ANNUAL SUMMARY REPORT

Project Title: R34 Evaluation of in-service road friendly suspension compliance methods utilising emerging technologies (Year 2 – 2015/16)

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`Author/s: Anthony Germanchev, Philip Roper, Chris Giang and Michael Byrne

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R34 Evaluation of in-service road friendly suspension compliance methods utilising emerging technologies

SUMMARY

This three year project was commissioned under the TMR/ARRB NACOE agreement to review and investigate the feasibility of testing the in-service compliance of road-friendly suspensions. The project is currently in Stage 2: Proof of concept, with the subsequent and final stage due for completion in 2017.

This report summarises the work completed in Stage 2 including the findings from tests conducted to evaluate the potential of in-service road-friendly suspension (RFS) testing methods.

The evaluation was undertaken by performing field testing of selected RFS measurement technologies. The results of the tests are summarised including limitations that would need to be considered prior to an operational evaluation in the final stage of the project.

The three steps involved in RFS certification were identified as excite, measure and analyse; each was assessed during the test program. A summary of the key findings is presented below.

Excitation methods

- VSB11 ramps proved to be suitable for single axles, but when used for more than one axle this method suffered from errors associated with the wheels dropping at different times and impulses being out of synchronisation. The practicality of this method was the major limitation including positioning the vehicle correctly and the need to remove ramps during the test to prevent interference. For these reasons this method is considered infeasible as an in-service compliance test method.
- The Road-Friendly Suspension Analyser (RFSA) proved to be reliable in what was a highly controlled test environment; however, it is not expected that this level of repeatability will be achievable when used to test in-service compliance in a roadside environment. The current design of the RFSA requires careful positioning and can pose clearance issues for some vehicles. These practical issues are considered to prohibit successful implementation as an in-service test method.
- The test methods conducted at higher speeds (5 km/h or greater) such as the pipe test and on-road test offer a much more practical option for in-service testing. The results obtained from these methods are highly sensitive to speed. Variations in speed can reduce the reliability such that they could not be relied upon unless the speed was managed to suit each vehicle.
- A test method involving small and light individual ramps was designed to address the practical issues described above. The results for this method were shown to be the most repeatable but were only conducted using a single-axle suspension. Tests involving a tandem and triaxle suspension are required to confirm its suitability for these systems.
- VSB11 certification requires the use of either the VSB11 ramps, the RFSA or chassis pull-up/pull-down methods. These excitation methods were shown to produce considerable variability, particularly when measuring damping ratio. If in-service test results are to be compared

to certification results, in order to determine the level of deterioration, the accuracy of the original test must be considered.

Measurement methods

- The measurement methods assessed included air pressure sensors, linear displacement transducers and load cells. All systems were proven to be suitable and at least equivalent to the approved VSB11 methods. The RFSA and DynaSsess methods measured axle hop which is considered to be an improvement in accuracy, but must be resolved during the analysis.

Analysis methods

- The analysis method stipulated in the VSB11 standard requires two successive peaks and a baseline value to be used for calculation. This requires selection, either manual or automated, either of which can result in errors and inconsistencies based on the selection made. These errors are more likely to occur if the measured data includes axle hop, roll and pitch. These can be overcome by selecting the correct points and applying analysis techniques to resolve these effects.
- The test results, particularly for those which included axle hop, showed significant variation due to an unsuitable analysis method being employed.

General findings

- Measurement data showed that the damping of RFS suspensions degraded over time as a result of shock absorber wear, whereas frequency, load sharing and mechanistic damping (without shock absorbers) remained unchanged.
- There are still knowledge gaps in the relationship between RFS systems (in particular varying the suspension characteristics of damping and frequency) and pavement wear. Until these are addressed, these is no scientific basis to differ from the existing requirements documented in VSB11, therefore recommendations and findings from this work relate to a system's ability to produce results comparable to VSB11 certification standards.
- Developments in on-board mass monitoring technology, vehicle telematics and the increased sophistication of heavy vehicle braking systems will continue and as these options become more advanced they may in the future provide methods for cost effectively monitoring the suspension performance of a number of vehicles during their normal operation.
- This stage of the project (proof of concept) has identified some methods as being suitable for implementation as in-service test methods and warrant inclusion in the further analysis to be completed in the final stage of the project. Conversely, a number of methods have been shown to be unsuitable and require modifications before they can be considered as in-service options. At this point the lack of a suitable excitation method limits the benefits of utilising on-board technology as an in-service test method.

Recommendations

- The analysis method using a multi-body model was shown to produce the most consistent results. An analysis method that applies a consistent method and that can resolve the effects of roll, pitch and axle hop and that is preferably automated, thus eliminating the chance of human error, is strongly recommended for an in-service compliance test.
- The recommended next step in this program of work is to evaluate the suitable methods (once finalised and agreed upon with the project team) as a pilot study to determine if satisfactory results can be replicated in terms of accuracy and repeatability. The pilot study will be conducted with in-service vehicles in a roadside inspection environment.

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1 INTRODUCTION

Heavy vehicles fitted with road-friendly suspensions (RFS) are permitted to operate on select routes at higher mass limits. This productivity benefit is permitted on the basis that an RFS reduces pavement damage. Vehicle standards bulletin 11 (VSB11) (Department of Transport and Regional Services, 2004) defines the test method for certifying a new suspension, however despite evidence that the performance of a suspension does degrade over time, there is no in-service compliance requirement for RFS.

This project is to be completed in three stages:

- Stage 1: Review and scoping 2014/15 (complete)
- Stage 2: Proof of concept 2015/16 (current)
- Stage 3: Operational evaluation 2016/17 (proposed).

The review completed under stage 1 included consideration of advancements in telematics, accreditation, software models and technologies and offered possibilities of new ways for in-service testing of RFS.

The preliminary findings of that review indicated that the major obstacles to an in-service test for RFS have been:

- identifying a cost-effective approach that does not involve removal of components or major interruption to the vehicle
- knowledge gaps and disagreement on the link between performance characteristics of a suspension, road friendliness and the amount of pavement wear.

On-board vehicle mass sensors and telematics have the potential to provide a cost-effective method for monitoring suspension health and the data necessary to understand the performance of the current heavy vehicle fleet.

This stage of the project aims to evaluate the possibility of utilising these technologies through a proof-of-concept testing program.

2 IN-SERVICE RFS MEASUREMENT SYSTEMS

An in-service measurement system is a device or method that can measure the performance of the suspension sufficiently to determine in-service road-friendly compliance. A request to industry was made to over 40 companies and individuals working in areas related to suspension performance and testing. The project was also raised and discussed at industry forums and meetings including the Australian Trucking Association (ATA) Industry Technical Council Meeting (October 2015), the Truck Industry Council Meeting (December 2015), the Australia Road Transport Suppliers Association (ARTSA) Annual General Meeting (February 2016), and has been discussed with the Queensland Trucking Association (QTA), the Heavy Vehicle Industry Association (HVIA formerly CVIAQ) and CVIA WA. A number of responses were received, two of which were from suppliers with products potentially capable of meeting the brief. Both systems were selected as suitable for evaluation as well as another system, identified during the literature review, which was also included in the test program. The systems selected for evaluation are listed in Table 2.1.

Table 2.1: In-service RFS measurement systems selected for evaluation

System no.	Product	Company	Type
1	CHEK-WAY Eliminator	Tramanco	On-board (permanently fitted)
2	RFS Analyser (RFSA)	ARRB Group	Stand-alone rig
3	DynaSsess	FormulaSpec	Wheel mounted (temporarily fitted)

Tramanco and FormulaSpec both responded to the industry request and were included for assessment based on their response and a brief description of their respective systems. The RFSA, which is currently owned and operated by ARRB, was included at the request of the TMR.

To prove RFS in-service compliance, the system should require the following:

- **Excite** – the suspension system under assessment should receive an impulse that is sufficient to excite all relevant modes of oscillation.
- **Measure** – the system must include a method for measuring the response of the suspension system with sufficient accuracy and resolution, including measurement of the test conditions.
- **Analyse** – the methods must analyse the response and determine the level of compliance.

These key criteria were used as a basis for the evaluation. Each system varies in its approach to measuring road friendliness, but each system covers these key areas of assessment, which are summarised in Table 2.2.

Table 2.2: Summary of system methods

No.	Product	Excitation	Measurement	Analysis	
				Data acquisition	File sharing
1	Chek-Way Eliminator (Tramanco)	A pipe or any section of road that excites suspension (e.g. potholes)	Air-bag pressure sensors with a 40 Hz sample frequency	Raw data file (encrypted hexadecimal) stored in memory of on-board unit	Downloadable via RS232 connection or wirelessly to a remote server via WIFI
2	RFS Analyser (ARRB)	Air-bag-raised platform which is dropped via sudden release blow-off valves	Load cells at a 100 Hz sample frequency	Raw data file in csv format requiring a laptop and software	Via any data acquisition software (i.e. MOTEC) via Ethernet cable or wirelessly
3	DynaSsess (FormulaSpec)	Vehicle driven over ramps placed underneath each tyre	Multiple sensors at a 85 Hz sampling frequency	Auto-generated data trace and pre-processed results stored in memory of remote PC or tablet	Wirelessly to a remote PC or a tablet via Windows software

2.1 System 1: CHEK-WAY® Eliminator

The Australian designed and manufactured ***CHEK-WAY® Eliminator*** is an on-board scale system that uses air pressure sensors to measure the axle group weights of a heavy vehicle. The system is highly configurable and includes the following key components: air pressure sensors, processing units, communication module and in-cabin display. Each of the key components is shown in Figure 2.1. This system offers advantages over typical on-board scales as it has the capability to sample and record data at a high frequency over a short period of time using various user defined and programmable functions. The systems own in-house custom software triggers various recording events when a peak pulse of a certain value in air pressure is registered. All of these events are recorded for a period of time before and after the peak pulse and are stored and/or exported as required.

Figure 2.1: CHEK-WAY Eliminator components

This system was evaluated during test program 1 (described in Section 5), conducted at the Tramanco workshop facility in Brisbane on 16–18 May, 2016.

Table 2.3 provides a summary of the details for system 1.

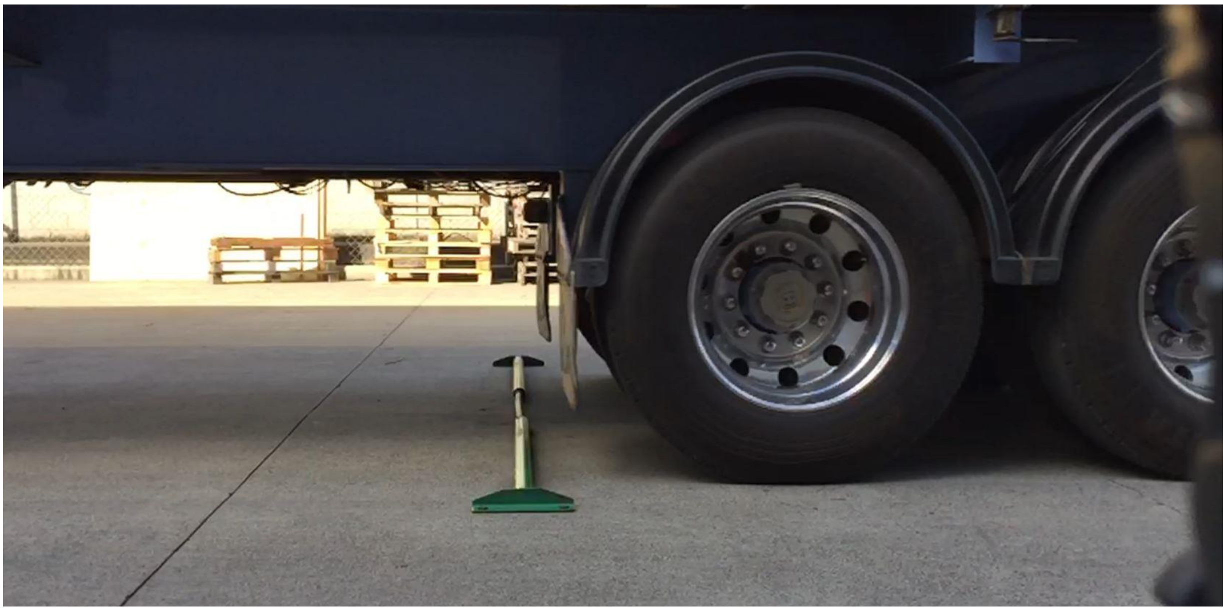
Table 2.3: System 1 details

Name	*CHEK-WAY® Eliminator*
Company	Tramanco Pty Ltd
Patent no.	Australian patents # 2004264997 and 2009200620 plus 18 more international patents and trade marks
Business type	Manufacturer of *CHEK-WAY® and KWIK-CHEK®* on-board scales
Contact	Roger Sack, Managing Director.
Email	roger@tramanco.com.au
Website	www.tramanco.com.au
Office	21 Shoebury St, Rocklea QLD 4106 Australia.

2.1.1 *System 1: Excitation method*

The excitation method for this system is one of either the pipe test shown in Figure 2.2 or any road section (Figure 6.44) sufficient to excite the suspension. The pipe is 58 mm in diameter and the vehicle is driven over the pipe at speed.

Figure 2.2: Pipe test used as excitation method for system 1



2.1.2 *System 1: Measurement method*

The measurement method for system 1 comprises two air pressure transducers (APT). Figure 2.3 shows the two sensors fitted to the rear axle of the triaxle trailer suspension; in this case an APT was already fitted to the vehicle for the purpose of an on-board scale and an additional sensor was added for the test to function as a system to measure damping and frequency.

Figure 2.3: Measurement method for system 1 comprising two air pressure transducers

2.1.3 *System 1: Analysis method*

The analysis method is proprietary software that includes an on-board processing unit shown in Figure 2.1. The software functionality includes identifying an event, logging the data and calculating the damping and frequency.

2.2 System 2: RFS Analyser

The RFSA is a purpose-built rig for VSB11 certification testing. The test system comprises three mobile platforms and ramps. Each platform is fitted with two air bags which are inflated to lift the vehicle and load cells to measure the weight under each tyre. The system requires an external air compressor capable of supplying a pressure of at least 120 psi. Data can be logged dynamically from the RFSA but requires a data acquisition system which is not part of this device. Figure 2.4 shows the RFSA with ramps in position.

Figure 2.4: Road-Friendly Suspension Analyser

The RFSA was evaluated during test program 2 (described in Section 5) completed at the DECA facility in Shepparton, Victoria on 26–27 May 2016.

Table 2.4 provides a summary of the details for system 2.

Table 2.4: System 2 details

Name	Road-Friendly Suspension Analyser
Company	ARRB Group Ltd
RVCS no	T9872
Patent no	None
Business type	Research & Consulting
Contact	Anthony Germanchev, HV Team Leader
Email	anthonyg@arrb.com.au
Website	www.arrb.com.au
Office	500 Burwood Hwy, Vermont South, VIC 3133

2.2.1 *System 2: Excitation method*

The excitation method for this system is the rig itself which raises a platform upon which each axle is positioned. Figure 2.5 shows the vehicle in the raised position. The rig is installed with air bags on each side of the rig, these which are filled with compressed air from an external source.

Figure 2.5: RFSA used as the excitation method for system 2

2.2.2 *System 2: Measurement method*

The measurement method for system 2 comprises the load cells positioned beneath each tyre. Data is logged at 100 z via an independent data acquisition system. Figure 2.6 shows the three platforms connected to a laptop.

Figure 2.6: Measurement method for system 2 comprising load cells for each wheel

2.2.3 *System 2: Analysis method*

There is no analysis method as part of this system. The analysis method used to assess data from this system was the approved VSB11 process in which points are selected manually.

2.3 System 3: DynaSsess

The DynaSsess system is shown in Figure 2.7. The system comprises custom-designed ramps (four required for a single axle), hub-mounted sensors (temporarily fitted) on both sides of the axle, and custom software serving as the data logger and user interface. The vehicle is driven forwards from a stop over the ramps dropping from a fixed height sufficient to excite the resonant frequency of the suspension. The response is measured by the sensors, which are then removed at the completion of the test. Data is analysed via custom software which can be installed on a tablet or PC.

Figure 2.7: DynaSsess test system

The DynaSsess system was evaluated during test program 3 (described in Section 5) completed at the ARRB test site in Vermont South, Victoria on 7–8 June 2016.

Table 2.5 provides a summary of the details for system 3.

Table 2.5: System 3 details

Name	DynaSsess
Company	FormulaSpec Pty Ltd
Patent no.	None
Business type	Consulting
Contact	Dr Nick Trevorrow, Director.
Email	nick@formulaspec.com.au
Website	www.formulaspec.com.au/
Office	21 Dally St Clifton Hill, VIC 3068

2.3.1 *System 3: Excitation method*

The excitation method for this system comprises 80 mm ramps positioned in front of each tyre prior to the test. Figure 2.8 shows the vehicle immediately prior to dropping off the ramp.

Figure 2.8: Individual 80 mm ramps used as the excitation method for system 3

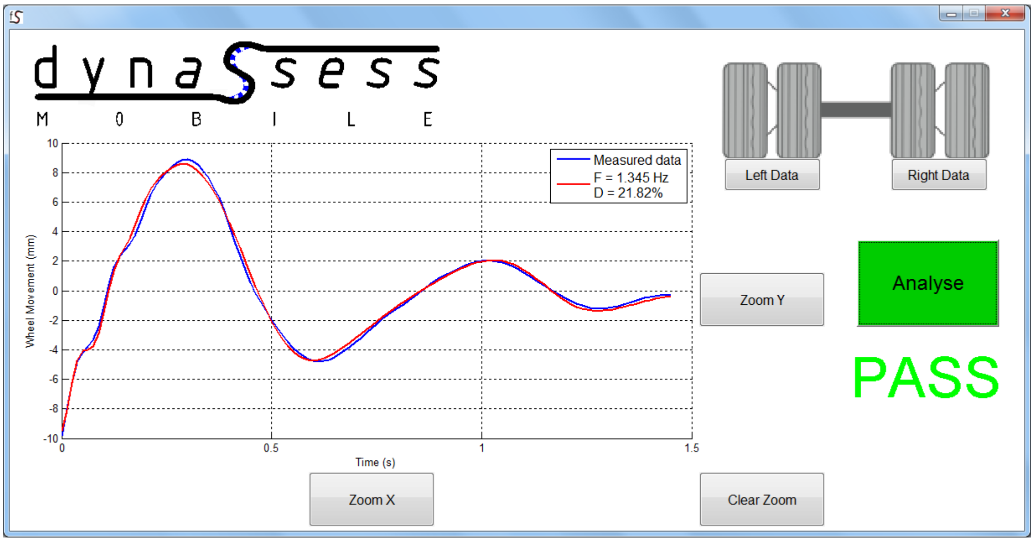
2.3.2 *System 3: Measurement method*

The measurement method for system 3 comprises sensors that are temporarily mounted to each side of the axle, shown in Figure 2.7 and Figure 2.8. The sensors send data wirelessly to a laptop or tablet. Data is logged at 85 z.

2.3.3 *System 3: Analysis method*

The analysis is an automated process which does not require the user to interpret the data. Rather, the software uses a multi-body dynamic model which represents the various modes of suspension behaviour, such as axle hop, roll and bounce. This model is fitted to the measured test data as shown in Figure 2.9. The resulting coefficient values are then able to be converted into Sprung Mass Frequency (F) and Mean Damping Ratio (DM) which are displayed via the user interface.

Figure 2.9: Screen capture of software used for analysis method for system 3

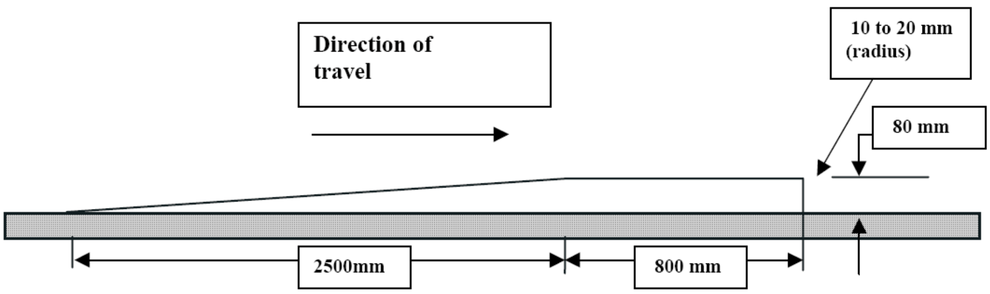


2.4 Reference system

2.4.1 *Reference system: Excitation method*

The excitation method used as the reference is the VSB11-approved 80 mm ramps. This method generates an impulse as the wheel rolls off the step and drops to the ground. This was the original European test method applied widely to single axles. It is described in Annex II of Council Directive 96/53/EC (Council of the European Union 1996), as depicted in Figure 2.10.

Figure 2.10: VSB11 ramp test



Source: Department of Transport and Regional Services (2004).

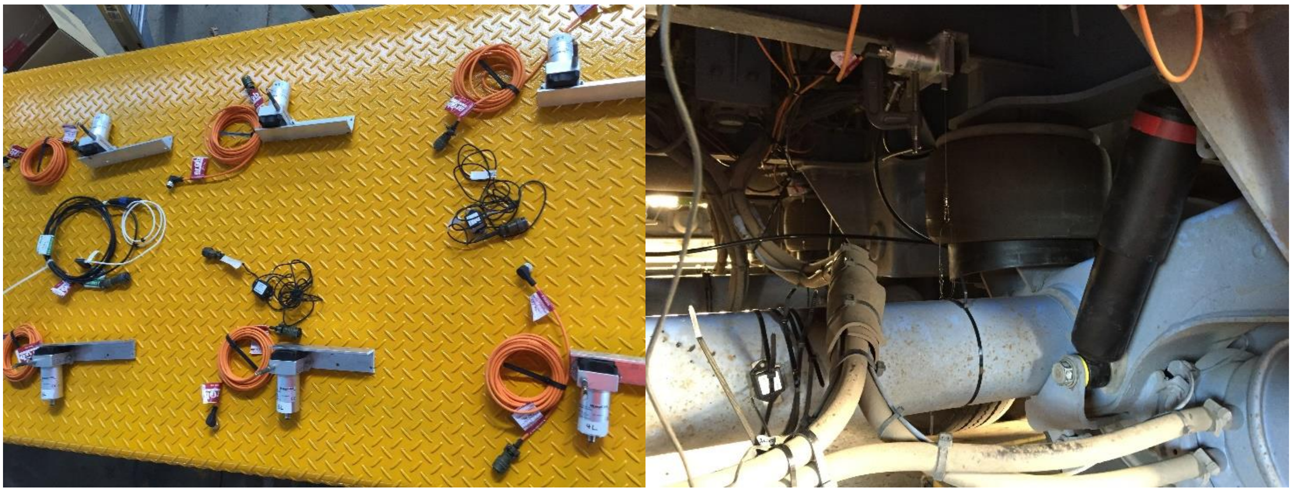
The VSB11 ramps were used as part of test programs 1 and 3. Figure 2.11 shows the ramps being used with a 4x2 rigid truck and a triaxle trailer suspension.

Figure 2.11: VSB11 ramps used for RFS testing

2.4.2 *Reference system: Measurement method*

The reference system included linear displacement transducers and air pressure sensors shown in Figure 2.12. These sensors were fitted to each vehicle and data was logged at 100 Hz using customised MOTEC software.

Figure 2.12: VSB11 ramps used for test program 3 with a 4x2 rigid truck



2.4.3 *Reference system: Analysis method*

To calculate the damping ratio, the first largest peak (A1) and the following peak (A2) was identified in the dataset by determining the changes in the slope of the line implied by the data. The peaks were then subtracted from a baseline value which was calculated by taking an average pressure or displacement of the time when the oscillations have settled down. The following equation was then applied to calculate the damping ratio:

$$Damping\ ratio = \frac{1}{2\pi}\ln\frac{A1}{A2} \qquad 1$$

where

A1 = peak amplitude of the first cycle of oscillation

A2 = peak amplitude of the second cycle of oscillation.

The frequency was calculated by taking the time when the first largest peak (T1) occurs and the time when the following peak (T2) occurs. The following equation was then applied to calculate the frequency.

$$Frequency = \frac{1}{(T2 - T1)} \qquad 2$$

where

T1 = time at which peak amplitude of the first cycle of oscillation occurs

T2 = time at which peak amplitude of the second cycle of oscillation occurs.

3 SHOCK ABSORBER PERFORMANCE

The function of a shock absorber is to absorb the energy caused by the vertical movement of the suspension. Shock absorbers are specifically designed and selected for each suspension application. Performance variations are influenced by different rebound lengths, compression and the use of multi-stage valving and different bore diameters (Australian Road Transport Suppliers Association 2001). Understanding shock absorber performance is an important requirement of this evaluation process. Expert advice and technical assistance was sought from an aftermarket shock absorber manufacturer (Powerdown) and suspension manufacturer (Hendrickson).

3.1 Selection and pre-testing of shock absorbers

The aim of the testing program is to determine the level of shock absorber damping that can be detected by each measurement system. Therefore the experimental design must include a range of shock absorbers varying in damping characteristics. The project management team agreed that a suitable range of damping should include a heavy duty shock absorber (that is RFS compliant) and a shock absorber that is approximately half the damping of the heavy duty shock absorber and another shock absorber with performance between the two. ARRB collaborated with Powerdown to determine a suitable set of shock absorbers to be used in the testing program, via a bench-top testing program.

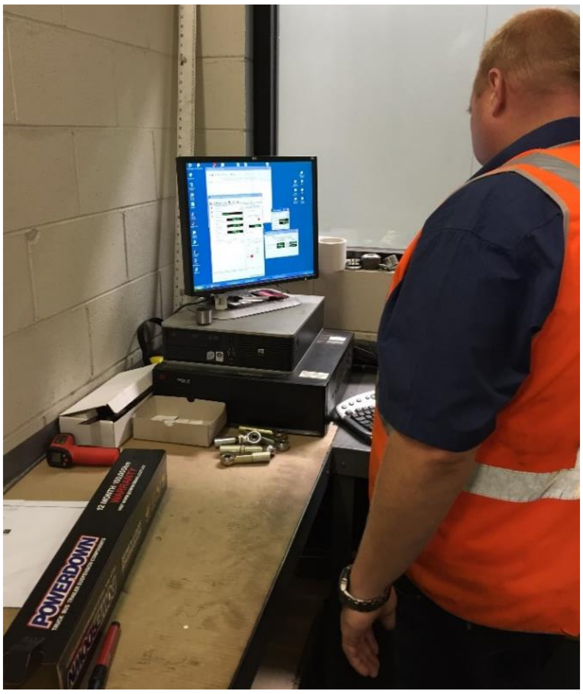
Tests were conducted at the Powerdown test facility. Three sets of shock absorbers were selected ranging in low, medium and high damping.

Figure 3.1 shows a shock absorber mounted in the Powerdown test rig and undergoing testing.

Figure 3.1: A shock absorber undergoing pre-testing

Each shock absorber was cycled through a warm-up procedure and a range of test speeds to measure the damping force prior to be used in the RFS field tests, as shown in Figure 3.2.

Figure 3.2: Warm-up procedure prior to recording performance data



Three shock absorbers were selected to be used in the testing program:

- a heavy-duty (HD) shock absorber with high damping and RFS certification
- a medium-duty (MED) shock absorber with medium damping
- a low-duty (LOW) shock absorber with low damping.

The low and medium-duty shock absorbers were tested at 8 speeds whereas the heavy-duty shock absorber was only tested at 5 speeds. The 3 highest test speeds were not used for the heavy-duty shocks, as the forces exerted on the rig during these tests can be high and the intention was to limit these if possible. The 5 speeds used for testing covered the range of speeds the shock absorbers would be expected to operate at during the testing program. Table 3.1 shows the test speeds used for testing. It is expected that the shock absorbers will operate below 2.0 Hz.

Table 3.1: Speeds for shock absorber tests

Test rig		Shock absorber		
Speed (m/s)	Frequency (Hz)	Low	Medium	High
0.05	0.320	☑	☑	☑
0.13	0.830	☑	☑	☑
0.26	1.660	☑	☑	☑
0.33	2.100	☑	☑	☑
0.39	2.480	☑	☑	☑
0.52	3.310	☑	☑	☒
0.66	4.200	☑	☑	☒
1.00m/s	6.370	☑	☑	☒

The shock absorber performance was quantified using force vs velocity and force vs displacement charts. Figure 3.3, Figure 3.4 and Figure 3.5 show the force vs displacement characteristics of the heavy-duty, medium and low-damping shock absorbers respectively.

Figure 3.3: Force vs displacement test results for a heavy-duty shock absorber

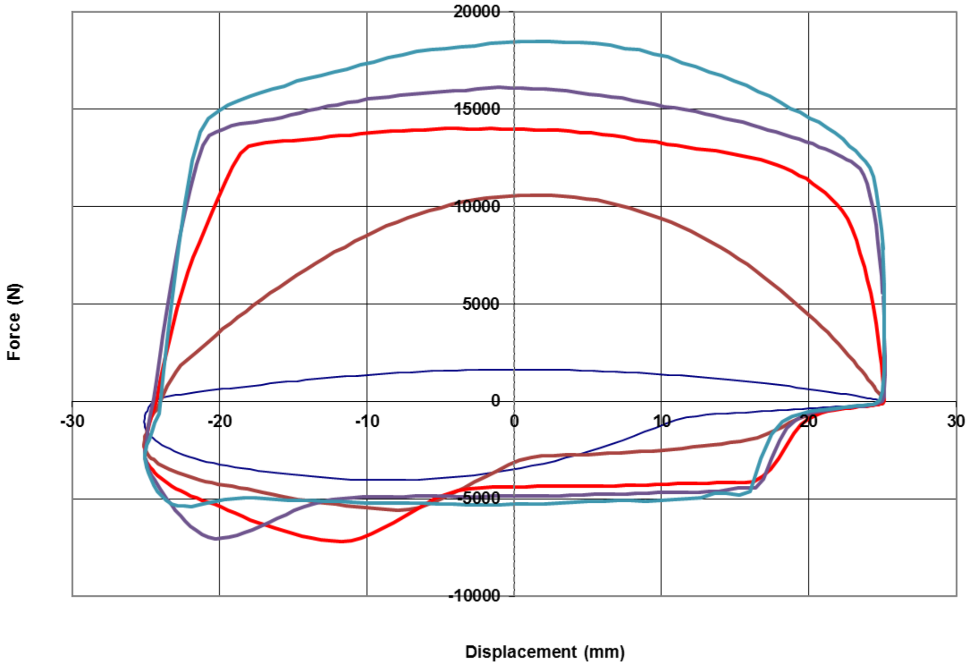


Figure 3.4: Force vs displacement test results for a medium-duty shock absorber

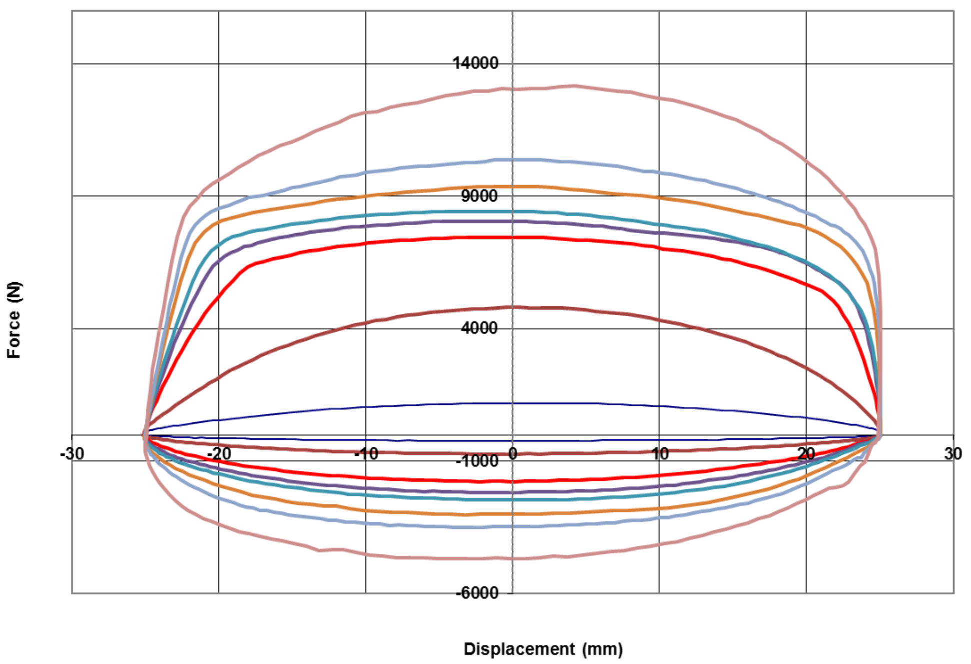


Figure 3.5: Force vs displacement test results for a low-damping shock absorber

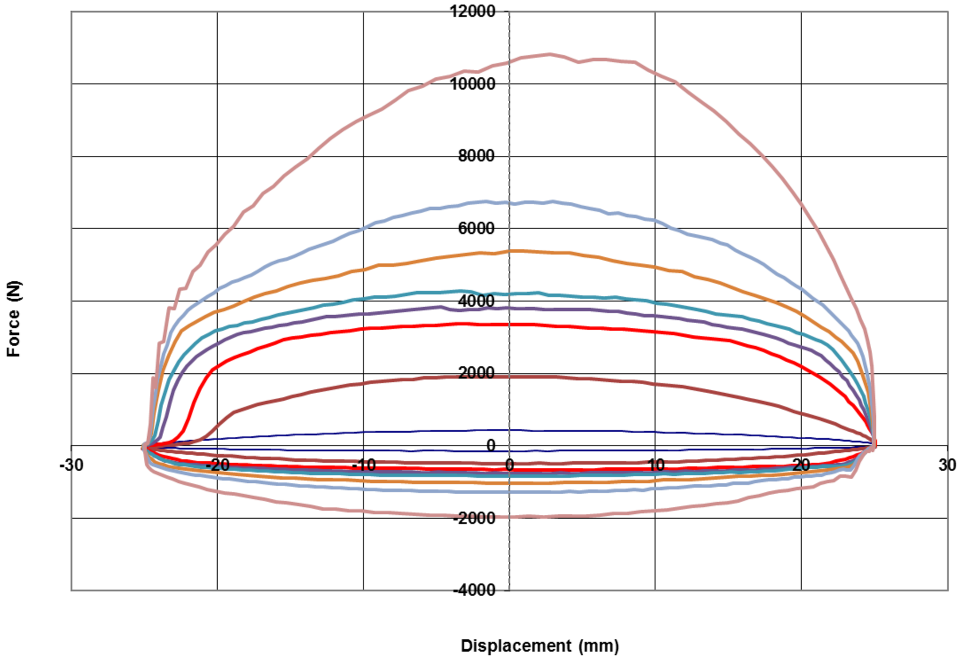
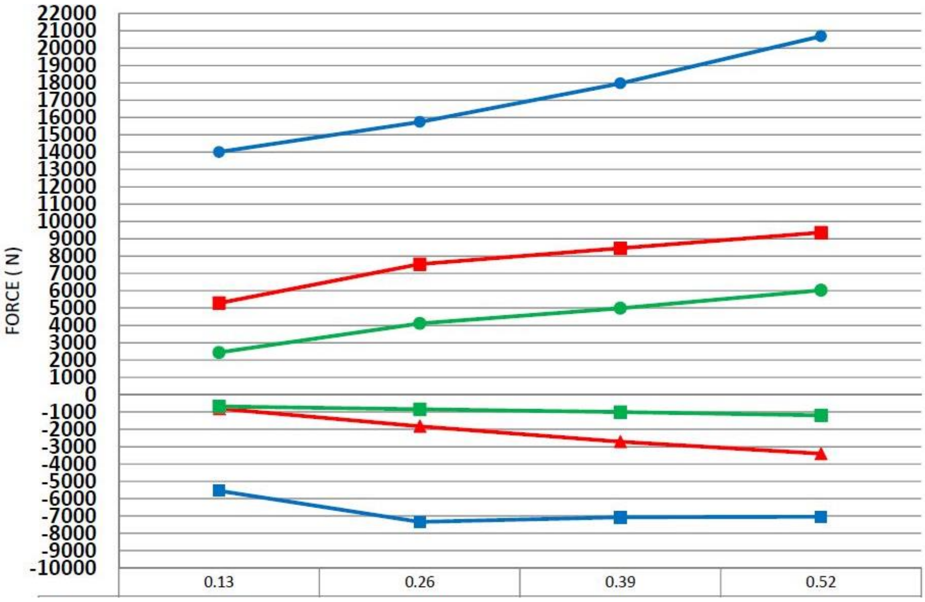


Figure 3.6 shows a summary of the peak force values for each shock absorber at four test speeds, for both the extension stroke and the compression stroke. The data points shown in the positive range of the y-axis represent the damping force in the extension stroke and the compression stroke force is shown in the negative range. The four data points are four speeds at which the tests were conducted: 0.13 m/s, 0.26 m/s, 0.39 m/s and 0.52 m/s.

Figure 3.6: Comparison of peak forces for each shock absorber



A summary of the peak damping forces for each of the shock absorbers is shown in Table 3.2, Table 3.3 and Table 3.4 for the low, medium and high-damping shock absorbers.

Table 3.2: Summary of peak damping force for low-damping shock absorbers

Test speed (m/s)	Low damping shock absorber						Lowest peak force (N)	Highest peak force (N)	Variability
	1	2	3	4	5	6			
0.05	430	611	498	407	518	473	407	611	**33%**
0.13	1,919	2,360	2,269	2,221	2,274	2,282	1,919	2,360	**19%**
0.26	3,377	3,747	3,459	3,027	3,693	3,657	3,027	3,747	**19%**
0.33	3,831	4,232	3,868	3,421	4,128	4,034	3,421	4,232	**19%**
0.39	4,278	4,576	4,324	3,831	4,545	4,417	3,831	4,576	**16%**
0.52	5,377	5,424	5,472	4,852	5,566	5,343	4,852	5,566	**13%**
0.66	6,749	6,523	6,742	5,988	6,841	6,419	5,988	6,841	**12%**
1.00	10,813	10,114	10,690	10,070	11,128	10,210	10,070	11,128	**10%**

Table 3.3: Summary of peak damping force for medium-damping shock absorbers

Test speed (m/s)	Medium-damping shock absorber						Minimum force (N)	Maximum force (N)	Variability
	1	2	3	4	5	6			
0.05	1,188	1,508	1,710	1,470	1,696	1,330	1,188	1,710	**31%**
0.13	4,805	4,808	5,140	5,082	5,679	4,874	4,805	5,679	**15%**
0.26	7,458	6,830	7,305	7,634	7,950	7,607	6,830	7,950	**14%**
0.33	8,059	7,402	7,897	8,200	8,465	8,158	7,402	8,465	**13%**
0.39	8,433	7,857	8,252	8,565	8,839	8,535	7,857	8,839	**11%**
0.52	9,377	8,796	9,184	9,508	9,737	9,445	8,796	9,737	**10%**
0.66	10,374	9,851	10,150	10,550	10,610	10,378	9,851	10,610	**7%**
1.00	13,164	12,672	12,673	13,406	13,106	13,024	12,672	13,406	**5%**

Table 3.4: Summary of peak damping forces for high-damping shock absorbers

Test speed (m/s)	High-damping shock absorber						Lowest peak force (N)	Highest peak force (N)	Variability
	1	2	3	4	5	6			
0.05	1,635	5,687	1,070	4,150	3,089	2,774	1,070	5,687	**81%**
0.13	10,597	13,397	13,106	13,813	13,014	13,123	10,597	13,813	**23%**
0.26	14,011	15,129	14,957	15,692	14,872	15,181	14,011	15,692	**11%**
0.39	16,144	17,451	16,991	17,764	17,175	17,233	16,144	17,764	**9%**
0.52	18,499	20,085	19,460	20,506	19,840	19,736	18,499	20,506	**10%**

There is a large variability in the test results for those conducted at the lowest test speed (0.05 m/s). For example, for the heavy-duty shock absorbers the lowest peak force was 1,070 N and the highest peak was 5,687 N, a variation of 81%. Although this is large difference, it should be noted that the forces involved at these speeds are low when compared with the 20 kN force generated at 0.52 m/s. The shock absorber will operate at speeds from 0 m/s up to approximately 0.5 m/s. The variation in force will affect the test results, and it is reasonable to expect a 10-15%

variation in damping for new shock absorbers. This tolerance will also apply to new suspensions certified as road-friendly.

Figure 3.7 shows the 3 sets of 6 shock absorbers selected for testing the triaxle suspension. Shock absorbers are colour-coded to identify low, medium and high damping.

Figure 3.7: Shock absorber sets for field tests with high, medium and low damping

4 EXPERIMENTAL DESIGN

There are two approaches that can be taken to evaluate the validity of a measurement system: a large sample from uncontrolled testing in which a large quantity of data is gathered and statistical analysis can be conducted to identify trends, or a small number of controlled tests in which key variables are investigated while other influencing factors remain unchanged. Based on ARRB's experience, conducting field tests of this nature requires the latter method which will allow for the effect of key variables to be quantified.

Using VSB11-approved test methods, the suspension damping ratio and frequency can be measured. If the performance of a suspension meets or exceeds the defined performance criteria, it can then be certified as road-friendly. The defined performance criteria for quantifying suspension road-friendliness are:

- static load sharing (no greater than 5% variation)
- frequency of oscillation of sprung mass (no greater than 2.0 Hz)
- damping capability (no less than 20% of critical damping)
- damping capability (no greater than 50% of total damping due to friction damping).

The key variables in the test conditions that affect measurement were identified as:

- shock absorber damping characteristics (high, medium, low)
- excitation method
- payload (axle-group weight)
- vehicle/trailer wheelbase
- tyre pressure
- suspension design
- temperature.

In order to quantify the effect of each of the key variables under examination a test matrix was developed for each of the three test programs. Each test program was designed to evaluate the test system with an approved VSB11 test method.

The test matrix for the first test program is shown in Table 4.1.

Table 4.1: Test matrix for the first test program

Test	Shock absorbers						Shock absorber type	Load	Test (excitation method)		
	Axle 1		Axle 2		Axle 3						
	Right	Left	Right	Left	Right	Left			VSB11 ramps	Pipe	Road
1	HD	HD	HD	HD	HD	HD	After market	Fully laden	☑☑☑	☑☑☑	
2	HD	HD	HD	HD	HD	OFF	After market	Fully laden	☑☑☑	☑☑☑	
3	HD	HD	HD	HD	OFF	OFF	After market	Fully laden	☑☑☑	☑☑☑	
4	HD	OFF	HD	OFF	HD	OFF	After market	Fully laden	☑☑☑	☑☑☑	
5	MED	OFF	MED	OFF	MED	OFF	After market	Fully laden	☑☑☑	☑☑☑	
5	OFF	OFF	OFF	OFF	OFF	OFF	After market	Fully laden	☑☑☑	☑☑☑	
9	MED	MED	MED	MED	MED	MED	After market	Fully laden	☑☑☑	☑☑☑	☑
10(1)	MED	MED	MED	MED	MED	MED	After market	Fully laden	☑☑☑	☑☑☑	☑
10	LOW	LOW	LOW	LOW	LOW	LOW	After market	Fully laden	☑☑☑	☑☑☑	
11	HD	HD	HD	HD	HD	HD	After market	Half laden	☑☑☑	☑☑☑	
12	MED	MED	MED	MED	MED	MED	After market	Half laden	☑☑☑	☑☑☑	☑
13	LOW	LOW	LOW	LOW	LOW	LOW	After market	Half laden	☑☑☑	☑☑☑	
14	HD	HD	HD	HD	HD	HD	New original	Half laden	☑☑☑	☑☑☑	

1 Test conducted with ride height control valve disconnected.

The second test program was conducted using the ARRB RFSA which is an approved VSB11 test method, therefore no comparison was made to other excitation methods. The test matrix included variations in shock absorbers to quantify known deficiencies in the drop method, previously identified in an National Transport Commission review (2008). The test matrix for the second test program is shown in Table 4.2.

Table 4.2: Test matrix for the second test program

Test	Shock absorbers				Type	Load	Test (excitation method)
	Axle 2		Axle 3				VSB11 RFSA drop test
	Right	Left	Right	Left			
1	HD	HD	HD	HD	New original	Fully laden	☑☑☑
2	HD	HD	HD	OFF	New original	Fully laden	☑☑☑
3	HD	OFF	HD	OFF	New original	Fully laden	☑☑☑
4	OFF	OFF	OFF	OFF	New original	Fully laden	☑☑☑

The third test program was designed to evaluate test system 3 and compare the results with an approved VSB11 test method.

The test matrix used for the third test program is shown in Table 4.3.

Table 4.3: Test matrix for the third test program

Test	Shock absorbers		Road type	Shock absorber type	Load condition	Test (excitation method)	
	Axle 2					System	VSB11 ramp
	Right	Left					
1	HD	HD	Asphalt	New original	Fully laden	☑☑☑	☑☑☑
2	HD	OFF	Asphalt	New original	Fully laden	☑☑☑	☑☑☑
3	OFF	OFF	Asphalt	New original	Fully laden	☑☑☑	☑☑☑
4(1)	HD	HD	Concrete	New original	Fully laden	☑☑☑	☑☑☑

1 Test 4 was conducted on a flat, level road surface.

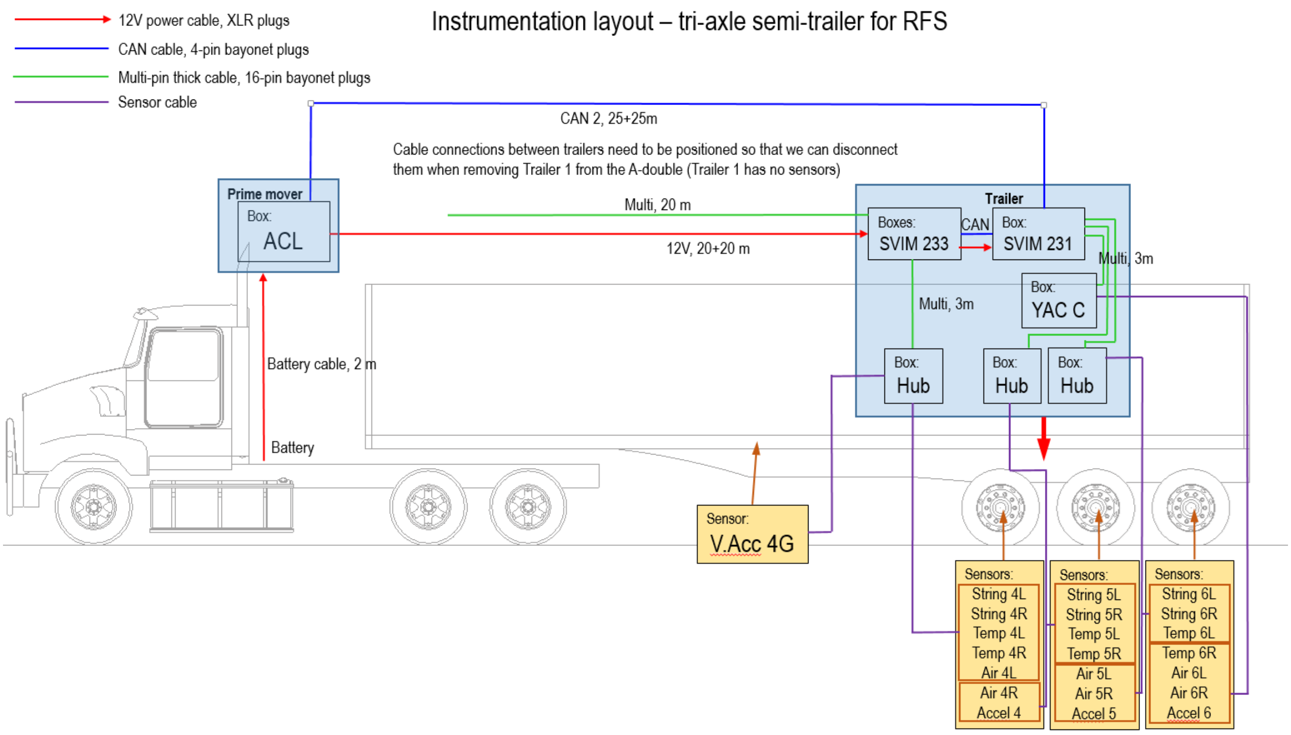
4.1 Reference measurement system

A reference system was fitted to each test vehicle and used for comparison with the systems under test. The reference system used for testing was ARRB's data acquisition system which comprises a Panasonic Toughbook, MOTEC data logger and the following sensors:

- GPS antenna and receiver
- 3 x accelerometers (4 g, single-axis) fitted to the centre of each axle
- 6 x air pressure transducers fitted to the left and right air bag lines
- 6 x air pressure transducers fitted to the left and right air bag lines
- 1 x accelerometer (4 g, single-axis) fitted to the trailer body.

The instrumentation layout for the triaxle semi-trailer is shown in Figure 4.1.

Figure 4.1: Reference system instrumentation layout used for semi-trailer



The same instrumentation layout was used for test vehicles 2 and 3, but as these vehicles were fitted with a tandem axle group and single axle, less sensors were required.

5 TEST PROGRAM

Each system was tested individually. The same experimental design was used for each system. The reference system used as a basis for comparison as each key variable was changed in isolation. The tests were conducted across a range of vehicles: triaxle semi-trailer, 6x4 prime mover and 4x2 rigid truck. The vehicles represent common vehicle types fitted with RFS and subsequently permitted to operate at HML.

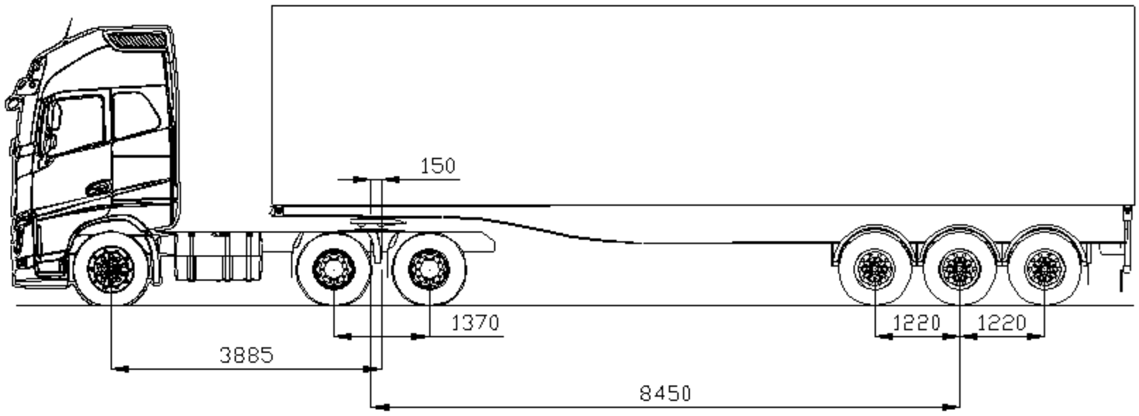
5.1 Test vehicles

The triaxle trailer used for test program 1 is shown in Figure 5.1.

Figure 5.1: Test vehicle 1: Triaxle semi-trailer

The dimensions of the triaxle trailer used for test program 1 are shown in Figure 5.2.

Figure 5.2: Test vehicle 1 dimensions

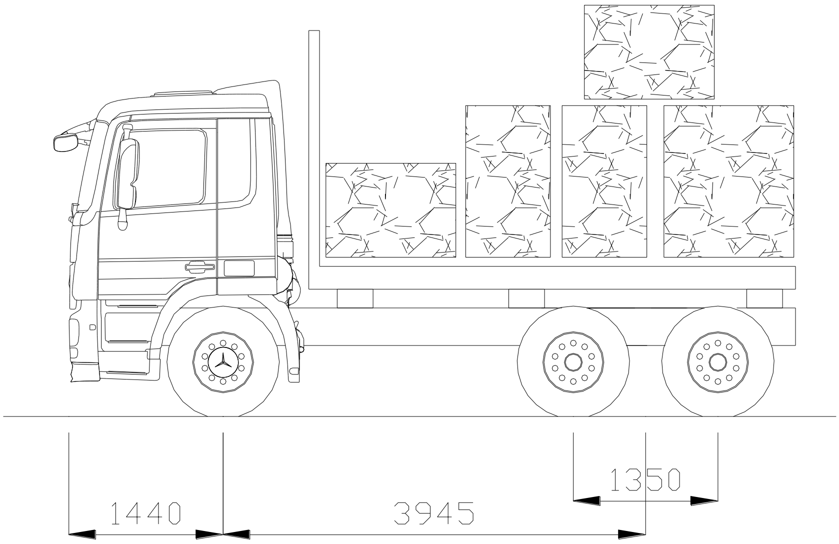


The 6x4 prime mover used for test program 2 is shown in Figure 5.3.

Figure 5.3: Test vehicle 2: 6x4 prime mover

The dimensions of the 6x4 prime mover used for test program 2 are shown in Figure 5.4.

Figure 5.4: Test vehicle 2 dimensions

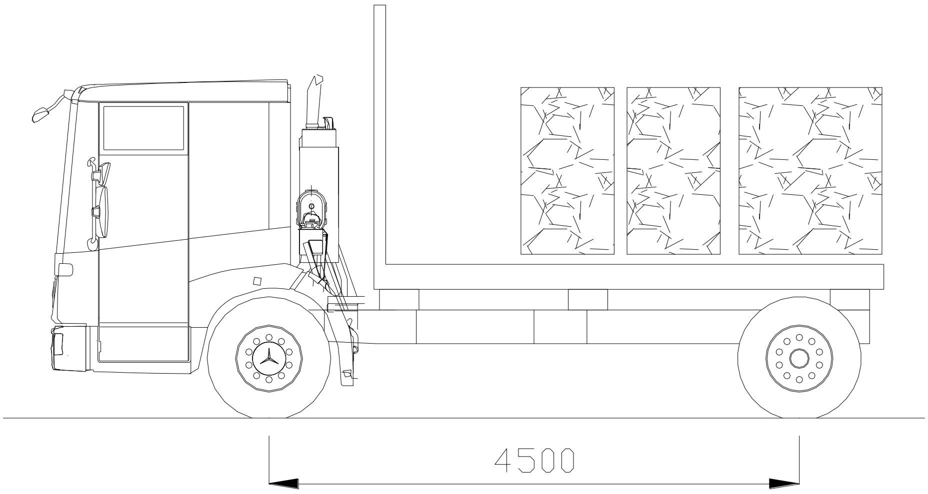


The 4x2 rigid truck used for test program 3 is shown in Figure 5.5.

Figure 5.5: Test vehicle 3: 4x2 rigid truck

The dimensions of the 4x2 rigid truck used for test program 3 are shown in Figure 5.6.

Figure 5.6: Test vehicle 3 dimensions



The specifications for the three test vehicles are listed in Table 5.1.

Table 5.1: Vehicle specifications

Specification	Vehicle 1	Vehicle 2	Vehicle 3
Test system fitted	CHEK-WAY Eliminator	RFSA	DynaSsess
Vehicle configuration	Prime mover semi-trailer	Prime mover (bob tail)	Rigid truck
Truck/trailer make	O'Phee	Mercedes Benz Actros	Mercedes Benz Econic
Suspension make	Hendrickson Intraax AAT250	Mercedes Benz 8-bag	Mercedes Benz 4-bag
Suspension type	Air	Air	Air
Original shock absorber	Hendrickson S-21699	A9603262304	A9613260800
RFS compliant	YES	YES	YES
Tyres	Continental 11R22.5	Bridgestone 295-80R22.5	Bridgestone 295-80R22.5
Axle spacing	1,220 mm	1,350 mm	NA
Wheelbase/S-dimension	8,450 mm	3,945 mm	4,500 mm

Each vehicle was weighed during the testing program using portable scales. The axle group weights for test vehicle 1, as tested, are shown in Table 5.2.

Table 5.2: Test vehicle 1 axle weights

	Axle 4 weight (kg)		Axle 5 weight (kg)		Axle 6 weight (kg)	
	Laden	Partially laden	Laden	Partially laden	Laden	Partially laden
Right (driver side)	3,380	2,660	3,520	2,980	3,600	2,780
Left (passenger side)	3,620	2,820	3,320	2,720	3,260	2,560
Total (by axle)	**7,000**	**5,480**	**6,840**	**5,700**	**6,860**	**5,340**
Total (by group)	**20,700**			**16,520**		

The axle group weights for test vehicle 2, as tested, are shown in Table 5.3.

Table 5.3: Test vehicle 2 axle weights

	Steer axle weight (kg)		Drive axle 1 weight (kg)		Drive axle 2 weight (kg)	
	Unladen	Laden	Unladen	Laden	Unladen	Laden
Right (driver side)	3,200	3,300	1,420	4,100	1,100	4,100
Left (passenger side)	3,060	3,360	1,020	4,400	1,280	4,160
Total (by axle)	**6,260**	**6,660**	**2,420**	**8,500**	**2,380**	**8,260**
Total (by group) laden	**6,600**		**16,760**			

The axle group weights for test vehicle 3, as tested, are shown in Table 5.4.

Table 5.4: Test vehicle 3 axle weights

	Steer axle weight (kg)		Drive axle weight (kg)	
	Unladen	Laden	Unladen	Laden
Right (driver side)	2,220	2,340	1,420	5,240
Left (passenger side)	2,280	2,600	1,520	5,200
Total (by axle)	**4,500**	**4,940**	**2,940**	**10,440**

5.2 Test systems

Figure 5.7 shows test system 1 fitted to the triaxle semi-trailer test vehicle. The left photograph shows the air pressure transducers plumbed into the air bag supply line using a t-piece joiner. The right photograph shows the CHEK-WAY processing unit (part of test system 1).

Figure 5.7: Test system 1 fitted to triaxle semi-trailer

Figure 5.8 shows the reference system fitted to the triaxle semi-trailer. The left photo shows the linear displacement transducer measuring vertical axle displacement and the air pressure transducer. The right photograph shows the accelerometer fitted to the axle and the junction box mounted to the chassis cross-member.

Figure 5.8: Reference system fitted to triaxle semi-trailer

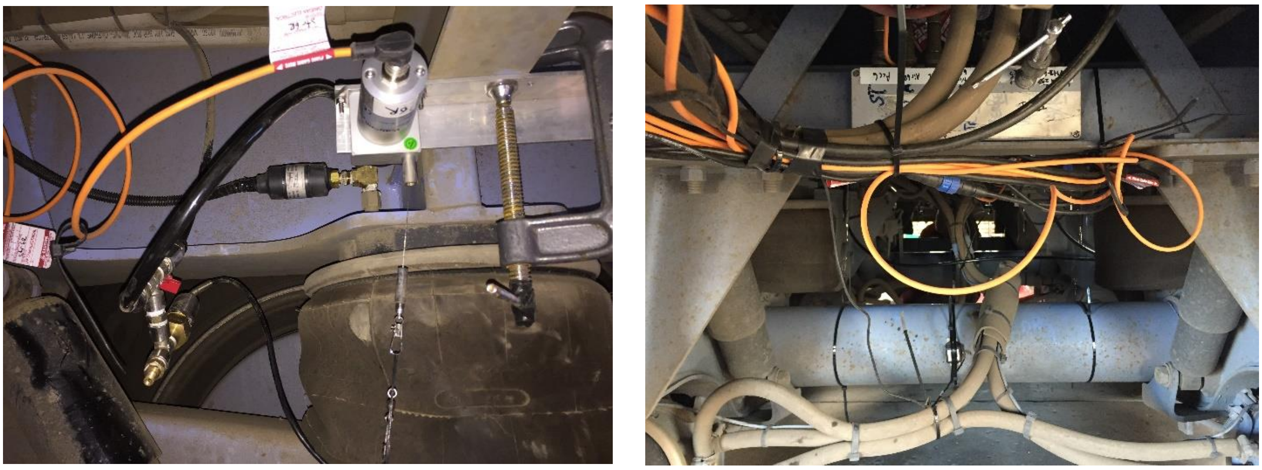


Figure 5.9 shows test system 2 (RFSA rig) with the fully laden 6x4 prime mover in position; the left photograph shows the linear displacement transducer mounted between the underside of the tray and rear axle. The excitation method for test program 2 was the VSB11 RFSA drop test, and was the same method for both the test system and reference system. The measurement method was the load cell sensors permanently fitted to the RFSA (test system 2) and the linear displacement sensors fitted to each axle (reference system).

Figure 5.9: Test system 2 used to assess a 6x4 prime mover

Figure 5.10 shows test system 3 fitted to the rear axle of the 4x2 rigid truck. Test system 3 comprises three main components – the measurement device fitted to the hub and shown in the left photograph, the excitation device (the ramps) shown in the right photograph, and the analysis software (not shown).

Figure 5.10: Test system 3 fitted to the 4x2 rigid truck

Figure 5.11 shows the reference system fitted to the 4x2 rigid truck.

Figure 5.11: Reference system fitted to the 4x2 rigid truck

5.3 Test plan

The RFS test plan was designed to assess the effects of changes in damper performance and vehicle mass. This was achieved through variations in these parameters. For the different configurations, the load remains unchanged while the dampers are varied. The other configurations involved varying the load mass while leaving the dampers unchanged.

Each configuration was tested in two ways, namely:

- driving off an 80 mm step (performed three times to achieve consistent results)
- driving over a pipe (performed three times to achieve consistent results).

This test was performed for two or three combinations of load and vehicle specification:

- fully laden, all high-rate shock absorbers
- fully laden, all low-rate shock absorbers
- fully laden, high-rate shock absorbers on one side of the vehicle and shock absorbers removed from the other side (optional).

An additional test was performed at normal road speed on a road circuit, crossing a surface irregularity such as a bridge joint.

Changing loads was accomplished by swapping containers.

Changing shock absorbers took between 10 and 45 minutes, depending on how many were changed at a given time.

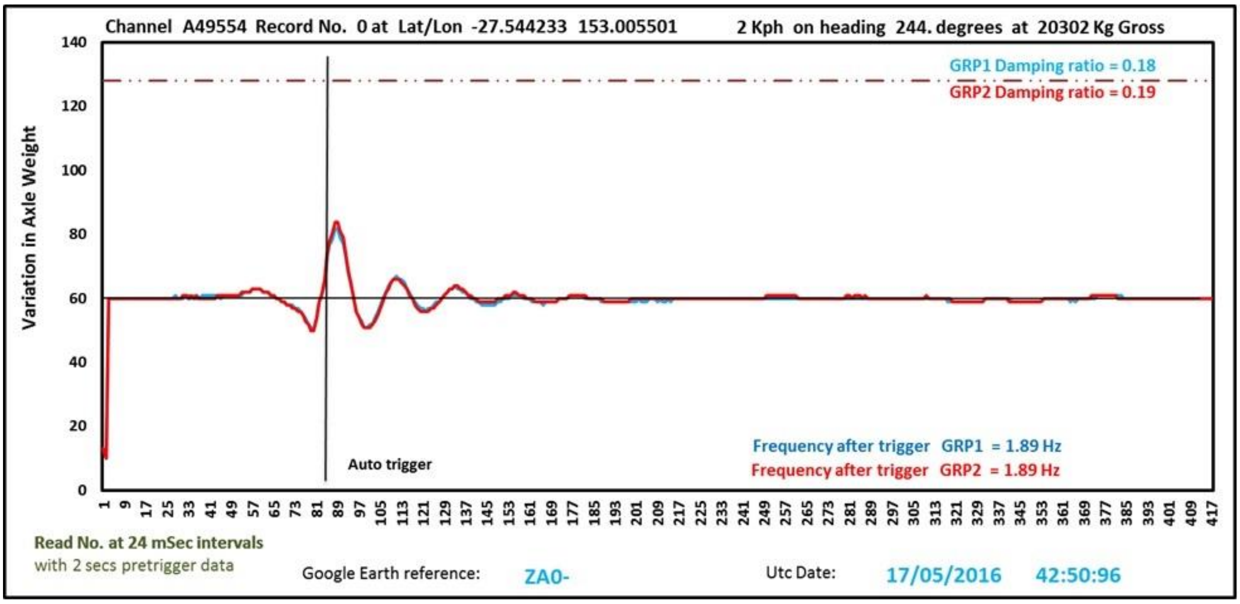
6 TEST RESULTS

The data logged from all test programs were analysed and the results are presented below. For test program 1 the data presented includes data logged via the reference system, data downloaded from test system 1 directly by ARRB and processed data supplied by Tramanco.

6.1 Results from Test program 1

Figure 6.1 shows the data trace supplied by Tramanco. This data trace is for Test 1 which is the triaxle fitted with heavy-duty shock absorbers performing the VSB11 ramp test. The y-axis is a unit less output from the air pressure sensors and the x-axis is the number of samples each at an interval of 24 m/s. The vertical black line located between 81 and 89 samples is an indication of an event trigger; when this occurs data is logged for starting approximately 2 seconds prior for a total of 10 seconds.

Figure 6.1: Data trace from Test system 1 (Test 1 HD ramp test fitted to triaxle semi-trailer)



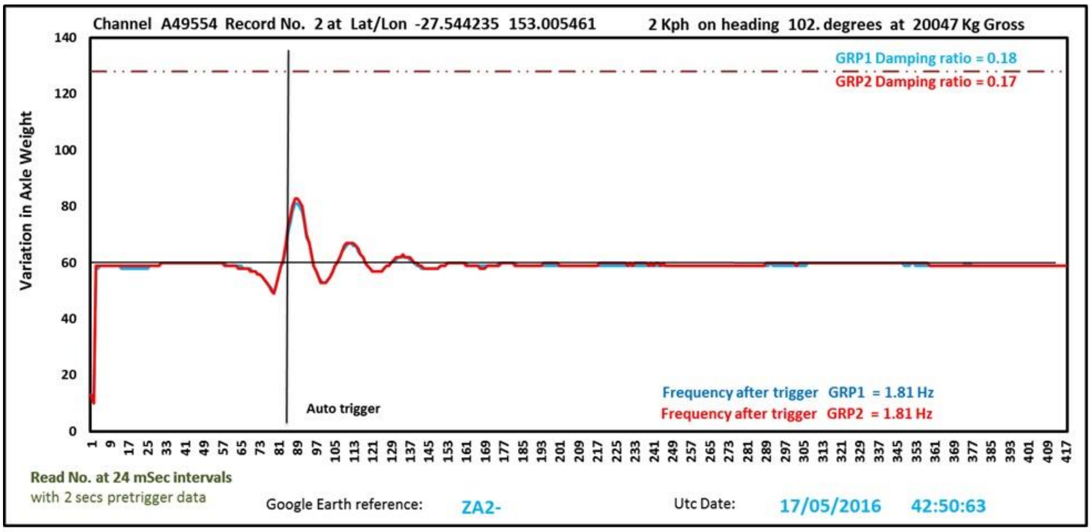
The processed data is ‘zeroed’ at a baseline value of 60 units. Therefore, this value represents no (zero) vertical displacement between the axle and the body. It should be noted that air pressure transducers measure a voltage linearly proportional to the pressure, not displacement so this is not a direct measure of displacement. The damping ratio can be calculated by using subsequent peak values, as would be done by measuring the oscillation in vertical displacement, as per VSB11.

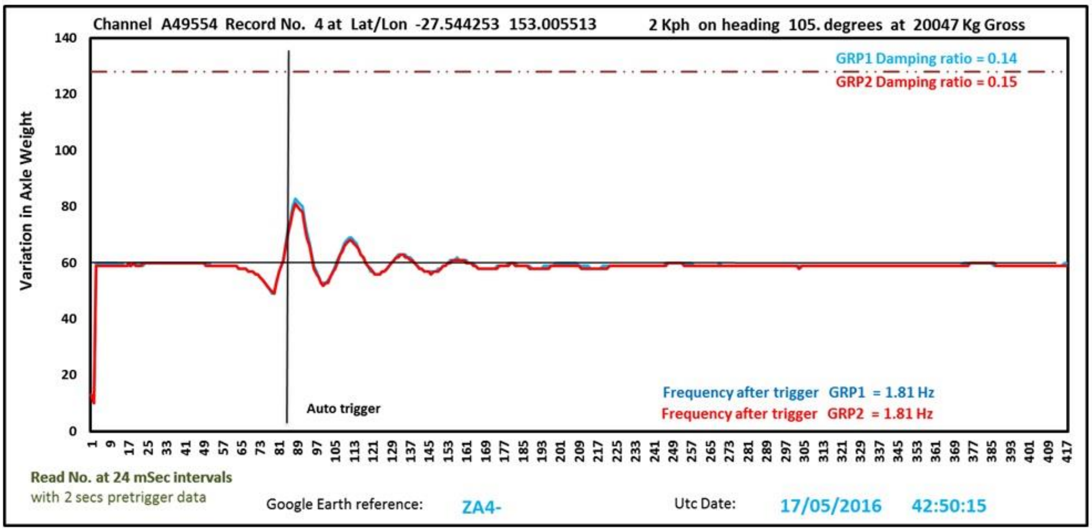
Two data traces are displayed on this chart, labelled GRP1 (light blue) and GRP2 (red). Typically, GRP1 and GRP2 would represent two axle groups e.g. drive group and trailer group with one transducer per axle group. In this instance, an additional air pressure transducer was fitted to the trailer axle group and the system was configured representing the left and right air bags on the last axle.

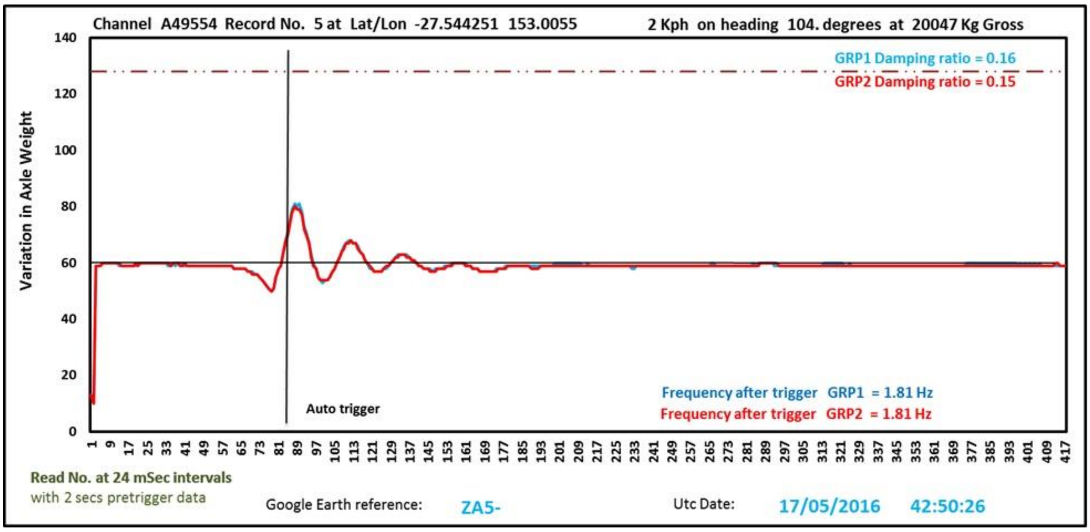
There are three distinct oscillations with three peaks above the baseline value and three troughs below the baseline. These peak values are used to calculate the damping ratio. The damping ratio based on the data obtained from left air bag pressure sensor is 18% and 19% from the right. The frequency of oscillation was calculated to be 1.89 Hz, obtained from both sensors.

Figure 6.2 shows the results obtained from three consecutive ramp tests with the vehicle in the same configuration. These results can be compared for repeatability.

Figure 6.2: Data trace from Test system 1: three consecutive ramp tests: (Tests 3, 4 and 5)



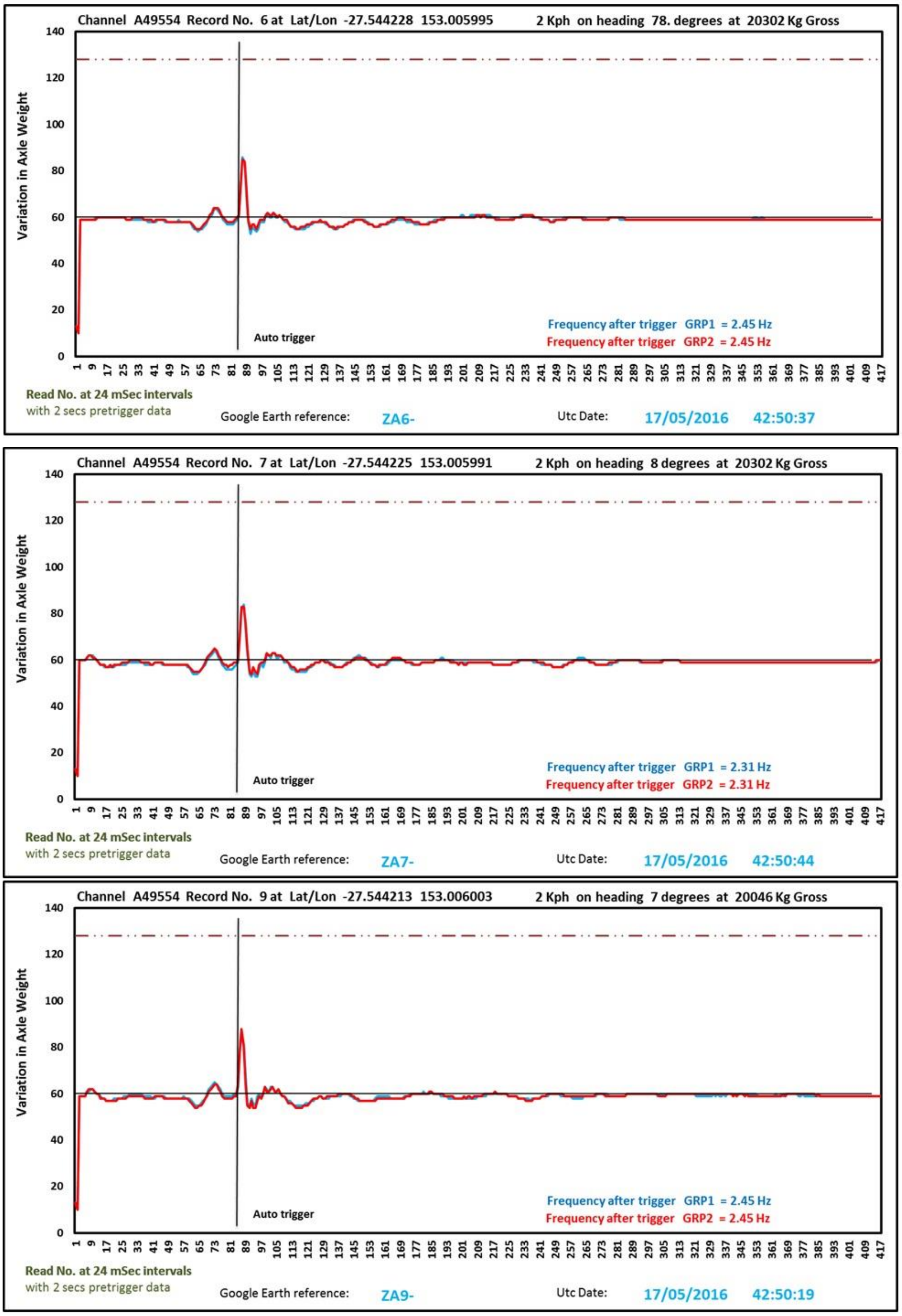




The frequency of each test is identical (1.81 Hz), this is expected as, frequency should not change. The damping ratio varies between left and right sides and between tests. The variation between the left and right is 0.1, varying between tests to be either above or below the other side. The damping ratio varies between 0.14 and 0.18, which is an increase of 28.5%.

Figure 6.3 shows three consecutive tests using the pipe method at 20 km/h. The shape of the data trace differs significantly when compared with the ramp test results for the same vehicle. The general shape is consistent between the three tests, but the frequency calculated both varies between these tests (2.45 Hz–2.31 Hz) and differs from the frequency of 1.81 Hz calculated from ramp tests. No damping ratio has been provided for these tests, as it was not possible to detect subsequent peaks from this over-damped response.

Figure 6.3: Data trace from Test system 1: three consecutive pipe tests (Tests 6, 7 and 9)



These results showed that neither the damping nor frequency of the suspension could be accurately measured when conducting a 'pipe test' at a speed of 20 km/h. This is because when travelling at a speed of 20 km/h the impulse provided by the pipe was insufficient to excite the suspension with sufficient magnitude. At this point in the test program, it was decided to continue evaluating the method, but at a lower speed (3–5 km/h).

The results of the subsequent tests conducted as part of test program 1 are presented in the sections of the report listed in Table 6.1

Table 6.1: Presentation of test results

Section no.	Section title
6.1.1	Repeatability of ramp tests: Fully laden with heavy-duty shock absorbers
6.1.2	Repeatability of ramp tests: Fully laden with medium-damping shock absorbers
6.1.3	Repeatability of ramp tests: Fully laden with low-damping shock absorbers
6.1.4	Repeatability of pipe tests: Fully laden with heavy-duty shock absorbers
6.1.5	Repeatability of pipe tests: Fully laden with medium-damping shock absorbers
6.1.6	Repeatability of pipe tests: Fully laden with low-damping shock absorbers
6.1.7	Summary of repeatability test results
6.1.8	Repeatability tests: Fully laden with no shock absorbers
6.1.9	Comparison of pipe vs ramp tests: Fully laden low-damping shock absorbers
6.1.10	Comparison of ramp tests: Fully laden 6HD vs 5HD vs 4HD
6.1.11	Comparison of pipe tests: Fully laden 6HD vs 5HD vs 4HD
6.1.12	Comparison of ramp tests: Fully laden HD vs MED vs LOW
6.1.13	Comparison of pipe tests: Fully laden HD vs MED vs LOW
6.1.14	Comparison of ramp tests: Fully laden medium-damping vs 3 removed
6.1.15	Comparison of pipe tests: Fully laden medium-damping vs 3 removed
6.1.16	Comparison of ramp tests: Fully laden with and without ride height control
6.1.17	Comparison of ramp tests: Medium-damping fully laden vs half laden
6.1.18	Comparison of pipe tests: Medium-damping fully laden vs half laden
6.1.19	On road test: Fully laden with medium-damping shock absorbers

6.1.1 *Repeatability of ramp tests: Fully laden with heavy-duty shock absorbers*

Figure 6.4 and Figure 6.5 show the three repeat tests for the vehicle fully laden and fitted with heavy-duty (HD) shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.4: Repeatability of ramp tests: pressure (HD shocks – fully laden)

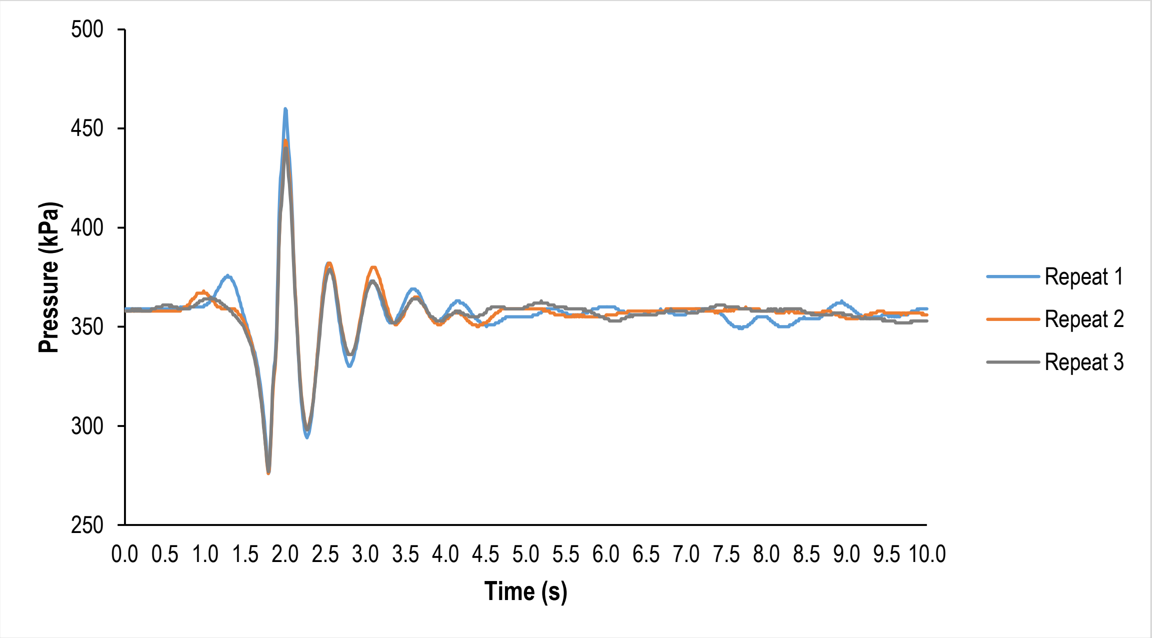
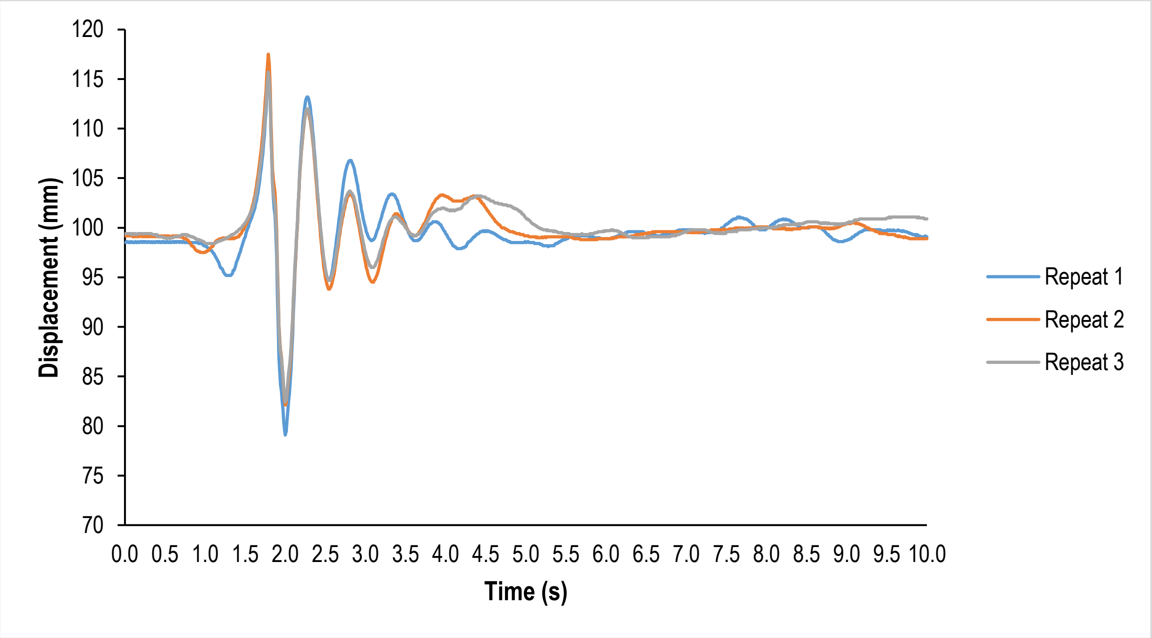


Figure 6.5: Repeatability of ramp tests: displacement (HD shocks – fully laden)



A summary of the results is presented in Table 6.2.

Table 6.2: Summary of results: Fully laden with HD shock absorbers

Load	Fully laden			
Shock absorbers	Heavy-duty			
Analysis	VSB11 ramp test			
Axle	Centre			
Measurement method	Air pressure transducer (APT)		Linear displacement transducer (LDT)	
Left/right sensor	Left	Right	Left	Right
Test 1 - Damping ratio (%)	19	22	19	23
Test 2 - Damping ratio (%)	18	20	15	18
Test 3 - Damping ratio (%)	19	19	16	17
Averaged result (%)	**20**		**18**	
Standard deviation	**1.38**		**2.83**	
Frequency (Hz)	**1.82**		**1.85**	

Commentary

This test produced similar averaged results from both the APT and LDT sensors of 20%–18% for damping and 1.82 Hz – 1.85 Hz for frequency respectively. The variation between the left and right sides of the axle and between repeat tests when measured by LDT is much greater compared with APT, despite the averaged results of both being similar. Noting that this is the same vehicle performing the same test only minutes later, this implies that the axles are rolling or the wheels are dropping off the ramps at different times. The variability measured by the LDT can be considered representative of what is occurring immediately following the drop off the ramps, despite this movement not being registered by the APT. This is most likely due to either a low latency in the air bag suspension itself or a slow response rate in the air pressure sensors.

6.1.2 *Repeatability of ramp tests: Fully laden with medium-damping shock absorbers*

Figure 6.6 and Figure 6.7 show the three repeat tests for the vehicle fully laden and fitted with medium-damping shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.6: Repeatability of ramp tests: pressure (MED shocks – fully laden)

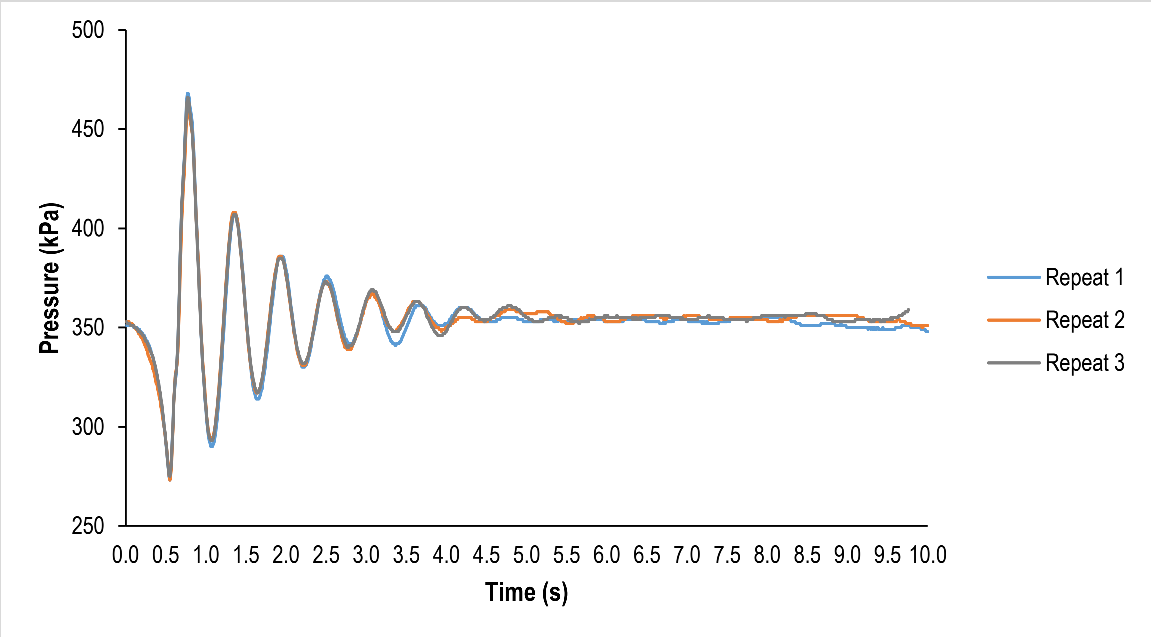
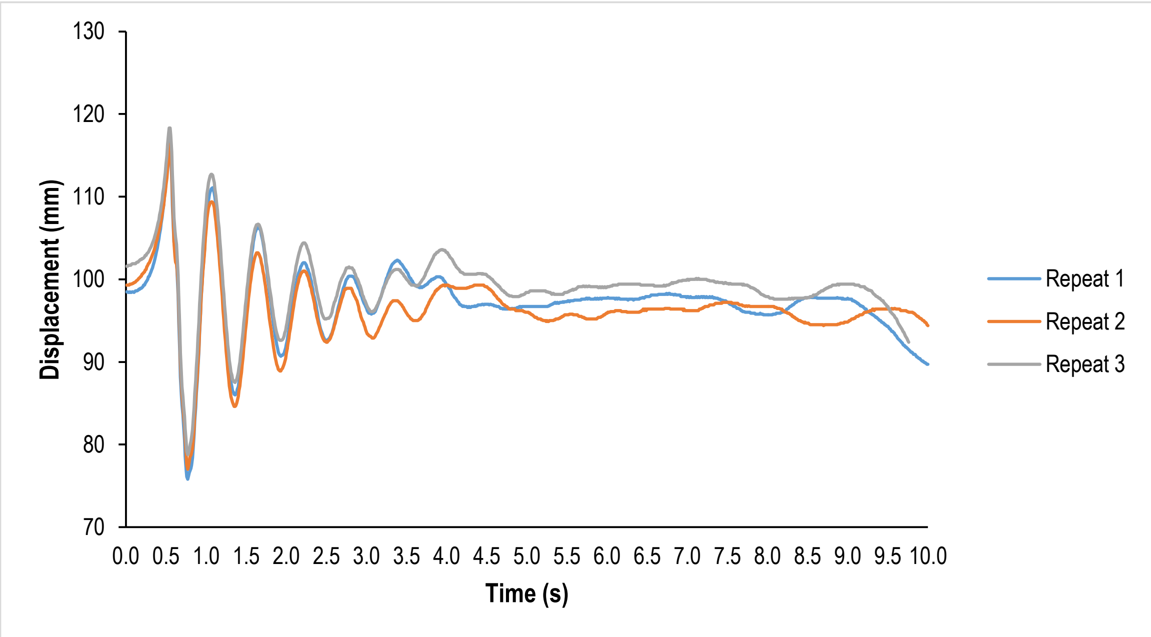


Figure 6.7: Repeatability of ramp tests: displacement (MED shocks – fully laden)



A summary of the results is presented in Table 6.3.

Table 6.3: Summary of results: Fully laden with MED shock absorbers

Load	Fully laden			
Shock absorbers	Medium-damping			
Method	VSB11 ramp test			
Axle	Centre			
Measurement method	Air pressure (APT)		Linear displacement (LDT)	
Left/right sensor	Left	Right	Left	Right
Test 1 - Damping ratio (%)	10	12	10	13
Test 2 - Damping ratio (%)	9	11	6	8
Test 3 - Damping ratio (%)	9	12	8	10
Averaged result (%)	**11**		**9**	
Standard deviation	**1.37**		**2.40**	
Frequency (Hz)	**1.76**		**1.72**	

Commentary

The results obtained for the medium-damping shock absorbers are consistent with the previous results, indicating similar averaged results for damping (11%–9%) and frequency (1.76 Hz−1.72 Hz). A similar observation can be made for these results where the variation between the left and right side and between repeats is greater for LDT than APT. The variability is significant, 6% from the left wheel on test 2 compared with 13% on the right wheel for test 1. As expected, the damping is less for this test than the previous test and both systems were able to detect the reduction in damping.

6.1.3 *Repeatability of ramp tests: Fully laden with low-damping shock absorbers*

Figure 6.8 and Figure 6.9 show the three repeat tests for the vehicle fully laden and fitted with low-damping (LOW) shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.8: Repeatability of ramp tests: pressure (LOW shocks – fully laden)

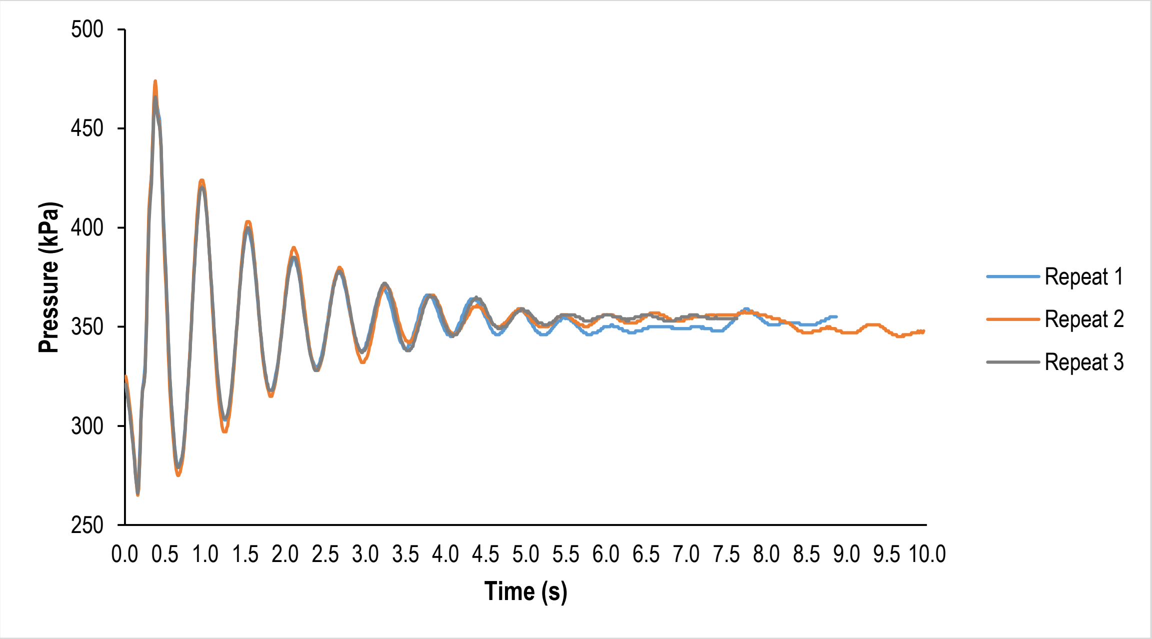
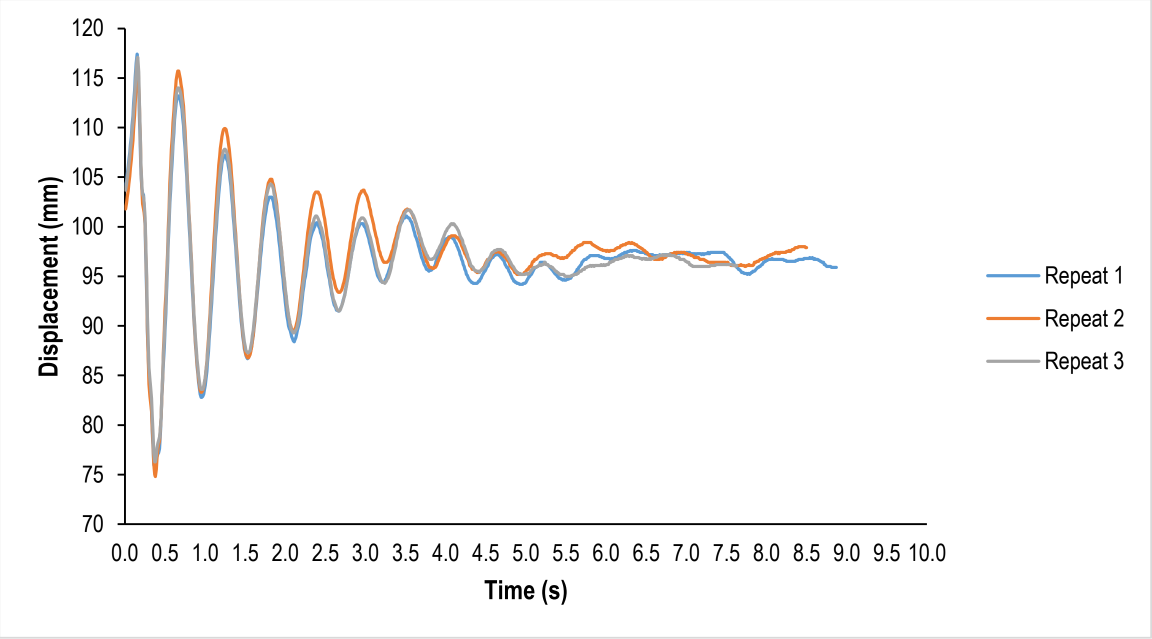


Figure 6.9: Repeatability of ramp tests: displacement (LOW shocks – fully laden)



A summary of the results is presented in Table 6.4.

Table 6.4: Summary of results: Fully laden with LOW shock absorbers

Load	Fully laden			
Shock absorbers	Low-damping			
Analysis	VSB11 ramp test			
Axle	Centre			
Measurement method	Air pressure		Linear displacement	
Left/right sensor	Left	Right	Left	Right
Test 1 - Damping ratio (%)	8	8	7	7
Test 2 - Damping ratio (%)	9	8	7	8
Test 3 - Damping ratio (%)	7	8	6	7
Averaged result (%)	**8**		**7**	
Standard deviation	**0.63**		**0.63**	
Frequency (Hz)	**1.80**		**1.74**	

Commentary

For the low-damping shock absorber, the variations between axle sides and repeats are less significant; this is most likely due to the system as a whole being less damped, resulting in less potential for variability based on the small difference between the first and second peaks of the data trace. A clear reduction in damping is evident and was able to be detected by both systems.

6.1.4 *Repeatability of pipe tests: Fully laden with heavy-duty shock absorbers*

Figure 6.10 and Figure 6.11 shows the three repeat tests for the vehicle fully laden and fitted with heavy-duty shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.10: Repeatability of pipe tests: pressure (HD shocks – fully laden)

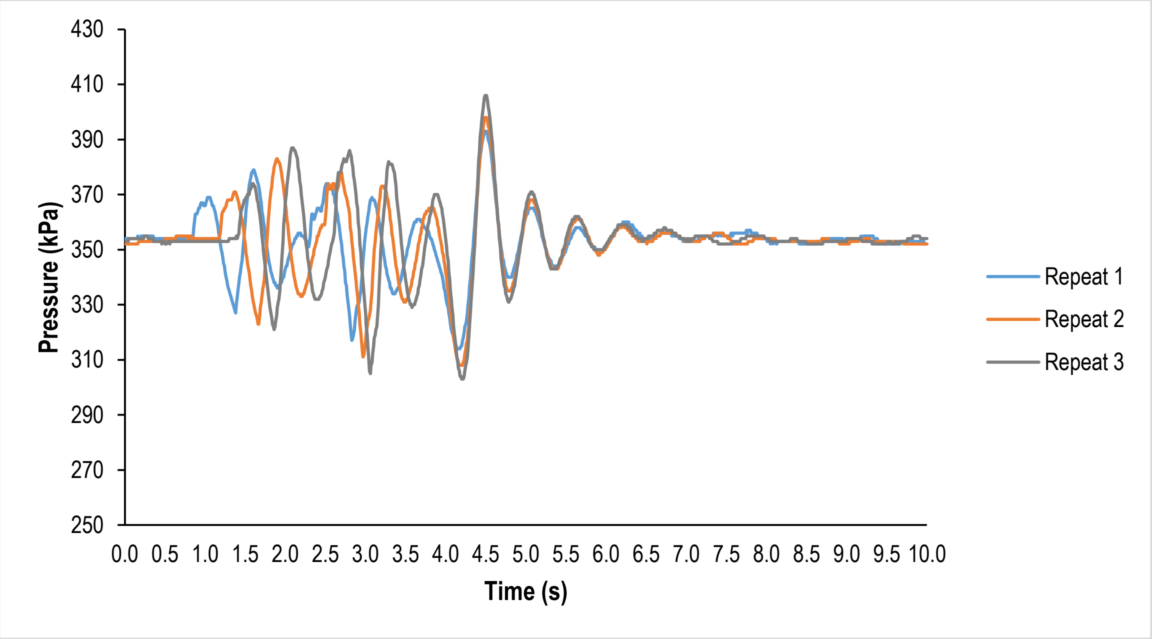
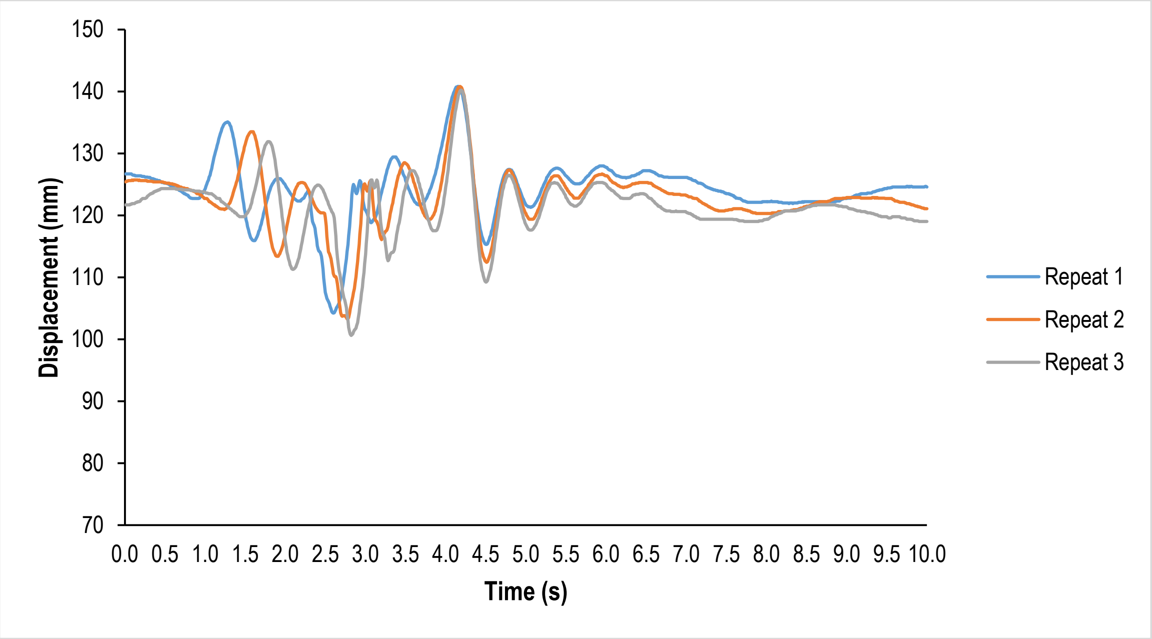


Figure 6.11: Repeatability of pipe tests: displacement (HD shocks – fully laden)



A summary of the results is presented in Table 6.5.

Table 6.5: Summary of results: Fully laden with HD shock absorbers

Load	Fully laden			
Shock absorbers	Heavy-duty			
Analysis	Pipe test			
Axle	Centre			
Measurement method	Air pressure		Linear displacement	
Left/right sensor	Left	Right	Left	Right
Test 1 - Damping ratio (%)	25	22	19	17
Test 2 - Damping ratio (%)	22	17	24	22
Test 3 - Damping ratio (%)	21	18	26	27
Averaged result (%)	**21**		**23**	
Standard deviation	**2.93**		**3.93**	
Frequency (Hz)	**1.74**		**1.81**	

Commentary

The results from the pipe test show significant variation for the sides of the axles and between repeat tests – a damping result of 17% compared with 27% between test 1 and test 3, for the right side. Unlike previous results from the ramp test, these variations were also recorded by the APT, confirming that the variability is greater for the pipe test than the ramp test. This is also evident visually when comparing both data traces. The variability is caused by each tyre striking the pipe one after the other in succession, as opposed to all wheels dropping off the ramps in unison. The data traces in Figure 6.10 show the three resultant peaks when each tyre strikes the pipe for the first time. Once the final axle has passed over the pipe, there are no more disturbances and if the speed is correctly matched to the natural frequency of the suspension the body will oscillate at this frequency. This consistent frequency of oscillation can be observed for all repeats. When compared with the ramp tests, there is a notable variation in the magnitude of each peak resulting from the pipe tests.

The results obtained from pipe tests overestimate the damping when compared with the ramp test; from the APTs the averaged result was 21% for the pipe compared with 20% for the ramp, and from LPTs it was 22% for the pipe with 18% for the ramp.

6.1.5 *Repeatability of pipe tests: Fully laden with medium-damping shock absorbers*

Figure 6.12 and Figure 6.13 show the three repeat tests for the vehicle fully laden and fitted with MED shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.12: Repeatability of pipe tests: pressure (MED shocks – fully laden)

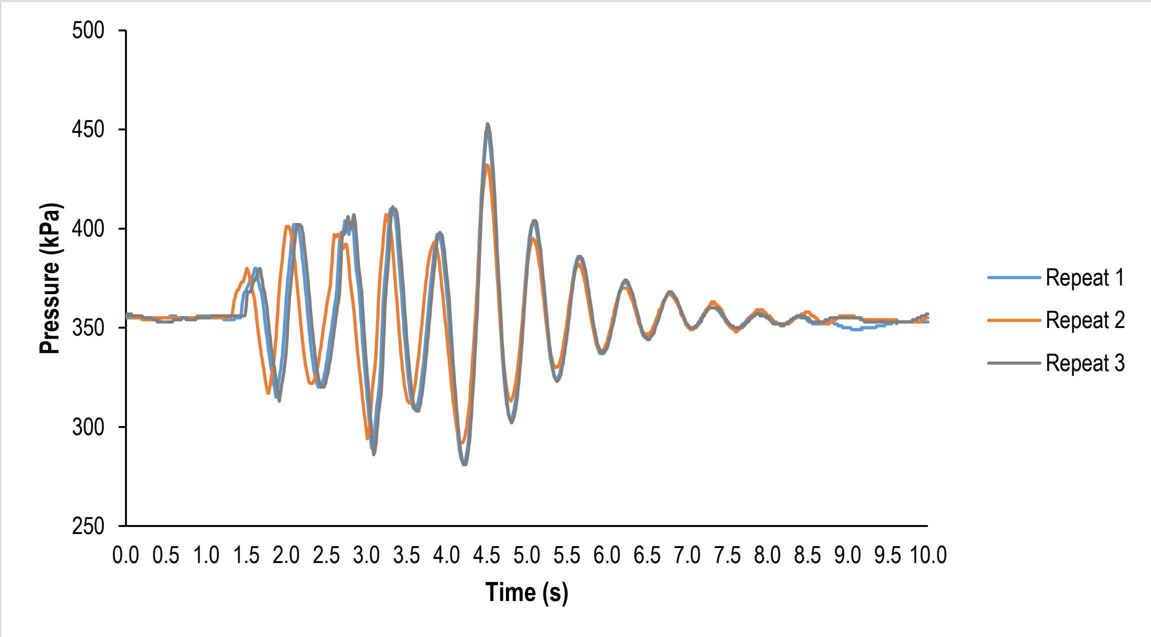
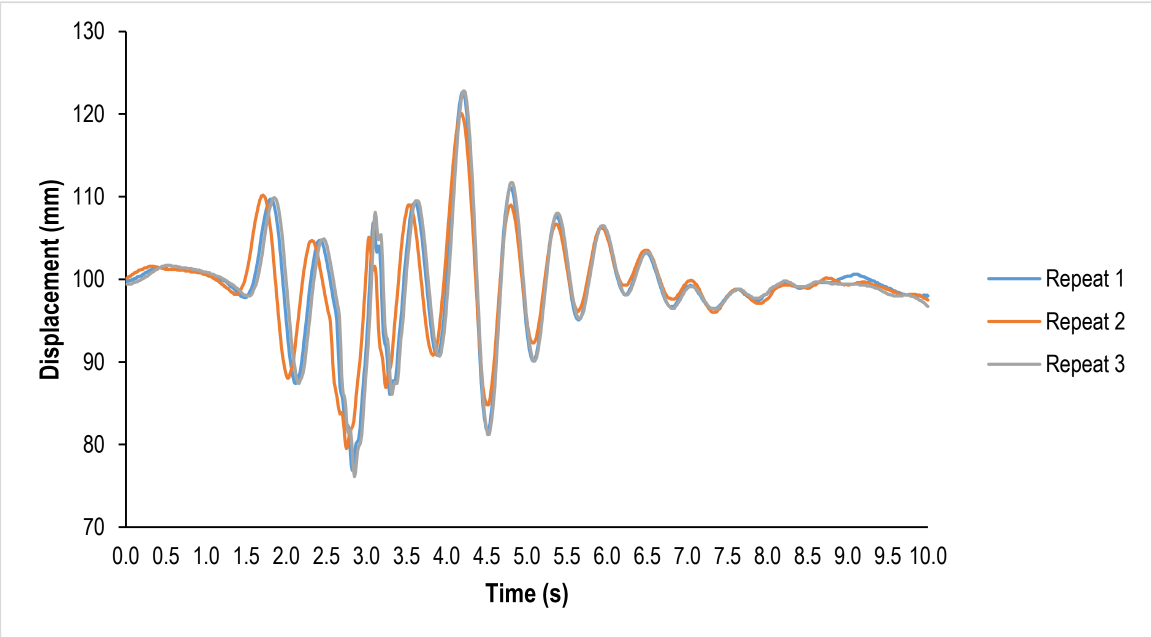


Figure 6.13: Repeatability of pipe tests: displacement (MED shocks – fully laden)



A summary of the results is presented in Table 6.6.

Table 6.6: Summary of results: Fully laden with MED shock absorbers

Load	Fully laden			
Shock absorbers	Medium-damping			
Method	Pipe test			
Axle	Centre			
Measurement method	Air pressure (APT)		Linear displacement (LDT)	
Left/right sensor	Left	Right	Left	Right
Test 1 - Damping ratio (%)	12	11	9	10
Test 2 - Damping ratio (%)	12	11	10	11
Test 3 - Damping ratio (%)	12	11	10	11
Averaged result (%)	**12**		**10**	
Standard deviation	**0.54**		**0.75**	
Frequency (Hz)	**1.72**		**1.74**	

Commentary

The results obtained for the medium-damping shockers are very similar to the results obtained by the ramp tests for the same shock absorber set-up. The visual appearance of the data trace indicates high repeatability with consistent magnitude and frequency. This implies that the driver has chosen the correct speed for these tests and the correct approach angle resulting in all the left and right tyres striking the pipe at the same time with the correct and constant speed. Note that the driver had completed over 20 passes over the pipe at this point in the testing program.

6.1.6 *Repeatability of pipe tests: Fully laden with low-damping shock absorbers*

Figure 6.14 shows the three repeat tests for the vehicle fully laden and fitted with low-damping shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.14: Repeatability of pipe tests: pressure (LOW shocks – fully laden)

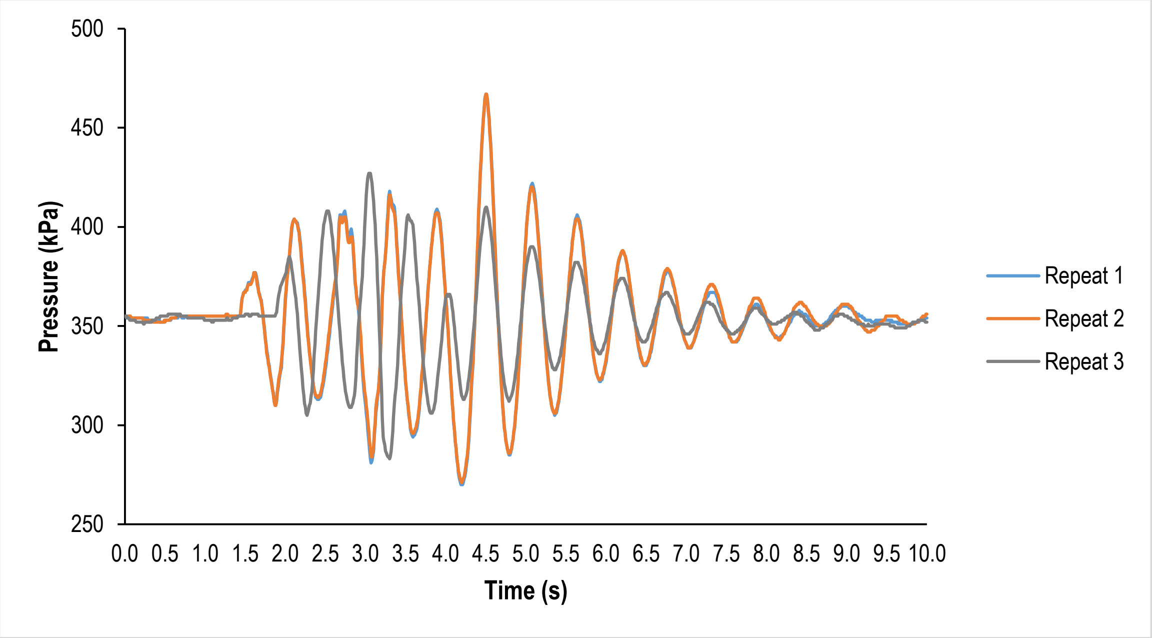
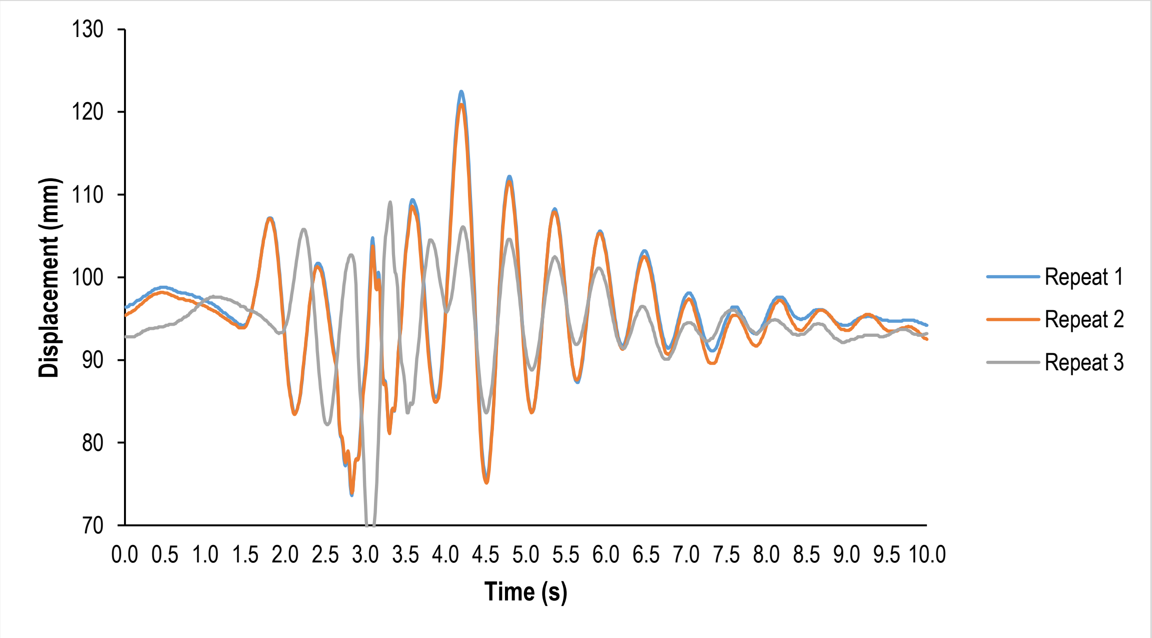


Figure 6.15: Repeatability of pipe tests: displacement (LOW shocks – fully laden)



A summary of the results is presented in Table 6.7.

Table 6.7: Summary of results: Fully laden with LOW shock absorbers

Load	Fully laden			
Shock absorbers	Low damping			
Method	Pipe test			
Axle	Centre			
Measurement method	Air pressure (APT)		Linear displacement (LDT)	
Left/right sensor	Left	Right	Left	Right
Test 1 - Damping ratio (%)	8	8	7	8
Test 2 - Damping ratio (%)	8	9	8	8
Test 3 - Damping ratio (%)	7	7	12	7
Averaged result (%)	**8**		**8**	
Standard deviation	**0.75**		**1.86**	
Frequency (Hz)	**1.75**		**1.79**	

Commentary

A similar result has been obtained here for the low damping with the pipe when compared with the ramp test, with only a small over-estimation of the damping. There is more variation in these results than the previous tests, implying that the test speed and approach angle where not ideal. This highlights how the pipe test results are sensitive to these two factors, in particular speed.

6.1.7 *Summary of repeatability test results*

A summary of the results is presented in Table 6.8.

Table 6.8: Summary of results of repeatability tests: Fully laden with HD, MED and LOW shock absorbers

Load	Fully laden											
Shock absorbers	Summary of low, medium and high											
Analysis	Summary of VSB11 ramps and pipe test											
Axle	Centre											
Measurement method	Air pressure (APT)						Linear displacement (LDT)					
Excitation method	VSB11 ramp			Pipe			VSB11 ramp			Pipe		
Shock absorbers	HD	MED	LOW	HD	MED	LOW	HD	MED	LOW	HD	MED	LOW
Averaged result (%)	20	11	8	21	12	8	18	9	7	23	10	8
Standard Dev.	1.38	1.37	0.63	2.93	0.54	0.75	2.83	2.4	0.63	3.93	0.75	1.86
Frequency (Hz)	1.82	1.76	1.80	1.74	1.72	1.75	1.85	1.72	1.74	1.81	1.74	1.79

Commentary

The summary of the repeatability results shows that with both the VSB11 ramps and the pipe test using either the APTs or LDTs a reduction in damping can be detected between the high, medium and low-damping shock absorbers. The standard deviation of the results obtained with the HD shock absorbers is greater when compared with the medium and low-damping shock absorbers. This result was consistent over all measurement methods. The measurement method with the greater standard deviation was linear displacement transducers. The excitation method with the greatest standard deviation was the pipe test.

6.1.8 *Repeatability tests: Fully laden with no shock absorbers*

Figure 6.16 and Figure 6.17 show the three repeat tests for the vehicle fully laden and fitted with no shock absorbers, for the ramp test and pipe test respectively.

Figure 6.16: Repeatability of ramp tests (no shocks – fully laden)

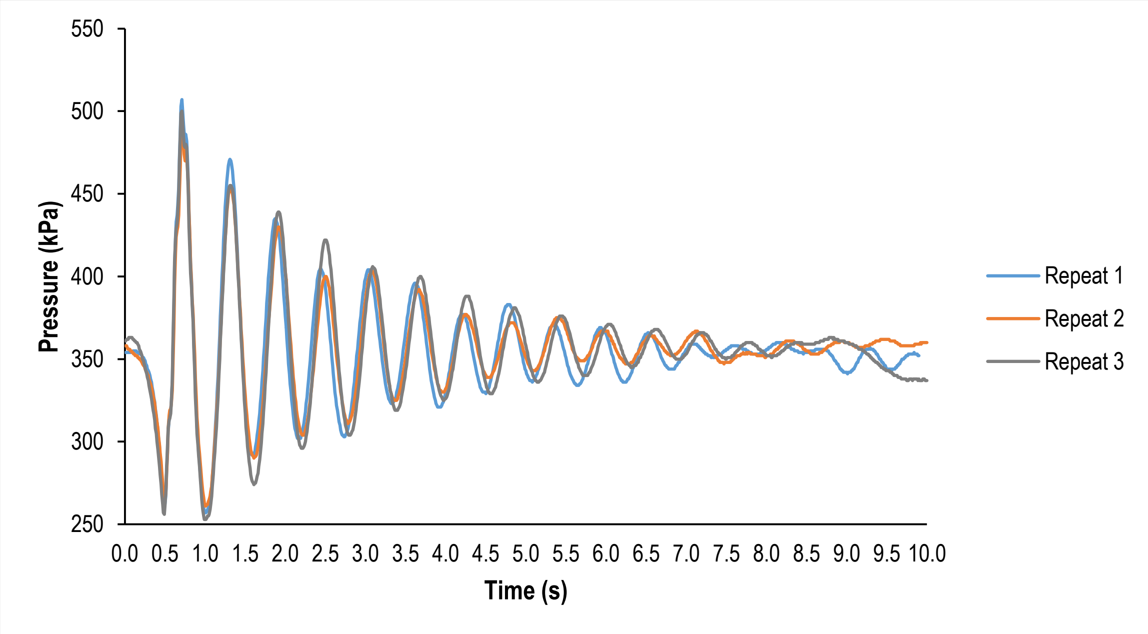
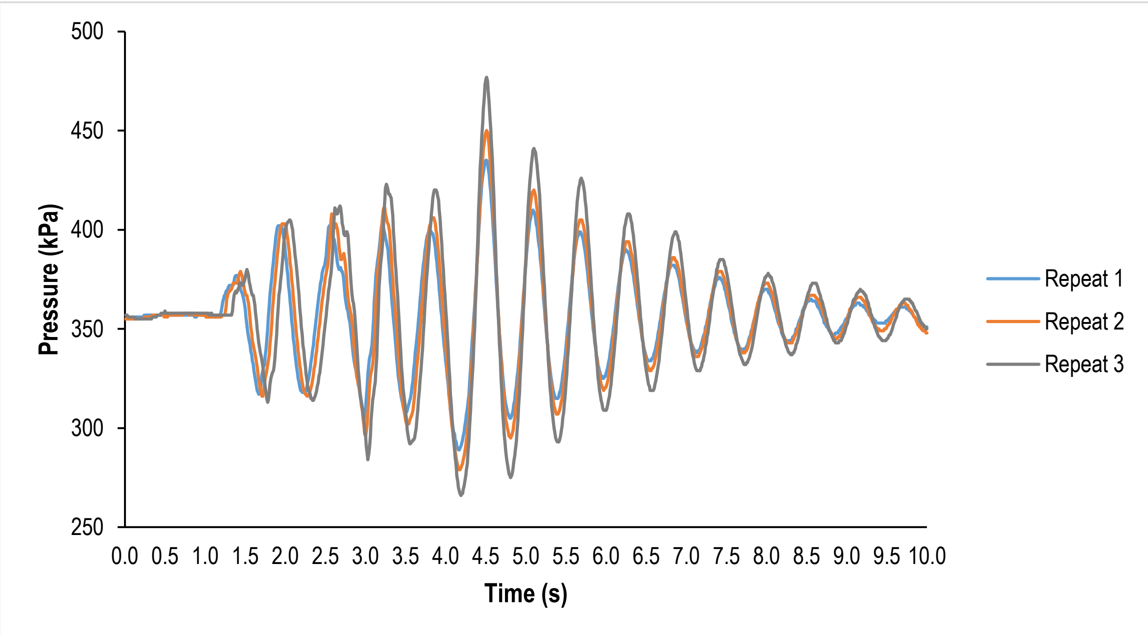


Figure 6.17: Repeatability of pipe tests (no shocks – fully laden)



A summary of the results is presented in Table 6.9.

Table 6.9: Summary of results: Fully laden with no shock absorbers

Load	Fully laden							
Shock absorbers	None fitted							
Analysis	Comparison of VSB11 ramp test and pipe test							
Axle	Centre							
Measurement method	Air pressure (APT)				Linear displacement (LDT)			
Excitation method	VSB11 ramps		Pipe		VSB11 ramps		Pipe	
Left/right sensor	Left	Right	Left	Right	Left	Right	Left	Right
Test 1 - Damping ratio (%)	8	8	8	6	5	7	7	6
Test 2 - Damping ratio (%)	10	10	7	6	5	7	5	5
Test 3 - Damping ratio (%)	7	8	6	6	5	5	5	6
Averaged result (%)	**9**		**7**		**6**		**6**	
Standard deviation	**1.23**		**0.84**		**1.03**		**0.82**	
Frequency (Hz)	**1.75**		**1.71**		**1.79**		**1.69**	

Commentary

The averaged damping results with no shock absorbers is only marginally less than the results for the low-damping shock absorbers. Testing the vehicle with no shock absorbers fitted is a requirement of VSB11. It is expected that the value obtained at certification will not change, as the wear component is removed. On this basis, it need not be a requirement of in-service testing to remove the shock absorbers and obtain a damping value with the shock absorbers removed.

6.1.9 *Comparison of pipe vs ramp tests: Fully laden with low-damping shock absorbers*

Figure 6.18 and Figure 6.19 show the data traces from both the pipe and ramp test for the vehicle fully laden and fitted with LOW shock absorbers, measured using APTs and LDTs respectively.

Figure 6.18: Comparison of pipe and ramp tests using APTs (LOW shocks – fully laden)

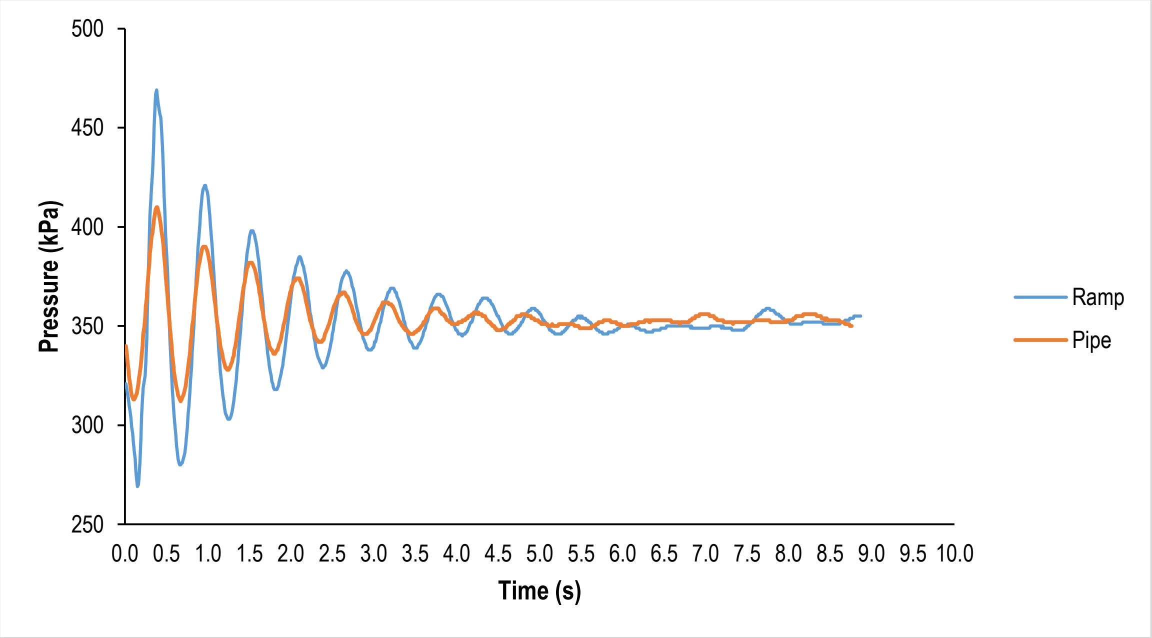
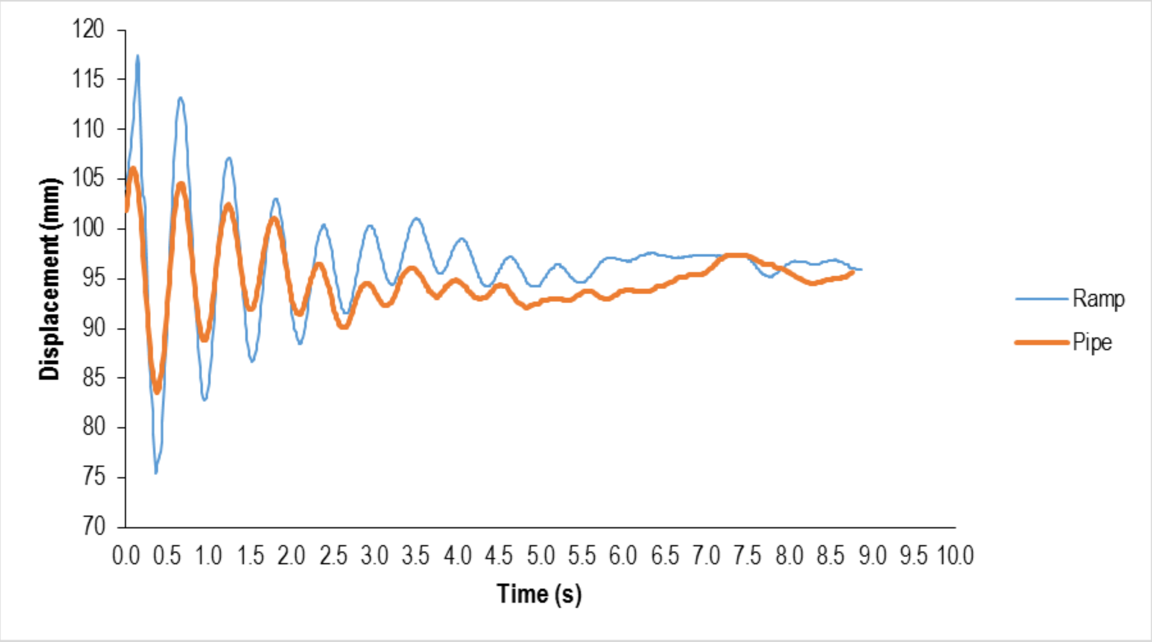


Figure 6.19: Comparison of pipe and ramp tests using LDTs (LOW shocks – fully laden)



A summary of the results is presented in Table 6.10.

Table 6.10: Comparison of results: Fully laden with LOW shock absorbers

Load	Fully laden							
Shock absorbers	All low-damping							
Analysis	VSB11 ramp test and pipe test							
Axle	Centre							
Excitation method	VSB11 ramps				Pipe			
Measurement method	APT		LDT		APT		LDT	
Left/right sensor	Left	Right	Left	Right	Left	Right	Left	Right
Test 1 - Damping ratio (%)	8	8	7	7	7	7	6	4
Test 2 - Damping ratio (%)	7	8	7	7	8	8	5	4
Test 3 - Damping ratio (%)	7	8	7	5	8	8	6	4
Averaged result (%)	**8**		**7**		**8**		**6**	
Standard deviation	**0.52**		**0.82**		**0.52**		**0.98**	
Frequency (Hz)	**1.80**		**1.75**		**1.76**		**1.79**	

Commentary

The difference in magnitude is clear when the ramp and pipe tests are overlayed on the same chart. Despite this the damping values are similar. The pipe test results are marginally lower than the ramp tests.

6.1.10 *Comparison of ramp tests: Fully laden 6HD vs 5HD vs 4HD*

Figure 6.20 and Figure 6.21 show the data traces from the ramp test for the tests with HD shock absorbers, one removed from the rear axle and both removed from the rear axle, measured with air pressure sensors and displacement sensors respectively.

Figure 6.20: Comparison of ramp tests: pressure (6HD, 5HD and 4HD – fully laden)

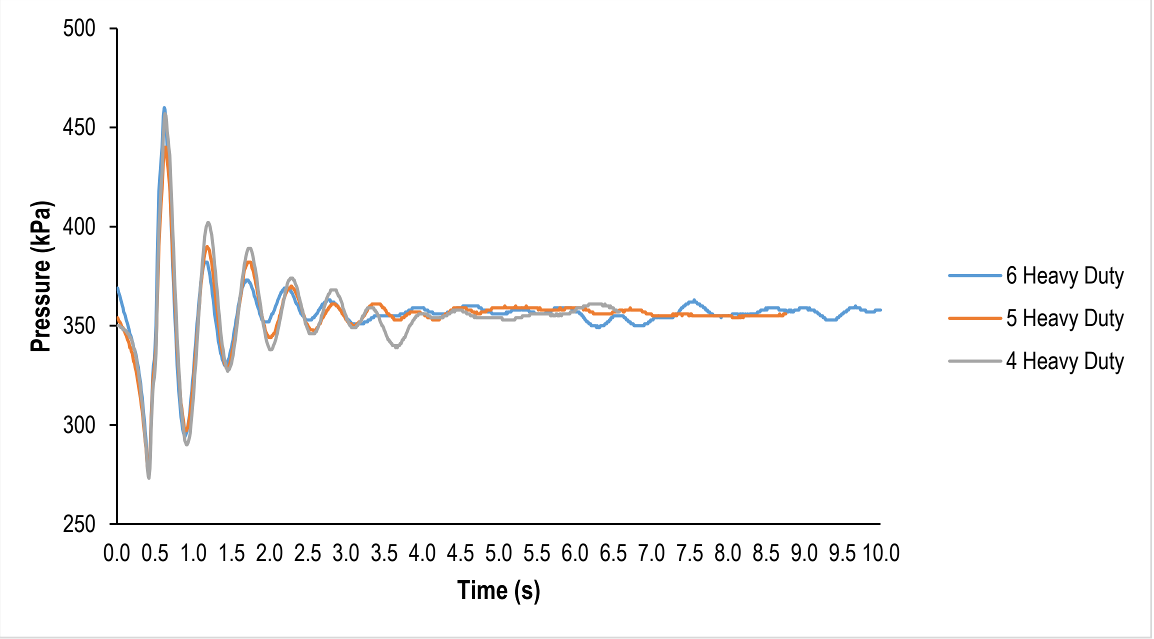
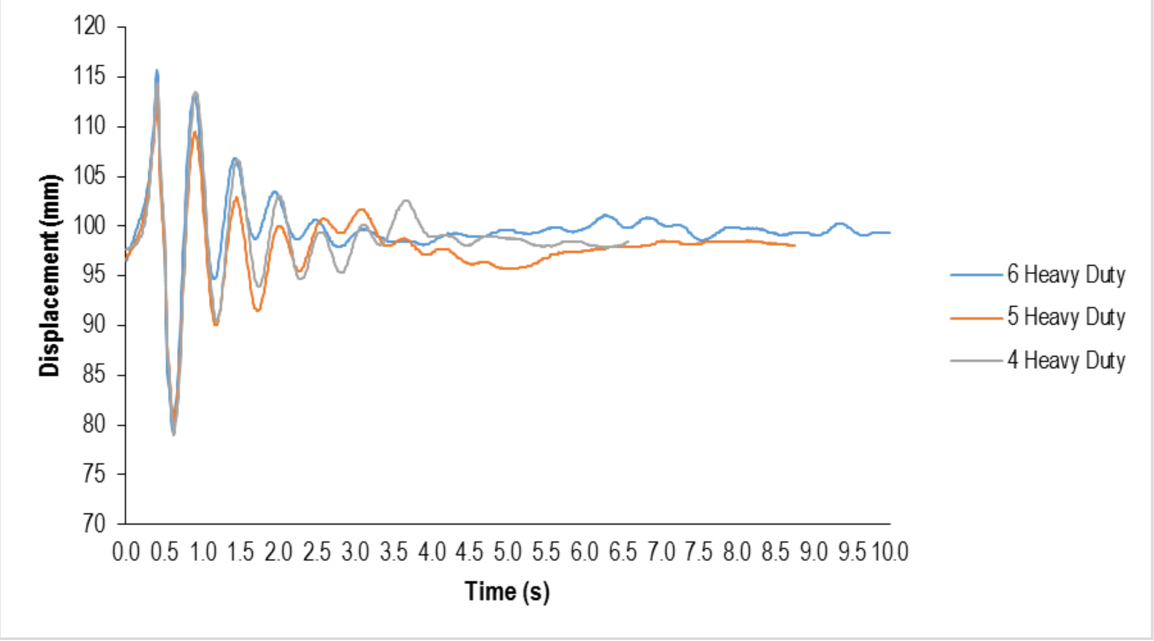


Figure 6.21: Comparison of ramp tests: displacement (6HD, 5HD and 4HD – fully laden)



A summary of the results is presented in Table 6.11.

Table 6.11: Summary of results: Fully laden 6HD, 5HD and 4HD shock absorbers

Load	Fully laden											
Shock absorbers	6HD, 5HD and 4HD											
Analysis	VSB11 ramp test for detection of removed shock absorbers											
Axle	Centre											
Measurement method	Air pressure						Linear displacement					
Shock absorbers	6HD		5HD		4HD		6HD		5HD		4HD	
Left/right sensor	L	R	L	R	L	R	L	R	L	R	L	R
Test 1 - Damping ratio (%)	19	22	13	14	12	13	13	10	17	13	8	9
Test 2 - Damping ratio (%)	19	20	13	14	10	11	24	19	28	24	11	13
Test 3 - Damping ratio (%)	20	21	9	11	12	12	26	20	42	20	11	10
Averaged result (%)	**20**		**12**		**12**		**19**		**24**		**10**	
Standard deviation	**1.17**		**1.97**		**1.03**		**6.19**		**10.26**		**1.75**	
Frequency (Hz)	**1.90**		**1.86**		**1.83**		**1.85**		**1.83**		**1.80**	

Commentary

The intention of these tests was to determine if a small change in damping could be detected by the systems. Removing one shock absorber from the triaxle suspension represents a reduction in damping of 16.67%; removing two shock absorbers represents a reduction in damping of 33.34%. Reductions are expected as each shock absorber is removed, however the results did not fall with the expected range. This is most likely due to the variations in the excitation method and measurement method being greater than the differences in damping that need to be detected by the system. The standard deviation of the test with 5 HD shock absorbers when measured with linear displacement sensors is over 10. This indicates that the test cannot be relied upon in this case to draw a robust conclusion on the ability for this system to detect the absence of a single shock absorber.

6.1.11 *Comparison of pipe tests: Fully laden 6HD vs 5HD vs 4HD*

Figure 6.22 and Figure 6.23 show the data traces from the pipe test for the tests with HD shock absorbers, one removed from the rear axle and both removed from the rear axle, measured with air pressure sensors and displacement sensors respectively.

Figure 6.22: Comparison of pipe tests: pressure (6HD, 5HD and 4HD – fully laden)

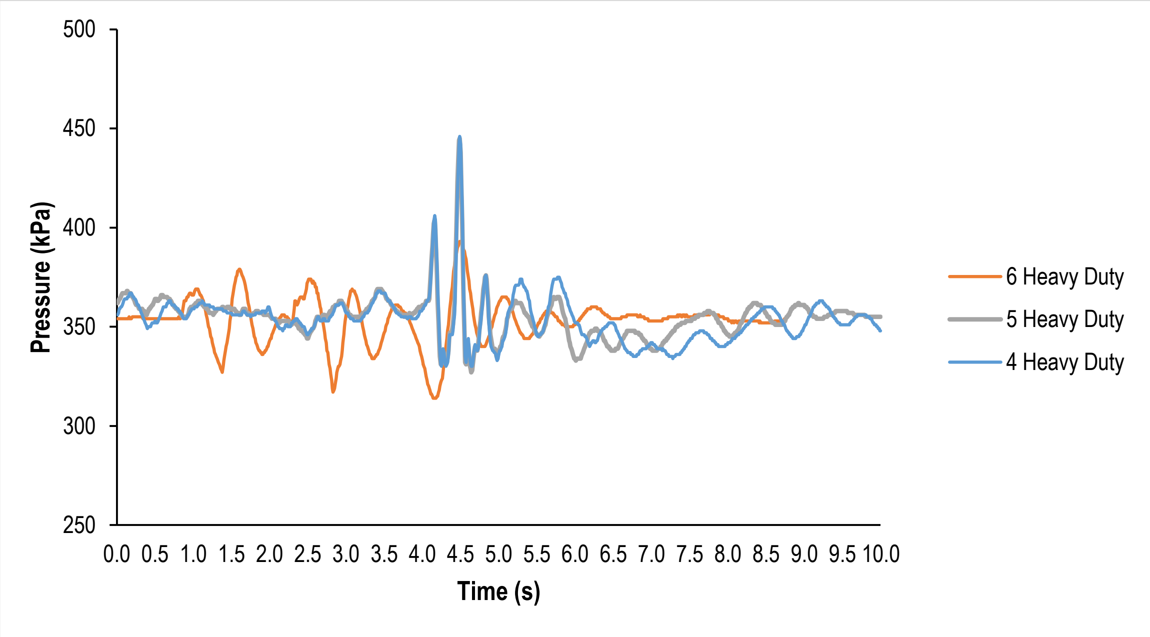
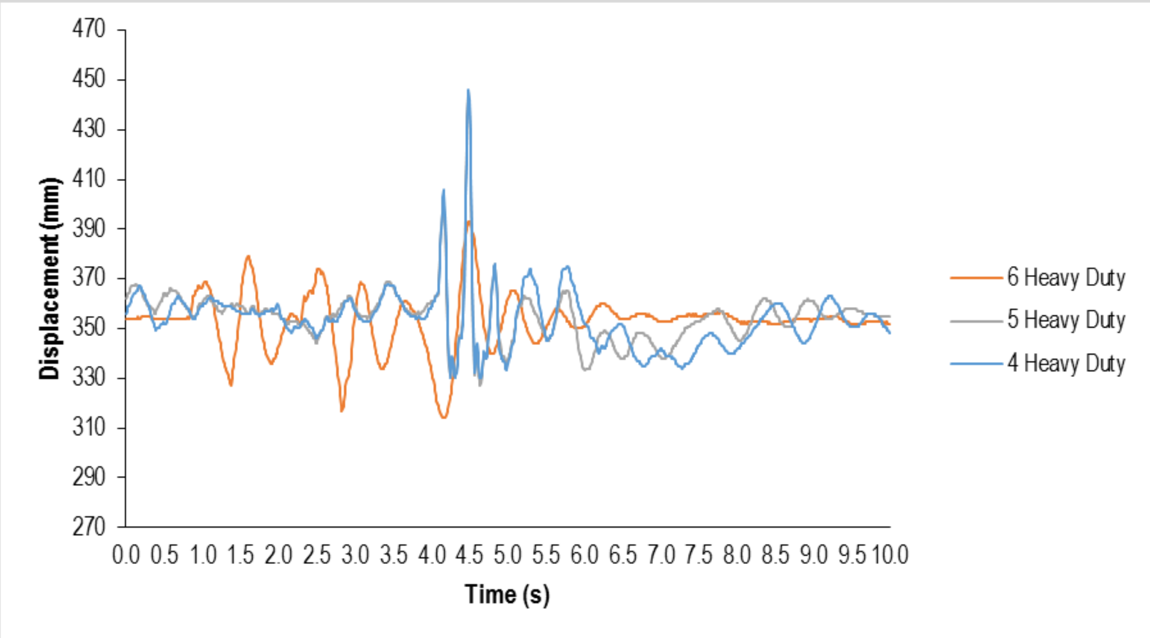


Figure 6.23: Comparison of pipe tests: displacement (6HD, 5HD and 4HD – fully laden)



A summary of the results is presented in Table 6.12.

Table 6.12: Summary of results: Fully laden 6HD, 5HD and 4HD shock absorbers

Load	Fully laden											
Shock absorbers	6HD, 5HD and 4HD											
Analysis	Pipe test for detection of removed shock absorbers											
Axle	Centre											
Measurement method	Air pressure (APT)						Linear displacement (LDT)					
Shock absorbers	6HD		5HD		4HD		6HD		5HD		4HD	
Left/right sensor	L	R	L	R	L	R	L	R	L	R	L	R
Test 1 - Damping ratio (%)	26	24	NA	NA(1)	NA	6	4	0	12	17	1	2
Test 2 - Damping ratio (%)	22	18	25	NA	8	7	6	3	10	12	1	3
Test 3 - Damping ratio (%)	22	19	NA	NA	21	21	6	4	NA	15	NA	2
Averaged result (%)	**22**		**NA**		**NA**		**4**		**NA**		**NA**	
Standard deviation	**2.99**		**NA**		**NA**		**2.23**		**NA**		**NA**	
Frequency (Hz)	**1.74**		**2.18**		**2.32**		**1.81**		**3.09**		**3.13**	

1 No peaks in oscillation could be detected from the data trace to calculate damping.

Commentary

These tests were conducted prior to adjusting the test speed for the pipe test from high to low, and therefore are invalid. In some instances no peaks could be identified to calculate the damping, and those that could be detected produced unreliable results.

6.1.12 *Comparison of ramp tests: Fully laden HD vs MED vs LOW*

Figure 6.24 and Figure 6.25 show the data traces from the ramp test with high, medium and low-damping shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.24: Comparison of ramp tests: pressure (HD, MED and LOW – fully laden)

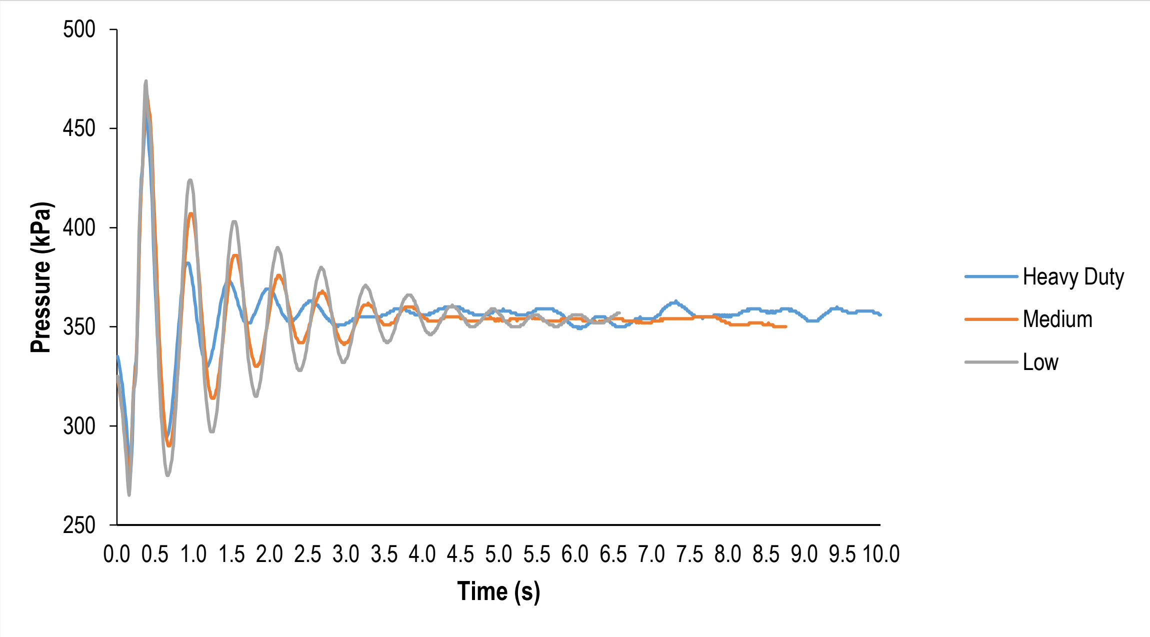
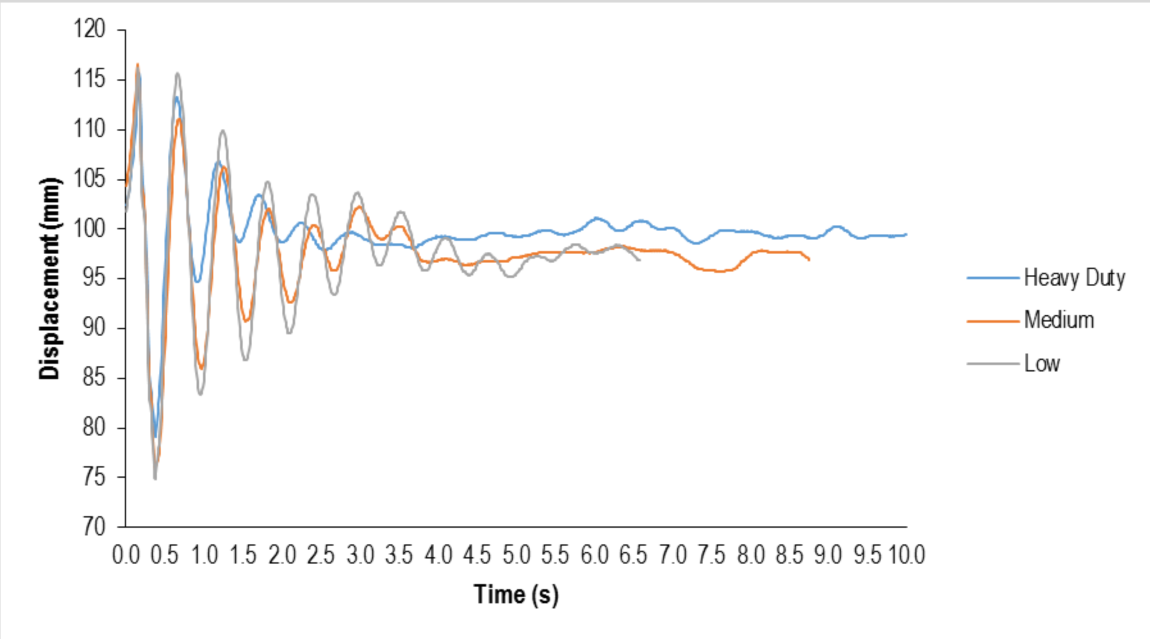


Figure 6.25: Comparison of ramp tests: displacement (HD, MED and LOW – fully laden)



A summary of the results is presented in Table 6.13.

Table 6.13: Summary of results: Fully laden HD, MED and LOW shock absorbers

Load	Fully laden											
Shock absorbers	HD, MED and LOW											
Analysis	VSB11 ramps comparison of shock absorbers											
Axle	Centre											
Measurement method	Air pressure (APT)						Linear displacement (LDT)					
Shock absorbers	HD		MED		LOW		HD		MED		LOW	
Left/right sensor	L	R	L	R	L	R	L	R	L	R	L	R
Test 1 - Damping ratio (%)	19	22	11	12	7	8	13	10	8	6	10	5
Test 2 - Damping ratio (%)	19	20	10	11	7	8	24	19	12	10	9	7
Test 3 - Damping ratio (%)	20	21	10	12	8	9	26	20	11	9	12	8
Averaged result (%)	**20**		**11**		**8**		**19**		**9**		**9**	
Standard deviation	**1.17**		**0.89**		**0.75**		**6.19**		**2.16**		**2.43**	
Frequency (Hz)	**1.90**		**1.76**		**1.80**		**1.85**		**1.72**		**1.74**	

Commentary

A clear reduction in damping has been detected by the APTs and LDTs between the high-damping and medium-damping tests, but there was less reduction changing between the medium and low dampers for the APTs and no change was recorded by the LDTs between these two dampers. The frequency varied inconsistently for both sensors, but more so for the APTs (1.9 Hz, 1.76 Hz and 1.8 Hz) which indicates a measurement or analysis error, as frequency should remain the same regardless of which dampers were fitted at the time.

6.1.13 *Comparison of pipe tests: Fully laden HD vs MED vs LOW*

Figure 6.26 and Figure 6.27 show the data traces from the pipe test for the tests with HD, MED and LOW shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.26: Comparison of pipe tests: pressure (HD, MED and LOW – fully laden)

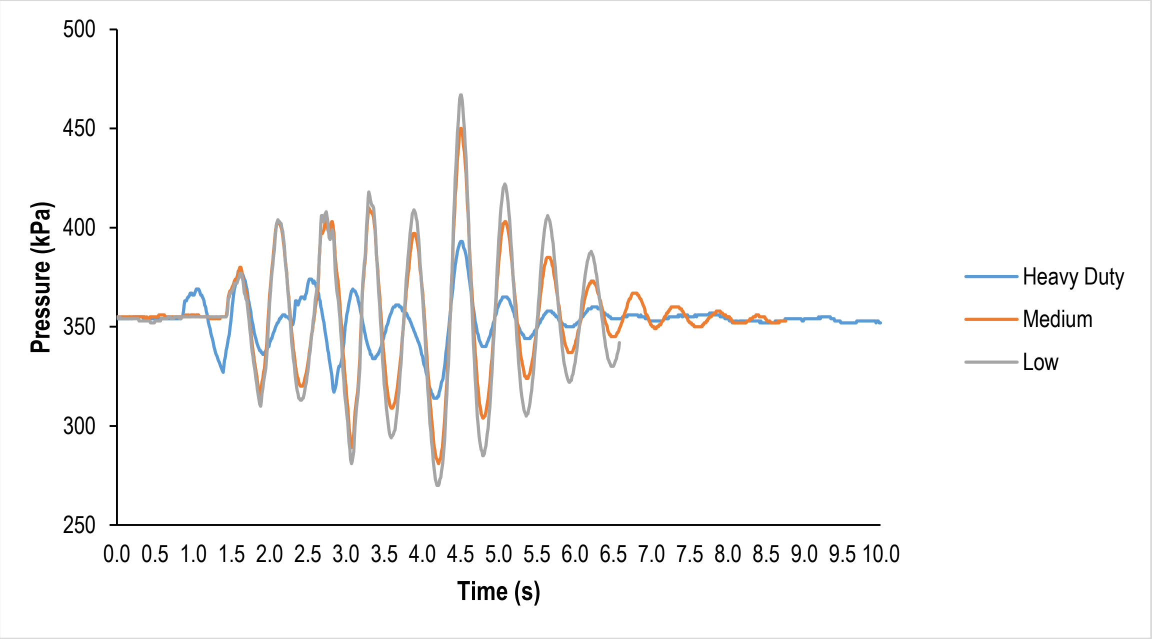
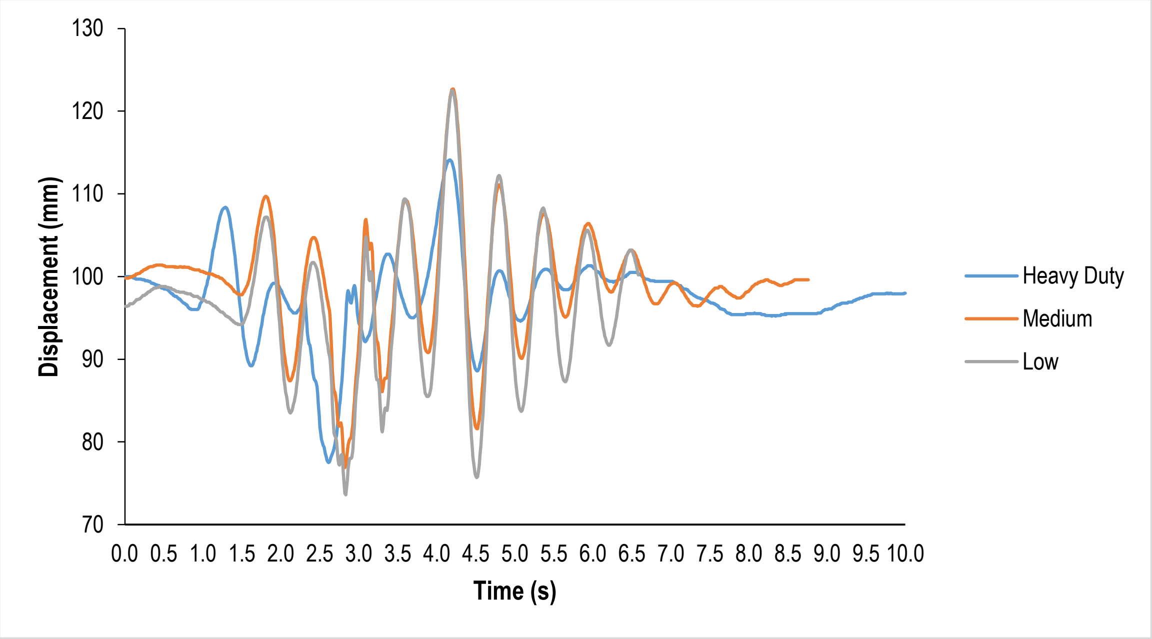


Figure 6.27: Comparison of pipe tests: displacement (HD, MED and LOW – fully laden)



A summary of the results is presented in Table 6.14.

Table 6.14: Summary of results: Fully laden HD, MED and LOW shock absorbers

Load	Fully laden											
Shock absorbers	HD, MED and LOW											
Method	Pipe											
Axle	Centre											
Sensor	Air pressure (APT)						Linear displacement (LDT)					
Shock absorbers	HD		MED		LOW		HD		MED		LOW	
Left/right sensor	L	R	L	R	L	R	L	R	L	R	L	R
Test 1 - Damping ratio (%)	25	22	12	11	8	8	19	17	09	10	7	8
Test 2 - Damping ratio (%)	22	17	12	11	8	9	23	21	10	11	8	9
Test 3 - Damping ratio (%)	21	18	12	11	7	7	26	27	10	11	12	13
Averaged result (%)	**21**		**12**		**8**		**22**		**10**		**10**	
Standard deviation	**2.93**		**0.55**		**0.75**		**3.92**		**0.75**		**2.43**	
Frequency (Hz)	**1.74**		**1.72**		**1.84**		**1.81**		**1.74**		**1.84**	

Commentary

Similar to the ramp test results, the pipe test results indicate an approximate 50% reduction in damping between the high-damping and medium-damping shock absorbers, but much less change between the medium and low-damping shock absorbers.

6.1.14 *Comparison of ramp tests: Fully laden medium-damping vs 3 removed*

Figure 6.28 and Figure 6.29 show the data traces from the ramp test with medium-damping shock absorbers fitted and 3 removed from the left (passenger) side of the vehicle, measured with air pressure sensors and displacement sensors respectively.

Figure 6.28: Comparison of ramp tests: pressure (6 MED and 3 removed – fully laden)

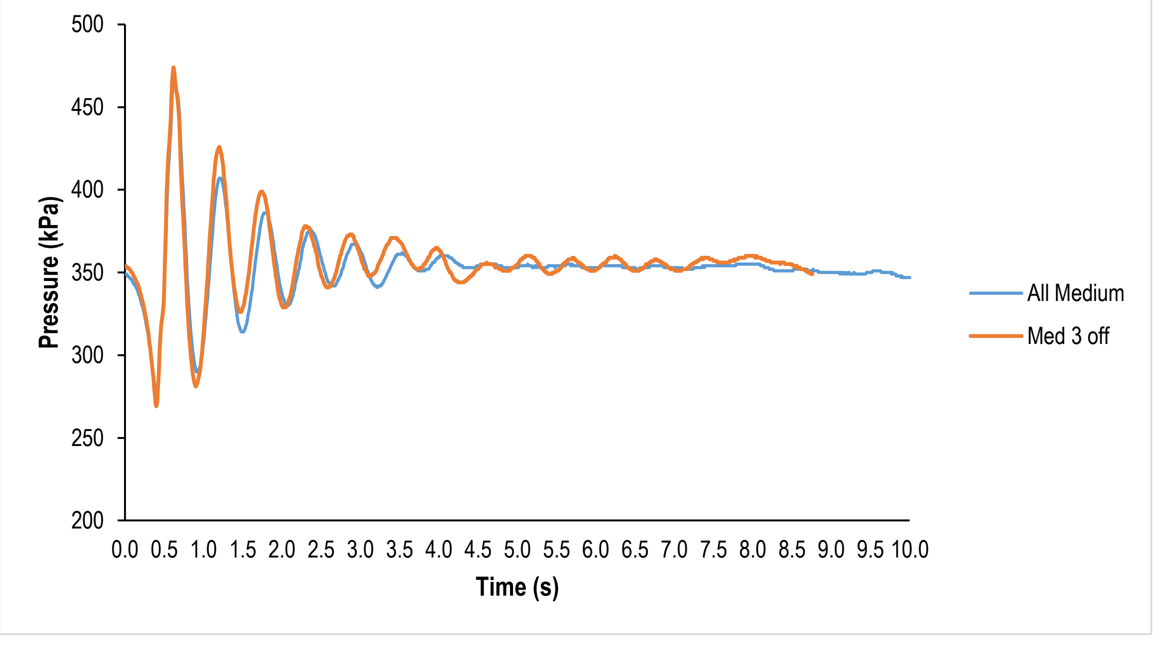
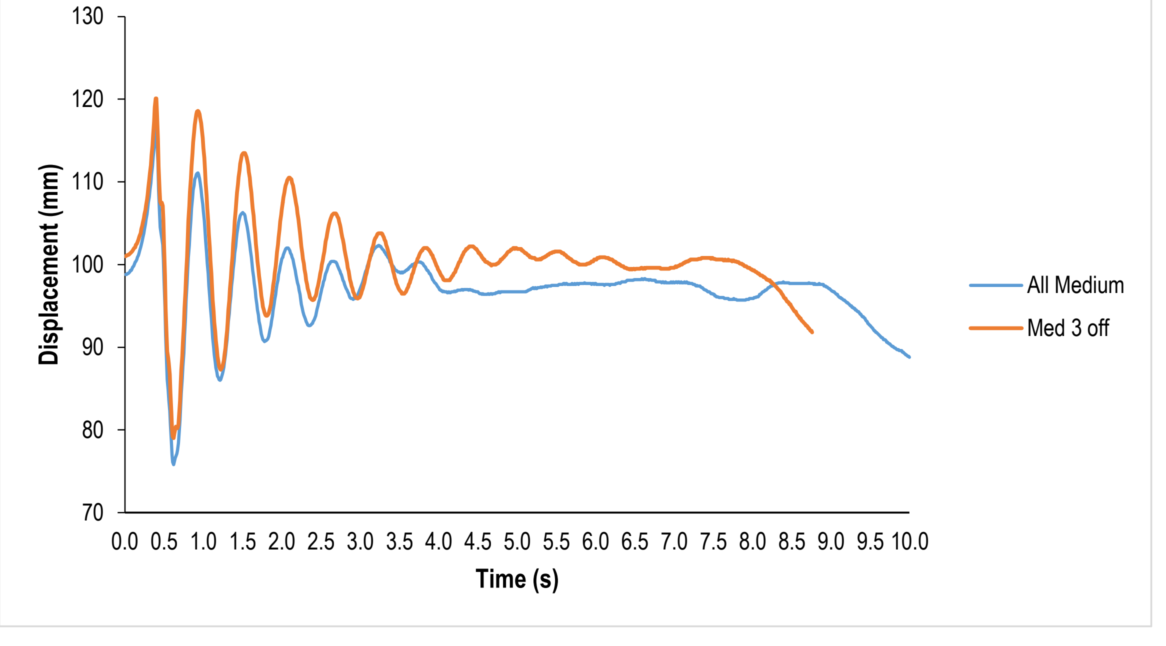


Figure 6.29: Comparison of ramp tests: displacement (6 MED and 3 removed – fully laden)



A summary of the results is presented in Table 6.15.

Table 6.15: Summary of results: Fully laden 6 MED and 3 removed

Load	Fully laden							
Shock absorbers	6 MED and 3 removed (from the left side of vehicle)							
Analysis	VSB11 ramps to detect shockers removed							
Axle	Centre							
Measurement method	Air pressure (APT)				Linear displacement (LDT)			
Shock absorbers	6 MED		3 removed		6 MED		3 removed	
Left/right sensor	L	R	L	R	L	R	L	R
Test 1 - Damping ratio (%)	10	12	7	8	10	13	5	6
Test 2 - Damping ratio (%)	9	11	8	8	6	8	6	6
Test 3 - Damping ratio (%)	9	12	6	7	8	10	6	6
Averaged result (%)	**11**		**7**		**9**		**6**	
Standard deviation	**1.38**		**0.82**		**2.40**		**0.41**	
Frequency (Hz)	**1.76**		**1.82**		**1.72**		**1.77**	

Commentary

The intention of this test was to determine if a larger change in damping can be detected by removing all 3 shock absorbers on the left side of the triaxle suspension group. It was also expected that this test would generate body roll, the effects of which would be assessed during this test.

The reduction in damping was less than 50%. This confirms previous findings that the actual reduction in damping is not reflected in the results due to variability in the test methods.

No evidence of body roll was noticeable in these tests.

6.1.15 *Comparison of pipe tests: Fully laden medium-damping vs 3 removed*

Figure 6.30 and Figure 6.31 show the data traces from the pipe test for the tests with 6 medium-damping shock absorbers fitted and 3 removed from the left (passenger) side of the vehicle, measured with air pressure sensors and displacement sensors respectively.

Figure 6.30: Comparison of pipe tests: pressure (6 MED and 3 removed – fully laden)

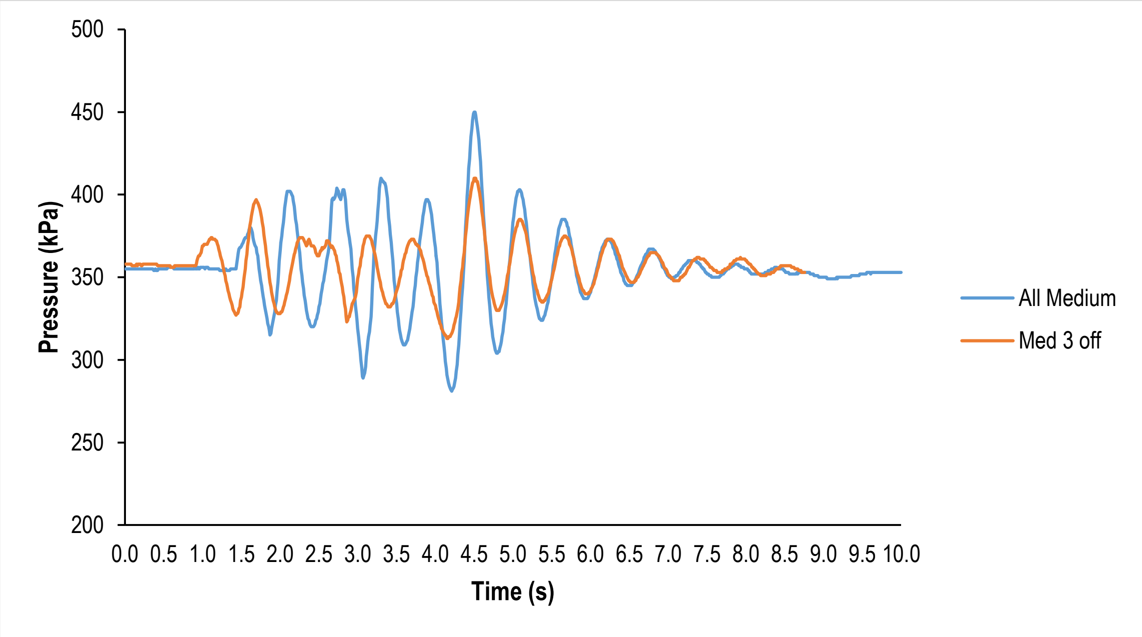
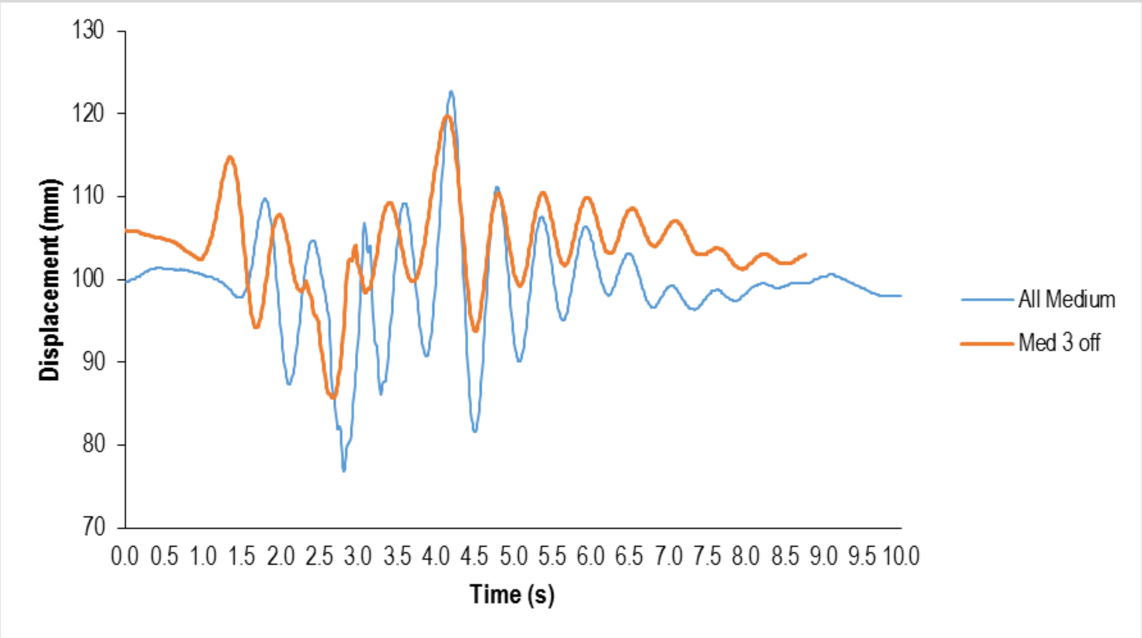


Figure 6.31: Comparison of pipe tests: displacement (6 MED and 3 removed – fully laden)



A summary of the results is presented in Table 6.16.

Table 6.16: Summary of results: Fully laden 6 MED and 3 removed

Load	Fully laden							
Shock absorbers	6 MED and 3 removed (from the left side of the vehicle)							
Analysis	VSB11 ramps to detect shockers removed							
Axle	Centre							
Measurement method	Air pressure (APT)				Linear displacement (LDT)			
Shock absorbers	6 MED		3 removed		6 MED		3 removed	
Left/right sensor	L	R	L	R	L	R	L	R
Test 1 - Damping ratio (%)	12	11	13	10	9	10	6	0
Test 2 - Damping ratio (%)	12	11	11	9	10	11	5	3
Test 3 - Damping ratio (%)	12	11	8	9	10	11	7	4
Averaged result (%)	**12**		**10**		**10**		**4**	
Standard deviation	**0.55**		**1.79**		**0.75**		**2.48**	
Frequency (Hz)	**1.76**		**1.82**		**1.72**		**1.77**	

Commentary

The pipe tests produced significantly different results from the ramp tests, for the first time during the test program, other than the tests affected by speed. There is a large variation between the repeat tests with 3 shock absorbers removed for both the APTs and LDTs. The averaged results from APTs do not indicate any change in damping despite 3 shock absorbers being removed. This is not possible and a result of error in the test method. The averaged result from LDTs is more in line with the expected reduction of 50%.

6.1.16 *Comparison of ramp tests: Fully laden with and without ride height control*

Figure 6.32 and Figure 6.33 Figure 6.30show the data traces from the ramp test with the vehicle fitted with 6 medium-damping, measured with air pressure sensors and displacement sensors respectively. Tests were conducted with the ride-height control (RHC) valve in place and then with it disconnected.

Figure 6.32: Comparison of ramp tests: pressure (6 MED with and without RHC – fully laden)

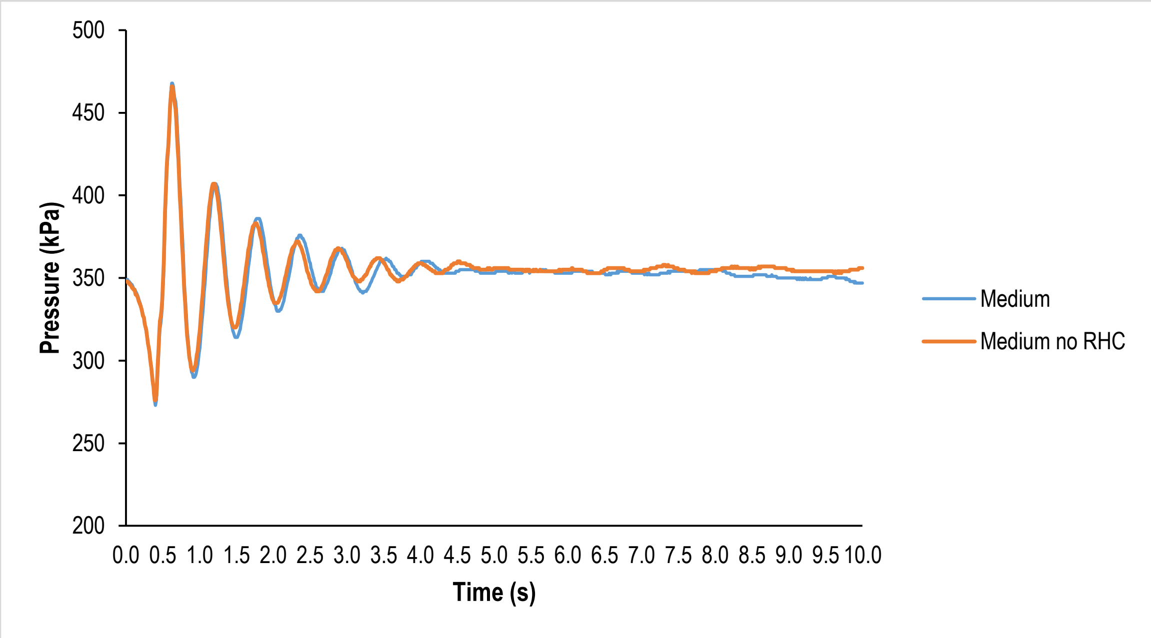
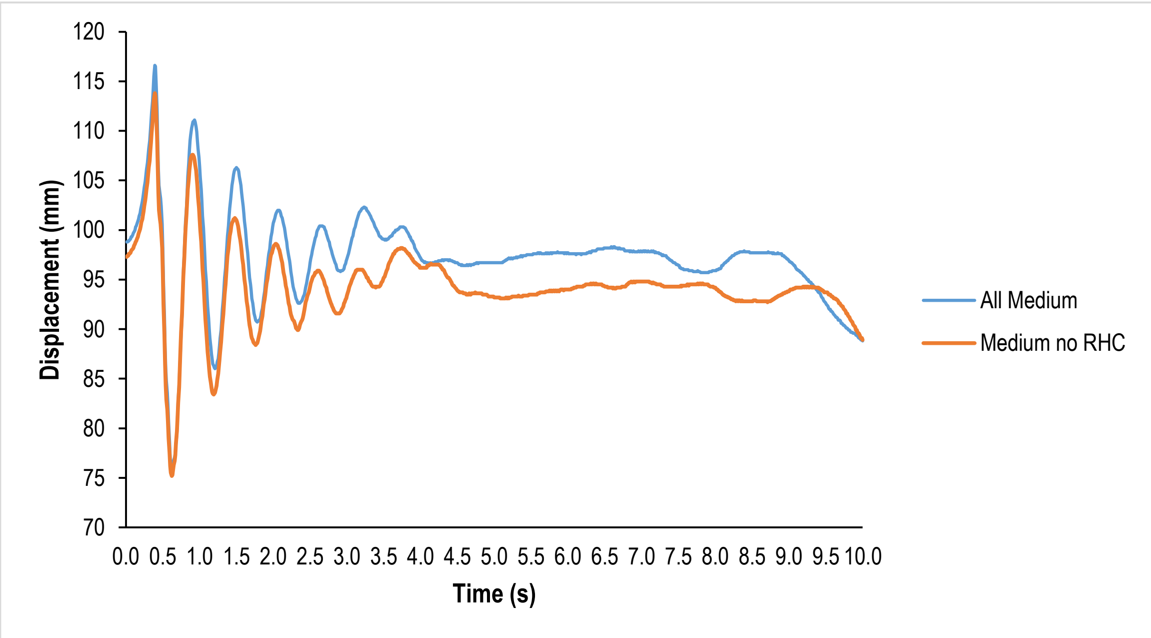


Figure 6.33: Comparison of ramp tests: displacement (6 MED with and without RHC – fully laden)



A summary of the results is presented in Table 6.17.

Table 6.17: Summary of results: Fully laden medium-damping with and without RHC

Load	Fully laden											
Shock absorbers	6 MED damping (with and without ride height control valve)											
Analysis	VSB11 ramp to detect differences due to RCH											
Axle	Front, centre and rear (F,C,R)											
Measurement method	Air pressure (APT)						Linear displacement (LDT)					
Shock absorbers	With RHC			Without RHC			With RHC			Without RHC		
Left/right sensor	F	C	R	F	C	R	F	C	R	F	C	R
Test 1 - Damping ratio (%)	11	11	12	10	11	13	12	12	11	10	9	9
Test 2 - Damping ratio (%)	10	10	13	10	11	11	12	7	12	12	10	9
Test 3 - Damping ratio (%)	10	11	14	9	11	12	12	9	12	11	10	10
Ave. by axle (%)	**10**	**11**	**13**	**10**	**11**	**12**	**12**	**9**	**12**	**11**	**10**	**10**
Averaged result (%)	**11**			**11**			**11**			**10**		
Standard deviation	**1.41**			**1.17**			**1.80**			**1.00**		
Frequency (Hz)	**1.75**			**1.78**			**1.71**			**1.76**		

Commentary

The intention of this test was to quantify the effect of the RHC valve. Tests were conducted with RHC and without. The averaged results indicate that this has no effect on the damping of the suspension. The RHC valve disconnected resulted in the final position (the vertical height) at which the suspension settles following the tests varying between tests, by approximately 5 mm. There is often some variation in this final position, even for those tests where the RHC valve was operating normally, although the difference was greater for these tests with it removed. The difference in final position can affect the results if not compensated for during the analysis, as it requires the difference to be removed prior to calculating the damping.

6.1.17 *Comparison of ramp tests: Medium-damping fully laden vs half laden*

Figure 6.34 and Figure 6.35 show the data traces for both the laden and half laden conditions for the ramp test with the vehicle fitted with medium-damping shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.34: Comparison of ramp tests: pressure (medium-damping – fully laden and half laden)

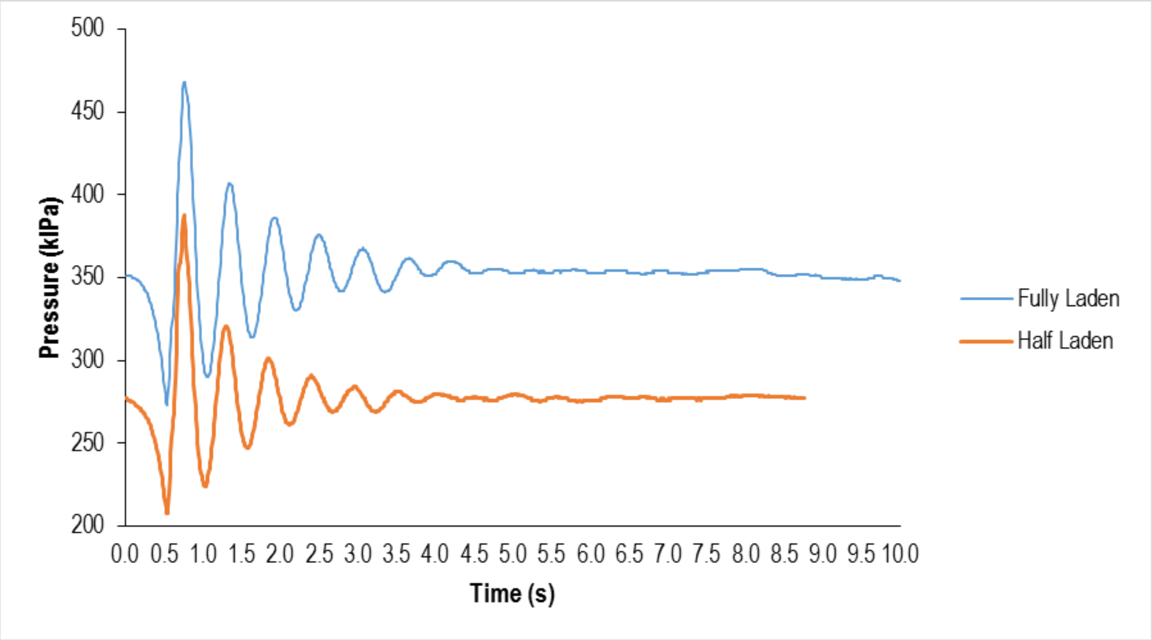
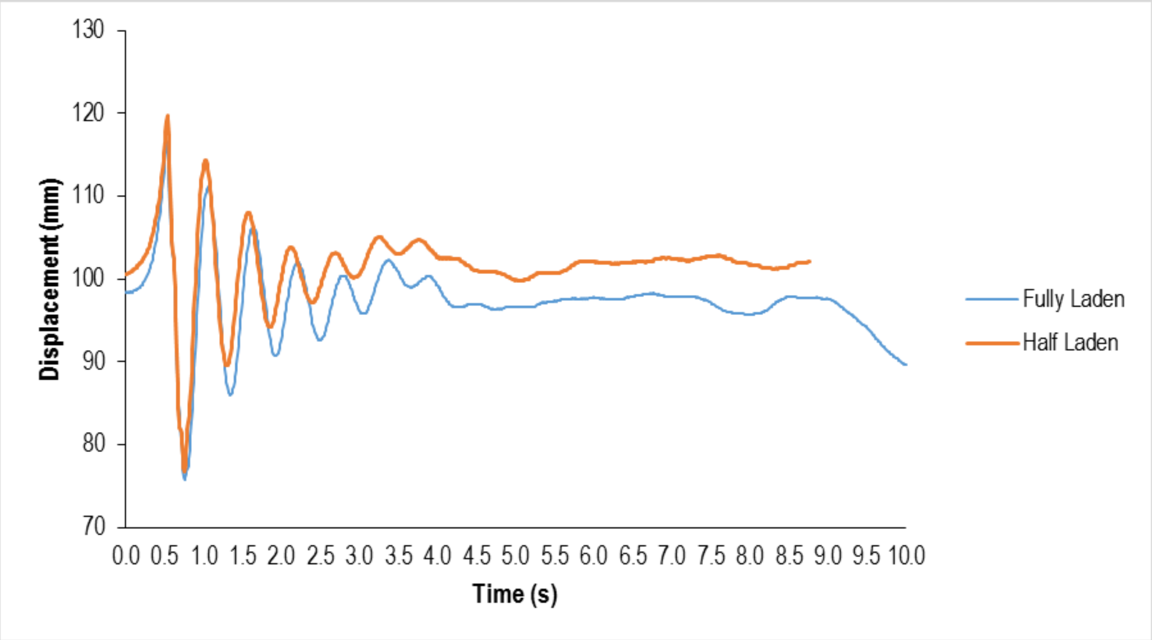


Figure 6.35: Comparison of ramp tests: displacement (medium-damping – fully laden and half laden)



A summary of the results is presented in Table 6.18.

Table 6.18: Summary of results: medium-damping fully laden and half laden – VSB11 ramp test

Load	Fully laden and half laden							
Shock absorbers	6 MED damping							
Analysis	VSB11 ramp to compare differences due to load							
Axle	Centre							
Measurement method	Air pressure (APT)				Linear displacement (LDT)			
Load	Laden		Half laden		Laden		Half laden	
Left/right sensor	Left	Right	Left	Right	Left	Right	Left	Right
Test 1 - Damping ratio (%)	10	12	14	15	10	13	15	12
Test 2 - Damping ratio (%)	9	11	13	16	6	8	15	12
Test 3 - Damping ratio (%)	9	12	14	16	8	10	16	12
Averaged result (%)	**11**		**15**		**9**		**14**	
Standard deviation	**1.38**		**1.21**		**2.40**		**1.86**	
Frequency (Hz)	**1.76**		**1.82**		**1.72**		**1.79**	

Commentary

The intention of this test was to quantify the difference between testing the vehicle laden and approximately half laden. It is clear that the results are affected by the change in load. No change in damping is expected as the vehicle was fitted with the same shock absorber, however the results have increased significantly. It can be concluded that tests must be conducted within the VSB11 tolerance of 5%.

6.1.18 *Comparison of pipe tests: Medium-damping fully laden vs half laden*

Figure 6.36 and Figure 6.37 show the data traces for both the laden and half laden conditions for the pipe test with the vehicle fitted with medium-damping shock absorbers, measured with air pressure sensors and displacement sensors respectively.

Figure 6.36: Comparison of pipe tests: pressure (medium-damping – fully laden and half laden)

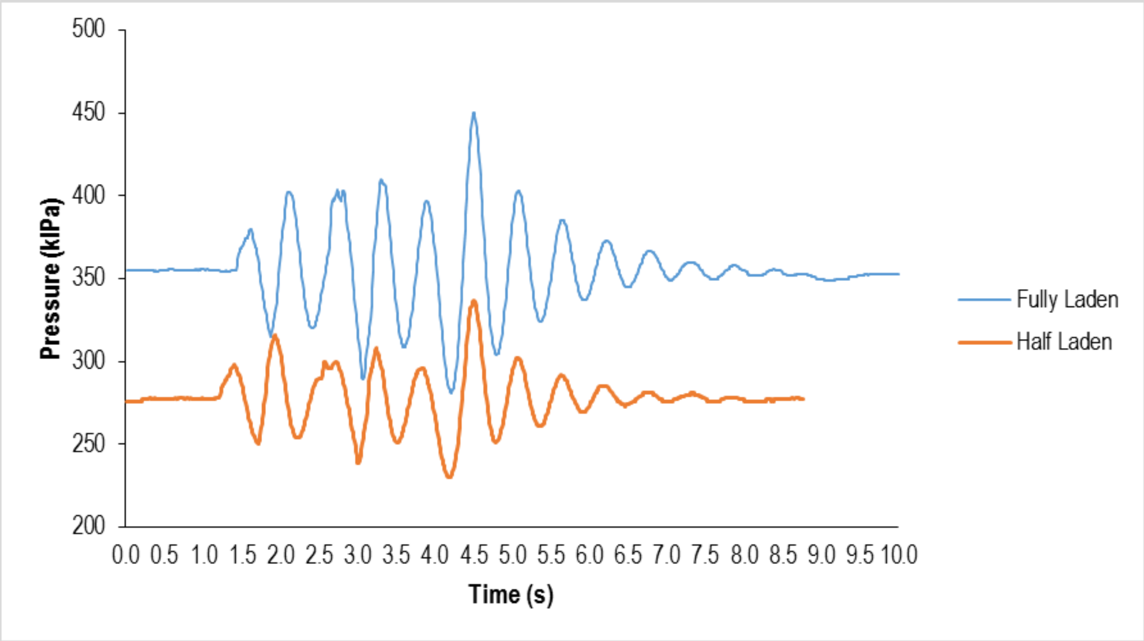
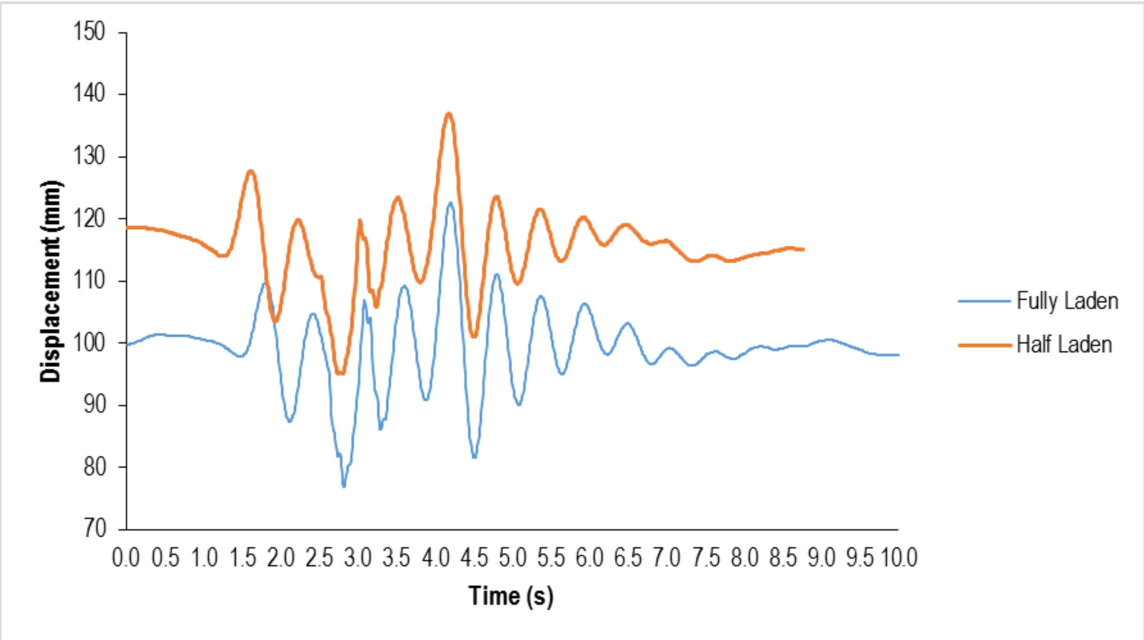


Figure 6.37: Comparison of pipe tests: displacement (medium-damping – fully laden and half laden)



A summary of the results is presented in Table 6.19.

Table 6.19: Summary of results: Medium-damping fully laden and half laden – pipe test

Load	Fully laden and half laden							
Shock absorbers	Medium-damping							
Analysis	Pipe test to compare differences due to load							
Axle	Centre							
Measurement method	Air pressure (APT)				Linear displacement (LDT)			
Load	Laden		Half laden		Laden		Half laden	
Left/right sensor	Left	Right	Left	Right	Left	Right	Left	Right
Test 1 - Damping ratio (%)	12	11	16	14	9	10	13	9
Test 2 - Damping ratio (%)	12	11	15	13	10	11	10	8
Test 3 - Damping ratio (%)	12	11	14	13	10	11	10	7
Averaged result (%)	**12**		**14**		**10**		**10**	
Standard deviation	**0.55**		**1.17**		**0.75**		**2.07**	
Frequency (Hz)	**1.72**		**1.79**		**1.74**		**1.78**	

Commentary

The pipe tests produced inconsistent results across the APTs and LDTs when compared with the ramp tests. The APTs followed a similar trend to the ramp tests, whereas the PDTs did not. Despite the inconsistency these results confirm that tests must be conducted within the axle group mass tolerance.

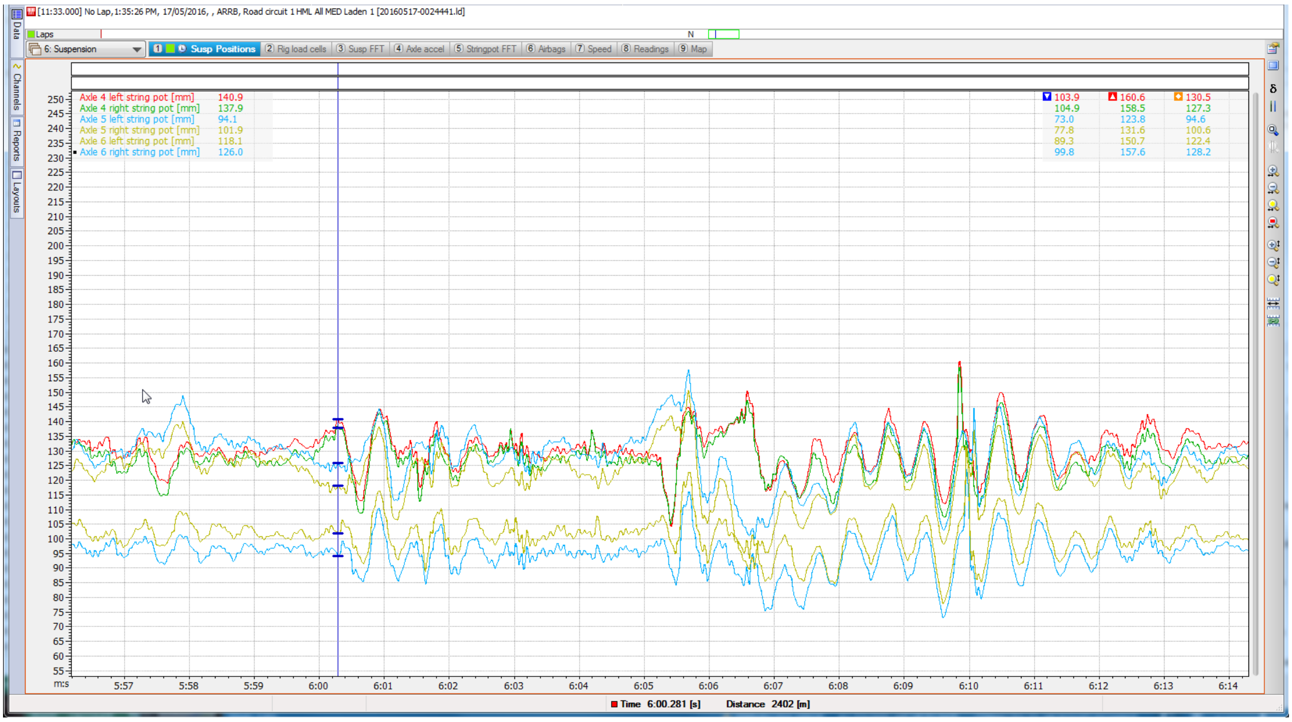
6.1.19 *On-road test: Fully laden with medium-damping shock absorbers*

On-road tests were conducted on Sherwood Rd, near the Brisbane Markets. For these tests the vehicle was fully laden and fitted with medium-damping shock absorbers. The vehicle was fitted with a GPS receiver to record speed and location during the tests. The vehicle was driven across a bridge which had earlier been identified as potentially able to excite the suspension. Figure 6.38 shows an aerial photograph of Sherwood Rd and the location of the bridge.

Figure 6.38: View showing bridge location for on-road testing

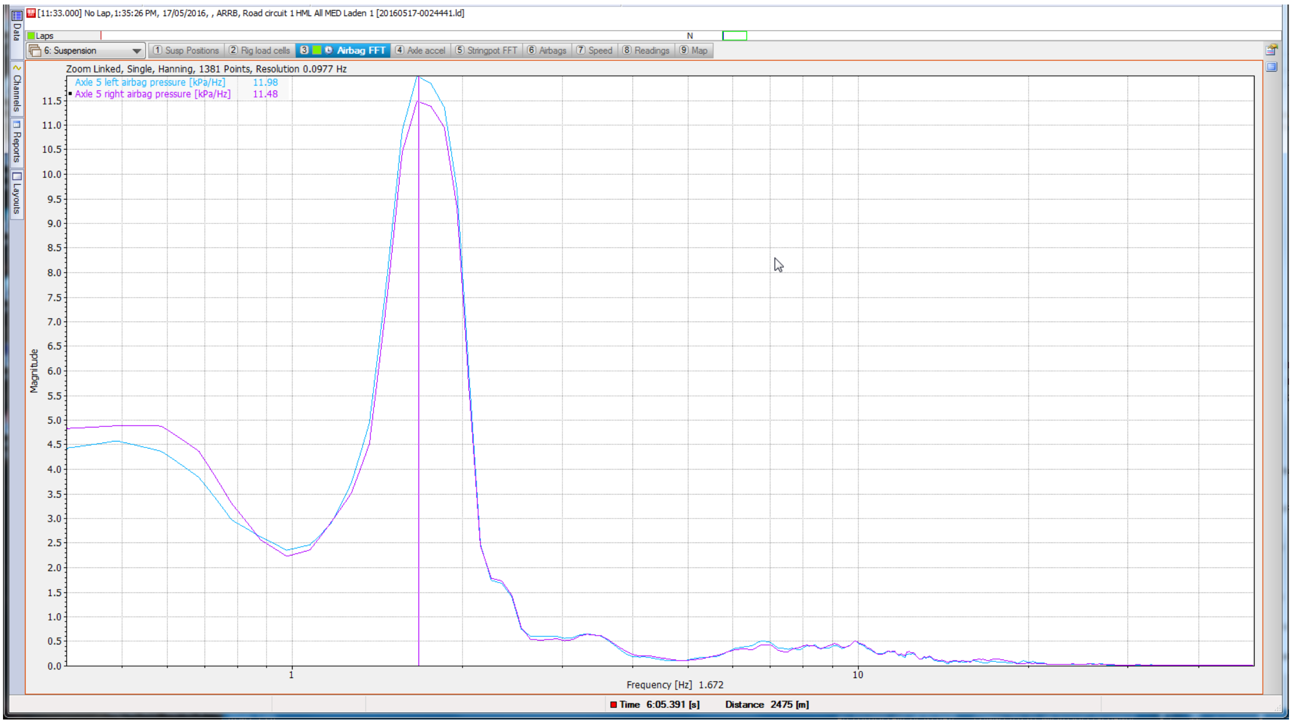
Data traces for both displacement and air pressure are shown in Figure 6.39 and Figure 6.41.

Figure 6.39: Displacement data trace from on-road tests – first pass



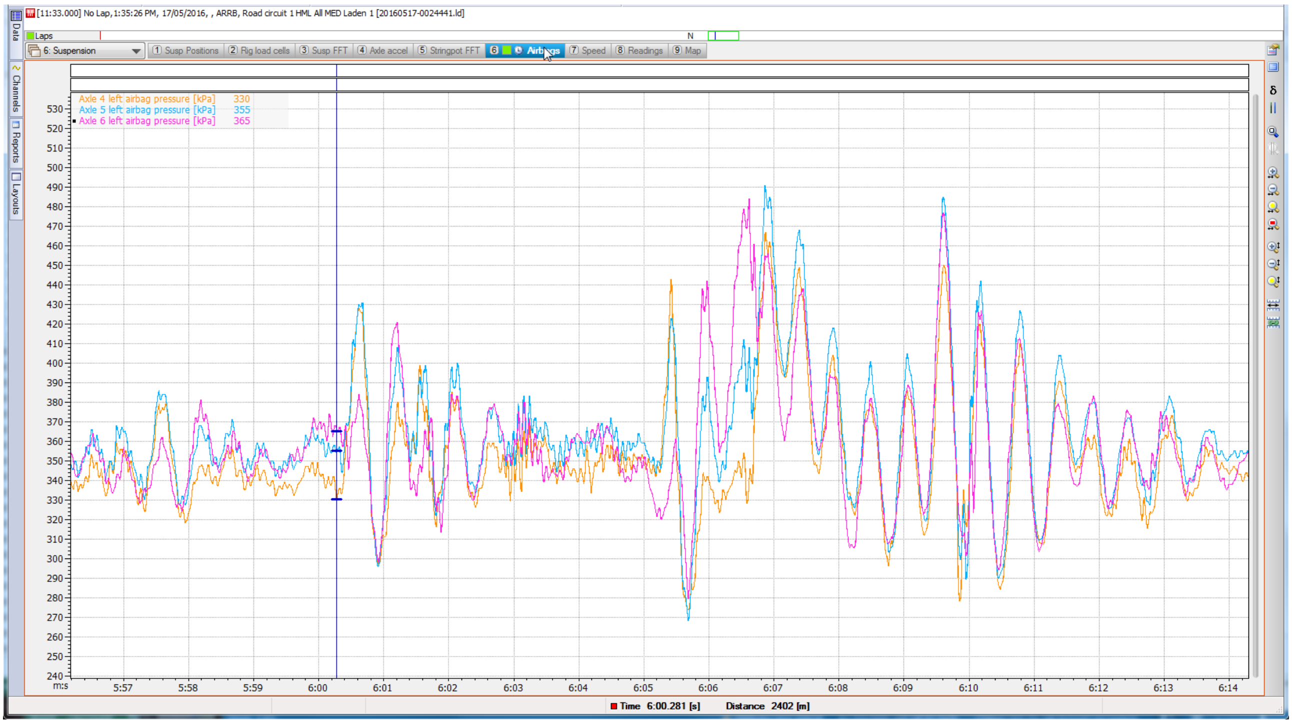
The appearance of the data traces obtained from on-road tests differs from the ramp and pipe tests. The first difference that becomes evident is the presence of higher frequencies in the data. The frequency spectrum of the data was analysed and is presented in Figure 6.40, which shows a dominant frequency of less than 2 Hz, which is consistent with the body-bounce frequency expected for this vehicle. There is also another frequency present near 10 Hz; this is consistent with the frequency of axle hop (the frequency at which the axle oscillates based on the tyre stiffness). This is a promising result and indicates that despite the disturbances due to the road surface the frequency of the suspension can be identified.

Figure 6.40: Frequency spectrum of the air pressure during on-road testing



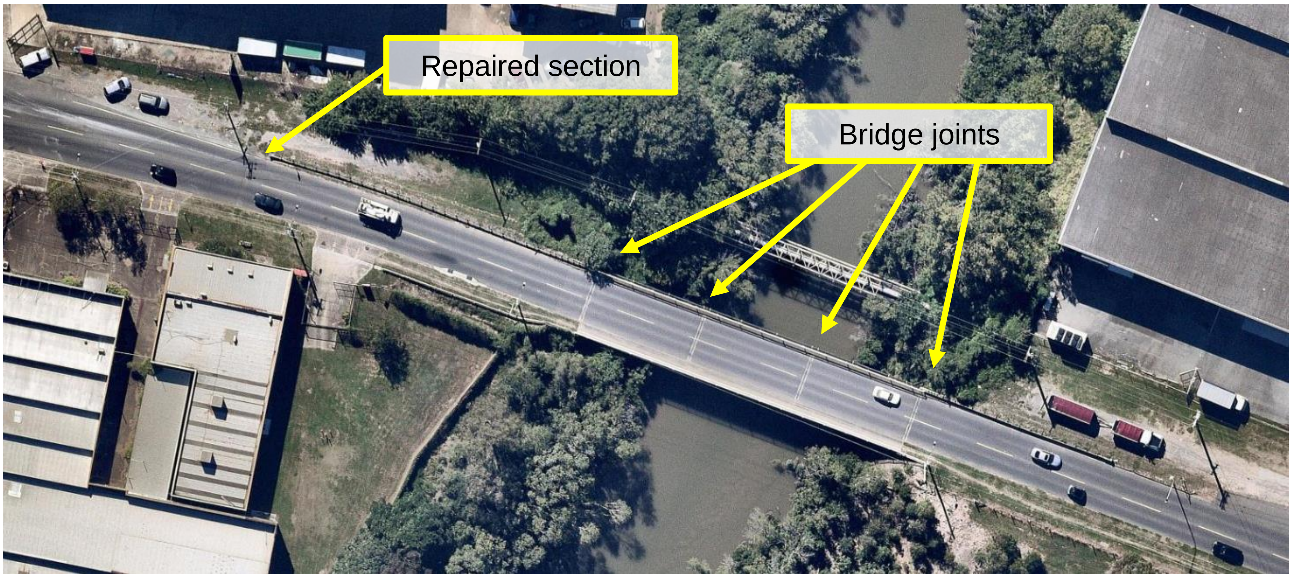
The data trace contains many peaks and troughs of varying frequency and magnitude. This data trace is more difficult to analyse than data obtained from the step tests in which there is a single pulse. The data trace from the APTs is shown in Figure 6.41. The data was analysed to locate the point at which the vehicle crossed the bridge, which is represented in Figure 6.41 by the vertical line. It is clear that at approximately the 6:00 time interval there is a large single impulse followed by a decaying trend similar in appearance to the data obtained from the pipe test method. This pattern was observed in the data measured by the LDTs and the APTs.

Figure 6.41: Air pressure data trace from on-road tests – first pass



The data shown in Figure 6.39 and Figure 6.41 is for a period of 18 seconds in which the vehicle travelling at 53 km/h crosses the four bridge joints and a repaired section of road shown in Figure 6.42. The total bridge span is 50 m, with approximately 16.5 m between each joint. At the speed it was travelling during this test (14.7 m/s) the vehicle crosses a bridge joint every 1.1 seconds. The repaired section of the road is approximately 58 m past the last bridge joint. It is possible that the large peak at approximately after the 6:09 interval coincides with the vehicle crossing the repaired section, as the vehicle would have travelled approximately 132 m since the first peak. The distance travelled is 24 m greater than the length of the bridge and distance to the repaired section (108 m), which indicates that there may be other inputs from other axles (steer axles) or other rough sections of road.

Figure 6.42: View showing bridge joints and repaired section of road



The difficulty with obtaining data sufficient to calculate damping from on-road tests is repeatability. To achieve repeatability it is necessary to excite the vehicle consistently with a known or unchanged input and then to eliminate any subsequent inputs. This is practically impossible to achieve on road under normal driving conditions. A second pass over the same road section was made shortly after the first pass and the data trace is shown Figure 6.43. Due to traffic conditions, the vehicle was able to travel at the posted speed limit of 60 km/h. The driver was instructed to maintain a similar lateral position in the lane, even so it was likely to vary between passes. All other variables remained unchanged. The data trace bears very little resemblance to the first pass, although, somewhat expected, the stark difference (possibly due to the increase in speed of 7 km/h) highlights the difficulties of the on-road method.

Figure 6.43: Air pressure data trace from on-road tests – second pass

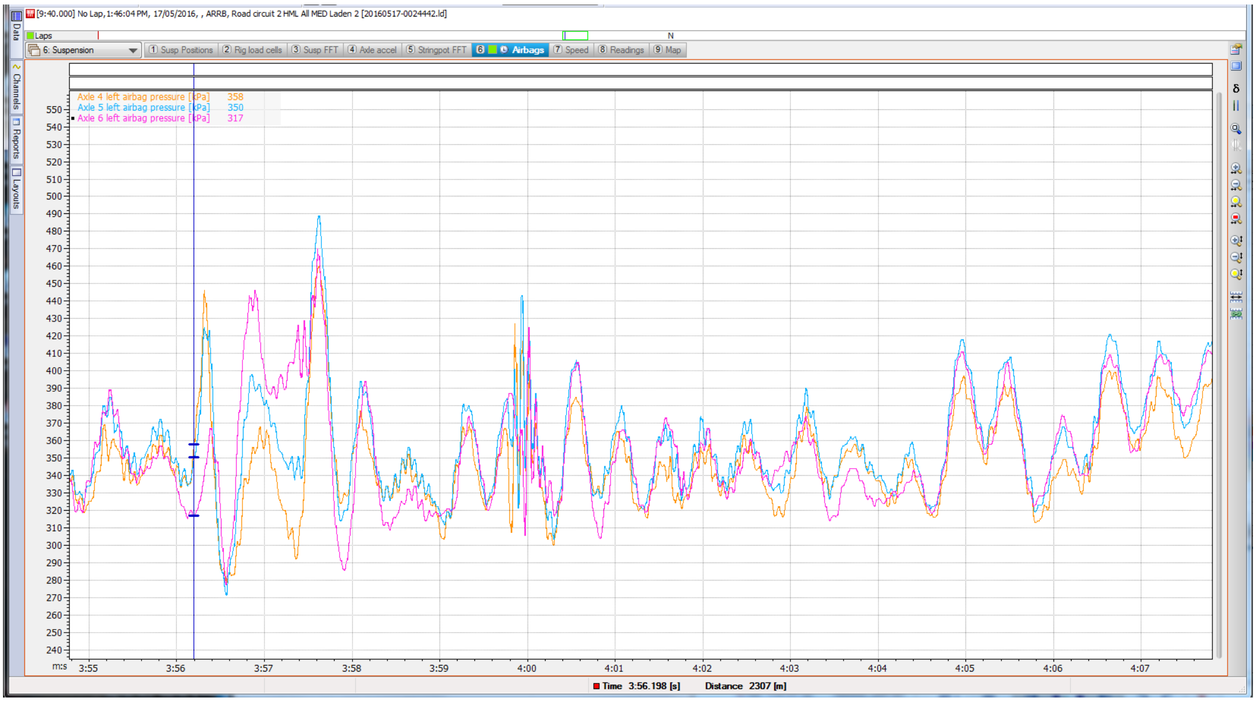


Figure 6.44 shows the triaxle semi-trailer during the on-road tests. The repaired section of the road is shown in the foreground. In this photograph the vehicle is travelling on the return trip, in the opposite direction as tested.

Figure 6.44: Test vehicle 1 during on-road testing

6.2 Results from Test program 2

Test program 2 was conducted using the RFSA and a 6x4 prime mover. The test system was the RFSA itself which lifts and drops the entire vehicle and measures the signal via load cells upon which the vehicle is positioned. The reference system was fitted to the vehicle and data obtained from both measurement systems was compared. For test program 2, the data presented was logged by ARRB for both the test system and the reference system.

6.2.1 *Repeatability of RFSA tests: Fully laden with HD shock absorbers*

Figure 6.45 and Figure 6.46 show the data traces (of the first axle) for the RFSA test with HD shock absorbers, for the RFSA load cells and linear displacement respectively.

Figure 6.45: Load cell data trace from RFSA – HD shock absorbers

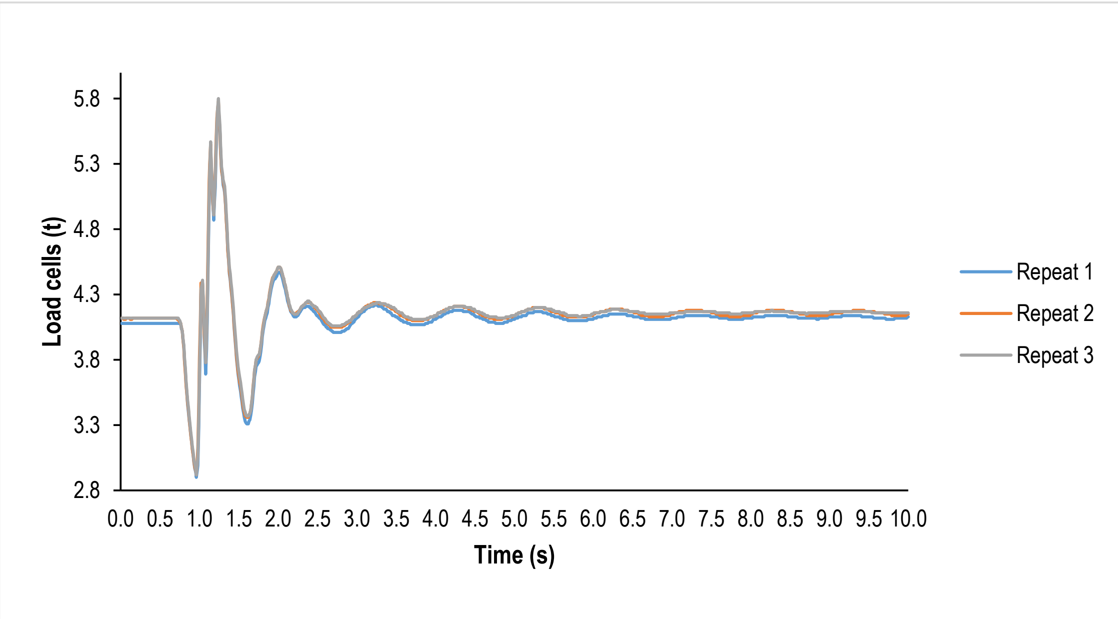


Figure 6.46: Reference system (linear displacement) data trace from RFSA – HD shock absorbers

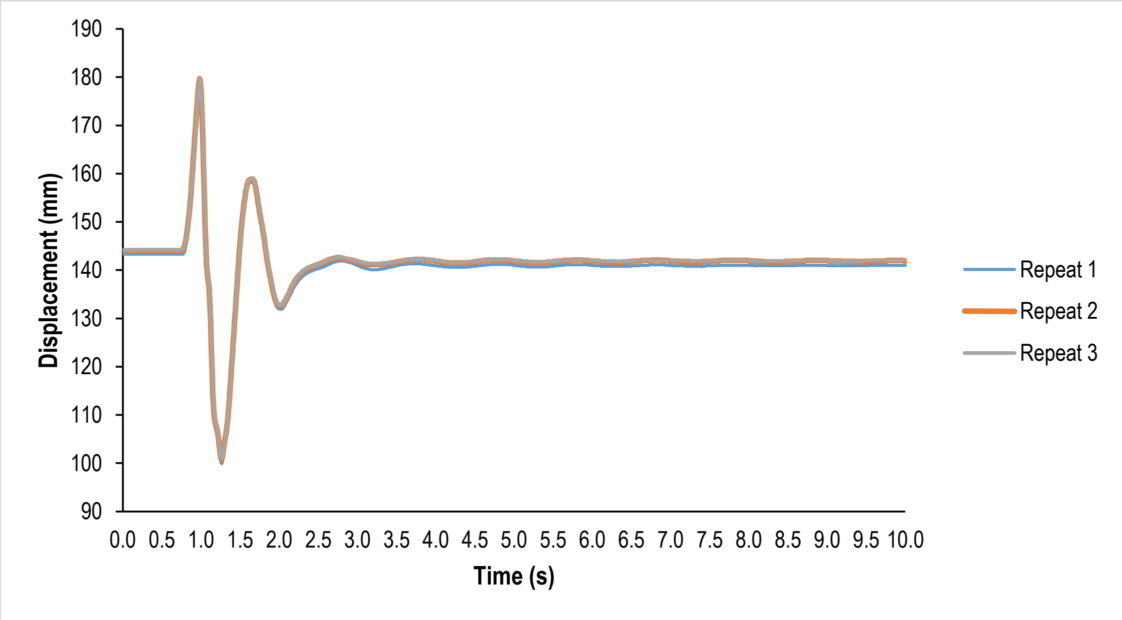


Figure 6.47 and Figure 6.48 show the data traces of both the first and second axles.

Figure 6.47: Load cell data trace from RFSA – HD shock absorbers

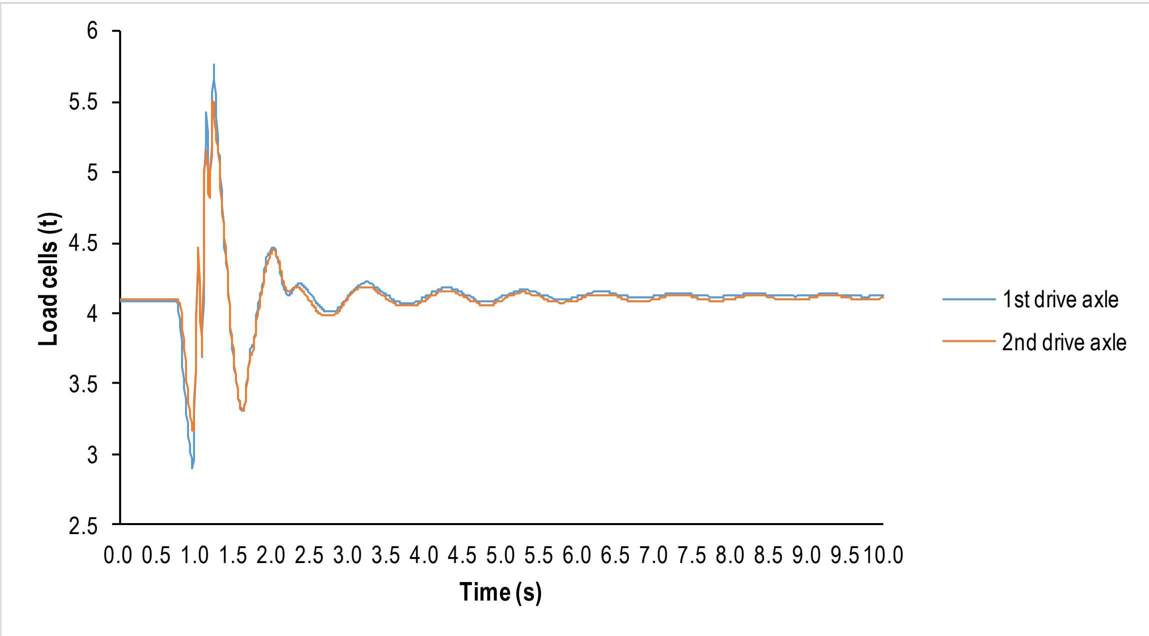
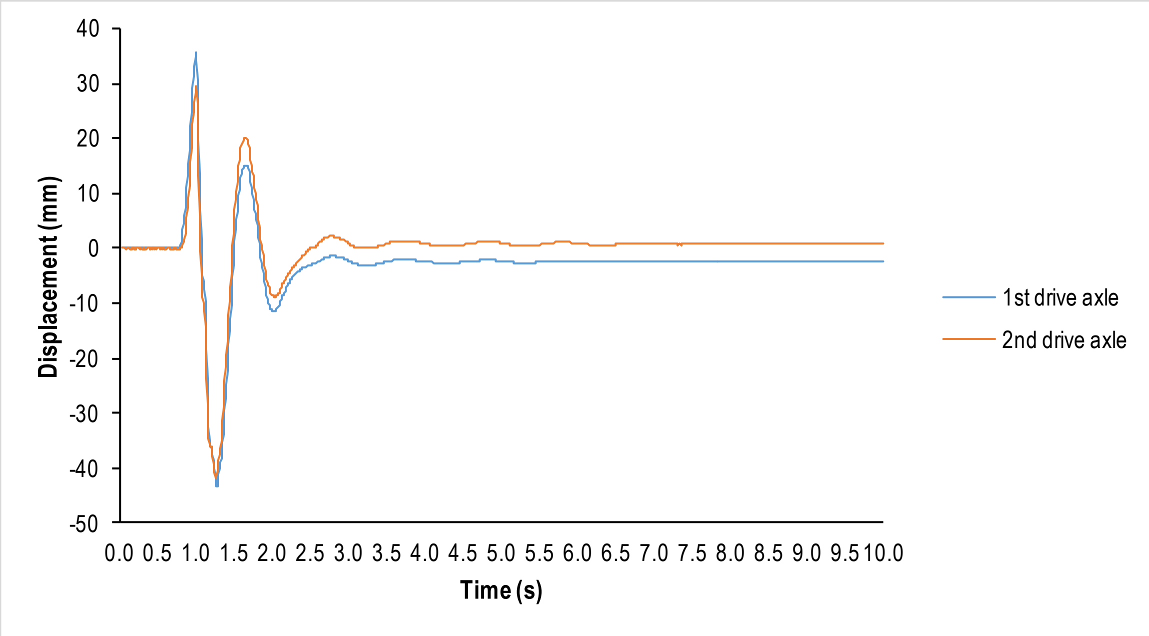


Figure 6.48: Reference system (linear displacement) data trace from RFSA – HD shock absorbers



A summary of the results is presented in Table 6.20.

Table 6.20: Summary of results: RFSA – heavy-duty shock absorbers

Load	Fully laden							
Shock absorbers	Heavy-duty							
Method	RFSA VSB11 drop test							
Axle	Both drive axles							
Sensor	RFSA (load cells)				Linear displacement			
Axle	1st drive		2nd drive		1st drive		2nd drive	
Left/right sensor	Left	Right	Left	Right	Left	Right	Left	Right
Test 1 - Damping ratio (%)	26	25	19	23	25	25	26	25
Test 2 - Damping ratio (%)	25	26	18	26	25	24	24	24
Test 3 - Damping ratio (%)	24	25	19	24	25	24	24	24
Averaged result	**25**		**22**		**25**		**25**	
Standard deviation	**0.75**		**3.27**		**0.52**		**0.84**	
Frequency	**1.39**		**1.39**		**1.84**		**1.84**	

Commentary

In the case of triaxle suspensions (as analysed in the previous section), it is acceptable to measure data from the centre axle only, because this axle is not affected by pitch unlike the front and rear axles of the group, which needs to be compensated for during the analysis. In the case of a tandem axle group, there is no middle axle so both the front and rear axles must be measured and the effects of pitching compensated for via calculation. The pitching effect can be seen in Figure 6.48, as the lines separate after the first compression stroke. Although the vertical displacement of the suspension indicates that the vehicle is pitching, this is not reflected in the data from the load cells, where the load on both the front and rear axles follows an almost identical path. The vertical displacement data also indicates that the final position of the first drive axle differs from its starting position. The final position of the axles directly influences the damping value, as the peaks are measured from this point, as it represents no (zero displacement) suspension movement.

The results obtained from the RFSA are very consistent. The calculated damping is higher than that from the LDTs and the frequency is much lower. The frequency is a result of an analysis error due to the additional higher frequency of oscillation present in this data. The higher frequency is the axle hop, which is present during this test, and therefore this data trace is a true representation of modes of oscillation present during this test. The load cells measure this higher frequency as the sensing unit is positioned beneath the tyres. A consequence of capturing the axle hop frequency is that the high frequency peaks must be compensated for through filtering or via the correct selection of points when calculating damping and frequency. The RFSA contains no automatic process for this, and the manual analysis method used to calculate the damping and frequency did not compensate for it correctly, hence the error in the frequency calculation and potentially overestimation of damping.

6.2.2 *Repeatability of RFSA tests: Fully laden with 1 shock absorber removed*

Figure 6.49 and Figure 6.50 show the data traces for the RFSA test with a shock absorber removed, for the RFSA load cells and linear displacement sensors respectively. Data from both the first and second drive axle of the 6x4 vehicle is shown.

Figure 6.49: Load cell data trace from RFSA – 1 shock absorber removed

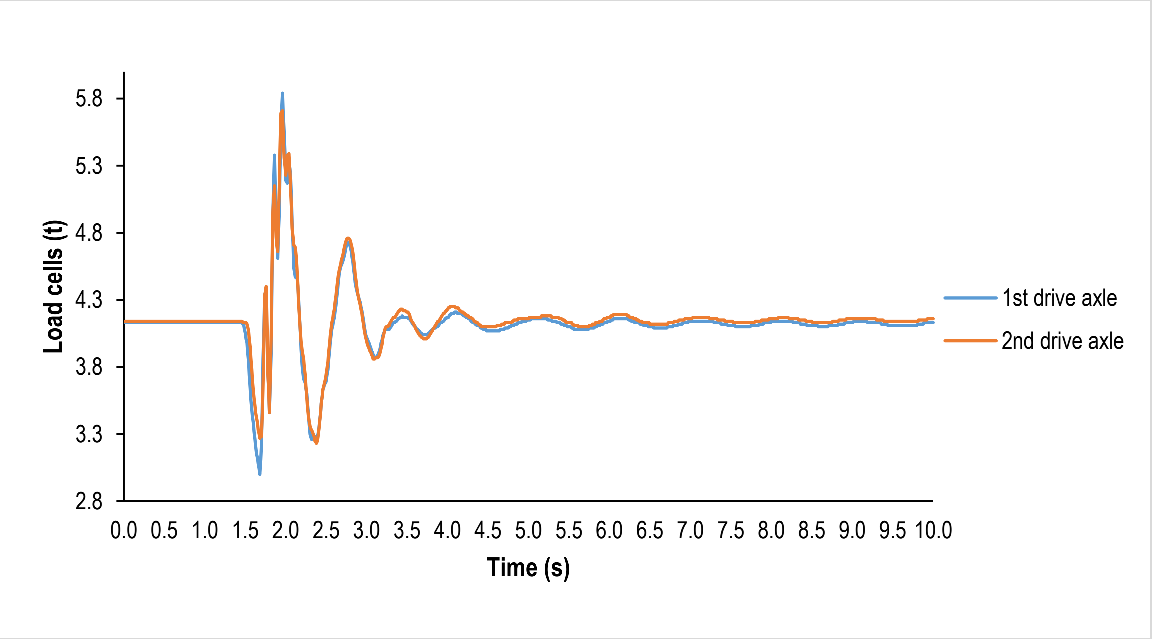
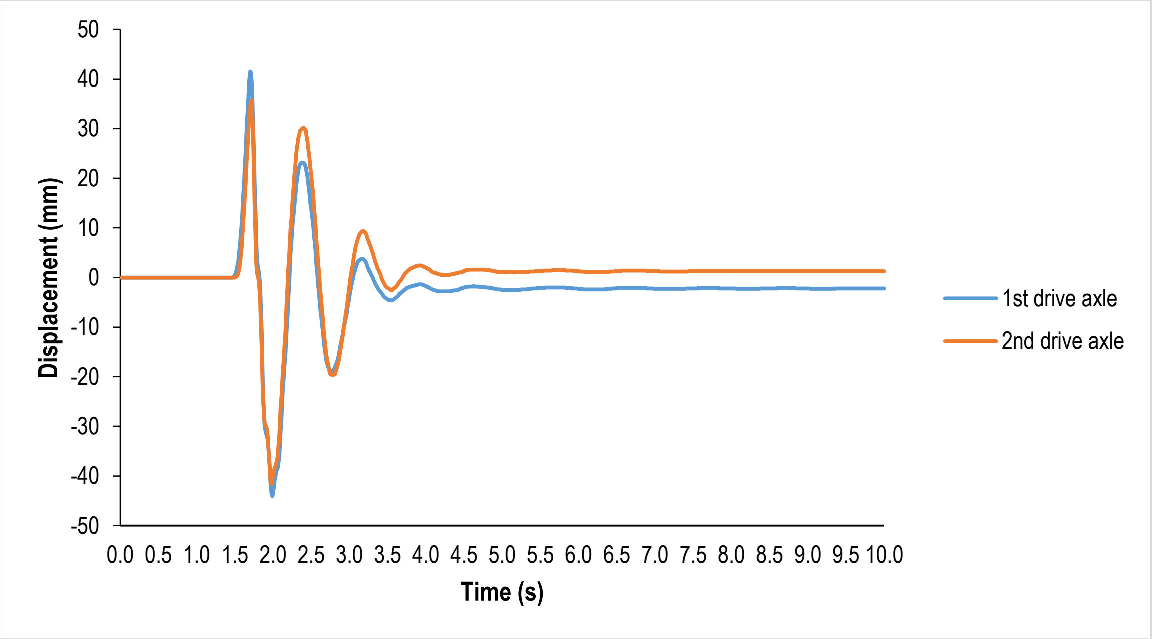


Figure 6.50: Reference system (linear displacement) data trace from RFSA test – 1 shock absorber removed



A summary of the results is presented in Table 6.21.

Table 6.21: Summary of results: RFSA – a shock absorber removed from rear axle

Load	Fully laden			
Shock absorbers	One shock absorber removed from rear axle			
Analysis	VSB11 RFSA drop test			
Axles	Both drive axles			
Measurement method	RFSA (load cells)		Linear displacement (LDT)	
Left/right sensor	Left	Right	Left	Right
1st drive - Damping ratio (%)	20	19	21	20
2nd drive - Damping ratio (%)	19	19	17	17
Averaged result (%)	**19**		**19**	
Standard deviation	**0.50**		**2.06**	
Frequency (Hz)	**1.28**		**1.79**	

Commentary

A reduction in damping within range expected was measured by both the RFSA and LDTs. The result measured by the RFSA was higher, most likely due to the presence of axle hop and this effect not being compensated for correctly during analysis.

6.2.3 *Repeatability of RFSA tests: Fully laden with 2 shock absorbers removed*

Figure 6.51 and Figure 6.52 show the data traces for the RFSA test with both shock absorbers removed from the rear axle, for the RFSA load cells and linear displacement sensors respectively. Data from both the first and second drive axle of the 6x4 vehicle is shown.

Figure 6.51: Load cell data trace from RFSA – 2 shock absorbers removed

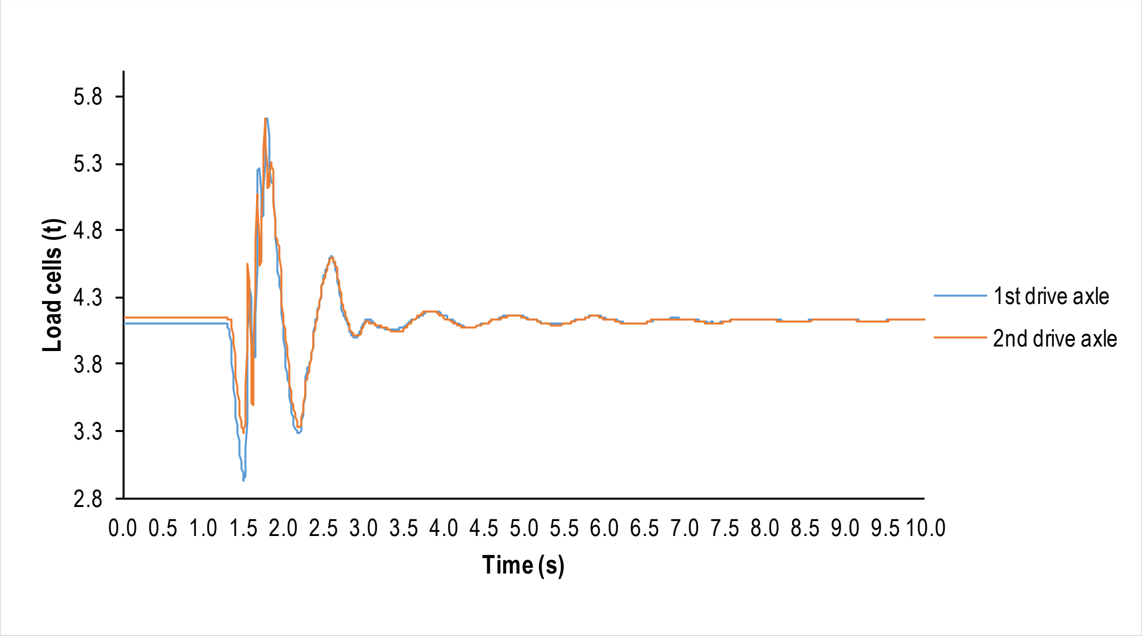
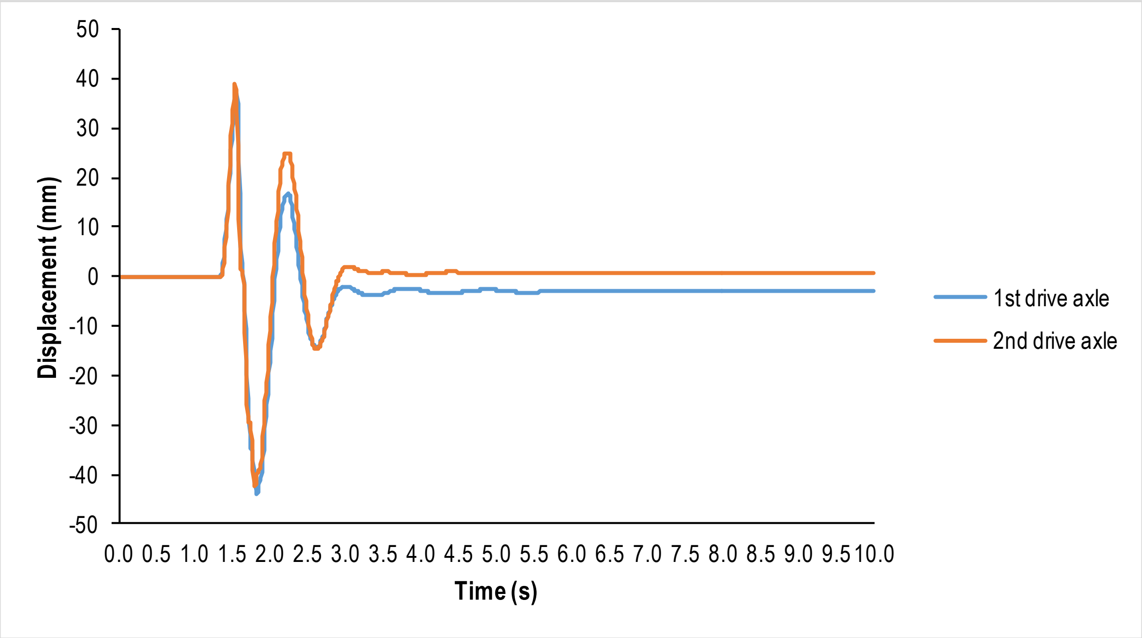


Figure 6.52: Reference system (linear displacement) data trace from RFSA test – 2 shock absorbers removed



A summary of the results is presented in Table 6.22.

Table 6.22: Summary of results: RFSA – both shock absorbers removed from rear axle

Load	Fully laden			
Shock absorbers	Both shock absorbers removed from rear axle			
Method	VSB11 RFSA drop test			
Axles	Both drive axles			
Sensor	RFSA (load cells)		Linear displacement	
Left/right sensor	Left	Right	Left	Right
1st drive - Damping ratio (%)	15	18	15	15
2nd drive - Damping ratio (%)	13	16	12	11
Averaged result	**16**		**13**	
Standard deviation	**2.08**		**2.06**	
Frequency	**1.39**		**1.80**	

Commentary

These results are consistent with the previous tests. The damping value with all shock absorbers was approximately 25%; with one shock absorber removed the damping reduced to 19% and with both removed from the rear axle it reduced to approximately 14%.

6.2.4 *Repeatability of RFSA tests: Fully laden with all shock absorbers removed*

Figure 6.53 and Figure 6.54 show the data traces (for the first axle only) for the RFSA test with all shock absorbers removed from the drive axles, for the RFSA load cells and linear displacement sensors respectively.

Figure 6.53: Load cell data trace from RFSA – all shock absorbers removed

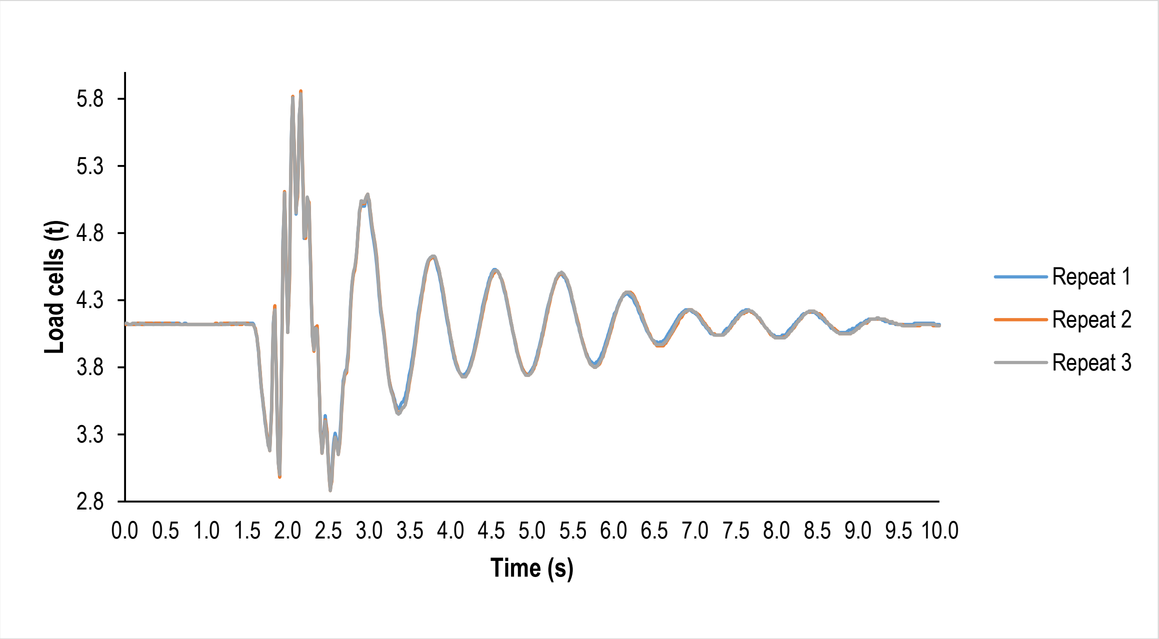
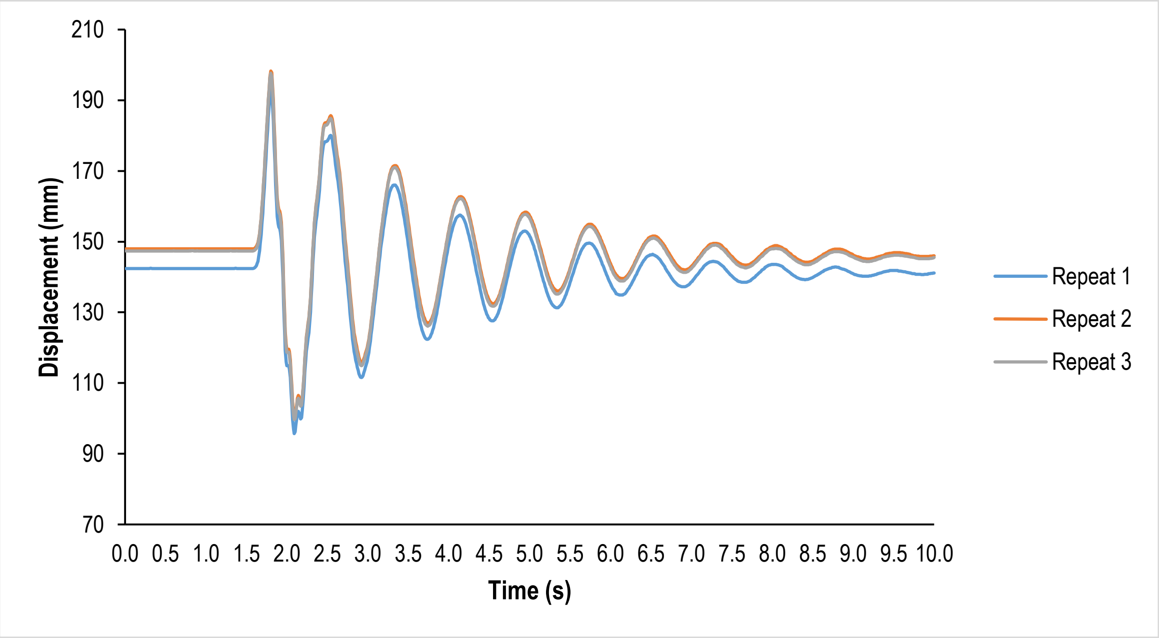


Figure 6.54: Reference system (linear displacement) data trace from RFSA test – all shock absorbers removed



A summary of the results is presented in Table 6.23.

Table 6.23: Summary of results: RFSA – all shock absorbers removed

Load	Fully laden							
Shock absorbers	None fitted							
Analysis	VSB11 RFSA drop test							
Axle	Both drive axles							
Measurement method	RFSA (load cells)				Linear displacement (LDT)			
Axle	1st drive		2nd drive		1st drive		2nd drive	
Left/right sensor	Left	Right	Left	Right	Left	Right	Left	Right
Test 1 - Damping ratio (%)	13	11	6	8	7	5	4	6
Test 2 - Damping ratio (%)	9	10	7	8	7	5	6	4
Test 3 - Damping ratio (%)	6	9	7	8	7	5	4	6
Averaged result (%)	**10**		**7**		**6**		**5**	
Standard deviation	**2.34**		**0.82**		**1.10**		**1.10**	
Frequency (Hz)	**1.39**		**1.47**		**1.84**		**1.26**	

Commentary

With no shock absorbers fitted the damping reduced to approximately 7%. With each progressive reduction in damping (removal of shock absorbers) the damping reduced by the expected amount. This result was not seen with the same consistency during the ramp and pipe tests. This indicates that the RFSA provides a more consistent drop. It should be noted that the tray was loaded by ARRB engineers to achieve even weight distribution left and right and fore and aft. When testing vehicles on the roadside, it is unlikely that the load distribution would be even; this would reduce the repeatability of the excitation method as the heavier axles will fall first causing pitching and rolling moments.

6.3 Results from test program 3

Test program 3 was conducted using the DynaSsess system on a 4x2 rigid truck. Test system 3 included custom-designed ramps, temporarily fitted sensors, a data logging and tablet-based user interface. This system provided the excitation, measurement and analysis method. The reference system was the VSB11 80 mm ramps as the excitation method, and the linear displacement sensors fitted to each axle and ARRB's data acquisition system as the measurement and analysis method. For test program 3, the data presented was logged by ARRB from the reference system when using the VSB11 ramps and the DynaSsess ramps (Figure 6.56).The data for test system 3 was provided to ARRB by FormulaSpec and is presented in Figure 6.55 and Figure 6.57.

6.3.1 *Repeatability of DynaSsess tests: Fully laden with HD shock absorbers*

Figure 6.55: FormulaSpec data from DynaSsess test method with all shock absorbers in place

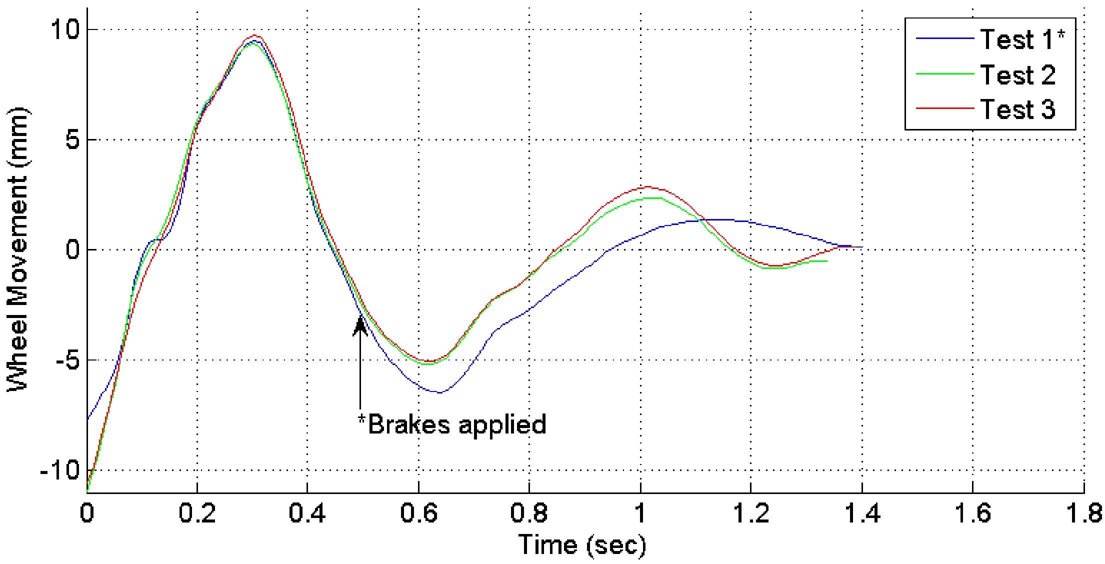


Figure 6.56: Reference system data from DynaSsess test method with all shock absorbers in place

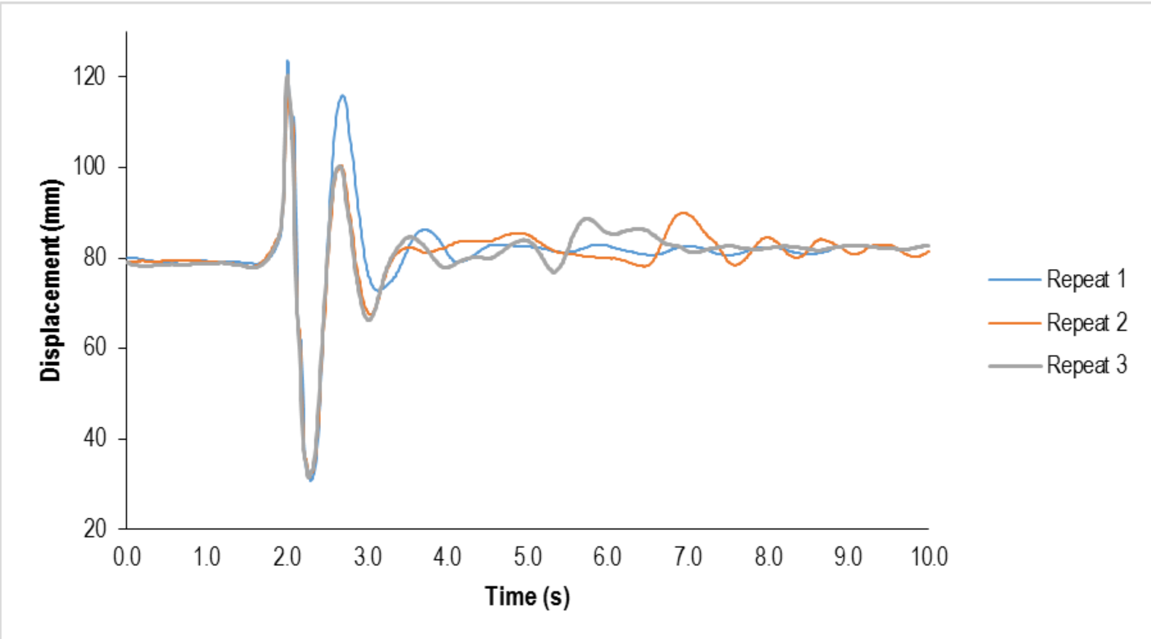
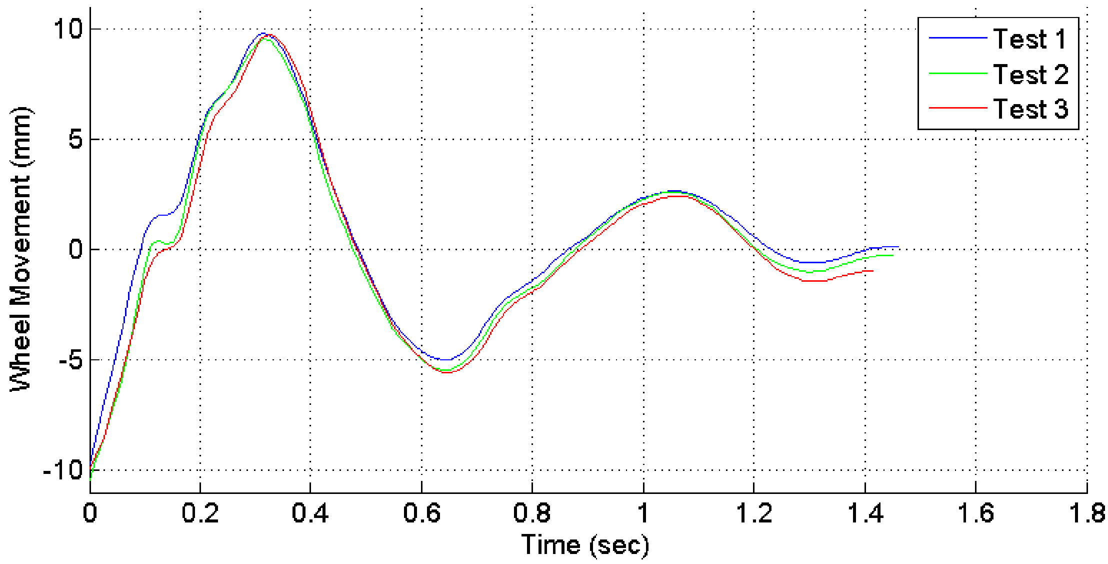


Figure 6.57 shows the data traces for the DynaSsess test with the vehicle with all shock absorbers in place. These results are for the repeat test which was conducted on a flat concrete surface; this test was conducted to replace the earlier test which had been affected by the brakes being applied.

Figure 6.57: FormulaSpec data from DynaSsess test method with all shock absorbers in place (flat road)



A summary of the results is presented in Table 6.24.

Table 6.24: Summary of results: DynaSsess – all shock absorbers in place

Load	Fully laden							
Shock absorbers	All fitted							
Analysis	DynaSsess test method							
Measurement method	DynaSsess				Linear displacement			
Axle	Asphalt		Concrete(3)		Asphalt		Concrete(3)	
	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)		Damping (%)	
					Left	Right	Left	Right
Test 1(1)	23.67	1.161	22.34	1.320	38	18	–	–
Test 2	22.64	1.353	21.82	1.345	20	22	–	–
Test 3	22.37	1.367	22.16	1.331	19	21	–	–
Averaged result(2) (%)	**22.5**		**22.1**		**21**		–	
Frequency (Hz)	**1.36**		**1.33**		**1.28**		–	

1 Brakes were applied prior to second peak which affected results.
2 Averaged result excludes the first test.
3 An additional test was conducted on a flat, level concrete surface; the reference system was not fitted for these tests.

Commentary

The DynaSsess results are reported with a much high accuracy and show excellent repeatability. The results are consistent between the tests conducted on the asphalt and concrete surface, despite the asphalt being an uneven surface with crossfall.

6.3.2 *Repeatability of DynaSsess tests: Fully laden with 1 shock absorber removed*

Figure 6.58 and Figure 6.59 show the data traces for the DynaSsess test with 1 shock absorber removed, for the DynaSsess measurement and analysis method and reference system respectively.

Figure 6.58: FormulaSpec data from DynaSsess test method with 1 shock absorber removed

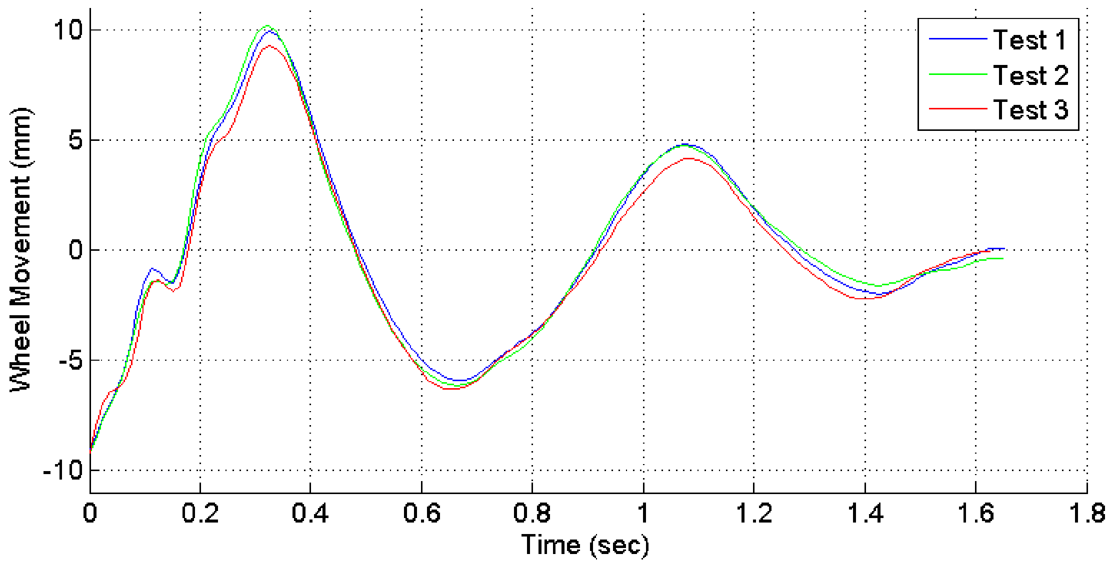
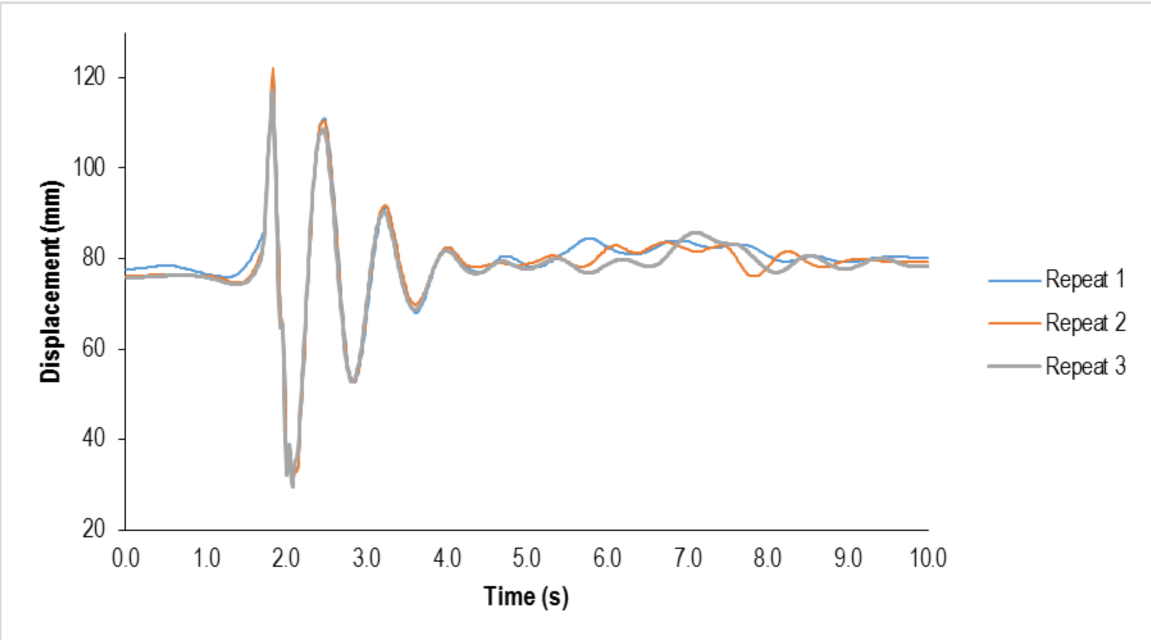


Figure 6.59: Reference system data from DynaSsess test method with 1 shock absorber removed



A summary of the results is presented in Table 6.25.

Table 6.25: Summary of results: DynaSsess – one shock absorber removed

Load	Fully laden			
Shock absorbers	One shock absorber removed			
Analysis	DynaSsess test method			
Measurement method	DynaSsess and reference system			
System	DynaSsess		Reference system (LDT)	
	Damping (%)	Frequency (Hz)	Damping (%)	Frequency(Hz)
Test 1*	13.93	1.297	14	1.25
Test 2	14.84	1.290	14	1.28
Test 3	13.90	1.287	14	1.33
Averaged result	**14.22**	**1.29**	**14**	**1.29**

Commentary

Both the DynaSsess and reference system results indicated a reduction in damping within the expected range after removing one shock absorber.

6.3.3 *Repeatability of DynaSsess tests: Fully laden with all shock absorbers removed*

Figure 6.60 and Figure 6.61 show the data traces for the DynaSsess test with all shock absorbers removed, for the DynaSsess measurement and analysis method and reference system respectively.

Figure 6.60: FormulaSpec data from DynaSsess test method with all shock absorbers removed

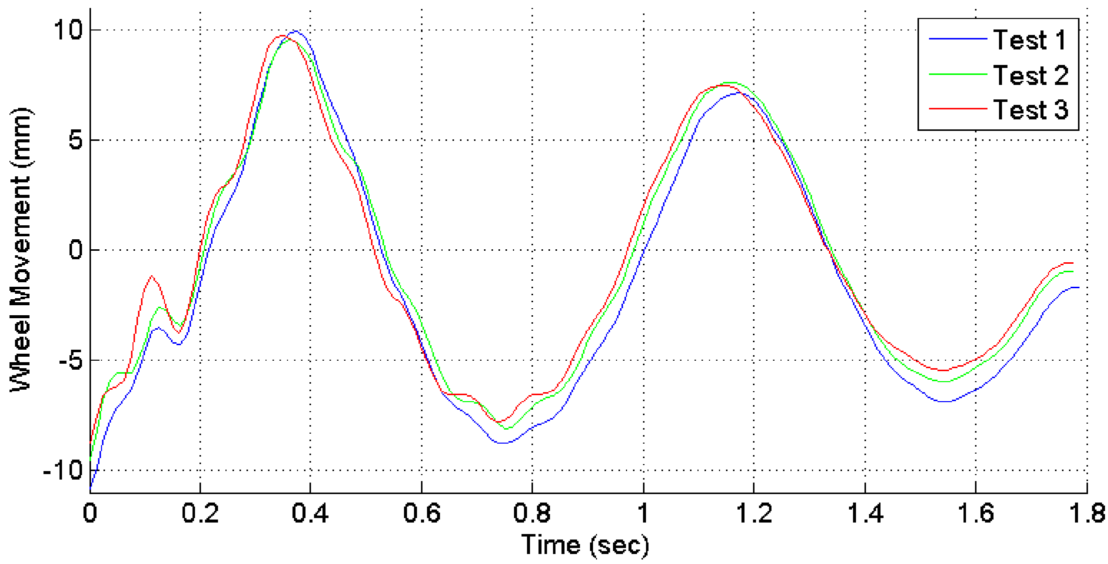
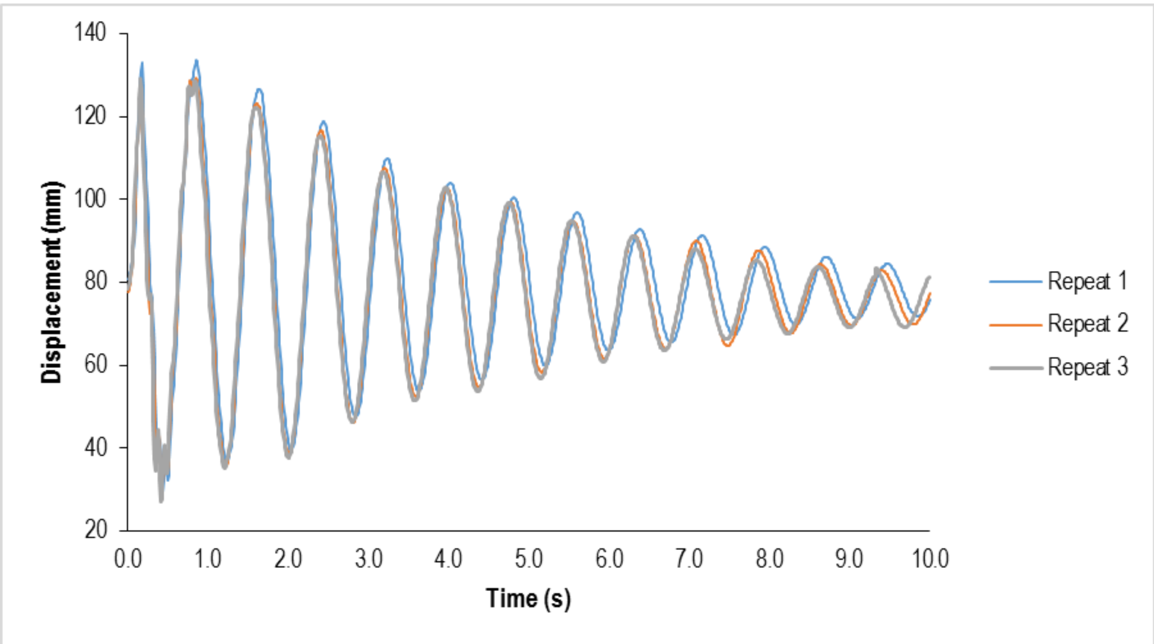


Figure 6.61: Reference system data from DynaSsess test method with all shock absorbers removed



A summary of the results is presented in Table 6.26.

Table 6.26: Summary of results: DynaSsess – all shock absorbers removed

Load	Fully laden			
Shock absorbers	None fitted			
Analysis	DynaSsess test method			
Measurement method	DynaSsess		Reference system (LDT)	
	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)
Test 1	4.50	1.244	2	1.25
Test 2	3.60	1.250	2	1.28
Test 3	4.29	1.252	2	1.28
Averaged result	**4.13**	**1.25**	**2**	**1.27**

Commentary

Both the DynaSsess and reference system results indicated a reduction in damping within the expected range after removing all shock absorbers. The damping results are much lower for the reference system, most likely due to the inaccuracy of the analysis method which bases the frequency on the first two successive peaks, which may not be representative of the system.

A summary of the results for test program 3 is presented in Table 6.27.

Table 6.27: Summary of results: DynaSsess – all tests

Load	Fully laden					
Shock absorbers	All options					
Analysis	DynaSsess test method					
Measurement method	DynaSsess			Reference system (LDT)		
Shock absorbers	All shocks on	One removed	None fitted	All shocks on	One removed	None fitted
Test 1[(1)] - Damping ratio (%)	23.67	13.93	4.50	18	14	0.02
Test 2 - Damping ratio (%)	22.64	14.84	3.60	22	14	0.02
Test 3 - Damping ratio (%)	22.37	13.90	4.29	21	13	0.02
Test 4 - Damping ratio (%)	22.34	–	–	–	–	–
Test 5 - Damping ratio (%)	21.82	–	–	–	–	–
Test 6 - Damping ratio (%)	22.16	–	–	–	–	–
Averaged result (%)	**22.1**	**14.22**	**4.13**	**21**	**0.14**	**0.02**
Standard deviation	**0.30**	**0.53**	**0.47**	**0.71**	**0.58**	**0.0**
Frequency (Hz)	**1.34**	**1.29**	**1.25**	**1.32**	**1.29**	**1.27**

1 Brakes were applied prior to the second peak which the affected results, and so were excluded from the average.

6.3.4 *Repeatability of VSB11 tests: Fully laden with all shock absorbers fitted*

Figure 6.62 and Figure 6.63 show the data traces for the VSB11 ramp test with all shock absorbers in place, for the DynaSsess measurement and analysis method and reference system respectively.

Figure 6.62: FormulaSpec data from VSB11 ramp test method with all shock absorbers in place

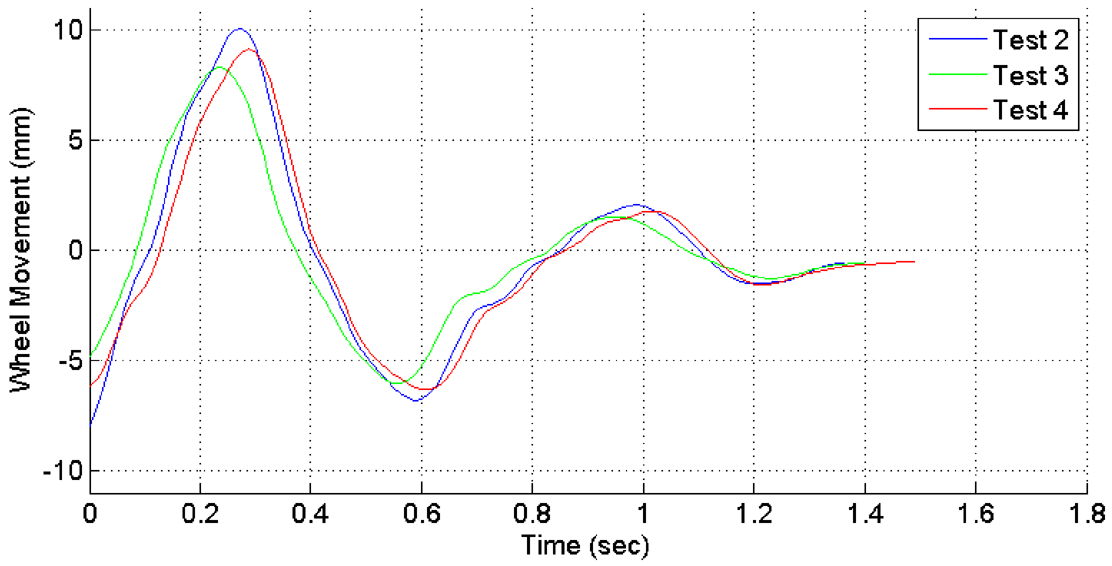
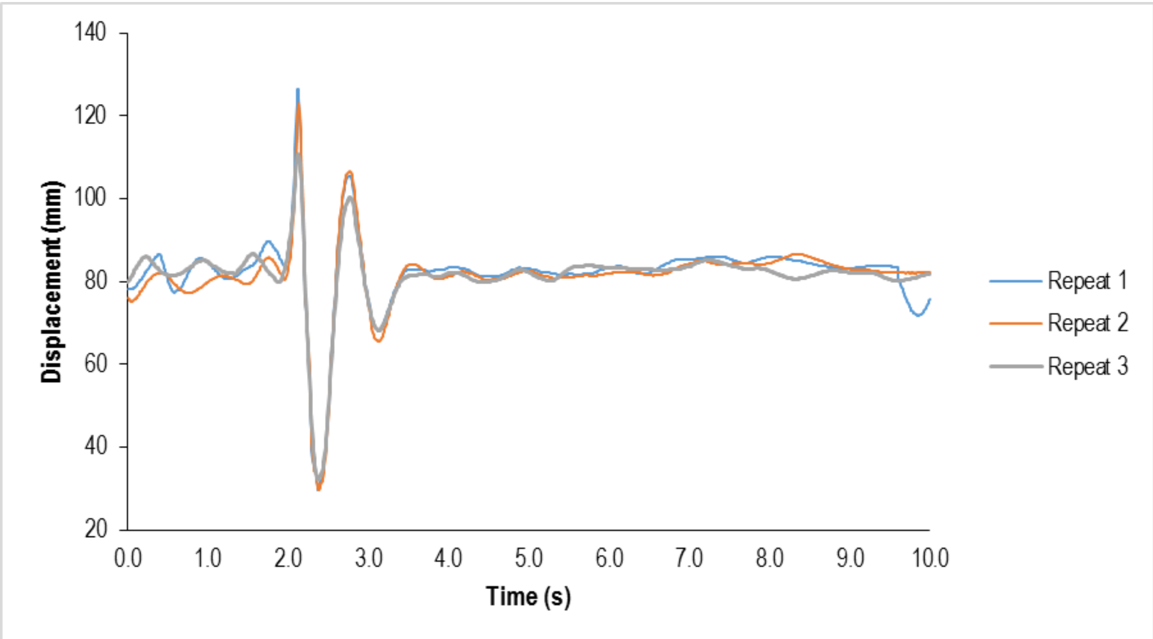


Figure 6.63: Reference system data from VSB11 ramp test method with all shock absorbers in place



6.3.5 *Repeatability of VSB11 tests: Fully laden with 1 shock absorber removed*

Figure 6.64 and Figure 6.65 show the data traces for the VSB11 ramp test with one shock absorber removed, for the DynaSsess measurement and analysis method and reference system respectively.

Figure 6.64: FormulaSpec data from VSB11 ramp test method with 1 shock absorber removed

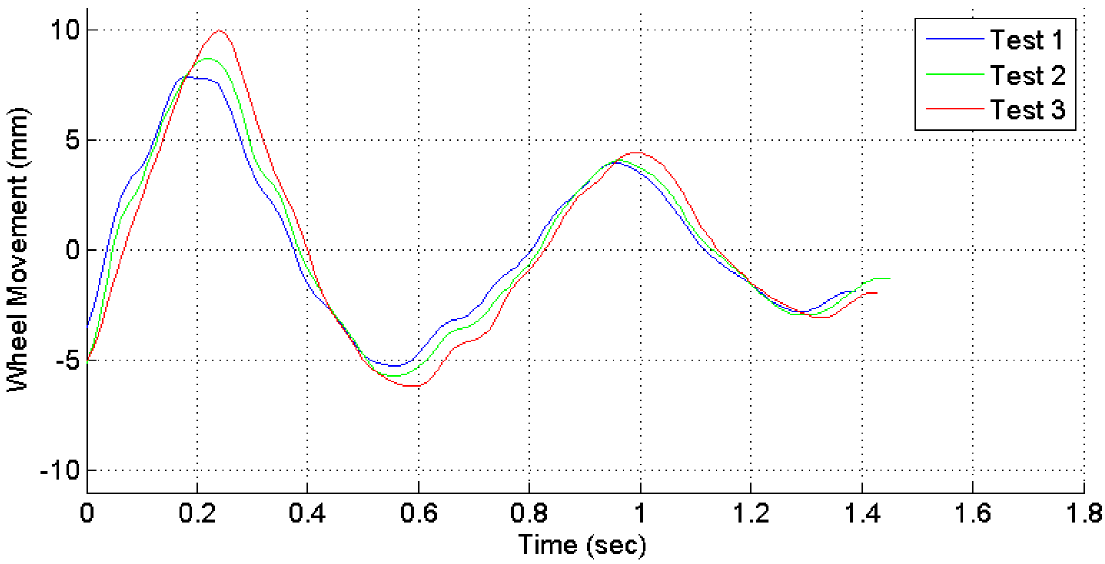
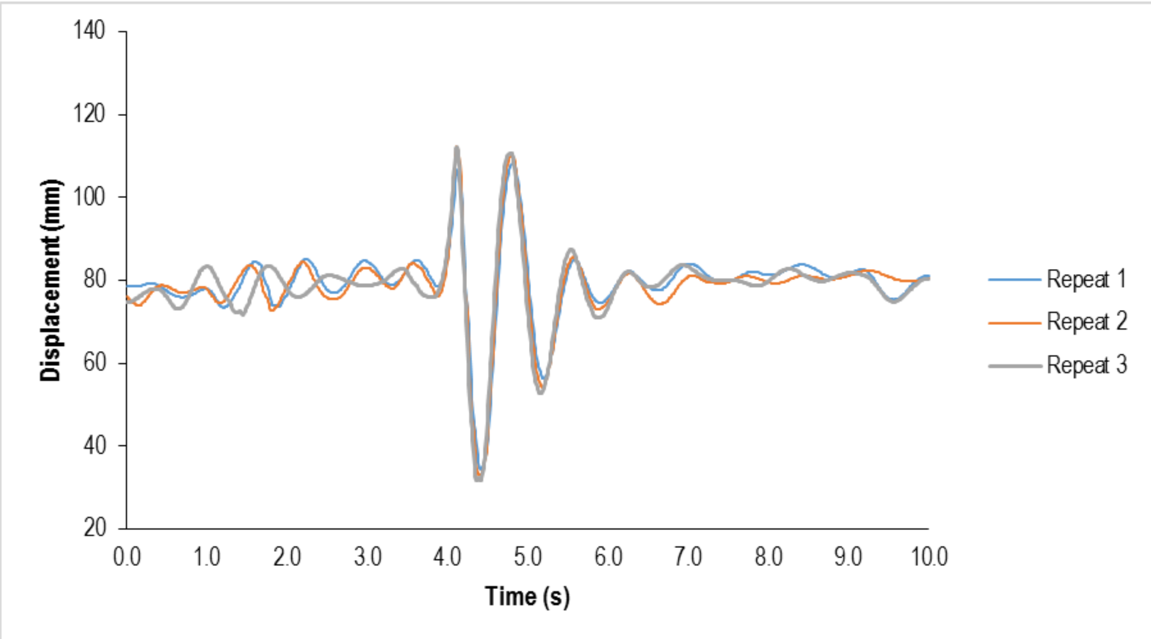


Figure 6.65: Reference system data from VSB11 ramp test method with 1 shock absorber removed



6.3.6 *Repeatability of VSB11 tests: Fully laden with all shock absorbers removed*

Figure 6.62 and Figure 6.67 show the data traces for the VSB11 ramp test with all shock absorbers removed, for the DynaSsess measurement and analysis method and reference system respectively.

Figure 6.66: DynaSsess system data from VSB11 ramp test method with all shock absorbers removed

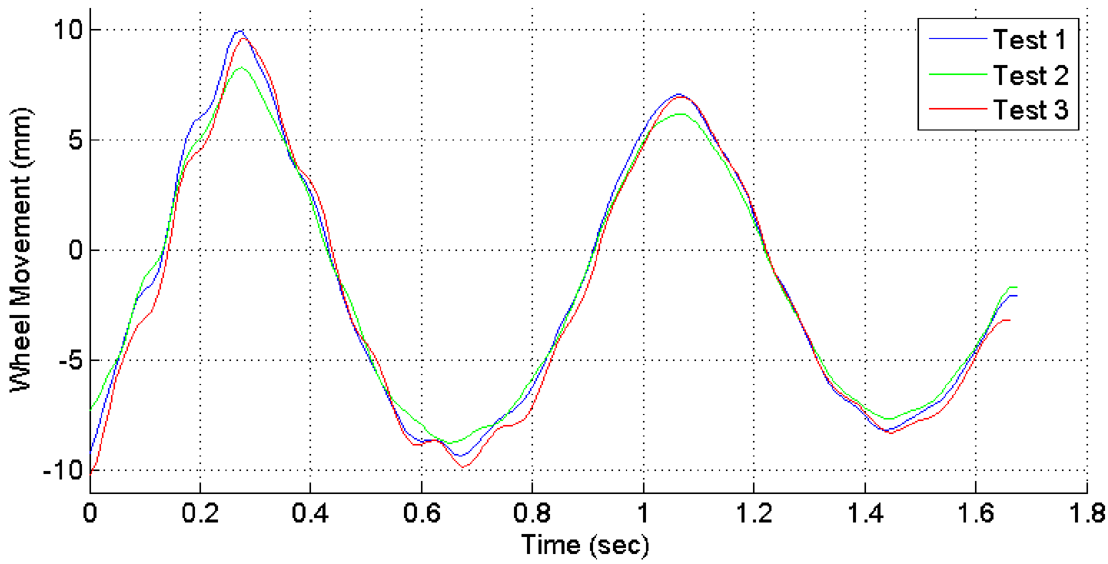
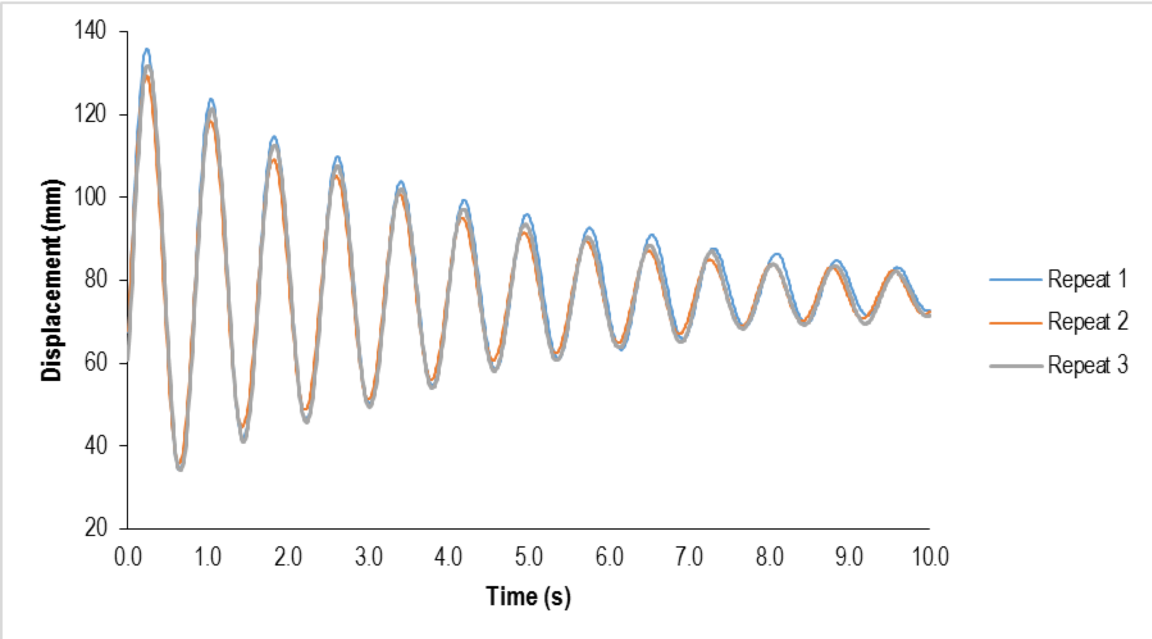


Figure 6.67: Reference system data from VSB11 ramp test method with all shock absorbers removed



A summary of the results is presented in Table 6.28.

Table 6.28: Summary of results: DynaSsess – all tests

Load	Fully laden					
Shock absorbers	All options					
Analysis	VSB11 test method					
Measurement method	DynaSsess			Reference system (LDT)		
	All shocks on	One removed	None fitted	All shocks on	One removed	None fitted
Test 1[(1)] – Damping ratio (%)	22.00	13.27	4.37	20	11	4
Test 2[(1)] – Damping ratio (%)	23.16	13.80	3.83	19	9	4
Test 3 – Damping ratio (%)	21.82	13.80	4.33	20	9	4
Averaged result (%)	**22.44**	**13.62**	**4.18**	**20**	**10**	**4**
Standard deviation	**0.73**	**0.31**	**0.31**	**0.58**	**1.15**	**0.0**
Frequency (Hz)	**1.368**	**1.361**	**1.281**	**1.32**	**1.31**	**1.27**

1 Left wheel was driven off the edge of the ramp.

Commentary

The results obtained from test system 3 using the VSB11 ramps were very similar to those when using the DynaSsess blocks, 22.50% compared with 22.44% for all shockers, 14.22% compared with 13.62% for 1 shock absorber, and 4.13% compared with 4.18% for no shock absorbers. This confirmed the repeatability of test 3 but also may be a reflection of the tests themselves being more repeatable because they were conducted with a 4x2 vehicle, with only a single axle compared to the tandem and triaxle groups in test programs 1 and 2. The reference system showed considerable variation in results particularly for the low-damping tests with results of 14%–10% and 2%–4%.

7 FINDINGS

The findings are based on the results of the field tests and presented by reviewing each system's performance in the three assessment requirements:

- excitation
- measurement
- analysis.

7.1 Review of excitation methods

Rolling 80 mm step method (VSB11 method)

This method generates an impulse as the wheel rolls off the step and drops to the ground. The VSB11 ramps were used as part of test programs 1 and 3. There are various issues associated with the technical accuracy of this method, however, the ramps proved to be suitable for testing a suspension comprising only a single axle.

Primarily, as the tyre rolls off the step, the tyre can envelop the edge profile of the 'corner' of the step, which softens and spreads the shape of the impulse. In an effort to address this, a forward speed of 5 km/h is prescribed to ensure the impulse occurs sufficiently to excite all relevant suspension modes. The practical issues that need to be managed are:

- achieving the prescribed speed (without pre-excitation of the suspension)
- removing steps to measure the response of a multi-axle suspension.

Additionally, a test of this nature inherently creates two impulses, the first occurring as the tyre drops off the step, the second as the tyre impacts with the ground. These impulses can overlap due to tyre envelopment, affecting suspension response, and rendering analysis difficult. Evidence of this was noticeable in the test results causing error in the measurement.

A practical issue with the step test is ensuring the simultaneous application of all impulses (i.e. all wheels fall off the step at the same instant). If this does not occur, other (asymmetric) modes may be excited and analysis is complicated. As shown in Figure 7.1, to achieve this the vehicle must be positioned on sets of blocks. In this case, and any situations when more than a single axle is tested, the front set of blocks must be moved immediately after the wheels roll off so the rear axle does not also run over them. This is considered to present a health and safety issue. This method was employed during the testing program and required four staff to be positioned by the blocks to remove them manually by pulling them away from the vehicle by ropes attached to each block. This method was acceptable to complete the testing, however, is not considered suitable as a repeatable method as part of roadside vehicle inspection and enforcement. It should also be noted that on several occasions the blocks were unable to be removed prior to the vehicle rolling into the leading block and interfering with the test results.

Figure 7.1: Demonstrating practical issues with the step method during test program 3

The vehicle should be travelling at 5 km/h when it falls off the step, which is not possible from a standing start, nor is it possible to have a 'run-up' as the disturbance created as the wheels mount the steps invalidates the response. For these reasons the VSB11 ramps are not considered to be suitable excitation method for in-service testing. The variability in the test results (due to small differences in the position of the blocks between tests) confirms this finding.

Open-road 'pothole' method (Test system 1)

The open-road pothole method has been proposed as a possible excitation method based on work presented in Davis (2010), in which it is described as the 'white noisy road test'. This work presented dynamic pavement forces according to the range of roughness values encountered during testing along the test section of road. The report stated that the mean and standard deviation of heavy vehicle wheel forces did not correlate with pavement roughness, however peak wheel forces did. This method offers great potential and would be ideal for utilising the existing on-board technologies currently fitted to vehicles. It would also allow for data to be logged during a journey and uploaded to a remote server for review at any time. This offers many advantages, most importantly eliminating the need to conduct roadside inspections. This method of excitation was assessed during test program 2, purely from the perspective of its suitability to excite the suspension and measure damping and frequency. Despite the findings of Davis (2010) the theory is that a profile of ordinary paved roads can suitably provide an impulse into suspension systems, as it is argued that the road profile contains sufficient variation to excite suspension modes. This study focused on locating road sections that would impart a single impulse that could produce a repeatable response from the suspension.

The test results showed that this method does not provide a single impulse necessary to excite the relevant modes as required by VSB11, and therefore is not considered suitable to generate results comparable with a VSB11-styled impulse delivery. Additionally, following the impulse delivery, the vehicle will continue at speed along the road surface. The road surface varies substantially in long and short wavelength roughness, and in wheel paths. The result of this is that the suspension continues to receive impulses introducing other effects such as body pitch and roll, making analysis difficult.

The data logged during on-road testing proved that this method did not provide a single impulse sufficient to excite the natural frequency followed by a period of time free from interference such that the damping of the suspension could be measured.

Pipe test (Test system 1)

The aim of the pipe test is to address the deficiency of on-road testing discussed above. The intention is that the 48 mm pipe provides an impulse and it is located on a smooth road surface such that the suspension is free from interference.

The pipe test generates an impulse by driving the vehicle over a rigid steel pipe of nominal outer diameter of 58 mm.

The vehicle is driven over the pipe in a direction perpendicular to the pipe's longitudinal axis, at low speed. The pipe test was evaluated during test program 2 at speeds between 3 and 5 km/h. Initially tests were conducted at 20 km/h as per the procedure for test system 1. The theory was that the higher the speed, the greater the force resulting in a higher peak in air pressure within the suspension system. Results presented in Section 6.1 showed that a speed of 20 km/h was not an effective method for exciting the suspension. The speed was reduced for subsequent tests and the earlier tests were also repeated at the lower speed. The lower speed produced much better results, as the suspension was able to be excited at the natural frequency of the suspension. During some tests the driver was not able to maintain a steady speed. Variations in speed of approximately 3–4 km/h from the target speed affected the results significantly. The target speed will vary between vehicles based on axle spacing. Although axle spacing does not vary greatly between suspension models it does need to be considered during testing and controlled precisely. It is expected that during roadside inspections the driver of the vehicle will be responsible for maintaining the target speed; this is an important variable that must be controlled.

The impulse this method generates has a considerably different magnitude to that generated by the step method. This difference results in underestimating the damping performance of the suspension system and invalidates this method as a direct means of evaluating suspension properties with respect to VSB11. However, this method maybe be sufficient to detect a significant degradation in performance that does not require high accuracy or direct comparison with VSb11 compliance. Further analysis is required to confirm this finding.

RFSA (Test system 2)

The 'road-friendly suspension analyser' (RFSA) excites the vehicle by raising the vehicle by 80 mm then suddenly dropping the platform on which the vehicle is positioned. The RFSA comprises separate test beds which individually support the axles of an axle group. A vehicle is driven onto the test beds and then raised to a height of 80 mm via a pneumatic system. On command from a control unit, air is exhausted from the pneumatic system, which instantaneously drops the raised vehicle.

The drop test method aims to eliminate tyre enveloping problems; however, the drop process occurs over a finite time, so the impulse may be spread and softened. Two concerns raised earlier regarding the step method (the creation of two impulses and achieving a simultaneous drop across all axles) is also relevant to this system. It is desirable for a drop test mechanism to drop the vehicle at acceleration equal to gravity to minimise the drop time, and ensure a repeatable and consistent test method; however, this is not easily achieved. A load distribution of the vehicle can affect the drop as the vehicle may pitch or roll depending on whether the vehicle load is biased to the front or rear or left or right.

The practical advantage of the drop test method is that the vehicle is raised from contact points common to all vehicles – the tyres. However, this requires that the vehicle is driven onto the rig and positioned accurately on the load plates; this poses four major disadvantages. Firstly, there must be suitable clearance between the vehicle and rig; some vehicles with underslung suspensions are not suitable for use with this rig. The driver must position the vehicle precisely on the load plates within 10–20 mm. This often takes even an experienced driver a number of attempts to perfect. Once the vehicle is in position the brakes must be released, as the tests conducted with the brakes applied are affected as the axle is not free to oscillate around the suspension pivot points.

When used for VSB11 certification these problems are negated somewhat, as the driver is experienced with the method, however, for roadside enforcement it is not expected that the drivers would be skilled at positioning the vehicle accurately and releasing and applying the brakes when required. This system is used frequently by ARRB engineers to conduct RFS certification tests and based on this experience the results obtained during this test program were proven to be highly repeatable due to the even load distribution of the vehicle and the care taken to position the vehicle’s payload. This is not always the case and this level of repeatability cannot be expected when testing vehicles in-service.

The position of the rigs must be adjusted to suit variations in axle spacing and wheel bases. Each individual rig must be moved into the correct position; with each platform weighing approximately 800 kg, this requires a forklift. The RFSA can be modified to address these practical limitations but in its current design it is impracticable for use as an in-service excitation method.

Test system 3

The excitation method used for test system 3 is similar to the VSB11 ramps, and is based on providing an impulse by having the vehicle driven over a ramp and dropping it off a fixed height sufficient to excite the resonant frequency of the suspension.

An advantage of the DynaSsess blocks is that they are positioned in front of the axle once the vehicle is stopped. This reduces the effects of drive errors associated with aligning the tyres with the ramps and maintains a correct and steady speed. Tests were conducted with a single axle only; testing with a tandem and triaxle group is necessary to confirm if this method reduces the errors associated with the axles not falling simultaneously.

7.1.1 *Summary of findings – excitation methods*

The excitation method using VSB11 ramps proved to be suitable for single axles, but when used for more than one axle this method suffered from errors associated with impulses being out of synchronisation. The practicality of this method was the major limitation as it required the driver to position the vehicle on top of the ramps, and for those ramps to be pulled from underneath the vehicle as the axles rolled off and prior to the following axle striking it. This proved a difficult task and is considered to make it infeasible as an in-service compliance test method.

The RFSA proved to be reliable in test program 2 producing highly repeated drops of the entire vehicle, in what was a highly controlled test environment. Based on ARRB’s experience testing a number of different vehicles using this system, it is not expected that this level of repeatability will be achievable when used to test in-service compliance. The current design of the RFSA requires careful positioning, as was the case with the VSB11 ramps, these practical issues are considered to be prohibitive to successful implementation as an in-service test method.

It should be noted that all VSB11 certifications have been completed using either the VSB11 ramps, the RFSA or chassis pull-up/pull-down methods contributing to the variability of the certification results. Despite the chassis pull-up/pull-down methods being permitted under VSB11, these were not included in this study based on the findings of a review of in-service test methods

National Transport Commission (2008) which rated the practicality of these methods as very low and unsuitable as options for testing vehicles in-service in a roadside environment.

The test methods conducted at higher speeds (5 km/h or greater) such as the pipe test and on-road test offer a much more practical option for in-service testing. The results obtained from these methods varied with speed, reducing the reliability such that they could not be relied upon unless the speed was managed to suit each vehicle. Test method 3 involving individual ramps was designed to address the practical issues described above. The results for this method were shown to be the most repeatable but were only conducted using a single-axle suspension. Tests involving a tandem and triaxle suspension are required to confirm its suitability for these systems.

7.2 Review of measurement methods

Air pressure sensors

Air pressure sensors were used as part of the reference measure system and fitted to the triaxle semi-trailer (test vehicle 1). Six pressure sensors were fitted to the triaxle to measure the variations in pressure due to roll (left and right) and pitch (between fore and aft axles). The analysis showed that there were small variations between the left and right side of the vehicle. This was due to body roll. The analysis method must consider this effect and compensate for it by summing the signals from both sides. This is discussed further in Section 7.3. Pitching can affect the results significantly and must be compensated for. Comparisons between the pressure on the front and rear axles showed a significant difference in shape and magnitude. The damping calculated using the front, middle and rear axles ranged between 9 and 12%. For a triaxle suspension it is sufficient to measure the air pressure of the middle axle only as the suspension will typically pitched about the middle axle. The analysis of the triaxle suspension presented in Section 6.1 confirmed this assumption and as such all results were based on data from the middle axle. However, the variation between the front and rear axles was not as great as expected, for example the test results with medium-damping shock absorbers were 10%, 11% and 13% for the front, middle and rear axles respectively. The difference between axles was more significant when using vertical displacement. This is discussed further in the following section.

Linear displacement transducers

Linear displacement transducers are the measurement sensors required by VSB11. Linear displacement sensors are fitted between the chassis and the axle and measure the vertical displacement of the axle (relative to the body) as the suspension compresses and extends during a test. The total vertical displacement (peak extension to peak compression) is typically in the vicinity of 40 mm during a VSB11 ramp test and 20 mm for a pipe test at low speed. As with measuring suspension performance via pressure sensors it is necessary to compensate for roll and pitch. Six sensors were fitted to the triaxle. The difference between axles was more significant; further analysis is required to understand the reason for this, but it may be a consequence of the slow response time in the air bags compared with the linear displacement sensors. The damping results calculated using the front, middle and rear axles with medium-damping shock absorbers were 4%, 9%, and 13% for the front, middle and rear axles respectively. For the results obtained from the VSB11 ramp tests the damping ratio calculated using the linear displacement sensors was less than the result obtained from air pressure sensors. This trend was observed consistently across all tests, conversely for the results obtained from the pipe test method. Further analysis of results is required to understand this outcome, however, it is expected to be a consequence of the restricted air flow within the air suspension, resulting in a less responsive data trace. The linear displacement transducers also contain a latency associated with their design, which effectively acts as a mechanical low pass filter, by not being responsive enough to register high-frequency inputs. The differences between both sensors are comparable and both air pressure sensors and linear displacement transducers are able to be used to measure both damping and frequency, assuming they are fitted correctly and the data obtained from them is analysed correctly.

Test system 1

Test system 1 typically utilises two air pressure sensors to measure the response of the suspension. This system will include the effects of using air pressure sensors (discussed earlier) particularly latency in signal response. The position of the sensor in relation to its proximity to the air bag may affect the accuracy of the signal as long air hoses will restrict air flow and act as pneumatic means of filtering the signal response – further analysis of the data is required to quantify this effect. The system includes the ability to measure the weight of the axle group which is a key for obtaining a valid confirmation if this is effective. Analysis has shown that tests performed below the 5% weight tolerance will invalidate the result. As this system is based on an on-board scale once the system has been calibrated it can determine the weight on the axle group and identify if the test weight is within tolerance.

The system also includes a GPS receiver and has the ability to provide the location and speed, this information could be utilised to dismiss tests in which the conditions were not suitable. It is understood that the current software discards tests at low speeds to eliminate reporting events during loading and unloading.

The data reviewed as report of this report only included two tests from the system provided; it is expected in the next work program that more test results can be analysed. This system uses air pressure sensors as the measurement device, as does the reference system, therefore the findings (listed above) for air pressure sensors are applicable to this system. Air pressure sensors were proven to be less responsive and not contain all modes of frequency present in the suspension, but nonetheless are comparable to results obtained by LDTs and therefore capable of measuring damping and frequency. The limitation of test system 1 is to identify that the input is consistent for either pipe tests or on-road tests. The current system is unable to determine if a change in damping is due to a change in the excitation method or due to a degradation in the suspension system.

Test system 2

As discussed in the previous section, the excitation method employed by the RFSA which is to lift and drop the entire vehicle has some practical issues that render the rig in its current state unsuitable for roadside enforcement. However, if these practical issues can be overcome, particularly those associated with lifting and dropping the vehicle without generating pitching or rolling modes, then the data trace generated from this method is the least effected by interference; for the tests involving the same vehicle with the same load (as was the case for this test program) this is the most repeatable of all the test methods. This measurement system includes axle hop (unlike APTs and LDTs) and this must be compensated for during the analysis process. The ability to measure axle hop is an improvement over the other measurement methods, as was the intention. The other measurement methods using APTs and LDTs fail to measure axle hop, unintentionally due either to mechanical filtering in the sensor or other limitations that prevent the high frequency signals to be measured. A system that measures axle hop is considered more accurate. Axle hop should be removed, to allow the suspension response to be analysed; axle hop can be removed easily with filtering or other analysis techniques. In the case of an analysis method that does not remove axle hope, the consequence can be worse than not measuring it all, resulting in significant errors.

Test system 3

The measurement method employed by test system 3 requires two sensors to be temporarily fitted to the wheel hubs on both sides of the vehicle, which are then removed at the completion of the test. The sensors used as part of this system were not disclosed to protect the intellectual property of the system owner. Post-processed data was provided to ARRB for review from which conclusions could be drawn. The measurement system included axle hop and the results were shown to be accurate and repeatable. The tests were only based on a single-axle suspension which is expected to be the simplest vehicle type to test for road friendliness. Tests involving a tandem and triaxle suspension are warranted to better understand the capability of this system.

7.2.1 *Summary of findings – measurement methods*

The measurement methods assessed included air pressure sensors, linear displacement transducers and load cells. The measurement method used as part of test system 3 was not disclosed to ARRB. All systems were proven to be suitable and at least equivalent to the approved VSB11 methods. The RFSA and DynaSsess methods measured axle hop which is considered to be an improvement in accuracy, but must be resolved during the analysis.

7.3 Review of analysis methods

The analysis method is considered a critical step in ensuring the correct assessment of the suspension. The analysis method required by VSB11 was followed to analyse all test data. To calculate the damping ratio, the first largest peak (A1) and the following peak (A2) were identified in the dataset by determining the changes in the slope of the line implied by the data. The peaks were then subtracted from a baseline value which was calculated by taking an average pressure or displacement of the time when the oscillations have settled down. In cases where the oscillations continued to occur for an extended period of time due to poor damping, the baseline value was selected before oscillations began.

The following equation was then applied to calculate the damping ratio:

$$Damping\ ratio = \frac{1}{2\pi}\ln\frac{A1}{A2} \tag{3}$$

where

A1 = peak amplitude of the first cycle of oscillation

A2 = peak amplitude of the second cycle of oscillation.

The frequency was calculated by taking the time when the first largest peak (T1) occurred and the time when the following peak (T2) occurred. The following equation was then applied to calculate the frequency:

$$Frequency = \frac{1}{(T2 - T1)} \tag{4}$$

where

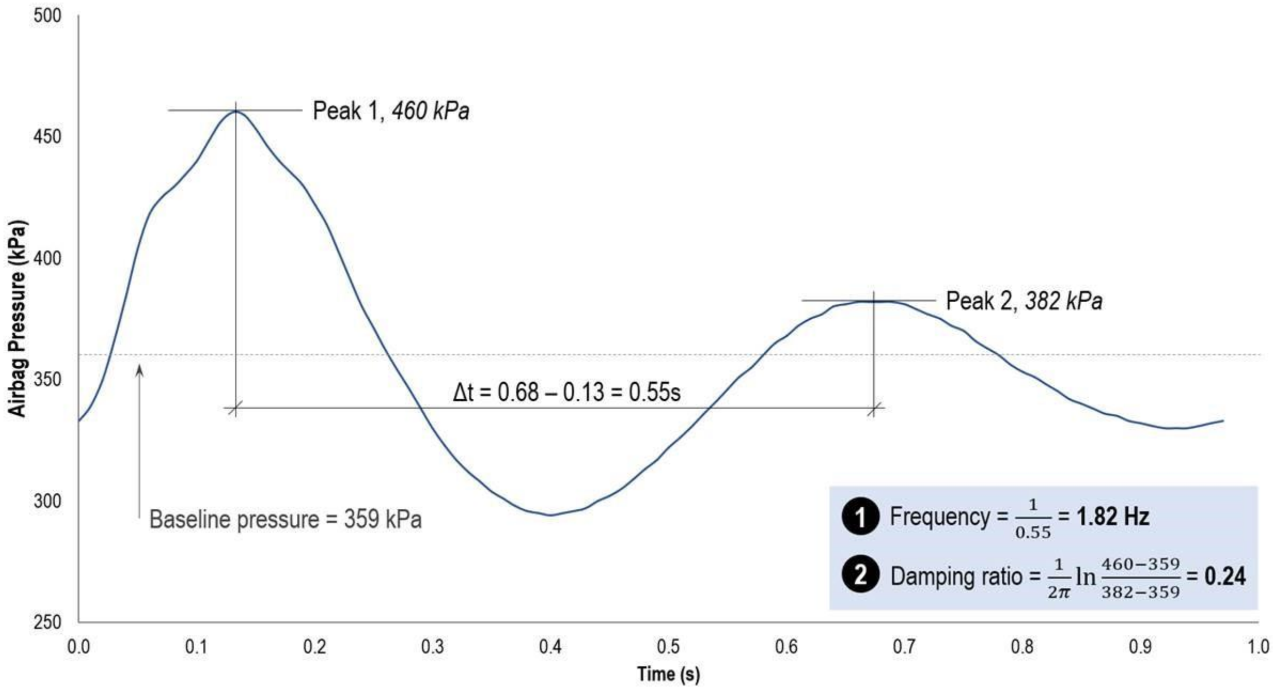
T1 = time at which peak amplitude of the first cycle of oscillation occurs

T2 = time at which peak amplitude of the second cycle of oscillation occurs.

Manual selection of two consecutive points (VSB11)

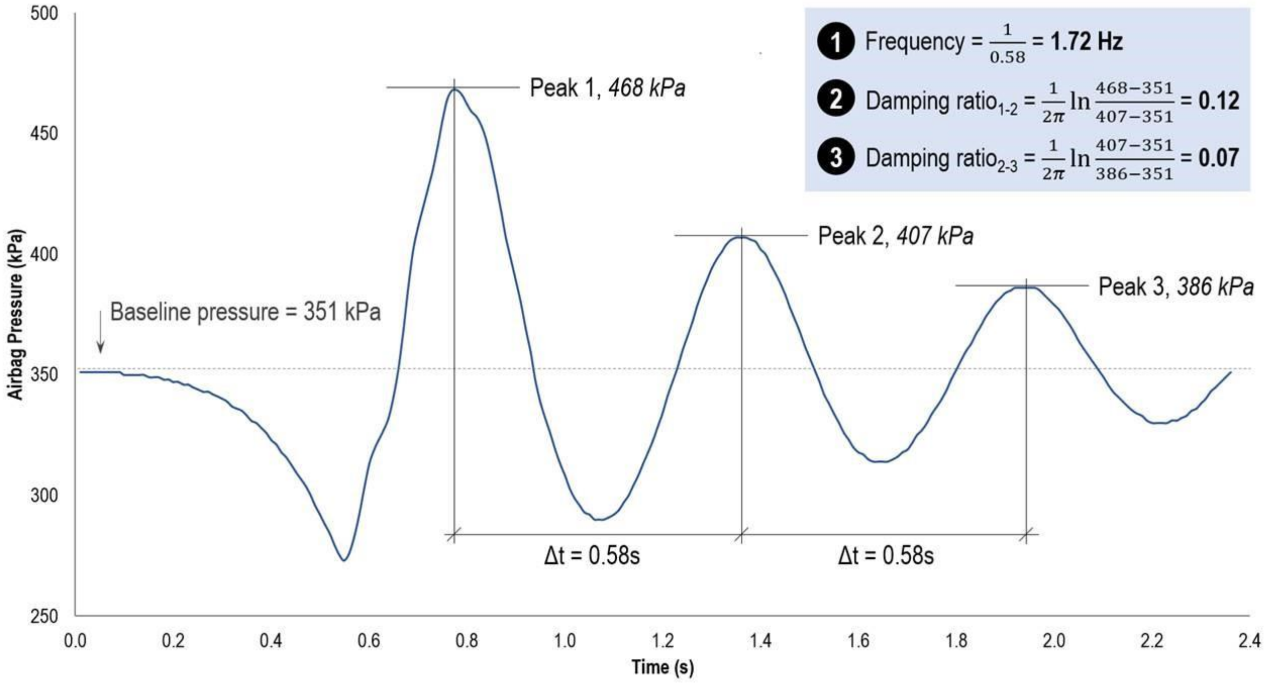
As described above, the method for calculating the damping ratio as per VSB11 is to identify two successive peaks. This process is demonstrated in Figure 7.2. In this example Peak 1 (460 kPa) is the first peak in magnitude upon compression after dropping off the 80 mm step, Peak 2 (382 kPa) is the next peak. A baseline value of 359 kPa has been determined for this test. The baseline represents no suspension deflection and the point at which the suspension oscillates. Using these values, the damping ratio is 24% and based on the time at which these two peaks occur the frequency is 1.82 Hz. This method was used to assess all reference system data and the data obtained from test system 2 as the RFSA does not include its own analysis method.

Figure 7.2: Example of calculating damping ratio using successive points



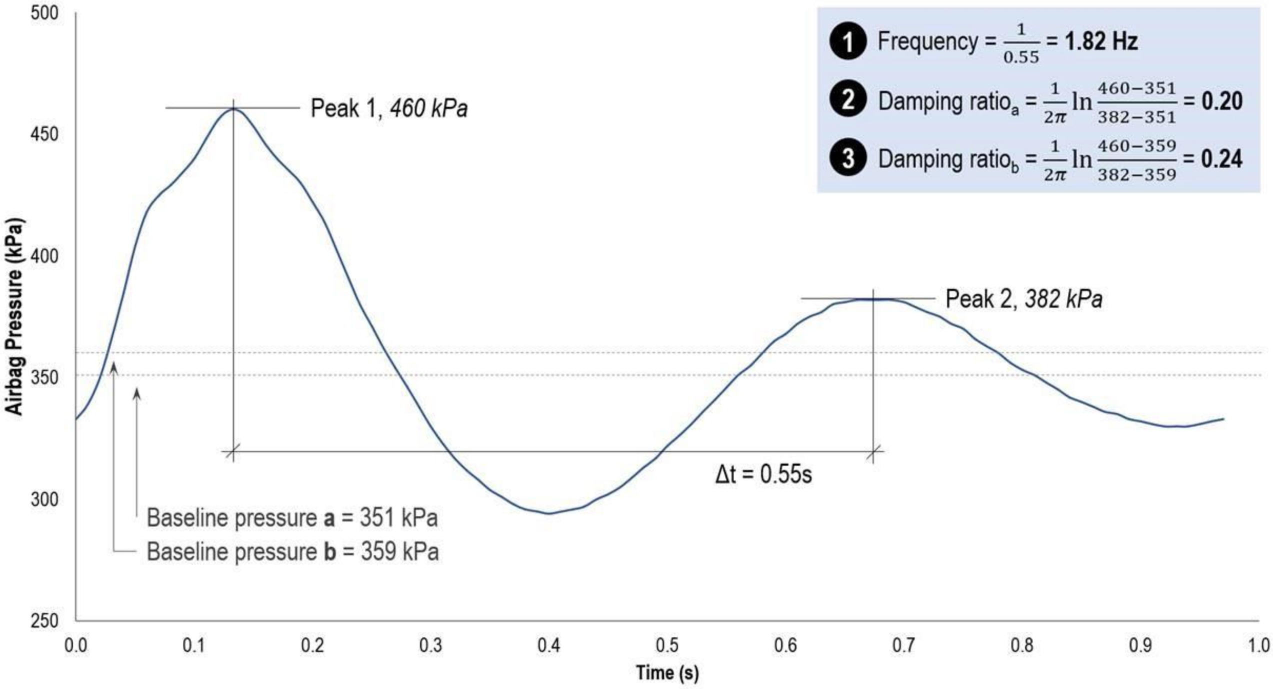
This means that the selection of which two peaks to use for the calculation is open to the interpretation of the user. The user is able to select any two successive peaks to calculate damping. This method produces consistent results only if every peak declines at the same rate from the first to the last. This is not the case for a number or reasons; it is the responsibility of the user to select two points that best represent the response of the suspension and to use the two points consistently across all tests. The selection of peaks can result in significant differences in damping ratio. Figure 7.3 shows an example data trace from test program 1 and the difference in results if the first and second peaks are used, compared with second and third peaks. The damping was calculated to be 12% or 7% depending on which peak is selected, whereas the frequency does not change.

Figure 7.3: Variation in damping due to selection of peaks



The other important step in analysing the data is to select the baseline value. It can be difficult to determine the true baseline value, particularly if the axles in the suspension group settle at different positions following the test. Figure 7.4 shows the variation in damping when using different baseline values. This example based on data from test program 1 shows a damping ratio of 20% or 24% depending on which value is used.

Figure 7.4: Variation in damping due to selection of baseline value



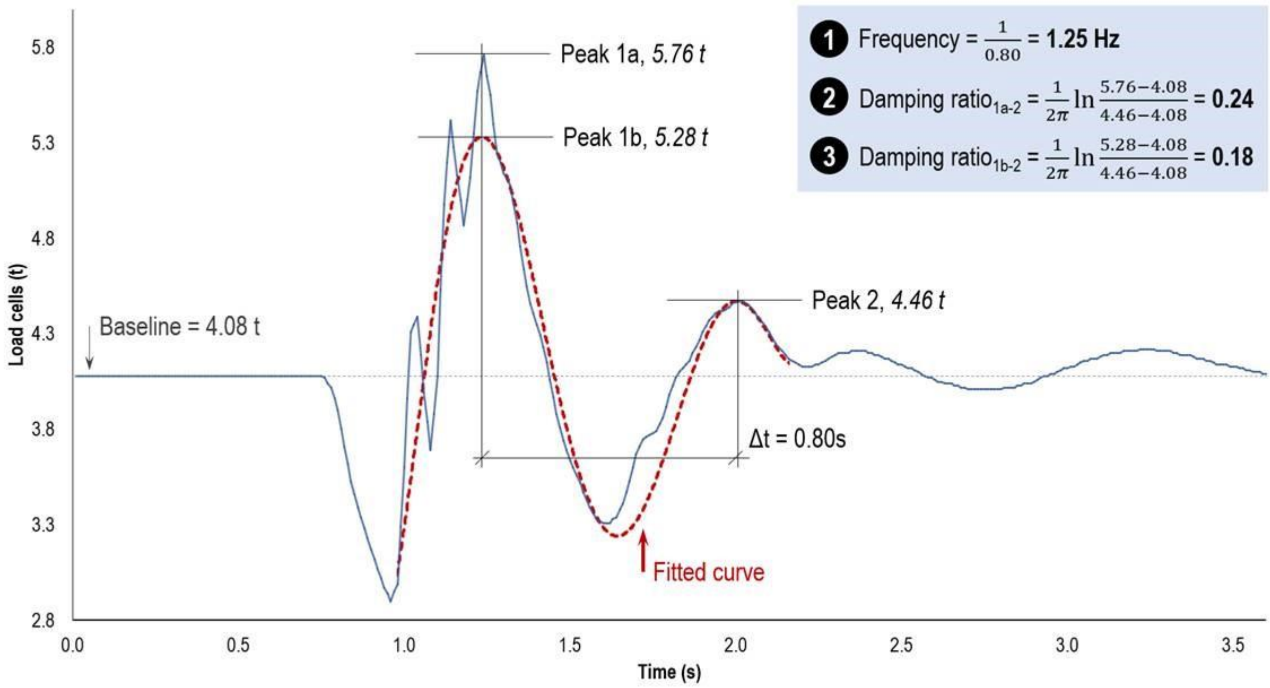
Test system 1

The results produced by this system were if not identical very similar to the reference system, which used the same sensor type and the VSB11 analysis. The analysis method for test system 2 is proprietary and was unable to be reviewed in detail, but based on the similarity of the results it is likely that the analysis method was VSB11 or a similar method that produced acceptable results. This system also employs additional analysis features, including the ability to identify peaks and to discard data below a certain speed threshold.

Test system 2

Test system 2 did not include an analysis method. The VSB11 method was used to analyse this data. Applying this method resulted in errors, as the data from the RFSA included the effects of axle hop that were correctly resolved by this method. Figure 7.5 shows an example of the variation possible due to axle hop if not resolved correctly during analysis. The data trace used in this example is from test program 2 which includes axle hop. The axle hop is present throughout the first oscillation; immediately after the drop is complete and the vehicle is bouncing on its tyres. This dissipates more quickly than the suspension oscillations so it is no longer present on the subsequent oscillations, the consequence is that if the maximum value is taken (5.76 t in this example) then this will overestimate the damping. If the effect of axle hop is not correctly resolved the damping is calculated to be 24% which is significantly higher than the correct damping value for this suspension of 18%.

Figure 7.5: Example of calculation with and without resolving axle hop



Test system 3

A different approach to data analysis has been employed by test system 3. Rather than allowing the user to select points and a baseline for input into a formula, the analysis method employs a multi-body dynamic model which represents the various modes of suspension behaviour, which can include axle hop, roll and bounce. This model is fitted to the measured test data. The resulting coefficient values are then able to be converted into sprung mass frequency (F) and mean damping ratio (DM). This approach was employed to specifically address the errors associated with user selection of points. This method can then be an automated process, in which the software will return the frequency and damping and either a pass or fail, depending on the results.

7.3.1 *Summary of findings – analysis methods*

The VSB11-approved analysis method requires two successive peaks and a baseline value to be manually selected. This can result in errors and inconsistencies based on the selection made. These errors are more likely to occur if the measured data includes axle hop, roll and pitch. These can be overcome by selecting the correct points and applying analysis techniques to resolve these effects. The test results, particularly for test program 2 which included axle hop, showed significant variation due to errors in the analysis method. The analysis method using a multi-body model was shown to produce the most consistent results.

An analysis method that applies a consistent method and that can resolve the effects of roll, pitch and axle hop and that is preferably automated thus eliminating the chance of human error is strongly recommended for an in-service compliance test.

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