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EXECUTIVE SUMMARY

Articulated vehicles registered in the UK are required to meet European braking legislation as specified in EU Directive 71/320/EEC or UNECE Regulation 13. This legislation requires the brakes on each part of a vehicle combination to perform within a compatibility corridor. Graphical plots of brake performance against applied pressure define these corridors. This is intended to ensure balanced and stable braking when any one towing vehicle is connected to any trailer or semi-trailer, particularly at high (emergency) decelerations. Concern has been expressed, however, that the legislation does not adequately consider what happens at low decelerations, which are much more likely to be used in normal driving. At low decelerations, threshold pressures (pressure in brake system at which brakes just start to apply) are an important determinant of brake balance, lining wear, stability and performance.

The objectives were to study vehicles over a range of threshold pressures permitted by the compatibility corridors of the ECE Regulation 13 (R.13) and develop proven proposals that would enhance braking performance and stability and reduce maintenance costs to the operating industry. The basic methodology was to use an articulated vehicle with variable brake threshold pressures and assess the dynamic and static braking performance and lining wear characteristics over the range of braking system threshold pressures permitted by R.13. The tests included a roller brake tester, dynamic performance tests on the TRL test track, and road trials involving high mileage travelling around a pre-determined test route.

Road trials were a substantial part of the assessment of each set-up. The route was 180km in length and comprised of a mixture of road types. For the first five set-ups the vehicle was driven over this route for either 11,000km or until a predetermined reduction in the brake efficiency was observed on the roller brake tester. The method employed on the roller brake tester was to measure the brake force at each wheel across the full range of coupling head pressure. The brake efficiency (brake force divided by gross vehicle mass) was related to coupling head pressure and the results from each test were compared with those from previous tests to ascertain if any appreciable degradation of braking performance was evident. All roller brake testing was carried out with the vehicle loaded to maximum laden weight.

The dynamic braking performance of the vehicle combination was established at the beginning of each threshold pressure set-up using snub tests, at a range of coupling head pressures, with the tests being repeated at the conclusion of each road trial. The towing vehicle was fitted with a brake pressure regulating device that allowed brake applications to be made at constant, pre-set pressures.

Track tests were conducted to quantify the relationship between the work done by each axle on the vehicle and the temperature rise of the brakes on that axle. By disabling the brakes on all but the particular axle(s) under investigation, the temperature profile for each axle could be directly compared to that recorded for the other axles after the same sequence of snubs.

Further track tests to simulate the operators use of the predominance valves were conducted. The tractor was set to the normal operating threshold pressure (0.4 bar) and the threshold pressure for the trailer was increased by the use of return springs. By adjusting the

predominance in the trailer control valves, the threshold pressure difference was negated and the performance assessed.

A number of track tests were undertaken to investigate the effect of stability of the HGV under braking conditions. The vehicle was set with differing threshold pressures, and the brakes were applied from velocities that were incremented by 10km/h. Three types of tests took place, braking on the full combination, or the tractor unit only, or the semi-trailer only.

Type approval tests were conducted at the Vehicle Certification Agency test centre (VTAC) and comprised of eight series of tests. For type approval, the tractor and trailer are tested independently and must comply with Annex 10 of R.13.

A towing vehicle with manufacturer supplied asbestos free linings, and a trailer with Regulation 13 Type III linings were used to determine the effect of varying threshold pressure within the range currently permitted by R.13. When the threshold pressures were set to 0.4 & 0.8 bar, which was somewhat within the permitted range, the trailer linings glazed and within 5,000km the trailer brake efficiency deteriorated to below that permitted by the UK annual vehicle inspection.

In order to ensure effective brake distribution, the braking effort on each axle should be approximately proportional to the static load on each axle. The axle load distribution was 15%, 25% and 20% for the steer axle, drive axle and each semi-trailer axle respectively. Work done was calculated upon the basis of brake temperature and showed that threshold pressures of 0.6 & 0.4 (difference -0.2) gave an efficiency distribution (10.5%, 23.1% and 22.1%) which was closest to the ideal. The brake distribution deviated from these values such that, the greater the threshold pressure difference, the greater the deviation.

The wear rate of the brake lining provided a good indication of the compatibility of the vehicle combination. With a threshold pressure difference of +0.4 (threshold pressures 0.4 & 0.8) the drive axle wear was approximately five times that of a trailer axle. The tractor linings would need to be replaced five times more frequently as the trailer. The combination closest to the ideal for efficiency distribution produced a wear rate ratio of 2:1 for the tractor drive axle to trailer.

Regulation 13 Type III brake linings have shown an improvement over Type II and the research has shown that threshold differences of 0.4 bar or more will start to produce glazing and vehicle brake performance degradation. Therefore, keeping the threshold pressure difference to within the range of ±0.2 bar would improve lining wear, vehicle braking performance and vehicle stability.

The 0.4 & 1.2 bar set-up provided poor dynamic braking in terms of Mean Fully Developed Deceleration (MFDD). However, when the predominance was set to +0.8 bar, thus providing effective zero threshold pressure difference, the performance was similar to that of a 0.4 & 0.4 bar threshold set-up. The +0.8 bar predominance could be achieved with either of the two control valves, one located on the tractor unit and one located on the semi-trailer.

The instrumented fifth wheel enabled the measurement of the forces acting during braking manoeuvres. For both longitudinal and vertical forces the trend was toward a common value that is indicative of the limiting conditions, which were when the wheels locked. This was infrequent at the lower speeds and lower pressures and became more frequent as the pressure and speed increased. Since jack-knife and trailer swing did not occur, the lateral forces did not show an overall trend.

For type approval tests, the braking performance of the tractor unit conformed to the type approval compatibility corridor over the range of coupling head pressures that were used. The semi-trailer met the type approval requirements when laden. However, when the tests were repeated with the semi-trailer unladen, the brake performance did not conform to the compatibility corridor. The brake efficiency was found to be lower than the required theoretical braking rate, thus an unladen semi-trailer would be under-braked.

The report recommends that the compatibility corridors for type approval should be narrowed, both at the check braking range (less than 2 bar coupling head pressure) to improve the wear rate of the brake linings, and also narrowed all the way up to 4.5 bar coupling head pressure to improve vehicle stability. The corridors for both tractor units and semi-trailer should be narrowed. Furthermore, if close compatibility were achieved then a relay valve with adjustable predominance would be unnecessary. Therefore, phasing out of predominance valves is recommended.

COMPATIBILITY OF HEAVY VEHICLE COMBINATIONS

1. INTRODUCTION

Articulated vehicles registered in the UK are required to meet European braking legislation as specified in EU Directive 71/320/EEC or UNECE Regulation 13 (R.13). This legislation requires the brakes on each part of a vehicle combination to perform within a compatibility corridor. Graphical plots of brake performance against applied pressure define these corridors. This is intended to ensure balanced and stable braking when any one towing vehicle is connected to any trailer or semi-trailer, particularly at high (emergency) decelerations. Concern has been expressed, however, that the legislation does not adequately consider what happens at low decelerations, which are much more likely to be used in normal driving. At low decelerations, threshold pressures (pressure in the brake system at which brakes just begin to operate) are an important determinant of brake balance, lining wear, stability and performance.

Previous research for VSE4 (S042C/VD) showed that there is a wide variation in threshold pressures amongst vehicles in the UK. More recent research (S290B/VD) showed that even small differences in threshold pressures between towing and towed vehicles, that are well within limits currently set by legislation, can cause rapid lining wear, poor balance and performance degradation.

The prior interim report (S291B/VD) discussed the preliminary tests conducted at a number of varying threshold pressures to provide a preview of anticipated results. This report relates to an expansion of the project to evaluate the earlier conclusions when applied to a vehicle combination using a semi-trailer with brakes built to the most recent legislative standards (09 series of amendments to UNECE Regulation 13). The results in this report are a more comprehensive study.

Specifically, this project has the following objectives:

- Compare the findings of earlier work on this subject with the results of comparative testing of a vehicle combination whose trailer is engineered to satisfy the latest UNECE braking standards (Regulation 13.09); these standards will be mirrored by the EU Directive.

- Examine the stability of the combination under the range of achievable decelerations over a range of vehicle speeds.

- Deliver data concerning the magnitude and direction of the forces developed at the towing vehicle/trailer coupling.

1.1 BACKGROUND

Concerns about the apparent difficulties faced by heavy vehicle operators in maintaining the performance of trailer brakes, together with widespread criticism of vehicle compatibility amongst vehicle operators, caused the UK Department of the Environment, Transport and the Regions (DETR) to conduct a survey of brake threshold pressures in the UK. The survey, conducted by the Transport Research Laboratory (TRL), involved some 236 vehicles and concluded that over 50% of the vehicle combinations had a threshold pressure range of 0.5 bar or more and 18% had a range greater than 0.8 bar which is the maximum permitted by R.13 (Robinson, 1994). The report also indicated that this variation was predictable by vehicle make thus indicating that it was a function of design and not maintenance.

This data supported the concern that certain vehicle combinations were effectively incompatible, because during normal driving only one part of the combination was doing any work; they are also consistent with the reported in-service problems of glazed brake linings and the subsequent low braking performance.

2. TEST AND EVALUATION PROCEDURES

2.1 VEHICLE DESCRIPTION

The vehicle used was a 1990 Volvo FL10 (4X2) tractor unit and a 1988 Montracon air-suspended tri-axle semi-trailer, as used for the previous trials (S290B/VD). The Volvo FL10 had S-cam drum brakes on the steer and drive axles with automatic slack adjusters. The semi-trailer had S-cam brakes with manual slack adjusters. Both units had braking systems that complied with ECE Regulation 13.06 (EC Directive 85/647). The vehicle was operated close to the maximum permitted laden weight and Table 1 shows the mass of the vehicle whilst static.

Table 1. Mass of test vehicle

	Axle number	Gross laden weight (kg)	Partially laden (kg)	Test weight, near fully laden (kg)
Steer axle (drum brakes)	1	6700	5220	5660
Drive axle (drum brakes)	2	10500	7260	9520
Towing vehicle		17000	12480	15180
Trailer 1 (drum brakes)	3	8000	4230	7160
Trailer 2	4	8000	4250	7080
Trailer 3	5	8000	4310	7150
Semi-trailer (Montracon tri-axle)		24000	12790	21390
Vehicle combination		38000	25270	36570

2.1.1 Brake Linings

The vehicle combination was fitted with new brake linings for this project. The Volvo FL10 steer axle was fitted with 410 x 175 mm brake linings and the drive axle was fitted with 410 x 200 mm. All the linings were supplied from Volvo and were from the same production batch.

Rubery Owen axles were fitted to the semi-trailer. All of the linings for the trailer were 420 x 175 mm and supplied by Rubery Owen Rockwell, also from the same batch.

2.1.2 Instrumentation

The data acquisition hardware was supplied by National Instruments and the software was written in-house by TRL. Rubbing K-type thermocouples, on the inside of the brake drum, were used to measure the temperature for each drum. The velocity was recorded by the use of a calibrated tooth wheel attached to the vehicle propshaft. In addition, the brake line pressures were measured at the following six points, coupling head, tractor load sensing valve, steer axle brake chamber, drive axle brake chamber, trailer load sensing valve and one trailer brake chamber on the rear axle.

In addition, an instrumented fifth wheel was fitted to the tractor unit. The fifth wheel was capable of measuring the forces in three directions, longitudinal, lateral and vertical.

The data was recorded in real time using a laptop PC. The data collection format and programme allowed on line processing to be undertaken, with the main analysis being carried out remotely.

The data was stored as text files to the PC, and three types of files were recorded. The first file continually recorded data at 0.1Hz and included elapsed time (of the run), overall distance travelled, brake drum temperature, and whether the brakes were being actuated at that moment in time. The second file was recorded whenever the brakes were applied, recording the data at 20Hz and included the elapsed time, vehicle speed, distance travelled during braking, the six pressures and the fifth wheel forces. The third type was a summary file that recorded the collated information from the brake application. It included the brake application number, elapsed time over the application, initial and final speed of vehicle, the brake drum temperatures at the start and end of the application, the mean pressures and the maximum pressure, as well as the mean and maximum forces on the fifth wheel.

2.1.3 Threshold pressure adjustment

The method used to alter the threshold adjustment on the semi-trailer has been retained from the previous tests, by the use of tension springs fitted between the chassis of the trailer and the brake-actuating arm. However, a greater number of tension springs were added to the actuating arm to increase the threshold pressure required to actuate the brakes. During the previous tests, springs were used on the tractor unit in the same way as on the trailer, but it was found that the springs became coil bound thus restricting the maximum attainable brake force. TRL judged that an improved system could offer easier adjustment and more reliable results to be obtained. An air actuator mechanism was developed and fitted prior to the tests described in this report.

To measure the threshold pressure, the vehicle axle was raised and a pressure gauge attached to the test point at the brake chamber. The wheel was turned by hand whilst a second operator depressed the brake pedal. The brake chamber pressure needed to prevent the wheel and tyre being turned by hand was then noted. If necessary, the tension springs or air actuator mechanism was adjusted and the procedure was repeated until the correct threshold pressure was obtained.

2.2 BEDDING IN

Normally, when new brake linings were fitted to an HGV, the drivers were advised to brake carefully and lightly for the first 200km. However, for the purposes of this research it was necessary to ensure that the linings were correctly and consistently bedded.

When new linings were fitted, the vehicle was operated for 2,000km partially laden and subjected to a roller brake test every 500km. The route encompassed motorway and A-road sections requiring a number of brake applications, with the threshold pressures set to 0.4 bar, to minimise the likelihood of glazing of the linings. After this initial 2,000km, the vehicle was then run at maximum test weight for a minimum of 500km until results from the roller brake tester became consistent; the axle weights are given in Table 1 above. The brake linings were also inspected to ensure an adequate contact area. A similar procedure was followed before each new series of tests for which the linings were abraded to remove imperfections and then bedded before the new series began. New linings were fitted only when there was insufficient lining thickness to be sure of completing a test series.

It should be noted that the linings used for this research took longer to bed than was necessary for the previous research with asbestos linings.

2.3 THRESHOLD PRESSURE SET-UPS

For the trials there were five different threshold pressure set-ups that were tested fully, both on the road routes and with snub tests. A further three set-ups with more extreme pressure differences, were tested less extensively; Table 2 below shows the threshold pressures evaluated. It should be noted that for this project the first set-up tested had a zero threshold pressure difference between the towing vehicle and semi-trailer. The difference was gradually increased as the project progressed. This differed from the previous project (S290B/VD) that began with a large difference that was gradually decreased before being increased in the opposite sense.

Furthermore, thorough servicing of the vehicles allowed a minimum threshold pressure of 0.4 bar to be used (more typical of commercial practice), whereas previously this had been 0.5 bar. The predominance was set to zero for all of the set-ups.

Threshold pressure difference will be referred to throughout this report. This is defined as the difference between the semi-trailer and the towing vehicle threshold pressure. A positive difference indicates that the semi-trailer threshold pressure is greater than that of the tractor thus for a low application pressure the tractor will be contributing most of the braking. The converse is true for a negative difference. A negative difference indicates that the semi-trailer threshold pressure is lower than that of the tractor, so for a low application pressure the trailer will be contributing most of the braking.

Table 2. Threshold Pressure Settings

	Towing vehicle threshold pressure (bar)	Semi-trailer Threshold pressure (bar)	Threshold pressure difference [semi-trailer minus towing vehicle] (bar)
Set-up 1	0.4	0.4	0.0
Set-up 2	0.4	0.6	+0.2
Set-up 3	0.4	0.8	+0.4
Set-up 4	0.6	0.4	-0.2
Set-up 5	0.8	0.4	-0.4
Set-up 6	0.4	1.0	+0.6
Set-up 7	1.0	0.4	-0.6
Set-up 8	0.4	1.2	+0.8

The research has evaluated a range of threshold pressure combinations, as indicated in Table 2 above, and chosen to lie within the boundaries as permitted by Regulation 13 (R.13); predominance was set to zero for all the tests. However, for the 8^{th} set-up a semi-trailer threshold pressure of 1.2 bar was used. This is outside the permitted corridor but was necessary, because it was not practical to reduce the towing vehicle threshold pressures below their inherent 0.4 bar. The difference in threshold pressure between towing vehicle and semi-trailer for the 8th set-up (+0.8 bar) was, therefore, within the permitted range of 0.2 & 1.0 bar.

2.4 ROAD TESTS

These tests were a substantial part of the assessment of each set-up. The route was 180km in length and comprised of a mixture of normal road types as follows: approximately 70 kilometres of rural, single carriageway A-road, 50 kilometres of dual carriageway A-road, 30 kilometres of motorway and 30 kilometres of urban road. For the first five set-ups the vehicle was driven over this route for either approximately 11,000km or until a predetermined reduction in the brake efficiency was observed on the roller brake tester.

The vehicle typically completed two laps a day and was in use five days a week. The first lap of each day started at about 08:00 and the second lap was finished by about 18:30. Each lap took approximately 3 and three-quarter hours to complete, corresponding to an average speed of approximately 48 km/h, and both laps included a mixture of rush hour and normal traffic.

During the road trials, two experienced, professional drivers provided most of the driving. The data (speed, deceleration, etc.) was inspected to ensure consistency between driving styles.

During the road trials it was necessary to change the route slightly through Aylesbury due to weight restrictions being introduced onto a number of bridges. However, it did not effect the overall distance travelled on each road run.

2.5 ROLLER BRAKE TESTS

As well as carrying out basic performance tests on the vehicle during the bedding-in process, roller brake testers were also used during the road trial assessment of each threshold pressure setting. The method employed was to measure the brake force at each wheel across the full range of coupling head pressure. Graphs were then drawn of brake efficiency (brake force divided by gross vehicle mass) against coupling head pressure. The results from each test were compared with those from previous tests to ascertain if any appreciable degradation of braking performance was evident. All roller brake testing was carried out with the vehicle fully loaded.

Performance was monitored during the road trials by means of static brake tests on a purposely installed roller brake tester. As in the track tests the performance was measured over a range of coupling head pressures to establish a vehicle reference; the mid trial values were then compared with this signature to indicate possible performance change that was then confirmed by dynamic testing at TRL.

2.6 TRACK TESTS (DYNAMIC PERFORMANCE)

2.6.1 Snub Tests

The dynamic braking performance of the vehicle combination was established at the beginning of each threshold pressure set-up using snub tests, with the tests being repeated at the conclusion of each road trial. Each snub is the application of the brakes, at a set pressure, to decelerate the vehicle from one known speed to another known speed. These snubs comprised of four brake applications per set to slow the vehicle as follows: 50-10km/h, 30-10km/h, 50-10km/h and 80-50km/h. This set of four snubs was repeated five times, giving a total of twenty snubs for each threshold set-up.

The brakes were cold (below 75^{o}C) prior to each test. Each cycle of snubs was repeated precisely, that is the brakes were applied at the same point on the (circular) test track. In this way the times and distances between brake applications were standardised so as to minimise any variation in the amount of cooling the brakes experienced between snubs. At the conclusion of the road trials of each particular threshold setting the combination was subjected to five repetitions of the four-snub cycle indicated above.

Each series of snub tests were repeated for a range of coupling head pressures: 1 bar, 2 bar, 3 bar, 4.5 bar and 5 bar, a total of 100 tests. A brake pressure-regulating device allowed the brakes to be applied at the constant, pre-set pressure. During each series the brake temperatures were recorded.

The Mean Fully Developed Deceleration (MFDD) was also calculated during the snub tests. The expression used to determine the MFDD was derived from that defined in ECE Regulation 13.08 but modified for the snub tests for which the final velocity was greater than zero, as follows:

$$MFDD = \frac{(0.8V_0)^2 - (V_1 + 0.1V_0)^2}{2S}$$

where:

V_0 = Initial velocity (at application of brakes, km/h).

V_1 = Final velocity (at release of brakes, km/h).

S = Distance travelled whilst reducing speed from 80% of V_0 to 10% of V_0 above V_1 (m).

2.6.2 Work done vs temperature tests

As with the previous project, S290B/VD, a series of track tests were conducted to quantify the relationship between the work done by each axle on the vehicle and the temperature rise on that axle. To achieve this, the brakes on all but the particular axles under investigation were disabled and a series of snub tests were conducted with a set application pressure of two bar.

Testing was halted after the cycle of twenty snubs had been completed or sooner if the brakes reached 300°C. By using this method, the temperature profile for each axle could be directly compared to that recorded for the other axles after the same sequence of snubs.

2.6.3 Predominance

Operators, in general, understand that it is desirable to have a balanced threshold mix between the tractor unit and the semi-trailer to enable good braking. If an operator considers that a vehicle has a poor threshold mix, they will adjust the predominance in the trailer control valves. The valve can provide a positive pressure, for example 0.6 bar in and 0.75 bar out, to overcome losses in the system and thus can enable a vehicle with a poor threshold combination to be a balanced system.

To simulate this, the tractor was set at its normal operating threshold pressure (0.4 bar) and the threshold pressure for the trailer was increased to each of 0.6, 0.8 and 1.2 bar (threshold pressure difference of +0.2, +0.4 and +0.8 bar respectively), by the use of return springs. By adjusting the predominance in the trailer control valves, with either the one fitted to the tractor or the one fitted to the trailer but not at the same time, this threshold pressure difference was negated and the performance was assessed.

2.6.4 Stability tests

A number of tests were undertaken to investigate the effect of stability of the HGV under braking conditions. The vehicle was set with threshold pressures of 0.8 & 0.4 followed by 0.4 & 0.8, and was driven in increments of 10km/h up to 80km/h or, for safety reasons, until axle locking occurred. The vehicle was tested in three conditions, braking on full combination, braking on the tractor unit only and braking on the semi-trailer only.

The stability of the vehicle was evaluated over two different surfaces. The first was dry rolled asphalt, a high friction surface, with a coefficient of 0.82. The second surface was a wet mastic asphalt surface with a coefficient of 0.56.

By using the pre-set device as described in section 2.6.1, application pressures of 1, 2, 3 and 4.5 bar were used. An independent observer recorded which axles were locking on each test. For safety reasons, an anti-jack-knife cable was fitted between the tractor and trailer.

2.6.5 Type approval tests

The type approval tests were conducted at the Vehicle Certification Agency test centre (VTAC) and comprised of eight series of tests. For type approval, the tractor and trailer are tested independently. The tractor unit was fitted with a load frame and laden to its maximum permitted weight. The trailer was coupled to VTAC's tractor that has a pre-set device fitted; similar to that fitted to the TRL vehicle. The trailer was laden in the configuration as described in section 2.1.

The tests conformed to Regulation 13 type 0 dynamic test with the gearbox in neutral. In order to comply, the results should fall in the compatibility corridors with a minimum threshold of 0.2 bar and a maximum threshold of 1.0 bar. However, the recommendations set out in the previous project suggested that the corridors should be restricted to a maximum threshold difference of 0.3 bar (Robinson, 1997). It was acknowledged that this may be impractical and, therefore, limits of either 0.4 - 0.8 or 0.5 - 0.9 bar were proposed.

Given that the majority of braking takes place at less than 1.8 bar, also known as the check braking area, it was agreed to keep the threshold levels as low as possible and the 0.4 - 0.8 bar range was used. Four tests were conducted on each of the units. First the vehicles were tested laden at thresholds of 0.4 and then 0.8 bar; these were repeated with the vehicles unladen. The vehicles initially were set to a braking pipe pressure of 0.5 bar and this was increased with increments of 0.5 bar up to 2.0 bar. Thereafter, increments of 1 bar until 8 bar or a brake pedal force of 700N was achieved. For Type 0 tests the brakes must be cold, therefore, all brake applications were made when the temperatures of the brake drums were less than 50^{o}C.

3. RESULTS

3.1 GENERAL

A graphical summary of the results from the snub tests and the road trials is provided in Annexes A to H with one Annex assigned to each set-up. The following graphs are included:

1. brake temperature time history during the road trials,

2. change in brake temperature during the snub tests, both before and after the road trials,

3. frequency of brake demand during the road trials related both to coupling head pressures and to acceleration rates,

4. MFDD for the track tests and the fifth wheel forces during the first road run,

5. RBT assessment of the brake efficiency of the towing vehicle, semi-trailer and overall combination.

The results are presented here in order of threshold pressure difference rather than in chronological order of testing.

3.2 BRAKE DEMAND DURING ROAD TRIALS

The frequency of brake demand, in terms of coupling head pressure, during the road trials was collated for all eight of the different threshold pressures. The results are given in Figure 1 below.

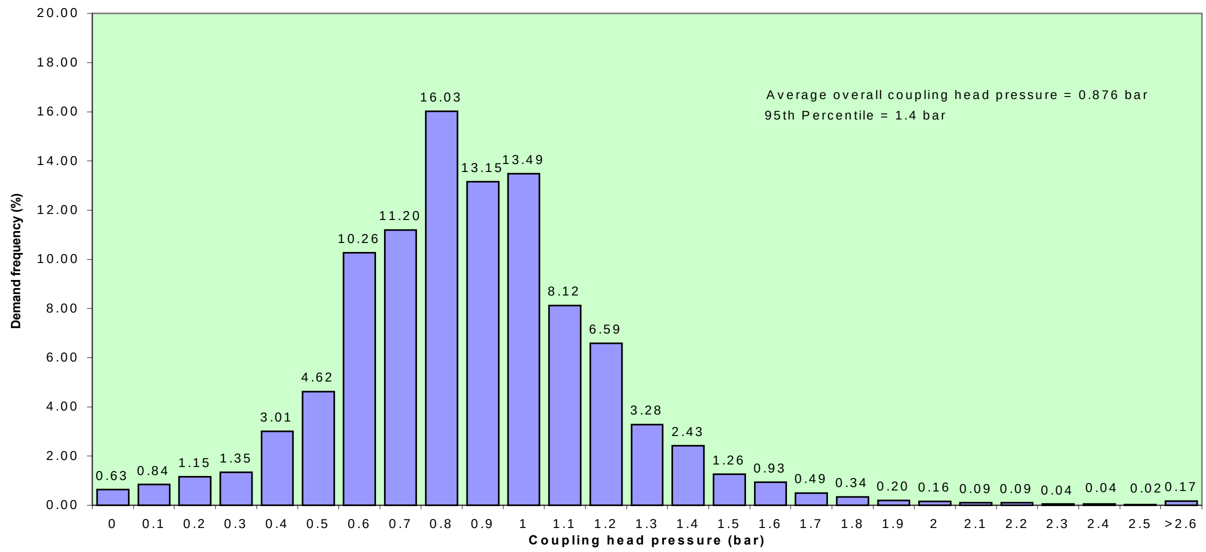

Figure 1: Average coupling head pressure for all road runs (sample size = 95452)

The overall average coupling head pressure was 0.876 bar for all of the eight set-ups. Figure 1 shows that the brake-demand closely follows a normal distribution. For all of the brake applications over all of the set-ups (95452 applications) the 95th percentile value showed that a majority of brake applications were at less than 1.4 bar. This was slightly less than for previous research conducted by TRL during which 95% of brake applications were less than 1.8 bar (Robinson, 1997). However, both results are consistent with other research (Fura, 1993) and confirm that the test route provided typical brake use.

3.3 COUPLING HEAD PRESSURES AND DECELERATION RATES

The data presented in Table 3, below, shows both the average coupling head pressure and the average vehicle deceleration. For both pressure and deceleration, the mean and 95th percentile values are provided; the average effective pressure is also provided. The effective pressure is equal to the mean coupling head pressure minus the threshold pressure. A higher effective pressure indicates a greater proportion of braking effort on that axle or group of axles.

It can be seen that, as the threshold pressure difference increases, the average coupling head pressure increases accordingly. This indicates that a greater line pressure was required to achieve the same braking effort across the combination. However, even for the individual set-ups the 95th percentile value (Table 3) shows that the majority of brake applications were at less than 1.8 bar.

Table 3. Pressure demand and vehicle deceleration

Threshold pressures (bar)				Coupling head pressure (bar)		Effective applied pressure (bar)		Calculated Deceleration (g)	
Set-up	Towing vehicle	Semi-trailer	Threshold pressure Difference	Average	95th Percentile	Towing vehicle	Semi-trailer	Average	95th Percentile
8	0.4	1.2	+0.8*	1.19	1.72	0.79	0.00	0.063	0.119
6	0.4	1.0	+0.6*	1.03	1.57	0.63	0.03	0.056	0.109
3	0.4	0.8	+0.4	0.93	1.36	0.53	0.13	0.063	0.108
2	0.4	0.6	+0.2	0.89	1.32	0.49	0.29	0.057	0.102
1	0.4	0.4	+0.0	0.79	1.24	0.39	0.39	0.059	0.112
4	0.6	0.4	-0.2	0.82	1.28	0.22	0.42	0.056	0.114
5	0.8	0.4	-0.4	0.95	1.58	0.15	0.55	0.053	0.117
7	1.0	0.4	-0.6*	1.01	1.50	0.01	0.61	0.061	0.120

* Indicates a shorter series of road trials (900km).

There was little variation in deceleration between set-ups for both average and 95th percentile. However, it was found that a threshold pressure difference of +0.2bar offered the most efficient braking when related to deceleration for a given threshold pressure difference. That is, the coupling head pressure is close to the minimum values obtained for both the average and 95th percentile, whilst the average deceleration is also low and the 95th percentile is at its lowest value.

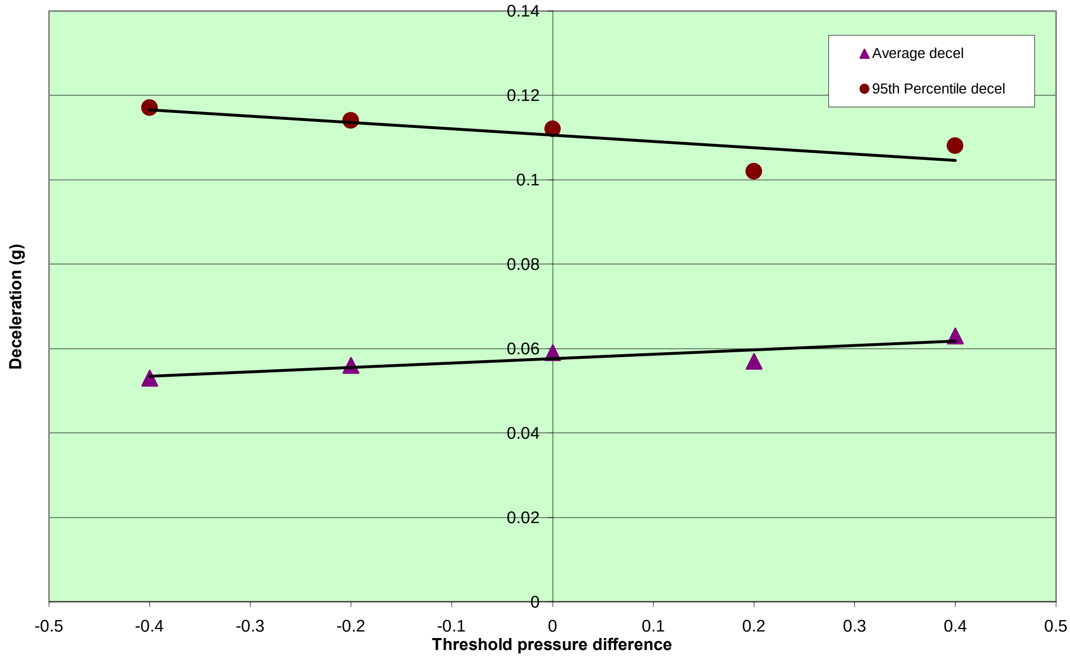

Figure 2: Deceleration of vehicle for five threshold pressure combinations

It can be seen from Figure 2 above, a negative threshold pressure difference, which indicates greater braking effort from the trailer particularly at low application pressures, gave a lower average deceleration but a higher 95th percentile value. However, the trend is for the two lines to begin converging at the positive pressure difference.

It is entirely possible that this trend may have been due to a variation in traffic conditions. However, a more likely explanation is the difference in brake performance. The driver may perceive that with a negative difference (where the trailer is doing more braking which he cannot 'feel' because he is more 'remote' from the trailer than the tractor unit) that the vehicle is braking at a deceleration lower than the measured value. This loss of 'confidence' in the braking would mean earlier braking at junctions leading to lower average deceleration. However, it would also mean there would be a tendency to over brake when the situation demands a shorter stopping distance leading to a higher 95% value.

3.4 BRAKE TEMPERATURES AND WORK DONE

3.4.1 Track tests

To achieve optimum braking, in terms of work done, the distribution of work done by each axle should be closely proportional to the weight distribution (Robinson, 1997). As indicated in Table 1, the axle loads of the test vehicle were 5660kg on the steer axle, 9520kg on the drive axle and 7160kg, 7080kg and 7150kg on the semi-trailer. Approximately 15% on the steer axle, 25% on the drive axle and 20% on each semi-trailer axle.

As part of the track tests, three series of snubs were conducted at different coupling head pressures. The vehicle was braked, using only the drive axle, only the steering axle and only the trailer brakes. The brake temperatures were recorded throughout the tests. The work done during each snub was calculated and this was plotted against temperature for each of the steer axle, drive axle and the trailer bogie. Thus graphs were obtained that correlated work done against brake temperature.

These results were used as the basis for calculating the work done during the road trials from the temperatures recorded and, in turn, for calculating the efficiency of the tractor axles and trailer bogie. Results for the snub tests are given in Table 4 below.

Table 4. Temperature rise during work done vs temperature correlation snub tests

Number of snubs	Velocity changes (km/h)	Cumulative change in Kinetic Energy (KJ)	Rise in temperature		
			Steer (^oC)	Drive (^oC)	Trailer (^oC)
2	50 to 10, 30 to 10	4556	63	55	20
4	50 to 10, 80 to 50	13525	157	154	69
6	50 to 10, 30 to 10	18081	157	158	89
8	50 to 10, 80 to 50	27050	213	224	124
10	50 to 10, 30 to 10	31606	208	227	133
12	50 to 10, 80 to 50	40575	250	278	155
14	50 to 10, 30 to 10	45131	235	269	162
16	50 to 10, 80 to 50	54100	285	303	180
18	50 to 10, 30 to 10	58656	>300	>300	182
20	50 to 10, 80 to 50	67625	>300	>300	na

It is well known that lining wear rates are proportional to brake temperature. Some work has been published which suggested that brake systems are adjusted, in-service using the predominance valve, to provide equal operating temperatures for each brake. This is alleged to provide a more even wear rate across the vehicle brakes and thus reduce maintenance costs.

However, a vehicle with brakes set to provide balanced operating temperatures does not necessarily have optimum braking efficiency. The work done by a brake is a function of brake design and the line pressure, which, in turn, is a function of the load sensing valve. Therefore, the operating temperature of the brakes is a function of the distribution of the load on each axle. Thus, if the predominance is set to give the same operating temperature then it is highly unlikely that this setting will give the optimum efficiency for each axle.

3.4.2 Road trials

The average rise in brake temperature (above ambient) was measured during the road trials for both set-ups and the results are shown in Table 5. The calculated work done by each axle is also provided. The work done by the tractor brakes was found to increase as the semi-trailer threshold pressure was increased. This is because increasing the semi-trailer threshold pressure results in a greater proportion of the braking effort being effected by the tractor brakes.

It must be noted that effects, such as cooling efficiency, have not been considered when calculating the work done by each axle. For example, in wet conditions it has been found that the drum temperature on the offside of the vehicle remains higher than that for the nearside. This may be because the nearside brakes are cooled by water-spray.

Table 5. Temperature rise and distribution of work done during road trials

Threshold pressure (bar)				Average temperature rise* (^oC)			Work done (%)		
Set -up	**Tractor**	**Semi-trailer**	**Threshold pressure difference**	**Steer axle**	**Drive axle**	**Semi-trailer**	**Steer axle**	**Drive axle**	**Semi-trailer (Each)**
8	0.4	1.2	+0.8	158.6	179.8	56.2	37.8	43.5	6.2
6	0.4	1.0	+0.6	150.2	153.4	35.4	44.3	42.9	4.3
3	0.4 **	0.8	+0.4	108.7	113.7	40.7	36.6	39.7	7.9
2	0.4	0.6	+0.2	89.4	115.1	44.9	27.0	43.3	9.9
1	0.4	0.4	+0.0	78.1	110.5	60.3	20.0	37.9	14.1
4	0.6	0.4	-0.2	74.7	113.5	114.1	10.5	23.1	22.1
5	0.8	0.4	-0.4	62.1	120.7	142.5	5.8	20.1	24.7
7	1.0	0.4	-0.6	32.4	63.7	113.5	3.0	11.8	28.4

* average temperature rise from ambient.

** severe glazing was noted on trailer linings.

The axle load distribution was 15% steer-axle, 25% drive-axle and 20% for each of the three semi-trailer axles (60% total). It can be seen that set-up 4, with a threshold pressure difference of -0.2 bar, provided a work done distribution which most closely matched the axle load distribution. However, 0.4 & 0.4 bar, set-up 1, shows more work done by the steer and drive axles, but less on the semi-trailer axles. This may be due to the load transfer effect moving approximately 2 tonnes from the semi-trailer to the tractor unit. Therefore the acceptable range, either side of the static load distribution, is -0.2 and 0.0 bar threshold difference.

The least efficient balance (farthest from the ideal) was measured with a threshold pressure difference of -0.6 and +0.6, set-ups 7 and 6 respectively.

However, it is interesting to note that the trailer linings suffered severe glazing during the road runs when the difference was +0.4 and consequently the trial was terminated part way through the planned distance of 11,000km. The road trial distance for the three threshold pressure differences of +0.8, +0.6 and -0.6 (set-ups 8, 6 and 7 respectively) was restricted to 1,000km and glazing was not evident. However, it is highly likely that glazing would have occurred if the vehicle had covered a greater distance.

3.5 WEAR RATES

The wear rate was calculated by measuring the thickness of both the brake lining and brake shoe together at specific points on the brakes. The location of measurement was behind each of the rivets that held the lining to the shoe.

By measuring the thickness just before and just after road trials, it was possible to calculate the wear rate for each set-up. Two symptoms of poor compatibility, commonly experienced in-service, are rapid lining wear and lining glazing. Figure 3 below shows the wear rate for the steer axle, drive axle and the trailer axles for each threshold pressure set-up.

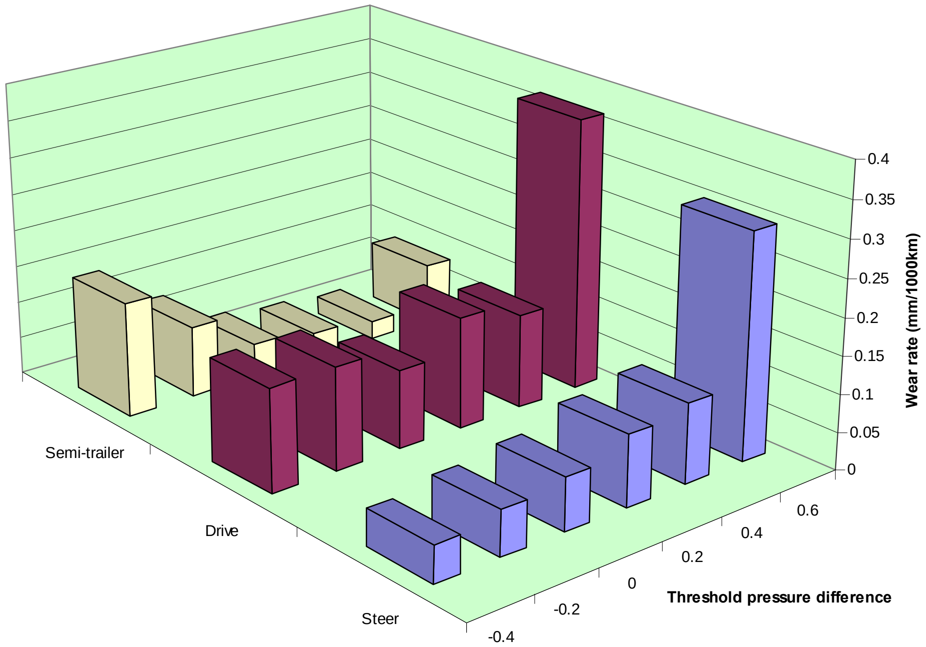

Figure 3: Wear rates

Set-up 3 with a threshold pressure difference of +0.4 (threshold pressures 0.4 & 0.8) produced a drive axle wear rate of 0.126 mm/1000km and a trailer axle wear rate of 0.026 mm/1000km a ratio of about 5:1. Thus the tractor linings would need to be replaced five times as often as the trailer, although a pressure difference of +0.4 bar is well within the permitted +0.8 bar difference. The combination closest to the ideal for efficiency distribution, difference -0.2 (0.6 & 0.4) produced a wear rate ratio of 2:1 for the tractor drive axle to trailer.

Overall the semi-trailer brake linings exhibited acceptably low wear rates during all five set-ups for which the vehicle was extensively tested, -0.4 to +0.4 threshold pressure difference. However, in set-up 3 with a difference of +0.4 (0.4 & 0.8) the trailer linings became glazed and the trial was terminated after 5,000km, less than half the planned 11,000. The glazed trailer linings caused substantial deterioration in the trailer braking efficiency, see section 3.7 below.

Glazing was not evident in the other set-ups but Table 3 above shows that the effective trailer line pressure for this set-up was 0.13 bar, substantially less than that for the other four set-ups whereas the average coupling head pressure was 1.36 bar, somewhat more than for the other four set-ups. Thus it would be expected that this differential would result in very little brake activity from the trailer and the average brake temperature of only 40.7^{o}C confirms this.

For the shortened series of trials (5 road runs, 900km), the pressure difference of +0.6 bar (threshold pressure 0.4 & 1.0, set-up 6) showed a markedly increased wear rate for all the axles. This was most likely due to the new linings wearing more rapidly at the centre of pressure than at the brake lining extremities. However, it must be noted that the ratio of wear rate for the drive to semi-trailer axles is 4.4:1, which is very similar to that for a pressure difference of +0.4bar.

3.6 FIFTH WHEEL FORCES

The fifth wheel forces were measured in three axes, vertical, longitudinal and lateral. The forces were recorded throughout the duration of each brake pedal operation. A negative longitudinal force represents compression in the coupling and thus, in theory, this would indicate that the trailer braking efficiency is less than that of the tractor at the applied pressure. Table 6 shows the mean forces generated at the fifth wheel over all the road trials.

Table 6. Fifth wheel forces during road trials

Threshold pressure (bar)				Mean forces at fifth wheel (kN)		
Set-up	**Tractor**	**Semi-trailer**	**Threshold pressure difference**	**Longitudinal**	**Vertical**	**Lateral**
8	0.4	1.2	+0.8	-13.7	+102.1	+0.0
6	0.4	1.0	+0.6	-12.6	+101.6	-0.7
3	0.4	0.8	+0.4	-13.7	+99.4	+1.0
2	0.4	0.6	+0.2	-10.9	+91.6	-0.6
1	0.4	0.4	+0.0	-9.7	+93.3	-2.0
4	0.6	0.4	-0.2	-1.2	+98.8	+2.1
5	0.8	0.4	-0.4	-2.5	+100.7	+1.4
7	1.0	0.4	-0.6	-2.4	+104.3	+2.3

The longitudinal force, during the road trials, showed a distinct trend in that it decreased from -13.7kN to -1.2kN as the threshold pressure difference decreased from +0.8 to -0.2 bar; a slight rise to -2.5kN for -0.6 bar and -0.4 bar pressure difference cannot be readily explained. From the theory this would indicate that the tractor was always operating more efficiently than the trailer. Whilst, for the threshold pressure differences, in the range +0.8 bar to +0.0 bar this may be true, it does not explain why the longitudinal force continues in compression for the range -0.2 bar to -0.6 bar.

The most logical explanation for the compression is that as soon as the driver removes his foot from the accelerator, the effects of aerodynamic forces, frictional losses and engine braking come into play. These have the most effect on the tractor unit, therefore causing compression in the fifth wheel, even before the brakes have been actuated.

The vertical force was the main measure of load transfer where positive indicated load transferred to the tractor. This measurement also showed a distinct trend of decreasing to a minimum as the pressure difference reduced from either positive or negative values. However, although a range of positive values is entirely consistent with expectations and the minimum at small values of threshold pressure difference is probably a function of the brake demand at the extremes of the pressure difference. This phenomenon could be examined more fully in a work programme for which the full range of braking conditions was controlled.

3.7 ROLLER BRAKE TESTS

Roller brake tests (RBT) were conducted at the beginning and end of each set-up. These were conducted using the same pressures as for the snub tests, namely 1, 2, 3, 4.5 and 5 bar, using the preset device. The results obtained showed any deterioration in braking performance over the trials. The graphs are presented in annexes (Annex A through to H) under the assigned set-up.

A limitation of the roller brake tester is that the wheels may lock under the higher pressure applications and hence the available brake force could be higher than that measured. Thus locking can produce a large disparity between the true brake force and that measured. For this reason the lower pressure applications provided a better insight into the relative performance between tractor and trailer, and furthermore, represent where the majority of braking actually occurs. The MFDD from the dynamic tests (snub tests) is presented in Table 7 for comparison.

It can be seen that the 'after' performance of the tractor unit remained within three percent of the 'before' performance for all the set-ups. This may have been because the automatic slack adjusters in the brakes kept the performance relatively constant.

The 'after' performance of the semi-trailer tended to reduce by several percent, except for the test involving the +0.0 threshold pressure difference, set-up 1, which increased substantially. This cannot be readily explained. The overall combination brake efficiency showed the same trend and confirmed that, in general, the brakes deteriorated during the trials. Maximum brake force cannot be attained at a brake line pressure of 2.0 bar, nevertheless performance at this pressure is a good indicator of brake efficiency.

The MFDD also shows the change in performance, however, given the limits of space and test equipment, the RBT remains the overall better measure of brake performance on the road.

Table 7. Vehicle braking efficiency - before and after road trials

Threshold pressures (bar)				Towing vehicle efficiency (roller brake output) at 2.0 bar (%)		Semi-trailer efficiency (roller brake output) at 2.0 bar (%)		Combination efficiency (roller brake output) at 2.0 bar (%)		MFDD (g) at 2.0 bar		
Set-up	**Towing vehicle**	**Semi-trailer**	**Threshold pressure difference**	**Before**	**After (diff)**	**Before**	**After (diff)**	**Before**	**After (diff)**	**Before**	**After**	**% change**
8	0.4	1.2	+0.8*	-	-	-	-	-	-	0.138	0.126	-9
6	0.4	1.0	+0.6*	-	-	-	-	-	-	0.147	0.152	+3
3	0.4	0.8	+0.4	32	32 (0)	17	14 (-3)	23	21 (-2)	0.207	0.171	-17
2	0.4	0.6	+0.2	27	24 (-3)	22	18 (-4)	24	20 (-4)	0.190	0.166	-13
1	0.4	0.4	+0.0	29	27 (-2)	14	22 (8)	20	24 (4)	0.217	0.190	-12
4	0.6	0.4	-0.2	26	28 (2)	29	24 (-5)	28	25 (-3)	0.215	0.183	-15
5	0.8	0.4	-0.4	21	22 (1)	25	18 (-7)	23	20 (-3)	0.176	0.174	-1
7	1.0	0.4	-0.6*	-	-	-	-	-	-	0.181	0.194	+7

*Indicates a shorter series of road trials (900km).

3.8 EFFECTS OF PREDOMINANCE

The effect of predominance was investigated by conducting snub tests on the TRL track. The trailer was set-up so that it had a different threshold pressure to that of the towing vehicle. The values chosen were, 0.4 & 0.6, 0.4 & 0.8 and 0.4 & 1.2, the same as set-ups 2, 3 and 8, giving a difference of +0.2, +0.4 and +0.8 bar respectively. The predominance was adjusted to give a notional balance of 0.4 & 0.4, firstly by using the trailer control valve (TCV) on the semi-trailer and then the trailer control valve on the tractor unit. This represented a balanced threshold mix of +0.0 bar, which corresponded to set-up 1 for which the difference was zero.

For all the results where a small adjustment in predominance was applied (+0.2 and +0.4 bar), it was found that the MFDD did not vary much between the trailer control valves and the actual MFDD for that threshold pressure difference and zero pressure difference. However, where an adjustment of +0.8 bar was required, it was found that both the control valves provided a reasonable threshold mix, and provided a better performance than the poor threshold mix of 0.4 & 1.2, which could not provide the same braking performance, see Figure 4 below. Comparative graphs of +0.2 and 0.4 bar are shown in Annex I.

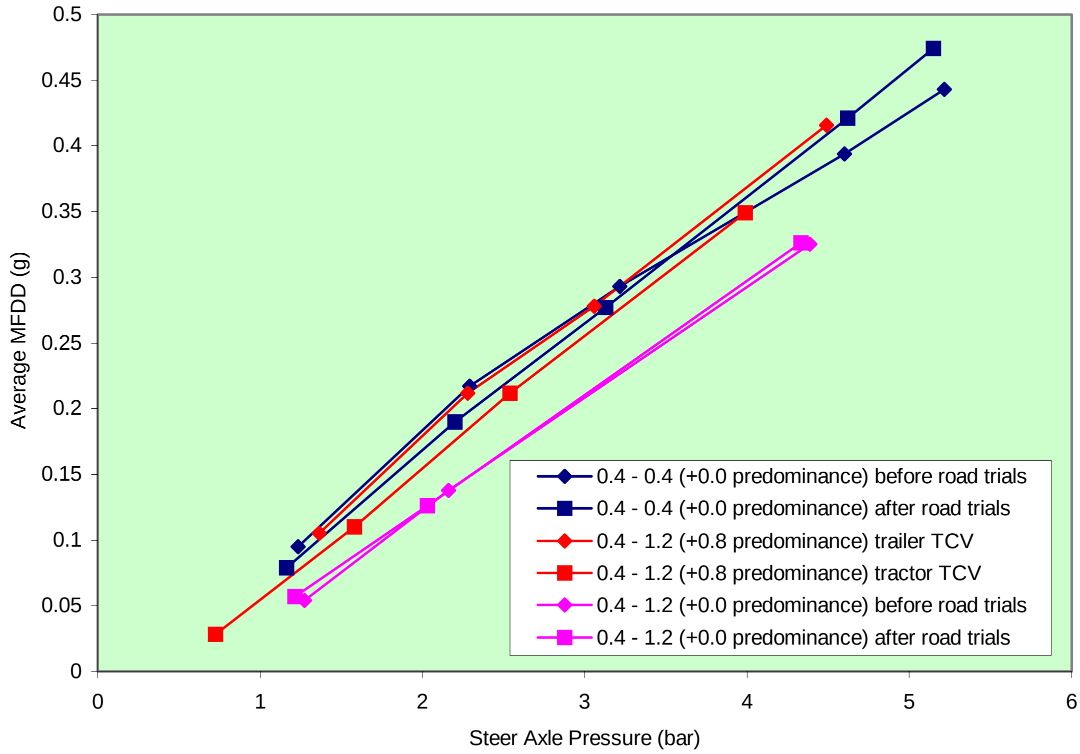

Figure 4: Comparison of predominance valves and threshold pressures

Figure 4 shows that a vehicle with an adverse threshold pressure difference, adjusted by predominance to improve this condition, gave a better dynamic performance than without predominance adjustment.

However, the use of a predominance valve should be seen as a 'quick fix' to overcome the poor balance. In the longer term a narrowing of the permitted corridors will provide a better overall threshold balance between the tractor and trailer, which will reduce the need for a predominance valve. It should be remembered that the predominance valve is of little value if the tractor has a high threshold when compared with that of the trailer, for example if the balance is 1.0 & 0.2 bar, as the predominance can only be adjusted to provide a positive difference.

3.9 STABILITY TESTS

3.9.1 Purpose and Method

The purpose of the stability tests was twofold: first to investigate the stability of the vehicle over the range of threshold pressure differences permitted by Regulation 13 and second to investigate the forces generated at the fifth wheel during these tests. It is known that jack-knife and other types of instability still occur on the roads in the UK in spite of the requirement that all new vehicles manufactured after 1992 be fitted with anti-lock braking systems. It is believed that the wide range of threshold pressure difference permitted by Regulation 13 may be leading to instability under certain conditions and these tests were designed to investigate this possibility.

As vehicle braking systems become more sophisticated, it may be possible to detect impending instability and adjust braking effort accordingly. A perfectly balanced braking system will, theoretically, result in minimal longitudinal force at the fifth wheel and load transfer will induce a vertical force proportional to the deceleration of the vehicle. It is also possible that rotation of the tractor relative to the trailer, or vice versa, will induce a lateral force that is proportional to factors that may indicate an impending jack-knife or trailer swing. Fifth wheel forces, longitudinal, vertical and lateral (turning) were thus measured and recorded to examine how they varied under controlled conditions. This was intended to be a brief feasibility study as a prelude for a more detailed investigation.

Two surfaces were used for the tests, a high coefficient of friction fine textured rolled asphalt, which was tested whilst dry, and a low coefficient of friction mastic asphalt, which was tested when wet. The vehicle was tested at different threshold pressure combinations and braked from different speeds at different applied pressures. The vehicle was also tested with the tractor brakes only and the trailer brakes only. Table 8 below gives the range of test conditions.

Table 8: Range of test conditions

Set-up	Threshold pressure difference	Coefficient of friction	Braking combination		
			Full combination	Tractor only	Trailer only
3	0.4 & 0.8 (+0.4)	Low	✓	✓	✓
1	0.4 & 0.4 (0.0)	Low	✓	✓	✓
		High	✓	✓	✓
5	0.8 & 0.4 (-0.4)	Low	✓	✓	✓

3.9.2 Results

An example of the output from the fifth wheel measuring device is given in Figure 5 below. This shows each of the forces against time for a test on the low coefficient surface when the vehicle was braked from 20km/h to rest at an applied pressure of 2 bar. As was expected the forces were transient during the test, particularly the longitudinal force at the onset of braking and at the end of the stop when the vehicle "juddered". For the purposes of analysis, a mean force was calculated by using the same principle as that for calculating the MFDD. That is, by using the range of values between 80% and 10% of the initial velocity. For example, when braking from 20km/h to 0km/h, as in Figure 5, the range of values used to calculate the mean forces would be from 16km/h to 2km/h, thus eliminating the initial drop at the onset of braking and the judder at the end stop. This method was used to calculate all the mean forces in the results given below.

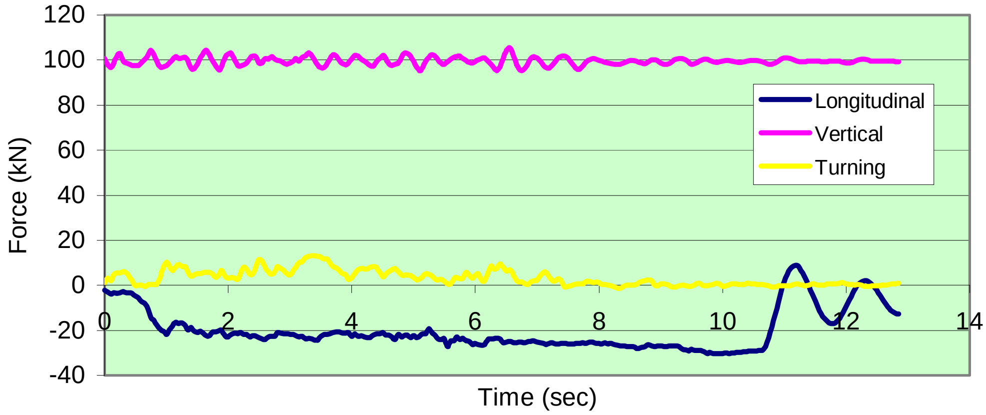

Figure 5: Effect of braking on fifth wheel forces

The TRL vehicle is not fitted with anti-lock braking (ABS) and thus the potential exists for the wheels to lock under excessive braking for differing surfaces. For the high coefficient of friction surface, no locking at the axles occurred. However, the results of the tests on the low coefficient surface produced a number of wheel locks, an example of which is shown in Table 9. An observer stood on the edge of the track and recorded the order of wheel locking. Whenever the tractor unit was involved in the brake application, the steer axle would lock first as designed, see Table 9 overleaf, irrespective of the threshold pressure thus preventing jack-knife or trailer swing.

Table 9. Order of axle locking

Threshold pressure difference	Surface coefficient	Type of vehicle braking	Speed	Coupling Head pressure			
				1 bar	2 bar	3 bar	4.5 bar
0.4 & 0.8 (+0.4)	Low	Full combination	10	1	1	1, 2, 4	
			20	1	1, 4	1, 2, 4	
			30	1, 4	1, 4, 2		
			40	1, 4, 2			
		tractor	10	1	1	1	1, 2
			20	1	1	1,2	
			30	1	1, 2		
		trailer	10	No locks	4	4	4
			20	No locks	4	4	3, 4
			30	No locks	4	3, 4	all
			40	No locks			
0.4 & 0.4 (0.0)	Low	Full combination	10	No locks	1	1	
			20	No locks	1	1	
			30	1	1	1, 2	
			40	1	1, 2		
		tractor	10	No locks	1	1	
			20	No locks	1	1	
			30	No locks			
		trailer	10	No locks	No locks	No locks	
			20	No locks	No locks	Trailer	
			30	No locks	Trailer		
			40	No locks	Trailer		
			50		Trailer		
	High	Full combination	10 to 70	No locks occurred over this range of speeds			
			80	No locks	No locks	No locks	
		tractor	10 to 70	No locks occurred over this range of speeds			
			80		No locks	No locks	No locks
		trailer	10 to 70	No locks occurred over this range of speeds			
			80			No locks	
0.8 & 0.4 (-0.4)	Low	Full combination	10	No locks	1	1	1
			20	No locks	1, 4, 5	1	1, 4, 2
			30	No locks	1, 4	1, 4, 2	
			40	No locks	1, 4, 2		
		tractor	10	No locks	1	1	1
			20	No locks	1	1	1, 2
			30	1	1, 2	1, 2	1, 2
		Trailer	10	No locks	No locks	4	4
			20	No locks	4	4	4, 3
			30	No locks	4	4, 3	all
			40		4		

1 = steer axle, 2 =drive axle, 3 =front axle on trailer, 4 = middle axle on trailer, 5 = rear axle on trailer, all = all three axles on trailer, Trailer = trailer axle lock unknown order or number

[grey box] = test not attempted for safety

Figure 6 shows the variation in fifth wheel longitudinal force (mean) for a range of braking stops from different speeds at different application pressures for a threshold pressure combination of 0.8 & 0.4 (set-up 5). All other graphs for the various combinations of brake applications are shown in Annex J. Also included for comparison are the series of graphs when only the tractor and only the trailer brakes were used. A negative value indicates that the fifth wheel was in compression and a positive value shows that the fifth wheel was in tension.

As can be seen, for the braking applications at a given pressure, the trend is toward a common point on the graph as the speed increases. This occurred because the coefficient of friction, between the tyre and the wet road surface, reduces as the speed increases (Robinson, 1997) and thus the available brake force and hence the longitudinal force decreased in these tests. The stability tests were conducted at a range of velocities (10, 20, 30 and 40km/h). During the tests at 10km/h, the available grip between the tyre and road was significantly greater than during the tests at 30 and 40km/h. Therefore, the compressive load in the fifth wheel was also greater during the tests at lower velocities for combination and tractor only braking. The longitudinal and vertical forces tended towards a minimum value as the velocity increased. This was indicative of the limiting condition, which were when the wheels locked on the wet surface. Maximum adhesion, and hence maximum brake effort occurs just before a wheel locks and this reduces during wheel locking at which point an increase in brake pressure ceases to give an increase in brake effort.

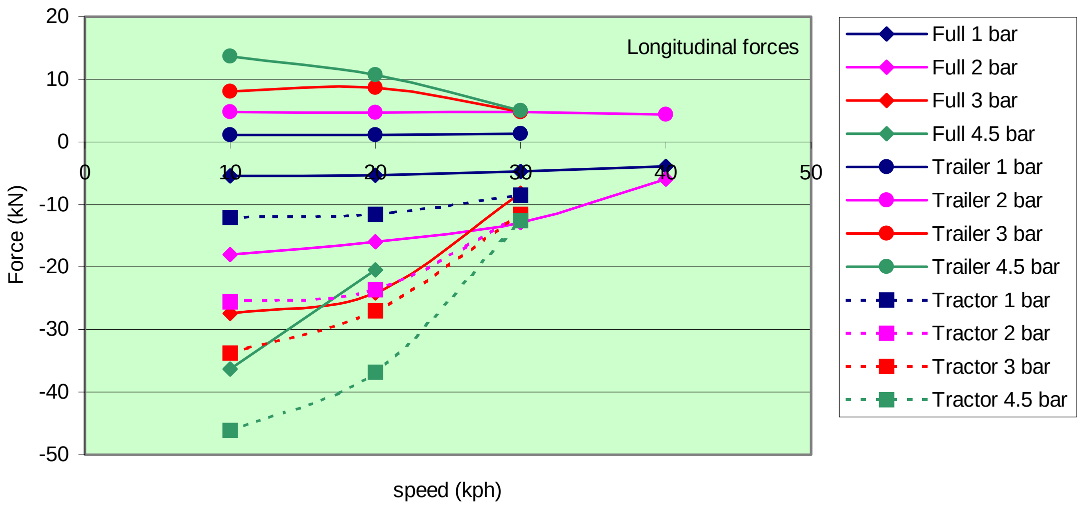

Figure 6: Straight line braking on low coefficient of friction surface (longitudinal)

It can be seen that at 1 bar the brake effort, and hence the longitudinal force, remained nearly constant for all conditions. An increase in brake application pressure provided a greater magnitude of longitudinal force at lower speeds where little or no wheel locking occurred. When more wheel locking occurred the longitudinal force dropped considerably. For example, on the full combination at 4.5 bar application pressure, only the steer axle locked and produced a longitudinal force of -36.3kN at 10km/h, but produced a force of -20.5kN at 20km/h when 3 axles locked. This difference (16.2kN) is substantial and could indicate when a mis-match in tractor and trailer braking is occurring. Furthermore, the overall trend was for the magnitude of the longitudinal force generated at the fifth wheel to be greatest when only the tractor or only the trailer brakes were used. Moreover, the force was compressive when only the tractor was braked and tensile when only the trailer was braked. These findings agree with theory and give confidence that the measurements may potentially be used as indicators of brake balance.

With regard to the vertical forces, shown in Figure 7, this is a good indication of the load transfer from the trailer to the tractor. It was found that the forces generated at 1 and 2 bar brake pressure were similar for both full combination and trailer only braking. However, at 3 bar and above it was found that although the trends were similar, there was more of a disparity in the results, and at 30km/h the vertical force was less than that for a 2 bar brake pressure. The tractor unit was different in that the vertical force remained close to 2 kN regardless of speed or brake pressure.

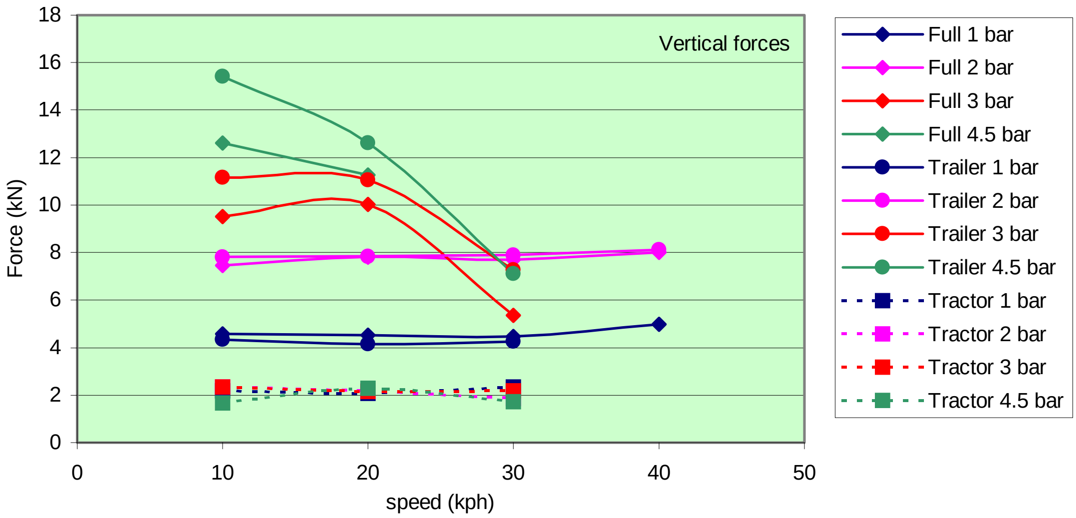

Figure 7: Straight line braking on low coefficient of friction surface (vertical)

The lateral force provided a greater scatter but the maximum force exerted was 11kN, see Annex J4. Potentially this is the best indicator of instability, however, the onset of jack-knife or trailer swing were not reached because of safety implications. Furthermore, it is more likely that these results will differ from those reported when the vehicle is braking on a bend rather than in a straight line. It is recommended that such events could be investigated using full safety precautions as part of a more extensive research program.

It would be advisable to take smaller increments of brake line pressure, possibly as low as 0.2 bar, whilst also varying the threshold pressures between tractor and trailer, and conducting tests on a varying radius curve as well as straight line braking.

3.10 TYPE APPROVAL

The type approval tests were conducted at the Vehicle Certification Agency - Vehicle Type Approval Centre (VTAC) as described in section 2.6.5. Threshold pressures of 0.4 bar and 0.8 bar were used, with the line pressure increasing with increments of 0.5 bar until 2.0 bar, and, thereafter in 1 bar increments up to a maximum of 7 bar. Tests were concluded when the maximum pedal force of 700N was achieved or when wheel lock occurred.

The type approval requirements, which must be met, are set out in Annex 10 of Regulation 13. Results should be presented in accordance with Diagram 3 and Diagram 4A, as shown in Annex 10 of Regulation 13. Diagram 3 refers to tractor units for semi-trailers in the laden and unladen condition, as shown in Figure 8 below. The results must fall within the defined corridors, and a further consideration is that to pass type approval the tractor unit must be capable of achieving a deceleration of $5m/s^2$, within the prescribed stopping distance.

The stopping distance is calculated from the equation: -

$$S \leq 0.15V + (V^2 \div 130)$$

Where S = stopping distance (m)
V = initial velocity (km/h)

Thus for a starting velocity of 60km/h the maximum permitted stopping distance is 36.69 metres.

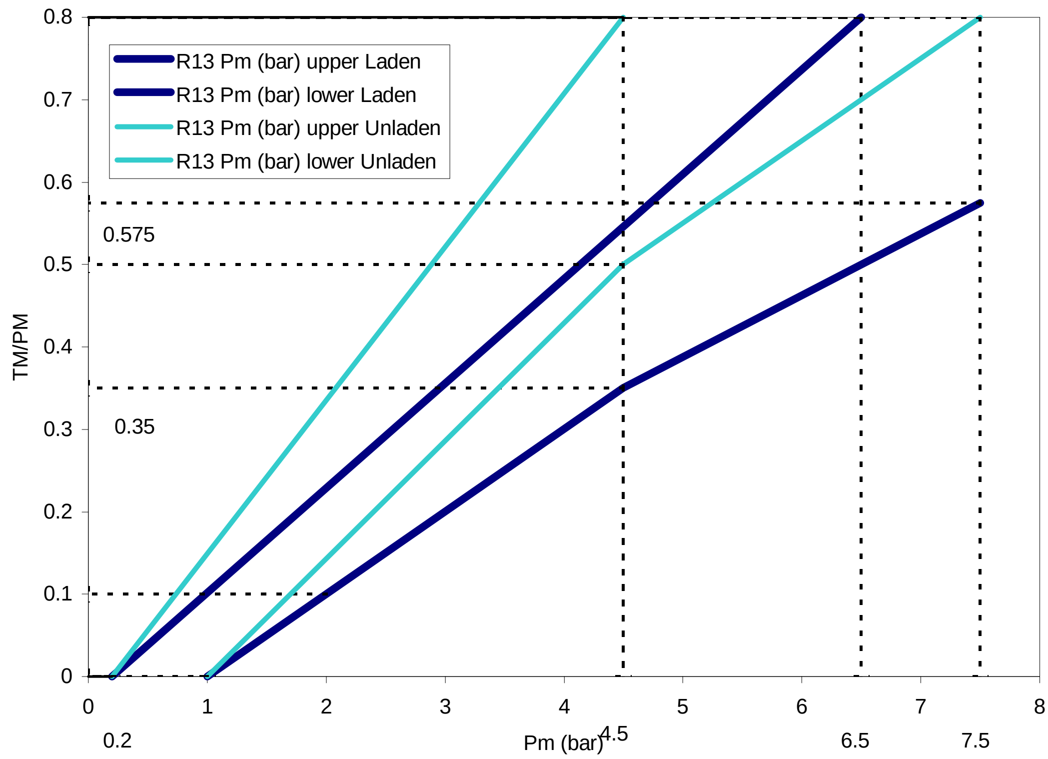

Figure 8: Diagram 3, Tractors for semi-trailers, from Regulation 13, Annex 10

The results from VTAC are provided in Annex K of this report. The results for the tractor unit, when laden with a load frame and set with a threshold pressure of 0.4 bar, showed that the unit was comfortably within the corridors for coupling head pressures of up to 3 bar. However, at the higher pressures the unit began to approach the lower limit of the corridor. Setting the tractor unit to a threshold pressure of 0.8 bar gave similar results, but a small number of runs fell just outside the lower limit of the corridors. As the normal operating threshold pressure was 0.4 and the vehicle would have originally been set up to pass type approval with this threshold it is not surprising that a few results from the 0.8 bar tests were outside of the corridor. It must be noted, however, that for both 0.4 bar and 0.8 bar threshold the vehicle achieved both the stopping distance, and the 5m/s^2 deceleration within the corridor necessary to pass type approval.

Further tests for the tractor unit were conducted unladen with threshold pressures of 0.4 and 0.8 bar. The vehicle easily passed the type approval, for both threshold pressures, although the results for the 0.4 bar threshold came close to the upper limit of the corridor.

Diagram 4A of Regulation 13, Annex 10, shows the graphs for semi-trailers, see figure 9 below. It should be noted that the corridors are modified to take account of various parameters as described below. The mass of the semi-trailer and centre of gravity height are used to generate values for the correction factors of K_c (laden) and K_v (unladen), which are then used to multiply the values defining the compatibility corridor. There are two separate corridors one for the laden condition and one for the unladen condition, which rotate either toward or away from the y axis depending upon the values of K_c and K_v.

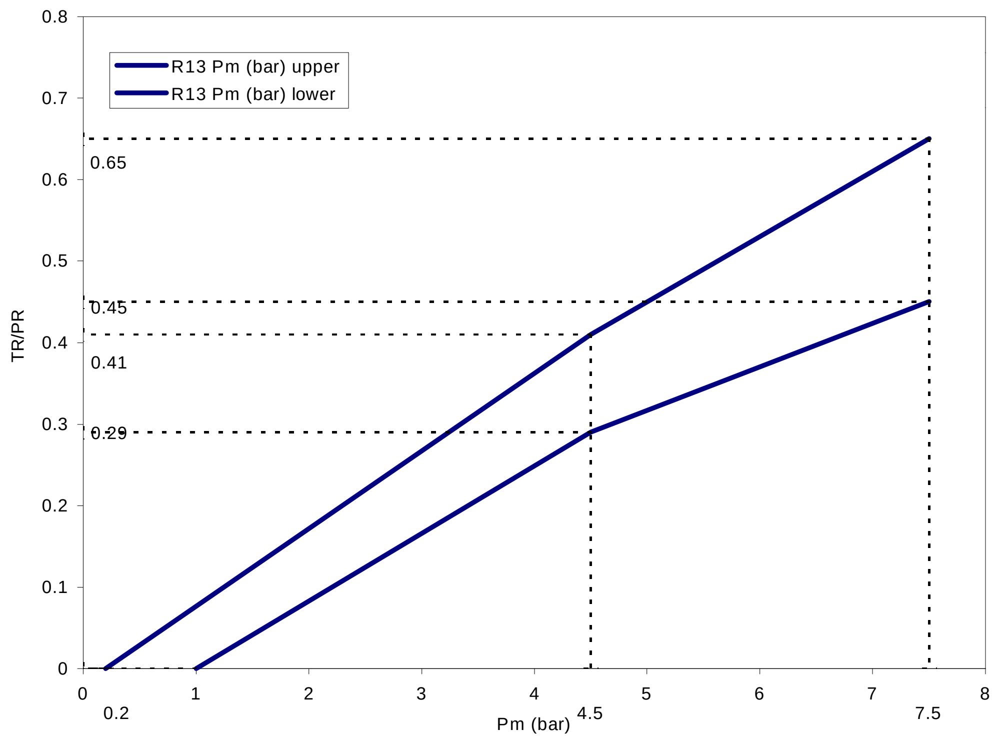

Figure 9: Diagram 4A, Semi-trailers, from Regulation 13, Annex 10

Type approval requirements for the semi-trailers are different to those for the tractor units. In this case the laden and unladen semi-trailer has to pass the criteria of a minimum of 4.5m/s^2 deceleration at a maximum service line pressure of 6.5 bar.

For the semi-trailer tests, the semi-trailer was coupled to VTAC's dedicated tractor unit. In the tests for the laden condition the load met the same configuration as for the road trials.

Although the semi-trailer was coupled to a tractor unit, only the brakes on the trailer were engaged which meant that the trailer was braking the combined vehicle mass. In Annex 4 of R.13, there is a corrective equation, which takes account of the mass of the tractor unit.

$$z_R = \frac{(z_{R+M} - R)(P_M + P_R)}{P_M} + R$$

Where R = rolling resistance, value = 0.01

z_R = braking rate of trailer

z_{R+M} = braking rate of the towing vehicle plus the trailer

P_R = total normal static reaction between road surface and wheels of trailer

P_M = total normal static reaction between road surface and wheels of towing vehicle

When the corrective equation had been applied the results for the laden semi-trailer showed that, for a natural threshold pressure of 0.4 bar, the results fell within the corridor, see figure 10 below. However, as for the tractor unit, when the threshold pressure was increased to 0.8 bar, there were a small number of runs that fell below the lower limit of the corridor. The most likely explanation for this is that the trailer was designed to have a threshold of 0.4 but setting the threshold pressure to a higher value, in this case by the use of return springs, decreased the braking rate slightly.

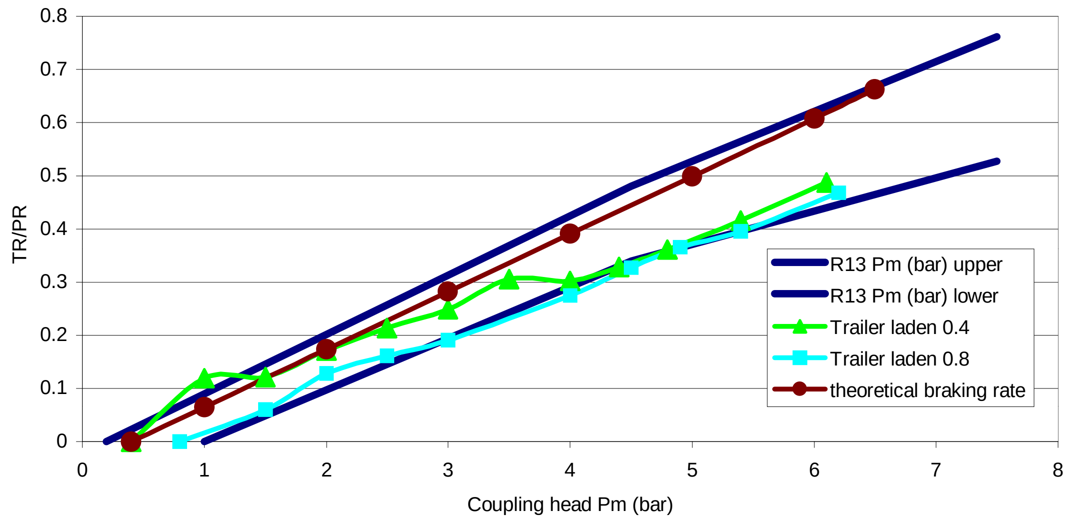

Figure 10: Dynamic test result and theoretical result for laden semi-trailers

After calculating the value of K_v, the unladen correction factor, it was found that the corridors increased in gradient significantly. Following normal type approval practice, the theoretical braking rate was calculated for the unladen semi-trailer, see figure 11, and this fell within the specified corridor. However, the braking rates, z_R, for the dynamic test results were outside the lower limit of the compatibility corridor.

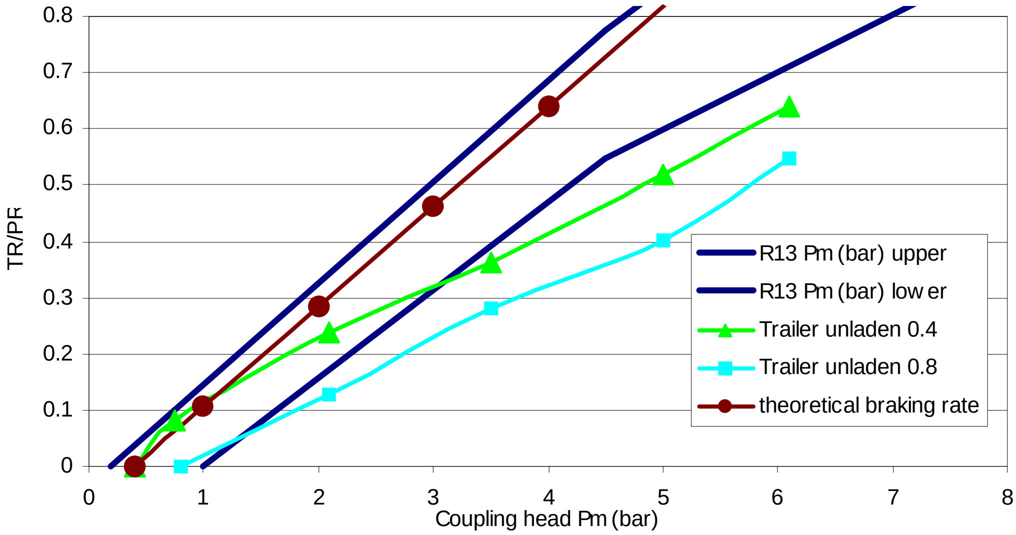

Figure 11: Dynamic test result and theoretical result for unladen semi-trailers

These results show that there is a critical difference between the theoretical braking rate and the actual braking rate. The test results for a threshold pressure of 0.4 bar lay within the permitted corridor up to 3 bar coupling head pressure, well within the normal operating conditions. However, for the threshold pressure of 0.8 bar, the dynamic tests showed that the curve falls outside the compatibility corridor almost immediately.

4. DISCUSSION

The discussion is based upon results from the research that show a need for a change in the way the compatibility corridors are formulated. An investigation into the compatibility between tractor units and semi-trailers has been conducted by an extensive programme of road, track and roller brake test work. During the test work, threshold pressure difference (trailer threshold pressure minus tractor threshold pressure) was varied between -0.6 bar up to +0.8 bar, which is the maximum permitted difference allowed by R13, and the performance of the braking system was analysed.

4.1 REVIEW OF OTHER STANDARDS / CODES OF PRACTICE

A number of other 'standards' exist which prescribe differing practices. The Institute of Road Transport Engineers IRTE code of practice recommends a difference of between 0.6 and 0.9 bar threshold for both tractors and semi-trailers (IRTE, 1994). The Swedish code of practice recommends a threshold pressure range of 0.5 to 0.7, a maximum permitted difference of 0.2 bar (Robinson, 1994). From the same report the New Zealand code of practice suggests an even smaller difference of 0.125 for each vehicle but 0.25 overall. The tractor should be kept in the range 0.675 to 0.8 bar and the semi-trailer in the range 0.55 to 0.675 bar. There is no information regarding the effectiveness of this code of practice, but there are obvious reservations of having the trailer brake before the tractor unit, due to the danger of trailer swing. However, it is unclear whether the practice is intended to have a lower threshold pressure for the semi-trailer to take into account pressure losses across any of the valves.

4.2 WEAR RATE

The results of the road trials have shown that the vast majority of brake applications were check braking with a coupling head pressure less than 2 bar. This is consistent with previous work (Robinson, 1997) and other work. The wear rate of the brake lining was recorded (see section 3.5) and compared for the range of threshold pressure differences. Figure 3 shows that as the threshold pressure difference approaches zero, the wear rate reaches an optimum over all axles. The acceptable range for wear rate was -0.2 to +0.2 bar threshold pressure difference.

4.3 WORK DONE

The appropriate range for the work done is represented by the values that are the closest to the load distribution, based upon static considerations. Based on the road trials, it was found that the threshold pressure difference, which achieved this (see section 3.4.2), was -0.2 bar. Zero bar threshold pressure difference showed slightly more work done on the tractor unit with reference to static considerations. However, when the threshold pressure difference was +0.2 bar or greater, the work done by the tractor unit was found to be unacceptably high. The acceptable range for work done was -0.2 to 0.0 bar threshold pressure difference.

4.4 STABILITY AND FIFTH WHEEL FORCE

Results of the stability tests (section 3.9) show the order of wheel lock (table 9), and that at a threshold pressure difference of +0.4 bar, there were wheel locks at a coupling head pressure as low as 1 bar. However, with a threshold pressure difference of -0.4 and 0.0 bar the vehicle was stable and the wheels did not lock under check braking (<2 bar) conditions. Therefore, the recommended threshold pressure difference range for the check braking would be from -0.4 to 0.0 bar.

Analysis of the results from the stability tests showed that for an increase in coupling head pressure there was a corresponding increase in the longitudinal force at the fifth wheel when braking in a straight line (Annex J5 to J8). During emergency braking, particularly on a bend, the compressive load at the fifth wheel will have a vector component lateral to the tractor which may cause a jack-knife under certain circumstances. A jack-knife can be virtually instantaneous giving the driver no warning and is an ever present potential hazard with an articulated vehicle.

During the road trials the mean vertical and longitudinal forces were calculated (table 6). The range of threshold pressures that gave a minimum, but compressive, longitudinal force, thus providing efficient brake distribution and good vehicle stability, was -0.6 to +0.2 bar.

4.5 EFFECT OF COMPATIBILITY CORRIDORS DURING EMERGENCY BRAKING

Vehicle stability is an important issue as described above. Narrowing of the compatibility corridors to a coupling head pressure of, for example, 2 bar would ensure better compatibility in the check braking area, and improve the wear rate. The question of tractor and semi-trailer compatibility at emergency braking, that is higher than 2 bar pressure at the coupling head, is a separate consideration.

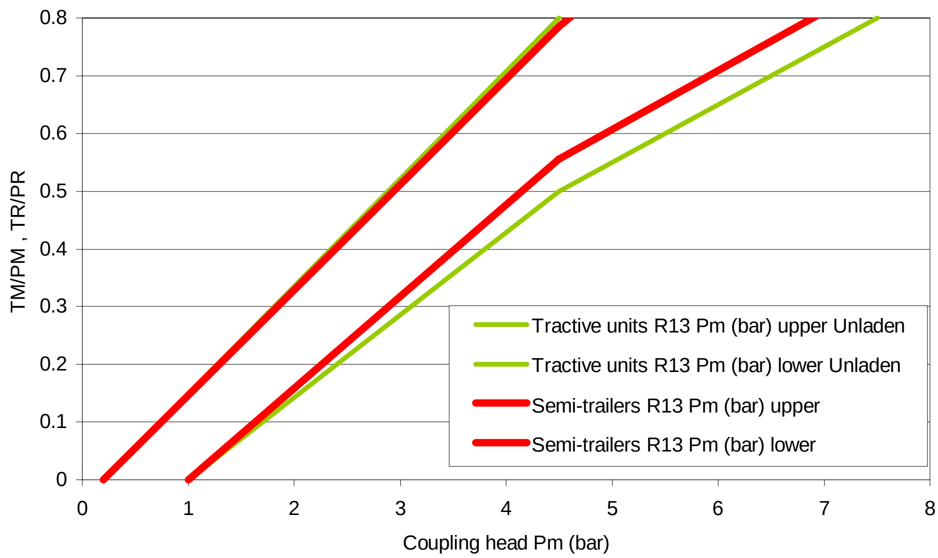

Figure 12: Unladen compatibility corridors for the TRL tractor unit and the TRL semi-trailer

Overlaying the compatibility corridors for the tested vehicles shows that they correlate well. In fact, for the lower boundary of the semi-trailer to match the lower boundary of the laden and unladen tractor unit, values of approximately 1.25 and 1.75 for K_c and K_v, respectively, would be required. For the tested vehicles the values of K_c and K_v were 1.17 and 1.89. Figure 12 above shows the unladen compatibility corridors for both the TRL tractor unit and the TRL semi-trailer. The semi-trailer corridor lies inside the tractor unit corridor.

Figure 13 shows the laden compatibility corridors for the TRL vehicles. Again, the semi-trailer corridor lies inside the tractor unit corridor except for a small area above 4.5 bar coupling head pressure. However, it would be expected that some combinations of vehicles would produce a far wider corridor than is shown in figure 13. For these combinations of vehicle, it is more likely that there would be an incompatibility.

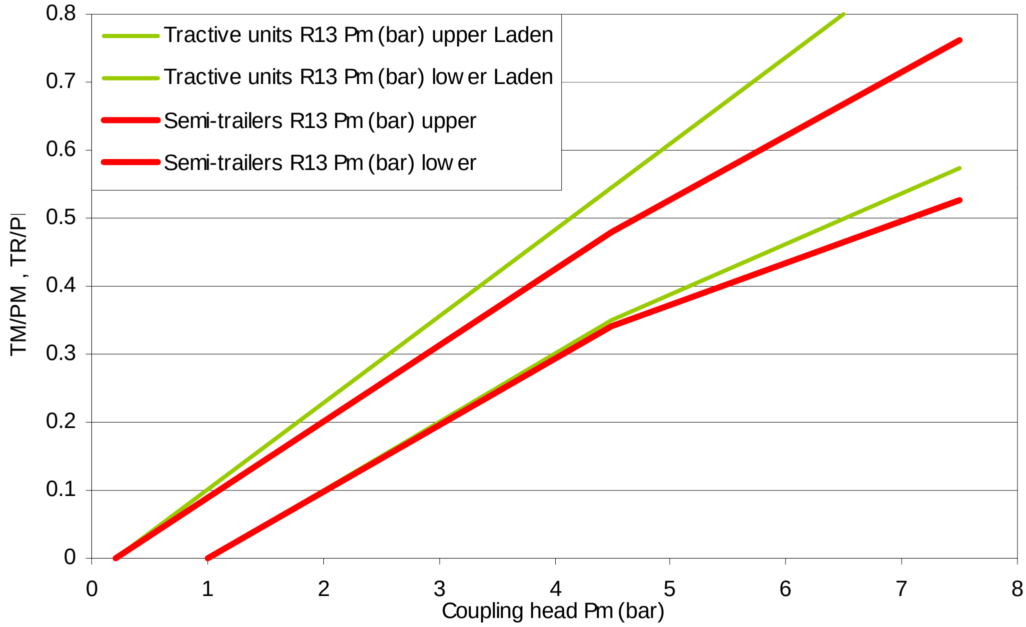

Figure 13: Laden compatibility corridors for the TRL tractor unit and the TRL semi-trailer

As the TRL semi-trailer was tested with concrete blocks, to simulate load, the centre of gravity was relatively low on the vehicle, and this gave a value of K_c =1.17. The majority of goods carried on the UK highways are of much less dense material and consequently the overall centre of gravity height could be much higher. For comparison, the centre of gravity of the TRL semi-trailer, when carrying a low density load, such as a container fully laden by weight and volume, would be higher but all other factors would remain the same. Raising the centre of gravity height to 2.5 metres produces a Kc value of 1.05 for the TRL semi-trailer.

The compatibility corridors for a semi-trailer Kc value of 1.05 are shown in figure 14. This shows that the vehicle combination may be highly incompatible when used for carrying laden containers.

TRL believes that narrowing the whole length of the corridor is the most progressive solution. For vehicles with corridors that diverge at the higher pressure ranges then the braking system could be inefficient under emergency braking. For example, when one vehicle operated at the lower end of the corridor, and the other vehicle operated at the high end of its corridor, see figure 14. In this example, at a coupling head pressure of 3 bar, the semi-trailer has the lower braking rate, z=0.174, and the tractor has a high braking rate, z=0.356, indicating a brake force of more than double that of the semi-trailer, which, even allowing for load transfer, would result in an under-braked semi-trailer.

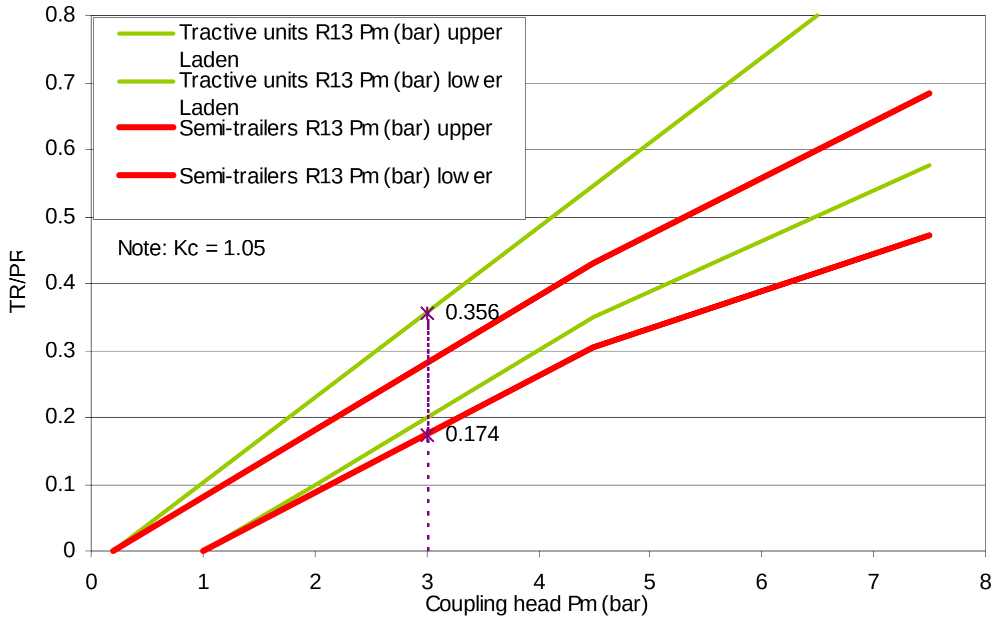

Figure 14: Laden compatibility corridors with potential incompatibility

With this tractor-trailer combination it is possible that on some road surfaces the wheels of the tractor unit will lock well before those of the semi-trailer leading to instability. Although the vehicle ABS may compensate in part for this imbalance, a TRL database has shown that failures of the ABS system have contributed to fatal and serious injury accidents. Therefore, it is essential that semi-trailer and tractor are compatible at high coupling head pressures to ensure instability is avoided. This could be achieved by keeping the threshold pressure difference to ±0.4 bar and/or specifying that the values of K_c and K_v, during type approval tests, should be approximately 1.25 and 1.75, respectively, with a tolerance to be determined.

4.6 ABS BENEFITS

For a number of years, the Transport Research Laboratory (TRL) has been conducting research into accidents that have involved Heavy Goods Vehicles (HGVs). Much of this work focuses on fatal accident data with the aim of assessing design changes in terms of cost benefit. This has proved useful in identifying cost-effective design improvements that may reduce the injury toll on British roads.

A specific database stores information on fatal HGV accidents which occurred during the period 1994 to 1996, and approximately half of the fatal accidents involving an HGV in the UK are recorded in this database. Investigation into this database revealed that there were two cases of trailer swing causing a fatality. One where only the tractor was fitted with ABS, and the second where the trailer ABS failed to function. ABS may have helped to reduce accidents, however, in the event of a failure, stability of the combination must be retained, and this may be best achieved with balanced braking that, in turn, can be guaranteed only with changes to the existing compatibility corridors.

4.7 PREDOMINANCE

It was found that adjustment to the predominance valve could, to some extent, compensate for a threshold pressure difference arising when the semi-trailer threshold pressure was somewhat greater than that for the tractor. However, experimental tests have shown that if one of the two tractor brake circuits were to fail, then predominance becomes zero and the brake system returns to a state of imbalance. In such circumstances a semi-trailer will be under-braked and the potential for jack-knife greatly increased. In addition tractor lining wear rate would increase and the trailer brakes may become glazed.

4.8 TYPE APPROVAL

The tests at VTAC (the type approval authority) have shown that it is possible for a vehicle to pass type approval but still fall outside the acceptable performance, particularly at a coupling head pressure of 4.5 bar, which is at the 'elbow' of the corridor; as was found with the laden tractor unit, with the threshold pressure set to 0.8 bar. It is essential that the vehicle performance should not fall outside the corridor at *any* coupling head pressure. This could be achieved by measuring the brake efficiency over a range of coupling head pressures. It is also essential that the methods used to approve a given vehicle should be representative of how that type of vehicle will be loaded in practice.

4.9 SUMMARY OF DISCUSSION

The discussion has identified findings upon which recommendations may be based. In particular there is evidence that the compatibility corridors need to be rationalised so that, for a given condition, laden or unladen, the tractor and trailer corridors are coincident or very nearly so. However, the corridors are generated on the basis of threshold pressure, x axis intercepts, and the gradient. The threshold pressure difference, tractor to semi-trailer, affects the performance of the vehicle in the check braking range, typically 0 bar to 2 bar and thus affects the lining wear rate and the ease with which the vehicle can be driven. The results for the road trials show that a vehicle with balanced brakes tends to achieve a lower average deceleration than one with considerable out of balance. In addition it was shown that on a low coefficient surface, wheel locking occurred at 1 bar and thus, in adverse road conditions, ice and snow for example, stability can be affected within the range 0 bar to 2 bar. It should also be noted that when motorway surfaces become worn the coefficient can fall to values as low as 0.2 at high speed (Roe et al, 1998).

Applied coupling head pressures of greater than 2 bar tend to indicate an emergency and the width of the corridor above this pressure is, therefore, related to safety for which stability is the main concern. Table 10 below indicates the threshold pressure difference, x axis intercepts, and the compatibility corridor range above 2.0 bar that are recommended from the results of this research.

Based upon safety under normal road conditions, the compatibility range above 2 bar should be limited to a difference of ±0.4 bar. When, the lining wear rate, work done and stability in adverse conditions are taken into account then the threshold pressure difference should be limited to -0.2 bar to +0.2 bar and remain no greater than this up to 2.0 bar. These conclusions are the basis of the recommendations for changes to the permitted compatibility corridors that are discussed in section 5 below.

Table 10: Recommendation based on technical results and analysis

	Range of threshold pressure difference (≤ 2 bar)	**Emergency braking compatibility range (>2 bar)**
Wear rate	-0.2 to +0.2 bar	
Work Done	-0.2 to 0.0 bar	
Stability	-0.4 to 0.0 bar	-0.4 to +0.4 bar
5th Wheel forces	-0.6 to +0.2 bar	-0.4 to +0.4 bar
Recommendation	**-0.2 to +0.2 bar**	**-0.4 to +0.4 bar**

5. CONCLUSIONS

1. A tractor unit with manufacturer supplied asbestos free linings and a semi-trailer with Regulation 13 Type III linings were evaluated to determine the effect of varying threshold pressure within the range currently permitted by Regulation 13.

2. During the road trials, the coupling head pressure, for 95% of brake applications, was 1.72 bar for a threshold pressure difference of +0.8 and 1.24 bar for a threshold pressure difference of zero. The average coupling head pressure ranged from 1.19 bar at +0.8 difference to 0.79 bar at zero difference. This was comparable with previous research at TRL (Robinson, 1997) during which 95% of applications were made at less than 1.8 bar and the corresponding average pressures were slightly greater. These results were also consistent with other research (Fura, 1993) and confirm that the chosen test route provided typical brake usage.

3. It was found that the linings on the semi-trailer glazed when the threshold pressures were set to 0.4 & 0.8 bar, difference +0.4 bar, and the trailer brake efficiency deteriorated to below that permitted by the UK after only some 5,000km of the planned 11,000km were travelled. It should be noted that the pressure difference of +0.4 bar was well within the permitted range of ±0.8 bar.

4. By measuring brake temperature, it was possible to calculate the work done by each axle and hence calculate the distribution of brake force. The static axle load distribution was 15%, 25% and 20% for the steer axle, drive axle and each semi-trailer axle respectively and thus the ideal brake force distribution would correspond to this distribution. It was found that threshold pressures of 0.6 & 0.4 (difference -0.2 bar) gave the closest to ideal efficiency distribution (10.5%, 23.1% and 22.1%). As the difference in threshold pressure increased, the brake distribution was found to deviate from this closest to ideal performance. The extreme work done distributions were, 44.3%, 42.9% and 4.3% for difference +0.6 bar, and 3.0%, 11.8% and 28.4% for difference -0.6 bar.

5. The wear rate of the brake lining was found to provide a good indication of the compatibility of the vehicle combination. It was found that a poor tractor-trailer wear ratio of 5:1 was achieved with a threshold pressure difference of +0.4 (threshold pressures 0.4 & 0.8) which was the worst wear rate ratio. The tractor linings would need to be replaced five times as often as the trailer, despite the set-up being well within the permitted 0.8 bar difference. The combination closest to the ideal efficiency distribution, difference -0.2 (0.6 & 0.4) produced a wear rate ratio of only 2:1 for the tractor drive axle to trailer.

6. Regulation 13 Type III brake linings have shown an improvement over Type II in terms of wear rate and glazing. Nevertheless, the research has shown that threshold differences of 0.4 bar or more will start to produce glazing and vehicle brake performance degradation, even with Regulation 13 Type III linings. Therefore, keeping the threshold pressure difference within the range of ±0.4 bar would improve lining wear, vehicle braking performance and vehicle stability.

7. When the predominance valve was used to adjust the threshold pressure to give a notional balanced braking system the braking performance was substantially superior to that of a poor threshold mix with no predominance. In the worst case, where an adjustment of +0.8 bar predominance was required, it was found that both the control valves provided a reasonable threshold mix, and provided a better dynamic braking performance than the unmodified poor threshold mix of 0.4 & 1.2 without predominance. It should be noted that failure of one of the two tractor brake circuits will cause the predominance to return to zero, when adjusted using the tractor sited relay valve.

8. The instrumented fifth wheel gave a measurement of the forces acting during braking. The coefficient of friction between the tyre and the wet road surface significantly decreases as the velocity increases. The stability tests were conducted at a range of velocities (10, 20, 30 and 40km/h). During the tests at 10km/h, the available grip between the tyre and road was significantly greater than during the tests at 30 and 40km/h. Therefore, the compressive load in the fifth wheel was also greater during the tests at lower velocities for combination and tractor only braking. The longitudinal and vertical forces tended towards a minimum value as the velocity increased. This was indicative of the limiting condition, which was when the wheels locked on the wet surface. Since jack-knife and trailer swing did not occur, the lateral forces did not show an overall trend.

9. For type approval tests, the braking performance of the tractor unit conformed to the type approval compatibility corridor over the range of coupling head pressures that were used. The semi-trailer met the type approval requirements when laden. However, when the tests were repeated with the semi-trailer unladen, the brake performance did not conform to the compatibility corridor. The brake efficiency was found to be lower than the required theoretical braking rate, thus under braking on the semi-trailer would be the result.

10. The current compatibility corridors, as indicated in Regulation 13, Annex 10, need to be narrowed to improve lining wear rate, as well as to prevent brake lining glazing, and thus to improve the safety of HGV articulated vehicles.

6. RECOMMENDATIONS

1. Small changes in the threshold pressure, and particularly between the tractor and trailer, can have serious consequences. Therefore, it is recommended that the compatibility corridors for type approval should be narrowed. Ideally, from this research, to a difference of ±0.2 bar for coupling head pressures below 2 bar and to ±0.4 bar above a coupling head pressure of 2 bar. Figure 15, below, sets out the "ideal" corridors (based upon this research) for the laden and unladen tractor unit.

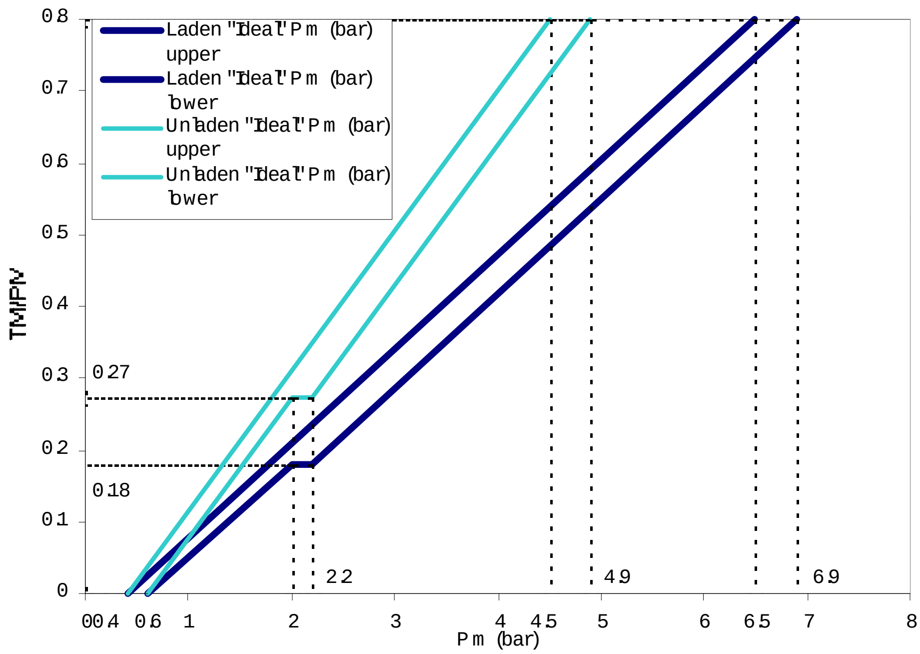

Figure 15: "Ideal" compatibility corridors for tractor units

2. It is recognised that meeting the criteria set by the "ideal" compatibility corridors, as shown in figure 15, may be difficult. Readily achievable compatibility corridors, that offer some improvement and which are based upon the current corridors set out in Regulation 13 Annex 10, have been generated, and are given below in figures 16 and 17. The compatibility corridors have been narrowed at the check braking range to improve the wear rate of the brake linings and to prevent glazing of the linings, and also narrowed up to 4.5 bar coupling head pressure to improve vehicle stability. The lower boundary of the corridor beyond 4.5 bar has remained unchanged. However, it should be noted that these corridors will not bring about the improvements to the same extent as those given in figure 15 above.

   For the tractor unit, the unladen corridor, shown in figure 16 below, has been calculated by moving the x axis intercept, for the upper boundary, from 0.2 bar to 0.4 bar. The gradient has altered slightly because a brake efficiency of 0.8 at 4.5 bar coupling head pressure has remained the same. This has ensured that there will be no perceived loss in brake efficiency, because this rate can be achieved by current vehicle designs. The lower boundary has been moved from an intercept, on the x axis, of 1.0 bar coupling head pressure to 0.6 bar. The gradient for the first part of the lower boundary (between 0.6 bar and 4.5 bar) has changed, but the second part (above 4.5 bar) has remained the same. This is due to using the current R13 co-ordinate (4.5 , 0.575) which will mean a comprehensive narrowing of the corridors at coupling head pressures below 4.5 bar. The overall narrowing of the compatibility corridor has altered the pressure difference at 2 bar and 4.5 bar coupling head pressures. Based upon the lower boundary and moving horizontally, the difference is 0.68 bar and 1.54 bar respectively. The current Annex 10 of Regulation 13 permits 1.03 bar and 1.66 bar for coupling head pressures of 2 and 4.5 bar.

The laden tractor unit corridors were calculated in the same manner as those for the unladen. Regulation 13 allows a pressure difference of 1 bar and 1.5 bar for coupling head pressures of 2 bar and 4.5 bar. The recommended corridors have a pressure difference of 0.64 and 1.43 for coupling head pressures of 2 and 4.5 bar.

The recommended corridors are shown in figure 16 below.

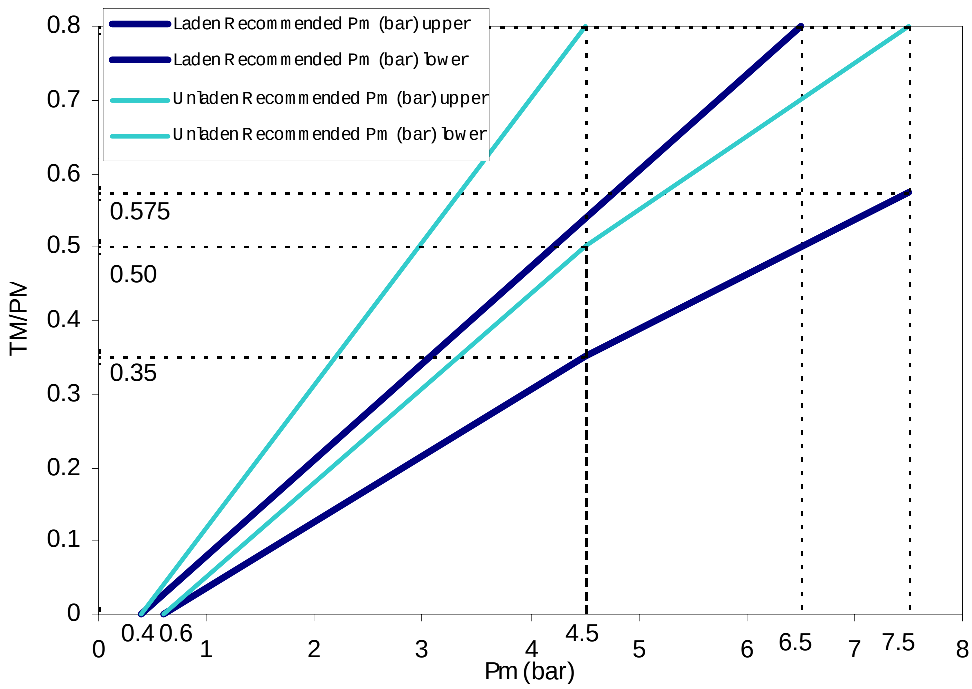

Figure 16: Recommended compatibility corridor for tractor units

The recommended corridors for the semi-trailer were also calculated in the same manner. For the boundary before the elbow the gradients were changed, whereas the gradients after the elbow (after 4.5 bar coupling head pressure) were kept the same as in Regulation 13. The upper boundary was moved from an intercept, on the x axis, of 0.2 bar to a new intercept 0.4 bar. The lower boundary was moved to 0.6 bar. In an unmodified state, where K_c =1.00, the pressure difference for 2 bar coupling head pressure is 0.56 bar, whereas in Regulation 13 it is 0.93 bar. At 4.5 bar coupling head pressure, the recommended corridors have a pressure difference of 1.20 bar which compares to a pressure difference of 1.26 bar currently permitted by Regulation 13.

To ensure compatibility between the tractor unit and semi-trailer, it is further recommended that the values of K_c and K_v should be limited and a tolerance established. This would provide a more representative test procedure in that the vehicle would be tested with its end use in mind, and also ensure that the corridors are coincident with each other in either the laden or unladen states. The unmodified recommended corridors for semi-trailers are shown in figure 17 below. Although these corridors are not as stringent as the "ideal", it is believed, based upon this research, that this represents the minimum desirable changes to the corridors.

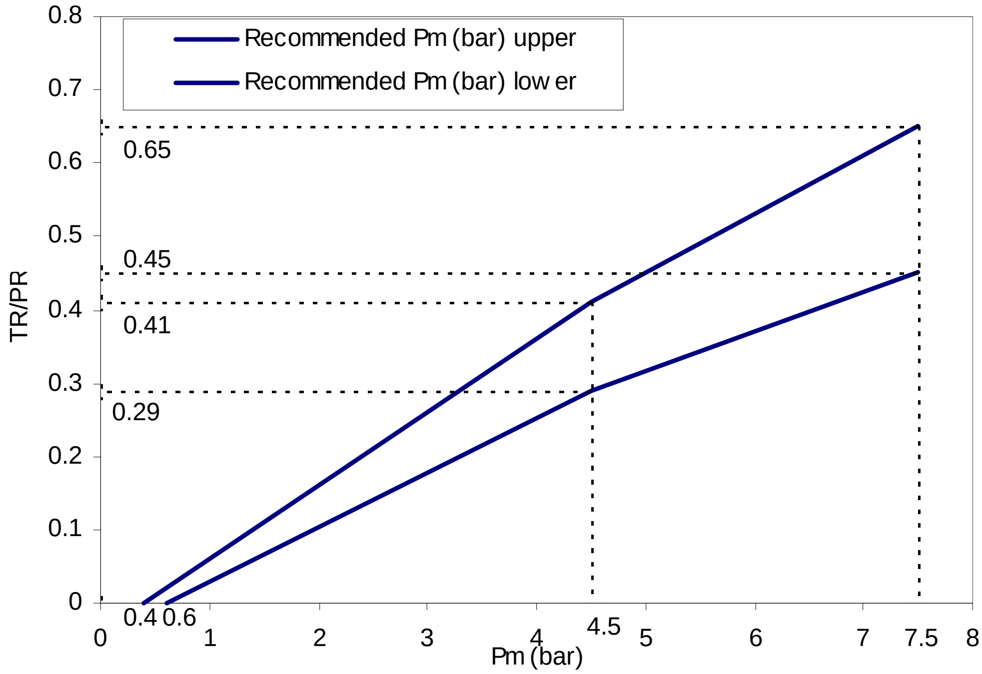

Figure 17: Recommended compatibility corridor for semi-trailers

3. Narrowing of the compatibility corridors means, from the outset, that tractor units and semi-trailers will have normal operating threshold pressures that are initially very close. With this in mind, it would mean that adjustment to a relay valve, by a vehicle operator, would be unnecessary. Therefore, phasing out of predominance valves is recommended. A relay valve would still be required, but it should be designed such that it is 'tamperproof'. Furthermore, the phasing out of predominance valves with large adjustment capabilities will eliminate the hazard of a trailer control valve that has significant predominance reverting to zero predominance, leading to unbalanced braking between tractor and semi-trailer, if one of the two tractor brake circuits fail.

4. The work done profiles show that balancing temperature across all axles does not necessarily produce balanced braking. Balanced braking is achieved by sharing work done by the equivalent ratio of the static load with an allowance for load transfer under severe braking. Manufacturers of vehicles, semi-trailers and/or axles could produce simple tables indicating to vehicle operators the correct temperature distribution applicable to each loading condition, thereby improving the lining wear and vehicle downtime.

5. Although the theoretical braking rate for unladen semi-trailers is based on sound mathematics, there is a need to verify that the vehicle can match the predicted braking rate later in the vehicle life, for example ten years after vehicle manufacture. Good maintenance is essential to ensure that optimum braking is sustained. Evidence should be provided to show that the theoretically derived regulatory requirements are met in practice.

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