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Brake testing: what faults can be found?

An investigation of the ability of various brake testing methods to detect mechanical or hydraulic brake faults on light vehicles

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ABSTRACT

Brakes can be considered the most important safety feature on a vehicle and must be maintained to ensure optimal performance. Brake testing machines provide a rapid method of investigating the performance of a vehicle's brakes and assessing whether they meet roadworthiness criteria. However, it is important for vehicle owners and roads authorities to understand the differences between brake testing methods, their advantages, their limitations, and to have confidence in the results they provide. This study presents an investigation of the ability of four brake testing methods to detect mechanical or hydraulic faults on light vehicles. A test vehicle, representative of a common passenger vehicle, was professionally fitted with equipment to enable the control and measurement of the brake pressure applied to individual wheels. A brake pedal robot that could supply a repeatable and consistent brake application force was also installed. Data was collected during a series of tests performed over two days at a private airstrip. In each test, a brake fault condition in the test vehicle was simulated by reducing the maximum brake pressures at individual wheels. The vehicle was then tested three times with a plate brake tester, a roller brake tester, a portable decelerometer, and during a high-speed stopping distance test (from 80 km/h).

KEYWORDS

Brake testing; Roller brake tester; Plate brake tester; Decelerometer; Brake fault; Brake testing; Stopping distance; SafeTstop

Summary

The objective of this study was to investigate the ability of four brake testing methods to recognise mechanical or hydraulic brake faults on light vehicles. Brakes can be considered the most important safety feature on a vehicle and must be maintained to ensure optimal performance. Even for modern vehicles with advanced electronic systems, the mechanical operation of brakes has changed little over the last decades. That is, a pair of friction pads mounted to calipers, and activated through a hydraulic system, which clamp onto a rotor attached to the wheels of the vehicle. A mechanical or hydraulic fault is unlikely to be identified by an electronic system and, as such, brake testing today is just as relevant as ever.

Brake testing machines provide a rapid method of investigating the performance of a vehicle's brakes and measuring them against roadworthiness criteria. However, it is important for vehicle owners and roads authorities to understand the differences between brake testing methods, their advantages and their limitations. It is also vital that all those involved are able to understand and interpret results, and to have confidence in them.

A test vehicle, representative of a common passenger vehicle, was professionally fitted with equipment enabling the control and measurement of the brake pressure applied to individual wheels. A brake pedal robot that could supply a repeatable and consistent brake application force was also installed. Four examples of commonly used brake testing equipment were acquired for the study:

- A SafeTstop plate brake tester,
- A Vehicle Inspection Systems roller brake tester,
- A Circuitlink Brake-Testa portable decelerometer, and
- A Racelogic Vbox 3iSL GPS data logger for use in high-speed stopping distance tests.

Data was collected during a series of test sets performed over two days at a private airstrip. In each test set, a brake fault condition in the test vehicle was simulated by adjusting the maximum brake pressures at individual wheels. The vehicle was then tested three times with each piece of brake testing equipment.

The implemented brake fault conditions all resulted in an increase to the test vehicle's stopping distance. The largest increase in stopping distance was over 75%, equating to an extra 20 metres for a vehicle travelling at 80 km/h.

During each of the brake fault conditions, the reported deceleration values from each of the brake testing methods were investigated and compared to the reported baseline deceleration (no brake fault). Despite differences in reported baseline decelerations, the results of all the testing methods were affected in similar ways with respect to the severity of the implemented brake fault conditions.

Both the plate brake tester and the roller brake tester were able to report left to right imbalance in brake forces. Additionally, the plate brake tester was able to provide a measurement of front to rear brake force balance.

The minimum brake performance criteria from the NSW Authorised Inspection Scheme were used to explore how the results from each brake testing method would have been assessed. Similar brake performance criteria are also used in New Zealand and most other Australian jurisdictions. Alarmingly, there were instances where severe brake faults would have passed the brake performance criteria. These included faults where both rear brakes were completely disabled, both front brakes were limited to 66% of maximum brake pressure, and both front brakes were limited to 54% of maximum brake

pressure, leading to increases in stopping distances of 30.0%, 45.8%, and 73.5% respectively. Based on the results of this study, it is suggested that a review of brake performance criteria is warranted.

The results reported by each of the brake testing methods were reviewed individually, and their ability to detect mechanical or hydraulic faults was summarised.

The high-speed stopping distance test reported the highest level of deceleration and the largest change in deceleration over the set of brake fault conditions tested. As such, this testing method was considered to have the best ability to measure deceleration. However, a measure of deceleration (in isolation) is not sufficient to detect faulty brakes, unless a vehicle’s stopping power was severely compromised. In addition, the testing method is unable to detect any kind of imbalance in a vehicle’s brakes. This means that faults which affect just a single wheel would not be identified.

The plate brake tester measures brake forces at each individual wheel and offered the most information about the performance of the test vehicle’s brakes, including peak and average deceleration, left to right brake force imbalance, and front to rear brake force balance. During this study, the plate brake tester reported results that were consistent with all the adjustments to brake pressure implemented. As such, the plate brake tester was considered to offer the most comprehensive report on a vehicle’s brakes and identified brake faults that reduced stopping power as well as left to right imbalance on either axle. By measuring the front to rear brake force balance, the plate brake tester identified when the rear brakes were severely compromised, but the vehicle still provided a relatively high overall deceleration.

The roller brake tester was able to report on peak deceleration and the left to right brake force imbalance on the front and rear axle. The results reported by the roller brake tester were inconsistent with those of the other brake testing methods as well as the implemented brake fault conditions. The peak deceleration measurements reported by the roller brake tester were consistently low. The reported peak deceleration values were reduced for fault conditions that affected the rear wheels, but not conditions that affected the front wheels. Similarly, the roller brake tester was able to accurately identify left to right brake force imbalance on the rear axle, but not for the front axle.

The decelerometer produced results that were comparable to the high-speed stopping distance test. As such, the decelerometer was considered capable of providing a reasonable understanding of a vehicle’s deceleration. This was not sufficient to identify faulty brakes, apart from situations where a vehicle’s stopping power was severely compromised. Additionally, the decelerometer was not able to measure left to right brake force imbalance and would therefore be unable to identify faults affecting individual wheels.

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1 Introduction

The ability of a vehicle to brake effectively in an emergency situation is crucial for the safety of the occupants and other road users. Indeed, brakes could be considered the most important crash avoidance system on a motor vehicle. Small reductions in brake performance can lead to large changes in impact speed, and increased risk of serious injury or death.

The brakes on modern vehicles feature numerous advanced electronic systems that assist with the braking task by monitoring, boosting, or regulating the brake forces. However, the mechanism that generates the braking force remains essentially the same as it was several decades ago; a pair of friction pads mounted to calipers, and activated through a hydraulic system, which clamp onto a rotor attached to the wheels of the vehicle. A mechanical or hydraulic fault is unlikely to be identified by an electronic system and, as such, brake testing today is just as relevant as ever.

At market introduction, the performance of vehicle braking systems are regulated in Australia though Australian Design Rule (ADR) 31. This standard prescribes minimum braking performance for passenger cars and assesses this by measuring the stopping distance in relation to the initial speed of the vehicle, or by measuring the average deceleration over the stopping distance, in a suite of tests.

Once a vehicle has been purchased, it becomes the owner's responsibility to ensure the brakes are operating to an adequate standard. This requires regular maintenance during which components, like worn brake pads, will be replaced. However, while maintenance will keep a brake system performing well, many common mechanical and hydraulic brake faults can reduce the braking efficiency of a vehicle. These faults can result in conditions such as under braking, brake drag, brake pull, brake grab and over braking, or brake shudder. These can range from mild and unnoticeable, to severe, where braking is severely compromised. Faults can develop over time and may be imperceptible to a driver.

To screen for faults, it is common for brakes to be inspected on a regular basis (often at the same time as other maintenance is being performed). In some Australian jurisdictions, and in New Zealand, the details and regularity of light vehicle inspections are mandated by law. Other jurisdictions allow vehicle owners to determine their own safety inspection schedule, but do conduct audits to review compliance with safety criteria.

While manual mechanical investigations still occur, it is common for brakes to be inspected using specialised brake testing equipment. This equipment quantifies brake performance rapidly without any requirement for labour intensive component disassembly and visual inspection. There is an expectation from vehicle owners and authorities that brake testing will detect deficient brakes and identify mechanical or hydraulic faults.

The objective of this study was to investigate the ability of various brake testing methods to identify mechanical and hydraulic faults on light vehicles. Furthermore, the study sought to explore the appropriateness of the brake performance criteria for roadworthiness in Australian and New Zealand.

In Section 2 a review of literature on relevant background topics is presented, including the prevalence of brake faults in the general fleet and their effects on safety, the effectiveness of vehicle inspection schemes, and a review of brake testing equipment. Then, Section 3 describes the methodology of the current study exploring how well four brake testing methods can detect faults in a vehicle's braking system. This is followed by a presentation of the results from each brake testing method in Section 4, and an exploration of these results against the NSW roadworthiness criteria in Section 5. A discussion of the study outcomes is provided in Section 6.

2 Background

This section provides some background on the topics relevant to this study. A brief literature review was conducted to assist with informing this background discussion. The focus of this literature review was light vehicles, but heavy vehicle literature was also reviewed where relevant. It was notable that there was generally only a small amount of published literature regarding the topics below. Furthermore, the literature that was found tended to have been published several decades ago. Significant advancements in vehicle systems and brake testing equipment (including improved computational power and diagnostics) are likely to have occurred in the intervening years, which may mean some of the findings are outdated.

2.1 Prevalence of brake faults in the general fleet and their effect on safety

Obtaining accurate and detailed data on the prevalence of vehicle defects in the general vehicle fleet is notoriously difficult. The most available data comes from crash incident reports submitted by traffic police. Based on this type of data, the prevalence of vehicle defects noted as the cause of a collision is consistently reported to be around 2 – 3% (Vaughan, 1993; Keatsdale, 1999; van Schoor et al., 2001; Das et al., 2019a).

Of these police-reported vehicle defects, issues with tyres and brakes were by far the most common. Das et al. (2019a) explored a national vehicle defects database in the US, along with police reported defect data for crashes that occurred in Louisiana. The most commonly reported defects were brakes, tyre failure, worn tyres, defective suspension, and engine failure. Similarly, van Schoor et al. (2001), who investigated crash data from South Africa, found that a large proportion of vehicle defects were noted to be underperforming brake systems.

It could be argued that the relatively small proportion of police-reported vehicle defects indicates that the issue is fairly minor, and more attention should be paid to other road safety issues. However, Vaughan (1993) points out that there is evidence to show that there is a tendency for vehicle faults to be under-reported, depending on the stringency of investigation. When crash causation factors are investigated to a high level, by experts in assessing vehicle condition, the proportion that involve some kind of vehicle fault can be as high as 18%. Furthermore, the faults reported by more thorough investigations are more complex than the easily identifiable faults noted in more basic investigations, such as tyre tread depth.

Indeed, van Schoor et al. (2001) conducted a random roadside mechanical assessment survey of light vehicles and found that over 10% had brake system issues related to inadequate brake fluid or leaks in the brake lines. This was despite not being able to comprehensively assess the brake systems of the selected vehicles due to time constraints. Although, it was acknowledged that South Africa has a second-hand car market that is larger than most developed countries and that the country's economic situation results in many vehicle owners conducing their own maintenance, or disregarding maintenance completely, to save money.

A rather comprehensive review of the prevalence of vehicle defects in Australia was commissioned by the Federal Office of Road Safety and conducted by Keatsdale (1999). Data was collated from most Australian states and territories, then combined to estimate a national average. While making a number of assumptions to account for unknown effects and under-reporting, it was estimated that the national average proportion of crashes caused by vehicle defects was somewhere between 2.3% and 7.7%.

Keatsdale (1999) also conducted a review of reports from several Australian state and territory vehicle inspection authorities. After again making some adjustments for assumptions about unknown effects, it was estimated that somewhere between 20 and 40 percent of the general Australian vehicle fleet may have some kind of defect.

2.2 Periodic vehicle inspection schemes

Vehicle inspection schemes are predicated on the theory that the review of a vehicle's condition by an expert will reduce the likelihood of a fault occurring that leads to (or contributes to) a crash. The assumption is that the probability of a fault-induced crash will be lowest immediately after an inspection but then increase over time, leading to a requirement for inspections to be repeated periodically to maintain effectiveness.

There is evidence that periodic inspections improve the mechanical condition of vehicles and lead to the identification of faults. Freund et al. (2002) reviewed the effectiveness of heavy vehicle inspections in the US and found that, over time, there had been a clear reduction in heavy vehicle brake fault detection as a result of regular inspections. Similarly, Keall and Newstead (2013) found that an increase in the regularity of a periodic inspection scheme from 12-monthly to 6-monthly would be likely to result in a 13.5% reduction in the prevalence of safety-related faults.

Despite the noted improvement in vehicle condition, there is some contradiction regarding the effectiveness of vehicle inspection schemes in preventing crashes within the literature. Das et al. (2019b) compared consumer complaints data regarding vehicle defects for states with and without a periodic inspection scheme in the US. Their analysis concluded that there was some indication that states with an inspection scheme would receive less complaints. However, this finding could not be correlated with fatal crash data from the same states.

A comparison of the crash rate in New Zealand for vehicles that had an up to date inspection record with vehicles that did not have a current inspection record was carried out by Blows et al. (2003). After accounting for a number of potentially confounding factors, such as driver age and average hours of weekly driving, it was found that vehicles without an up to date inspection record were more likely to be involved in an injury crash.

Conversely, a study by Fosser (1991) found no effect from a periodic inspection scheme in Norway. The study consisted of dividing a pool of 204,000 vehicles into three groups. One group had 46,000 vehicles that were inspected annually over three years, another group had 46,000 vehicles that were inspected only in the first year of a three year period, and the final group had 112,000 vehicles that were never inspected. The crash rates of the vehicles in each of the three groups was investigated over the three-year period and no significant difference was found.

Schroer & Peyton (1978) explored the crash rate of vehicles that did and did not participate in a voluntary inspection scheme in the US state of Alabama. It was found that vehicles which did participate had a crash rate that was 9.1% lower than vehicles that did not participate. However, the applicability of this finding to the present-day is questionable given the age of the study.

Another older study from New Zealand by White (1986) investigated the frequency of defect-related crashes in relation to the time since a vehicle was last inspected. It was found that the crash rate did increase slightly over time since the last inspection. However, it was also found that the defect-related crash rate was high even in the first weeks after an inspection. This was suggested to be an indication that the inspection process may not be able to capture all relevant faults and/or that the role of defects as a crash-related factors is over-represented.

A further aspect to consider when reviewing periodic vehicle inspection schemes is the cost. Even if a periodic inspection scheme is assumed to be effective in preventing crashes there are significant costs involved in the operation and studies usually do not find them to be cost effective. For example, Keall and Newstead (2013) investigated the expected impact of increasing the frequency of periodic vehicle inspections in New Zealand from every 12 months to every 6 months and found that, while crashes may be reduced by around 8%, the costs in fees and regulation would far outweigh the benefits.

Similarly, the Australian Federal Office of Road Safety commissioned study into periodic vehicle inspections by Keatsdale (1999) conducted an analysis that indicated the benefit-cost ratio of a national scheme would be between 0.22 and 0.38. However, despite this finding, it was acknowledged that a vehicle inspection capability and random screening process should be maintained across the states and territories.

In the context of the above, most jurisdictions in Australia and New Zealand provide criteria for brake performance. Police and other authorities have the power to require owners to have their vehicle assessed if they have some suspicion of a fault. Some jurisdictions require all vehicles to undergo a safety inspection on a regular basis or when there is a transfer of ownership.

The brake performance criteria for each jurisdiction was obtained by reviewing the relevant sections of government websites. These criteria are presented in Table 2.1 below. All jurisdictions also list other less quantitative criteria that must be met (e.g. that the vehicle does not vibrate or swerve while braking) and sometimes require a visual inspection to confirm the condition of elements such as brake pads, brake lines, and calipers.

An in-depth investigation of the rationale for the criteria in each jurisdiction was beyond the scope of this study but it is clear that some common levels of minimum performance have been identified and adopted.

Table 2.1
Performance criteria for light vehicle brakes in Australia and New Zealand

Jurisdiction	Minimum peak deceleration required	Minimum average deceleration required	Maximum left to right imbalance allowable
Australia			
ACT	60% g	39% g	30%
NSW	60% g	47% g	30%
NT	60% g	39% g	30%
QLD	60% g	39% g	-
SA	60% g	39% g	-
VIC	60% g	-	30%
New Zealand	-	50% g	20%

2.3 Brake testing methods

There are several methods, utilising various pieces of equipment or technology, that have been developed to assess brake performance on light vehicles. The usefulness of these methods depends on their accuracy, the ease with which an assessment can be performed, the time required to perform an assessment, the safety of the assessment (e.g. any requirement for the test vehicle to be moving at various speeds), and the ease of interpretation of the results that are produced.

As described above, brake inspection schemes exist in many jurisdictions around Australia and internationally – both for heavy vehicles and light vehicles. These brake inspection schemes each specify approved brake testing methods that can be utilised during the inspection. In most cases, there are four commonly accepted brake testing methods:

- Plate brake testing machine,
- Roller brake testing machine,
- Portable brake testing decelerometer, and a
- High-speed stopping distance test.

Each of these brake testing methods are described in further detail below.

In addition to these generally approved brake testing methods, others also exist. These include 'torque testers' and thermal diagnosis of heat generation during braking. A torque tester consists of a mechanism which grips a wheel between two friction pads and, with the vehicle's brakes applied, applies a torque while measuring the force required to rotate the wheel. An evaluation of a torque tester for the testing of heavy vehicle brakes, described by Flick (1996), found that it was reasonably accurate and able to identify significant faults. However, it is assumed that the torque tester method was not embraced extensively by the industry, possibly due to the complexity of the mechanism and the time requirement to conduct an assessment one wheel at a time.

A method of measuring braking force by monitoring the heat build-up during brake application was described by Segal (1999). An experiment to investigate the ability of this heat generation diagnosis method found that it was able to successfully predict brake forces. However, it was not clear how this predictive capability would be affected by brake faults and no further literature was found regarding the thermal diagnosis method.

2.3.1 Plate brake testing machine

A plate brake testing machine (plate brake tester) consists of one or two pairs of plates that are arranged in line with the wheels of the vehicle path, either as an above ground installation or seated flush with the floor surface. All plates are instrumented with load cells that measure forces in the direction of travel. Weight scales, just prior to the brake test plates, are sometimes also utilised to measure the vertical force (mass) of a vehicle during a test. Alternatively, the mass of a vehicle can be manually entered into the test machine by an operator.

As a vehicle is driven onto the plates at low speed (around walking pace), the brakes are applied rapidly and firmly, and the load cells quantify the individual brake forces at each of the four wheels. Importantly, this process occurs dynamically, as it would on the road, and measures the brake forces while accounting for the forward pitch (and weight shift) of the vehicle. For a light vehicle an experienced operator can perform a brake test in less than 10 seconds.

Using the measured brake forces and vehicle mass, a plate brake tester can provide results regarding the overall capability of a vehicle's braking system (i.e. deceleration), the imbalance between the left and right wheels of each axle, and the front to rear brake force balance.

An early evaluation of the suitability of a plate brake tester to assess brakes during inspections of heavy vehicles in the US was performed by Flick (1995). The results provided by the plate brake tester during a series of assessments of two heavy vehicles, that were affected by various levels of brake deficiencies (achieved by altering the heavy vehicle's brake slack adjuster to inappropriate positions), were compared to the results of an in-ground roller brake tester. The study observed that, while there was a slightly greater variability in the plate brake tester results, there was reasonable agreement between the results of the two brake testing methods. The plate brake tester was also said to be able to successfully detect deficiencies in the brake system, provided the applied braking pressure was sufficient. A further analysis compared the results reported by the plate brake tester to stopping distance from an initial speed of 60 mph. Compared to the correctly adjusted brake condition, the study concluded there was generally good agreement between the change in stopping distance and the change in deceleration reported by the plate brake tester for each of the various levels of deficiency in the brakes. Finally, the ability of the plate brake tester to detect imbalance between the brake forces generated by the left and right wheels of a single axle was investigated by instigating a deficiency to just one wheel. The plate brake tester was found to be capable of detecting this type of situation, again provided the braking input was sufficient, and it was noted by Flick (1995) that a 30% imbalance was a suitable threshold for the identification of an issue.

In summary, Flick (1995) concluded that the plate brake tester was able to provide a quick assessment of heavy vehicle brake performance and enable the rapid screening of a great number of vehicles. It was noted that some minor brake faults may not be detected, but severe faults (which are the most likely to result in dangerous situations) could be identified readily.

Another brief investigation into the capability of plate brake testers to assess heavy vehicles during inspections in the US was performed by Hodgson et al. (2005). They found that the plate brake tester had the capability to determine the weight and brake forces generated by each individual wheel during a single pass. Through this capability, the plate brake tester was able to highlight individual wheels that may be underperforming and require further, more thorough, investigation.

An assessment of the accuracy of the results produced by a plate brake tester for testing with heavy vehicles was performed by Shaffer and Loy (2005). Various calibrated masses and forces were applied to the plate brake tester and compared to the reported results. The study found that the plate brake tester had a good level of accuracy with a maximum error of only 0.93%.

No literature could be found which investigated the use of plate brake testers in the analysis of light vehicle braking systems.

2.3.2 Roller brake testing machine

A roller brake testing machine (roller brake tester), sometimes referred to as a roller dynamometer, consists of a pair of high friction cylinders that are set some distance apart, such that the wheel of a vehicle can rest on top. Motors are used to rotate the roller cylinders at low speed, which then rotate the wheels of a vehicle's front or rear axle. Load cells within the roller brake tester are able to measure the weight of the vehicle's axle and the horizontal reaction force that is generated as the brakes are applied. Each axle of the vehicle is measured separately, and the results are combined to provide an overall assessment of braking performance. For a light vehicle this test takes around 60 seconds per axle.

With the data collected during the test, the roller brake tester is able to provide a measure of a vehicle's deceleration and identify any imbalance between the left and right brake forces of each axle.

Shaffer and Loy (2005) explored the accuracy of a roller brake tester for use in assessing heavy vehicles by applying various calibrated weights and forces to the machine and analysing the reported results. They suggested the roller brake tester had a good accuracy, with a maximum error of 1.85%. The repeatability of the roller brake tester's results were also investigated by performing ten repeated brake tests on the same heavy vehicle. The variability in the test result was found to be 5.3%.

A study of roller brake testers in the assessment of light vehicles was performed by Orynycz et al. (2019). The goal of the study was to determine whether differences in tyre pressure and tyre wear had an effect on the roller brake tester results. As a part of this testing, a set of 15 baseline tests were performed while the vehicle was in optimal condition, with various time intervals between each test (either two minutes, four minutes, or six minutes). The overall variability in the results of the 15 tests was calculated to be 8%, but there was no indication that the period of time between each test affected the result. The main analysis consisted of conducting a series of tests while varying both tyre pressures using a worn tyre on one wheel and an optimal tyre on the other. This series of tests was repeated for two different vehicles, and with the vehicles loaded with additional mass and unloaded. Based on the results, Orynycz et al. (2019) concluded that none of the differences in tyre pressure, tyre wear, or vehicle mass had any significant effect on the brake efficiency reported by the roller brake tester.

In their concluding remarks Orynycz et al. (2019) suggested that the roller brake tester is more suited to evaluating the entire braking system of a vehicle as a whole, rather than individual tyres (wheels). This sentiment was supported by Li et al. (2011) who described the theory behind the operation of a roller brake tester and developed a mathematical model to explore what factors are important to obtaining a valid test result. Three main factors were described as important. First, it was shown that the geometry of the roller brake tester machine, including the diameter of the roller cylinders and the distance between them, define the maximum amount of brake force that the system is able to measure. In circumstances where a vehicle's brakes are able to generate a force beyond this maximum, the vehicle will be ejected from (lifted out of) the roller machine and the greater force will not be measured. The second factor described as important was the coefficient of friction between the roller brake tester and the wheels of the vehicle. If the friction cylinders of the roller become worn over time, then the capability of the machine to detect higher amounts of brake force was likely to be diminished. The final factor was the coefficient of friction between the untested wheels and the floor. The untested wheels contribute to preventing the tested wheels from being ejected, so a reduced friction force will result in a degraded ability to measure higher amounts of brake force. As such, the condition of the brakes on the untested axle, and their ability to generate a sufficient amount of friction with the floor, will contribute to the measured result for the axle under test.

Another study exploring the use of a roller brake tester with light vehicles was conducted by Firdaus et al. (2020). This study focussed on investigating how the results of the roller brake tester are affected by the type of brake pedal activation. Three types of brake application were applied during a series of roller brake tests (presumably with an optimally operating light vehicle); a rapid firm application, a gradually increasing application, and a sustained cyclical press and release application. The findings of the testing showed that the sudden application and the gradual application both resulted in the same amount of maximum brake force being measured. The press and release application resulted in a lower amount of maximum brake force being measured. No mention was made in the study of whether the brake application type affected the roller brake tester's ability to detect left to right force imbalance, or whether the findings were still relevant when testing a vehicle with a faulty braking system.

2.3.3 Portable brake testing decelerometer

A portable brake testing decelerometer (decelerometer) consists of a set of accelerometers within a battery powered device, that is placed into a vehicle being tested. Some decelerometers are mounted rigidly (with some kind of locking device), semi-rigidly (e.g. with suction caps to the windscreen), or simply placed in an appropriate location (like the passenger seat or footwell). The decelerometer is switched on and an initial calibration is performed while stationary. A test is then conducted by driving the test vehicle up to a specific speed (usually between 30-50 km/h) and then braking heavily to a stop. An area of flat bitumen is required where the test can be completed safely, away from other road users. Once within the safe area, the test takes approximately 30 seconds to complete.

The sensors within the decelerometer device measure and record the motion of the vehicle as it decelerates. Using these measurements, the decelerometer is able to report the peak and average deceleration achieved by the vehicle during the braking event. Because these measurements are taken during a real-world braking event the vehicle will pitch forward and the braking system will experience the effects of sustained heat/pressure build-up. These effects mean the results should have a strong correlation to what would be experienced in an emergency braking manoeuvre.

However, the decelerometer is unable to measure individual brake forces and will not detect any kind of left to right brake force imbalance or front to rear brake force balance. Furthermore, mild reductions in brake performance (particularly in the rear wheels) may not be identified.

A study by Luker (2008) provided an overview of how decelerometers operate and compared the performance of several devices. All the devices tested were able to measure deceleration to a reasonably good level of accuracy.

2.3.4 High-speed stopping distance test

A high-speed stopping distance test is considered to be one of the authoritative tests that certify the stopping ability of a braking system. The test involves bringing a vehicle up to a certain speed and applying the brakes at a certain level. The stopping distance is measured from the point the driver begins to apply the brake until the vehicle stops. Accelerometers inside the car (preferably mounted rigidly at the vehicle centre of mass) measure the deceleration of the braking event. This data can then be used to calculate the mean fully developed deceleration (d_m) according to the following formula:

$$d_m = \frac{v_b^2 - v_e^2}{25.92(s_e - s_b)}$$

Where:

v_o = initial vehicle speed in km/h,

v_b = vehicle speed at 0.8 v_o in km/h,

v_e = vehicle speed at 0.1 v_o in km/h,

s_b = distance travelled between v_o and v_b in metres,

s_e = distance travelled between v_o and v_e in metres.

As the test is conducted at high speed, more energy is dissipated during the braking event. This results in greater, and more sustained, heat/pressure build-up which can lead to conditions such as component expansion and brake fade. As such, the high-speed stopping distance test delivers a more comprehensive assessment that is representative of what would occur during a real-world emergency braking situation.

For these reasons, a high-speed stopping distance test is utilised within Australian Design Rule (ADR) 31, and equivalent regulations in Europe (UNECE R13-H) and the US (FMVSS 135), to assess the braking performance of new vehicle designs.

However, due to the requirement of a significant stretch of flat bitumen, that is free of other traffic, the test is prohibitive to perform unless a dedicated test track is available. Additionally, repeatability of results can be affected by variations in surface friction, wind, and drivers.

A study by Johnston et al. (1999) investigated the effect that various factors, such as drivers, vehicles, surfaces, and use of ABS had on stopping distances during high-speed tests (from 100 km/h). It was found that tests performed in the same conditions did provide relatively consistent stopping distance results, but there was a variability of approximately 8.9% in the stopping distances attributed to differences in driver's braking applications. Given the drivers in the study were professionals, with many years of experience, it would be expected that untrained drivers would display an even greater variability in results. A repeatable method of applying a specific braking force would therefore be advisable if a consistent result was desired.

3 Methodology

The objective of this study was to investigate the ability of various brake testing methods to detect mechanical or hydraulic brake faults on light vehicles. In order to achieve this, a test vehicle was fitted with equipment to enable the adjustment of the maximum brake pressure at each wheel. A brake pedal robot was then fitted into the vehicle to enable a specific and repeatable brake application. Several different brake faults were simulated by reducing the maximum brake pressure on various wheels of the test vehicle. For each fault condition the vehicle was tested using three common brake testing methods as well as undergoing a high-speed stopping distance test. Details regarding the various aspects of the study methodology are presented below. The methodology was reviewed by the National Measurement Institute (NMI) to ensure the independence and validity of the data that was collected.

While the methodology used in this study endeavours to implement a consistent braking application during each of the brake testing methods and the various brake fault conditions, there will always be differences. Each of the brake testing methods use different mechanisms or sensors to measure and compute a level of performance for different aspects of a vehicle's braking system. For example, the plate brake tester and roller brake tester do not "measure" a vehicle's deceleration directly but, rather, use formulas to calculate deceleration based on measurements of the braking forces generated by each wheel and the mass of the vehicle. Furthermore, the environment for each brake testing method is different and this will create inconsistencies. For example, the decelerometer will experience natural variations in the coefficient of friction along the test track, while the plate brake tester and roller brake tester generally exhibit a very consistent friction during all tests. Further sources of inconsistencies include temperature, wind, roadway surface undulations, or differences in signal filtering.

Every practicable effort was made to control for the factors that may produce inconsistences in the results. Nevertheless, some will inevitably remain and so the methodology in this study, as well as the analysis, will focus on exploring how well each brake testing method is able to detect faulty brakes individually, rather than directly comparing reported measurements between testing methods.

3.1 Test vehicle

The test vehicle used during the study was a 2011 Kia Cerato SLi hatchback (shown in Figure 3.1), representative of a common passenger vehicle. The test vehicle was supplied for use in the study by SafeTstop.

The Kia Cerato had an automatic transmission, all wheel disc brakes, a front-wheel-drive, and was equipped with antilock brakes (ABS), electronic stability control (ESC), emergency brake assist (EBA) and traction control.

The test vehicle was fitted with standard tyres and brakes, which were in good condition, and equipped with a cable-operated handbrake that was independent of the main braking system. A NRMA safety check prior to the study found it to be in a good, roadworthy condition (see Appendix A).

Figure 3.1
Test vehicle: 2011 Kia Cerato hatchback

3.2 Brake pressure adjustment and logging equipment

Prior to the study the test vehicle was professionally fitted with equipment to enable control of the brake pressure at each wheel. With this equipment installed it was possible to reduce the maximum brake pressure that was provided to individual wheels and simulate common mechanical or hydraulic brake fault conditions. Additionally, pressure sensors were fitted and connected to a logging system that recorded the brake pressure being applied at the brake of each wheel.

The layout of a typical light vehicle brake system, along with the arrangement of the pressure adjustment and logging equipment is shown in Figure 3.2. Force on the brake pedal pushes a piston in the brake master cylinder that results in fluid pressure being created in the brake line and the brakes being applied. The higher the pressure the higher the braking effort. Most modern vehicles utilise a vacuum assistance module (not shown in the diagram) between the pedal and the master cylinder to increase the force pushing on the piston in the master brake cylinder. Typically, the master cylinder will have two outputs: one to the front brakes and one to the rear brakes. If a vehicle is fitted with ABS (as is the case for the test vehicle) then the pressure created on the front and rear brake lines is directed through an ABS module. This module splits the front and rear pressure lines further to left and right wheels and can modulate the pressure going to each wheel based on information from the ABS computer modules.

For this study, pressure sensors were installed to measure the pressures being generated on the front and rear brake lines coming from the master cylinder, as well as the pressures being generated on the brake line to each individual wheel. Pressure reducing valves and cut-off valves were placed in the brake lines of each individual wheel, after the ABS module but before the pressure sensors. Flexible braided brake line (ADR approved) was used between the ABS module and the valve setup to allow the pressure reduction valves and cut-off valves to be accessible for adjustment during the study as shown in Figure 3.2. Details of the valves and sensors equipment that were used is provided below.

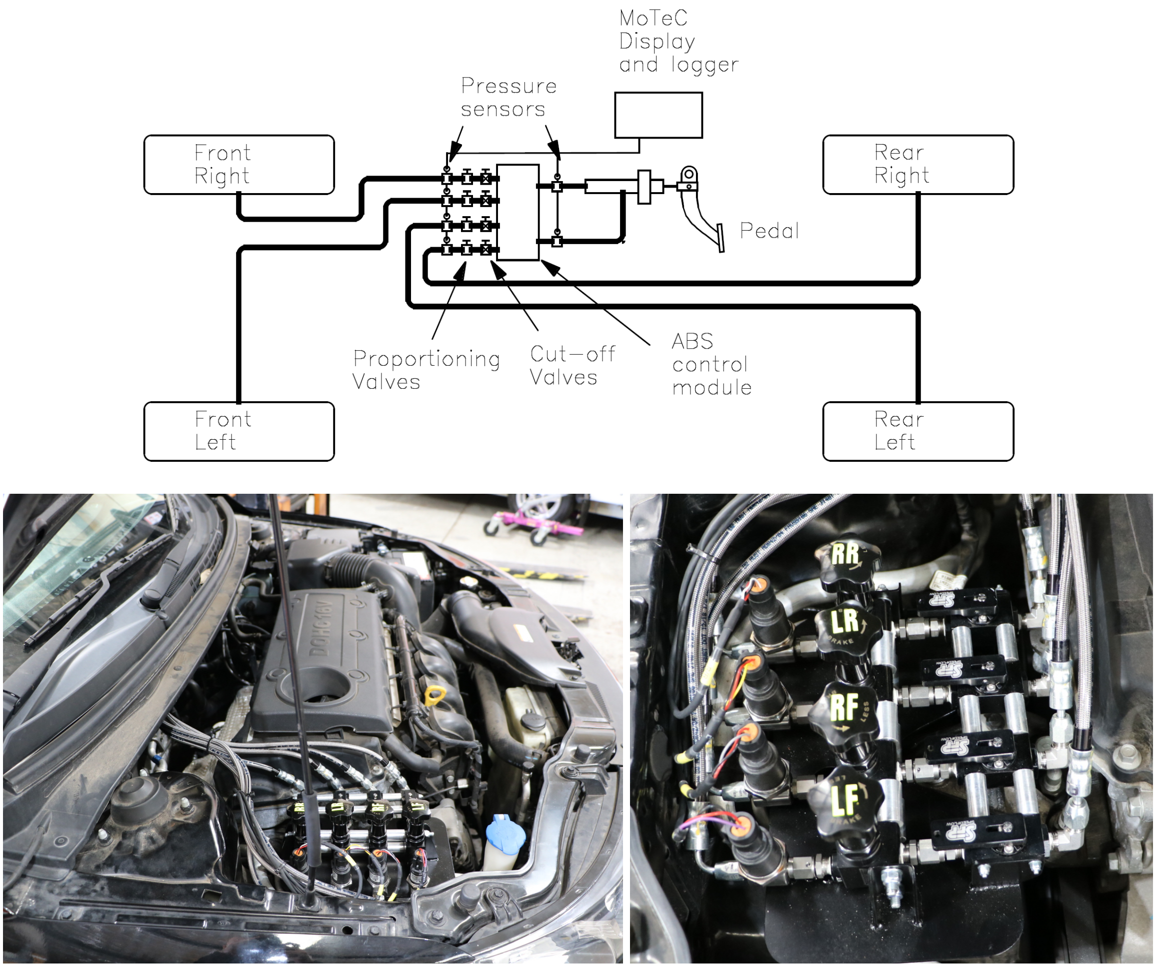


Figure 3.2
Brake system layout and arrangement of pressure sensors, pressure reduction valves, and cut-off valves

3.2.1 Pressure reduction valves

The pressure reduction valves (also known as brake proportioning valves) allow control over the maximum amount of pressure delivered to each wheel. The valves used in this study were Aeroflow Performance branded pressure reduction valves (part number AF64-3042). The brake pressure reductions were adjusted by rotating knobs on top of the pressure reduction valves. These could be rotated from zero (completely open, resulting in no pressure reduction) to a maximum of 12 turns which resulted in an approximate 50% reduction in the brake line pressure to the corresponding wheel. The graph in Figure 3.3 shows an example of the approximate relationship between the inlet and outlet pressures of the valve for the minimum (0 turns), middle (6 turns), and maximum (12 turns) settings.

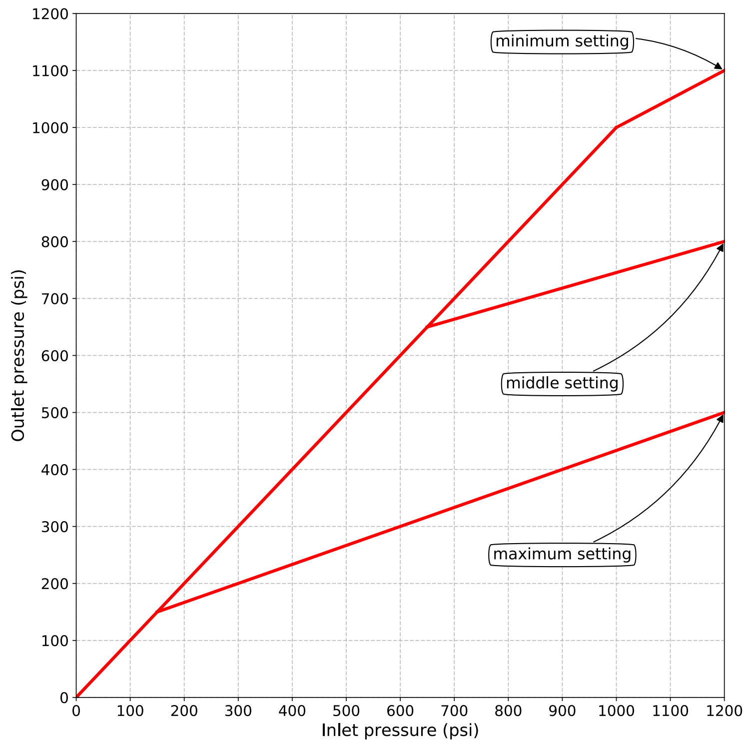


Figure 3.3
Example of inlet and outlet pressure relationship for pressure reduction valves

3.2.2 Cut-off valves

The cut-off valves allowed a brake line to be isolated from all pressure generated when applying the brake pedal. Speedflow branded cut-off valves were used (part number 650-02-BLK) which featured a lever on top that could be rotated 90 degrees to close the valve. The cut-off valves had two settings: fully open or fully closed.

3.2.3 Pressure sensors

Honeywell pressure sensors were used (part number H-PS2000G) to enable accurate pressure measurements of the brake lines up to 2,000 psi. The pressure sensors were connected to a MoTeC C125 data logger (see below) that was positioned in the cabin of the vehicle. Performance details about the pressure sensors can be found in Appendix B.

3.2.4 Data logger

Brake line pressure was logged continuously by a MoTeC C125 data logger at 100 Hz whenever the ignition was switched on. The MoTeC C125 included a screen to display data in real time which was mounted to the centre console of the test vehicle (see Figure 3.4). The pressure data for the front and rear brake lines between the master cylinder and ABS unit and the brake lines going to each individual wheel was recorded internally on the MoTeC C125 unit and downloaded at the end of each day of testing.

Figure 3.4
MoTeC C125 for displaying and logging the brake line pressures at each wheel

3.3 Brake pedal robot system

As found by Johnston et al. (1999), it was unlikely to be possible to deliver specific and repeatable brake applications via human operation. To ensure repeatable brake applications, a custom mountable braking robot was used to apply a specific force on the brake pedal of the test vehicle. The braking robot was attached to the driver seat-mounts for stability and allowed for manual override of braking at any time if required for safety. Photographs of the braking robot in the driver footwell, connected to a brake pedal, are shown in Figure 3.5. Also shown is the control interface used to tune the force applied by the robot as well as the brake robot triggering controller (attached to the steering wheel). A pushrod incorporating a load cell (to collect data on the force being applied) and a slip-joint (to allow for a manual braking override) connects the robot to the brake pedal via a rotating arm. The robot arm is rotated by a high-power brushless motor that is controlled by custom software which allows a specific brake application profile to be requested. A remote control is used to trigger the pre-programmed brake application.

During this study the brake robot was set to apply (and maintain) a constant force upon the brake pedal immediately when activated. The level of force applied by the robot was adjusted to a level at which the test vehicle's ABS was just being activated. This level was found during a series of brake tests on the test track. It was decided that there was little to gain by applying a higher force than that needed to activate ABS.

The load applied to the brake pedal was measured by a Dacell 1 kN load cell (model number UU-K100) integrated into the pushrod. The voltage measured by the load cell passed through an amplifier and recorded by the brake robot system. The load cell was appropriately calibrated by a NATA accredited laboratory (see Appendix C). Note that a separate pedal load sensor for the CircuitLink decelerometer (see Section 3.4.3) was also integrated into the pushrod, in-line with the Dacell load cell.

Figure 3.5
Brake pedal robot showing the pushrod connection to the brake pedal, the attachment point to the driver seat-mounts, as well as the control interface and triggering controller (attached to steering wheel)

3.4 Brake testing equipment

As noted above, three commonly used pieces of equipment are used to test for faulty brakes on light vehicles: plate brake testers, roller brake testers, and decelerometers. An example of each was obtained for use in this study. Additionally, the equipment required to accurately record the performance of the test vehicle during a high-speed stopping distance test was also obtained. The details of all testing equipment utilised are described below.

3.4.1 SafeTstop plate brake tester

A SafeTstop plate brake tester (shown in Figure 3.6) was supplied by SafeTstop and installed by the manufacturer, including the use of two Dynabolts to secure the system to the concrete floor. Calibration certificates for the plate brake tester can be found in Appendix D. The SafeTstop unit was a 4-plate system that uses high-sensitivity load cells in the plates that determine the braking force at each individual wheel during the braking process. An additional, separate pair of integrated weight scales measure the mass of a vehicle as a test is being conducted.

A test is conducted by driving a vehicle onto the plate brake tester at a speed of between 3-6 km/h, putting the vehicle into neutral gear, and then applying the brakes firmly when advised by the system. A secondary test is then conducted by driving forward slowly and applying the handbrake firmly when advised by the system.

Results are provided immediately on screen and saved onto the system for later retrieval if required. An immediate print-out of the results is also supplied. An example of the results from a test with the SafeTstop plate brake tester is shown in Figure 3.7. Note that in this test there was a fault at the front right wheel.

The results present the following details, along with graphs which display the measured brake forces over the duration of the test:

- Test and system details:
    - Photo proof to identify correct vehicle,
    - Date/ time,
    - Vehicle details,
    - Examiners number,
    - Inspection station number,
    - Next calibration due date,
    - Serial number, and
    - Adjustable PASS/FAIL criteria according to local roadworthiness requirements.
- Footbrake results:
    - Maximum brake force on each wheel in newtons,
    - Weight on each wheel in kilograms,
    - Difference of brake force on each axle in %,
    - Front to rear brake force difference in %,
    - Front versus rear brake force application in milliseconds,
    - Peak deceleration in %g,
    - Average deceleration in %g,
    - Brake pedal force in newtons, and
    - Vehicle test speed in kilometres per hour.
- Handbrake results:
    - Maximum brake force on each wheel in newtons,
    - Difference of brake force in %,
    - Peak deceleration in %g, and
    - Average deceleration in %g.

Figure 3.6
SafeTstop plate brake tester equipment

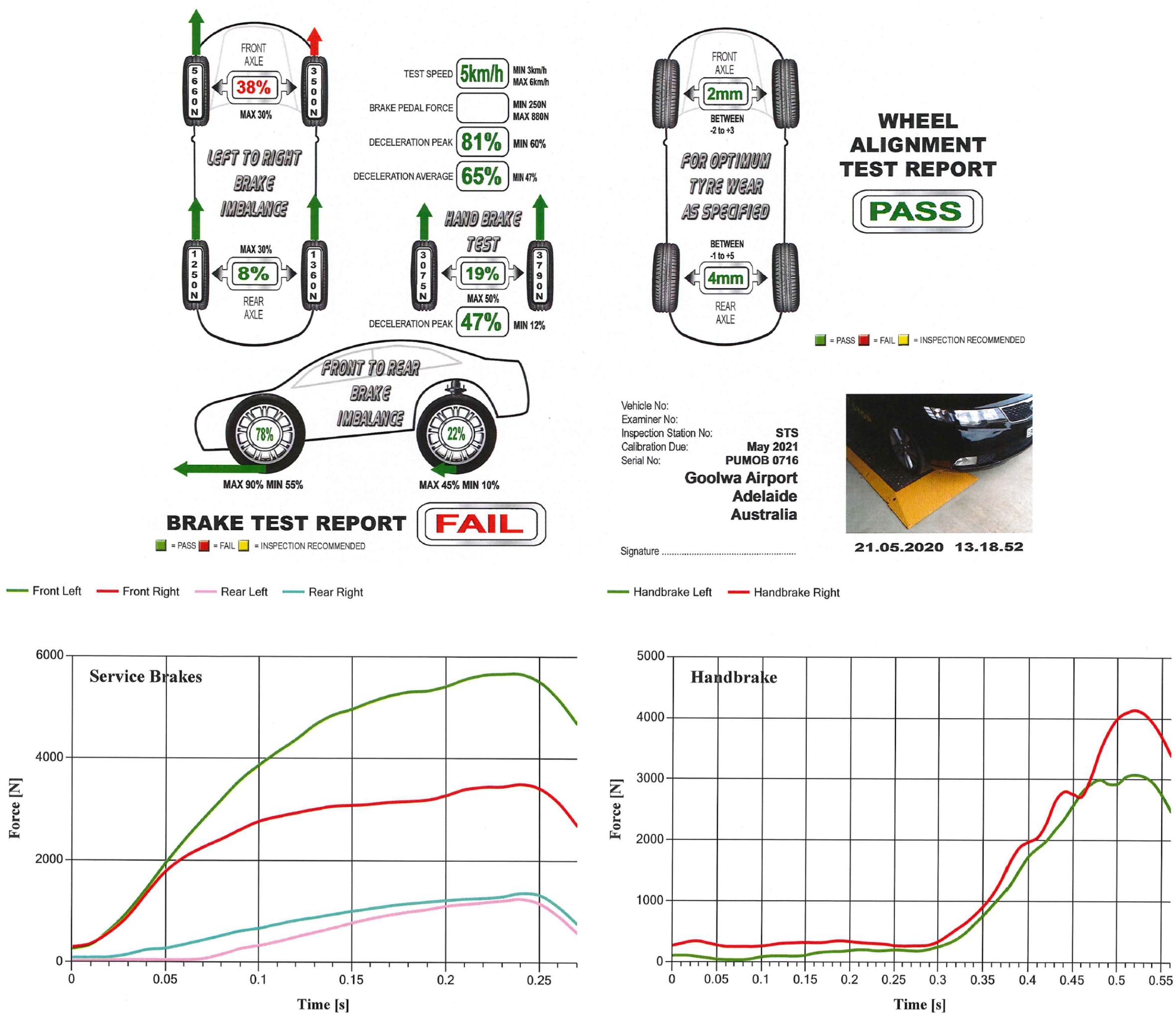


Figure 3.7
SafeTstop plate brake tester example results (indicating a fault at the front right wheel)

3.4.2 Vehicle Inspection System roller brake tester

The roller brake test system used in this study was a portable roller brake tester manufactured by Vehicle Inspection System (VIS) as shown in Figure 3.8. The portable roller brake tester was supplied and operated by the South Australian Department of Infrastructure and Transport (DIT) and sees extensive use in heavy vehicle brake testing. The roller was set up by an experienced operator from the department and a certificate of calibration was provided (see Appendix E). The roller brake test system had four rotating cylinders, two rotating each wheel of a single axle. The front and rear axles are tested separately, and the results combined to obtain the overall brake performance of the vehicle.

The testing process for the roller brake tester consisted of driving a vehicle up the ramps and positioning the front axle wheels within the slot between the two rollers. The vehicle is put into neutral gear and the operator then activates the roller brake tester which begins to rotate the wheels of the vehicle at slow speed (around 0.5 km\h). When instructed by the operator, the driver applies the brakes. Load cells within the roller brake tester measure the maximum amount of brake force provided by each wheel of the axle being tested. This procedure is then repeated for the rear axle of the vehicle.

During testing it is common for the vehicle to be ejected from the roller brake tester. This situation is detected by the roller brake tester (via the red cylinders between the rollers) at which point the test is halted.

Results of the test are printed immediately in the form of a docket that lists all the measurements (see example in Figure 3.9). Because the VIS roller brake tester was designed as a mobile unit it did not have any capability to save results into any kind of digital format.

The results present the following details:

- Test and system details:
    - Serial number,
    - Test number,
    - Date / time,
    - Software version,
    - Vehicle details,
    - Next calibration due date,
    - Adjustable PASS/FAIL criteria according to local roadworthiness requirements, and
    - Examiners ID.
- Footbrake results:
    - Maximum brake force on each wheel in newtons,
    - Difference of brake force on each axle in %,
    - Deceleration generated on each wheel in metres per second per second,
    - Weight on each wheel in kilograms,
    - Net rolling resistance at wheel in newtons, and
    - Peak deceleration in %g.

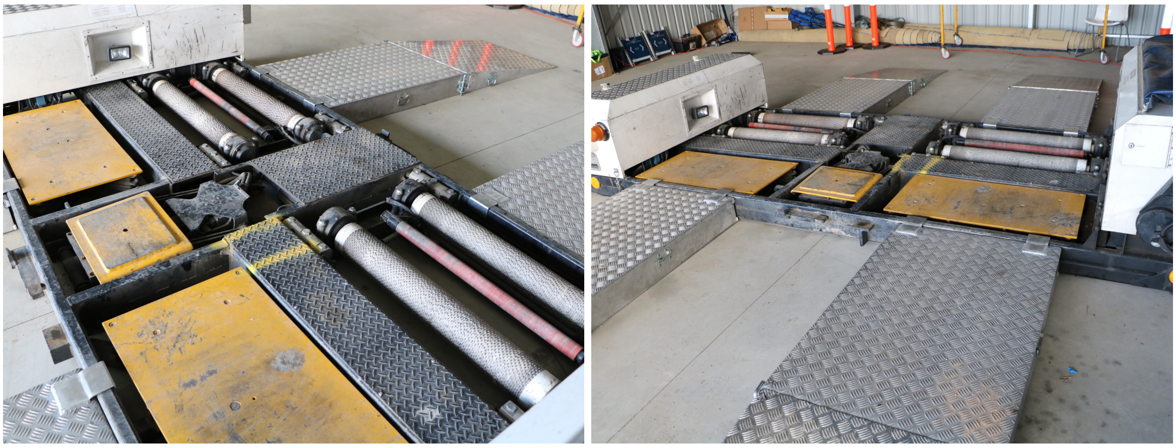


Figure 3.8
VIS roller brake tester

VEHICLE INSPECTION REPORT

Weight Readings Not For Trade Use
VIS S/N: 44562 Test No.: 751
20/05/20 Time: 10:30:58P SW V:7.33
Vehicle ID: KIA T38
Odometer:
Next Cal: 31/03/2021 DefsV: 12
Steer Axles: 1

	LHS	RHS	TOT	P/F
AXLE 1				
Max Brake Fr N	2514	2777	5292	
Brake Balance %	-	-	90	P
Max Decel'n m/s/s	5.9	5.9	5.9	P
Axle Weight kg	424	463	888	
Net Roll Res N	23	71	95	
Dynamic Decel m/s/s	5.8	5.9	5.9	P
Dynamc Weight kg	430	466	897	
AXLE 2				
Max Brake Fr N	1484	1628	3113	
Brake Balance %	-	-	91	P
Max Decel'n m/s/s	5.1	5.4	5.3	P
Axle Weight kg	289	299	588	
Net Roll Res N	7	47	55	
Dynamic Decel m/s/s	5.2	5.6	5.4	P
Dynamc Weight kg	283	289	573	
Total Vehicle Summary				
Max Brake Fr N	-	-	8405	
Max Decel'n m/s/s	-	-	5.7	
Dynamic Decel m/s/s	-	-	5.7	P
Dynamc Weight kg	-	-	1470	

Vehicle Inspected By:

Signature ....

Figure 3.9
VIS roller brake tester example results

3.4.3 Circuitlink Brake-Testa portable decelerometer

An industry standard portable brake testing decelerometer, the Circuitlink Brake-Testa RxG (see Figure 3.10) was supplied, in-kind, for the duration of the study by SafeTstop. The device was provided to CASR in the original packaging and had been recently calibrated (see certificate in Appendix F).

Prior to performing a brake test, details of the test vehicle and the operator are entered into the device via the front keypad. The main device is then placed onto the passenger seat or passenger footwell. A force sensor, attached to the device via a cable, is then placed over the vehicle's brake pedal. While stationary, a new test is then initiated on the Brake-Testa. The driver then accelerates the test vehicle up to a speed of approximately 30 km/h and applies the brakes firmly until the vehicle comes to a stop. The decelerometer then immediately prints the test results onto a docket (see example in Figure 3.11) and saves a copy internally. The location of the test (latitude and longitude) is also reported as the roadworthiness criteria in some Australian jurisdictions require decelerometer tests to be performed on specific roads where the coefficient of friction is known.

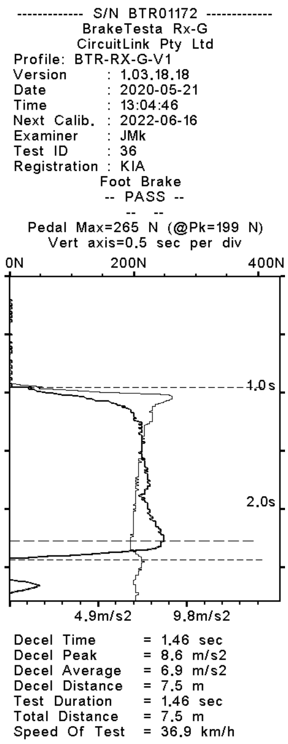
The results present the following details along with a graph showing the force on the brake pedal and the deceleration over the duration of the test:

- Test and system details:
    - Serial number,
    - Test number,
    - Date / time,
    - Software version,
    - Vehicle details,
    - Next calibration due date,
    - Adjustable PASS/FAIL criteria according to local roadworthiness requirements, and

- Examiners ID.

- Footbrake results:
  - Maximum force on brake pedal in newtons,
  - Deceleration time in seconds,
  - Peak deceleration in metres per second per second,
  - Average deceleration in metres per second per second,
  - Deceleration distance in metres, and
  - Speed of test in kilometres per hour.

Figure 3.10
Circuitlink Brake-Testa portable decelerometer


------------- S/N BTR01172 -------------
BrakeTesta Rx-G
CircuitLink Pty Ltd
Profile: BTR-RX-G-V1
Version : 1.03.18.18
Date : 2020-05-21
Time : 13:04:46
Next Calib. : 2022-06-16
Examiner : JMk
Test ID : 36
Registration : KIA
Foot Brake
-- PASS --
-- --
Pedal Max=265 N (@Pk=199 N)
Vert axis=0.5 sec per div

Decel Time = 1.46 sec
Decel Peak = 8.6 m/s2
Decel Average = 6.9 m/s2
Decel Distance = 7.5 m
Test Duration = 1.46 sec
Total Distance = 7.5 m
Speed Of Test = 36.9 km/h

Figure 3.11
Circuitlink Brake-Testa portable decelerometer example results

3.4.4 Racelogic Vbox 3iSL GPS data logger

To accurately record the position and dynamics of a vehicle during a high-speed stopping distance test, a high-accuracy Global Positioning System (GPS) with Real-Time Kinematic (RTK) correction and Inertial Measurement Unit (IMU) integration was utilised. The Racelogic VBOX 3i RTK +IMU system is able to capture the position (to an accuracy of ±1.8 cm for a typical brake stop) and acceleration (to a resolution of 0.01 g) of a vehicle while undergoing a high-speed stopping manoeuvre. Certifications for the Racelogic system can be found in Appendix G.

The Vbox 3iSL has two GPS antennas that are mounted to the roof of a vehicle (see Figure 3.12). One of the antennas is also integrated with an IMU. The GPS antennas and IMU feed their signals into a GPS engine within the data logger which calculates and records the dynamics of the vehicle at a frequency of 100 Hz. The vehicle dynamics calculations are improved further by GPS correction signals from a base station that is set up nearby.

The data recorded by the Vbox 3iSL can be downloaded easily and processed to determine the stopping distance or average deceleration during a high-speed braking event.

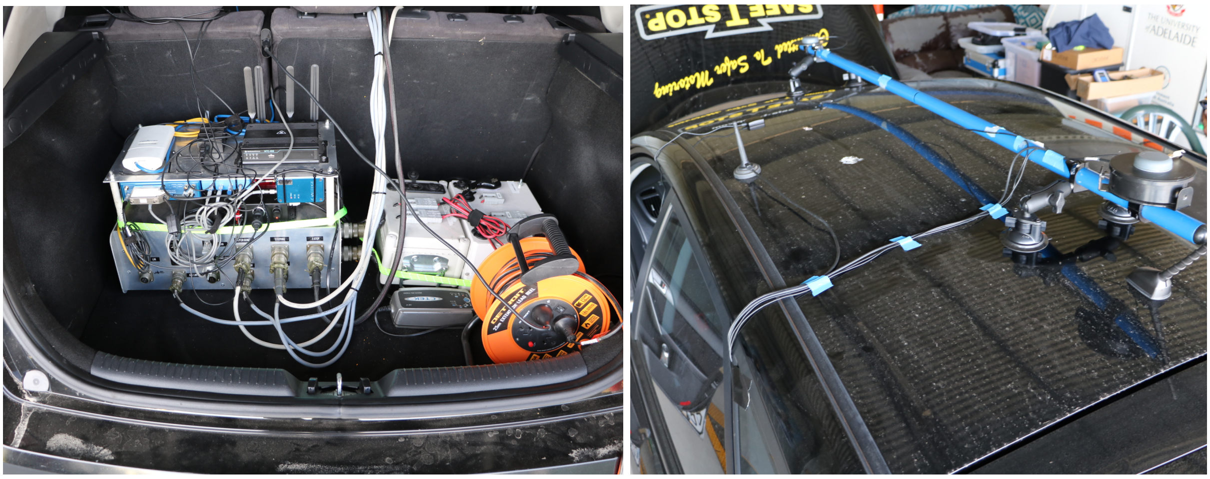


Figure 3.12
Racelogic Vbox 3iSL data logging equipment and roof-mounted GPS antennas with IMU integration

3.5 Data collection procedure

Data collection occurred over four days in late May 2020, with the first days dedicated to setup and preparation, while testing occurred on the final two days.

3.5.1 Setup

On the first day, the test vehicle was delivered to a CASR lab in Adelaide where the brake robot was installed. This involved fitting the robot to the driver seat-mounts and constructing a custom bracket to attach the pushrod to the brake pedal. Additionally, the Circuitlink Brake-Testa was inspected, and a modification was made to the pushrod of the brake pedal robot to integrate the decelerometer's brake pedal force sensor.

On the second day, the test vehicle was delivered to Goolwa Airport (a private airstrip in regional South Australia). The main bitumen runway was relatively flat, around 1.8 km long, and made available for testing over the duration of data collection phase. A large hangar was also available for use with low speed testing and for overnight storage.

The second day was reserved for preparation which included the setup of the plate brake tester by SafeTstop within the hangar as well as the installation of the Vbox data logger and Circuitlink decelerometer into the test vehicle. The decelerometer was installed into the passenger footwell, facing the appropriate direction, as per the manufacturer instructions (see Figure 3.13). CASR researchers also conducted familiarisation activities with the plate brake tester, the decelerometer, and the pressure adjustment valves to gain an understanding of how they work and how to operate them safely. A video conference was also held with experts from the National Measurement Institution (NMI) to review the equipment set up and usage (see Section 3.7).

At the beginning of the third day the VIS roller brake tester was delivered by DPTI vehicle inspection officers. The officers set up the roller brake tester within the hangar.

Figure 3.13
Installation of decelerometer in passenger footwell

3.5.2 Testing

For the remainder of the third day (which ended early due to poor weather) and the fourth day, data collection was conducted for multiple test series with each of the brake testing methods.

A test series was initiated by first adjusting the pressure reduction valves and cut-off valves to simulate the desired brake fault condition. This was either a baseline condition where all the valves were set to be fully open, so there was no limitation to the test vehicle's braking system, or a fault condition. The set of test conditions that were implemented during data collection is shown in Table 3.1 below, with details regarding the positions of the pressure reduction valves and cut-off valves. A description of the test condition is also provided, along with a pictogram that diagrammatically shows the effect of the valve settings on the maximum brake pressures at each wheel. These pictograms are used frequently in presentation of the results in Section 4.

After adjusting the pressure reduction and cut-off valves, each test series was conducted in the sequence described below. This sequence was guided by the checklist in Appendix H and conducted by three CASR researchers: one driving the test vehicle, one managing the checklist sequence, and one managing the data collection from the various pieces of testing equipment.

First, the weight of the vehicle was measured and compared to the weight recorded at the start of testing. Any difference, most likely due to fuel losses, was corrected by adding the appropriate amount of extra mass in the form of weight bags.

The temperature of the brakes was then measured with a contactless thermometer. At the start of each test period (i.e. the start of the day or after a break such as lunch) the test vehicle's brakes were warmed by performing four brake-to-stop manoeuvres from 80 km/h on the airstrip. The measurements taken during testing were then used to ensure the rear brakes were within 20-50 degrees Celsius and the front brakes were within 30-60 degrees Celsius. If the temperatures were outside these ranges, the brakes were either warmed again or left to cool as required.

A wireless tyre pressure and temperature monitor was fitted to the tyre valves on each wheel of the test vehicle. This device was used to check the pressures and temperatures of each tyre remained consistent during each test series.

The brake pedal was then applied to check the measured readings from the brake line pressure sensors via the MoTeC C125 screen within the test vehicle. This was done to ensure that consistent pressures on the brake lines were being measured throughout the test series and test sets. It also enabled the researchers to ensure that any fault condition was being implemented properly, and that the correct brake line pressures were being reduced by an appropriate amount.

Next, the test vehicle was driven onto the airstrip and three tests with the decelerometer were performed. These tests consisted of the test driver activating the Circuitlink device, executing the initialisation process, accelerating the vehicle to a speed of around 35 km/h, and then triggering the brake pedal robot. All tests were performed in sequence and in the same direction along the airstrip.

Three high-speed stopping distance tests (referred to hereafter as stopping distance tests) were then performed. These tests consisted of the test driver activating the Vbox equipment, accelerating to high speed, setting the cruise control for 80 km/h, allowing the vehicle speed to settle, and then triggering the brake pedal robot. All tests were performed in sequence and in the same direction along the airstrip.

The test vehicle was then returned to the hangar where the brake temperatures were checked again, in the same way as above.

Next, three tests on the plate brake tester were performed. The test driver positioned the test vehicle in line with the plate brake tester, then released the brake to allow the vehicle to reach a speed of about 3-6 km/h. Once the vehicle was on the plate brake tester the driver would change the transmission of the vehicle to neutral and wait for the signal from the plate brake tester to trigger the brake pedal robot. The plate system then alerted the driver to continue and complete a handbrake test.

Three tests on the roller brake tester were performed last. The test driver would manoeuvre the test vehicle up the ramps of the roller brake tester such that the front axle was within the rollers. The roller brake tester was operated by DIT inspection officers who advised when the test driver should trigger the brake pedal robot. The same process was repeated to perform a test on the rear axle of the test vehicle.

At the conclusion of a test series, all printed results from the various testing equipment were collected and collated. A new test condition was then implemented, and the test sequence was repeated.

3.5.3 Experiences with the roller brake tester

While testing using the roller brake tester, it was noteworthy that on all tests of the front axle, the test vehicle was ejected from the machine rather quickly. This did not occur on any tests of the rear axle. After the first few sets of brake testing, it was clear that the roller brake tester was reporting peak deceleration values that were significantly lower than the other brake testing methods.

The brake robot was programmed to apply the brakes rapidly and to a force that was at the point of triggering the ABS. After discussion, the DIT vehicle inspection officers suggested that a slower, or more gradual, brake application may allow the roller brake tester more time to thoroughly assess the brakes before the vehicle was ejected.

To maintain the consistency of the brake pedal applications in the study, the brake robot was still used for the main data collection tests (as described above). However, for many of the brake fault conditions, an additional two tests were performed on the front axle with roller brake tester: a gradually increasing manual brake application, and a second gradually increasing manual brake application with the handbrake applied constantly from the beginning of the test. The test vehicle was still ejected from the machine during these manual brake applications.

Based on the additional data collected during the manual brake applications, a number of observations were made. Noting that these observations are based on a very small amount of data, they should be treated as anecdotal. However, they are presented here to provide some potential explanation for some of the findings that are presented in the Results section.

The first observation was that, as suggested by Firdaus et al. (2020), there was generally little difference in the reported peak deceleration regardless of whether the brake were applied in a rapid, strong manner by the brake robot or in a gradually increasing manner by the test driver. Although, there were a few cases in which the manual application did result in greater amount of peak deceleration.

Secondly, it was far more likely for the roller brake tester to correctly detect left to right imbalance on the front axle during a manual brake application compared to a robotic application. It is suggested that the sharp brake application by the brake robot may have masked left to right imbalance by ejecting the test vehicle too quickly.

Manual brake applications with the handbrake applied resulted in a consistently higher level of peak deceleration being reported, compared to the brake robot applications (and the manual application without handbrake). Using the handbrake during a footbrake test is clearly not a valid procedure, but it does provide some clues as to why the peak deceleration values reported by the roller brake tester were so low.

Based on the study of roller brake tester limitations by Li et al. (2011), and the experiences during data collection in this study, several potential explanations for the low reported peak deceleration are suggested.

The friction between the roller cylinders and the test vehicle's tyres may be low. This was considered unlikely, given the machine is used for inspections and maintained/calibrated frequently, but included here for completeness.

As the roller brake tester was a mobile unit, rather than an in-ground unit, the test vehicle was noted to be tilted slightly during testing of the front axle (rear wheels lower the front wheels – see Figure 3.14) and this may have reduced the amount of force required for the machine to eject the vehicle.

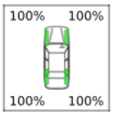
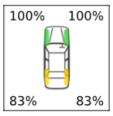
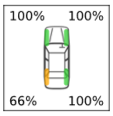
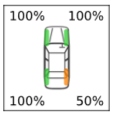
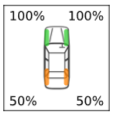
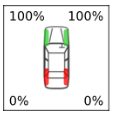
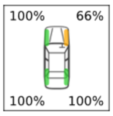
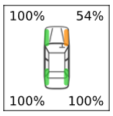
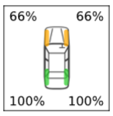
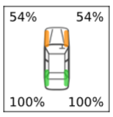
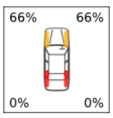
The test vehicle's rear wheels were on the metal ramps of the mobile unit during testing, rather than concrete or bitumen as would be the case with an in-ground unit, and this may have reduced the amount of force required for the machine to eject the vehicle.

Finally, it was suspected that the geometry of the VIS machine's rollers may not be suitable for measuring higher levels of peak deceleration.

The experiences described here are likely to have affected the results presented in Section 4 and Section 5 below.

Figure 3.14
Test vehicle on the roller brake tester

Table 3.1
Brake pressure reductions for each test condition

Test condition	Pictogram	Pressure reduction valve position				Cut-off valve position				Description
		FL	FR	RL	RR	FL	FR	RL	RR	
Baseline		0	0	0	0	-	-	-	-	All wheels at maximum brake pressure
Fault condition A		0	0	4	4	-	-	-	-	Rear wheels limited to 83% of maximum brake pressure
Fault condition B		0	0	8	0	-	-	-	-	Rear left wheel limited to 66% of maximum brake pressure
Fault condition C		0	0	0	12	-	-	-	-	Rear right wheel limited to 50% of maximum brake pressure
Fault condition D		0	0	12	12	-	-	-	-	Rear wheels limited to 50% of maximum brake pressure
Fault condition E		0	0	-	-	-	-	X	X	Rear wheels disabled
Fault condition F		0	8	0	0	-	-	-	-	Front right wheel limited to 66% of maximum brake pressure
Fault condition G		0	11	0	0	-	-	-	-	Front right wheel limited to 54% of maximum brake pressure
Fault condition H		8	8	0	0	-	-	-	-	Front wheels limited to 66% of maximum brake pressure
Fault condition I		11	11	0	0	-	-	-	-	Front wheels limited to 54% of maximum brake pressure
Fault condition J		8	8	-	-	-	-	X	X	Rear wheels disabled and front wheels limited to 66% of maximum brake pressure

3.6 Data processing

As a result of the testing described above, a number of data sets were generated. Data regarding the braking performance of the test vehicle was generated by each of the brake testing methods; the plate brake tester, the roller brake tester, and the decelerometer. Brake performance data during the stopping distance test was also collected by the Vbox positioning equipment.

Furthermore, during each test, data regarding the force applied to the brake pedal and the induced brake pressures at each wheel was recorded by the brake robot system and the MoTeC system respectively.

Each of these sets of data was processed, and associated with one another (where appropriate), as described below.

3.6.1 Plate brake tester data

Each test conducted with the plate brake tester produced a .PDF file with the results of that test. This .PDF file was printed automatically at the conclusion of each test.

During the testing process all printed results were collected and collated in a file folder that indicated the conditions of the test being conducted. At the conclusion of the testing phase, a digital version of all the generated .PDF files were transferred to the researchers via Dropbox and catalogued into a digital folder system.

The plate brake tester data contained the following details of relevance for each test:

- Date,
- Time,
- Brake forces generated at each of the four wheels,
- Left to right brake force imbalance on both the front and rear axle,
- Front to rear brake force balance,
- Peak deceleration, and
- Average deceleration.

The plate brake tester also provided a graphical output showing the increase in brake force over the test period. However, this data was not utilised in this study.

All relevant data from the plate brake tester .PDF results were transcribed into a .CSV file format, where each row contained the details for a single test, for ease of analysis.

3.6.2 Roller brake tester data

Each test conducted on the roller brake tester produced a paper docket with the results of that test. No digital version of the test results was recorded by the roller brake tester.

During testing all paper dockets were collected and collated in a file folder that indicated the conditions of the test being conducted (i.e. the brake fault condition). The roller brake tester results docket contained the following details of relevance for each test:

- Date,
- Time,

- Brake forces generated at each of the four wheels,
- Left to right brake force imbalance on both the front and rear axle, and
- Peak deceleration.

At the end of the testing phase the results of the paper dockets were transcribed by hand into a digital .CSV format, where each row contained the details for a single test, and catalogued into a digital folder system.

3.6.3 Decelerometer data

Each test conducted with the decelerometer produced a paper docket with the results of that test. The data contained on this docket was also saved on the CircuitLink device in .CSV format and as an image file.

During testing all paper dockets were collected and collated in a file folder that indicated the conditions of the test being conducted. At the conclusion of the testing phase, all .CSV files and image files were downloaded from the CircuitLink device and catalogued into a digital folder system.

The decelerometer data contained the following details of relevance for each test:

- Date,
- Time,
- Peak deceleration,
- Average deceleration,
- Deceleration distance, and
- Vehicle test speed.

The .CSV files downloaded from the CircuitLink device were combined into a single file and then rearranged such that each row contained the details for a single test.

3.6.4 Stopping distance test data

During the stopping distance tests, data was collected using the Vbox 3i dual antenna GPS system with corrections from a base station. Prior to the commencement of each test (or a sequential set of tests) the Vbox was activated to record and the file number was noted along with the conditions of the test being conducted. Recording was halted at the end of each test (or set of tests).

At the end of the testing phase, all data files were downloaded from the Vbox device and catalogued into a digital folder system.

The recorded files consisted of data, recorded at 100 Hz, arranged in sequential rows similar to that within a .CSV file. The following relevant details were recorded during each test:

- Date,
- Time,
- Latitude,
- Longitude, and
- Velocity.

Each file was then processed in the follow way. First the data relevant to each individual test was isolated by finding periods where the velocity increased to approximately 75 km/h (the typical stopping distance test speed), held steady, and then suddenly decelerated to stationary. The point within these periods where the deceleration of the vehicle began to increase was then identified. The speed of the vehicle at this point was recorded as the 'initial test velocity'. The ADR 31 mean deceleration formula (Section 1.3.4) was then used to calculate the average deceleration of the vehicle between 80% of the initial velocity and 10% of the initial velocity.

The initial velocity and average deceleration details for each test were then saved into a .CSV file where each row contained the details for a single test.

While processing the Vbox data, several random checks were made to ensure that the device was reporting zero velocity at appropriate points (e.g. at the start and end of a test) to confirm that there was no wander in the positioning system.

3.6.5 Brake force data

Each time the brake pedal robot was activated, the system automatically logged all data. Prior to the commencement of each test (or a sequential set of tests) the brake robot system was set to generate a new file. This process closed the currently open file (with the data logged to that point), opened a new file, and began logging once more. The name of the currently open file was noted at the end of each test (or set of tests), along with the brake testing method being applied and the conditions of the test being conducted.

During the course of the testing phase, the brake robot data files were progressively downloaded and catalogued into a digital folder system.

The recorded data files were in .CSV format and contained the following relevant details for each test, recorded at a dynamic frequency that ranged between 50 and 100 Hz:

- Date,
- Time, and
- Brake pedal force.

The files were then processed to identify where each individual test was occurring by finding periods where the brake pedal force increased to a certain level, maintained that level, and then reduced to zero. The maximum brake pedal force achieved within these periods was then recorded. This maximum brake pedal force was then associated with the corresponding test data recorded for each of the brake testing methods. As such, the test details recorded on individual rows of .CSV files for the plate brake tester, roller brake tester, decelerometer, and stopping distance test were appended with the maximum brake pedal force applied during that test.

3.6.6 Brake pressure data

Whenever the engine on the test vehicles was running, the MoTeC system was automatically logging all data regarding the brake pressures applied to each wheel into a proprietary file format. There was no simple interface with the MoTeC system, so a single large data file was downloaded at the end of each test day and catalogued into a digital folder system.

The proprietary files were opened using the commercial MoTeC software, which allowed the data to be exported into a .CSV format. This was done for all the test files which contained the following relevant details recorded at 100 Hz:

- Date,
- Time,
- Brake pressure at front left wheel,
- Brake pressure at front right wheel,
- Brake pressure at rear left wheel, and
- Brake pressure at rear right wheel.

Each file was processed to identify where relevant braking applications had occurred during testing. Because the brakes of the test vehicle were frequently applied manually during manoeuvring between tests, this was a time-consuming process. First, all individual braking applications were identified by finding where the brake pressures increased and then decreased back to zero. The timing of these brake applications was then used to isolate only those that occurred while a test was being conducted.

The maximum amount of brake pressure at each wheel during the relevant brake application sequences was then recorded. These maximum brake pressures were then associated with the corresponding test data recorded for each of the brake testing methods. As such, the test details recorded on individual rows of .CSV files for the plate brake tester, roller brake tester, decelerometer, and stopping distance test were appended with the maximum brake pressures that were achieved for each wheel during that test.

3.7 National Measurement Institute review

To ensure the independence and validity of the study, the methodology described above was reviewed by metrology specialists from the National Measurement Institute (NMI). The NMI specialists provided guidance on suitable measures to avoid uncertainty or inaccuracy in the data being collected and reviewed the calibration certificates of all the equipment that was used to identify any potential technical limitations. A report by the NMI specialists is attached in Appendix I. The concluding statement from that report is provided below.

> *The National Measurement Institute of Australia (NMI) conducted an assessment of the equipment and measurement methodology used by CASR to perform a series of experiments comparing the capability of three different types of brake testers to detect deliberately introduced faults in vehicle braking systems.*
>
> *The assessment concluded that the measurements that CASR conducted were appropriate to give confidence in the validity of the comparative testing.*

4 Results – Reported brake performance

Over the two days of data collection, a robotic system was used to apply a total of 156 braking events. During these braking events the available brake pressure at individual wheels of the test vehicle's braking system were limited in various ways through the use of pressure reduction and cut-off valves to simulate brake faults of various severity. The effects of these fault conditions were evaluated by four brake testing methods: a plate brake tester, a roller brake tester, a decelerometer, and a stopping distance test. The data collected during these brake tests was collated, processed, and the results are presented below.

First, the robotically applied brake pedal forces, and the elicited individual wheel brake pressures, are reviewed in order to determine the level of consistency between the brake testing methods. Next, the effects of the brake fault conditions are examined to determine how they alter the test vehicle's stopping distance. The levels of peak deceleration and average deceleration reported by each brake testing method are then presented. Finally, the levels of left to right wheel imbalance and front to rear brake force balance, reported by those brake testing methods that are able to provide a measurement, are explored.

A summary of all the results presented in this section is provided in Appendix J.

4.1 Consistency of brake applications

It is important to consider whether the brake applications during the tests performed during each of the brake fault conditions were consistent. Systematic differences in the application of the brake pedal, and the induced brake pressures, would mean the various brake testing methods were not presented with the same conditions and, thus, their ability to identify faults may be misinterpreted.

The subsections below present and explore the consistency of the robotic brake pedal forces, the consistency of the induced brake pressures, and the consistency of the limitations elicited through the pressure reduction and cut-off valves during each of the brake testing methods.

4.1.1 Brake pedal force

The brake pedal forces recorded during the robotic brake applications with the four brake testing methods, during all test conditions, are summarised in Figure 4.1 as box plots. The roller brake tester required an individual brake application for the front and rear axles, and these are shown separately.

Apart from the stopping distance test, the brake pedal forces recorded during testing were rather consistent. The median brake pedal force ranged from a minimum of 215.4 N for the roller brake tester (front axle) to a maximum of 236.3 N for the plate brake tester. Additionally, the interquartile ranges of the results for the plate brake tester, roller brake tester, and decelerometer were similar in size, and showed a large amount of overlap.

The median brake pedal force for the stopping distance testing method was higher at 270.0 N, and the interquartile range was greater.

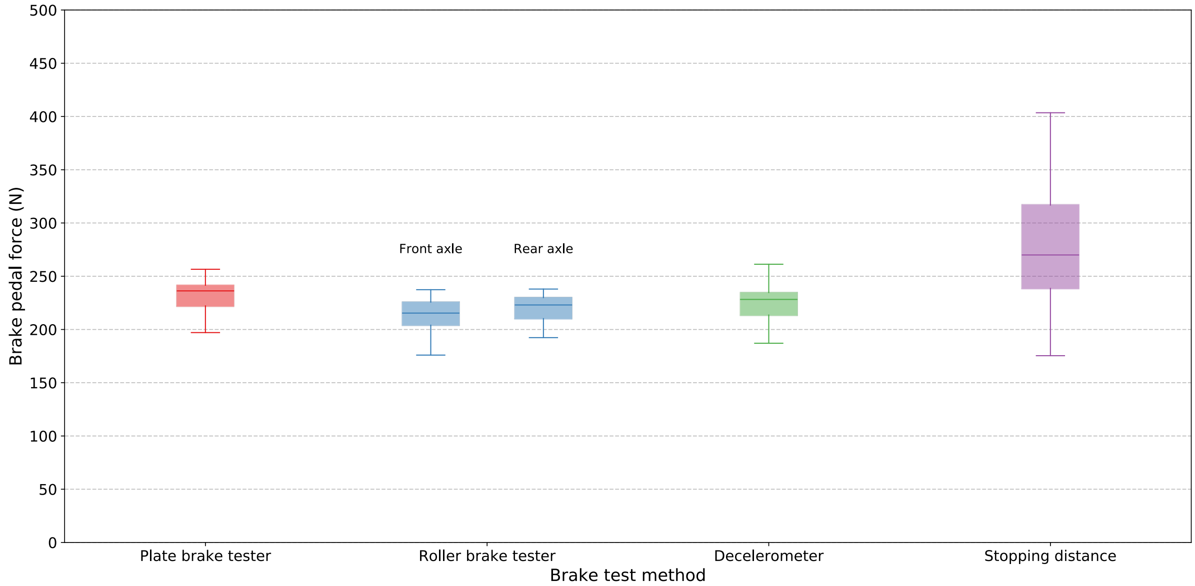


Figure 4.1
Brake pedal forces recorded with each of the brake testing methods

The greater brake pedal forces recorded during the stopping distance tests (and the decelerometer to a lesser degree) are suspected to be the result of a 'reaction force' acting on the brake pedal at higher levels of deceleration. That is, when the vehicle is decelerating more strongly the mass of the brake pedal robot is pitched/rotated forward and this applies an additional force onto the brake pedal. To investigate this further, the brake pedal force was compared to the average deceleration developed during each stopping distance test, as shown in Figure 4.2. As suspected, at greater amounts of average deceleration there was a tendency for increased brake pedal forces.

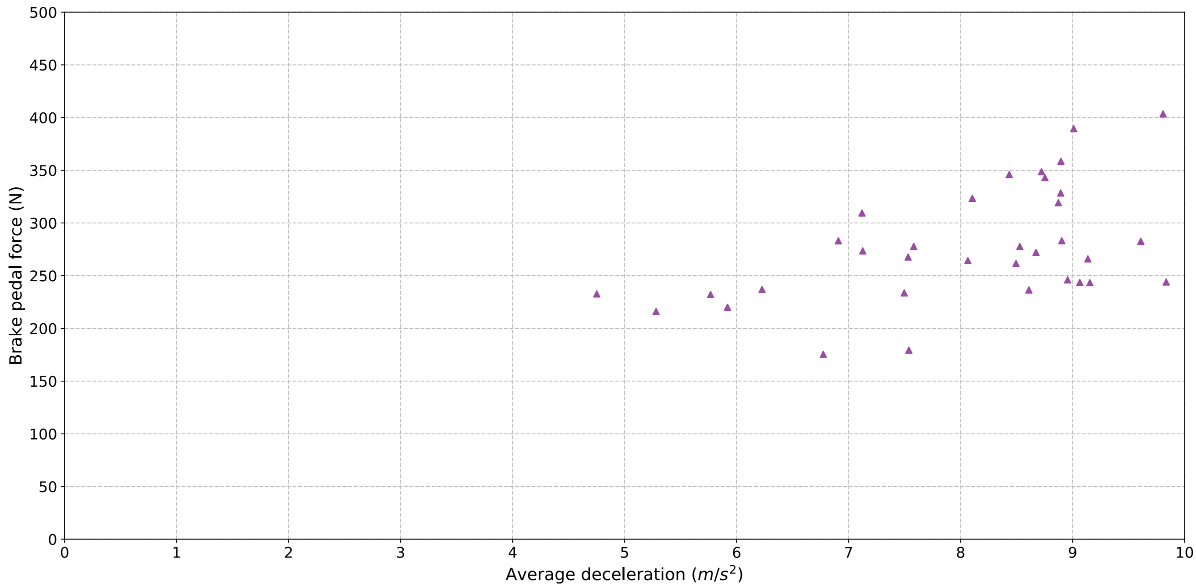


Figure 4.2
Brake pedal force vs average deceleration during stopping distance tests

4.1.2 Brake pedal force vs brake pressure

It was important to establish whether the increase in brake pedal force for the stopping distance tests (and potentially the decelerometer tests) had resulted in a greater amount of brake pressure being generated at the test vehicle's wheels. Figure 4.3 shows the braking pressures at each wheel of the test vehicle for given amounts of brake pedal force during baseline tests with all four brake testing methods. While the stopping distance tests generally result in slightly higher amounts of brake pressure, there was no indication that brake pressure increased further for greater amounts of brake pedal force. The brake pedal force applied by the pedal robot was set at the point where the ABS would be triggered. The ABS triggered for many of the stopping distance tests and it is suspected that the ABS system prevented the brake pressures rising further with the increased pedal forces.

Overall, all of the brake testing methods produced similar amounts of brake pressure at each wheel during the baseline tests; usually between 1,200 and 1,400 psi.

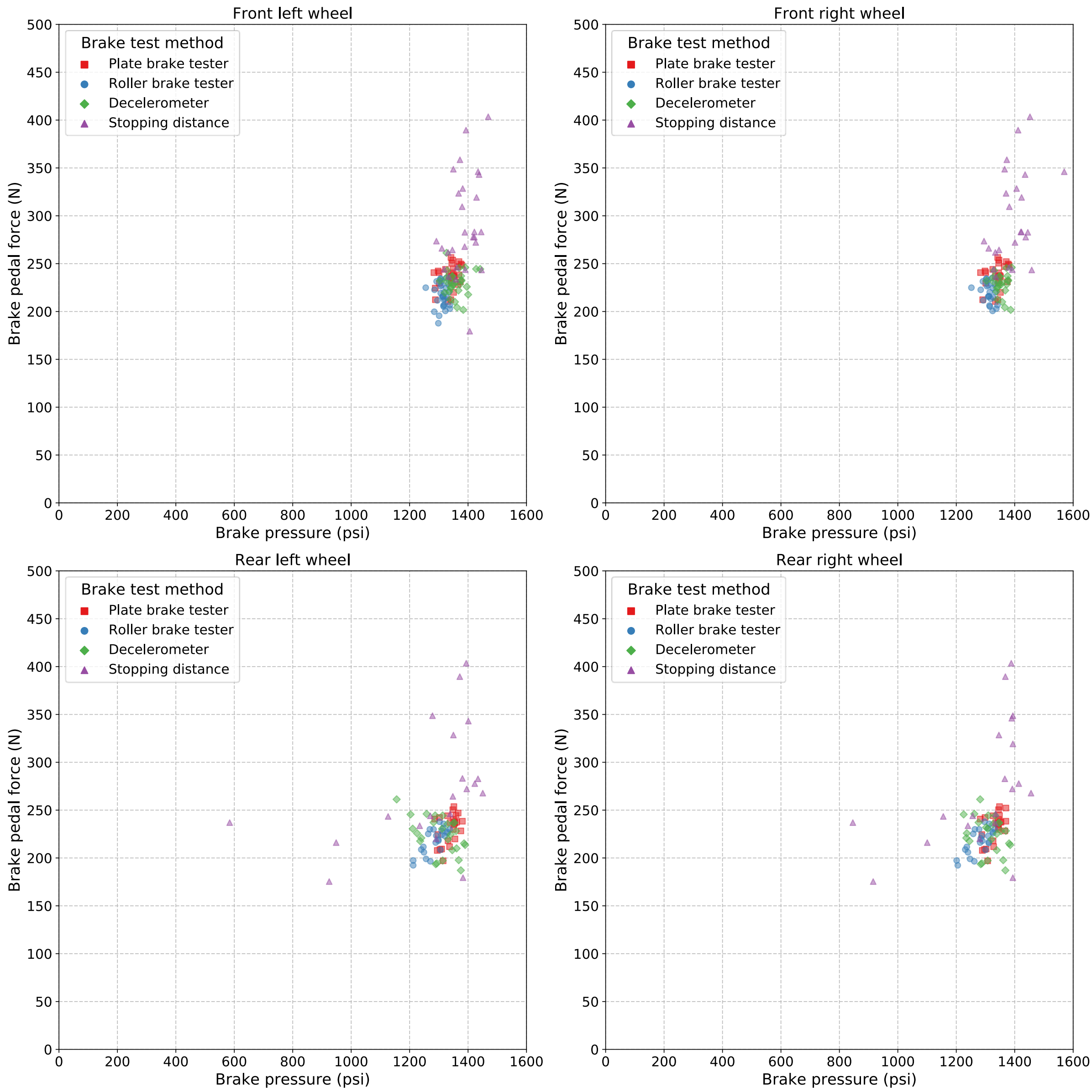


Figure 4.3
Brake pressure elicited at each wheel for a given amount of brake pedal force

4.1.3 Effect of brake pressure adjustment valves

After establishing that the brake pressures during the baseline condition tests were consistent between the four brake testing methods, it was important to consider how the brake pressures were affected by adjustments to the pressure reduction valves. Figure 4.4 shows the brake pressures at each wheel generated with the pressure reduction valves set to various positions on the test vehicle. A box plot is depicted where there was sufficient data for a given valve position (five tests or more), while individual points are provided where smaller amounts of data were available.

There was relatively good consistency between the valve position and the brake pressure developed at each wheel for each brake testing method. Furthermore, there appears to be a generally linear trend between the valve position and the amount of brake pressure (noting that the pressure reduction valve could only limit brake pressure down to about 50% of maximum).

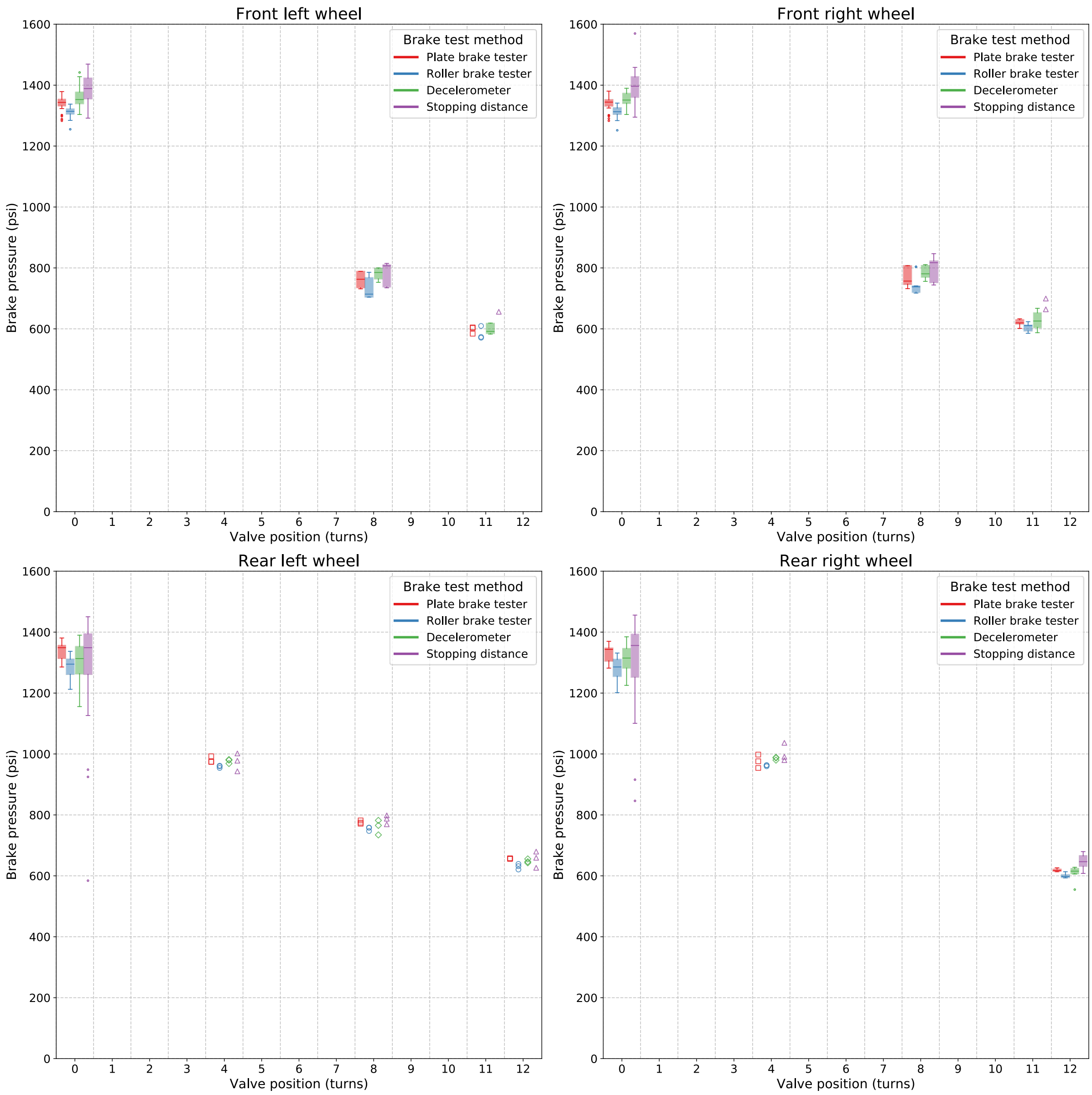


Figure 4.4
Brake pressure produced at each wheel for a given pressure reduction valve position

4.2 Effect of fault conditions on stopping distance

In order to explore each brake testing method's ability to detect brake faults, a number of adjustments were made to the amount of available brake pressure at each of the four wheels of the test vehicle. These adjustments were made to simulate the conditions that would result from common mechanical and hydraulic brake faults.

Each brake adjustment is likely to affect the test vehicle in different ways. The results of the stopping distance brake tests were used to provide an objective, real-world measurement of the severity of the brake pressure reductions. Table 4.1 shows the average deceleration recorded during each of the brake fault conditions as well as with no faults (baseline conditions) using the ADR 31 formula for mean fully developed deceleration (d_m). The calculated equivalent stopping distance from an initial speed of 80 km/h is also shown.

Figure 4.5 displays the average stopping distance for each of the baseline condition tests that were performed. The Figure shows a pictorial representation of the brake fault condition (all wheels set to 100% in the case of the baseline conditions), as well as the average stopping distance for an initial speed of 80 km/h. Additionally, the average stopping distance for an initial speed of 80 km/h for all the baseline conditions combined (baseline average) is shown, along with error bars that display two standard deviations in either direction.

In Figure 4.6 the stopping distance for an initial speed of 80 km/h during each of the brake fault conditions is shown. Again, a pictorial representation of the fault condition is provided. The baseline average stopping distance are overlaid onto the stopping distance results for each fault conditions, to provide context. A T-test was used to investigate which fault conditions resulted in a stopping distance that was greater than the baseline stopping distance. Fault conditions where the T-test resulted in a p-value of less than 0.05 are indicated with an asterisk.

All the brake fault conditions resulted in an increased stopping distance. These increases ranged from minor, and not significantly different to the baseline average, to extreme. The greatest increase in stopping distance was over 75%, which occurred when both rear brakes were disabled and the front brakes were limited to 66% of maximum brake pressure.

It is also worth noting that some of the brake fault conditions resulted in varying levels of brake imbalance, where one side of the vehicle brakes more severely than the other. However, the effect of this imbalance, in vehicle handling was not measured in this study.

Table 4.1
Average deceleration and stopping distance as a result of each test condition

Test condition	Average deceleration during stopping distance test (m/s/s)	Average stopping distance from an initial speed of 80 km/h (m)
Baseline 1	9.16	27.0
Baseline 2	8.84	27.9
Baseline 3	9.55	25.9
Fault condition A	9.03	27.3
Fault condition B	8.64	28.6
Fault condition C	8.57	28.8
Fault condition D	8.38	29.5
Fault condition E	7.05	35.0
Fault condition F	7.54	32.7
Fault condition G	7.54	32.7
Fault condition H	6.31	39.1
Fault condition I	5.28	46.8
Fault condition J	5.26	46.9

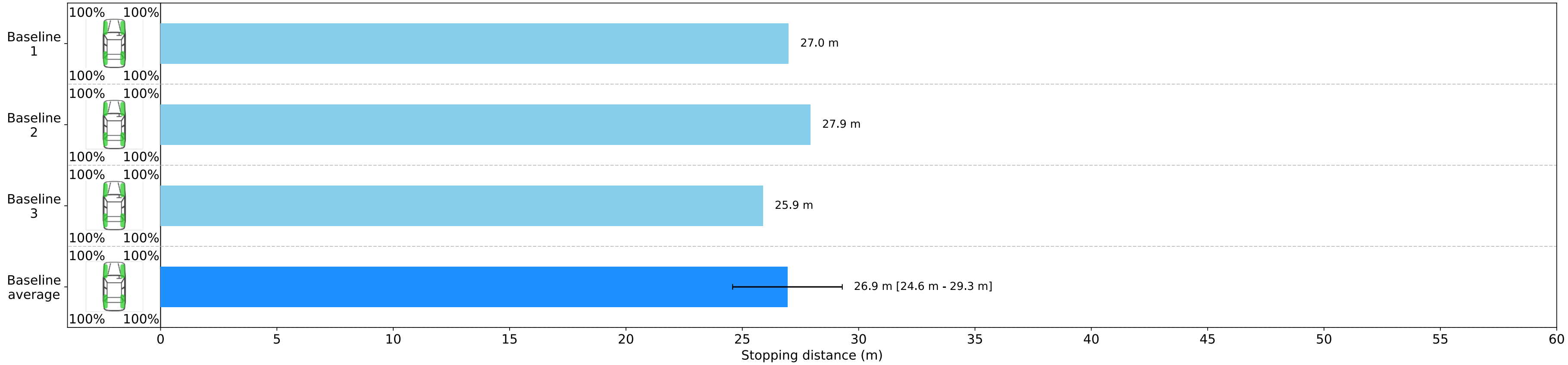


Figure 4.5
Average stopping distances during baseline tests

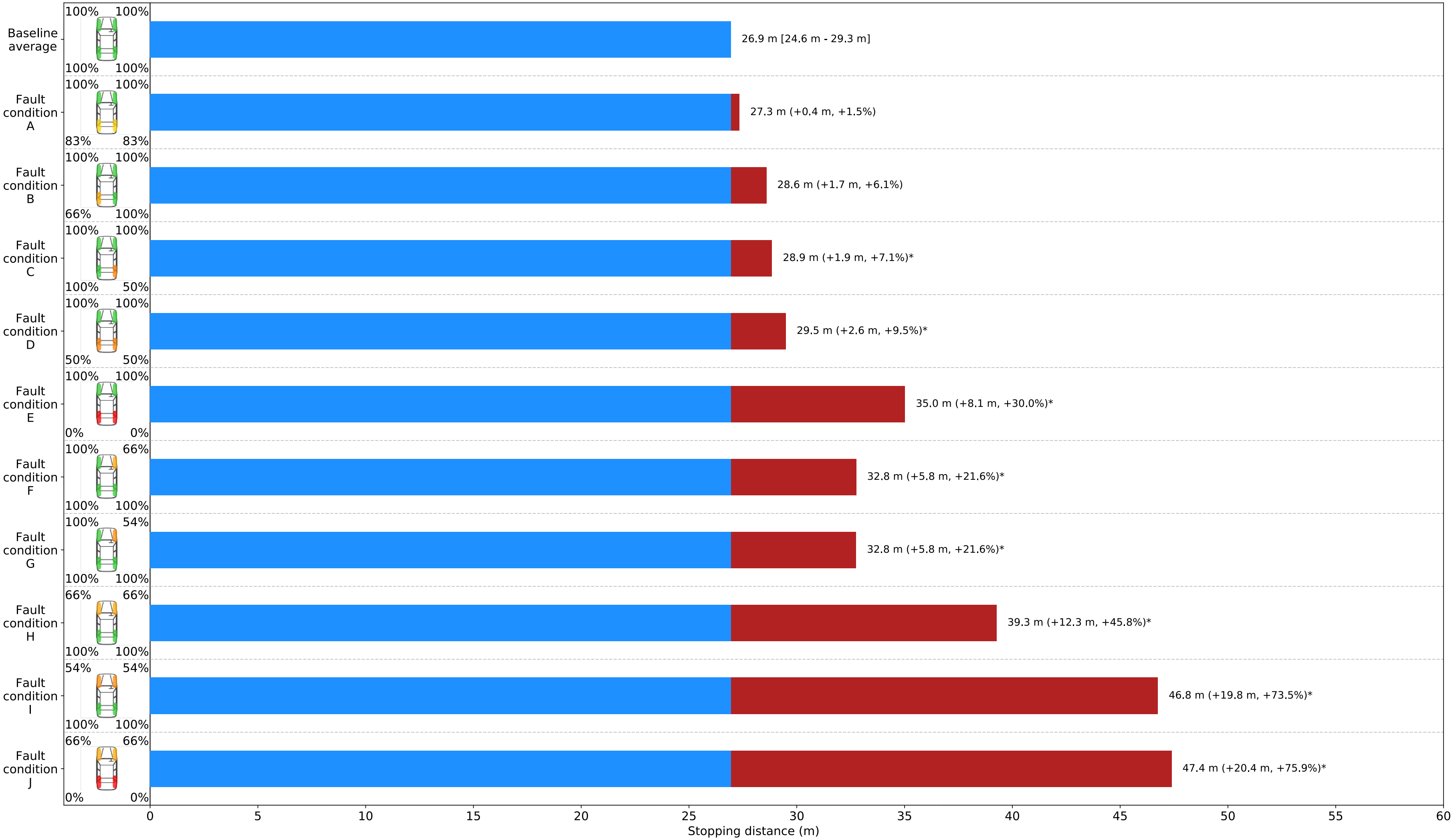


Figure 4.6
Average stopping distances during each brake fault condition

4.3 Reported deceleration

During a brake to stop sequence, the deceleration experienced by a vehicle builds quickly to a peak value before it then plateaus to a slightly lower value for the remainder of the braking sequence (Luker, 2008). In some cases, increased deceleration also occurs towards the end of the braking sequence. This peak deceleration value represents the maximal amount of braking friction that was achieved by the vehicle. Outside of the peak deceleration period(s), the deceleration over the course of a braking sequence typically occurs at a steady level until the vehicle comes to a stop. Average deceleration is a measure of this steady state value and represents the average deceleration over the entire braking sequence.

The peak and the average deceleration reported by the plate brake tester and the decelerometer is shown in Figure 4.7, along with the peak and average deceleration calculated during the stopping distance test. The roller brake tester used in this study only reported a peak deceleration (which is shown in Figure 4.7) but did not report an average deceleration.

Figure 4.7 is divided into columns which depict the peak and average deceleration measured during tests performed with the various brake fault conditions that were elicited through the pressure reduction and/or cut-off valves (shown diagrammatically at the bottom of the Figure). The first column in the Figure depicts the decelerations measured during all baseline tests for each brake testing method. A T-test was used to compare the measured decelerations during each fault condition to the baseline measurements. A bold indicator is shown for reported values where this T-test comparison resulted in a p-value less than 0.05, indicating a statistically significant difference. Reported values that were not found to be significantly different to the baseline are shown with a faded indicator.

In general, the decelerations reported by the decelerometer were highest, followed by those reported by the plate brake tester and then the peak decelerations reported by roller brake tester. It is worth noting that the decelerometer directly measures deceleration through accelerometers within the device, while the plate brake tester and roller brake tester calculate a deceleration using a measurements of brake force and vehicle mass over a short time period.

In addition to the observations regarding the results of the roller brake tester in Section 3.5.3, a few further observations can be made from Figure 4.7. The first is that the peak decelerations reported by the roller brake tester are indeed much lower than those reported by the other brake testing methods. Second, it can be seen that where the rear brake pressures have been reduced, the roller brake tester has a tendency to report drastically lowered peak decelerations.

Despite the differences in the magnitude of the peak decelerations reported by each brake testing method, they are all affected by the brake fault conditions in generally similar ways (although, with some minor differences). That is:

a) **Minor brake pressure reductions to the rear wheels resulted in little change in peak deceleration**

There was no significant change in either the peak or average deceleration reported by the plate brake tester during fault conditions A to D. This was also for the case for the stopping distance test, apart for fault condition D which resulted in a significant reduction in both peak and average deceleration. For the decelerometer, there was no significant change in the reported peak deceleration, but average deceleration was found to be reduced slightly in fault conditions A and C. The roller brake tester reported a significant reduction in peak deceleration for all the fault conditions.

b) **Disabling both rear wheels resulted in a reduction in peak deceleration**
During fault condition E, decelerations were found to have reduced significantly by almost all the brake testing methods. Only peak deceleration reported by the decelerometer was found to have not reduced to a statistically significant level.

c) **Very minor brake pressure reductions to one or both of the front wheels resulted in little significant change in peak deceleration**
In fault conditions F and G, where brake pressure reductions were made to just one of the front wheels, the results were mixed. The plate brake tester found significant reductions in deceleration during fault condition G, but not for fault condition F. On the other hand, all decelerations were found to have significantly reduced during the stopping distance test. This was also true for the decelerometer results, apart from the reported peak deceleration during fault condition G. The roller brake tester measured a significant increase in peak deceleration for fault condition G, but not for fault condition F.

d) **Greater brake pressure reductions to the front wheels resulted in decreasing levels of peak deceleration**
Larger brake pressure reductions in fault conditions H and I resulted in significant reductions in deceleration reported by the plate brake tester, decelerometer, and the stopping distance test. The roller brake tester reported a significant increase in peak deceleration for fault condition I but not for fault condition H.

e) **Disabling both rear wheels in combination with brake pressure reductions to the front wheels resulted in a drastic reduction in peak deceleration**
Brake fault condition J resulted in very significant reductions to the decelerations reported by all the brake testing methods.

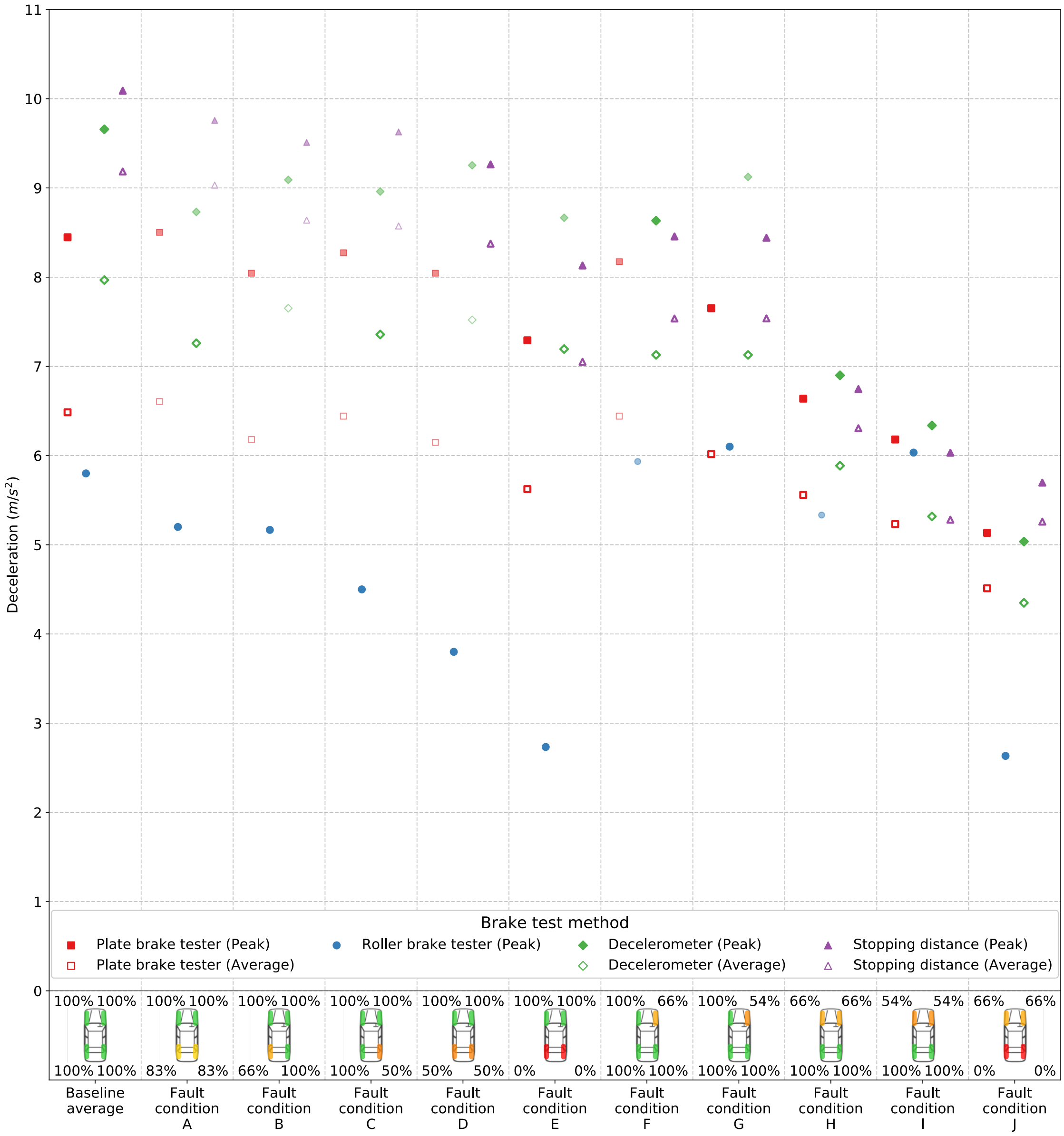


Figure 4.7
Decelerations reported by the testing methods during each brake fault condition (statistically significant differences [$p < 0.05$] between fault conditions and the baseline average are shown with bolded indicators)

4.4 Reported left to right brake force imbalance

A braking system that is operating satisfactorily will provide the same level of brake force on the left and right wheels of each axle. If this does not occur, then there is a risk that the vehicle will be dragged to the left or right during an emergency stop.

The amount of left to right brake force imbalance, at both the front and rear axle, for the plate brake tester and roller brake tester is shown in Figure 4.8. The Figure shows the amount of imbalance, reported by the brake testing methods, plotted against the measured amount of imbalance in brake pressure. A dashed line is drawn to depict the ideal correlation between the brake pressure imbalance and the imbalance reported by the brake testing methods.

During testing there were four fault conditions in which there was a left to right imbalance generated in the brake pressures of a single axle. In brake fault conditions F and G, there was an imbalance generated in the front axle brake pressures of around 43% and 54% respectively. The plate brake tester was able to accurately detect these imbalances, while the roller brake tester was not.

Brake pressure imbalances of around 42% and 54% in the rear axle were generated during brake fault conditions B and C respectively. Both the plate brake tester and roller brake tester were able to detect these rear axle imbalances to a good degree of accuracy.

For the remainder of the fault conditions the brake pressure imbalance was practically zero (less than 8% in all cases). However, in some tests performed with the plate brake tester an imbalance of around 50% was reported for the rear axle. Investigation of these tests found that they were conducted during brake fault conditions where the rear brake pressures had been reduced to zero through the application of the cut-off valve. In these situations, some small amount of rolling resistance was still detected, to varying degrees, on each of the rear wheels, leading to a reported imbalance.

This residual rolling resistance, when both rear brakes were disabled, also caused the roller brake tester to mistakenly report large amounts of left to right imbalance. Additionally, this situation also resulted in the roller brake tester incorrectly reporting a large imbalance on the front axle.

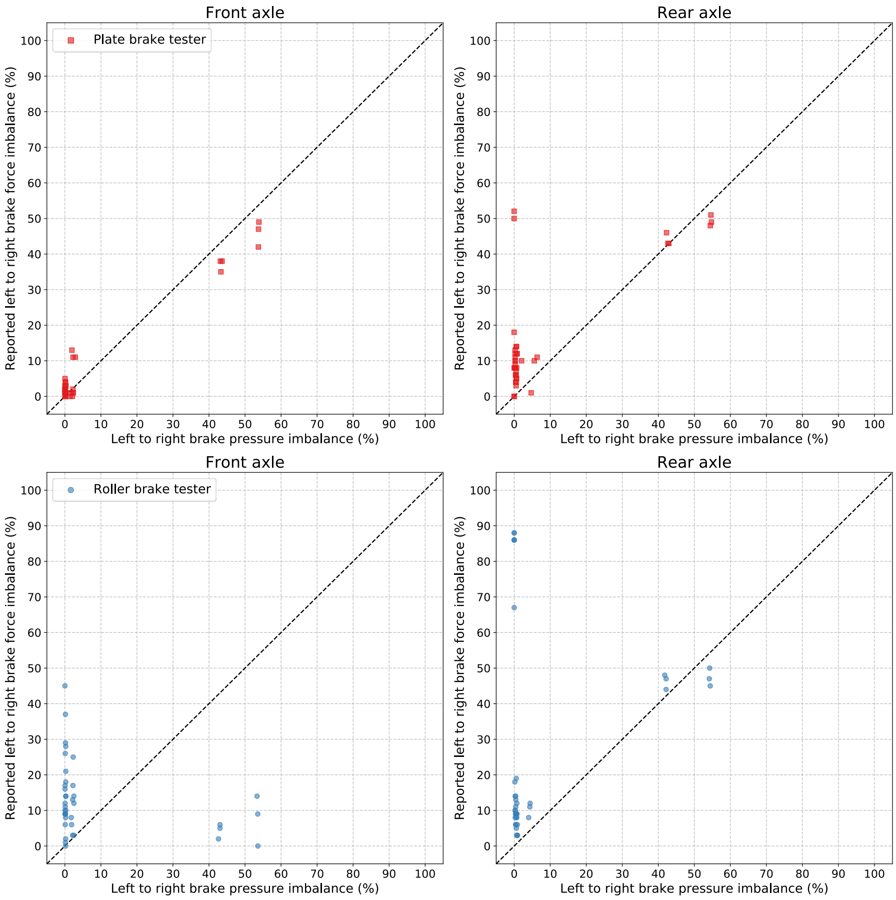


Figure 4.8
Reported left to right brake force imbalance compared to the brake pressure imbalance

4.5 Reported front to rear brake force balance

An optimally operating braking system will generate a suitably balanced amount of braking at the front and rear axles of a vehicle. The appropriate level of balance (the amount of brake force at the front wheels versus the rear wheels) is unique to each vehicle and depends on factors such as the mass distribution and suspension geometry. During braking a vehicle will pitch forward, and this results in a greater amount of weight being applied to the front wheels while the rear wheels become unloaded. As such, the front wheels are typically able to provide a greater amount of brake force relative to the rear wheels. When a vehicle's braking system does not meet the designed front to rear brake force balance, then it may indicate there is a fault. It is not possible to know exactly what the designed front to rear balance should be (other than asking the manufacturer), but for typical modern vehicles the front wheels usually provide more than half of the braking force.

The plate brake tester was the only testing method to report the front to rear brake balance. The front to rear brake force balance reported by the plate brake tester, compared to the front to rear brake pressure balance, is shown in Figure 4.9. A vertical line is drawn at 50% front to rear brake pressure which depicts where the braking at the front and rear axles was equal. To the left of this line represents fault conditions where the front axles brake pressures were lower than on the rear axle. To the right of the line represents fault conditions where the rear axle brake pressures were lower than on the front axle.

In conditions where the brake pressures were equal on the front and rear axles (on the line), the plate brake tester reported a front to rear brake force balance of 80%-20%. As the front to rear brake pressure balance decreased (to the left of the line) so did the reported front to rear brake force balance. Similarly, as the pressure balance increased (to the right of the line), so did the reported brake force balance. Where the rear brakes were disabled completely, the plate brake tester was able to correctly report a front to rear brake force balance of almost 100%-0%.

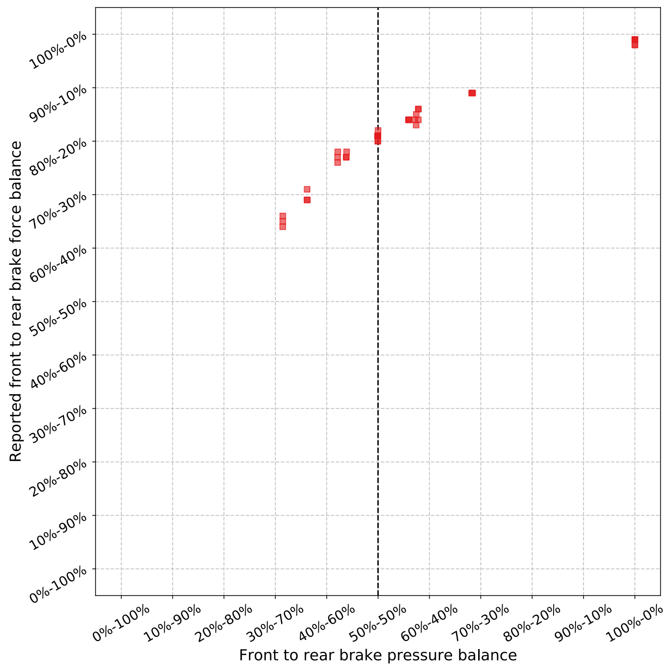


Figure 4.9
Front to rear brake force balance reported by the plate brake tester

5 Results – Brake performance assessment

Presented below are the test results for each of the brake fault conditions assessed by the three recognised brake testing methods. These results are compared to the minimum brake performance criteria from the NSW Authorised Inspection Scheme and a pass or fail is indicated in the tables below. The tables also show the increase in stopping distance that was measured for each fault condition. The brake fault conditions are grouped into similar categories for discussion.

To meet a roadworthy standard, the NSW brake performance criteria requires an average deceleration of greater than 47% g, a peak deceleration of greater than 60% g, and a left to right brake force imbalance (on both axles) of less than 30%. Other jurisdictions in Australia and New Zealand also mandate similar brake performance criteria, as was shown in Table 2.1.

The decelerometer is not able to measure left to right braking imbalance. As such, the limit of 30% in left to right brake force imbalance cannot be assessed when a decelerometer is used to measure brake performance.

The roller brake tester does not provide an average deceleration. Only the maximum deceleration is provided in the tables below for the roller brake testing method.

The plate brake tester is able to measure all assessed elements of brake performance criteria. In addition, while not a measure of performance that is recognised by the NSW roadworthy standard, the plate brake tester measures information on front to rear brake balance and this was also included in the tables below.

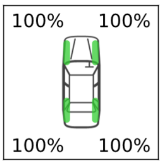
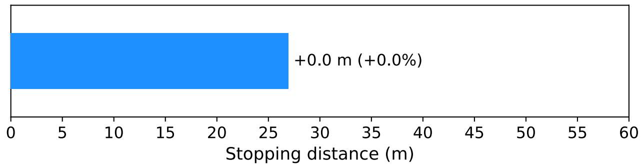
A summary of all the assessment outcomes presented in this section is provided in Appendix J.

5.1 Baseline condition (no brake fault)

No faults were present in the brake system during the baseline condition which is representative of an optimally operating vehicle. The results reported by each of the brake testing methods are shown in Table 5.1.

The plate brake tester and the decelerometer both passed all the criteria comfortably. However, the roller brake tester reported a peak deceleration of 59% g and incorrectly failed the vehicle.

Table 5.1
Brake performance results during baseline condition

<table>
<tr><td colspan="2">Brake force pressure reduction fault condition</td><td colspan="1">
</td><td colspan="2">Baseline – No pressure reductions</td></tr>
<tr><td colspan="2">Stopping distance increase</td><td colspan="3">
</td></tr>
<tr><td rowspan="2">Factor</td><td rowspan="2">Pass criteria (NSW)</td><td colspan="3">Brake testing method</td></tr>
<tr><td>Plate brake tester</td><td>Roller brake tester</td><td>Decelerometer</td></tr>
<tr><td>Average deceleration</td><td>> 47% g</td><td>6.5 m/s² | 65% g</td><td>Not measured</td><td>8.0 m/s² | 82% g</td></tr>
<tr><td>Peak deceleration</td><td>> 60% g</td><td>8.4 m/s² | 86% g</td><td>5.8 m/s² | 59% g</td><td>9.7 m/s² | 99% g</td></tr>
<tr><td>Left to right imbalance (front)</td><td>< 30%</td><td>2%</td><td>11%</td><td>Not measured</td></tr>
<tr><td>Left to right imbalance (rear)</td><td>< 30%</td><td>10%</td><td>10%</td><td>Not measured</td></tr>
<tr><td>Front to rear brake balance</td><td>None</td><td>81%</td><td>Not measured</td><td>Not measured</td></tr>
<tr><td>Overall</td><td>All above</td><td>Pass</td><td>Fail</td><td>Pass</td></tr>
</table>

5.2 Brake force pressure reduction to both front wheels

Reductions to the brake pressures on both front wheels, as might be expected to occur during a master cylinder by-pass fault, were assessed during brake fault conditions H and I. Both fault conditions resulted in substantial increases in stopping distance (45.8% and 73.5% respectively), indicating that the stopping performance of the vehicle had been drastically compromised.

The results reported by each of the brake testing methods are shown in Tables 5.2 and 5.3.

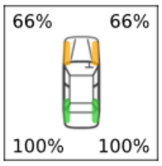
Despite the dangerous increases to the stopping distances, the results from the plate brake tester and the decelerometer passed the brake performance criteria.

The peak deceleration reported by the roller brake tester during fault condition H failed the brake performance criteria. Curiously, during brake fault condition I, where there was a greater pressure reduction than in fault condition H, the roller brake tester recorded a peak deceleration result that passed the performance criteria.

The plate brake tester was able to identify the change in front to rear balance compared with the baseline condition. While the front to rear brake force balance on all vehicles is different, the result of 65% - 35% for fault condition I is suggestive of a brake fault.

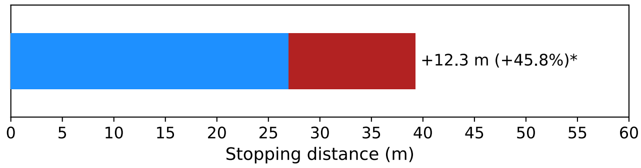
Table 5.2
Brake performance results during brake fault condition H

Brake force pressure reduction fault condition



Front wheels limited to 66% of maximum brake pressure
(e.g. master cylinder by-pass)

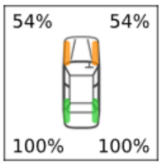
Stopping distance increase



Factor	Pass criteria (NSW)	Brake testing method		
		Plate brake tester	Roller brake tester	Decelerometer
Average deceleration	**> 47% g**	5.6 m/s² | 57% g	Not measured	5.9 m/s² | 60% g
Peak deceleration	**> 60% g**	6.6 m/s² | 67% g	5.3 m/s² | 54% g	6.9 m/s² | 70% g
Left to right imbalance (front)	**< 30%**	0%	6%	Not measured
Left to right imbalance (rear)	**< 30%**	5%	5%	Not measured
Front to rear brake balance	**None**	70%	Not measured	Not measured
Overall	**All above**	Pass	Fail	Pass

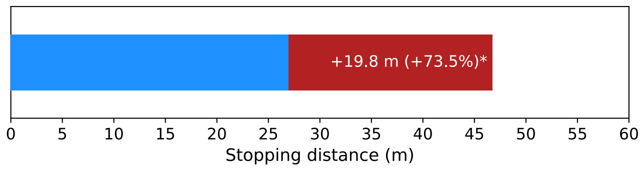
Table 5.3
Brake performance results during brake fault condition I

Brake force pressure reduction fault condition



Front wheels limited to 54% of maximum brake pressure
(e.g. master cylinder by-pass)

Stopping distance increase



Factor	Pass criteria (NSW)	Brake testing method		
		Plate brake tester	Roller brake tester	Decelerometer
Average deceleration	**> 47% g**	5.2 m/s² | 53% g	Not measured	5.3 m/s² | 54% g
Peak deceleration	**> 60% g**	6.2 m/s² | 63% g	6.0 m/s² | 61% g	6.3 m/s² | 64% g
Left to right imbalance (front)	**< 30%**	12%	14%	Not measured
Left to right imbalance (rear)	**< 30%**	5%	10%	Not measured
Front to rear brake balance	**None**	65%	Not measured	Not measured
Overall	**All above**	Pass	Pass	Pass

5.3 Brake force pressure reduction to single front wheel

Reductions to the brake pressures on just a single front wheel, as might be expected to occur with a seized caliper slide, were assessed during brake fault conditions F and G. These fault conditions resulted in increases in stopping distance of 21.6% which could make the difference between a crash occurring or affect the severity of a collision. In addition, the offset in the brake forces could result in the vehicle swerving dangerously under heavy braking.

The results reported by each of the brake testing methods are shown in Tables 5.4 and 5.5.

All of the brake testing methods produced results that passed the mean and peak deceleration criteria. Only the plate brake tester was able to identify the left to right brake force imbalance and reported an imbalance over 30% which resulted in a fail under the brake performance criteria.

The decelerometer does not provide a measure of left to right brake force imbalance, and the roller brake tester failed to detect any significant imbalance.

Table 5.4
Brake performance results during brake fault condition F

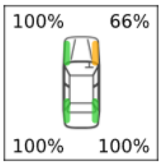
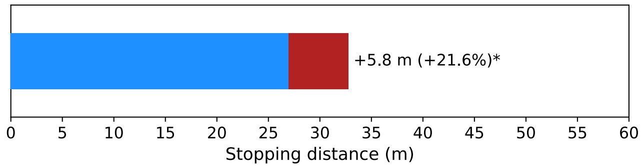
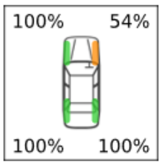
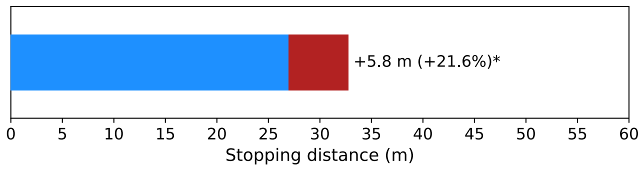
Brake force pressure reduction fault condition			Front right wheel limited to 66% of maximum brake pressure (e.g. seized caliper slide)	
Stopping distance increase				
Factor	**Pass criteria (NSW)**	**Brake testing method**		
		Plate brake tester	Roller brake tester	Decelerometer
Average deceleration	**> 47% g**	6.4 m/s² | 65% g	Not measured	7.1 m/s² | 72% g
Peak deceleration	**> 60% g**	8.2 m/s² | 84% g	5.9 m/s² | 60% g	8.6 m/s² | 88% g
Left to right imbalance (front)	**< 30%**	37%	4%	Not measured
Left to right imbalance (rear)	**< 30%**	6%	6%	Not measured
Front to rear brake balance	**None**	77%	Not measured	Not measured
Overall	**All above**	Fail	Pass	Pass

Table 5.5
Brake performance results during brake fault condition G

Brake force pressure reduction fault condition			Front right wheel limited to 54% of maximum brake pressure (e.g. seized caliper slide)	
Stopping distance increase				
Factor	**Pass criteria (NSW)**	**Brake testing method**		
		Plate brake tester	Roller brake tester	Decelerometer
Average deceleration	**> 47% g**	6.0 m/s² | 61% g	Not measured	7.1 m/s² | 72% g
Peak deceleration	**> 60% g**	7.7 m/s² | 78% g	6.1 m/s² | 62% g	9.1 m/s² | 93% g
Left to right imbalance (front)	**< 30%**	46%	8%	Not measured
Left to right imbalance (rear)	**< 30%**	13%	6%	Not measured
Front to rear brake balance	**None**	77%	Not measured	Not measured
Overall	**All above**	Fail	Pass	Pass

5.4 Brake force pressure reduction to both rear wheels

Reductions to the brake pressures on both rear wheels, as might be expected with a faulty proportioning valve, were assessed during brake fault conditions A, D, and E. As a result, the test vehicle's stopping distance was affected to varying amounts. During fault conditions A and D, the stopping distance was only increased a small amount and was not found to be significantly different to the baseline stopping distance. This indicates the difficulty in identifying such conditions. For brake fault condition E, where the rear brakes were disabled, the stopping distance was increased by 30.0% compared to baseline – a potentially dangerous situation.

The results reported by each of the brake testing methods are shown in Tables 5.6 to 5.8.

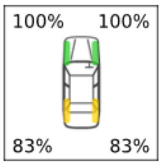
Peak and average decelerations well above the minimum performance criteria were reported by both the plate brake tester and decelerometer. This was not true for the roller brake tester, which reported peak decelerations below the minimum performance criteria.

The plate brake tester correctly reported low values of left to right imbalance for all the fault conditions. The roller brake tester also reported low values for left to right imbalance during fault condition A. But this was not the case during brake fault conditions D and E. For fault condition D, the roller brake tester incorrectly reported a left to right imbalance on the front axle of 30%, failing the brake performance criteria. For fault condition E, the roller brake tester reported an excessive amount of left to right imbalance on the rear axle.

The plate brake tester was able to identify progressive changes in the front to rear brake force balance. Notably, for brake fault condition E, the plate brake tester reported a front to rear balance of 99% - 1%. While the deceleration values were within the brake performance criteria, this extreme level of front to rear balance would have showed clearly that the rear brakes were faulty.

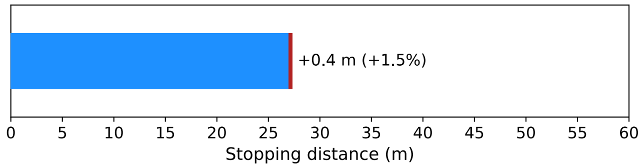
Table 5.6
Brake performance results during brake fault condition A

Brake force pressure reduction fault condition



Rear wheels limited to 83% of maximum brake pressure
(e.g. fault proportioning valve)

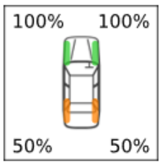
Stopping distance increase



Factor	**Pass criteria (NSW)**	**Brake testing method**		
		Plate brake tester	Roller brake tester	Decelerometer
Average deceleration	**> 47% g**	6.6 m/s² | 67% g	Not measured	8.0 m/s² | 82% g
Peak deceleration	**> 60% g**	8.5 m/s² | 87% g	5.2 m/s² | 53% g	8.7 m/s² | 89% g
Left to right imbalance (front)	**< 30%**	3%	5%	Not measured
Left to right imbalance (rear)	**< 30%**	11%	17%	Not measured
Front to rear brake balance	**None**	84%	Not measured	Not measured
Overall	**All above**	Pass	Fail	Pass

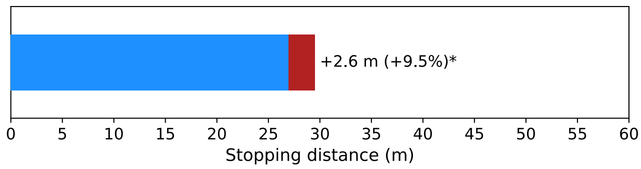
Table 5.7
Brake performance results during brake fault condition D

Brake force pressure reduction fault condition



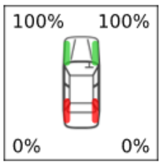
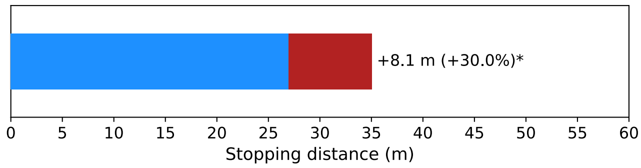
Rear wheels limited to 50% of maximum brake pressure
(e.g. fault proportioning valve)

Stopping distance increase



Factor	**Pass criteria (NSW)**	**Brake testing method**		
		Plate brake tester	Roller brake tester	Decelerometer
Average deceleration	**> 47% g**	6.1 m/s² | 62% g	Not measured	7.5 m/s² | 76% g
Peak deceleration	**> 60% g**	8.0 m/s² | 82% g	3.8 m/s² | 39% g	9.3 m/s² | 95% g
Left to right imbalance (front)	**< 30%**	2%	30%	Not measured
Left to right imbalance (rear)	**< 30%**	7%	10%	Not measured
Front to rear brake balance	**None**	89%	Not measured	Not measured
Overall	**All above**	Pass	Fail	Pass

Table 5.8
Brake performance results during brake fault condition E

Brake force pressure reduction fault condition			Rear wheels disabled (e.g. fault proportioning valve)	
Stopping distance increase				
Factor	**Pass criteria (NSW)**	**Brake testing method**		
		Plate brake tester	Roller brake tester	Decelerometer
Average deceleration	**> 47% g**	5.6 m/s² | 57% g	Not measured	7.2 m/s² | 73% g
Peak deceleration	**> 60% g**	7.3 m/s² | 74% g	2.7 m/s² | 28% g	8.7 m/s² | 89% g
Left to right imbalance (front)	**< 30%**	1%	25%	Not measured
Left to right imbalance (rear)	**< 30%**	9%	86%	Not measured
Front to rear brake balance	**None**	99%	Not measured	Not measured
Overall	**All above**	Pass	Fail	Pass

5.5 Brake force pressure reduction to single rear wheel

Brake pressure reductions to just a single rear wheel, as might be expected in a situation where there was air in the hydraulic system, were assessed during brake fault conditions B and C. Only fault condition C resulted in a stopping distance that was significantly greater than the baseline. However, an imbalance in the left to right brake forces of a vehicle can pose a dangerous situation when braking heavily, particularly if applied during cornering.

The results reported by each of the brake testing methods are shown in Tables 5.9 and 5.10.

The plate brake tester and decelerometer reported mean and peak decelerations well above the brake performance criteria. However, for both fault conditions, the roller brake tester reported a peak deceleration that was well below the brake performance criteria.

While the decelerometer is not able to measure left to right brake force imbalance, both the plate brake tester and the roller brake tester were able to accurately identify the imbalance in the rear axle (resulting in a failure of the brake performance criteria).

Table 5.9
Brake performance results during brake fault condition B

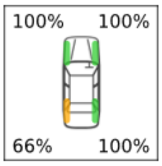
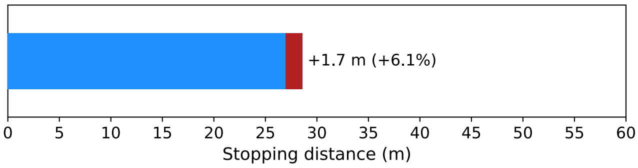
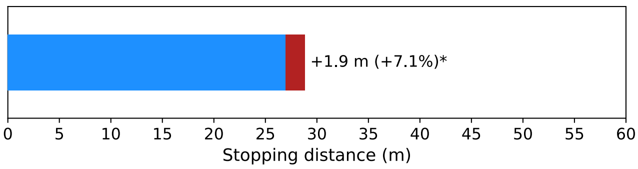
Factor	Pass criteria (NSW)	Brake testing method		
Brake force pressure reduction fault condition			Rear left wheel limited to 66% of maximum brake pressure (e.g. air in the hydraulic system)	
Stopping distance increase				
		Plate brake tester	Roller brake tester	Decelerometer
Average deceleration	**> 47% g**	6.2 m/s² | 63% g	Not measured	7.7 m/s² | 78% g
Peak deceleration	**> 60% g**	8.0 m/s² | 82% g	5.2 m/s² | 53% g	9.1 m/s² | 93% g
Left to right imbalance (front)	**< 30%**	3%	5%	Not measured
Left to right imbalance (rear)	**< 30%**	44%	46%	Not measured
Front to rear brake balance	**None**	84%	Not measured	Not measured
Overall	**All above**	Fail	Fail	Pass

Table 5.10
Brake performance results during brake fault condition C

Factor	Pass criteria (NSW)	Brake assessment method		
Brake force pressure reduction fault condition			Rear right wheel limited to 50% of maximum brake pressure (e.g. air in the hydraulic system)	
Stopping distance increase				
		Plate brake tester	Roller brake tester	Decelerometer
Average deceleration	**> 47% g**	6.4 m/s² | 65% g	Not measured	7.4 m/s² | 75% g
Peak deceleration	**> 60% g**	8.3 m/s² | 85% g	4.5 m/s² | 46% g	9.1 m/s² | 93% g
Left to right imbalance (front)	**< 30%**	2%	22%	Not measured
Left to right imbalance (rear)	**< 30%**	49%	47%	Not measured
Front to rear brake balance	**None**	85%	Not measured	Not measured
Overall	**All above**	Fail	Fail	Pass

5.6 Brake force pressure reduction affecting all wheels

A reduction to the brake pressures in all four wheels of the test vehicle, as might occur in the event of a brake booster failure, was assessed in brake fault condition J. The effect of this condition, in terms of increased stopping distance, was an extreme 75.9%. This was the most severe fault condition implemented during the study. A vehicle with this type of fault would be extremely dangerous.

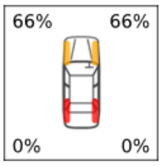
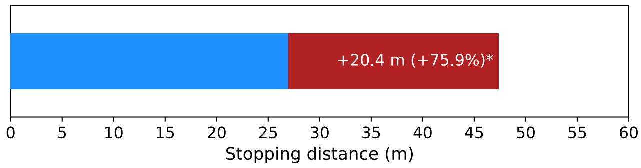
The results reported by each of the brake testing methods are shown in Table 5.11.

Reassuringly, all the brake assessment methods reported deceleration results that failed the brake performance criteria. It was noteworthy that this was the only fault that resulted in a fail for the decelerometer.

A large left to right brake force imbalance was reported for the rear axle by both the plate brake tester and the roller brake tester. As the rear brakes were disabled this was likely to be because the measured brake forces were so low that even a small difference resulted in a large reported imbalance.

The plate brake tester was also able to identify a front to rear balance of 98% - 2%, which provided even more evidence that the rear brakes were not performing adequately.

Table 5.11
Brake performance results during brake fault condition J

<table>
<tr><td colspan="2">Brake force pressure reduction fault condition</td><td>
</td><td colspan="2">Rear wheels disabled and front wheels limited to 66% of maximum brake pressure (e.g. brake booster failure)</td></tr>
<tr><td colspan="2">Stopping distance increase</td><td colspan="3">
</td></tr>
<tr><td rowspan="2">Factor</td><td rowspan="2">Pass criteria (NSW)</td><td colspan="3">Brake testing method</td></tr>
<tr><td>Plate brake tester</td><td>Roller brake tester</td><td>Decelerometer</td></tr>
<tr><td>Average deceleration</td><td>> 47% g</td><td>4.5 m/s² | 46% g</td><td>Not measured</td><td>4.3 m/s² | 44% g</td></tr>
<tr><td>Peak deceleration</td><td>> 60% g</td><td>5.1 m/s² | 52% g</td><td>2.6 m/s² | 27% g</td><td>5.0 m/s² | 51% g</td></tr>
<tr><td>Left to right imbalance (front)</td><td>< 30%</td><td>1%</td><td>14%</td><td>Not measured</td></tr>
<tr><td>Left to right imbalance (rear)</td><td>< 30%</td><td>34%</td><td>81%</td><td>Not measured</td></tr>
<tr><td>Front to rear brake balance</td><td>None</td><td>98%</td><td>Not measured</td><td>Not measured</td></tr>
<tr><td>Overall</td><td>All above</td><td>Fail</td><td>Fail</td><td>Fail</td></tr>
</table>

6 Discussion

The objective of this study was to investigate the ability of four brake testing methods to recognise mechanical or hydraulic brake faults on light vehicles. Brakes can be considered the most important safety feature on a vehicle and must be maintained to ensure optimal performance. Even for modern vehicles with advanced electronic systems, the mechanical operation of brakes has changed little over the last decades. That is, a pair of friction pads mounted to calipers, and activated through a hydraulic system, which clamp onto a rotor attached to the wheels of the vehicle. A mechanical or hydraulic fault is unlikely to be identified by an electronic system and, as such, brake testing today is just as relevant as ever.

The literature review presented in Section 2 explored the prevalence of brake faults in the general fleet and their effect on safety. Much of the data regarding the prevalence of crashes resulting from vehicle faults comes from police reports and indicates that they are rare (2-3%). However, it was acknowledged that police do not necessarily have the time, nor the training, to identify all vehicle faults. The small number of studies that explored data based on more in-depth investigations of vehicle faults found that they may actually be responsible for closer to 10% of crashes (or even higher). Furthermore, a study that looked at the prevalence of vehicle faults in the general vehicle fleet found that up to 40% of vehicles may be affected by some kind of defect. Regardless of the data source, all studies indicated that brake faults were one of the most commonly reported vehicle faults.

Fortunately, the literature also indicated that periodic vehicle inspection schemes are an effective method of improving the mechanical condition of vehicle in the general fleet and reducing the prevalence of vehicle faults. However, the effectiveness of inspection schemes in reduced fault-related crashes was less clear with contradictory findings within the literature. On top of this, the high cost of facilitating periodic inspection schemes means many jurisdictions in Australia find them difficult to justify. Even so, all jurisdictions in Australia and New Zealand dictate performance criteria that light vehicles must meet to be considered roadworthy. These criteria include performance standards for brakes such as a minimum required peak deceleration and a maximum allowable amount of left to right imbalance in brake forces.

Brake testing machines provide a rapid method of investigating the performance of a vehicle's brakes and checking whether they meet the roadworthiness performance criteria. However, it is important for vehicle owners and roads authorities to understand the differences between brake testing methods, their advantages, their limitations, and to have confidence in the results they provide. The operation of three brake testing methods (generally accepted by industry and authorities) were described and relevant literature was reviewed. These were plate brake testing machines, roller brake testing machines, and portable brake testing decelerometers. In addition, an outline of the high-speed stopping distance test was provided.

Section 3 described the methodology for the study, which involved professionally fitting equipment to a common passenger vehicle to enable the control of the brake pressure applied to the individual wheels to simulate common brake faults. The installed equipment consisted of pressure reduction valves, cut-off valves, and pressure sensors at each wheel. The pressure sensors were connected to a data logger to record the brake pressures achieved during testing.

A brake pedal robot, capable of supplying specific and repeatable brake applications, was also installed. This brake pedal robot provided a consistent force upon the brake pedal when activated, which was logged by a load cell integrated into the robot system. The robot was programmed to provide a force that was just strong enough to trigger the test vehicle's ABS.

Four examples of brake testing equipment were acquired for use in the study:

- A SafeTstop plate brake tester,
- A Vehicle Inspection Systems roller brake tester,
- A Circuitlink Brake-Testa portable decelerometer, and
- A Racelogic Vbox 3iSL GPS data logger for use in high-speed stopping distance tests.

Data collection then occurred during a series of test sets performed over two days at a private airstrip. During each test set, a brake fault condition was simulated using the equipment installed onto the test vehicle to adjust the maximum brake pressures at individual wheels. The vehicle was then tested three times on each piece of brake testing equipment. During the data collection process, checks were made to monitor and regulate the consistency of the test vehicle's weight, tyre pressures, tyre temperatures, and brake pad temperatures. Checks were also made to monitor the consistency of the readings from the brake pressures and the accuracy of the Racelogic Vbox GPS equipment. A test set with the vehicle in a baseline condition (no adjustments to maximum brake pressure) was performed at the beginning, at a midpoint, and at the end of the data collection activities to check for any possible changes in the test vehicle over time.

The data collected from the four brake testing methods, the brake pedal robot, and the brake pressure sensors was collated, combined where necessary, and processed into a format suitable for analysis.

The equipment and methodology used in the study was reviewed by metrology specialists from the National Measurement Institute. They produced a report which concluded that the measurements conducted were appropriate to give confidence in the validity of the comparative testing.

During data collection (and the processing/analysis of the test data) it became clear that the results of the roller brake tester were, in many cases, considerably different to the results reported by the other brake testing methods. More precisely, the roller brake tester reported peak decelerations that were consistently low (exacerbated even further when brake pressures on the rear wheels of the test vehicle were reduced), failed to recognise brake pressure imbalances on the front axle, and incorrectly reported an imbalance on the front axle when none existed.

It is not clear whether this is a common issue when using roller brake testers with light vehicles, as the small amount of literature on the subject that could be found was focussed on heavy vehicles.

In Section 4, it was shown that the methodology used in this study was successful in implementing relatively consistent brake pedal applications during the testing. During the high-speed stopping distance tests, there was some tendency for an increased force to be applied to the brake pedal, but this did not result in a large corresponding increase in brake pressure. The recorded brake pressures, elicited through adjustments to the pressure reduction and cut-off valves, were also relatively consistent during testing of the various brake fault conditions and with the four brake testing methods.

The implemented brake fault conditions all resulted in an increase to the test vehicle's stopping distance. This increase ranged from minor, and not significantly different to the stopping distance in the baseline condition, to extreme. The largest increase in stopping distance was over 75%, which equates to an extra 20 metres for a vehicle travelling at 80 km/h.

In terms of reported peak and average deceleration, each testing method reported different values for the baseline condition. The high-speed stopping distance test reported the highest decelerations, followed by the decelerometer, the plate brake tester, and finally the roller brake tester (which was drastically lower than the other testing methods).

As the severity of the fault conditions increased (leading to greater stopping distances), the reported decelerations decreased correspondingly with respect to the baseline decelerations for all testing methods (apart from the roller brake tester.)

Reductions to the brake pressures in the rear wheels did not affect the reported decelerations significantly, until the rear wheels were completely disabled. Brake pressure reductions to just a single front wheel also did not result in any significant reduction to the reported decelerations. When brake pressure reductions were applied to both front wheels, then a clear reduction to the reported decelerations was observed. This effect was even greater when the front wheel pressure reductions were combined with disabling the rear brakes.

Both the plate brake tester and the roller brake tester were able to report on the left to right imbalance in brake forces. This was not a capability of the decelerometer, or indeed the high-speed stopping distance test. The left to right brake pressure imbalance for each fault condition was clearly measured by the plate brake tester on both the front and rear axles. The roller brake tester was able to correctly identify left to right imbalance on the rear axle but not on the front axle.

Only the plate brake tester was able to provide a measurement for the front to rear brake force balance. The front to rear brake force balance reported by the plate brake tester was compared to the front to rear brake pressure adjustment for each fault condition. The reported values were consistent with the adjustments in the front to rear pressure balance. Notably, the plate brake tester was able to correctly identify when the rear brakes of the test vehicle had been disabled by reporting a front to rear brake force balance of almost 100% - 0%.

In Section 5, minimum brake performance criteria from the NSW Authorised Inspection Scheme was applied to the reported results from each brake testing method, during each of the brake fault conditions. The increase in stopping distance, brought about by each brake fault condition, was used as a measure of severity to provide some context.

Setting aside the results of the roller brake tester (which were inconsistent with the implemented fault conditions), the effectiveness of the brake performance criteria in identifying brake faults, based on the results of the approved brake testing methods, was mixed. For brake fault conditions where there was an implemented imbalance in the left to right brake pressures (on the front or rear axle), the plate brake tester was able to identify this imbalance and the vehicle would have failed the brake performance criteria. For these same brake fault conditions, the decelerometer (which was not able to measure left to right imbalance) would have deemed that the vehicle had passed the brake performance criteria.

In the remaining brake fault conditions, where there was no left to right imbalance, the only criteria on which to assess the performance of the brakes was the peak and average decelerations. It was only for the most severe brake fault condition, where the stopping distance was increased by 75.9%, that the plate brake tester and decelerometer reported peak and average deceleration values that fell below the brake performance criteria. Alarmingly, there were instances where severe brake faults would have passed the brake performance criteria. These included faults where both rear brakes were completely disabled, both front brakes were limited to 66% of maximum brake pressure, and both front brakes were limited to 54% of maximum brake pressure, leading to increases in stopping distances of 30.0%, 45.8%, and 73.5% respectively.

Conclusions

This was the first study, to the authors' best knowledge, that investigated the use of plate brake testers with light vehicles and the first to conduct back to back investigations of multiple brake testing methods on light vehicles.

In general, all the brake testing methods were easy to perform and relatively quick. Each took less than a few minutes, although the decelerometer and the high-speed stopping distance test did require a clear roadway which required extra “travel time” (and additional safety implications that needed to be considered).

The results reported by each of the brake testing methods were reviewed individually, and their ability to detect mechanical or hydraulic faults was summarised.

The high-speed stopping distance test is recognised as an objective test of a vehicle brakes. It reported the highest level of deceleration and produced the largest change in reported deceleration over the set of brake fault conditions that were tested. As such, this testing method was considered to have the best ability to measure deceleration. However, a measure of deceleration (in isolation) is not sufficient to detect faulty brakes, unless a vehicle’s stopping power was severely compromised. In addition, the testing method is unable to detect any kind of imbalance in a vehicle’s brakes. This means that faults which affect just a single wheel would not be identified.

The plate brake tester measures brake forces at each individual wheel and offered the most information about the performance of the test vehicle’s braking system, including peak and average deceleration, left to right brake force imbalance, and front to rear brake force balance. During this study, the plate brake tester reported results that were consistent with all the brake fault conditions that had been implemented. As such, the testing method was considered to be able to offer the most comprehensive report on a vehicle’s brakes and identify brake faults that result in reduced stopping power as well as left to right imbalance on either axle. By measuring the front to rear brake force balance, the plate brake tester was also able identify when the rear brakes were seriously compromised in situations where the vehicle was still providing a relatively high level of overall deceleration. The plate brake tester was the only brake testing method to provide this information.

The roller brake tester was able to report on peak deceleration and the left to right brake force imbalance on the front and rear axle. The results reported by the roller brake tester were inconsistent with those of the other brake testing methods and with the implemented brake fault conditions. It is unknown whether this was representative of roller brake testers in general, or unique to the machine that was used in this study. The peak deceleration reported by the roller brake tester were consistently low. The reported peak deceleration values reduced for fault conditions that affected the rear wheels, but not conditions that affected the front wheels. Similarly, the roller brake tester was able to accurately identify left to right brake force imbalance on the rear axle, but not for the front axle.

The decelerometer was found to produce results that were comparable to the high-speed stopping distance test. As such, the decelerometer was considered to be able to provide a reasonable understanding of a vehicle’s deceleration. This would not be sufficient to identify brake faults, apart from situations where a vehicle’s stopping power was severely compromised. Additionally, the decelerometer was not able to measure left to right brake force imbalance and would therefore be unable to identify a range of faults that result in diminished braking to just a single wheel.

The minimum brake performance criteria from the NSW Authorised Inspection Scheme were used to explore how the reported results from each brake testing method would have been assessed. It was found that significant and severe faults, resulting in extreme increases in stopping distance, would still pass the minimum required levels of peak and average deceleration. Most other Australian states and territories, as well as New Zealand, define brake performance criteria that are similar to the criteria used in NSW.

Most modern vehicles are able to generate greater amounts of deceleration compared with vehicles from the past when the brake performance criteria were originally formulated. Based on the results of this study, it is suggested that a review of the brake performance criteria used in all Australian and New Zealand jurisdictions is warranted in order to keep pace with the capabilities of modern vehicles and improve the overall safety of the general vehicle fleet.

Acknowledgements

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Appendix A – Vehicle inspection

NRMA **Safety check**

Inspection Type ☐ Service ☐ Other | Tick OK | X Requires Attention | N/A Not applicable | Current Odometer km

PRE ROAD TEST ☐ Noteworthy Damage ☐ Key/Remote ☐ S'Cover/Flr mat/Radio off ☐ Warning Lights | Service Due ______/______ ________,______ km

ROAD TEST ☐ Powertrain ☐ Driveline ☐ Brake/Bearings ☐ Steering/Suspension ☐ Steering centralised | Service provider

GENERAL
☐ Handbrake operation
☐ Seatbelt cond/operation
☐ Bonnet/boot release
☐ A/C & fan operation
☐ Scan check (if applicable)
☐ Fuel flap/cap release
☐ Wiper arm/blade cond
☐ Cabin filter
☐ Horn/Lights/Pedal Pads
☐ Wipers/Washer aim
☐ Bounce Test
☐ Check Spare

Tyre Placard Details

Load	Speed	F.PSI	R.PSI

☐ Lock nut cond

UNDER BONNET
☐ Bonnet Struts
☐ Engine Air Filter
☐ Throttle/Intake
☐ Drive belts
☐ Auto Trans Fluid (if applicable)
☐ T/belt within date/km
☐ Upper Mountings
☐ Brake/Clutch lines/components
☐ Brake/Clutch fluid cond/test
☐ Power Steer level/leaks
☐ Cooling system
☐ Coolant level
☐ Rust/Limescale Contamination
☐ Coolant cond/age/strip test

Pressure Test Required? NO | YES
Test Result ☐

System Test

PASS	MARG	FAIL	CCA

ALT CHARGE RATE V | TYPE/ BRAND

☐ Terminal Condition

HOIST MIDWAY
☐ Wheel bearings
☐ Steering rack ends
☐ Suspension leaks
☐ Wheel nut/studs/bolts
☐ CV Boot
☐ Rack boots
☐ Other

Brake Pads

	Good	Low		*Recommend Replacement Material Remaining(mm)*
LHF	>6mm	5-4mm	<3mm	
RHF	>6mm	5-4mm	<3mm	
RHR	>6mm	5-4mm	<3mm	
LHR	>6mm	5-4mm	<3mm	

Brake Discs/Drums

Manufactures Min Specs		*Actual*	*Fit for Use*
Front	LHF	mm	☐
	RHF	mm	☐
Rear	RHR	mm	☐
	LHR	mm	☐

☐ Caliper/Slides
☐ Dustboots/Rubbers
☐ Wheel Cylinders
☐ Spring/clips
☐ Flexible hose/fittings

TYRES
Size Fitted ________________
Brand ____________________

Tread Depth Remaining

	Outer	Mid	Inner		Inner	Mid	Outer
LHF				RHF			
LHR				RHR			
Spare							

☐ Wheel Alignment Visual
☐ Tyre Condition
☐ Correct tyres fitted
☐ Other

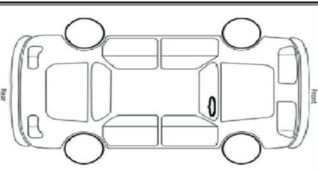
Inflated tyre pressure to
Front PSI | Rear PSI | Spare PSI

HOIST FULLY RAISED
☐ Engine leaks/condition
☐ Steering System condition
☐ Suspension Condition
☐ Gearbox leaks/level
☐ Driveline/universal joints
☐ Exhaust System condition
☐ Lower brake line/clutch lines/slave cylinder
☐ Fuel line condition/leaks
☐ Differential(s) leaks/level
☐ General underbody cond
☐ Grease joints(if applicable)

SERVICE OPERATIONS FINALISED
☐ Under Vehicle Levels & adjustments
☐ Oil filter tight & clean
☐ Sump plug tight & clean
☐ Rotate & Balance(if applicable)
☐ Under bonnet Levels & adj
☐ Service Indicator reset
☐ Logbook / Service Sticker

Suggested repairs	Labour	Parts	Quote

Parts Used	Qty	Parts Used	Qty



Repairs and consumables
$
Plus Service Cost
$
Customer approved
$

Team Member Completing the job
Confirm all works completed as required
----
signature & initials

Final Road Test
and inspection satisfactory
----
signature & initials

Ensure vehicle is free of grease, oil and hand marks before making it ready for collection

DCG-7490

Tax invoice

Motorserve Pty Ltd
ABN 41 121 715 393
license number MVRL43713
Tax invoice no. 30860440859
Issue date 15/05/2020
Page **1** of **2**

2 Cosgrove Rd
Strathfield South 2136 NSW
(02) 8755 7799
AU23816

[redacted]

Membership number: 2037102

Vehicle details

Make:	KIA	**Model:**	CERATO
Kms:	79444	**Registration number:**	[redacted]
VIN:	[redacted]	**Registration date:**	24/03/2021

Invoice summary

Product	Description
SCI - 40 Point Safety Check	Carried out 40 Point Safety Check Front brakes 8/8mm approximately remaining Rear brakes 8/8mm approximately remaining Windscreen condition ok Rear tyres good Spare tyre good Battery condition ok Front tyres - good

Parts and labour	Quantity	Price
	Subtotal	**$80.00**

Cont'd over

Appendix B – Honeywell pressure sensor details

DATASHEET PART 58043

HONEYWELL 2000 PSI PRESSURE SENSOR

The 2000 PSI (13785 kPa) Honeywell MLH pressure sensor is a 0 to 2000 PSI gauge pressure sensor suitable for use with fluids in applications such as fuel, oil or coolant pressure.

COMPATIBILITY

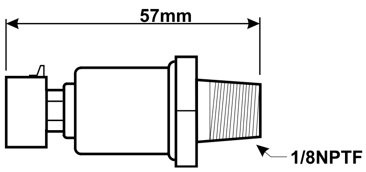
Suitable for use with:

- M84 ECU
- Hundred series ECUs
- M1 series ECUs
- All MoTeC data loggers

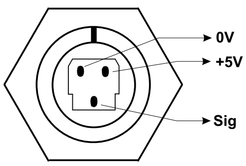
Connector

MoTeC connector part number: 65013

SPECIFICATIONS



The Honeywell pressure sensor is an analogue sensor with 0 to 5 V output (working range generally 0.5 V - 4.5 V). The sensor signal wire can be used with any Analogue Voltage (AV) input on compatible devices, see the signal pin table below.



Looking into sensor connector

Connection is to a regulated 5 V supply and 0 V sensor ground, and should be to the same device that is reading the signal. See the relevant MoTeC device documentation for pin numbers.

CALIBRATION

Manual Calibration

0.5 V = 0 PSI (0 kPa)

4.5 V = 2000 PSI (13789 kPa)

Using the ECU Manager

For M84, M400, M600, M800 and M880.

Use predefined calibrations:

#100 Pres(PSI) Ti 2000PSI Abs

kPa: no predefined calibration available, use a custom table with manual calibration.

Using M1 Tune

For M130, M150, M170, M190, M141, M142, M181 and M182.

Use manual calibration for the sensor calibration table.

Using the Display/Logger Manager

For SDL3, ADL3, CDL3, C125, C185, C127 and C187.

Use the predefined calibration: Honeywell MLH 0-2000PSIG.

ECU AVAILABLE SIGNAL PINS

M84	M400, M600, M800	M880	M130*	M150*	M170*	M190*	M141/M142*	M181/M182*
A15, A17, A25, B22	A14, A15, A16, A17, A25, B20, B21, B22	6, 7, 12, 18, 26, 35, 36, 44	A14, A15, A16, A17, A 25, B20, B21, B22	C14, C15, C16, C17, C25, D20, D21, D22, B10, B11, B12, B16, B17, B18, A3, A4, A5	A6, A7, A12, A18, A26, A35, A36, A44	C42, C36, C35, C28, C29, C11, C12, C6, C13, C7, A13 A35, A34, A41, A27, A28, A29, A38	C14, C15, C16, C17, C25, D20, D21, D22, B10, B11, B12, B16, B17, B18, A3, A4, A5	C42, C36, C35, C28, C29, C11, C12, C6, C13, C7, A13 A35, A34, A41, A27, A28, A29, A38

* Availability of some M1 series ECU pins may be limited depending on channel assignments for specific firmware packages.

 Check for latest version at www.motec.com 1 www.efi HARDWARE .com

Honeywell 2000PSI Gauge Pressure Sensor P/N H-PS2000G

Drawing Revision 1 - 21/7/2014

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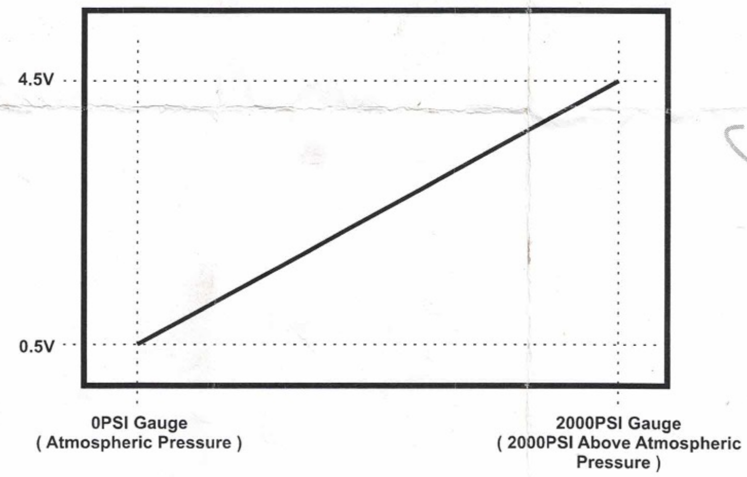
www.efihardware.com

info@efihardware.com
(03) 9873 5400
+613 9873 5400
(03) 9873 5955
+613 9873 5955

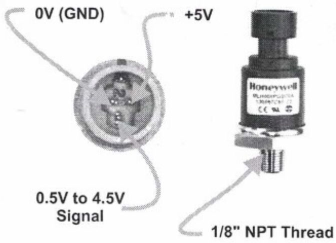
Pressure Vs Voltage



NOTES:

Gauge Pressure is pressure above atmospheric pressure. You might also think of it as "boost pressure".

This is an active sensor. Do not use a pull-up resistor on the signal of this sensor. The output is driven to the correct voltage by the electronics inside the sensor.



APPLICATIONS:

This sensor is most often used to monitor brake fluid pressure.

This sensor has a stainless steel body.

Appendix C – Calibration records: Brake robot load cell

Abstec Calibrations Australia Pty Ltd
A.C.N. 074 824 847 ABN 91 751 155 014
79 Ledger Road, Beverley SA 5009
Telephone (08) 8244 1355
Facsimile (08) 8445 1377
Toll Free: 1800 247 555
www.abstec-calibrations.com.au

Calibration Report on a Load Cell

Report No.: **A33460FB**
Print Date: 29/04/2020
Page 1 / 2

For: The University of Adelaide
Centre for Automotive Safety Research
Ground Floor, Engineering Annexe
Gate 5, Frome Road, Adelaide SA 5005

Machine Location: Laboratory
Calibration Date: 29-Apr-2020
Calibration Due: 29-Apr-2022
Ambient temperature during test: 20 ± 1 °C
System Details:

	Load Cell	Indicator
Manufacturer:	Dacell	Keithley
Serial Number:	D0607084	605325
Model / Type:	UU-K100	2000
I D Number:	Nil	
Capacity:	1 kN	
Excitation Voltage:	10 V DC	

Force Application: Externally Applied compression
Force Indication: Digital

Reference Standard:
Australian Standard AS 2193-2005
Methods for the calibration and classification of
Force - Measuring Systems of Testing Machines

Preliminary Inspection:
The device was in a satisfactory operating condition and did not require any adjustments.

Calibration Procedure:
The device was calibrated using procedures in accordance with AS 2193-2005 (Section 3).
Abstec TPM 2 / 2.6.
Three series of tests were made in the compression direction using equipment traceable to Australian Measurement Standards.
Reference equipment used : Load Cell s/n: 7008052,

Calibration Results:
The classification is based on requirements of readability, repeatability and error.

ilac-MRA NATA Accreditation No. 11087

Accredited for compliance with ISO/IEC 17025 - Calibration.
The results of the tests, calibrations and/or measurements included in this document are traceable to Australian/national standards.
NATA is a signatory to the ILAC Mutual Recognition Arrangement for the mutual recognition of the equivalence of testing, medical testing, calibration and inspection reports. This document shall not be reproduced except in full. NATA accreditation number 11087.

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Telephone (08) 8244 1355
Facsimile (08) 8445 1377
Toll Free: 1800 247 555
www.abstec-calibrations.com.au

Report No.: A33460FB
Print Date: 29/04/2020
Page: 2 of 2

Calibration Results: compression

Applied Force kN	Mean Reading mV	Error %	Repeatability %	k Value	Uncertainty ± kN	Class AS 2193
0.1	2.042	0.1	0.1	2.0	0.0004	A
0.2	4.082	0.0	0.1	2.0	0.0004	A
0.3	6.128	0.0	0.1	2.0	0.0004	A
0.4	8.170	0.0	0.1	2.1	0.0004	A
0.5	10.215	0.0	0.1	2.0	0.0005	A
0.6	12.263	0.0	0.0	2.0	0.0006	A
0.7	14.306	0.0	0.0	2.0	0.0007	A
0.8	16.352	0.0	0.0	2.0	0.0008	A
0.9	18.398	0.0	0.0	2.1	0.0009	A
1.0	20.443	0.0	0.0	2.3	0.0010	A

Notes : A negative error indicates the applied force is greater than the calculated force. The error is the difference between the applied force and the calculated force.

Calculation: Use the following equation to determine the Force in terms of Deflection.

$$\text{Force} = aR^2 + bR + c$$

Where:

R= Instrument readings
a= -2.08174E-06
b= 0.04895
c= 0.00013

Uncertainty: The estimated uncertainties associated with the tabulated values are expressed at approximately 95 % confidence level.

Conclusion: The device was found to conform with the requirements of AS 2193-2005.

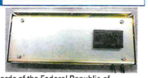
Signed ....
G L Smith
Approved Signatory

NATA
Accreditation No. 11087

Appendix D – Calibration records: SafeTstop plate brake tester

HKM Messtechnik

Sensors | Calibration certificate



Type Sensor WS - weigh platform

Serial number rechts

The standards used for these measurements are traceable to the national standards of the Federal Republic of Germany at the Physikalisch-Technische Bundesanstalt (PTB).
The following measurements were determined under the gravitation prevailing in Freiburg:
Gravitation (according to the Weights and Measures Office, Freiburg) g[m/s²] = 9,8081

Load [N]	Load [kg]	Required value [mA]	Measured value [mA]	Error [% f.s.] *
0	0	2,0700	2,0700	0,00
981	100,02	2,8702	2,8700	0,00
1962	200,04	3,6703	3,6700	0,00
2942	299,96	4,4696	4,4700	0,00
3923	399,98	5,2698	5,2700	0,00
4904	499,99	6,0700	6,0700	0,00
5885	600,01	6,8701	6,8700	0,00
6866	700,03	7,6703	7,6700	0,00
7846	799,95	8,4696	8,4700	0,00
8827	899,97	9,2698	9,2700	0,00
9808	999,99	10,0699	10,0600	-0,10

Nominal load (Pressure force) 1000 kg
Output from 2,1 mA
up to 10,1 mA
Measuring temperature 20 °C

Insulation resistance > 4 GΩ
Required accuracy ± 0,25 % f.s. *

2x DK 1t5-WS02

Accuracy achieved? Yes

Calibration date 20 July 2020

Calibrated by (Dennis Hörnig)

HKM-Messtechnik GmbH Ziegelhofstr. 228 D-79110 Freiburg www.hkm-messtechnik.de

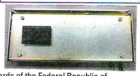
Next inspection due **July 2021**

* f.s.(full scale) = maximum output = 10,1 mA

| HKM-Messtechnik GmbH | Ziegelhofstr. 228 | 79110 Freiburg, Germany | Phone: +49(0)761/89607-0 | www.hkm-messtechnik.com

HKM Messtechnik

Sensors | Calibration certificate



Type Sensor WS- weigh platform

Serial number links

The standards used for these measurements are traceable to the national standards of the Federal Republic of Germany at the Physikalisch-Technische Bundesanstalt (PTB).
The following measurements were determined under the gravitation prevailing in Freiburg:
Gravitation (according to the Weights and Measures Office, Freiburg) g[m/s²] = 9,8081

Load [N]	Load [kg]	Required value [mA]	Measured value [mA]	Error [% f.s.] *
0	0	2,0700	2,0800	0,10
981	100,02	2,8702	2,8700	0,00
1962	200,04	3,6703	3,6700	0,00
2942	299,96	4,4696	4,4700	0,00
3923	399,98	5,2698	5,2700	0,00
4904	499,99	6,0700	6,0700	0,00
5885	600,01	6,8701	6,8600	-0,10
6866	700,03	7,6703	7,6600	-0,10
7846	799,95	8,4696	8,4600	-0,10
8827	899,97	9,2698	9,2600	-0,10
9808	999,99	10,0699	10,0600	-0,10

Nominal load (Pressure force) 1000 kg
Output from 2,1 mA
up to 10,1 mA
Measuring temperature 20 °C

Insulation resistance > 4 GΩ
Required accuracy ± 0,25 % f.s. *

2x DK 1t5-WS02

Accuracy achieved? Yes

Calibration date 20 July 2020

Calibrated by (Dennis Hörnig)

HKM-Messtechnik GmbH Ziegelhofstr. 228 D-79110 Freiburg www.hkm-messtechnik.de

Next inspection due **July 2021**

* f.s.(full scale) = maximum output = 10,1 mA

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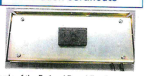
HKM Messtechnik

Sensors | Calibration certificate



Type Sensor WS- weigh platform

Serial number Mitte

The standards used for these measurements are traceable to the national standards of the Federal Republic of Germany at the Physikalisch-Technische Bundesanstalt (PTB).
The following measurements were determined under the gravitation prevailing in Freiburg:
Gravitation (according to the Weights and Measures Office, Freiburg) g[m/s²] = 9,8081

Load [N]	Load [kg]	Required value [mA]	Measured value [mA]	Error [% f.s.] *
0	0	2,0700	2,0700	0,00
981	100,02	2,8702	2,8700	0,00
1962	200,04	3,6703	3,6700	0,00
2942	299,96	4,4696	4,4800	0,10
3923	399,98	5,2698	5,2700	0,00
4904	499,99	6,0700	6,0700	0,00
5885	600,01	6,8701	6,8700	0,00
6866	700,03	7,6703	7,6700	0,00
7846	799,95	8,4696	8,4700	0,00
8827	899,97	9,2698	9,2700	0,00
9808	999,99	10,0699	10,0700	0,00

Nominal load (Pressure force) 1000 kg
Output from 2,1 mA
up to 10,1 mA
Measuring temperature 20 °C

Insulation resistance > 4 GΩ
Required accuracy ± 0,25 % f.s. *

2x DK 1t5-WS02

Accuracy achieved? Yes

Calibration date 20 July 2020

Calibrated by (Dennis Hörnig)

HKM-Messtechnik GmbH Ziegelhofstr. 228 D-79110 Freiburg www.hkm-messtechnik.de

Next inspection due **July 2021**

* f.s.(full scale) = maximum output = 10,1 mA

| HKM-Messtechnik GmbH | Ziegelhofstr. 228 | 79110 Freiburg, Germany | Phone: +49(0)761/89607-0 | www.hkm-messtechnik.com

HKM Messtechnik

Force measurement
Weighing technology
Sensor technology

Force gauges | Calibration Certificate

Type Dynamometer ZW 5.0 / 500

Serial number 1809030058

The standards used for these measurements are traceable to the national standards of the Federal Republic of Germany at the Physikalisch-Technische Bundesanstalt (PTB).

Load [N]	Reading [N]	Reading error [% f.s.]
0	0	0,00
500	499	-0,02
1000	1000	0,00
1500	1499	-0,02
2000	1999	-0,02
2500	2499	-0,02
3000	2998	-0,04
3500	3498	-0,04
4000	3998	-0,04
4500	4498	-0,04
5000	4999	-0,02

Nominal load (Tension force) 5000 N

Required accuracy ± 0,25 % f.s.

Accuracy achieved? Yes

Calibration date 10 September 2019

Calibrated by (Dennis Hörnig)

Next inspection due **September 2020**

| HKM-Messtechnik GmbH | Ziegelhofstr. 228 | 79110 Freiburg, Germany | Phone: +49(0)761/89607-0 | www.hkm-messtechnik.com

SafeTstop Calibration Certificate

Model: Long Track Ultima Plate Brake Tester (4 plate)

Serial number: PUMOB0716 Build date: July 2016

FRONT LEFT Brake Plate

Applied Force in Newton	Actual Force in Newton	Measuring Error (N)
500	497	-3
1000	998	-2
1500	1497	-3
2000	2000	0
2500	2501	+1
3000	3005	+5
3500	3501	+1
4000	4000	0
4500	4503	+3
5000	5004	+4

FRONT RIGHT Brake Plate

Applied Force in Newton	Actual Force in Newton	Measuring Error (N)
500	503	+3
1000	1004	+4
1500	1501	+1
2000	2003	+3
2500	2499	-1
3000	2997	-3
3500	3500	0
4000	4007	+7
4500	4504	+4
5000	5001	+1

REAR LEFT Brake Plate

Applied Force in Newton	Actual Force in Newton	Measuring Error (N)
500	498	+2
1000	1004	+4
1500	1503	+3
2000	1996	-4
2500	2503	+3
3000	3000	0
3500	3495	-5
4000	4000	0
4500	4503	+3
5000	4998	-2

REAR RIGHT Brake Plate

Applied Force in Newton	Actual Force in Newton	Measuring Error (N)
500	495	-5
1000	1000	0
1500	1501	+1
2000	1998	-2
2500	2500	0
3000	3007	+7
3500	3502	+2
4000	4003	+3
4500	4500	0
5000	5004	+4

Test Equipment:

Calibration Tool	Dynamometer	ZW 5.0/500	HKM Messtechnik Force Gauge
Serial Number	1107060013		
interval	1 N		
range	Max. 5kN		
Last calibration	03/09/2018	Calibration due	03/09/2020

Calibration Date: 14/05/2020 Test Conditions: Dry, 19°C

Test location: 1/44 Eddie Rd, Minchinbury

Calibrated by: R. GARTNER Signature

Calibration Next Due May 2021

Appendix E – Calibration records: VIS roller brake tester

NEPEAN
Transport
™

VIS Service Automation

CERTIFICATE OF CALIBRATION

This is to certify that VIS Check equipment listed herein was calibrated in accordance with the VIS Check calibration procedure to manufactures standards in accordance with AS/NZS 4613:1999 Automotive brake testing equipment - Roller brake tester.

All weights and measures used are certified by a registered testing Authority.

Serial Number	
Next Calibration Due	
Date	
Location	
Procedure (Version No)	**1.23**
Calibration Tooling Traceability	
Weight Calibration ID	39831
Weight Jig Due Date	26/7/20
Registered Authority	Precision Calibrations
Force Calibration Jig ID	69660
Force Jig Due Date	30/7/20
Registered Authority	Precision Calibrations

Performed By: R Hamilton ____________________

Signature: ______________________________

Date: ______________________________

Appendix F – Calibration records: Circuitlink decelerometer

Report Generated on Tue Apr 07 03:44:50 UTC 2020 BrakeTesta Calibration Certificate Report Version 20180716-1

BrakeTesta RX Calibration Certificate CAL-BTR-001-097

Circuitlink

Certificate Details

Certificate Number	CAL-BTR-001-097	**Calibration Date**	2020-04-07 09:52:19. +10:00
Calibration	Circuitlink	**Calibration**	24.00° C
Calibration Reference	Circuitlink BT Calibration Manual 1.1		
Next Calibration	2022-06-16 10:00:00. +10:00		

BrakeTesta Details

Serial Number	BTR01172	**Condition**	New
Part Number	0085001 (BrakeTesta RxG)	**Firmware Version**	BrakeTesta RX 1.3.18.18
Description	BrakeTesta RxG	**Test Count**	0

Test Equipment

Calibration Tool	Angular Calibration Box 1	**Calibration Tool**	Indicator and Load Cell
Calibration	Circuitlink	**Calibration**	AIC / XTRAN
Calibration Model	Orthogonal Box Mk1	**Calibration Model**	PM4 / S1W-2KN
Last Calibration	2020-04-07	**Last Calibration**	2020-04-07

Pedal Transducer	Before	Error	After
0N			0N
50N			50 N
500N			500 N
850N			850 N

Accelerometer	Before	Error	After
X +ve			1000 mG
Y +ve			1000 mG
Z +ve			1000 mG

Calibrated By	Name	Mario Delos-Reyes
	Date	2020-04-07 09:52:19.
	Signature	
Checked By	Name	Adel Sharobim
	Date	2020-04-07 09:52:19.
	Signature	

Appendix G – Calibration records: Racelogic Vbox 3iSL

CERTIFICATE OF CALIBRATION

RACELOGIC

Customer	Centre for Automotive Safety Research	Equipment	100Hz GPS Datalogger
Location	Australia	Model	VB3iSLRTK-V5
Customer ID #		Serial Number	071547
In tolerance as received (Y/N)	N/A (New Unit)	Issue Date	05-07-19
Certificate No.	030667	Expiry Date	04-07-20
Temperature	22.8 °C	Engineer	Gary Watson
Humidity	34 %		

Calibration Procedure

The unit under test was subjected to the standard production test procedure. This procedure covers measured velocity by the VBOX over a simulated test course. Simulation data is provided via a UKAS calibrated GPS simulator. Note: Distance is calculated by integration of the Speed signal, which is calibrated using the GPS simulator, this ensures that the distance accuracy satisfies the specification of 0.05% and <50cm per Km. Analogue output voltage and digital output frequency are checked for calibration against simulated speed. Voltage output range is configured to 5 volts at 100Km/h. Frequency output is configured to 25Hz per Km/h. VBOX indicated values are taken from compact flash data.

Equipment Used

	Equipment	Serial Number	CAL Cert No.	CAL Due
Simulation of GPS	C025	021999	3005950002	14-05-20
Analogue Voltage measurement	C020	327202	3090	10-09-19
Frequency Measurement	C021	325484	3089	10-09-19

Results

Accuracy of analogue and digital output signals

Applied Speed	Analogue Output 1			Analogue Output 2		
	Expected	As received	As returned	Expected	As received	As returned
30 Km/h	1.500 V ± 5.0mV	-	1.501 V	1.500 V ± 5.0mV	-	1.501 V
60 Km/h	3.000 V ± 5.0mV	-	3.001 V	3.000 V ± 5.0mV	-	3.002 V
100 Km/h	5.000 V ± 5.0mV	-	5.002 V	5.000 V ± 5.0mV	-	5.003 V

Applied Speed	Frequency Output		
	Expected	As received	As returned
30 Km/h	750 Hz ± 2.5Hz	-	750 Hz
60 Km/h	1,500 Hz ± 2.5Hz	-	1,500 Hz
100 Km/h	2,500 Hz ± 2.5Hz	-	2,501 Hz

Simulation of constant speed by GPS simulator

Applied simulated value	VBOX indicated speed		
	Criteria	As received	As returned
30 Km/h	±0.1 Km/h	-	29.99 Km/h
60 Km/h	±0.1 Km/h	-	59.99 Km/h
100 Km/h	±0.1 Km/h	-	99.99 Km/h
400 Km/h	±0.1 Km/h	-	399.99 Km/h

Simulation of constant heading by GPS simulator

Applied simulated value	VBOX indicated heading		
	Criteria	As received	As returned
0°	±0.1°	-	0.01°
90°	±0.1°	-	90.00°
180°	±0.1°	-	180.00°
270°	±0.1°	-	269.99°

Summary

The unit passed all standard production tests and was found to be fully compliant with the product specification. Racelogic certifies the above instrument meets or exceeds published specifications, and has been calibrated using instruments and standards of known accuracies, which are traceable to ISO/IEC: 17025 standard.

Calibration Engineer ________

Racelogic Ltd. Unit 10 Swan Business Centre, Osier Way, Buckingham MK18 1TB.
Tel +44 (0) 1280 823803 Fax +44 (0) 1280 823595

RACELOGIC VBOX

Certificate of Conformity

Customer Name:	Centre for Australia Safety Research	Equipment:	VBOX Inertial Measurement Unit
Location:	Australia	Model:	RLVBIMU04-V2
Issue Date:	05-07-19	Serial Number:	071749

Procedure

RLVBIMU04-V2 modules are manufactured to conform to the following specifications.

IMU Specification

	Accelerometers	Gyros
Full Scale	200 m/s^2	450 °/s
Bandwidth	375 Hz	415 Hz
g-sensitivity	N/A	<0.015°/s/g
Non-orthogonality	<0.05 deg	<0.05deg
Non-linearity	<0.1% FS	<0.01% FS
Noise Density (1σ)	<80 µg/√Hz	<0.015 °/s/√Hz

Basic Test Results

Measured Noise Density (1σ)	77.6 µg/√Hz	0.008 °/s/√Hz

Racelogic certifies that this product performs to the specifications stated on the relevant product data sheet.

Signed: ____________________

For Racelogic Ltd

Head Office: Unit 10, Swan Business Centre, Osier Way, Buckingham, Bucks MK18 1TB, England
Tel: +44 (0)1280 823 803 Fax: +44 (0)1280 823 595 Email: sales@racelogic.co.uk Web: www.racelogic.co.uk

Appendix H – Data collection checklist

Standard Operating Checklist

CENTRE FOR
AUTOMOTIVE
SAFETY RESEARCH

THE UNIVERSITY of ADELAIDE

BTC

Document no.:
Page: 1/1

Title: **Brake Test Checklist**

Date printed: 28/7/20

Vehicle			
Test condition			
LF	RF	LR	RR
Test date		Time	
Test driver			
CabinTemperature	(ºC)		
External temperature	(ºC)		

ACTIONS			**CHECK**
Record weight of vehicle, adjust with ballast if required (kg)			
LF	RF	LR	RR
Tyre pressures (PSI)			
LF	RF	LR	RR
Tyre temperature (ºC)			
LF	RF	LR	RR
Brake temperature (ºC)			
LF	RF	LR	RR
Brake robot set load (N)			
Brake robot set speed (rpm)			
Brake robot maximum displacement (mm)			
Settle and measure brake line pressures (kPa)		Front	Rear
LF	RF	LR	RR
Roller brake test number			
Roller data file			
Plate brake test number			
Plate data file			
Clear to enter roadway			
Decelerometer test number			
Decelerometer data file			
Decelerometer vbox file			
Confirm 100-0 km/h manual brake stop			
Brake temperature (ºC)			
LF	RF	LR	RR
100-0 km/h data file			
100-0 km/h vbox file			
Brake line pressures post test (kPa)		Front	Rear
LF	RF	LR	RR
Roller brake test number			
Roller data file			

Notes:

Appendix I – National Measurement Institute review

Australian Government
Department of Industry, Science, Energy and Resources

National Measurement Institute

Review of measurement methods and instrumentation used to assess vehicle brake testing systems

Laurence Dickinson and Simon Dignan

6 October 2020

www.measurement.gov.au

Report related to NMI contract reference 20/010/255, 19 May 2020.
Version 1, dated 9 September 2020
Version 2, dated 6 October 2020

Contents

Background

The National Measurement Institute of Australia (NMI) was contracted by The University of Adelaide, Centre for Automotive Safety Research (CASR), to assess the metrological suitability of measurement methods and instrumentation used by CASR for the evaluation of the SafeTstop vehicle brake tester system, in comparison to several other common forms of vehicle brake testers. This was in relation to CASR being separately contracted by SafeTstop (Workshop Solutions Pty Ltd) to compare their brake tester with other industry standard methods.

CASR Brake Tester Evaluation Scheme Overview

The brake tester evaluation scheme was designed and conducted by CASR to use commonly available test vehicles with introduced and reproducible braking system faults. These faults were created by altering the braking force distributed to each of the vehicle's wheels by adjusting pressure regulating valves attached to the brake lines associated with each wheel, altering the brake fluid pressures, and hence braking forces applied. Pressure sensors were used to measure the hydraulic pressure in each brake line and a 'Brake Robot' was used to ensure a consistent force profile was applied to the vehicle's brake pedal for each test.

The vehicle braking performance, with the introduced fault conditions, was evaluated by CASR using four different common brake testing methods:

- a plate brake testing machine,
- a roller brake testing machine,
- a portable brake testing decelerometer instrument, and
- High-speed deceleration and stopping distance test, which was used as a control for comparing with the three brake tester machines / instruments listed above.

An analysis of the performance of each method to detect the induced braking system fault was conducted by CASR.

NMI Assessment Scope

This NMI assessment was focused primarily on the metrological suitability of measurement methods, instrumentation suitability, calibration, technical limitations and likely uncertainty / accuracy issues.

The assessment covered items including:

1. A review of the facility's determination of what main physical units (e.g. acceleration, force etc.) were to be measured or derived in order to satisfy the requirements of the application, and the appropriateness of the measurement methodology to achieve this.
2. Suitability of equipment and instrumentation to perform measurements to the precision and tolerances required by the application and, where applicable, traceability of measurements to recognised physical measurement standards through accredited calibration.
3. A review of experiment and apparatus design to determine if the correct parameters were being measured (as in point 1 above), what controls are in place to ensure correct operation of measurement systems, and how are influencing quantities, that may affect measurement results, minimised or accounted for.
4. A review of uncertainty within the measurements, and how these are accommodated within the experimental design and subsequent data analysis.

The NMI assessment specifically did not cover:

1. A review of how measurement results are used or interpreted for the purpose of evaluation or comparison of the brake testers.

2. A review of the management of the trial by CASR, testing facilities, or documentation control, against any quality standards and guides such as ISO 9001 or ISO 17025, although the NMI team may have utilised these standards as a bases for parts of the assessment. The findings of this report shall not be interpreted as a compliance statement against any standard or guide.

Assessment Program

This assessment was conducted in three stages, these being:

1) Stage 1: Pre-testing review of CASR's project proposal, experimental plan, equipment calibration records, as well as an interview with CASR staff. This was also an opportunity for NMI to provide some advice and suggestions to CASR on specific issues relating to measurement quality, getting the most out of the measurement equipment and the use of checks and balances to ensure reliability of equipment and measurement results.
2) Stage 2: Tour of the test site covering the facilities and equipment used at Goolwa Airport on CASR's first day on site.
3) Stage 3: Post-testing interview with CASR staff, conducted approximately one week after completion of the trial field work.

Due to interstate travel restrictions in response to the 2020 COVID-19 pandemic crisis, all meetings, interviews, and the site tour were required to be conducted remotely via video conferencing.

The report authors (NMI technical experts and NATA signatories in the fields of Force and Acceleration measurement) consulted with other NMI technical experts and NATA signatories in the fields of Time & Frequency, Temperature, and Pressure, while evaluating the equipment used and measurements taken in CASR's brake testing trials.

Stage One – Pre-testing Review and Interview

Prior to the initial interview, NMI reviewed the documentation supplied by CASR, including their project proposal, experimental plan, listing of the measuring equipment to be used, and equipment checks and calibration records. CASR staff and NMI assessors then met for approximately one hour on 14 May 2020 for the interview, and the following is a summary of the discussions and recommendations from this meeting, as well as NMI's evaluation of the application's measurement goals and instrumentation:

Brake testers used in evaluation

The three brake testing machines / instruments that were evaluated are all commercially available and typically used by Australian roads authorities, or their authorised representatives, to assess vehicle brake performance. These units were:

- CircuitLink BrakeTesta RX – A small decelerometer-based instrument.
- SafeTstop long track ultima – A plate brake testing machine.
- VIS-Check - A roller brake testing machine.

CASR had taken steps to ensure that these three brake testing machines / instruments were functioning in accordance with the manufacturer's specifications, and supplied the NMI assessment team with current manufacturer's calibration certificates for each unit. Is was noted that none of these certificates appear to be from an accredited calibration facility.

CircuitLink

- A calibration certificate was provided for the Circuitlink BrakeTesta RX, dated 7 April 2020, indicating that the unit had successfully undergone a manufacturer's check. Typical recommended recalibration intervals for acceleration measuring equipment is usually 12 months, however the Circuitlink certificate indicated a recalibration due date of June 2022.

- The certificate appeared to indicate that the unit's triaxial accelerometers were calibrated against the acceleration due to Earth's local gravity, as well as the brake pedal force sensor calibrated for forces up to 850 N. Both these measurements appear to be using static forces. The certificate did not provide any information on calibration measurement uncertainty, a consideration for geographical changes to the acceleration value of local gravity, any required tolerances, or a pass / fail determination. However, the indicated measurement results match the applied stimulus to the stated resolution, and it is assumed that the manufacturer would not have issued the certificate if the unit was not working to within specifications.

SafeTstop

- The Calibration certificate from SafeTStop on unit with serial number PUMOB0716 was dated 14 May 2020 (suggested recalibration interval of 12 months based on AS/NZS 4613:2017). This certificate appears to be a hand-written test record with data on four load cells that were tested with static load forces. It is believed that the loads were applied horizontally to the plate brake testing machine, although there is no indication on the certificate about the orientation of the applied force. The data indicated a maximum error across the four load cells of 1% for the lowest applied tested force of 500 N, which reduces to 0.2% for test loads of 1.5 kN to 5 kN. The certificate also indicated that the load cell force reference used was calibrated in September 2018 (*03/09/2018*), and due for recalibration in September 2020, which coincides with the recommended recalibration interval for force measuring equipment of 2 years. No information on the uncertainty components of these measurements were provided, and the NMI assessors did not have any information on the specified measurement tolerances of the SafeTStop system or calibration process. The certificate also did not provide a pass / fail determination on the equipment, however it is assumed that the manufacturer would not have issued the certificate if the unit was not working to within specifications. AS/NZS 4613:2017 states that for brake force measuring instruments '*the accuracy of the braking force measurement shall be ± 5% for an identical force on each wheel*', and '*the measured results shall not deviate by more than 2% from each other*'. Based on the maximum stated error of 1% across all measurements, the SafeTStop plate brake testing machine appears to be operating within requirements within the limitations of the evidence provided.

VIS-Check

- The certificate of calibration for the VIS-Check roller brake tester, from the manufacturer Nepean Transport, indicates that the unit with serial number 44651 was tested on 27 April 2020 (12-month recommended calibration interval), and that the unit complies with AS/NZS 4613:1999. Although the manufacturer does not appear to be NATA accredited to perform calibrations, the certificate does indicate that the masses and load cells used as references had current calibrations from a registered NATA calibration laboratory. It is also noted that the current edition of AS/NZS 4613 is dated 2017, therefore the calibration certificate is referencing an outdated standard.
- It is noted that the specifications of the VIS-Check system from the manufacturer's web site indicates that the unit can test a maximum brake force of 40 kN and support an axial load of up to 15,000 kg. AS/NZS 4613:2017 Section 5 describes two classifications of brake testers: '*A light duty instrument for measuring light vehicle brake force is one which has a capacity of measuring a brake for of at least 8 kN*', and '*A heavy duty instrument for measuring heavy vehicle brake force is one which has a capacity of measuring a brake force of at least 30 kN*'. Additionally AS/NZS 4613:2017 section 6.2 defines a Light Duty instrument as accepting tyre sizes with a minimum of 450 mm rolling diameter, and a Heavy Duty instrument accepting tyre sizes with a minimum of 600 mm rolling diameter. From these observations, it would appear that the VIS-Check roller brake testing machine used for the CASR trials could be

classified under AS/NZS 4613:2017 as a Heavy Duty instrument intended to test larger vehicles.

NMI recommended each brake tester should be installed, configured and adjusted in strict accordance with the manufacturers' instructions, and operated by appropriately trained and experienced operators, as would be the expected for normal use by road authorities. Ideally the equipment should have a recent calibration or manufacturers' check testing certificate, with records kept demonstrating steps taken to verify that the systems being evaluated were representative of the model, and were functioning to the manufacturer's specifications.

Test vehicles

The two vehicles available to CASR for the brake tester trails were common models available in Australia, which were specially fitted out with measurement instrumentation and other equipment with the aim to introduce specific and consistent faults within the vehicle's braking system, while also allowing for resetting to a no-fault / normal operation condition for baseline control tests.

NMI recommended the baseline performance of each instrumented test vehicle be configured with no brake system faults, and to be determined using a 'trusted' method, or methods, at various times during the test program. This could be used to track the test vehicle performance, and flag any possible unintentional faults within the vehicle and test equipment. This data could also be used to determine the variance of the test vehicle's braking performance.

Weather conditions during the period of testing did not allow for quality data to be taken from one of the vehicles, a Toyota Hilux. NMI has been advised that only data from the other vehicle, a Kia, was used in CASR's analysis.

System checks

NMI highlighted the need for, and importance of, systematically documenting observations and storing data, and performing system checks including data transfers, validating analysis software and embedding system cross-checks in the testing scheme. For example, determining the baseline performance of the test vehicle at regular intervals during testing as a means of checking for consistent performance of the test vehicle.

Brake pedal force and brake line pressure measurements

Force

A fundamental premise for the experiments conducted within the CASR June 2020 trial, is that the test vehicle brakes are intended to be applied in a consistent and reproducible manner during all of the measurement scenarios across all days of testing. The main parameter that would normally be expected to be applicable for monitoring the effectiveness of the application of the vehicle brakes, would be the time-dependant force applied to the vehicle's brake pedal.

ADR31[1] describes a number of scenarios with stipulated applied brake pedal forces, for example, section 2.1.1 states a brake pedal force range during testing of '6.5 – 50 daN' (65 to 500 N), and there are several references in other sections of ADR31 with values within this range. However, there is no indication within the document, or any other related document that the NMI assessors were able to view, to describe how accurate any brake pedal force measurements should be, or any requirements for calibration of force sensors used for this type of application. Taking the quoted values of forces in ADR31 as an indication, it could be said that the least expectation of ADR31, is that brake pedal force measurements should have an uncertainty better than half the least-significant digit quoted. In the example case above, this would be ± 0.5 N

To accurately describe the time profile of the applied force requires a determination of what the minimum frequency would be that contained all spectral information needed to reliably compare the

[1] Australian Design Rule 31/04 Brake Systems for Passenger Cars, Australian Government. September 2017.

applied force time profiles. Making a reasonable assumption that the foot pedal system, incorporating linkages and the vehicle's vacuum assist servo, were not designed to have a frequency response greater than what an average human operator could possibly apply to the foot pedal, and considering that the ABS Anti-Lock Braking System in most vehicles has a pulse frequency estimated to be between 5 and 10 Hz [2], a reasonable estimate of the required minimum sampling rate would be double the expected highest frequency of interest (Nyquist limit), of double the highest ABS frequency. This would be a highest frequency of interest of 20 Hz (equivalent to an event of interest of no faster than 0.05 seconds), with a minimum sample rate of 40 Hz. It is considered that most modern signal digitising instruments have stable time bases with insignificant uncertainties, when looking at a sample frequency of less than a few hundred hertz, and where traceability of time is not important.

For the brake testing trials, a Brake Robot, developed by CASR, was used to apply a controlled force to the vehicle's brake pedal during braking operations. This mechanism comprised a motorised linear actuator with a load cell that measured the compressive force applied to the vehicle's brake pedal.

The load cell used was a 1 kN Dacell model UU-K 100 'S'-type tension and compression cell, that was connected to a custom signal conditioner, and sampled with a ADS122C04 24-Bit digitiser incorporated within a Raspberry Pi system. The ADS122C04 is specified to have a sample rate of up to 2 kHz with a potential acquisition voltage resolution of less than 1 μV (dependant on chip supply voltage). However, unwanted noise pick-up from electronics, power supplies, digital lines and RF noise from other sources, is very likely to be the limiting factor. The NMI assessors anticipate that there would be at least 1 mV or more of noise present in the system, although if the ADS122C04 is configured in a differential arrangement, some of this noise may cancel out. The Raspberry Pi system is optimally recording the digitised force signal at 100 Hz, but this is understood to vary significantly during the course of measurements due to the nature of how the Raspberry Pi functions. To overcome this issue, the Raspberry Pi also received a GPS time stamp from the Racelogic system with at least 100 Hz accuracy (0.01 sec resolution), that is appended to each sample of the force signal voltage. Assuming a minimum of 1 mV of usable voltage resolution, this roughly equates to a force resolution of 0.18 N, based on values provided to the assessment team for the sensitivity of the load cell (Certificate No. A33460FB).

CASR provided a NATA calibration certificate of the Dacell connected to a Keithley 2000 digital volt meter, with compression only static forces being applied (Certificate No. A33460FB, dated 29/04/2020. It's noted that the typical recommended calibration interval of this arrangement is 2 years). The uncertainty of measurement during the calibration was stated as < 0.1N across the range (or 0.1% at half capacity).

NMI assessed the force measuring setup to be well designed and suitable for the application. It was noted that the calibration certificate was applicable for static loads only, not dynamic as in this application, and the load cell was calibrated with a different sampler (a Keithley 2000) that was not present during the brake tester trials. Without evidence of calibration or suitable checks for operation of the Raspberry Pi sampler used with the Dacell load cell (both analogue signal acquisition, and any digital processing to derive a value of force), the values of force logged are not traceable quantities and should be considered indicative only. However, these values are suitable for comparative assessment of forces applied to the brake pedal during the experimental trials.

For the frequency range of interest, 20 Hz, it is NMI's experience that the difference between the static and dynamic calibration is typically less than 0.1%, although this is a generalisation as NMI does not have data on the dynamic response of the model of load cell used in the CASR trials. However, it is expected that the cell output will be within 0.1% of the true force acting on the cell at all times, and the data captured at approximately 100 Hz should adequately capture the applied force profile over time for the purpose of evaluating the consistency of the force profile.

[2] Sourced from information provided by DITEX https://autoditex.com/page/anti-lock-braking-system-abs-9-1.html

It was recommended that the vehicle cabin temperature should be controlled to minimise thermal effects on the load cell (manufacturer spec. 0.05% of load / 10°C & 0.1% of output effect on zero load). It is unlikely the Brake Robot's performance will change significantly over time, however to give increased confidence, a check could be done by applying non-changing loads (e.g. a static weight) to the cell at various times and comparing readings to affirm correct operation of the system.

Modern vehicles have systems that automatically distribute braking loads between the vehicle's four wheels in a ratio designed to maximise stability and control during heavy braking, while adapting to changing conditions of the vehicle's attitude, and road conditions. The effectiveness of vehicle braking is also significantly influenced by the vacuum assist servo, and the reserve of vacuum pressure available. Due to these designed characteristics, the force applied to the brake pedal was not considered by the assessment team to be a dependable indicator over all measurement scenarios for the overall amount of braking force applied to the vehicle wheels, even during baseline tests where the brake system is operating normally. A more representative measurement, proportional to the braking force applied to each wheel, is the pressure within the hydraulic brake lines that directly feeds the pistons in each wheel.

Pressure

Direct measurement of the hydraulic pressure to each wheel provides the ability to determine the braking distribution during introduced brake faults, when proportioning regulator valves were adjusted to artificially change the effectiveness of the vehicle brakes.

CASR, in their design of the experimental set up, had requested that the vehicles were supplied with four Honeywell H-PS2000G pressure sensors (Part 58043 from MoTec, which also appear to have the Honeywell model number MLH02KPSB06A according to the data sheet from MoTec). These are fitted to the hydraulic lines that feed the brake pistons. There was also an additional two pressure sensors that measured the combined hydraulic pressures to the front, and rear, of the vehicle. The pressure sensors were sampled by a MoTeC C125 logging and display system. Both the pressure sensors and MoTeC system were provided by SafeTstop, who also provided the test vehicles.

SafeTstop utilised a third party to professionally install the pressure sensors and MoTec system. The NMI assessors do not have any information on who installed the pressure sensors or what the installation specifications were.

Information on the characteristics of the Honeywell MLH02KPSB06A pressure sensors from the manufacturer, show the units to have a specified maximum pressure indication of 2000 psi (13785 kPa), and provide an analogue voltage output of 0.5 V to 4.5 Vdc across this pressure range. The units are specified to have a best accuracy of ± 0.25% for full scale (in this case approx. 34 kPa), a Total Error Band of 2% full scale (275 kPa) for pressures above 100 psi (690 kPa), and a response time of 2 ms (500 Hz).

The manufacturer's data sheet for the MoTeC C125 had a specified 1.33 mV resolution for the analogue voltage measurements from the pressure sensor, but no indication of accuracy or stability. 1.33 mV would translate to roughly 5 kPa resolution. The unit had a specified maximum logging frequency of 500 Hz.

Although ADR31 does mention measuring the pressure in the hydraulic brake lines of a vehicle as part of brake evaluations of new and modified systems, it does not describe how accurate any hydraulic pressure measurement should be, or any requirements for calibration of the pressure sensors. The NMI team also did not find any references to the requirements of pressure sensor calibration and accuracy in the documents available during the assessment.

Taking the reasonable approach to assume that the pressure in the brake lines are roughly proportional the applied force to the vehicle's brake pedal, and that the requirements of measuring the hydraulic pressure would be proportional to the requirements for measuring brake pedal force, then if the required accuracy of the brake force sensor was ± 0.5 N for the minimum 65 N applied peak force, then the accuracy would be 0.5 in 65 or about ± 0.8 %. This would reduce to ± 0.1 % if the maximum braking peak force of 500 N was applied with the same resolution. CASR reported that baseline tests produced between roughly 8200 and 9600 kPa (1200 and 1400 psi), which would then suggest an uncertainty of pressure measurement within the range of ± 8 kPa to ± 77 kPa. It is also reasonable to assume that sampling rates for pressure measurements could also be based on the sampling requirements of the brake pedal force measurements, with an estimated minimum sample frequency of 40 Hz.

The specifications of the Honeywell pressure sensors and MoTeC data logger, with a resolution of 5 kPa, an accuracy of ± 34 kPa, and sample rate of up to 500 Hz, could be considered as within the suggested requirement range outlined above.

No details for checking the correct operation of the hydraulic pressure measurement system, or any information on calibration, were provided for the pressure sensors and data logger to the assessment team, so the assessors were unable to determine the reliability of the pressure measurements and must conclude that without this information, pressure readings should be taken as indicative only.

NMI recommended that some form of check or calibration be carried out on the hydraulic pressure sensors and sampler, due to the importance of these measurement in monitoring the actions of the proportioning valves on the distribution of fluid pressure to the brakes. A base assumption in the CASR trials, is that the clamping force applied by the brake pads to the brake rotor disks at each wheel is roughly proportional to the brake line fluid pressure to the pistons in each wheel, and this appears reasonable. Based on this, the reading of each transducer relative to each other transducer when exposed to the same pressure source should provide a means to check the performance of the pressure sensors, at least against one another. This should be at a range of pressure levels that span those normally seen during the trials. Ideally, one or more of the sensors should later be calibrated at an accredited laboratory, or compared with another pressure sensor that has a current traceable calibration, to provide some bases for pressure measurement traceability.

Vehicle velocity and deceleration measurements

Two of the brake tester methods investigated by the CASR trial involved the test vehicle driven up to speed on the test track before the brakes were applied to monitor the vehicle deceleration profile and stopping distance.

When basing a test on the ability of the vehicle to decelerate from a set speed, accurate measurements of acceleration are required, as well as determining the initial, pre-brake velocity. Acceleration, velocity, and displacement are related vector quantities, and one can be derived from the others if there is sufficient sampling resolution and accurate timing. Generally, high-sensitivity triaxial inertial accelerometers are employed for deceleration measurements, as is used in the Circuitlink brake tester, as the acceleration signals can be integrated to derive velocity, and with the arrangement of three orthogonally-mounted accelerometer sensors, care is not required in aligning the sensors with the direction of travel. The triaxial arrangement, when analysed as orthogonal vector quantities, also compensates for any pitching or swaying of the vehicle during braking.

Vehicle acceleration and velocity measurements are not applicable when the roller brake testing machine and plate brake testing machine are being used, as the vehicle is at a standstill during the test, or traveling at such low speeds that vehicle initial velocity and deceleration rates would not be relevant.

As the high-speed stopping distance tests are being used as a baseline for checking the consistency and repeatability of the various configurations of induced faults, it is seen as important that the measure of velocity and acceleration are accurately made to allow reliable comparisons between brake fault conditions, and to demonstrate vehicle operational checks from day to day during the trials.

ADR31 does not provide much information on the accuracy or calibration requirements of equipment used to perform deceleration tests. However, it does indicate that there should be a maximum uncertainty of ± 3% on acceleration readings for deriving velocity and distance travelled. This was taken by the NMI assessors as a recommended minimum baseline for acceleration and velocity measurements. No information was seen by the assessment team about the requirement for acceleration sampling rates. However, taking a similar approach to that in previous sections and assuming that the highest frequency of interested for vehicle movement is 20 Hz, and also making the additional assumption that there is a possibility that at some point there might be a requirement to integrate the digitised accelerometer signals to derive velocity and/or displacement, which in turn may require some form of low-pass digital filtering with a frequency limit of, say, double the frequency of interest, 40 Hz, to remove spurious events that could adversely affect the integration process, then a reasonable estimate of the minimum required sample rate that could resolve 40 Hz would be 80 Hz. Based on this, the NMI assessment team reasoned that any sample rate of 80 Hz or above would be adequate for the application.

For the road tests, CASR utilised a Racelogic VBox Inertial Measurement Unit (IMU) that comprised triaxial linear acceleration and angular (gyroscope) acceleration sensors, with sampler, model RLVBIMU04-V2, S/N 071749, paired with GPS Data logger, Racelogic VBiSLRTK-V5 S/N 071547. The GPS system incorporates a GPS satellite receiver as well as applying real-time corrections from a fixed base station. The combined output from all these sensors were analysed and merged within the proprietary VBox system to provide composite measurements of the vehicle deceleration profile, instantaneous velocity, and distance/position at 100 samples per second (100 Hz).

The IMU was mounted to a framework attached to the test vehicle roof along with the GPS antenna. The manufacturer specifications of the IMU sensor indicates the linear sensors have a non-linearity of ± < 0.1% for full scale acceleration of 200 m/s/s, ± 0.03 % for 9.8 m/s/s (1 g_n), a resolution of 400 μm/s/s, and with a 1 year stability of ± 0.05 m/s/s (0.005 g_n). No specification was provided for the sample rate, although this is believed to match the 100 Hz input rate of the VBox processor. A manufacturer certificate of conformity to these specifications was provided for the NMI assessment team, with an issue date of 5 July 2019. The typical recommended recalibration interval for an accelerometer with electronic signal conditioning and sampler is 1 year. The assessment team noted that this document did not indicate that the certificate was issued from an accredited calibration laboratory, and is not considered evidence of measurement traceability. However, the certificate does confirm that the manufacturer has checked that the unit was functioning correctly, is stable, and operating to within specified tolerances. NMI also noted that the manufacturer specified measurement tolerances are not technically supportable, as they are substantially less than any of the publically listed accredited uncertainties of any national laboratory.

According to the instrument's specifications, the GPS module provided velocity measurements with an accuracy of ± 1 cm/s (± 0.036 km/h), which appears reasonable for such devices that utilise differential GPS with corrections from a fixed base station. It is assumed by the NMI team that the lowest velocity of interests would be 1 km/h, therefore the stated accuracy is well within requirements.

NMI reviewed the manufacture's calibration certificate for the GPS unit, dated 5 July 2019 (typical recommended recalibration intervals for such devices is 1 year), and noted that this document did not appear to have been issued under an appropriate accreditation. NMI also noted that the receiver was calibrated using a GNSS simulator, a method that likely did not simulate the unpredictable parts of the signal path such as the effect of the ionosphere, and local conditions such as signal obstructions and reflections. However, the airfield used as a test location was flat and relatively clear of obstructions, so it is expected that the GPS receiver operated well within the requirements of the application.

It was recommended that two relatively easy checks be applied several times during the test period to check for accuracy and correct operation of the system, these were:

1) Zero velocity check with the receiver stationary. This will give an idea of the influence of the local environment and atmospheric conditions on the day and also gives a practical estimate of accuracy, and
2) A check of the GPS specified location at least at one fixed known location, this will give an idea of repeatability of the location accuracy of the GPS.

The assessment team considered that the IMU / GPS system was suitable for the purpose of the application within the specified tolerance, but that the measurement results are not traceable.

Supplementary measurements

Tyre pressure measurements

Tyre inflation pressure can affect the rolling resistance of a vehicle, as well as affect the vehicle's dynamics, and alter the effectiveness of the vehicle to brake. For the purposes of the brake tester evaluation, CASR determined that it was desirable to maintain the tyre conditions at consistent parameters throughout the trial and across each of the brake tester methods investigated. The NMI team did not identify any specifications or calibration requirements that should be applied for tyre pressure measurements in any documentation reviewed for the assessment, and it is understood that the absolute values of tyre inflation air pressure was not important, provided that these values were consistent throughout the trials, and can be shown to be within the broad range recommended by the manufacturer of the tyre for the type of test vehicle used. The tyre pressure measurements would be expected to vary with the use of the vehicle and environmental temperature, so any comparison in tyre pressure would need to be taken under similar environmental and pre-use conditions.

For the CASR brake tester evaluation, a wireless ARB tyre pressure monitoring system was used to monitor the pressure in each of the four tyres. No measurement specifications were available for this instrument, or any other information on manufacturer's specifications, performance checking or calibration, so the NMI assessment team were unable to determine the accuracy and reliability of these sensors. However, measurements of tyre pressure is understood not to be factored in as part of the CASR trial data analysis, and were recorded only as indicative readings for periodic logging of vehicle conditions. When used in this context, the instrumentation appears adequate for the task.

Brake temperature measurements

The effectiveness of vehicle brakes can be affected by the temperature of the brakes, and CASR had identified that this was an important quantity to monitor. CASR employed a Repco RTS195 non-contact infrared (IR) thermometer for the purpose of determining the consistency of brake pad temperatures during the trials. It is understood that IR temperature measurements were made off the surface of a steel sleeve that housed the brake pads (assumed to be ceramic), that was visible through a hole in the brake assembly.

Infrared thermometers rely on the principle of a material to emit light in the infrared spectrum, which is dependent on the surface temperature of the material, and the ability of the surface material to absorb and emit infrared radiation (referred to as its emissivity). For example, mild steel has an emissivity that can range from approximately 0.07 for polished steel, to 0.79 for oxidised steel. Typically, most IR thermometers are calibrated against black body sources with an emissivity of 1.00, or a plate calibrator with an emissivity of approximately 0.95. As a consequence, IR thermometers would be expected to read significantly lower than the true surface temperature, unless the correct emissivity correction is applied. In practice, it would be expected that the steel sleeve inspected could have significant variations in surface qualities that might range from smooth, polished and relatively reflective, to surfaces that are significantly scratched, and have layers of rust, dust, water, oil or other contaminant on it. However, over the period of testing, the effects of surface condition may be expected to be sufficiently constant to allow comparison between tests.

Generally, the "point and shoot" type of IR thermometer used typically has a viewing circle of F/8, taking the average temperature of a region, e.g. ~ 2 to 3 cm in diameter at 20 cm, around the sighting laser point (if present). The accuracy of typical IR thermometers can be fairly good, even for relatively low-cost instruments, with an estimation of ± 3 degrees Celsius or less not unreasonable for such instruments that are in good serviceable condition.

The temperature of the steel sleeve that was inspected with the IR thermometer may not be representative of the temperature of the brake pad, as both stainless steel and the ceramic pad material are relatively poor conductors of heat.

The NMI team did not identify any specifications or calibration requirements that should be applied for brake temperature measurements in any documentation reviewed for the assessment. Additionally, no specifications for accuracy, or any information on calibration or operational checks were available for the IR thermometer during the assessment, so the NMI team were unable to determine the accuracy and stability of this instrument. Without this information, and also considering the potential variation of IR measurements due to the nature of the surface quality of the part of the brake being inspected, the IR measurements for brake temperature should be regarded as indicative only.

NMI understands that brake pad temperatures are not factored in as part of the CASR trial data analysis, and were recorded only as part of periodic logging of vehicle conditions, e.g. to potentially verify brakes were warm / cold prior to testing. When used in this context, the instrumentation appears adequate for the task.

Test environmental condition measurements
Measurements for air temperature, wind speed, and wind direction were taken from the airport weather monitoring station, and were not reviewed by NMI.

NMI did not make any evaluation of any potential adverse effects of the environment and testing location on the measurement equipment, such as radio transmitters and radar systems, which might be expected to be employed around an airport.

Stage Two – Site Tour

A half-hour 'virtual' site tour was conducted on 19th of May 2020 from Goolwa Airport in South Australia, via a remote video conference link. This tour provided the NMI assessors an opportunity to view the equipment and experimental setup, as well see the brake testers used in the comparison.

The tour covered most of the equipment used for testing. The CASR team did a 'walk-through' of the Kia test vehicle, showing the relevant features of the vehicle, including the Brake Robot, brake system pressure regulators, measurement system, and roof mounted acceleration and GPS logger. The tour included viewing the Circuitlink brake tester located in the passenger foot well, and the SafeTstop plate brake tester system, which had been set up within the shed. The roller brake testing machine was unavailable for viewing during the tour, as it had not yet arrived on site, and was due be installed on the following day.

NMI assessors were impressed with the setup and were satisfied that the measuring equipment was as described by CASR.

Stage Three – Post-trial Interview

A video meeting was conducted a week after the field trials at Goolwa Airport had been completed, during which CASR had an opportunity to present a brief summary of their results, and the process of testing during the trial.

CASR did report a number of problems encountered during the trials, mainly related to adverse weather conditions on the trial schedule, and a consistent problem experienced with the roller brake tester ejecting the vehicle during the testing, which caused issues with data collection. No issues were reported with the instrumentation and associated measurements.

It was noted earlier in this assessment report that the roller brake testing machine used might be classified according to AS/NZS 4613:2017 as a *Heavy Duty instrument for measuring heavy vehicle brake force*. It is unclear if the results of the CASR study comparing brake-tester methods would also apply to roller brake tester machines classified under AS/NZS 4613:2017 as *Light Duty instrument for measuring light vehicle brake force*.

The NMI assessors discussed the measurement related aspects of the overall design of each experimental setup, and that it appeared to be well thought-out and implemented, and fit for purpose for the expectations of the trials.

NMI assessors were satisfied that measurements appeared to be performed in accordance to the experimental plan that was reviewed during Stage One of the assessment.

Assessment Findings

The assessment found that the experimental setup and methodology used by CASR was appropriate and fit-for-purpose for the intended application of ensuring testing consistency over the period of the brake testing trials.

The review found that the instrumentation used had specifications suitable for this purpose, with the major items having either a manufacturer's conformance check or a calibration dated within a year of the trial. This documentation provides evidence that CASR has made appropriate efforts to ensure that their equipment was operating within accepted manufacturer specifications.

However, the measurements reviewed could not be shown to demonstrate measurement traceability, either because the certificates lacked required accreditation information, such as a NATA or similar logo, or the equipment was used in a configuration that significantly deviated from that described in the calibration report. The assessment team noted that there were no formal requirements for the tests to have traceable measurements.

Conclusion

The National Measurement Institute of Australia (NMI) conducted an assessment of the equipment and measurement methodology used by CASR to perform a series of experiments comparing the capability of three different types of brake testers to detect deliberately introduced faults in vehicle braking systems.

The assessment concluded that the measurements that CASR conducted were appropriate to give confidence in the validity of the comparative testing.

It was observed that the lack of measurement traceability may limit the comparability of measurements between subsequent trials, or those that might be performed by other laboratories.

NMI did not assess how the measurement results were used or interpreted for the purpose of evaluation or comparison on brake testers.

Revision Amendments

The second version of this report, dated 6 October 2020, has been amended for the following:

- 'Safe-T-Stop' replaced with 'SafeTstop'.
- 'VISCheck' replaced with 'VIS-Check'.
- 'Skid plate testing machine' replaced with 'Plate brake testing machine'.
- 'On-road stopping distance test' replaced with 'High-speed stopping distance test'
- Indication that only testing data from one vehicle was used by CASR in their analysis.

- Inclusion of a review of the manufacturer calibration certificates supplied for the three types of brake tester machines / instruments.
- Inclusion of the possible classification of the roller brake testing machine under AS/NZS 4613:2017 as a *Heavy Duty instrument for measuring heavy vehicle brake force*.
- Indication that SafeTstop utilised a third party to install the pressure sensors and MoTec systems within the test vehicles.

In addition, there are several minor typographical and grammatical corrections from the first version.

Appendix J – Study results summary

Figure J.1 provides a summary of the results for each brake testing method during each of the tested brake faut conditions.

The figure contains seven axes showing various results for the ten fault conditions as well as the baseline average condition.

The first axis shows the details of the specific brake pressure limitations applied for each fault condition. The available brake pressure at each wheel is shown as a percentage of the maximum. This was set via adjusting the pressure reducing and cut-off valves attached to the corresponding wheels of the test vehicle. A pictogram of a vehicle is provided with a colour coded indication of the maximum available brake pressure at each wheel (green being 100%, then transitioning through yellow, orange, and finally red representing 0%).

The second axis shows the percentage increase in stopping distance compared to baseline, for an initial speed of 80 km/h, elicited by each brake fault condition.

The third axis shows the front to rear brake force balance reported by the plate brake tester during each fault condition. The roller brake tester and decelerometer do not measure this factor.

The fourth and fifth axes show the amount of left to right brake force imbalance reported for the front and rear axle respectively. This data was reported by the plate brake tester and roller brake tester, but not by the decelerometer. An imbalance of 30% or greater is deemed a fail according to the NSW brake performance criteria. Results that pass the criteria are shown in green, while those that fail are shown in red.

The sixth axis shows the peak deceleration (in m/s^2) reported during each brake fault condition by the different brake testing methods. Results that are different to the baseline average, to a statistical significance level of 95%, are shown will a filled marker. Those that are not significantly different to the baseline average are shown with an empty marker. A peak deceleration below 60% g (5.89 m/s^2) is deemed a fail according to the NSW brake performance criteria. This pass/fail limit is shown as an orange line.

The seventh axis shows the average deceleration (in m/s^2) reported during each brake test setup for all four brake testing methods. Results that are different to the baseline average, to a statistical significance level of 95%, are shown will a filled marker. Those that are not significantly different to the baseline average are shown with an empty marker. An average deceleration below 47% g (4.61 m/s^2) is deemed a fail according to the NSW brake performance criteria. This pass/fail limit is shown as an orange line.

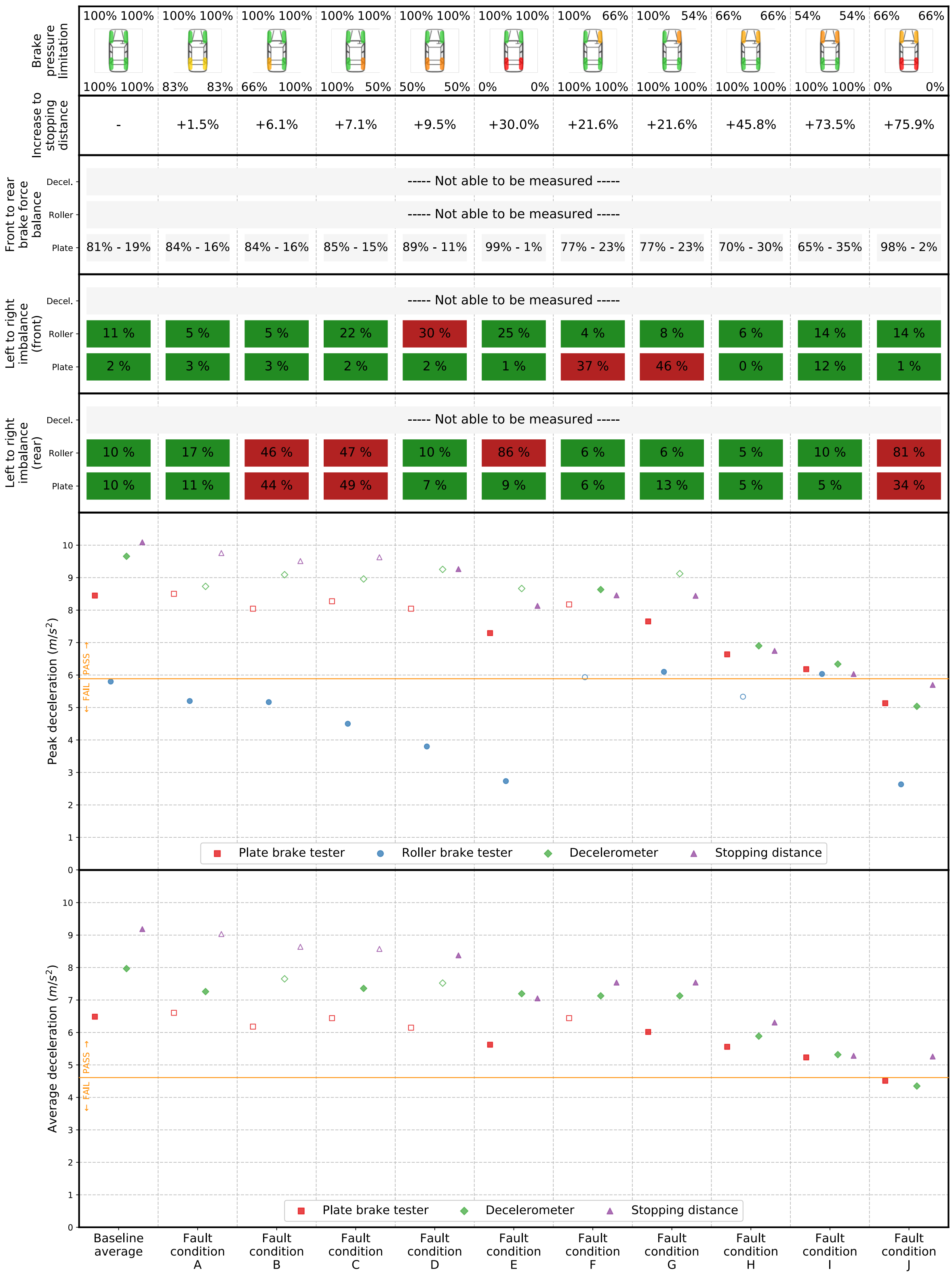


Figure J.1
Summary of study test results