Guidance on Brake Testing for Rubber-tyred Vehicles

Operating in Quarries, Open Cast Coal Sites and Mines

EPIC Training and Consulting Services Ltd in conjunction with
the Off-highway Plant and Equipment Research Centre (OPERC)

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Whilst written principally in a UK context, for the most part, the principles and concepts discussed within this publication hold equal international relevance.

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Summary

In the past, brake testing of rubber-tyred vehicles operating in quarries, opencast coal sites, mines and similar environments, comprised ‘simple’ stopping distance tests, typically carried out at daily or weekly intervals. More recently, many operators of such plant have progressed to using a brake testing method that employs electronic instrumentation, as a means of determining the ‘**brake ratio**’ of a vehicle. This is because instrumented testing gives more accurate results. Accordingly, the time between performing these instrumented tests has increased to monthly, or even 3-monthly intervals.

For both ‘simple’ and ‘instrumented’ test methods, international standard ISO 3450 is often (wrongly) used as the guide to acceptable brake performance testing regimes. The ISO standard contains formulae that enable either a stopping distance or a brake ratio (depending on which test method is used) to be calculated. However, these calculated values are minimum levels of braking ability, necessary for a vehicle to be placed on the market. That is, the ISO standard is a minimum standard for manufacture, not a maintenance standard. To put this into context, it is likely that any ‘modern’ vehicle will have levels of braking performance approaching twice these minimum ISO values.

In using these ISO values as routine test pass or fail criteria, organisations may be indirectly accepting that brakes on modern vehicles can deteriorate by up to 50 per cent before their operators become concerned with braking ability. In addition, test conditions on site (particularly speed and gradient) may be much less onerous than those used in ISO 3450, which produces low test results. The overall outcome of which may be a 'poor' brake test result, but one that exceeds a low level pass criterion and is not, therefore, seen as a test failure.

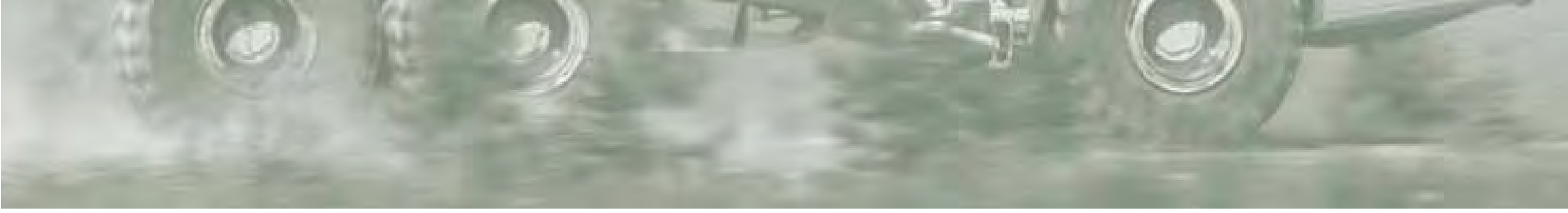
Another common problem with some brake testing regimes is that they do not readily correlate to site operating conditions; in particular to gradients, but also to vehicle speed and load. The law requires organisations to ‘ensure’ that work equipment is suitable (safe) for the conditions of use it will encounter. This means being able to demonstrate that vehicle braking capabilities are adequate for actual site operating gradients, speeds and loads. Naturally therefore, any testing regime should accurately take account of the site conditions which the vehicle will be exposed to.

In order to address these shortcomings regarding brake testing of rubber-tyred vehicles, this guide explains the **brake ratio method of brake testing**. A step-by-step guide on how to correlate braking performance with actual site conditions and how to design and put in place a suitable brake test regime is preceded by several discussion chapters. (Hence, if you already have an understanding of this method of brake performance testing, then skip straight to the *Step-by-step Guide*).

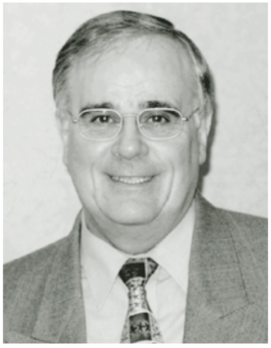
The following convention is used to highlight significant information:

- **Text in bold** is used to highlight a point of principle;
- Text in a box highlights a cautionary note; and
- Footnotes provide added information.

The guidance was prepared by a working group of the *Quarries National Joint Advisory Committee* (Appendix A). The written report was compiled in collaboration with *EPIC Training and Consulting Services Ltd* and the *Off-highway Plant and Equipment Research Centre* (OPERC).



Preface



Mr Barry Robinson MBE, OPERC Chief Examiner.

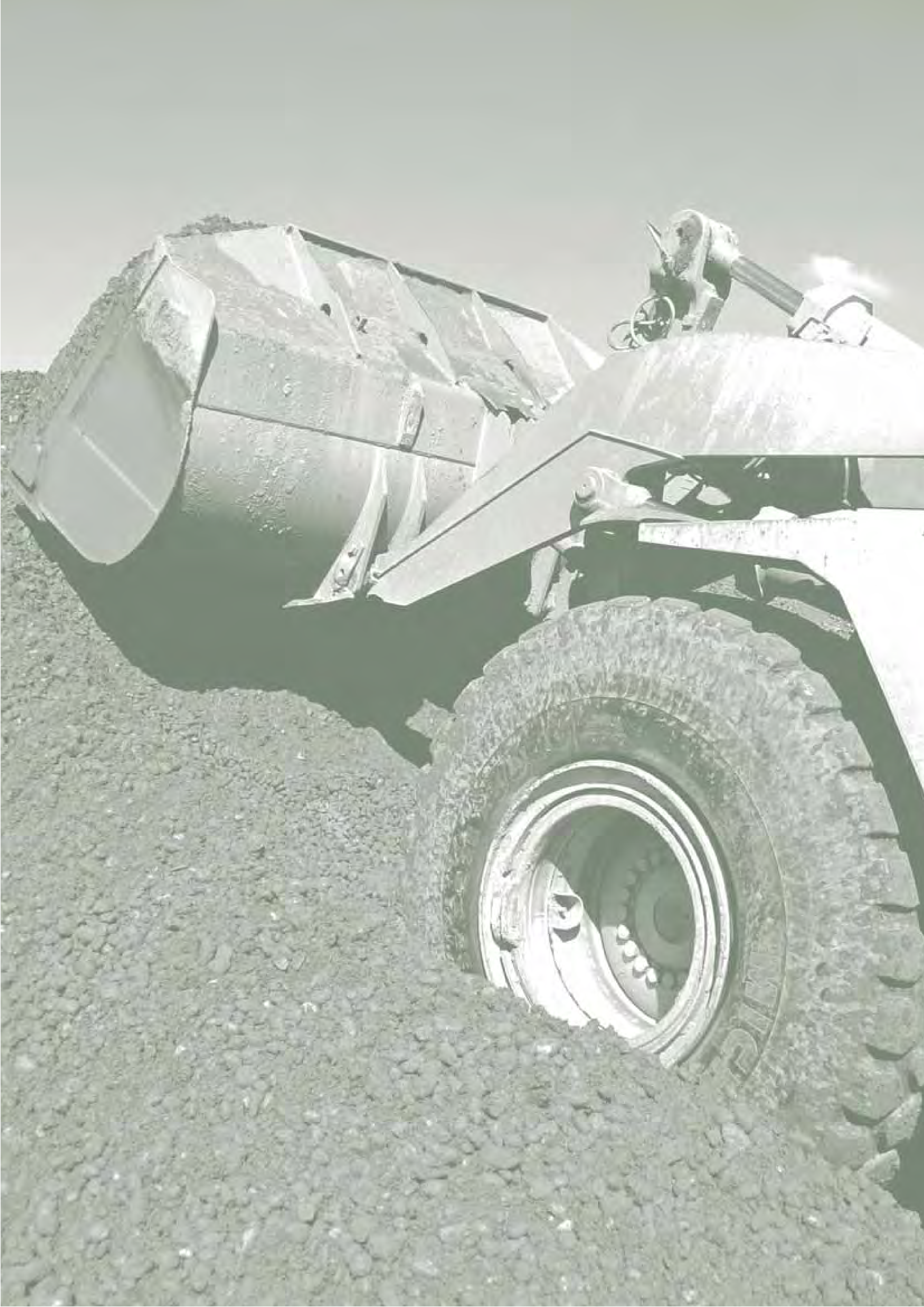
Each year within Great Britain, approximately 50 people are killed as a result of accidents that in some way involve workplace transport. In striving to improve upon this unfortunate statistic, workplace transport safety should encourage *safe sites, safe drivers* and *safe vehicles*. This guidance document is concerned with the latter and focuses upon vehicular braking systems in particular.

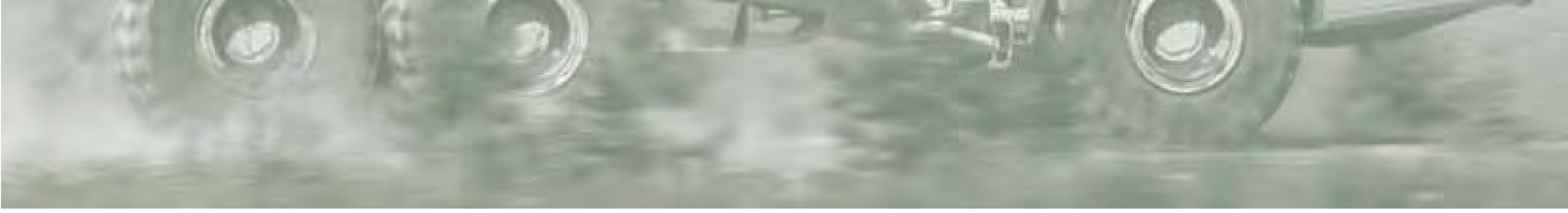
The need for safe braking systems on any type of vehicle is all too obvious, but this need assumes even greater importance for those vehicles operating in the quarrying and mining sectors, where large plant items, heavy loads and steep haul road gradients might be experienced.

Advancements in vehicular brake testing technologies mean that less robust methods, such as stopping distance tests, can no longer be relied upon to accurately (or adequately) assess the efficacy of braking systems. Additionally, the criteria by which brake test results are evaluated must also be appropriate, if reliable test decisions (e.g. pass/fail) are to be arrived at.

This guidance document describes how electronic brake testing equipment may be used to establish ‘brake ratio’, as a means of reliably assessing the efficacy of braking systems of rubber-tyred vehicles operating in quarrying and mining environments. The guidance presented is not mandatory, but it does represent best practice and in doing so, sets about encouraging ‘safe vehicles’ and thereby safer use of workplace transport generally.

OPERC Executive, March 2007.





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Introduction

What is this Booklet About?

This booklet contains guidance for brake testing self-propelled, rubber-tyred vehicles such as those used in quarries, at opencast coal sites, on mine surfaces or underground in mines. The guidance may also be useful in other industries where similar vehicles are used, such as mineral processing and construction.

The guidance uses '**brake ratio**' as the measure of brake performance (in contrast to other measures of brake performance, such as stopping distance). Following the guidance in this booklet is not compulsory, but it is recommended that any other chosen method of testing brake performance, should be equally as effective as the measures described here.

The types of vehicle covered by this guidance include:

- dumpers, wheeled loaders, tractors, graders and similar earth moving vehicles;
- service vehicles that operate on work sites, such as rough terrain type lift trucks; and
- passenger vehicles that operate on work sites, such as 4x4's.

The guidance is not appropriate to slow moving vehicles that stop almost instantly (i.e. before brake ratio can be measured), such as a coal mine free steered vehicles. For these latter types of vehicle, other kinds of brake test(s) may be more suitable.

Who Should Read this Booklet?

The intended readership of this guidance is:

- site operators who are responsible for providing vehicles;
- site managers who are responsible for vehicle operation and maintenance; and
- those who carry out vehicle brake testing.

Site operators and managers may require the assistance of competent persons with relevant academic knowledge, to supervise and / or undertake the technical activities covered in this guidance.

The guidance may also be useful for:

- safety representatives;
- employee representatives; and
- those who are involved with driver training and assessment.

2 Relevant Legal Requirements

The following is an indication of some relevant legislation. For complete bibliographic listings of these, see *Further Information* at the end of this guide.

Section 2 of the *Health and Safety at Work etc.* Act 1974, places a general duty on employers to take reasonable action to ensure the safety of people at work. Such duty extends to the provision and maintenance of plant, which for the purposes of that Act, must also be considered as safe.

Regulation 4 of the *Provision and Use of Work Equipment Regulations 1998* and the Approved Code of Practice and Guidance, require plant and equipment to be suitable for the purposes for which it is provided.

Regulation 5 of the *Provision and Use of Work Equipment Regulations 1998* and the Approved Code of Practice and Guidance, require that equipment is appropriately maintained such that its performance does not deteriorate to the extent that it puts people at risk.

Regulation 9 of the *Quarries Regulations 1999* and Approved Codes of Practice, require that persons carrying out brake testing are competent by virtue of training, experience and knowledge, to do that work.

Regulation 12 of the *Quarries Regulations 1999* and Approved Codes of Practice (ACoP), require the operator to prepare and keep up to date, a suitable written scheme for systematic inspection, maintenance and testing. ACoP 95 highlights that it is particularly important that the scheme covers vehicles.

Regulation 14 of the *Quarries Regulations 1999* and Approved Codes of Practice and Guidance, require the operator to make vehicle rules, that include cross-references to the scheme for inspection and maintenance of plant. The Guidance, Appendix 4, paragraph 14, requires that a suitable inspection scheme be in place to ensure vehicle brakes are kept in good condition at all times.

What is Brake Testing?

Braking Systems

Vehicles may be provided with any combination of the following braking systems:

- a service brake – used for stopping and holding;
- a secondary or emergency brake – used for stopping if the service brake fails;
- a parking brake – used to hold a vehicle stationary; and
- retarders – an energy absorbing brake normally used to control speed.

It will generally be necessary to test the performance of all braking systems provided on a vehicle, to ensure that safety is maintained.

Cautionary Note 1

There is controversy surrounding the dynamic testing of secondary (emergency) brakes. Some argue that this brake should not be tested dynamically, because to do so risks causing damage to the vehicle. But, from a safety point of view, it is difficult to justify that a brake that would be relied on in an emergency should never be tested. A secondary brake must be capable of safely stopping a vehicle under the most onerous conditions of use, and information will be required to verify this. Where there is justifiable reason not to carry out dynamic testing of secondary brakes, then manufacturers should be asked to provide a suitable, alternative test procedure that is capable of demonstrating that secondary braking is compatible with site operating conditions and can be safely maintained. Less frequent test intervals might be justified on a little used braking system.

Brake Testing

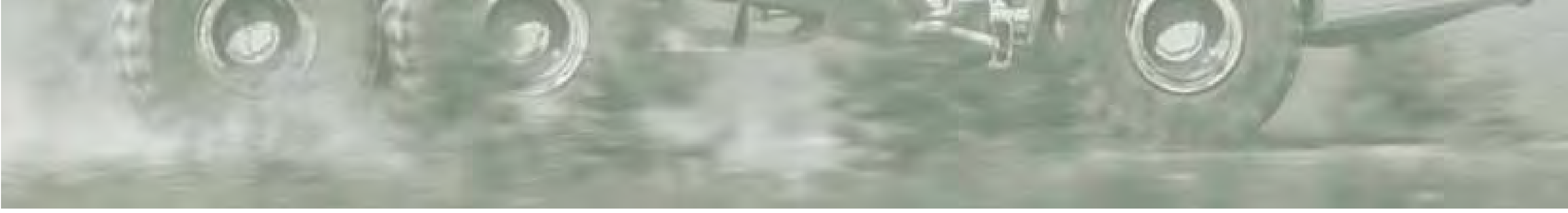
The designer of a vehicle determines the level of performance of its braking system(s). The user (employer) has a duty to ensure that the vehicle selected is suitable for the conditions of its intended use. For example, the brakes must safely stop and hold the vehicle in the most onerous working conditions that might be expected of it – such as when it is carrying its maximum load down its maximum operating gradient.

Brake testing is a procedure for periodically checking that a vehicle's brakes are maintained (working) at a level of performance that does not put people at risk. Usually, this means:

- **ideally, that their level of performance has not significantly reduced below the design level performance; or**
- **at the very least, that their level of performance exceeds that required for safe working under the most onerous site conditions of speed, load and gradient.**

Examples of brake performance tests include:

- instrumented brake testing – where an instrument is used to measure brake performance when stopping, usually in terms of a brake ratio;
- simple stopping distance tests – where the distance to stop a vehicle from a pre-determined speed is measured;
- a hold test – where the vehicle is parked on a pre-determined slope and the brakes are applied to see if they hold;
- a stall test – where the engine attempts to drive through the brakes; and
- a pull test – where a hydraulic ram, or similar, attempts to pull a vehicle through its brakes.



Service and emergency brakes are designed to stop a vehicle that is moving and a park brake is designed to hold it stationary. Stopping distance tests and instrumented tests are carried out dynamically and are therefore appropriate to service and emergency brakes (refer to *Cautionary Note 1* earlier). A hold test is a static test and is therefore appropriate to parking brakes.

Simple stopping distance tests and stall tests are a quick and easy check of any brake, but are often imprecise and cannot easily be related to actual operating conditions, in order to give a clear indication of adequate brake performance. Pull tests are a useful alternative where dynamic testing is impractical. Using a pull test, brake force can be measured by a dynamometer.

Brake performance achieved during testing has to be compared to some pre-determined acceptable brake performance values. That is, results must be evaluated against pass/fail criteria. The best comparator is the design specification, i.e. the performance defined by the manufacturer when the brakes are in good condition.

The Problem with Simple Stopping Distance Tests

For a simple stopping distance test, a series of marker posts are arranged in a line with 1m spacing between them. The driver of the vehicle being tested accelerates to the test speed and maintains this speed until the first marker post is reached; at which point the brakes are applied in an attempt to bring the vehicle to a stop as quickly as possible. The stopping distance is the distance travelled beyond the first marker post.

The stopping distance is made up of the braking distance plus the distance travelled by the vehicle during the short ‘delay time’ it takes the brakes to achieve full effort after the pedal has been applied. It also includes the distance travelled during the driver’s reaction time; this being any slight delay in applying the brakes after passing the first marker post.

The main problem with simple stopping distance tests is that they are not very precise. For example, the theoretical braking distance for a vehicle travelling at 15mph (24kph) on level ground is about 7.5m. If there is a 20 per cent error in the speed and the actual test speed is only 12mph (19kph), then the stopping distance will be reduced to about 5m. If there is a 10 per cent downward slope instead of a level test road, then a 15mph vehicle will stop after about 11.5m. Also, the driver’s reactions are important. If there is a 0.5 second delay in applying the brakes as the driver passes the first marker post, then at 15mph this will increase the stopping distance by a further 3.5m.

Consequently, in such a series of tests all intended to be under the same test conditions for a vehicle travelling at 15mph, it is possible to achieve a stopping distance of 7.5m in the first test; while subsequent tests could result in a stopping distance anywhere between 5m (i.e. 20 per cent speed error) and 15m (i.e. a downward slope plus driver reaction time).

Instrumented Testing

When properly carried out, instrumented testing is much more accurate than the simple stopping distance method and hence, more likely to show up brake deficiencies.

Instrumented testing can also be used as part of a site risk assessment to demonstrate that vehicle braking capabilities are adequate, when compared to the site gradients, speeds and loads that they are to encounter.

The brake ratio method of testing is ideal for both of these uses.

Some Simple Dynamics

What is Brake Ratio?

An appreciation of the term brake ratio is essential to understanding instrumented brake testing using the brake ratio method.

In simple stopping distance tests it is the stopping distance that is measured and compared with some standard value as a means of considering brake performance. In contrast, when electronic instruments are used to measure brake performance, they usually measure brake ratio. By definition:

$$\text{brake ratio} = \frac{\text{brake force exerted by the wheels}}{\text{vehicle weight}}$$

The brake force exerted by the wheels results in a linear (in line of travel) retardation of the vehicle. This force is generated by the wheel brakes exerting a braking torque (measured in Newton-metres, Nm), which will be applied to the outside of the wheel and tyre at a rolling radius depending on the wheel size (measured in metres, m). The vehicle design will set these values.

For example, assume that a dump truck has a laden mass of 67,230 kg (multiply by 9.81 to convert to weight). The total braking torque for its 6 wheels is 224,971Nm, acting at a tyre rolling radius of 0.887m.

$$\text{Therefore, the brake ratio} = \frac{224{,}971 / 0.887\ \text{N}}{67{,}230 \times 9.81\ \text{N}} = \frac{253{,}631}{659{,}526} = 0.384$$

The brake ratio is usually expressed as a percentage, i.e. 38.4 per cent[1].

Instrumented Brake Testing

From simple dynamics, brake force F = vehicle mass M x retardation f. Also, vehicle weight W (due to gravity) = vehicle mass M x *g* (acceleration due to gravity). By 'juggling' these two equations slightly, we see that F / W = f / *g*. That is, the ratio of force / weight is the same as the ratio of retardation / *g* and is known as the brake ratio. Hence:

$$\text{brake ratio} = \frac{\text{brake force}}{\text{vehicle weight}} \quad \text{and it is also} = \frac{\text{retardation}}{g}$$

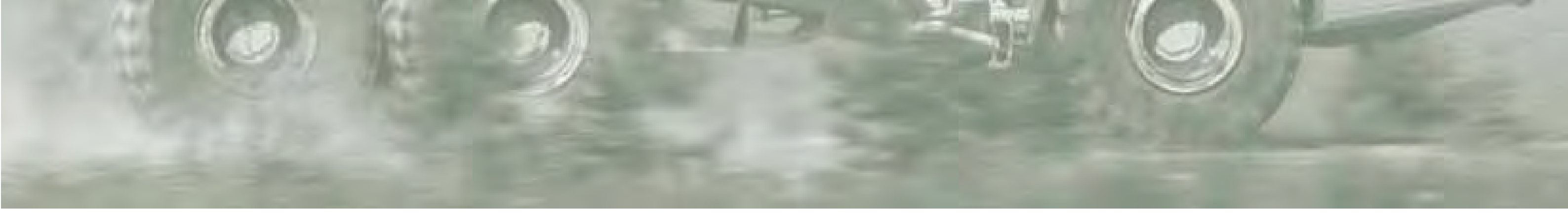
An electronic brake test instrument usually contains a single axial transducer that measures retardation. And if the instrument expresses this measured retardation as a fraction of *g*, we have measured the brake ratio.

So, if manufacturers tell us what the designed braking force is for a particular machine we can easily calculate the design brake ratio for that machine. A brake test instrument can then be used to measure the actual operating brake ratio, in order to compare this with the design brake ratio to assess brake performance.

In practice, the operating brake ratio is likely to be less than the design brake ratio for a brand new vehicle, because the brakes will have deteriorated slightly with use. A practical margin would be say 10 per cent of the design brake ratio. So, in the example above, we should expect instrumented brake testing results for that vehicle of at least (38.4 minus 10 per cent) 34.5 per cent.

There are several kinds of test instrument available, which are either mechanically or electronically operated.

[1] Brake ratio is often referred to as brake efficiency when expressed as a percentage, but in this guidance document, the term brake ratio is consistently used so as to avoid confusion.



The mechanical instruments, sometimes called inertia meters, are reasonably accurate if tests are conducted on smooth level roads. However, if the roadway surface is uneven, then ‘bumps’ can affect the readings on the inertia meter. Under such test conditions, they may tend to give higher than actual readings.

Cautionary Note 2

The test procedures referred to in this guidance are aimed at electronic instruments specifically designed to test the brakes on heavy off-road vehicles and to automatically compensate for any variation in gradient when doing so. The use of other instruments, such as those designed to test on good level surfaces only (i.e. instruments that cannot automatically compensate for variations in gradient or tolerate rutting in the travel surface etc.), if used under such off-road circumstances could lead to potentially dangerous errors in measurement.

The Effects of Speed, Load and Gradient

A vehicle will stop differently under different conditions of speed, load or gradient. It is important to understand why and how these conditions affect stopping ability, because when brake testing we have to compare like with like.

The Effect of Speed on Stopping Distance

The faster a vehicle is travelling the longer it will take to stop. In fact, twice the speed results in approximately four times the required braking distance.

For example, take a dump truck that has a brake ratio of 30 per cent. In this case, the retardation along level ground will be 2.94m/s/s (i.e. 30 per cent of *g*). If it is travelling at 12.5kph (3.47m/s) when the brakes are applied, then the braking distance will be (using the dynamics formula of $v^2 = u^2 + 2fs$, where the final speed is zero):

$$\frac{v^2}{2f} = \frac{3.47 \times 3.47}{2 \times 2.94} = 2.05\text{m}$$

For the same dump truck, with the same brake ratio, this time travelling at 25kph (6.94m/s), i.e. twice the speed, when the brakes are applied the braking distance will be:

$$\frac{6.94 \times 6.94}{2 \times 2.94} = 8.18\text{m}.$$

That is, 4 times longer.

Consequently, in stopping distance testing, it is critical to ensure that the same speed is maintained in all tests otherwise results will vary widely.

The Effect of Load on Stopping Distance

A laden vehicle will take longer to stop than an unladen vehicle. This is because the rate of retardation that the brakes can achieve will be less for a laden vehicle than for an unladen vehicle. For example, if a dump truck has a brake ratio of 30 per cent, this means that it is capable of developing a brake force in the direction of travel equal to 30 per cent of the vehicle weight. But is this 30 per cent of the laden weight or 30 per cent of the unladen weight?

If the design brake ratio is given as a percentage of the laden weight and we test unladen, then the brake ratio we measure will not be the same. We will not be comparing like with like; so the overall assessment of brake performance will be flawed. Fortunately, it is easy to convert from a laden brake ratio to an unladen one. From basic dynamics:

Force = Mass x Retardation.

The maximum braking force a vehicle is capable of developing can be assumed to be constant for any condition of load, provided it is caused to be developed. Therefore:

Mass Laden x Retardation Laden = Mass Unladen x Retardation Unladen.

The laden and unladen masses are standard information. So, if we measure either the retardation laden or the retardation unladen, we can calculate the other. As mentioned previously, we see that brake ratio and retardation as a percentage of *g* are interchangeable. So, for example, if the laden mass is 67,230kg and the unladen mass is 30,730kg, then for a laden brake ratio of 30 per cent the equivalent brake ratio for an unladen vehicle is:

$$\text{Unladen brake ratio} = \frac{67{,}230 \times 0.3}{30{,}730} = 65 \text{ per cent.}$$

For the same vehicle, the retardation laden is 30 per cent of *g*, and unladen 65 per cent of *g*, i.e. 2.94 m/s/s and 6.38 m/s/s. The unladen vehicle, which is approximately half the weight, will stop twice as quickly.

Testing unladen is likely to induce skidding, as the higher brake ratio approaches the coefficient of friction between the wheels and the road surface.

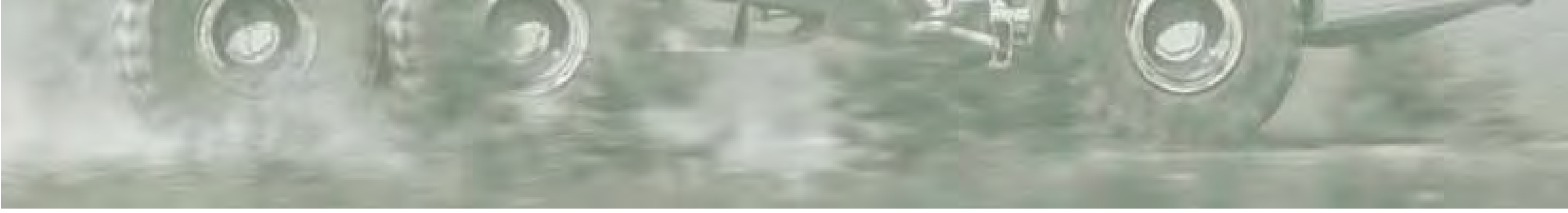
The Effect of Gradient on Stopping Distance

A vehicle travelling down a gradient will take longer to stop than a vehicle travelling at the same speed on level ground. This is because on a gradient, gravity will try to accelerate the vehicle down the slope and this effect has to be overcome, before the brakes can begin to stop the vehicle.

The best way to consider the effect of gradients is to think in terms of percentage slopes. That is, a 1 in 10 gradient is a 10 per cent slope, and 1 in 12 is 8.3 per cent. In this way, the fraction of a vehicle’s weight acting down the gradient is equal to the percentage slope of the gradient.

A vehicle with a 30 per cent brake ratio can apply all that effort into stopping on level ground, but when travelling down a gradient it must overcome the weight acting down the gradient first. So, on a 1 in 10 gradient (10 per cent slope) this leaves only 20 per cent for stopping. On a 1 in 12 gradient (8.3 per cent slope) it leaves 21.7 per cent for stopping.

So, to ensure that a vehicle can travel safely down a gradient, the total brake ratio must be equal to, or greater than, the gradient expressed as a percentage plus an amount of brake ratio necessary to stop the vehicle.



How Much Brake Ratio is Required for Stopping?

There is no prescribed amount of brake ratio that is required to stop a vehicle. Rather, it is a matter for the risk assessment to decide. However, 10 per cent is a good rule-of-thumb absolute minimum. If the brake ratio on a vehicle is less than 10 per cent, its driver may not feel they are slowing down quickly enough when in a braking situation.

Taking this rule-of-thumb into account would mean, for example, that for a 1 in 10 down-gradient, i.e. 10 per cent slope, the vehicle brake ratio should be no less than 20 per cent. That is, 10 per cent for the gradient and 10 per cent for stopping. Note however, that braking distance increases at approximately double the increase in speed. So, to ensure safe stopping distances at higher speeds, the amount of brake ratio necessary just for slowing down may be 15 per cent, 20 per cent, or even more.

Table 1 compares braking distances for speeds of 5 to 35 kph at 5kph increments and given brake ratios of 5 to 20 per cent inclusive. So for example, row six of the data in the Table confirms that at 30kph, if a vehicle only had 10 per cent brake ratio left for slowing down then the braking distance would be about 35m; but if it had 20 per cent then the braking distance would drop to about 18m. Figure 1 meanwhile represents this data graphically. The resulting shorter braking distances as a result of increasing brake ratio are clearly visible from the lines on the graph in this Figure.

Cautionary Note 3

When considering the data in Table 1 and Figure 1, it should be noted that the given braking distances have not included allowance for a driver's reaction time, or for the slight delay from first applying the brake to achieving full brake effort, both of which will add to the overall stopping distances shown. For example, from velocity = distance / time, a 0.5 second delay when travelling at 25kph would result in a distance travelled of about 3.5m before braking becomes effective.

Cautionary Note 4

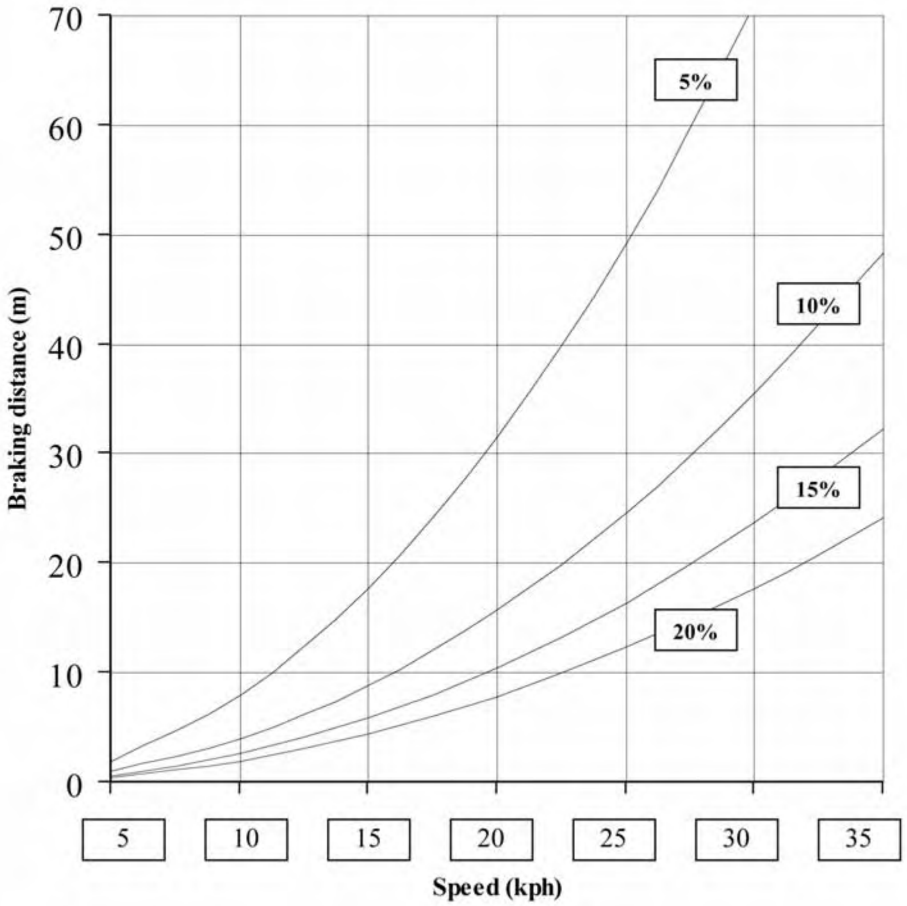
The 5 per cent data given in Table 1 and Figure 1 are included because some emergency brake systems are 50 per cent of the service brake. So, if the service brake ratio for slowing down is 10 per cent, then in such cases the emergency brake would only be 5 per cent and the examples shown demonstrate the very long braking distances that would result.

Table 1. Tabular comparison of braking distances at different vehicle speeds

	Braking distance for various brake ratios(m)			
Speed (kph)	5%	10%	15%	20%
5	1.96	0.98	0.66	0.49
10	7.89	3.94	2.63	1.97
15	17.74	8.87	5.91	4.44
20	31.54	15.77	10.51	7.88
25	49.28	24.64	16.43	12.32
30	70.98	35.49	23.66	17.74
35	96.60	48.30	32.20	24.15

Note. Doubling the brake ratio halves the braking distance; doubling the speed increases the braking distance by approximately four times.

Figure 1. Graphical comparison of braking distances at different vehicle speeds



Using Peaks and Plateau Levels

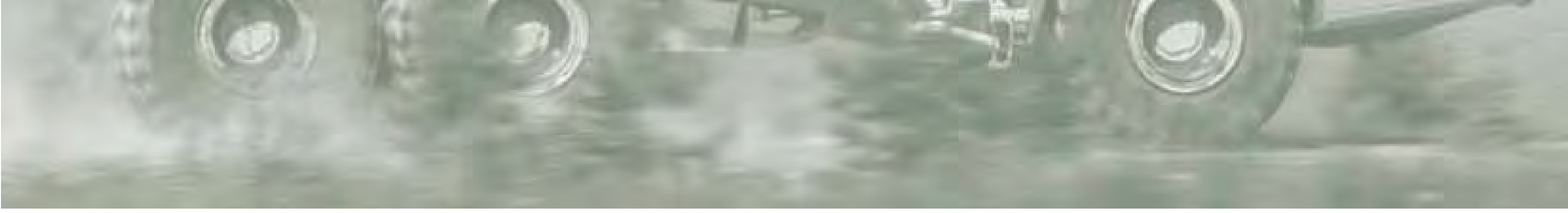
To understand peaks and plateau levels consider the curves labelled 1 to 5 in Figure 2. Curve 1 shows that the vehicle stops quickly, typically from a slow speed on level ground. In this example, very little brake effort is caused to be developed; the brake effort peaks and then drops off as the vehicle starts to slow down immediately. The subsequent curves 2 and 3, demonstrate that as speed and gradient effects are increased, more brake effort is developed (i.e. the peak gets higher) and the time taken to stop increases (i.e. the base of the curve gets wider).

This effect continues until eventually the brake effort reaches the maximum the vehicle is capable of developing, as shown by curve 4. If speed and gradient are increased beyond this, then no more brake effort can be developed, so in order for the vehicle to be brought to a halt the maximum brake effort is sustained for a longer period of time – see curve 5. This is the 'plateau level'. That is, the maximum brake effort a vehicle is capable of developing.

In the earlier chapter *What is brake testing?* it was identified that brake testing should show:

- ideally, that brake performance has not significantly reduced below design levels; or
- at the very least, that the level of brake performance exceeds that required for safe working under the most onerous conditions of speed, load and gradient.

In order to achieve the ideal of the first bullet, a plateau level of braking must be caused to be developed during testing.

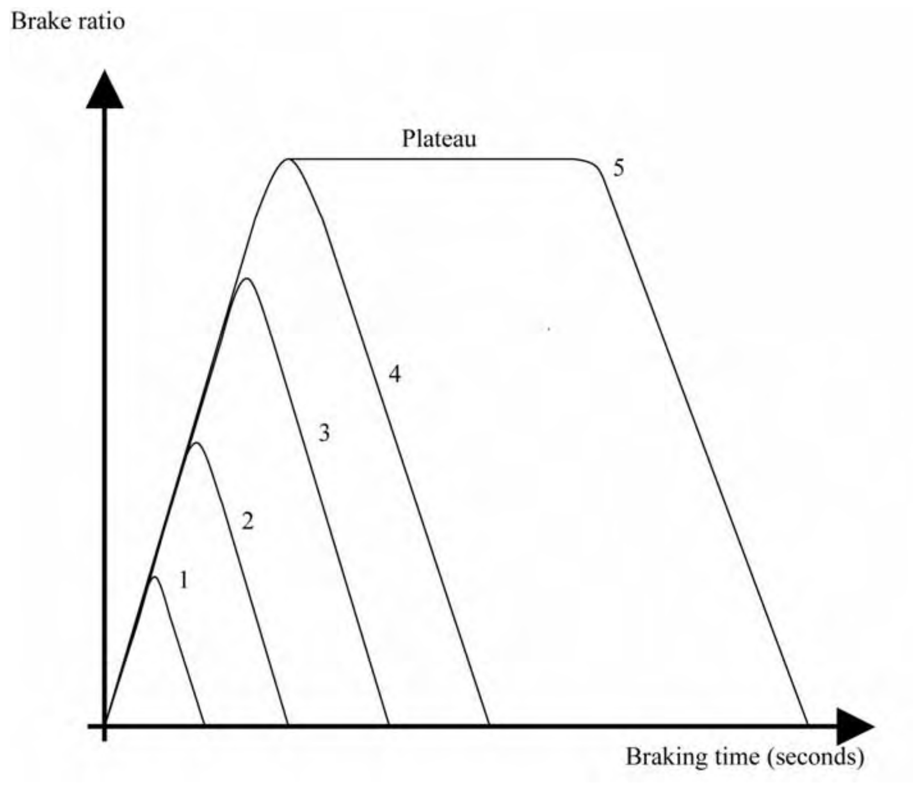


If a laden vehicle is run down an operating grade at sufficient speed then a plateau level, i.e. maximum possible braking effort, will be caused to develop. By carrying out a series of tests that progressively increase vehicle speed, then the optimum (necessary) speed to achieve this plateau level can be determined for future reference.

However, site constraints may make it impractical or even unsafe to test under such conditions. Where this is the case, then the second bullet becomes relevant. In this case the peak may not be accurately repeatable, but in each test the brake ratio should exceed the maximum operating gradient plus 10 per cent (or more), as mentioned in the section above *Effects of gradient on stopping distance*.

The main advantage of instrumented testing using brake ratio as a measure of brake performance, is that the results can be readily and accurately compared to operating conditions. If plateau levels are achieved during testing, the brake performance trend from a series of tests over a period of time can be observed.

Figure 2. Brake ratio versus braking time showing peaks and 'plateau'



A Typical Brake Test Instrument

How Does it Work?

A typical electronic brake test meter contains: a linear accelerometer; an arrangement for sampling, digitising, storing and processing the signal from that accelerometer; and a display.

The linear accelerometer automatically measures the slope (the sine of the inclination) when the vehicle is stationary at the start or end of a brake test run. It also measures the retardation during braking. The slope effect (whether it is positive, negative or zero) is added to the retardation to give a total brake ratio.

Depending on the type, the instrument is triggered (started) either manually, such as by a pressure pad on a brake pedal, or automatically. Once triggered, it starts sampling the instantaneous retardations. Sampling is carried out at intervals possibly as often as 500 times a second.

The software in the instrument will decide when the braking period starts and finishes. These are pre-determined points, for example, constantly attaining a level of retardation above 10 per cent *g* (for the start), and dropping constantly below 10 per cent *g* (for the stop). Between these points it is assumed that the brakes are fully applied. These start and stop points for the braking period are arbitrary and can sometimes be set by the user.

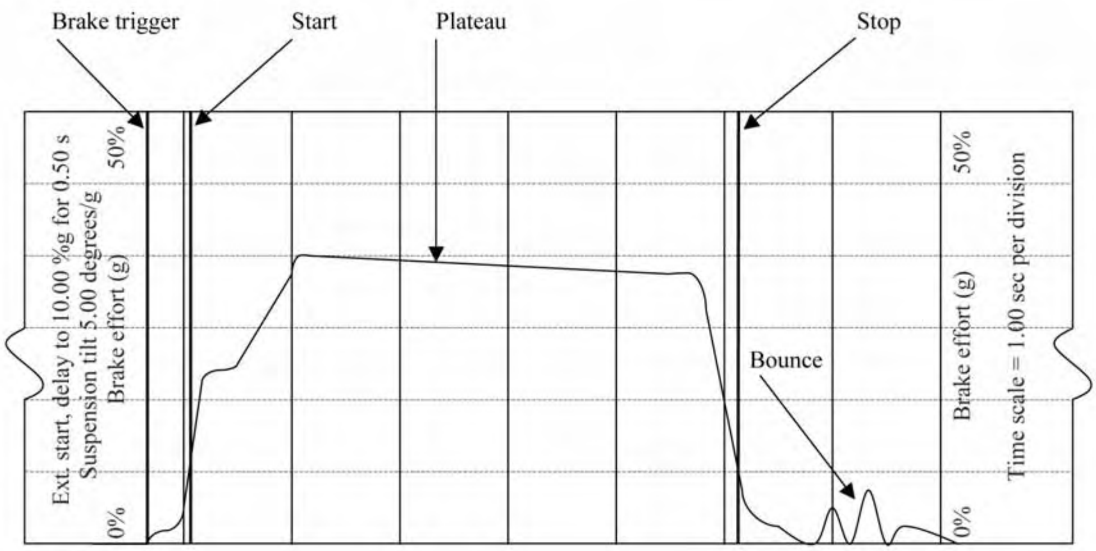
The time interval between triggering the instrument (e.g. by pressing the pressure pad on the brake pedal) and the point at which the brake is assumed to be fully applied, is the brake delay time.

Theoretical equations for calculating retardation assume that retardation is constant, whereas it usually varies with time, rising initially and then reducing as the vehicle comes to a stop (with a peak or a plateau in between). What an instrument typically displays as a single value brake ratio is the average value of all the instantaneous retardations measured at each sampling interval between the start and stop points (plus any slope effect).

Usually, working with the average brake ratio keeps things simple and errs on the side of caution. If the plateau level of braking is achieved, then the longer the plateau the closer the average value of brake ratio will be to the maximum value. If a peak level of braking is achieved (and not a plateau), then it could be argued that at the very least this level of braking would be maintained if called upon to do so.

A printer incorporated into the brake test instrument may produce a printed record of the average brake ratio, the test incline, the brake delay time, the speed when braking was initiated, the stopping distance and the brake ratio / time graph. A sample graphical printout from such an instrument is shown in Figure 3. This identifies the brake trigger point (when the instrument is started), and the start and stop lines of full braking (the 10 per cent *g* lines).

Figure 3. Example of brake test instrument print-out



Brake Delay Time

When using brake ratios to measure brake performance no consideration is given to the brake delay time. Brake delay is not usually a maintenance problem on modern braking systems, but it could be.

A fault in the braking system that resulted in a delay in the brakes being applied could significantly affect the overall stopping distance, but would not be apparent from the brake ratio.

However, as mentioned above, instrumented test results often include the delay time, and a quick check that this is a ‘reasonable’ value should be sufficient. In this context, reasonable is typically about 0.2 seconds and probably not more than 0.5 seconds for modern vehicles.

For precise information on brake delay time for a particular vehicle, refer to the manufacturer’s test information.

Some Sources of Error

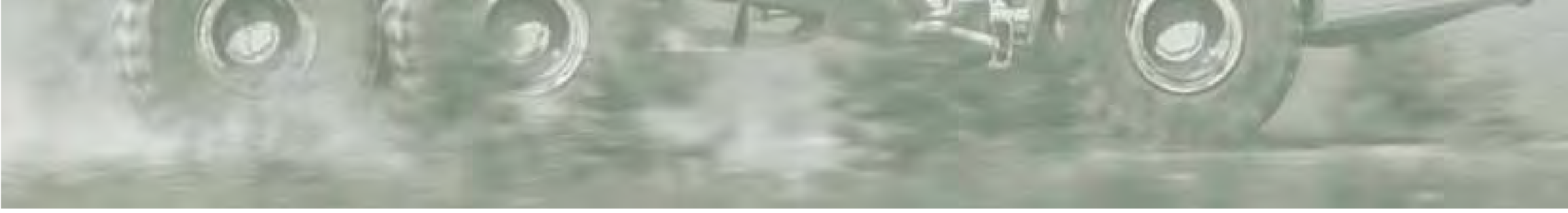
It is worth noting that different electronic brake test instruments use different software; so brake ratio may be calculated from different parameters or in a different way, depending upon which instrument is used. Consequently, a comparison of results for the same vehicle, achieved using different instruments, may highlight small differences.

It is also worth noting that vehicle brakes must retard both the translational (in line of travel) and rotational masses. That is to say, the brakes have to stop the motion of the vehicle mass in a straight line; while also having to stop the rotation of the wheels and other rotating parts of the engine or transmission, particularly if the transmission is not disconnected from the wheels when braking.

The fraction of the total braking effort of a vehicle that retards the translational mass (of that vehicle), is traditionally known as the ‘c-factor’ and is normally expressed as a decimal, for example, 0.95. Some brake testing instruments assume that the rotating parts are small enough to be neglected, and the c-factor is unity. At this time, there is little or no information readily available on c-factors for individual vehicles.

Electronic brake test instruments measure retardation in the line of travel. In order to get an accurate measurement, the axis of the instrument should be parallel to the ground. The easiest way to achieve this is to set the vehicle on level ground and then set the test instrument level on the vehicle. If the vehicle is on a slope, then the slope must be measured and the instrument set to the same slope on the vehicle. If the axis of the instrument is not parallel to the ground then a slight error in readings will result.

During braking, weight transfer from one axle to another can cause the body of the vehicle to tip forward on the suspension, and mean that the instrument is no longer parallel to the road surface, which gives rise to small errors in retardation readings. However, if the instrument manufacturer's operating instructions are followed (e.g. for correct set up and use) then under 'normal' test conditions these small errors will not impact test results. Some instruments may make an allowance for vehicles tipping forward by a few degrees.



Practical Considerations

The Test Site

For dynamic testing, the test site must be safe. In practice this normally means:

- there must be no risk of the test vehicle colliding with other vehicles operating on site;
- there should be ample distance ahead of the brake test site for the test vehicle to stop more slowly (i.e. overrun) if brakes are defective; and
- allowance should be made for a vehicle pulling or veering to one side during the test.

Skidding will increase the stopping distance and make the brakes appear less effective, so is not a true measure of braking performance. If skidding occurs, then the test may be invalidated. Wet conditions are the most likely cause of skidding. However, if testing is carried out with unladen vehicles then skidding may occur even on dry roads. For this reason, brake testing is best carried out with a laden vehicle.

Ideally, the test site should have a dry, smooth, hard surface and be either level or have a constant downward slope.

Frequency of Testing

The frequency of periodic instrumented testing should be based on the risk assessment. For example, to ensure performance is maintained, older vehicles (that therefore, typically will have less efficient braking systems) may require more frequent testing than will more modern vehicles. More frequent testing may also be appropriate where steep gradients feature on the site at which a vehicle normally operates. Because of their specific characteristics, different vehicles working on the same site may have different test frequencies. Similarly, due to differing environmental conditions, the same type of vehicles that are working on different sites may also require different test frequencies.

More frequent, simple driver stopping tests should be used to ‘back up’ formal periodic instrumented testing. Having determined by instrumented testing that the brakes are in good condition, a subsequent simple stopping test may be marked out by two posts (representing start and acceptable stop positions), on a regularly used section of haul road. This would permit drivers to test periodically, such as at the start of a shift or daily during routine vehicle use. Ideally, testing should be down-slope and with load. Equally, referring to the aspects of a safe site mentioned above, the test area should be selected with consideration given to safe stopping.

A stall test is another method of frequent, simple testing to back up periodic instrumented testing. There are also available built-in versions of some electronic brake test instruments that are permanently fitted into a vehicle. Such an instrument allows drivers to perform simple instrumented tests on a daily basis, and is much better than a simple stopping distance test.

In practice, a typical service brake test regime would consist of:

- a simple, driver stopping / instrumented test, or stall test, carried out either per shift or daily; and
- an instrumented test at an interval of between 1 and 3 months (depending on the vehicle / environmental circumstances as indicated earlier) carried out by a competent person.

Repeatability of Results

Repeatability means that when testing the same vehicle(s) with the same effective brakes under the same conditions of load, gradient and speed then the same results should be obtained. As already mentioned, repeatability with stopping distance tests is very difficult. Repeatability of instrumented brake testing results can be achieved with a proper understanding of what is being measured.

Test instruments usually produce graphical results (retardation versus time) of the braking cycle, from the driver hitting the brake pedal, to the vehicle coming to a stop. The initial slope of the brake test graph (refer Figure 3) carries on rising as the brake force continues to develop. After a short while the brake force will have developed to its maximum value. If there is sufficient momentum, this maximum value will be sustained for a short while and as mentioned earlier, this is called the plateau level, because the slope of the graph levels out. After the plateau, the graph slopes downwards as the vehicle comes to a stop.

If the momentum of a vehicle is such that the brakes can stop it before the maximum brake force is caused to be developed (for example, if the vehicle is moving slowly), it will stop quickly with little brake effort and a plateau level will not be achieved. Under such circumstances the brake test result graph will simply reach a peak and then fall off to zero as the vehicle stops.

If a plateau level is reached, results are repeatable. If a plateau level is not reached then different peaks will be reached on each test and results will not be accurately repeatable.

Plateau levels are sometimes difficult to determine from graphs. This is because the horizontal time scale may be extended such that an interval of 1 second appears to be stretched out (and under such circumstances this is probably just an extended peak). A proper plateau level is therefore one that is sustained for at least 2 or 3 seconds.

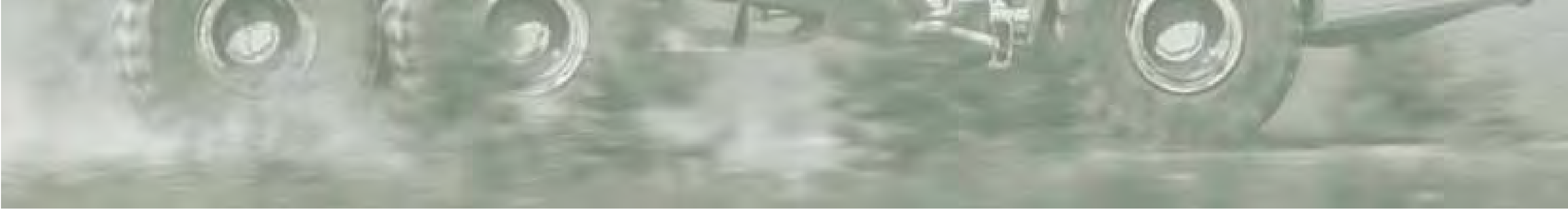
Pass and Fail Criteria

BS EN ISO 3450 : (1996)[2] requires a minimum brake performance equivalent to 17 per cent brake ratio for a category of dumper having an unladen weight of under 32t when tested with full payload; and 19 per cent for dumpers over 32t. However, some modern dumpers will readily achieve twice this level of braking.

Actual braking performance should always be compared with the design level; if performance is compared with the minimum standard then a very significant deterioration may occur and result in an unsafe vehicle being operated.

Hence, the minimum level of braking required in the standard should not be used as an automatic pass/fail level during routine periodic testing. Instead, users should obtain information from the vehicle manufacturer that enables them to determine the design brake ratio.

[2] BS EN ISO 3450:1996. Safety of earth-moving machinery. Specification for braking systems and performance requirements and test procedures for rubber-tyred machines. British Standards Institution. ISBN: 0-580-26308-8.



Other Tests and Checks

Testing is not just a procedure for establishing the performance of a braking system. It should also include other tests and checks that verify the ongoing reliability of the braking system. For example, daily checks should be carried out by drivers to ascertain that fluid levels and operating pressures are correct, warning devices are working and that simple stopping and holding tests appear normal.

Other periodic tests and checks by technicians might include[3]:

- checking the pressure in stored energy devices (also known as accumulators[4]);
- testing warning devices on stored energy systems (these devices are typically activated before the pressure drops below the specified level necessary to maintain secondary brake performance requirements);
- testing interlocks (such as devices that prevent start-up unless the park brake is applied);
- leakage checks, e.g. for brake fluid loss or air leakages;
- wear checks on friction discs;
- general checks of the condition of brake system pipes; and
- draining water from compressed air tanks.

Vehicle Damage Caused by Heavy Braking

Vehicles continue to get larger and braking systems more efficient; the end result is that some suspension and chassis components are heavily stressed during heavy braking. However, it is reasonable to expect service and emergency brakes to be tested dynamically, but testing should be no more frequent than is necessary to demonstrate ongoing satisfactory brake performance, and (testing) should be designed such that it is in line with any operating restrictions imposed by the manufacturer (see also *Cautionary Note 1* earlier).

Park brakes are designed purely for the purpose of holding a vehicle stationary and so there is no similar justification for testing these dynamically. Damage may be caused if park brakes are tested dynamically.

[3] See manufacturers' maintenance manuals for full details of other periodic checks and tests required.

[4] An accumulator is a small vessel used to store energy and may be used in vehicle steering and braking circuits. The stored energy is provided to operate these critical functions and allow a vehicle to be stopped safely if, for example, the engine cuts out unexpectedly. Typically, accumulators are pre-charged with an inert gas, which the operating air/fluid (compressed air or hydraulic fluid) compresses. When the engine (compressor or pump) stops, the gas in the accumulator expands and delivers sufficient air/fluid at sufficient pressure to operate the critical systems for a short time. If this pre-charge of gas is slowly lost over a period of time, then the stored energy will be reduced, possibly to zero.

Step-by-step Guide

This final chapter of the booklet presents a step-by-step guide to determining initial required braking capability for a vehicle along with a pass level for subsequent testing.

Step 1: Establish Maximum Brake Ratio

The first step is to establish the maximum, or design, brake ratio of the vehicle. If it is a new vehicle then the manufacturer must provide adequate information to the user. This may be in the form of a stated brake ratio or it may be information on braking torque exerted at the wheels (refer to *What is brake ratio?* earlier if necessary).

If it is not a new vehicle and there is little or no available information on braking capability, then a test instrument can be used to determine the maximum achievable brake ratio. This is achieved in a series of tests (ideally following a thorough overhaul of the braking systems), by progressively testing a fully laden vehicle and increasing the speed at each test, until no increase in brake ratio is recorded. This is then the maximum brake ratio for the vehicle, i.e. the plateau level (refer to *Repeatability of Results*).

If several vehicles of the same type are tested, then all should achieve similar results. If they do not, then an 'outstanding' result may indicate a fault. The more vehicles that are tested, the more reliable is the derived maximum brake ratio for that particular vehicle type.

Let us assume that the brake ratio of a fully laden new vehicle is 38.4 per cent, (conveniently rounded down to 38 per cent).

Step 2: Determine Conditions of Use

Having established the braking capabilities of a particular vehicle, the next step is to determine its conditions of use. That is, the gradient, the speed limit, and any other factors that might increase risk. For example, a bend at the bottom of a gradient where overrunning might result in a collision with vehicles travelling in the opposite direction.

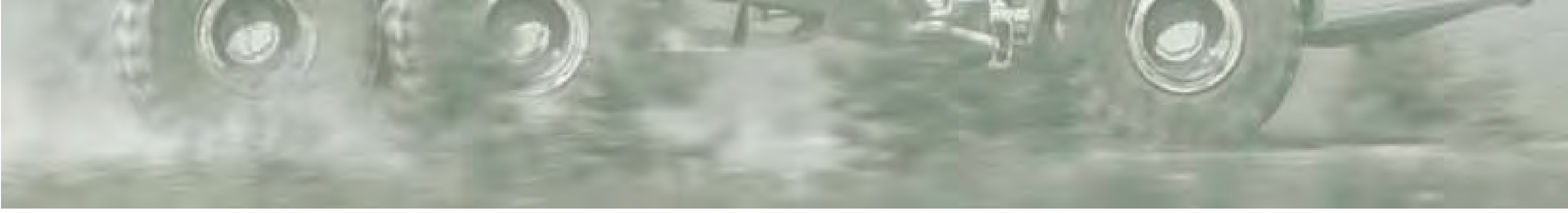
Let us assume (in this worked example) that the gradient is 1 in 12 (i.e. 8.3 per cent). The gradient is quite long and the road is good, so the manager's preferred permissible operating speed limit for the gradient is 25kph. But there is a bend at the bottom of the gradient, and the ability to stop in a reasonably short distance, say 15 to 20m, would reduce the risk of overrunning and collision.

After deducting 4m from this stopping distance for distance travelled during the driver's reaction time (refer to *Cautionary Note 3*), then the amount of brake ratio needed just for slowing down and stopping at 25kph (refer to Table 1 and Figure 1 detailing braking distances at different speeds for varying brake ratios) would be 20 per cent, (i.e. 12.32m being closest fit for 15 to 20m less 4m).

The minimum brake ratio considered necessary for safe travel of a fully laden vehicle down the gradient is therefore (20 + 8.3 =) 28.3 per cent which is conveniently rounded up to 29 per cent.

Cautionary Note 5

Skidding negates this analysis, because the stopping distance would be so much longer. Similarly, overloading needs to be controlled, otherwise the retardation will be reduced and once again the stopping distance would be so much longer.



Step 3: Determine Pass/Fail Criteria

A pass/fail criterion exactly equal to the total brake ratio just determined in *Step 2* makes no allowance for acceptable brake deterioration between tests, for example, as a result of permitted lining wear. Consequently, the brake ratio just determined in *Step 2* should be increased by say 10 per cent of its value, so in the example, the required operating brake ratio becomes 32 per cent. This is the value that testers should regard as the minimum pass figure for this vehicle under the conditions of use described.

Usually, a series of three brake tests is carried out and in each case the result should exceed this minimum pass figure. The results may differ for reasons described in the section *'Repeatability of Results'*.

Step 4: Identify Deteriorating Trends

The value determined in *Step 3* is a peak value (32 per cent). It is less than the design brake ratio determined in *Step 1* (38 per cent), which is a plateau level (see *Using Peaks and Plateau Levels*). If a plateau level is reached, results are repeatable. A comparison of plateau level results from one test to another will allow a deteriorating trend in brake performance to be monitored.

In addition, if brake test conditions allow plateau levels to be developed, a more accurate and hence more reliable pass/fail criterion than the minimum can be determined. By applying the same practical tolerance as in *Step 3*, then we may assume that the design brake ratio (which is the plateau level) determined in *Step 1* (38 per cent), may fall off by up to say 10 per cent[5] of its value, i.e. to 34 per cent, before concern is raised.

This (34 per cent value) exceeds the minimum pass figure of 32 per cent determined in *Step 2* and so it may not be immediately unsafe to operate the vehicle, but, here we are saying that nevertheless the vehicle should be taken out of service for investigation if brake ratio does fall below 34 per cent, because the deterioration of the brakes is the concerning factor.

Cautionary Note 6

If the minimum pass/fail criterion in *Step 3* is very low compared to the design brake ratio in *Step 1*, for example 15 per cent compared to 40 per cent, then a large fall-off in brake performance could result before concern was raised. In this case, testing in line with *Step 4* is more reliable.

Step 5: Check Delay Time

Finally, the brake delay time, i.e. the time taken from 'hitting the pedal' to the start of braking, should be checked. This is often printed out numerically by the brake test instrument in the list of results. It is important to remember that the brake ratio is measured after the start of braking and any delay in brake application would not be recognised. However, any delay in brake application could significantly increase the stopping distance, even though the brake ratio shows the brakes are performing effectively.

[5] The 10 per cent margin described in Steps 3 and 4 is arbitrary, and should be determined by a competent person.

To Summarise (for this example)

1. Design brake ratio = 38 per cent;
2. Maximum gradient 1 in 12, so brake ratio for slope = 8.3 per cent; permitted speed of 25kph, so brake ratio for stopping in 15 to 20m (with driver delay allowance of 4m) = 20 per cent; rounding up, total brake ratio required = 29 per cent;
3. Allowing for some deterioration (add 10 per cent to last), minimum test brake ratio for safe operation = 32 per cent;
4. The best pass / fail criterion is determined from plateau level testing and comparing this with the design value, i.e. plateau value results should be between 34 and 38 per cent (i.e. design value less a practical tolerance); if it drops below 34 per cent it fails; and
5. Check the brake delay time.

Repeat steps 1 to 5 for any other brake, e.g. secondary (or emergency) brake, that is to be tested dynamically.

Recording Test Results

Figure 4 shows an example of a brake assessment form, recording commissioning information against which future test results will be compared. The results of all periodic brake tests must be recorded and the report trail should be auditable. It will also be useful to record the trends, e.g. a comparison of results over a period of time. Software is available to record test information and trends for individual vehicles using PCs.

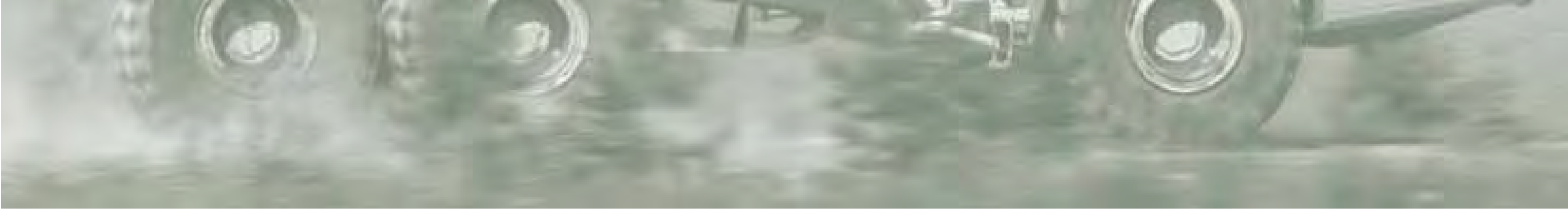


Figure 4. Specimen brake test assessment record form

PAGE 1 OF 2 – SITE / VEHICLE DATA AND BRAKE TEST DETAILS

Workplace: *Bloggs Quarry*

Vehicle Data

Vehicle type: *Catex 123*

Unladen weight (w): *30.73 Tonnes*

Maximum load (L): *36.5 Tonnes*

Gross weight (W): 67.23 Tonnes

Laden / unladen ratio (W/w): 2.19

Design brake ratio: *38.4%*

Site Data

Maximum gradient: *8.3%*

Permitted max. speed: *25kph*

Required retardation (service): *20%*

Required retardation (secondary): *10%*

Minimum required brake ratio (laden): *32%*

Service Brake

Test description: *35kph, laden, 10% downgrade, will cause plateau level braking*

Comments: *Test with dry road conditions only, on specified safe test site*

Test frequency: *1-monthly*

Pass/fail criterion: *34%*

Secondary Brake

Test description: *35kph, laden, 10% downgrade, will cause plateau level braking*

Comments: *Test with dry road conditions only, on specified safe test site*

Test frequency: *3-monthly*

Pass/fail criterion: *25%*

Additional Tests

Description: *A check of accumulator pre-charge should be carried out and recorded 6-monthly*

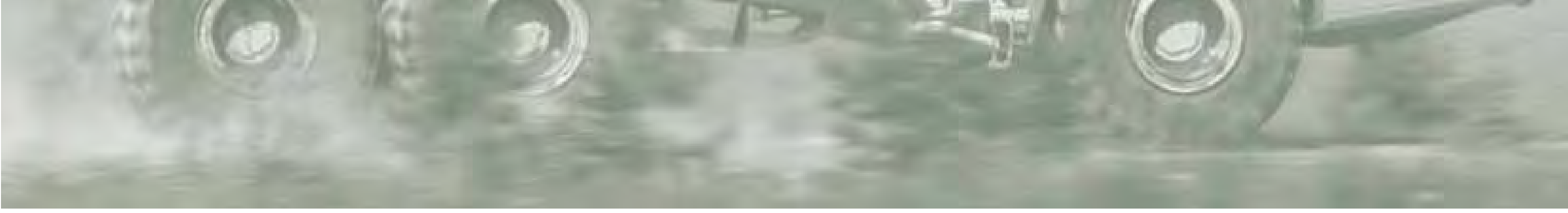
Manager's name: ______________________ Signature: ____________________________

Date: ________________________________

PAGE 2 OF 2 – BRAKING TRENDS

Test results		Test details		
Service brakes	***Emergency brakes***	***Tester name***	***Signature***	***Date of test***
38		S. I. Time	S. I. Time	8 Jan 2007
39	29	S. I. Time	S. I. Time	5 Feb 2007
38		S. I. Time	S. I. Time	5 Mar 2007
37		S. I. Time	S. I. Time	2 Apr 2007
33*	27	S. I. Time	S. I. Time	7 May 2007
38		S. I. Time	S. I. Time	4 Jun 2007

*Brakes adjusted and retested giving 38%



Further Information

Health and Safety at Quarries. Quarries Regulations 1999. Approved Code of Practice. London: HSE Books. ISBN: 0-7176-2458-7.

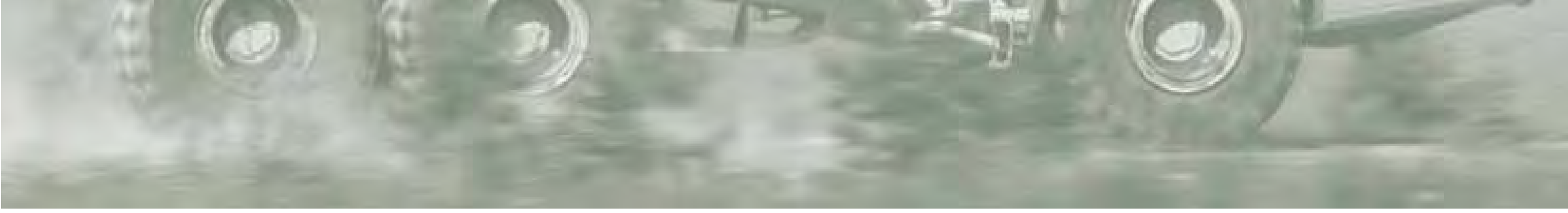
Simple Guide to The Provision and Use of Work Equipment Regulations 1998. The Health and Safety Executive, document ref: INDG 291. ISBN: 0-7176-2429-3.

The Health and Safety at Work Etc. Act (1974). London: HMSO. ISBN 0-1054-3774-3.

The Provision and Use of Work Equipment Regulations (1998). Statutory Instrument No. 2306. Accessible on the Office of Public Sector Information website at: www.opsi.gov.uk/ (viewed February 2007).

The Quarries Regulations (1999). Statutory Instrument 1999 No. 2024. Accessible on the Office of Public Sector Information website at: www.opsi.gov.uk/ (viewed February 2007).

Various other information on the safe operation of plant and equipment is available on the website of the *Off-highway Plant and Equipment Research Centre* (OPERC). See: www.operc.com.



Appendix A

The Quarries National Joint Advisory Committee (Working Group attendees and visitors)

Attendee	Company	Attendance		
		25/4/06	7/4/06	5/9/06
Martin Holyoak	HSE Mines Inspectorate	•	•	•
Roy Bush	HSE Quarries Inspectorate	•	•	•
Graham Crawshaw	EPIC Training and Consulting Services	•	•	•
Barry Robinson	OPERC		•	•
David Edwards	OPERC			•
Chuck Crowell	Caterpillar USA			•
David Wootton	Caterpillar UK			•
Dan Roley	Caterpillar USA			•
Par-Olaf Gaard	Volvo Sweden			•
Martyn Brawn	Volvo UK			•
George Ferguson	Aggregate Industries UK	•	•	•
Richard Bland	HJ Banks Mining	•	•	•
Graham Chissel	Walters Group	•	•	•
Steff Madin	UK Coal	•	•	•
Kevin Shaw	UK Coal	•	•	
Geraint Morris	Lafarge Aggregates		•	
Martin Yorke	Midland Quarry Products	•		
Manocher Salek	Scottish Coal			•
Bill Bailey	Foster Yeoman	•		•
Rory Graham	Foster Yeoman		•	

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