance) but which cannot readily be explained.

The clear variation in friction which these experiments show is in the fully deflated (-100%) state of the run flat tyre. Here the friction number is of the order of 10 less than the value for the inflated tyres.

For the accident investigator, these data confirm that tyre friction on wet surfaces is very variable. They give some indication as to how it might change in different circumstances, but in general it can only be estimated roughly and does not lend itself to precise calculations of speed.

4.2 Vehicle experimental programme: straight line braking

All runs with the two tyres investigated (normal and run-flat) were made on the dry surface with ABS active. The MFDD figures as a multiple of *g* can be summarised as follows.

With the normal tyres the average values in each condition ranged between 1.07 (front tyres at -60% pressure) and 1.17 (side tyres at -60% pressure), which gives a figure for the amount by which the square root of the higher figure exceeds that of the lower of 4.6%. The standard deviation in each set of runs is of the same order. The plot of MFDD against degree of under-inflation shows no clear trend with changing pressure. (Table 10 and Figure 3.1)

With the run-flat tyres, excluding the -100% inflation figures, the average values ranged between 1.02 (all tyres at -30%) and 1.04 (all tyres at normal pressure): a square root difference of only 1.0%. The various -100% inflation runs gave values of 0.88 to 0.90, a square root difference with the normal pressure figure of 7.5 to 8.7%. Again the standard deviations were of the same order. The plot of the MFDD values showed no trend in the 0% to -60% range, only dropping markedly at -100%. (Table 11 and Figure 3.1)

Looking at the adjusted mean stopping distances for both tyres, these show essentially the same effects, with only the -100% under-inflation producing a significantly different result.

For a car fitted with four run flat tyres, the stopping distance was shown experimentally to be 21.6m when all tyres were 100% under-inflated. Using equation 1 and this stopping distance the deceleration achieved during the experiment can be calculated to have been 0.76g. It is now possible, by way of illustration, to compare the performance of two vehicles, one with four correctly inflated run flat tyres and one with four fully deflated run flat tyres. If the two vehicles were travelling at 40 mile/h and started to brake at a distance of 19.1m from an obstacle, the vehicle with correctly inflated tyres would stop in the distance before the obstacle was reached. However, the car with flat tyres would collide with the obstacle at 14 mile/h.

The conclusion to be drawn from the vehicle straight-line braking experiments is that substantial under-inflation, down to at least -60%, does not materially affect the braking rate of a car with ABS. Only with fully deflated run-flat tyres is there a significant reduction in braking. For ABS equipped vehicles it is recommended that data should be used that is specific to the case being investigated.

4.3 Vehicle experimental programme: handling

The lateral acceleration of a vehicle is used by accident reconstructionists to calculate speed from the curvature of the path of a vehicle, and the accuracy of such a calculation is generally reckoned to be ±10% (Lambourn (1989)). Here again it is the square root of the acceleration which is of consequence in the calculation.

The results in the vehicle step steer experiments have a similarity to those from the straight line braking: at under-inflation levels down to -50% the effects are small, and it is only when the run flat tyre is at -100% inflation that a substantial reduction in the lateral acceleration is evident. (Figures 3.3 and 3.4). For comparison between the correctly inflated tyres and where one rear run flat tyre is completely deflated, this reduction in lateral acceleration is equivalent to the critcal speed for a 50m radius bend being reduced from 45 mile/h to 35 mile/h.

There is, however, a reduction in the lateral acceleration as the pressure is reduced from normal to -50%, with the steady state figure for the normal tyre changing from 0.84g to 0.75g, and for the run flat tyre from 0.82g to 0.75g. The square roots of these differ by 5.8% and 4.6%, and therefore do not bear appreciably on accident reconstruction practice.

The behaviour with the fully deflated run flat tyre is clearly different, and is graphically shown in Figure 3.7. Although a lateral acceleration of around 0.5g was achieved - which exceeds what would typically be demanded in ordinary driving - greater lateral acceleration could be required during emergency avoidance manoeuvres. Willard (1998) proposed that a minimum lateral acceleration of 0.3g be achieved before the onset of oversteer in order to provide adequate deflated handling capability because 99.8% of the total distance travelled by the “average driver” occurs at lateral accelerations below 0.3g.

The results in the step steer in a turn experiments show, once again, little dependence on tyre pressure down to the -50% under-inflation level, with no obvious variation in peak lateral acceleration and only small increases in yaw rate and slip angle. With the fully deflated run flat tyre, however, the situation is very different. Figure 3.11 shows that when additional steering input is applied during a steady state cornering manouvre the vehicle quickly becomes unstable and spins. For the accident investigator this instability would be very evident from the path of the tyre marks: it is also likely that the tyre would be found to have come away from it outer bead seat.

5 Conclusions

The following conclusions can be drawn from this research:

- Whilst they may matter considerably in accident causation, statistically significant differences seen in the results of the pavement friction tests are generally not striking differences in the context of accident reconstruction (and solely in that context). In wet conditions, when compared to the normal tyre, the low profile tyre showed a reversal of the maximum/minimum friction characteristics. There was also a lower friction number compared to the dry condition and there was greater variation. These outcomes would be of some significance for accident reconstruction. Within the ±30% inflation range for the run flat tyres there were no differences in performance that would be significant for accident reconstruction. In the fully deflated state, the performance of the run-flat tyre would make a material difference to an accident investigator.
- The straight line braking performance of the car investigated with ABS, on a dry surface, was not significantly affected by up to 60% under-inflation of tyres. There was a significant reduction in braking performance for the fully deflated run-flat tyre.
- The stopping distance measured during the vehicle experiments on a dry surface from 40 mile/h using an ABS equipped vehicle was in-between the values predicted using the equations of motion and the locked wheel and rolling wheel peak friction values. This is as would be expected since an ABS vehicle would utilise higher friction than locked wheel friction, but would not sustain the rolling wheel peak friction. This highlights the need for accurate measurements to be used when investigating accidents involving vehicles fitted with ABS. The situation would be further complicated if only one tyre is under-inflated because different tyres would have different friction characteristics.
- There was a reduction in lateral acceleration achieved in step steer experiments as the tyre pressures were deflated to -50% for both the normal and run-flat tyres and this may be important in general; however, these reductions are considered of little consequence for accident reconstruction purposes. The fully deflated run flat tyre was able to achieve performance that exceeds that required for ordinary driving, however to achieve this, the vehicle required to travel a path with a radius approximately 60% larger than a vehicle with correctly inflated run flat tyres. The effect of fully deflating the run flat tyre would be to reduce the critical speed for a 50m radius bend by 10 mile/h.
- The step steer in turn experiments showed that a fully deflated run-flat tyre resulted in a loss of control when the additional steering input was applied. This type of instability would be evident from the tyre marks at the scene, and whilst potentially dangerous, would not necessarily mis-lead the accident investigator.

Acknowledgements

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This work would not have been possible without the use of the Pavement Friction Tester (PFT), which is owned by the Highways Agency (HA). The authors would like to thank the HA for their permission to use this equipment."

References

Arndt M W and Arndt S M (2006). *Tests documenting vehicle handling with a temporary-use rear tire and run-flat rear tire.* SAE 2006-01-0905, 2006.

Bailey D (2000). Skid *tests – the influence of tyre pressure and load.* Impact: The Journal of the Institute of Traffic Accident Investigators, **9** (3) 52-55, 2000.

BSI (1989). *Road vehicles – Lateral transient response experiment methods.* BS AU 230:1989. ISO 7401:1998.

BSI (1990*).* *Sampling and examination of bituminous mixtures for roads and other paved areas – Part 105: Methods of test for the determination of texture depth.* BS 598-105:1990.

Dodd M (2003). *Draft PNCAP braking protocol: Part 1.* TRL Ltd (Unpublished document – available on direct personal application only).

Dunlop (2006). *Dunlop tyres technical information*. www.dunloptyres.co.uk/our tyres/car/technicalinformation/#dsst, accessed March 2006.

Highways Agency (2004). *Manual of contract documents for highway works, Volume 1 – Specification for highway works.*

Hulme P (2004*).* *Tyre pressures and handling.* Impact: The Journal of the Institute of Traffic Accident Investigators. **13** (2) 32-35, 2004

Lambourn RF (1989). *The calculation of motor car speeds from curved tyre marks.* J Forensic Science Society. **29** 371-386.

Willard LW Jr (1998). *Self-supporting tire performance criteria and testing.* SAE International Congress and Exposition, Detroit, Michigan, Febrary 1998, reference 980257.

Appendix A. Straight line braking - statistical analysis

A.1 Normal tyres

A.1.1 Initial investigation of Stopping Distance

Table 20 lists the mean stopping distance values for each of the seven inflation groups. The means are averages of the pure stopping distance numbers and do not take into account adjustments for any covariates that might be relevant.

Possible covariates are Entry Speed, Mean Initial Speed, Change in Initial Speed, Initial Steering Angle, Overall Steering Angle, Average Brake Force, Reaction Time, Rise Rate, Delay Time, Mean*Acc, and Peak*Acc.

The largest overall stopping distance is in inflation group 2 **-** the normal inflation in all tyres closely followed by a 30% reduction in all tyres. The shortest occurs in inflation group 1 (-30% inflation in both front tyres).

Table 20. Unadjusted mean stopping distance for each tyre inflation group

Inflation	Mean	Std. Deviation	Rank
-30% F	18.34	.634	1
Normal	19.43	.363	7
-60% F	18.86	.655	4
-60% S	18.94	.540	5
-30% A	19.39	.742	6
-60% A	18.80	.827	3
-30% S	18.45	.945	2

Figure A.1 shows the distribution of stopping distances. The noise within this distribution is required to be approximately normal before further statistical tests are completed. The data are normal and an investigation into the distribution of errors shows a distribution sufficiently normal so tests to determine differences in stopping distances across inflation groups can proceed. Figure A.2 is testing for a time or a day effect. It shows averages of all seven inflation groups for each replicate and a random pattern suggesting no time effect at work in the data.

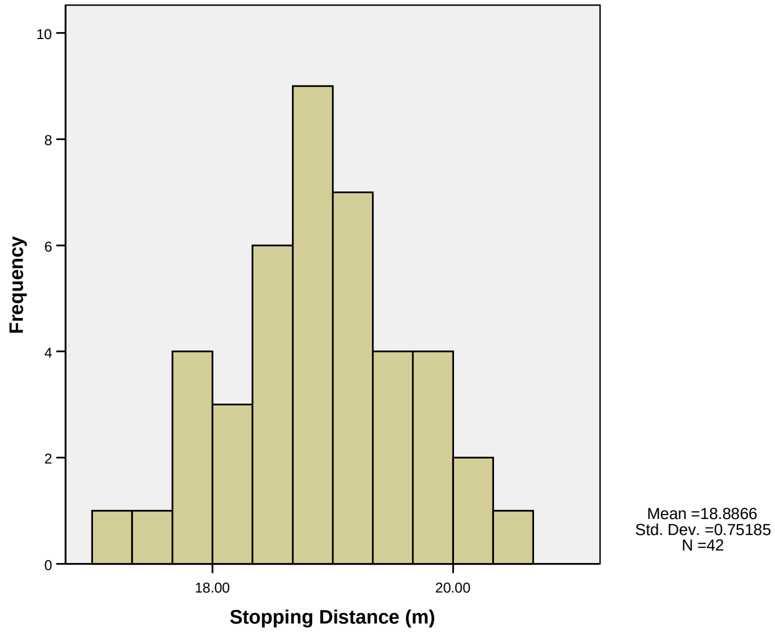

Figure A.1. Histogram of distribution of stopping distance

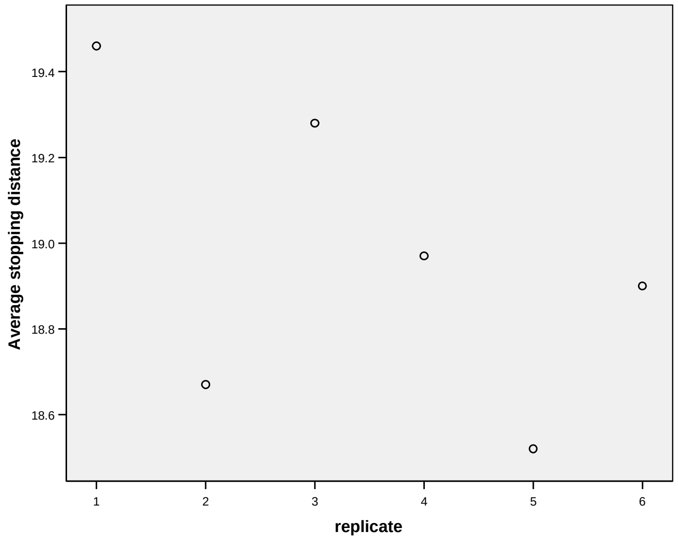

Figure A.2. Average by replicate

A.1.2 Covariate plots

Plots of outcome versus each covariate follow to determine relationships between covariates and stopping distance. Random patterns are seen in all plots except entry speed and mean*acc. Entry speed is highly related to stopping distance.

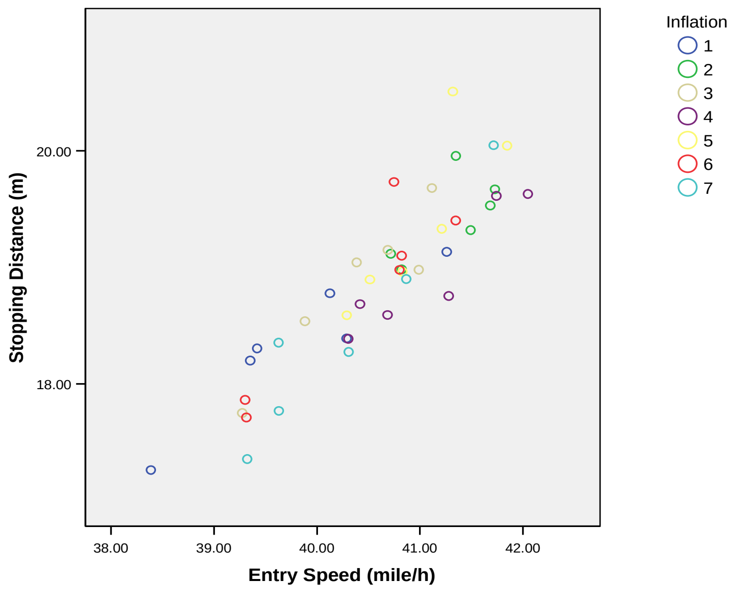

Figure A.3. Stopping distance by entry speed

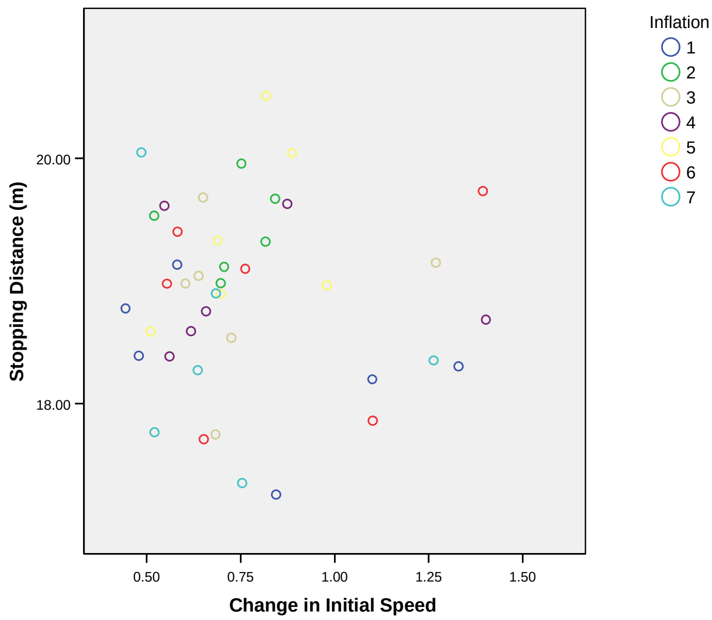

Figure A.4. Stopping distance by change in initial speed

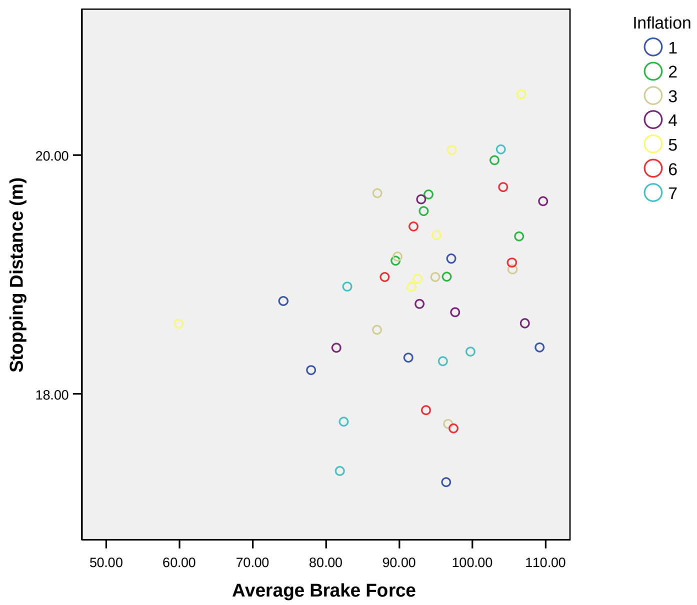

Figure A.5. Stopping distance by average brake force

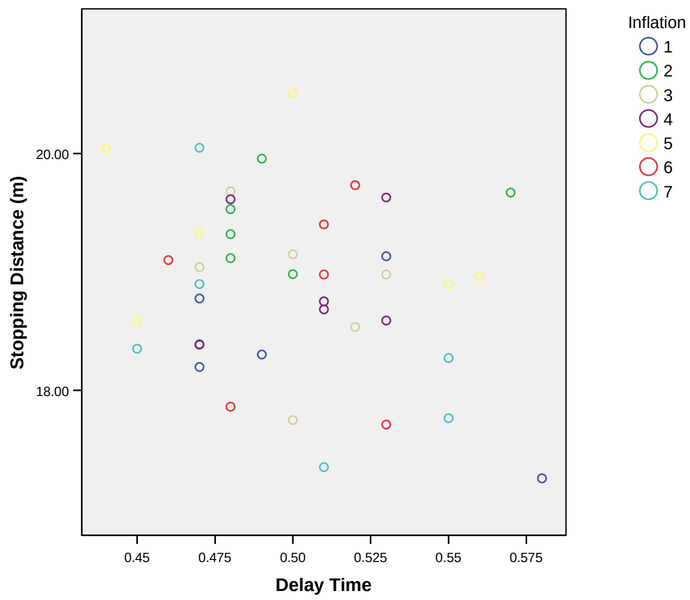

Figure A.6. Stopping distance by delay time

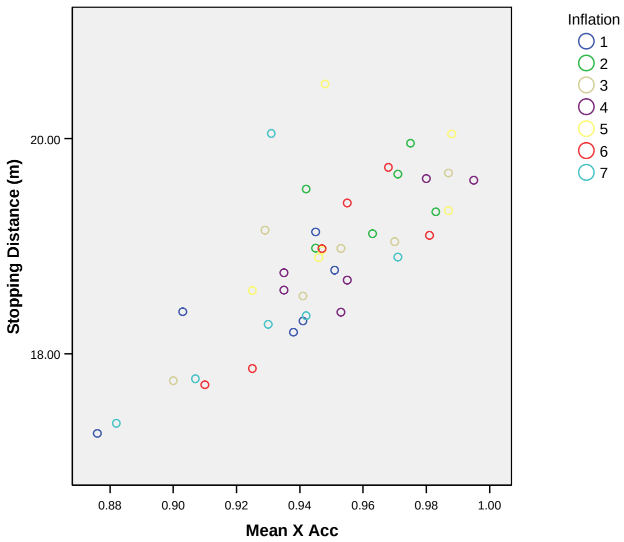

Figure A.7. Stopping distance by mean*acc

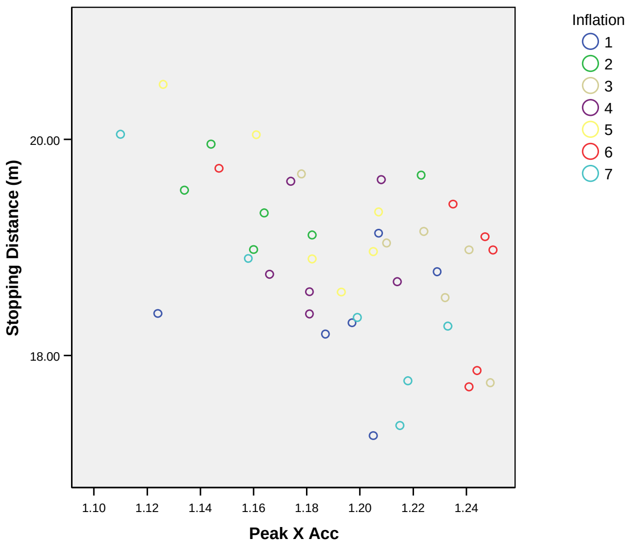

Figure A.8. Stopping distance by peak*acc

A.1.3 Analysis

The possible covariates are listed above in section A.1.1. Due to the large number of covariates it is important to pick out those that have a significant effect on the outcome. This is achieved using a regression process. The covariates are entered in to a regression predicting stopping distance and those without a significant effect on the prediction of stopping distance are removed. Also removed are cases where the co-linearity statistic (VIF) is bigger than 10. This removes variables which can be predicted using other covariates.

The regression process suggests that Entry Speed and Change in Initial Speed remain in the analysis. If the significance rules had been lifted slightly then the covariates that would also remain in the analysis are Average Brake Force, Reaction Time and Delay Time. These extra variables make conceptual sense, but without them the conclusions remain the same.

It is now possible to analyse the effect of inflation on stopping distance whilst allowing for the important covariates. It is detected (using an ANCOVA procedure) that inflation does have a significant effect on stopping distance. However, entry speed explains a higher proportion of the variance than inflation (84.2% and 31.1% respectively).

Adjusting for the two covariates mentioned above, the expected marginal means are compared to the original means below. The order of average stopping distances changes quite dramatically once adjustments are made for the important covariates. It is important to control for these covariates as the correlation of entry speed with stopping distance shows. The shortest average stopping distance occurs at -60% S.

Table 21. Mean stopping distances for each tyre inflation group, unadjusted and adjusted

Inflation	Unadjusted Mean	Rank	Adjusted Mean	Rank
-30% F	18.34	1	19.02	5
Normal	19.43	7	18.85	3
-60% F	18.86	4	19.04	6
-60% S	18.94	5	18.53	1
-30% A	19.39	6	19.05	7
-60% A	18.80	3	18.94	4
-30% S	18.45	2	18.78	2

Significant differences are detected between the following inflation conditions:

- -30% front and -60% side
- -60% front and -60% side
- -30% all and -60% side
- -60% all and -60% side

These differences can also be seen in the plot below showing adjusted means by inflation level.

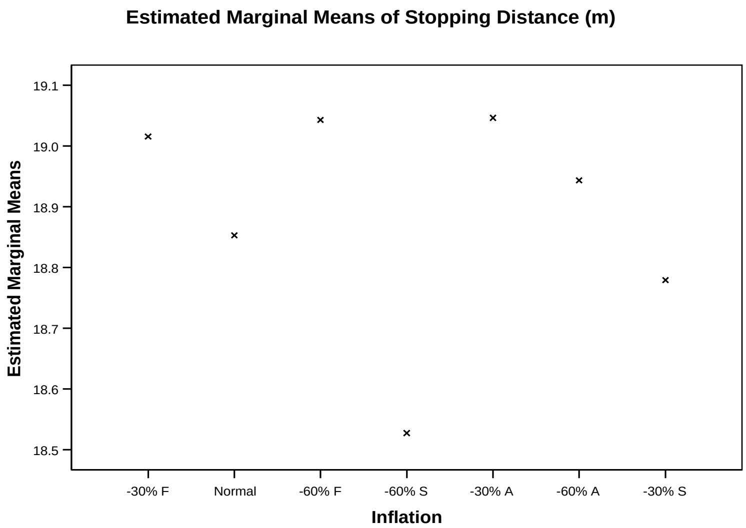

Figure A.9: Adjusted mean for each inflation point

A.1.4 Initial investigation of MFDD

Table 22 lists the mean stopping distance values for each of the seven inflation groups. The means are averages of the pure MFDD and do not take into account any adjustments for covariates (mentioned above) that might be relevant. The largest overall MFDD is in the -60% side. The smallest occurs in -60% frontal.

Table 22. Unadjusted mean MFDD for each tyre inflation group

Inflation	Mean	Std. Deviation	Rank
-30% F	1.14	0.016	3
Normal	1.11	0.026	6
-60% F	1.07	0.098	7
-60% S	1.17	0.020	1
-30% A	1.13	0.056	5
-60% A	1.14	0.096	4
-30% S	1.14	0.046	2

Figure A.10 shows the distribution of MFDD. The distribution of errors is required to be approximately normal before further statistical tests are completed. The error data is sufficiently normal to assume a normal distribution and tests to determine differences in MFDD across inflation groups can proceed. Figure A.11 is testing for a time or day effect. It shows averages of all seven inflation groups for each replicate and a pattern that could be random or may show a time effect at work in the data. The analysis will be completed assuming both cases: that the pattern is random and that there is no time effect, and with an adjustment made for time effect.

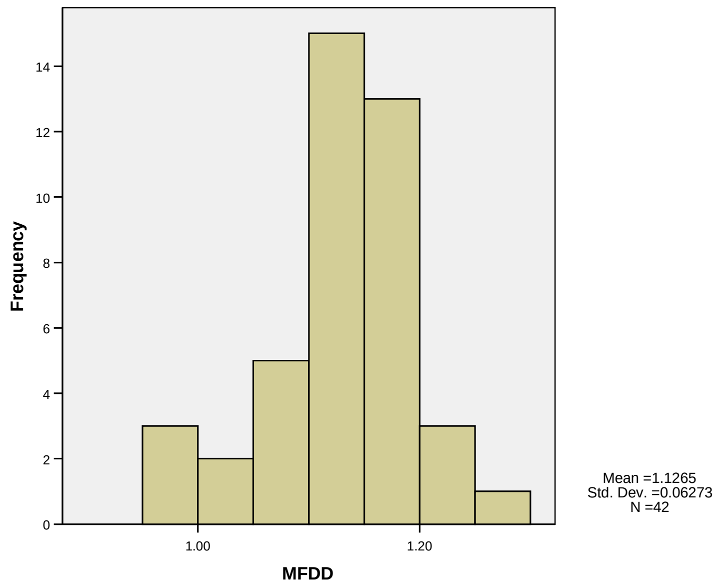

Figure A.10. Histogram of distribution of MFDD

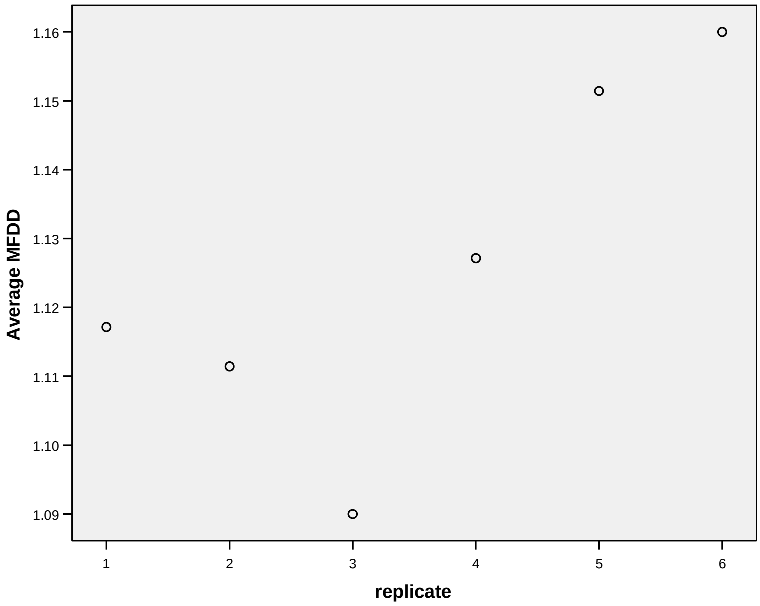

Figure A.11. Average by replicate

A.1.4.1 Covariate plots

Plots of outcome versus each covariate were plotted to determine relationships between covariates and MFDD. Random patterns are seen in all plots including entry speed. Entry speed is plotted here as an example.

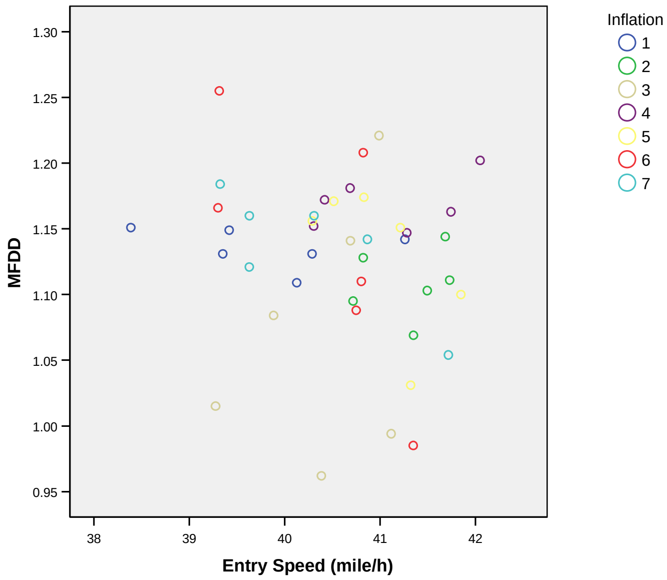

Figure A.12. MFDD by entry speed

A.1.4.2 Analysis

The regression process suggests that no covariates should remain in the analysis. There are no significant correlations of covariates with MFDD either. It is detected (using an ANOVA procedure) that inflation does not have a significant effect on MFDD. When a time effect adjustment is made, the same conclusions are reached – there are no significant covariates and inflation does not have a significant effect on time-adjusted MFDD.

A.2 Run flat tyres

A.2.1 Initial investigation of Stopping Distance

Table 23 lists the mean stopping distance values for each of the six inflation groups. The means are averages of the pure stopping distance numbers and do not take into account any adjustments for covariates (mentioned above) that might be relevant. The largest overall stopping distance is for -100% All closely followed by -100% Front. The shortest occurs in -60% All.

Table 23. Unadjusted mean stopping distance for each tyre inflation group

Inflation	Mean	Std. Deviation	Rank
-30% A	19.18	0.909	3
-100% A	21.59	1.751	6
-100% F	21.56	1.230	5
Normal	19.12	0.455	2
-60% A	18.54	1.226	1
-100% S	21.41	1.480	4

Figure A.13 shows the distribution of stopping distances. There is a gap in the centre of the histogram which could imply that this is a bi-modal distribution split by those running on flat and those not running on flat. This proposal is strengthened by seeing the divide in averages in Table 23.

Figure A.14 is testing for a time or day effect. It shows averages of all seven inflation groups for each replicate and a pattern that could be random or may show a time effect at work in the data. The analysis will be completed assuming both cases: that the pattern is random and that there is no time effect, and with an adjustment made for time effect.

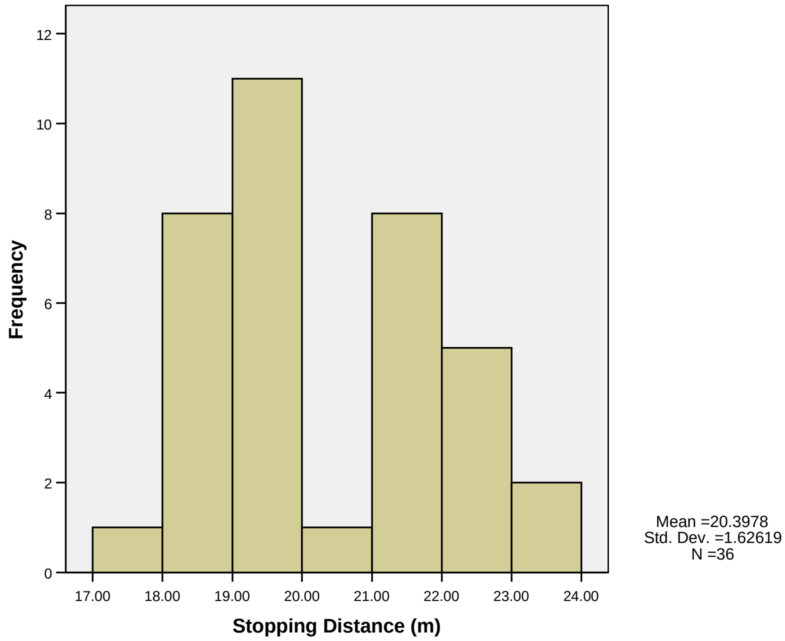

Figure A.13. Histogram of distribution of stopping distance

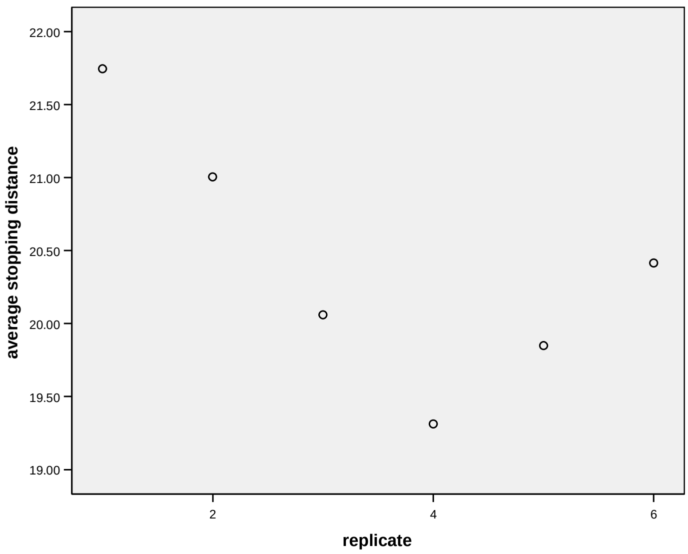

Figure A.14. Average by replicate

A.2.1.1 Covariate plots

Plots of outcome versus each covariate were plotted to determine relationships between covariates and stopping distance. Random patterns are seen in all plots except entry speed. Entry speed is highly related to stopping distance.

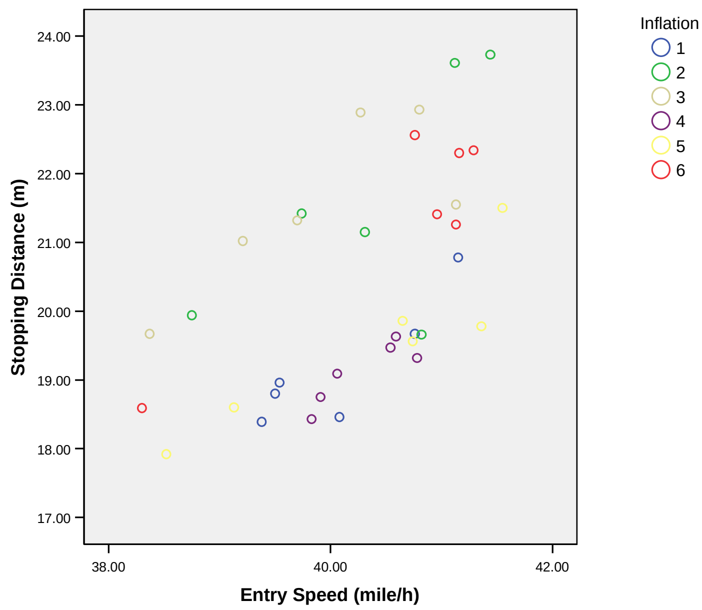

Figure A.15. Stopping distance by entry speed

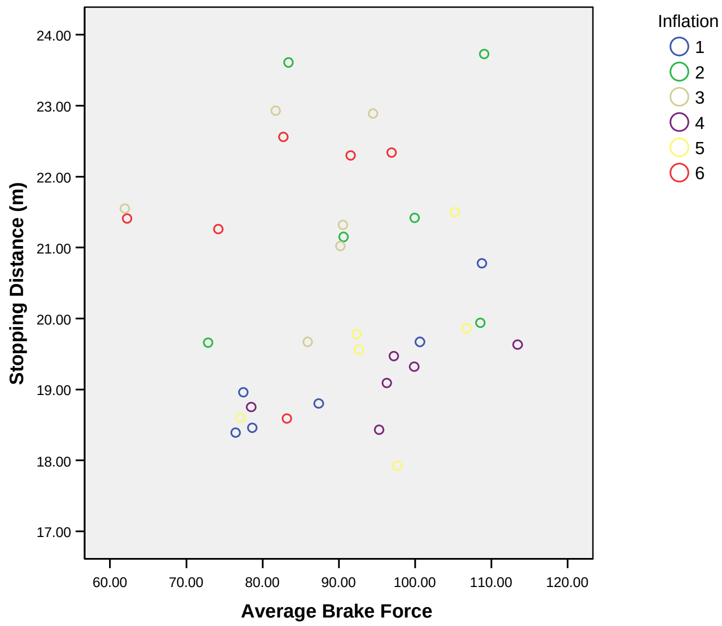

Figure A.16. Stopping distance by average brake force

A.2.1.2 Analysis

The possible covariates are listed above in the introduction. Due to the large number of covariates it is important to pick out those that have a significant effect on the outcome. This is achieved using a regression process. The covariates are entered in to a regression predicting stopping distance and those without a significant effect on the prediction of stopping distance are removed. Also removed are cases where the co-linearity statistic (VIF) is bigger than 10. This removes variables which can be predicted using other covariates.

Due to the bi-modal distribution there are several different ways of treating the data. The regression process can include a factor that splits the two groups by flat tyre and not flat tyre (groups 2, 3, 6 and groups 1, 4, 5) as well as covariates. This achieves covariates of Entry Speed and Average Brake Force. Alternatively we have allowed for the change in average of the two groups and adjusted accordingly. This suggests no covariates are appropriate.

It is also possible to apply the regression analysis to the whole data set without taking account of the two groups. This shows that the covariates that are useful are Entry Speed, Rise Rate and Reaction Time. This was deemed to be an unsatisfactory design as it does not allow for the obvious group split.

The regression process of choice suggests that the covariates that should be included in the model are Entry Speed and Average Brake Force.

It is now possible to analyse the effect of inflation on stopping distance whilst allowing for the important covariates. It is detected (using an ANCOVA procedure) that inflation does have a significant effect on stopping distance. In fact inflation explains the highest proportion of the variance (79.9%).

Adjusting for the two covariates mentioned above, the expected marginal means are compared to the original means below. The order of average stopping distances changes a small amount once adjustments are made for the important covariates. The shortest average stopping distance occurs at Normal, and the longest at -100% Front.

Table 24. Mean stopping distances for each tyre inflation group, unadjusted and adjusted

Inflation	Unadjusted Mean	Rank	Adjusted Mean	Rank
-30% A	19.18	3	19.42	3
-100% A	21.59	6	21.36	5
-100% F	21.56	5	22.09	6
Normal	19.12	2	18.90	1
-60% A	18.54	1	19.32	2
-100% S	21.41	4	21.30	4

Significant differences are detected between all points in the flat tyres (-100% inflation) and all points in the non-flat tyres (normal, -30% and -60% inflation):

- -30% all and -100% all
- -30% all and -100% front
- -30% all and -100% side
- normal and -100% all
- normal and -100% front
- normal and -100% side
- -60% all and -100% all
- -60% all and -100% front
- -60% all and -100% side

These differences can also be seen in the plot below showing adjusted means by inflation level.

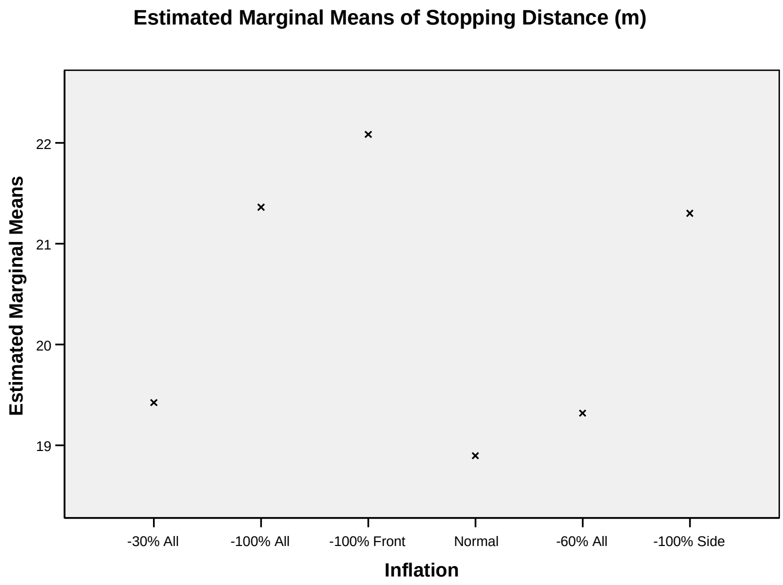

Figure A.17. Adjusted mean for each inflation point

Treating the two groups separately suggests that inflation is not important in determining differences within the two inflation groups. This strengthens the result above and guarantees that the only differences between the six inflations are the differences mentioned above between the two inflation groups.

In treating a time effect, Entry Speed is the only covariate that is significant in the model. However, the conclusions reached are the same.

A.2.2 Initial investigation of MFDD

Table 25 lists the mean MFDD values for each of the six inflation groups. The means are averages of the pure MFDD and do not take into account any adjustments for covariates (mentioned above) that might be relevant. The largest overall MFDD is in the Normal inflation group. The lowest occurs in -100% frontal.

Table 25. Unadjusted mean MFDD for each tyre inflation group

Inflation	Mean	Std. Deviation	Rank
-30% A	1.02	0.025	3
-100% A	0.89	0.083	5
-100% F	0.88	0.043	6
Normal	1.04	0.026	1
-60% A	1.03	0.042	2
-100% S	0.90	0.035	4

Figure A.18 shows the distribution of MFDD. Again a bi-modal distribution is suggested, but normal distributions are sufficient within groups.

Figure A.19 is testing for a time or day effect. It shows averages of all six inflation groups for each replicate and a pattern that could be random or may show a time effect at work in the data. The analysis will be completed assuming both cases: that the pattern is random and that there is no time effect, and with an adjustment made for time effect.

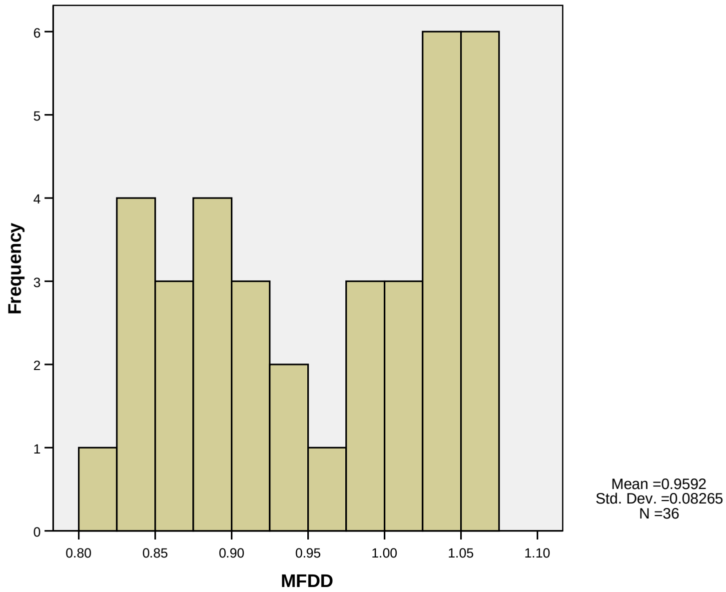

Figure A.18. Histogram of distribution of MFDD

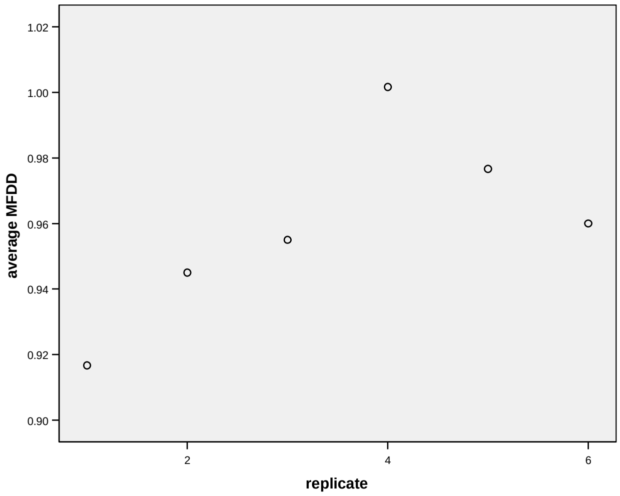

Figure A.19. Average by replicate

A.2.2.1 Covariate plots

Plots of outcome versus each covariate were plotted to determine relationships between covariates and MFDD. Random patterns are seen in all except mean*acc and peak*acc where positive correlations can be seen and a split between the two groups is also obvious.

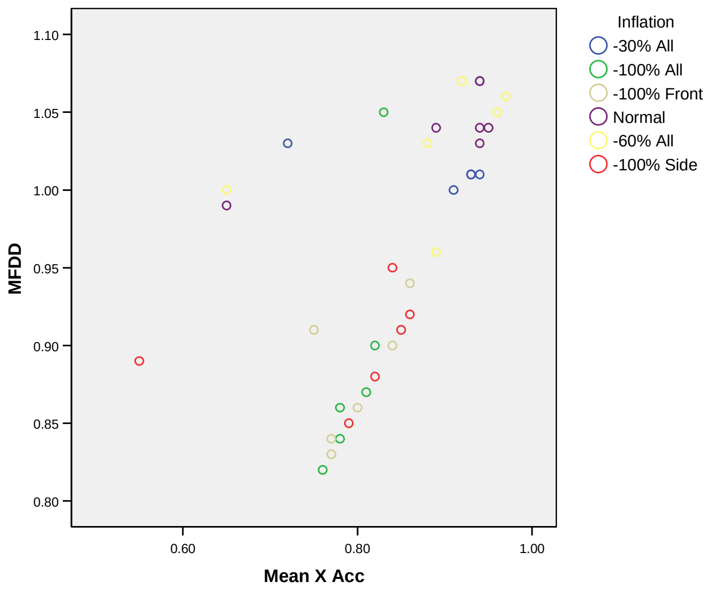

Figure A.20. MFDD by mean*acc

A.2.2.2 Analysis

The initial regression process suggests that covariates Average Brake Force, Reaction Time and Delay Time should remain in the analysis. The same covariates are suggested with the process that includes inflation group in the process. It is detected that inflation does have a significant effect on MFDD, and the significant differences occur between the same groups as mentioned for stopping distance.

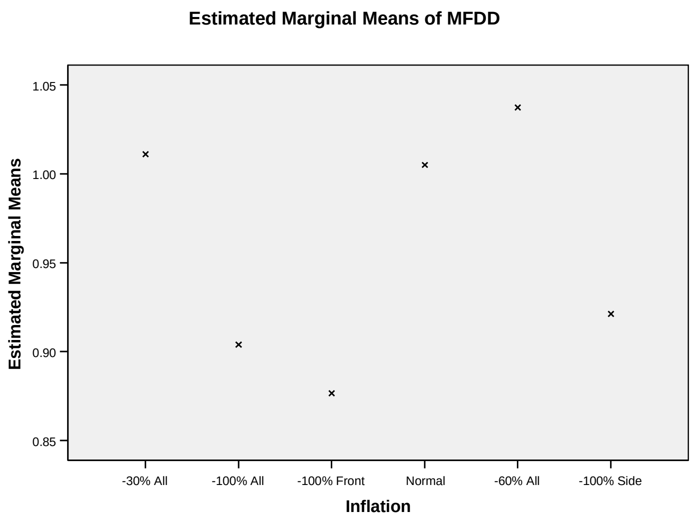

Figure A.21. Adjusted mean for each inflation point

When a time effect adjustment is made, the same conclusions are reached, so overall, it is clear that with run flat tyres there is a significant difference in stopping distance and MFDD between those running on flat and those not running on flat. No differences are found within these two groups.

Table 26. Mean MFDD for each tyre inflation group, unadjusted and adjusted

Inflation	Unadjusted Mean	Rank	Adjusted Mean	Rank
-30% A	1.02	3	1.01	2
-100% A	0.89	5	.90	5
-100% F	0.88	6	.88	6
Normal	1.04	1	1.01	3
-60% A	1.03	2	1.04	1
-100% S	0.90	4	.92	4

A.3 Conclusions

Using an ANCOVA procedure for normal tyres, it has been possible to detect a significant effect of inflation on stopping distance. Significant differences have been found between stopping distances for the following inflation pairs: -60% side is significantly different to -30% front, -60% front, -30% all and -60% all. The shortest average adjusted stopping distance was recorded for -60% side and the longest at -30% all.

Testing the MFDD results for normal tyres showed that inflation does not have a significant effect on MFDD.

An equivalent ANCOVA procedure for run flat tyres has shown that inflation has a significant effect on stopping distance and MFDD, in fact it explains 80% of the variation in the stopping distance data. Both outcomes have a bimodal distribution split by those on -100% (flat) inflation and those on inflations normal, -30% and -60% (i.e. not flat). Significant differences between these two modes have been detected in stopping distance and MFDD.

Appendix B. Step steer experiments - statistical analysis

The following analysis compares the values of the following outcome variables:

- o lateral acceleration,
- o yaw rate and
- o slip angle,

Within each of these variables, the following measurements are considered:

- o Response time $T_{peak} – T_0$,
- o Response time $T_{90\%} – T_0$,
- o Peak and
- o Steady state

Explanatory variables are inflation group (Table 9 for run flat tyres and Table 8 for normal tyres) and tyre type – run flat tyres and normal tyres.

B.1 Initial investigation

Histograms were plotted of each outcome by tyre type to check for outliers and normality. Figure B.1., Figure B.2 and Figure show the distributions of Response time $T_{peak} – T_0$ for each variable and the two tyre types. The underlying noise in the data is required to be normally distributed before further statistical tests are completed. Slip angle T_{peak} (Figure) is removed from the analysis due to non-normality.

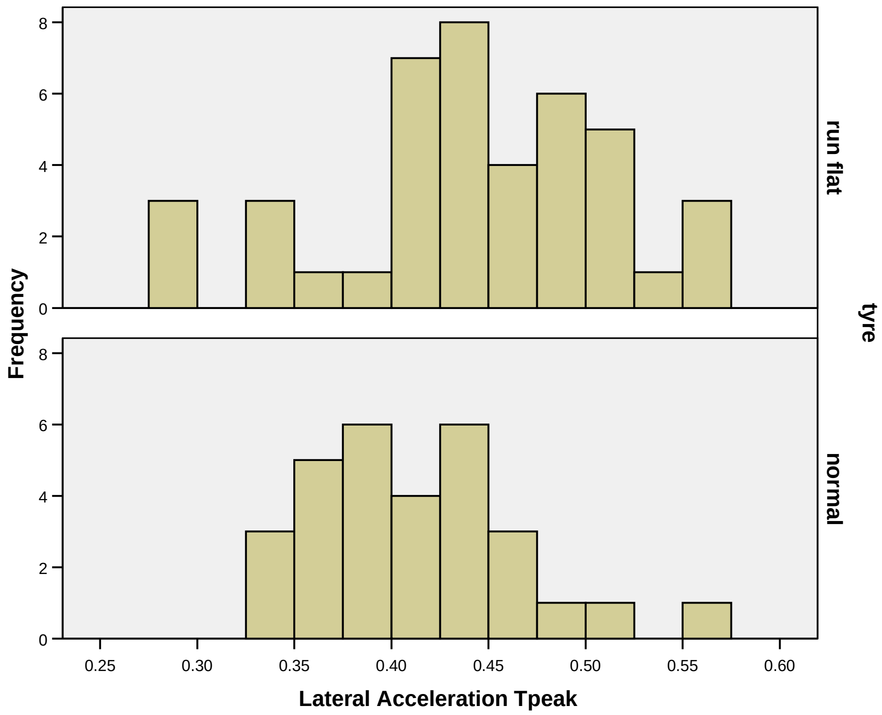

Figure B.1. Histogram of distribution of Lateral Acceleration: Response time $T_{peak} – T_0$

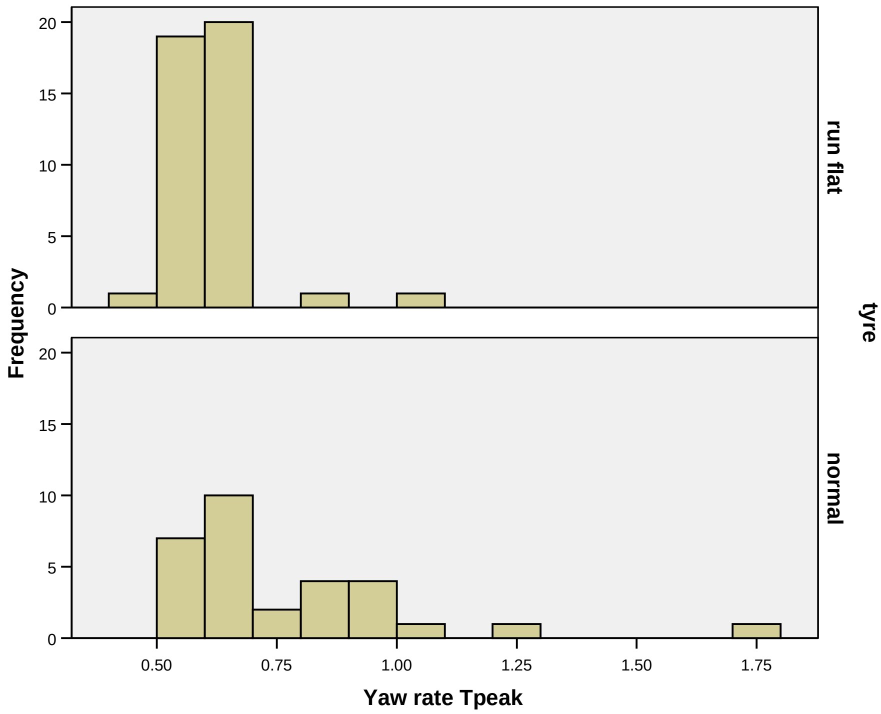

Figure B.2. Histogram of distribution of Yaw rate: Response time $T_{peak} – T_0$

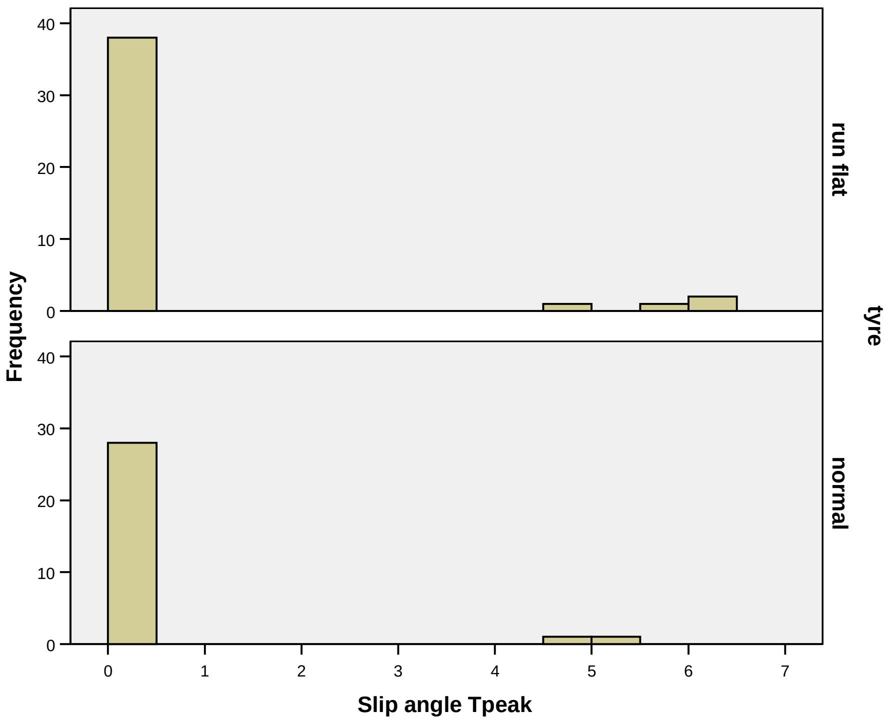

Figure B.3. Histogram of distribution of Slip angle: Response time $T_{peak} – T_0$

Figure B.4 is testing for a time of day effect. It shows averages and 95% confidence intervals of Lateral Acceleration: Response time $T_{peak} – T_0$ of all seven (for run flats - r) or five (for normal tyres -

n) inflation groups for each replicate and a random pattern suggesting no time effect at work in the data.

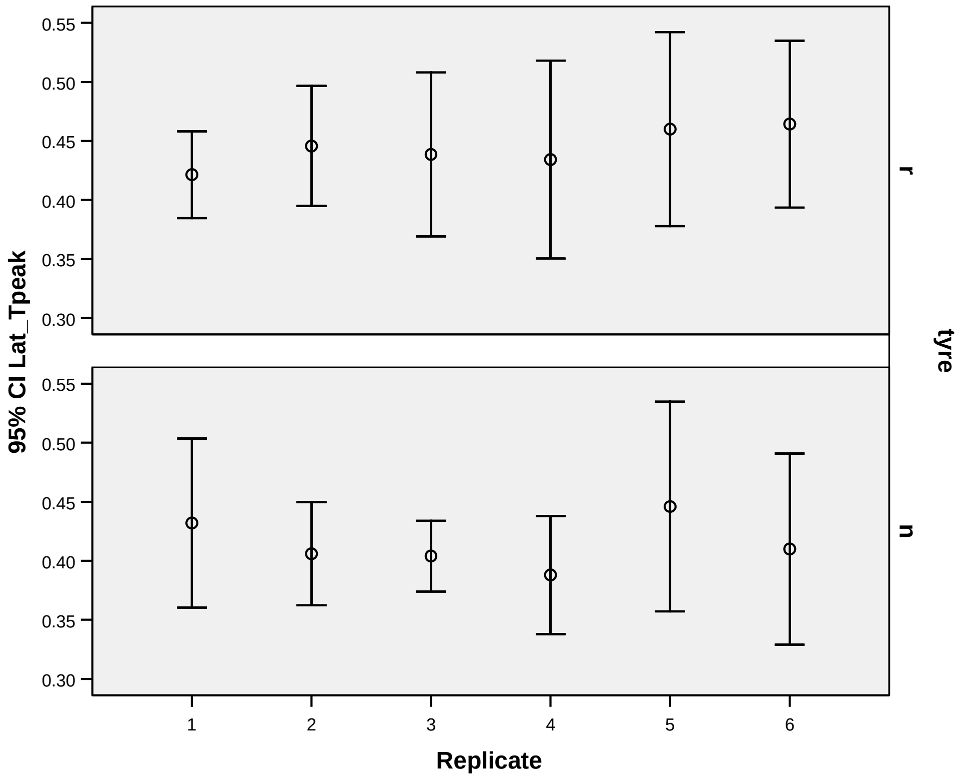

Figure B.4. Average by replicate

B.2 Analysis

The aim of the analysis is to detect any differences between outcome measures for different inflations and tyre types.

For each of the outcomes, a univariate ANOVA procedure was carried out to determine the variables that affect the outcome measure. These variables are listed for each outcome in Table 27. Columns 2, 3 and 4 contain effect size for each significant variable – this is the amount of variation in the data that the variable explains. Column 2 shows that in all but four outcomes, tyre is a significant variable, that is, there are differences in results between normal and run flat tyres for corresponding inflations. This is probably due to differences in run flat tyre experiments where the inflation level was -100%. ‘ns’ in Table 27 indicates a variable is not significant (at the 5% level) in describing the variation in the data. Within tyres, differing inflations are identified using a second ANOVA procedure for each tyre group.

Table 27. Significant variables and effect size in each outcome

Outcome	Tyre type (run-flat or normal)	Inflation levels	Tyre*Inflation
Lateral T Peak	0.215	0.374	ns
Lateral T 90	0.326	0.628	ns
Lateral Peak	0.072	0.923	0.285
Lateral Steady	ns	0.978	0.36
Yaw T Peak	0.166	ns	ns
Yaw T 90	ns	0.493	ns
Yaw Peak	ns	0.965	0.314
Yaw Steady	0.441	0.977	0.132
Slip T90	ns	0.346	ns
Slip Peak	0.086	0.714	ns
Slip Steady	0.442	0.393	ns

Figure B., Figure and Figure show average values and their 95% confidence intervals for Response time $T_{90\%}$ - T_0 for each outcome and tyre type. Differences between inflations can be detected in these plots, for example in Figure B., Front -100% and All -100% (run-flat tyres) have a lower lateral acceleration than all other inflations, and this is seen to be a significant difference between these and all other inflations in Table 30.

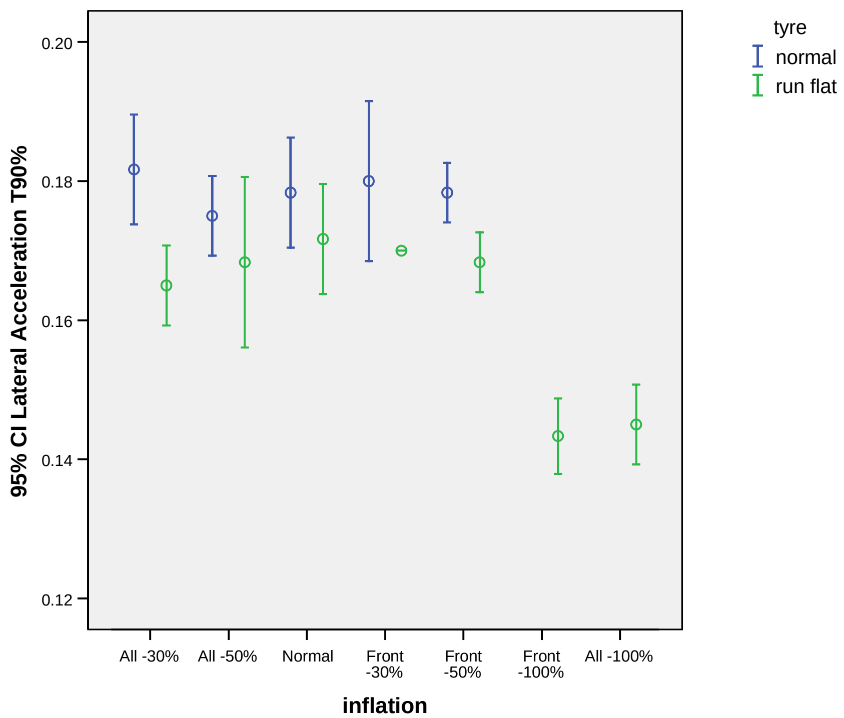

Figure B.5. Lateral Acceleration T90% average (and 95% confidence intervals) plot for each inflation

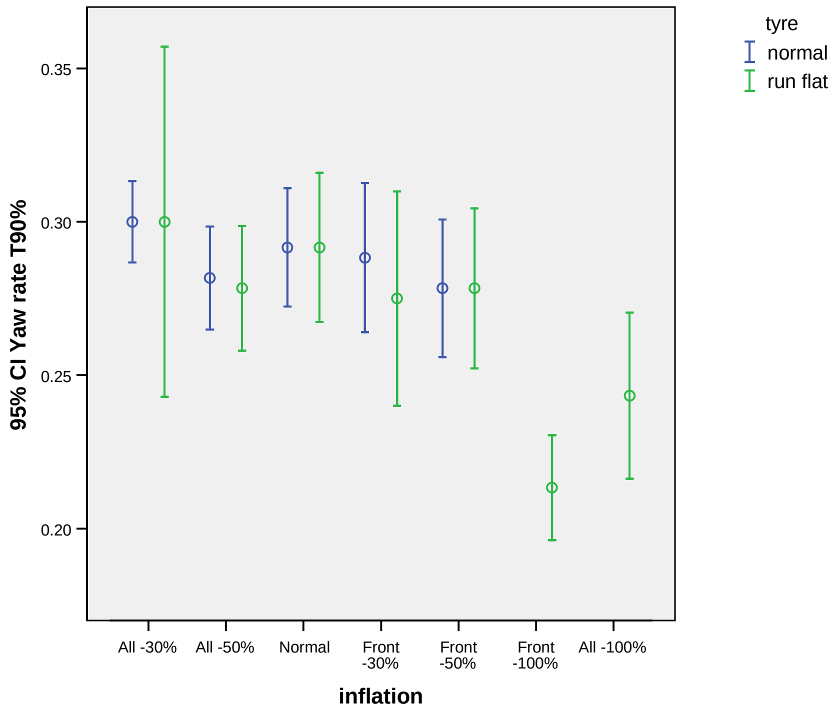

Figure B.6. Yaw rate T90% average (and 95% confidence intervals) plot for each inflation

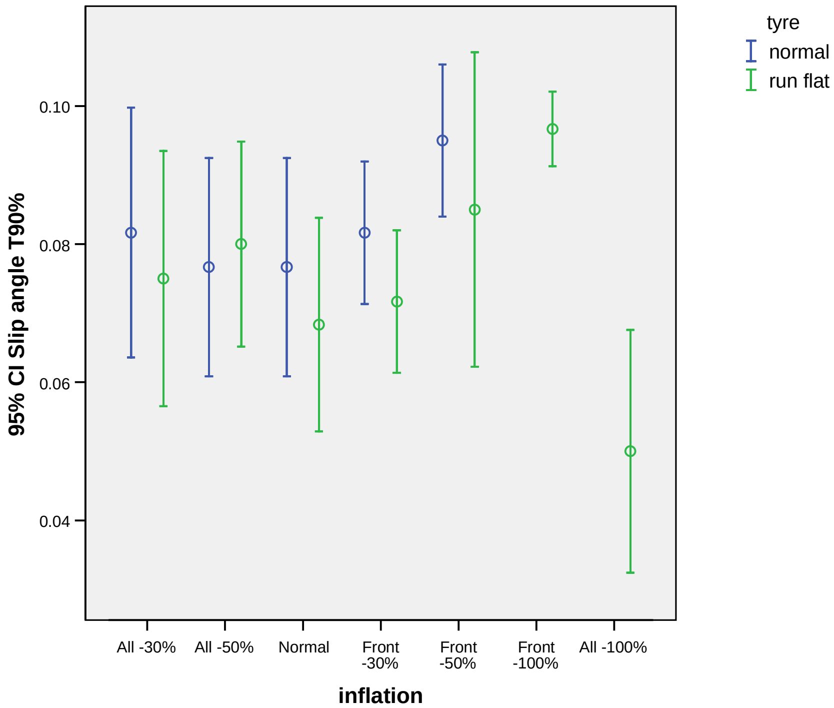

Figure B.7. Slip angle T90% average (and 95% confidence intervals) plot for each inflation

Table 28. Significant inflation factor within tyres and outcomes

Outcome	Normal	Run-flat
Lateral T Peak	ns	p<0.01
Lateral T 90	ns	p<0.01
Lateral Peak	p<0.01	p<0.01
Lateral Steady	p<0.01	p<0.01
Yaw T Peak	ns	ns
Yaw T 90	ns	p<0.01
Yaw Peak	p<0.01	p<0.01
Yaw Steady	p<0.01	p<0.01
Slip T90	ns	p<0.01
Slip Peak	p<0.01	p<0.01
Slip Steady	ns	p<0.01

Note: 'ns' indicates more than a 5% chance of no difference; 'p<0.01' – there is less than 1% chance of no difference

Table 28 shows the two tyre types and within each tyre type, whether there are differences in inflations for the outcome. 'ns' stands for not significant, that is there are no significant differences between inflations within the tyre. The table is followed by a grid for each outcome showing differences between inflations. A box shaded in blue depicts that we can sure that there is a less than 1 in 20 chance of there not being a significant difference between inflations. For example, Table 29 shows only differences for run-flat tyres, as Table 28 indicates that there are no differences between inflations in normal tyres. It indicates that there is a significant difference (less than 5% chance of being no difference between inflations) between inflations -100% Front and all other inflations, a significant difference between Normal and -100% All and a significant difference between -30% Front and -100% All. A table with more blue shown signifies more significant differences can be found between inflations.

Table 29. Significant differences between inflations (coloured blue) for Lateral T Peak: run-flat tyres

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F		■	■	■	■	■	■
-30A	■						
-50A	■						
Norm	■					■	
-50F	■						
-100A	■			■			■
-30F	■					■	

Table 30. Significant differences between inflations (coloured blue) for Lateral T 90%: run-flat tyres

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F							
-30A							
-50A							
Norm							
-50F							
-100A							
-30F							

Table 31. Significant differences between inflations (coloured blue) for Lateral Peak: normal tyres (left) and run-flat tyres (right)

	-30A	-50A	Norm	-50F	-30F
-30A					
-50A					
Norm					
-50F					
-30F					

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F							
-30A							
-50A							
Norm							
-50F							
-100A							
-30F							

Table 32. Significant differences between inflations (coloured blue) for Lateral Steady state: normal tyres (left) and run-flat tyres (right)

	-30A	-50A	Norm	-50F	-30F
-30A					
-50A					
Norm					
-50F					
-30F					

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F							
-30A							
-50A							
Norm							
-50F							
-100A							
-30F							

Table 33. Significant differences between inflations (coloured blue) for Yaw T 90%: run-flat tyres

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F		■	■	■	■		■
-30A	■					■	
-50A	■						
Norm	■					■	
-50F	■						
-100A		■		■			
-30F	■						

Table 34. Significant differences between inflations (coloured blue) for Yaw Peak: normal tyres (left) and run-flat tyres (right)

	-30A	-50A	Norm	-50F	-30F
-30A		■	■	■	
-50A	■		■		■
Norm	■	■		■	■
-50F	■		■		■
-30F		■	■	■	

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F		■	■	■	■		■
-30A	■		■	■		■	
-50A	■	■		■	■	■	■
Norm	■	■	■		■	■	■
-50F	■		■	■		■	
-100A		■	■	■	■		■
-30F	■		■	■		■	

Table 35. Significant differences between inflations (coloured blue) for Yaw Steady state: normal tyres (left) and run-flat tyres (right)

	-30A	-50A	Norm	-50F	-30F
-30A		■	■	■	
-50A	■		■		■
Norm	■	■		■	■
-50F	■		■		■
-30F		■	■	■	

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F		■	■	■	■	■	■
-30A	■		■	■		■	
-50A	■	■		■		■	■
Norm	■	■	■		■	■	■
-50F	■			■		■	■
-100A	■	■	■	■	■		■
-30F	■		■	■	■	■	

Table 36. Significant differences between inflations (coloured blue) for Slip angle T 90%: run-flat tyres

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F							
-30A							
-50A							
Norm							
-50F							
-100A							
-30F							

Table 37. Significant differences between inflations (coloured blue) for Slip angle Peak: normal tyres (left) and run-flat tyres (right)

	-30A	-50A	Norm	-50F	-30F
-30A					
-50A					
Norm					
-50F					
-30F					

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F							
-30A							
-50A							
Norm							
-50F							
-100A							
-30F							

Table 38. Significant differences between inflations (coloured blue) for Slip angle Steady state: run-flat tyres

	-100F	-30A	-50A	Norm	-50F	-100A	-30F
-100F							
-30A							
-50A							
Norm							
-50F							
-100A							
-30F							

B.3 Conclusions

A series of ANOVA analyses to detect significant differences in tyre and inflation responses to a handling test have been completed. It has been determined that there is a difference in the response of two different tyres in all but four outcome measured. This will be somewhat as a result of different results in -100% inflation runs, only available in run-flat tyres.

The second series of ANOVA results splits the tyre types into two separate groups and demonstrates the outcomes for which there is a difference in results between inflations. Significant differences ($p < 0.01$) are detected for all but one outcome in run-flat tyres, that is, different inflations of run-flat tyres behave differently in this handling test. For normal tyres, the results are different – only in four outcomes are significant differences found between inflations. Most differences found between inflation in run-flat tyres are between -100% and all other inflations, and this clearly is not an inflation used in the normal tyre study design, so fewer differences are to be expected within this normal tyre set.

The grids generated above show differences in inflations within each tyre type. In all but Slip angle T90 and Slip angle steady, run flat tyres at '-100% Front' inflation produce a significantly different outcome to other inflation types, that is, run-flat tyres are seen to behave differently at '-100% Front' to all other inflations tested. For most outcomes this is also true for '-100% All' inflation.

Appendix C. Step steer in turn experiments - statistical analysis

C.1 Introduction

Data have been collected in step in turn tests. Six replicates for each set of tyre pressures, and tests for normal tyres and run-flat tyres have been completed. Outcome variables are peak values of lateral acceleration, yaw rate and slip angle. Explanatory variables are inflation group (normal inflation, -30% and -50%) and tyre (run-flat and normal).

C.2 Initial investigation

Histograms were plotted of each outcome by tyre type to check for outliers and normality. Figure C.1. shows the distribution of yaw rate by tyre. An outlier is obvious in the run-flat tyre. This is the 2nd replicate of normal inflation on a run flat tyre and is excluded from the analysis. Figure C.2, Figure C.3 and Figure C.4. show the distributions of all outcomes with the outlier excluded.

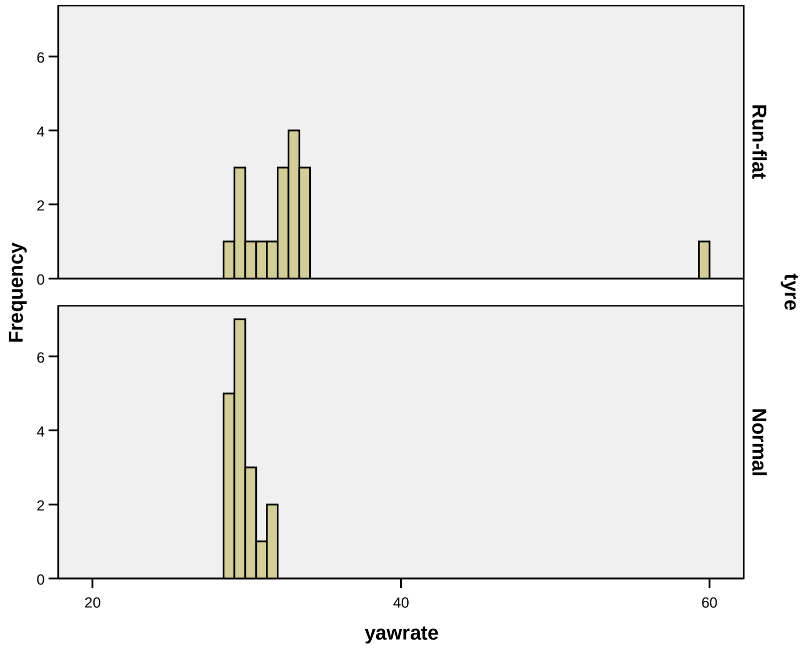

Figure C.1. Histogram of distribution of Yaw rate

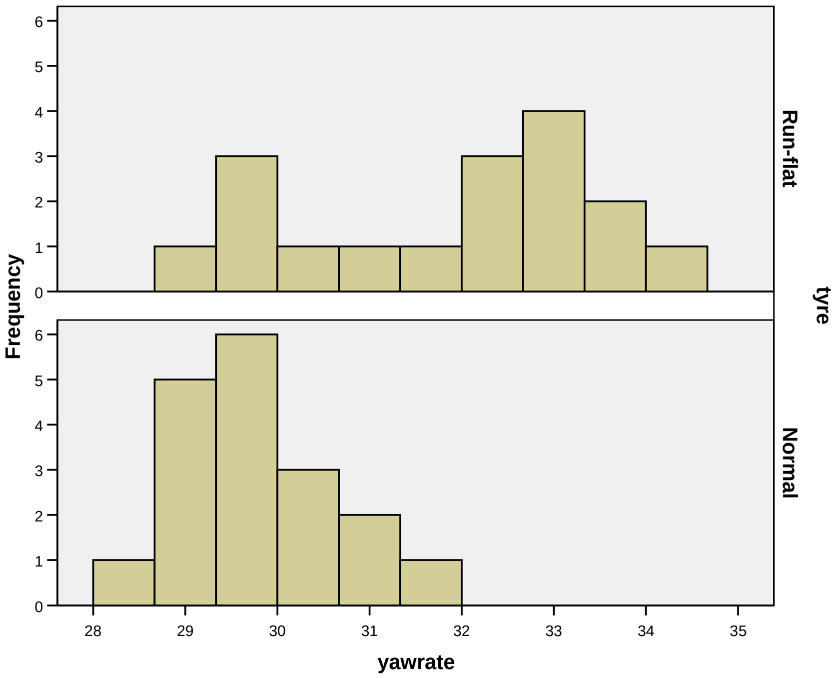

Figure C.2. Histogram of distribution of Yaw rate (removing outlier)

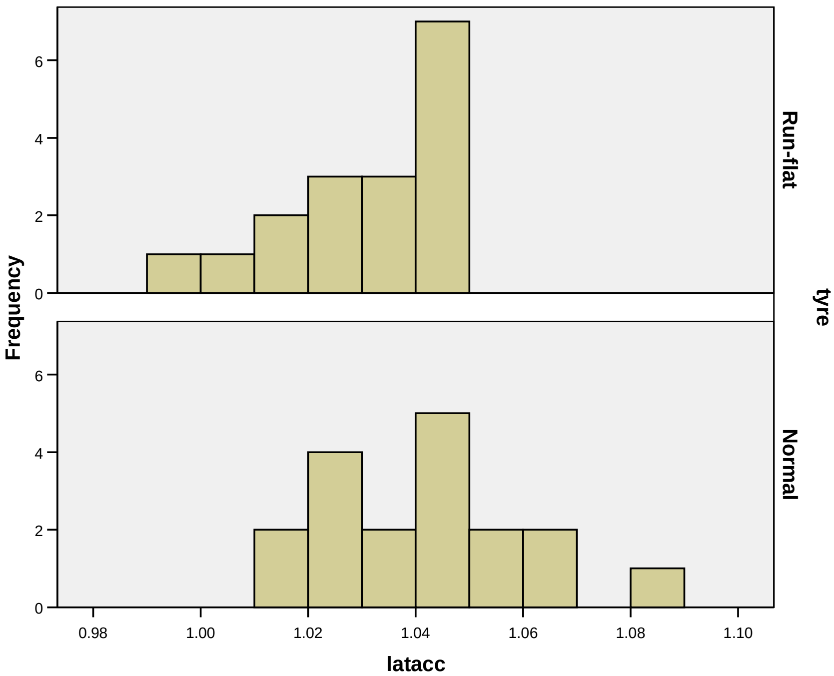

Figure C.3. Histogram of distribution of lateral acceleration (removing outlier)

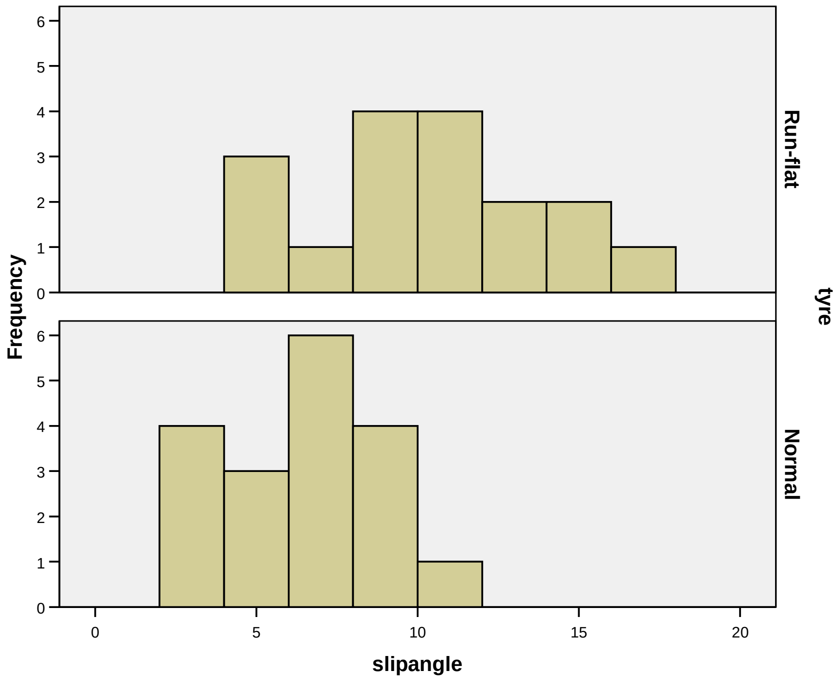

Figure C.4. Histogram of distribution of slip angle (removing outlier)

C.3 Analysis

The aim of the analysis is to detect any differences between outcome measures for different inflations and tyre types.

For the outcomes, a univariate ANOVA procedure was carried out to determine the variables that affect the outcome measure. These variables are listed for each outcome in Table 39. Columns 2 and 3 contain effect size for each significant variable – this is the amount of variation in the data that the variable explains. Column 2 shows that in all outcomes, tyre is a significant outcome ($p < 0.10$), that is, there are differences in results between normal and run flat tyres. 'ns' in Table 39 indicates a variable is not significant (at the 10% level) in describing the variation in the data. Within tyres, differing inflations are identified using a second ANOVA procedure for each tyre group.

Table 39. Significant variables and effect size in each outcome

Outcome	Tyre	Inflation
Yaw rate	0.397	ns
Lateral acceleration	0.442	0.537
Slip angle	0.099	ns

*** 'ns' represents not significant at the 10% level. i.e. there is a less than 1 in 10 chance that there is not a significant difference between tyres or inflation levels**

Table 40 shows the two tyre types and within each tyre type, whether there are differences in inflations for the outcome. '$p < 0.01$' denotes a significant difference in results between inflations at the 1% level, i.e we can be 99% sure that there is a difference in effect of inflation. 'ns' stands for not significant, that is there are no significant differences between results for inflations within the tyre. The table is followed by a grid for each outcome showing differences between inflations. A box shaded in blue depicts that we can sure that there is a less than 1 in 20 chance of there not being a significant difference between inflations. For example Table 41 shows only differences for run-flat tyres, as Table 40 indicates that there are no differences between inflations in normal tyres. It indicates that there is a significant difference (less than 5% chance of being no difference between inflations) between inflations 'Normal' and all others. In fact this is the case for all outcomes where a significant difference is found.

Table 40. Significant inflation factor within tyres and outcomes

Outcome	Normal	Run-flat
Yaw rate	ns	$p < 0.01$
Lateral acceleration	ns	ns
Slip angle	$p < 0.01$	$p < 0.01$

*** 'ns' represents not significant at the 5% level. i.e. there is a less than 1 in 20 chance that there is not a significant difference between inflation levels**

Table 41. Significant differences between inflations (coloured blue) for Yaw rate (run-flat tyres)

	Normal	-30%	-50%
Normal			
-30%			
-50%			

Table 42. Significant differences between inflations (coloured blue) for Slip angle: normal tyres (left) and run-flat tyres (right)

	Normal	-30%	-50%
Normal			
-30%			
-50%			

	Normal	-30%	-50%
Normal			
-30%			
-50%			

C.4 Conclusions

A series of ANOVA procedures have been carried out to detect differences within outcome measures for different inflations and tyre types. Tyre type is an important factor in explaining some of the variation in the data sets – it has a significant effect in all three outcomes tested. There are differences within tyre type too – for Yaw rate in run flat tyres and for Slip angle in run flat and normal tyres significant differences are found between normal inflation and under-inflation (-30% or -50%).