NACOE
NATIONAL ASSET CENTRE OF EXCELLENCE

FINAL REPORT

Project Title: R34 - Evaluation of In-Service Compliance for Road Friendly Suspensions using Emerging Technologies (2016/17)

Project No: PRS16111

Author/s: Anthony Germanchev & Philip Roper

Client: Queensland Department of Transport and Main Roads

Date: November 2017

AN INITIATIVE BY:
arrb GROUP
Queensland Government

SUMMARY

Heavy vehicles fitted with road-friendly suspensions (RFS) are permitted to operate on select routes at higher mass limits (HML). This productivity benefit is afforded on the basis that an approved RFS causes less pavement damage than one without it. New suspensions are tested and certified as road-friendly; however, despite evidence that the performance of a suspension degrades over time, there is no in-service compliance requirement or test protocol for RFS.

The purpose of this project was to review the requirements for in-service testing of suspensions to confirm their road-friendly characteristics. This included identifying technologies that offered solutions that are both accurate and repeatable for the on-road testing of vehicles.

Research by others has shown that poorly-maintained vehicle components such as shock absorbers have a significant impact on vehicle maintenance costs. These also adversely affect the road friendly characteristics of suspensions that subsequently increase road damage.

To confirm the in-service RFS characteristics, three key elements are required: sufficient excitation of the suspension, accurate measuring systems and technical analysis of the results. The detailed technical requirements of each of these elements must be defined.

It was found that the on-board vehicle scales evaluated in the project have sufficient measurement accuracy but the lack of a suitable excitation method prevents them from being a viable solution. Current technologies lack the ability to isolate the effects of variations in the road surface, vehicle dynamics and environmental factors.

A preferred RFS test method was identified that limits these variations to an acceptable level. However, this project revealed that there are consistency issues with existing certifications that must be overcome first. The variations possible under current certification methods for new suspensions as documented in Vehicle Standard Bulletin VSB11 prevent comparison with in-service test results. For the project to progress, a targeted review of VSB11 is recommended which should focus on minimising variations in performance.

Following a satisfactory review of VSB11, industry will be engaged through discussions with the Australian Trucking Association, and a proposal to the Department of Infrastructure and Regional Development (DIRD) and the National Heavy Vehicle Regulator (NHVR) drafted.

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

Heavy vehicles fitted with road-friendly suspensions (RFS) are permitted to operate on select routes at higher mass limits (HML). This enables greater payloads to be carried including an additional 2.5 t per triaxle group on a trailer (an increase of over 10% compared with general mass limits (GML). This productivity benefit is permitted on the basis that a RFS reduces pavement damage. *Vehicle standard bulletin 11* (VSB11) (Department of Transport and Regional Services 2004 (DOTARS) 2004) defines the test method for certifying a new suspension; however, despite evidence that the performance of a suspension degrades over time, there is no in-service compliance requirement for RFS.

The Australian Road Research Board (ARRB) was commissioned by Queensland Department of Main Roads (TMR) under the NACoE work program to conduct a review of compliance requirements for RFS and options to address this issue including technologies offering potential solutions for the in-service testing of RFS.

This project was completed in three stages:

- Stage 1: Review and scoping 2014/15
- Stage 2: Proof of concept 2015/16
- Stage C: Operational evaluation 2016/17.

The findings of all three stages of the project are summarised in this final report.

In addition to this final report, annual summary reports were produced at the conclusion of Stage 1 and Stage 2. At the completion of each of these stages the findings were reviewed and incorporated into the scope of the next program of work. Significant learnings during Stages 1 and 2 resulted in an improved understanding of the feasibility of implementing an in-service compliance standard. These learnings, and how they were incorporated into the work program, are described briefly in the following section.

1.1 Progressive Findings from Stages 1 and 2 of the Project

The review completed during Stage 1 of the project included consideration of advancements in telematics, accreditation, software models and technologies and possible 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 were:

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

The outcomes of Stage 1 are discussed in this final report. However, it was known after Stage 1 was completed that, without this relationship, it would not be possible to develop an in-service standard based on the performance levels of the suspension. Consequently, Stage 2 focussed on aligning in-service requirements with the existing certification requirements of VSB11. Stage 2 of the project continued as planned, with the possibility of utilising these technologies through a proof-of-concept testing program, but with the performance criteria based on VSB11.

The findings from Stage 2 were based on a testing program designed to evaluate the effectiveness of different in-service test methods. A summary of the results is included in this report. Key findings were incorporated into the final stage of the project, the most significant being the issues identified in the certification requirements of VSB11. Stage 3 has focused on understanding the implications of these issues in terms of a potential in-service compliance standard. Also of importance was an evaluation of the DynaSses system, particularly the system's applicability to tandem and triaxle groups.

1.2 Project Scope

The need for an in-service compliance standard has been raised by road managers previously and studies have been undertaken; the most recent was completed by the NTC (2008), yet the issue remains largely unresolved. The aim of this project was to present a way forward through either a technology-based solution, or failing this, by identifying the impediments and the steps required to overcome them.

The productivity benefits afforded to vehicles fitted with RFS and the need for an in-service requirement is important to Queensland and TMR but these benefits are also realised nationally. The findings from this project have national implications and any changes or future work will be implemented with the assistance of the National Heavy Vehicle Regulator (NHVR) in consultation with the Commonwealth Department of Infrastructure and Regional Development (DIRD). The NHVR has been actively involved during each stage of this project.

1.3 Method

The project involved the following tasks:

1. literature review – a summary of research which led to the introduction of RFS and HML
2. identification and review of technologies suitable for in-service compliance testing
3. field testing and analysis of selected technologies
4. define requirements for test standards
5. consult with industry and disseminate knowledge.

1.4 Layout of Report

This report provides a recap of the RFS measurement systems that were investigated in Stage 2, the vehicles on which they were tested, the test procedure employed and the results of further testing using one of the systems on two further axle configurations. Full details of each testing system and the results for all vehicles previously tested are available in the Stage 2 report.

The following sections introduce the basic concept of RFS and present a summary of international research, RFS performance requirements and the systems considered as potential in-service compliance solutions. The purpose of these sections is to provide a general overview of the freight task and the types of vehicles, including the attributes that must be considered.

- **Section 2: Background** – an overview of the research which led to the introduction of HML and RFS requirements, the outcome of recent reviews and the identification of knowledge gaps.
- **Section 3: Literature review** – a summary of the research relating to suspension characteristics and the effects on pavement wear including dynamic loading.
- **Section 4: Technology-based solutions** – the possible technologies that could be used as part of an in-service compliance standard.
- **Section 5: In-service RFS measurement systems** – a listing and review of three systems considered for evaluation.

The following sections outline the aim, method and results of the field testing conducted in Stage 2 and Stage 3 of the project and a review of on-board data logged as part of an operational evaluation of System 1 (see Section 5.1).

- **Section 6: Test design** – the aim of the test program, including the test matrix, the systems tested and the vehicles used in the evaluation.
- **Section 7: Test results** – a summary of the Stage 2 test results and analysis of the Stage 3 test results.
- **Section 8: Review of on-board mass data** – includes a review of sample data logged during normal operation of a B-double.

The following sections present the key findings based on the testing and operational evaluation of all the systems, a summary of the views of the industry, based on consultation with major suspension manufacturers, a summary of the key findings and recommendations for further work.

- **Section 9 : Research findings** – the key findings based on the review of technologies, system testing and operational evaluation, including recommendations for a review and requirements for a new standard.
- **Section 10: Industry consultation** – consultation with the key stakeholders likely to be affected by the findings of this project and their responses.
- **Section 11: Summary of key findings –**a summary of the key findings from all three stages of the project.
- **Section 12: Recommendations** –ARRB's recommendations and next steps.

2 BACKGROUND

The development of RFS and its introduction into the Australian heavy vehicle fleet can be marked by four major steps:

1. research identifying that some suspensions are more 'road-friendly' than others
2. the development of a performance standard for RFS
3. the introduction of the Higher Mass Limits (HML) scheme, with RFS as a requirement
4. an investigation of in-service test methods to monitor continuing compliance of RFS equipment.

A brief background to each of these is now provided.

2.1 Recognition of Road-friendliness

The DIVINE (Dynamic Interaction between the Vehicle and INfrastructure Experiment) project (OECD 1997) is considered the pre-eminent research on the topic of RFS. The research definitively recommended that suspension systems should be considered to be 'road-friendly' if compliance with specified limits for certain measurable performance characteristics were demonstrated. These characteristics included:

- the natural frequency of suspension oscillation
- the overall suspension system damping ratio
- the percentage of total damping attributed to friction damping.

2.2 Development of a Performance Standard

The understanding gained through the DIVINE project led to the development of formalised performance criteria for road-friendliness, as well as a method for testing the performance of heavy vehicle suspension systems.

The defined performance criteria are:

- static load sharing between axles in a group (no greater than 5% variation between axles)
- 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).

These requirements were originally published in 1999 and subsequently revised in the Australian Federal Regulation *Certification of road-friendly suspension systems* (*Vehicle Standards Bulletin 11 (VSB11)*) (DoTARS 2004).

2.3 Introduction of Higher Mass Limits (HML)

The maximum load a heavy vehicle can carry is limited and enforced by the state road agencies. Mass limits are based on an economic evaluation of the asset wear resulting from axle loads. In 1998, the National Road Transport Commission[1] (NRTC) investigated the economic effects of allowing axle load increases for vehicles with RFS (at the time considered to be solely limited to air

1 Now National Transport Commission (NTC).

suspension types). Subsequently the higher mass limits (HML) scheme was adopted by most state and territory jurisdictions.

Required conditions for heavy vehicles to operate at HML vary across different jurisdictions but all include the stipulation that the vehicle must be fitted with a certified RFS system. The inclusion of RFS as an operational requirement of HML is based on the understanding that RFS allows a greater mass to be carried for a similar overall effect on infrastructure.

2.4 Investigation of In-service Compliance of RFS

The current standard (VSB11) defines the requirements for certifying a new suspension as road friendly. Despite the understanding that the performance of RFS does degrade over time, mainly due to in-service degradation of shock absorber damping characteristics, there is no in-service compliance standard. Accordingly, it is considered necessary to monitor and correct the in-service degradation of RFS.

In 2008, the NTC commissioned an investigation into the In-service Performance Assurance for RFS (NTC, 2008). A technical assessment of the management of the in-service performance of RFS reported that the preferred method was to test the vehicle’s shock absorbers.

The costs and benefits of the tests were estimated. It was concluded that the costs exceeded the benefits under a range of assumptions and that in-service compliance options therefore could not be justified on economic grounds. Consequently, there is currently no in-service test for RFS. Instead, visual inspections of the bushes, airbags and tyres are undertaken to assess the health of the vehicle’s RFS, as distinct from its continued degree of compliance with RFS requirements.

3 LITERATURE REVIEW

This section of the report presents the outcomes of the literature review and consolidates the background material on the topic of the in-service testing of RFS. The documents identified as relevant to this project are listed in Table 3.1.

The aim of the review was to identify the following:

- the influence of suspension type and characteristics on system performance
- dynamic loads, dynamic load sharing and spatial repeatability
- the effects on pavement wear
- estimating the cost-benefit ratio of RFS
- suspension certification and in-service testing and maintenance.

Table 3.1: Summary of documents reviewed

Document Name	Author(s)	Date
▪ Mass limits review – Technical supplement No 2 – road and bridge impacts	▪ NRTC	▪ 1996
▪ OECD DIVINE programme – Final report – dynamic interaction of heavy vehicles with roads and bridges	▪ OECD	▪ 1997
▪ OECD cooperative international research into vehicle-road interaction – DIVINE project	▪ K Sharp, P Sweatman & R Addis	▪ 1997
▪ In-service assessment of road-friendly suspensions	▪ P Sweatman, S McFarlane, J Komadina, D Cebon	▪ 2000
▪ Evaluation of in-service compliance of road-friendly suspensions	▪ MM Starrs, Ian Wright & Assoc. & ARRB	▪ 2000
▪ Air suspension code: guidelines for maintaining and servicing air suspensions for heavy vehicles, ARTSA Code 01	▪ Australian Road Transport Suppliers Association (ARTSA)	▪ 2001
▪ The benefits of road-friendly suspensions	▪ A Collop & D Cebon	▪ 2002
▪ Impacts of vehicles with higher mass limits on NSW roads	▪ D Cebon	▪ 2004
▪ Certification of road-friendly suspension systems Vehicle Standards Bulletin No 11	▪ Department of Transport and Regional Services	▪ 2004
▪ Analysis of heavy vehicle suspension dynamics using an on-board mass measurement system	▪ L Davis & R Sack	▪ 2004
▪ Testing of heavy vehicle suspensions – proof-of-concept: 'white-noisy road test' and 'pipe test' to determine suspension parameters	▪ L Davis	▪ 2005
▪ An in-service survey of heavy vehicle suspensions	▪ C Blanksby, R George & A Germanchev	▪ 2006
▪ Determining heavy vehicle suspension dynamics using an on-board mass measurement system	▪ L Davis & R Sack	▪ 2006
▪ Further development of in-service suspension testing for heavy vehicles	▪ L Davis, S Kel & R Sack	▪ 2007
▪ Heavy vehicle suspensions – testing and analysis - a literature review.	▪ L Davis & J Bunker	▪ 2007
▪ In-service performance assurance for road friendly suspensions	▪ NTC	▪ 2008
▪ Measuring heavy vehicle wheel loads dynamically	▪ Austroads	▪ 2009
▪ Heavy vehicle suspension- testing and analysis (PhD thesis)	▪ L Davis	▪ 2010
▪ Measurement and analysis of dynamic wheel loads	▪ Austroads	▪ 2012
▪ Vehicle-pavement interaction modelling	▪ RL Roebuck et al.	▪ 2012

A brief summary of the findings of the literature review is now presented. Each of these topics is discussed in relation to in-service compliance of RFS.

3.1 Summary of Findings of Literature Review

The literature review highlighted the knowledge gaps in the relationship between RFS systems and pavement wear. While considerable research had been conducted in this area, the review highlighted that the following was not known:

- the relationship between pavement type and pavement wear resulting from RFS
- the relationship between suspension characteristics and dynamic loading
- the level of compliance of in-service suspensions with current RFS requirements.

While each of these knowledge gaps has an effect, a lack of knowledge regarding the relationship between suspension characteristics and dynamic loading was critical as it prevented an in-service standard from being set. This was because the relationship between suspension frequency and damping, and the resulting dynamic loading applied to the pavement, could not be defined at that time.

The research conducted in measuring dynamic wheel loads did not result in the development of a cost-effective on-board sensor that could accurately measure the dynamic loads, which would be required for determining in-service compliance.

The practical issues of conducting a roadside test that strictly adheres to the requirements of VSB11 rendered such options unviable, in particular the requirement to remove shock absorbers and load the vehicle to the specified test weight. These requirements were unlikely to be overcome by advancements in technology; conversely, the costs associated with each were more likely to increase as they depended on labour rates and required the freight vehicle to be off the road for some period. Alternative options that utilise on-board technologies provided a most cost-effective solution.

The option of pursuing an alternative path to VSB11 remained available but first the relationship between suspension characteristics and pavement wear must be understood. These alternatives were identified as offering more practical solutions for in-service performance assurance in the future. Determining and applying a tolerance for acceptable performance provided flexibility that could allow for a viable solution.

4 TECHNOLOGY-BASED SOLUTIONS

The following engineering solutions were identified as suitable for measuring suspension performance and warranted further investigation:

- on-board scales (high and low frequency)
- linear displacement sensors
- accelerometers
- tyre pressure sensors
- Electronic Braking System (EBS) control modules.

Figure 4.1 shows two on-board scale devices that can be fitted to a vehicle to measure mass, using an air pressure transducer (left) and load cells (right).

Figure 4.1: Examples of on-board scales

An EBS module is shown Figure 4.2. Such technology is common on trucks and prime movers and it is also is becoming increasingly common on new trailers. This module is the basis for any electronic braking system; it can include sensors to record wheel speeds and air bag pressure and communicate with other devices via the controller area network (CAN). Data can be sent to the vehicle's telematics device and communicated via the mobile network or other wireless platforms.

Figure 4.2: Electronic Braking System (EBS) module

4.1 Vehicle Instrumentation and Data Acquisition

The accuracy, resolution and frequency of the data available from in-field measurements are limitations for determining in-service compliance. It is acknowledged that the aim of the next stage of this project is to utilise technology that is commercially available and that utilise existing devices and existing specifications. The key data requirements that have been identified and require investigation in the next stage of this project are:

- accuracy of mass measurements
- calibration of on-board scales
- location accuracy
- ability to align road survey and vehicle data (obtained for difference sources)
- data sampling rate.

5 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. In Stage 2 of the project, over 40 companies and individuals working in areas related to suspension performance and testing were asked to provide information regarding in-service RFS measurement systems that may meet the requirements of the project brief. 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) and the Australia Road Transport Suppliers Association (ARTSA) Annual General Meeting (February 2016). Discussions were also held with the Queensland Trucking Association (QTA), the Heavy Vehicle Industry Association (HVIA formerly CVIAQ) and CVIA WA. Two responses were received 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 5.1. The RFSA, which is currently owned and operated by ARRB, was included at the request of TMR.

Table 5.1: 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)	Australian Road Research Board	Stand-alone rig
3	DynaSses	FormulaSpec	Wheel mounted (temporarily fitted)

Each system varies in its approach to measuring road friendliness, but all systems cover the key areas of assessment. Operational details of each system are summarised in Table 5.2.

Table 5.2: Summary of systems

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 Wi-Fi
2	RFS Analyser (ARRB)	Air bag raised platform which is dropped via sudden release blow-off valves	Load cells with 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	DynaSses (FormulaSpec)	Vehicle driven over ramps placed underneath each tyre	Multiple sensors with 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

5.1 System 1: CHEK-WAY® Eliminator

The CHEK-WAY® Eliminator is an on-board scale system that uses air pressure sensors to measure the axle group weights of a heavy vehicle. It was designed and manufactured in Australia. The components are shown in Figure 5.1. Further details are provided in Appendix B.1.

Figure 5.1: Components of CHEK-WAY® Eliminator

This system was evaluated during test program 1 (described in the Stage 2 report), at the Tramanco workshop facility in Brisbane on 16-18 May 2016. Details are provided in Table 5.3.

Table 5.3: Details of System 1

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® Eliminator 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

5.2 System 2: RFS Analyser

The RFSA is a purpose-built rig designed for VSB11 certification testing. It comprises three mobile platforms and ramps as shown in Figure 5.2. Each platform is fitted with two air bags, which are inflated to lift the vehicle. Load cells in the platforms measure the weight imposed by each tyre. Further details are provided in Appendix B.2.

Figure 5.2: Road Friendly Suspension Analyser (RFSA)

The RFS Analyser was evaluated during test program 2 (described in the Stage 2 report), at the DECA facility in Shepparton, Victoria, on 26-27 May 2016. Details are provided in Table 5.4.

Table 5.4: Details of System 2 (RFSA)

Name	Road Friendly Suspension Analyser
Company	Australian Road Research Board
RVCS No.	T9872
Patent No.	None
Business type	Research & Consulting
Contact	Anthony Germanchev, HV Team Leader
Email	anthony.germanchev@arrb.com.au
Website	www.arrb.com.au
Office	500 Burwood Hwy, Vermont South, Vic 3133

5.3 System 3: DynaSses

The DynaSses (Dynamic Assessment) system is shown in Figure 5.3. The system comprises custom-designed ramps (four are required for a single axle with dual tyres), hub-mounted sensors (temporarily fitted) at each end 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 analysis is via custom software which can be installed on a tablet or PC. Further details are provided in Appendix B.3.

Figure 5.3: DynaSses test system (Dynamic Assessment)

The DynaSses system was evaluated during test program 3 (described in the Stage 2 report), at the ARRB test site in Vermont South, Victoria, on 7-8 June 2016. Details are provided in Table 5.5.

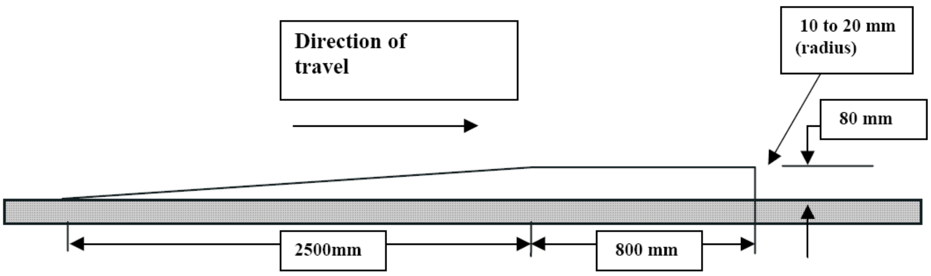
Table 5.5: Details of System 3

Name	DynaSses
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

5.4 Reference System

The reference system was the VSB11-approved 80 mm ramps. This method generates an impulse as the wheel rolls off the step and drops to the ground (see Figure 5.4). This was the original European test method applied widely to single axles. It is described in Annex II of Council Directive 96/53/EC (European Union 1996).

Figure 5.4: Step method as defined in VSB11



Source: European Union 1996; DOTARS 2004.

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

To calculate the damping ratio, the 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, over the time when the oscillations had settled down. The following equation was then applied to calculate the damping ratio:

$$Damping\ ratio = \frac{1}{2\pi}\ln\frac{A1}{A2} \quad (1)$$

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

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

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.

6 TEST DESIGN

There are two approaches that can be taken to evaluate a 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, the latter method allows the effect of key variables to be quantified.

Using (VSB11 approved) test methods, 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 effect measurement are:

- 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 systems using an approved VSB11 test method.

6.1 Performance of Shock Absorber

The function of a shock absorber is to absorb the energy caused by the vertical movement of the suspension. Understanding shock absorber behaviour is an important requirement of this evaluation process. Expert advice and technical assistance was sought from an after-market shock absorber manufacturer (Powerdown) and suspension manufacturer (Hendrickson).

The aim of the testing program was to determine the level of shock absorber damping that could be detected by each measurement system. The test program included a range of shock absorbers varying in damping characteristics. ARRB collaborated with Powerdown to identify a suitable set of shock absorbers to be used in the testing program, via a bench-top testing program.

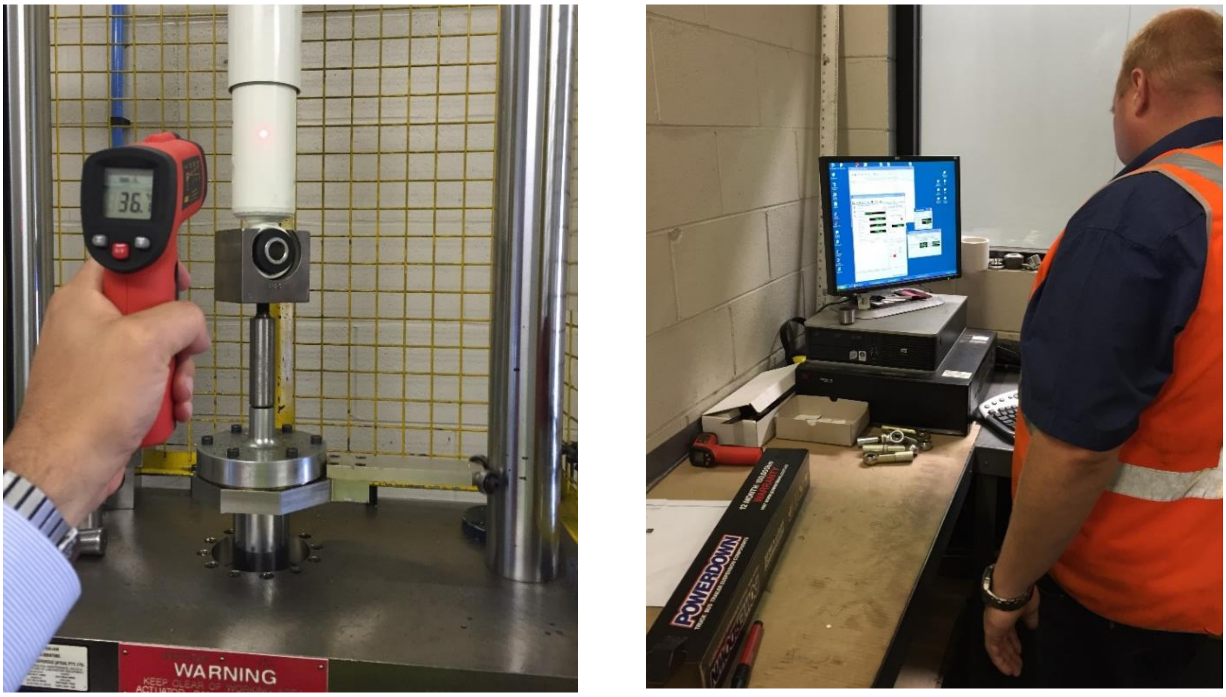
The following three shock absorbers were selected to be used in the testing program:

- 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.

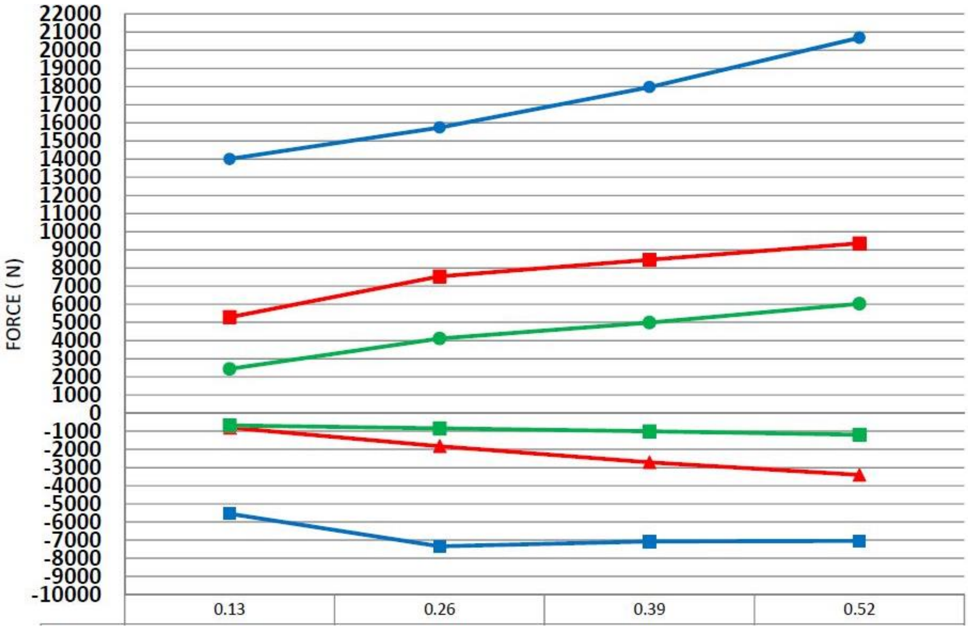
Tests were conducted at the Powerdown test facility. The warm-up procedure prior to recording performance data is shown in Figure 6.1.

Figure 6.1: Warm-up procedure prior to recording performance data



A summary of the peak forces for each shock absorber at four test speeds, for both the extension stroke and the compression stroke, is shown in Figure 6.2. The data points shown in the positive range of the y-axis represent the damping force in the extension stroke, while compression stroke force is shown in the negative range. The four data points are the four speeds at which the test were conducted: 0.13 m/s, 0.26 m/s, 0.39 m/s and 0.52 m/s.

Figure 6.2: Comparison of peak forces for each shock absorber



Further details of the performance of the shock absorber are provided in Appendix C.

6.2 Test Matrix

The test matrix for Stage 1, Stage 2 and Stage 3 of the testing is shown in Table 6.1, Table 6.2 and Table 6.3 respectively.

Table 6.1: Test matrix: Stage 1

Test	Shock absorber						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.

Table 6.2: Test matrix: Stage 2

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	☑☑☑

Table 6.3: Test matrix: Stage 3

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 conducted on a flat level road surface.

6.3 Test Vehicles

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. The triaxle trailer used in Stage 1 of the testing is shown in Figure 6.3, the 6x4 prime mover used in Stage 2 is shown in Figure 6.4 .

The 4x2 rigid truck used in Stage 2 is shown in Figure 6.5, whilst the 6x4 rigid truck also used in Stage 3 is shown in Figure 6.7: . The triaxle trailer used for the additional testing in Stage 3 is shown in Figure 6.7. It was loaded with steel weights to a GML load of 20 tonne.

Figure 6.3: Triaxle semi-trailer used in Stage 1 of testing

Figure 6.4: 6x4 prime mover used in Stage 2 of testing

Figure 6.5: 4x2 rigid truck used in Stage 2 of testing

Figure 6.6: 6x4 rigid truck used in Stage 3 of testing

Figure 6.7: Triaxle semi-trailer used in additional testing during Stage 3

The specifications for the three vehicles used in Stage 1 and 2 are listed in Table 6.5.

Table 6.4: Vehicle specifications: Stage 2

Specification		Triaxle trailer	6x4 prime mover	4x2 rigid truck
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	–	–
RFS compliant		Yes	Yes	Yes
Tyres		Continental 11R22.5	Bridgestone 295-80R22.5	Bridgestone 295-80R22.5
Axle spacing		1220 mm	1350 mm	NA
Wheelbase/S-dimension		8450 mm	3945 mm	4500 mm

The specifications for the two test vehicles used in Stage 3 are listed in Table 6.5.

Table 6.5: Vehicle specifications

Specification	Vehicle 1	Vehicle 2
Test system fitted	DynaSses	DynaSses
Vehicle configuration	Semi-trailer	Rigid truck
Truck/trailer make	Vawdrey	Isuzu FVR
Suspension type	Air	Mechanical
RFS compliant	YES	NO
Tyres	Various, 11R22.5	Michelin 11R22.5
Axle spacing	1500 mm	1400 mm

6.3.1 Axle Loads

Each vehicle was weighed during the testing program using portable scales. The axle group loads for the triaxle semi-trailer, as tested, are shown in Table 6.9.

Table 6.6: Axle group loads: triaxle semi-trailer

	Axle 4 (kg)		Axle 5 (kg)		Axle 6 (kg)	
	Laden	Partially laden	Laden	Partially laden	Laden	Partially laden
Right (driver side)	3380	2660	3520	2980	3600	2780
Left (passenger side)	3620	2820	3320	2720	3260	2560
Total (by axle)	**7000**	**5480**	**6840**	**5700**	**6860**	**5340**
Total (by group)	**20700**			**16520**		

The axle group loads for the 6x4 prime mover, as tested, are shown in Table 6.10.

Table 6.7: Axle group loads: 6x4 prime mover

	Axle load (kg)					
	Steer axle		Drive axle 1		Drive axle 2	
	Unladen	Laden	Unladen	Laden	Unladen	Laden
Right (driver side)	3200	3300	1420	4100	1100	4100
Left (passenger side)	3060	3360	1020	4400	1280	4160
Total (by axle)	**6260**	**6660**	**2420**	**8500**	**2380**	**8260**
Total (by group) laden	**6600**		**16760**			

The axle group loads for the 4x2 rigid truck, as tested, are shown in Table 6.8.

Table 6.8: Axle group loads: 4x2 rigid truck

	Axle load (kg)			
	Steer axle		Drive axle	
	Unladen	Laden	Unladen	Laden
Right (driver side)	2220	2340	1420	5240
Left (passenger side)	2280	2600	1520	5200
Total (by axle)	**4500**	**4940**	**2940**	**10440**

The axle group weights for the triaxle semi-trailer are shown in Table 6.9.

Table 6.9: Axle group loads: triaxle semi-trailer

	Axle load (kg)		
	Axle 4	**Axle 5**	**Axle 6**
	Laden	**Laden**	**Laden**
Right (driver side)	3200	3220	3240
Left (passenger side)	3240	3260	3240
Total (by axle)	6440	6480	6480
Total (by group)	**19400**		

The axle group weights for 6x4 rigid truck are shown in Table 6.10.

Table 6.10: Axle group loads: 6x4 rigid truck

	Axle load (kg)		
	Steer axle	**Drive axle 1**	**Drive axle 2**
	Laden	**Laden**	**Laden**
Right (driver side)	2900	2800	2800
Left (passenger side)	2900	2600	2720
Total (by axle)	**5800**	**5400**	**5520**
Total (by group) laden	**5800**	**10920**	

6.4 Test Systems

Figure 6.8 shows the CHEK-WAY® Eliminator system fitted to the triaxle semi-trailer.

Figure 6.8: CHEK-WAY® Eliminator system 1 fitted to triaxle semi-trailer

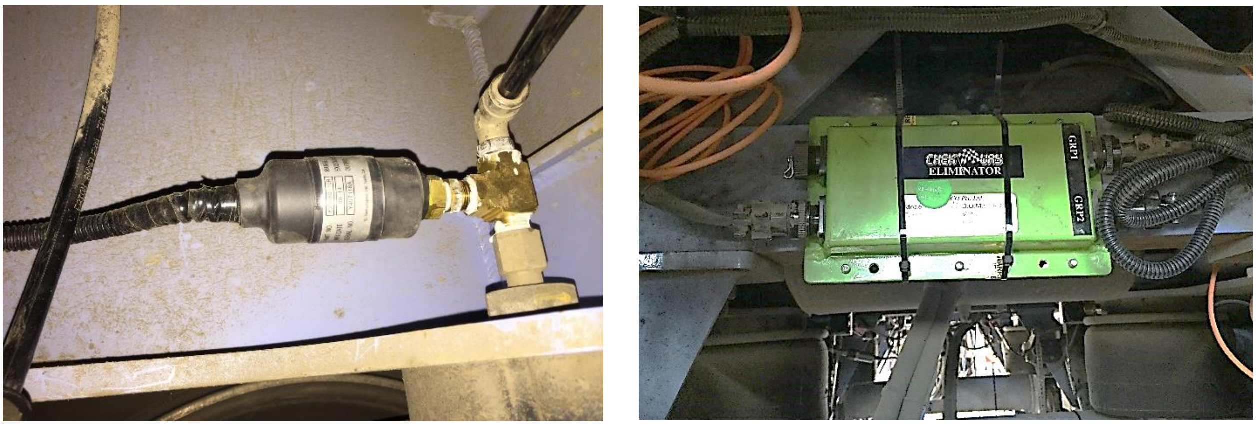


Figure 6.9 shows the reference system fitted to the triaxle semi-trailer. The photo on the left shows the linear displacement transducer (LDT) measuring vertical axle displacement and also the air pressure transducer. The photograph on the right shows the accelerometer fitted to the axle and the junction box mounted to the chassis cross member.

Figure 6.9: Reference system fitted to triaxle semi-trailer

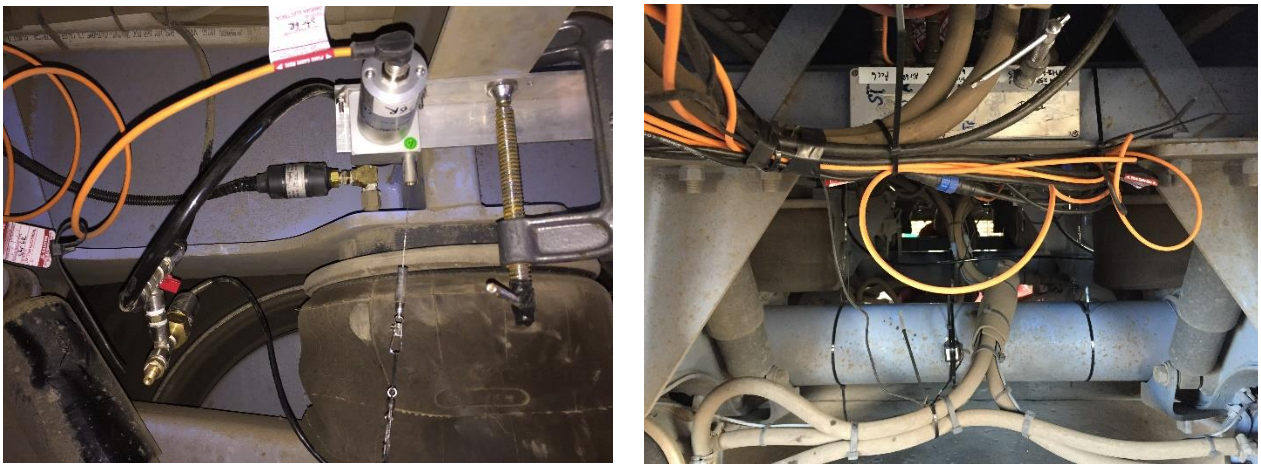


Figure 6.10 shows the RFSA rig with the fully laden 6x4 prime mover in position. The photograph on the left shows the LDT mounted between the underside of the tray and the rear axle. The excitation method for test program 2 was the VSB11 RFSA drop test, and the same method was used for both the test system and the reference system. The measurement methods were the load cell sensors permanently fitted to the RFSA system 2 and the LDTs fitted to each axle (reference system).

Figure 6.10: RFSA used to assess the 6x4 prime mover

Figure 6.11 shows the DynaSsess system fitted to the rear axle of the 4x2 rigid truck. The system comprises three main components: the measurement device fitted to the hub and shown in the left photograph, the excitation device (ramps) shown in the right photograph, and the analysis software (not shown).

Figure 6.11: DynaSsess system fitted to 4x2 rigid truck

Figure 6.12 shows the reference system fitted to the 4x2 rigid truck.

Figure 6.12: Reference system fitted to 4x2 rigid truck

6.5 Test Program – Stage 2

The RFS test plan was designed to assess the effects of changes in damper performance and vehicle mass. This was to be achieved by varying those parameters. For the different configurations, the load remained unchanged while the dampers were varied. The other configurations involved varying the load while leaving the dampers unchanged.

Each configuration was tested in two ways:

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

- driving over a pipe (performed three times to achieve consistent results).

Testing was performed for the following 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 speed on a road circuit; this involved crossing a surface irregularity such as a bridge joint.

6.6 Test Program – Stage 3

The Stage 3 test program involved the DynaSses system only. The purpose of this set of tests was to show that the DynaSses was compatible with tandem and triaxle groups, which was identified as a potential limitation of the system during Stage 2 testing. Two test vehicles were used, one fitted with a tandem group and one with a triaxle group.

7 RESULTS OF TESTING

The data logged from all the test programs was analysed and the results are presented in this section of the report. The tests conducted during both Stages 2 and 3 are shown in Table 7.1.

Table 7.1: Presentation of test results

Test No.	Subtitle
1	Evaluation of 'pipe' test excitation method
2	Repeatability of ramp tests: fully laden with HD shock absorbers
3	Repeatability of ramp tests: fully laden with MED shock absorbers
4	Repeatability of ramp tests: fully laden with LOW shock absorbers
5	Repeatability of pipe tests: fully laden with HD shock absorbers
6	Repeatability of pipe tests: fully laden with MED shock absorbers
7	Repeatability of pipe tests: fully laden with LOW shock absorbers
8	Summary of repeatability test results
9	Repeatability tests: fully laden with NO shock absorbers
10	Comparison of pipe vs ramp tests: fully laden 6 LOW
11	Comparison of ramp tests: fully laden 6HD vs 5HD vs 4HD
12	Comparison of pipe tests: fully laden 6HD vs 5HD vs 4HD
13	Comparison of ramp tests: fully laden HD vs MED vs LOW
14	Comparison of pipe tests: fully laden HD vs MED vs LOW
15	Comparison of ramp tests: fully laden MED vs 3 OFF
16	Comparison of pipe tests: fully laden MED vs 3 OFF
17	Comparison of ramp tests: fully laden MED vs No RHCV
18	Comparison of ramp tests: fully laden MED vs half laden MED
19	Comparison of pipe tests: fully laden MED vs half laden MED
20	On road test: Fully laden with MED shock absorbers
21	Triaxle semi-trailer DynaSsess tests
22	6x4 rigid truck – tandem drive group

All test results from Stage 1 are included in Appendix C. The on-road test results are discussed in Section 7.1 and a brief summary of the findings from Stage 2 testing is presented in Section 7.2. The data obtained from the Stage 3 test program were analysed and the results are presented in Section 7.3.

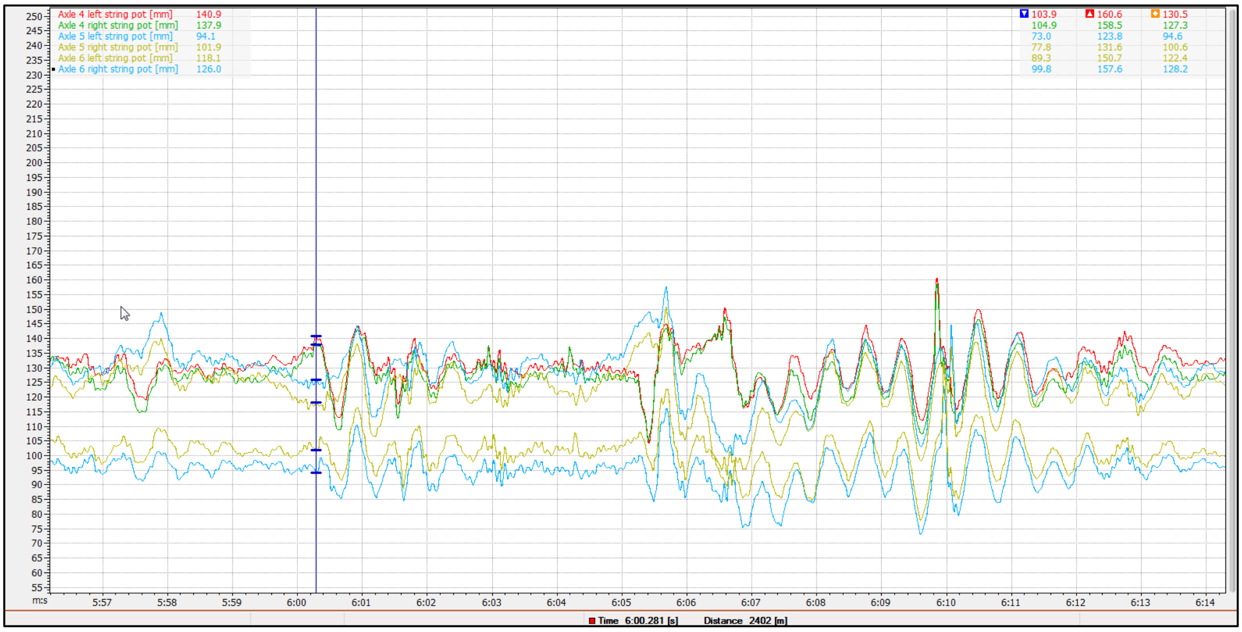
7.1 Results of On-road Testing

On-road testing was conducted on a section of Sherwood Rd, near the Brisbane Markets. The test 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 testing. The vehicle was driven along a section of the road where a repaired section of pavement had been identified as suitable to excite the suspension. An aerial photograph of Sherwood Rd and the location of the bridge which immediately preceded the repaired section is shown in Figure 7.1.

Figure 7.1: Map showing bridge location for on-road testing

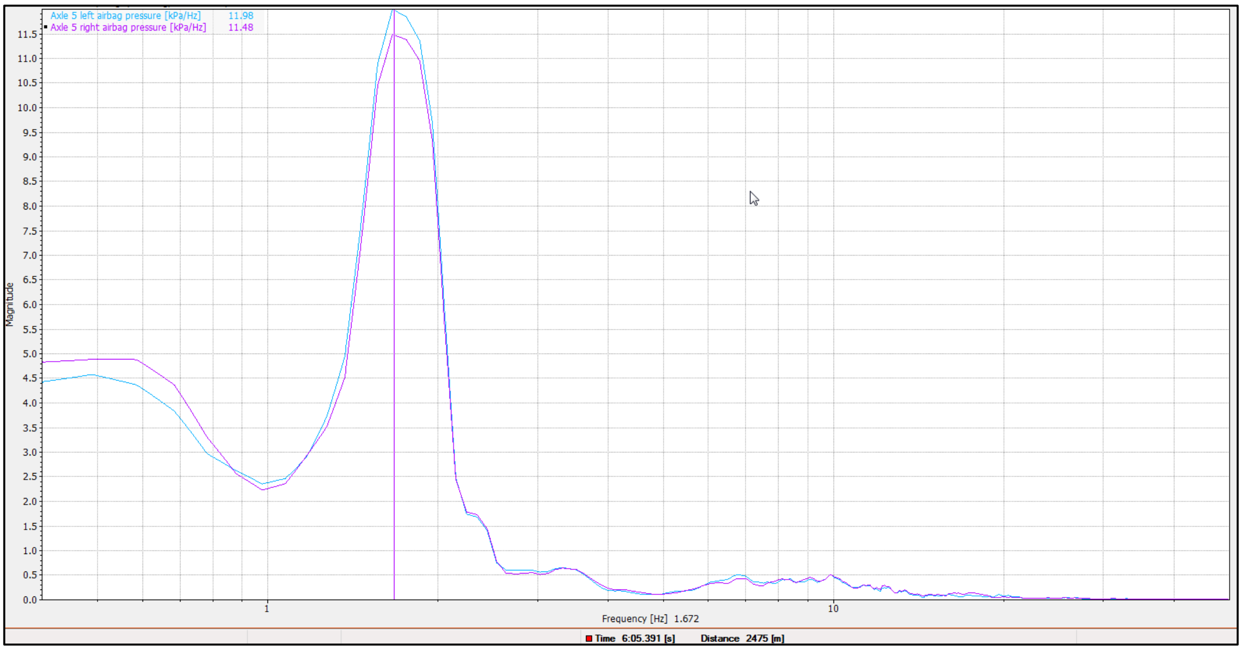
Both displacement and air pressure data was recorded while crossing the repaired section (marked with the vertical blue line) as shown in Figure 7.2 (displacement) and Figure 7.4 (air pressure) respectively.

Figure 7.2: Displacement data trace – first pass



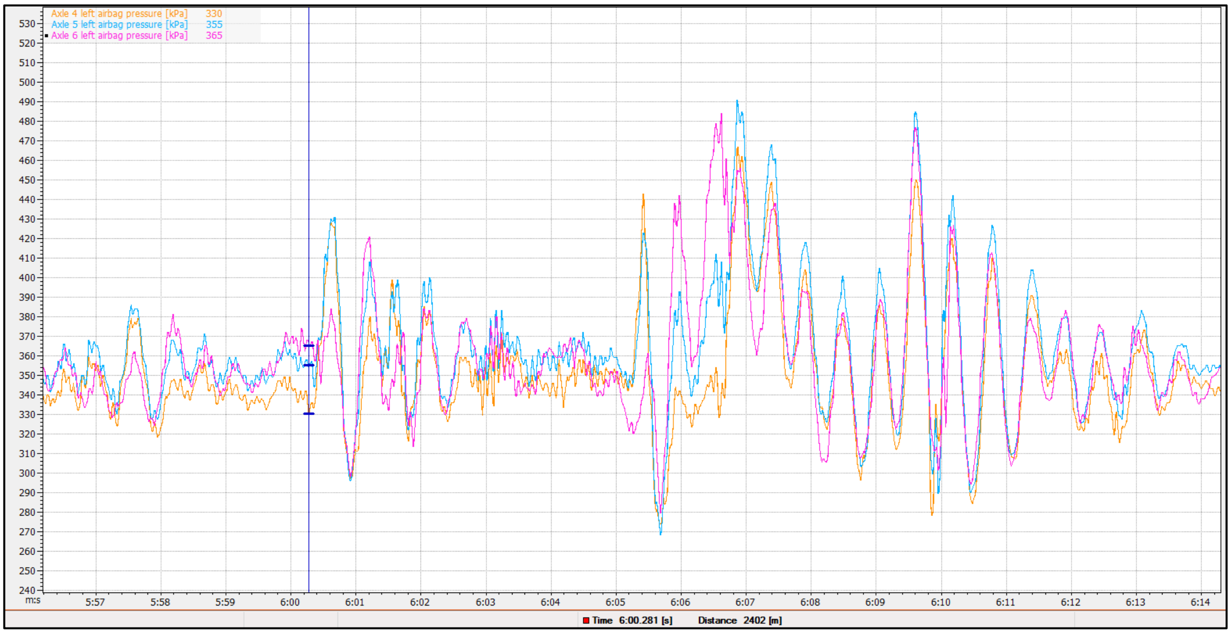
The appearance of the data traces obtained from the on-road testing for the ramp and pipe tests differed. The first difference that becomes evident was the presence of higher frequencies in the data. The frequency spectrum of the data was analysed and it is presented in Figure 7.3. It shows a dominant 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, which is consistent with the axle hop frequency (the frequency at which the axle oscillates based on the tyre stiffness). This was a promising result and indicated that, despite the disturbances due to the road surface, the frequency of the suspension could be identified.

Figure 7.3: Frequency spectrum during on-road testing (air pressure)



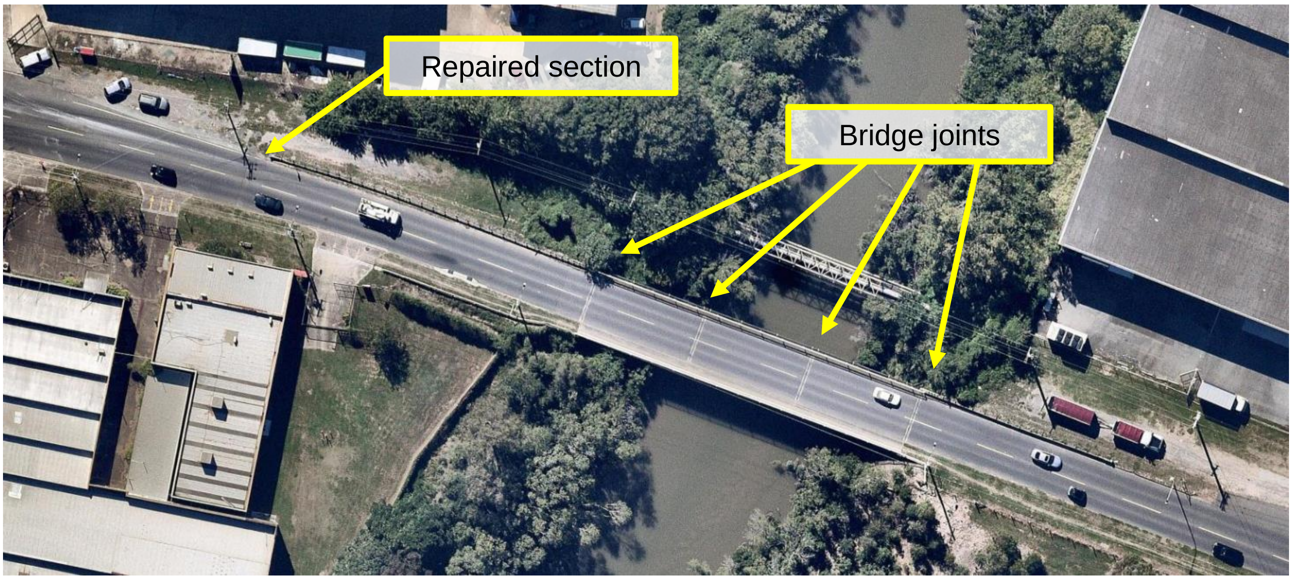
The data trace contained many peaks and troughs of varying frequency and magnitude. This data trace was more difficult to analysis than data obtained from the step tests in which there is a single pulse. The data trace from the air pressure transducers (APTs) is shown in Figure 7.4. The data was analysed to locate the point at which the vehicle crossed the bridge, which is represented in Figure 7.4 by the vertical line. It is clear that, at approximately the 6:00 time interval, there was a large single impulse followed by a decaying trend similar in appearance to the data obtained from ramp testing. This pattern was present in the data obtained from both the LDTs and the APTs.

Figure 7.4: Air pressure data trace – first pass



The data shown in Figure 7.2 and Figure 7.4 is for a period of 18 seconds, during which the vehicle travelling at 53 km/h crosses the four bridge joints and a repaired section of road as shown in Figure 7.5. The total bridge span was 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 crossed a bridge joint every 1.1 seconds. The repaired section of the road was 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 was 24 m greater than the length of the bridge and the distance to the repaired section (108 m). This indicates that there may be other inputs from other axles (steer axles) or other rough sections of road.

Figure 7.5: Map showing bridge joints and repaired section of road



The difficulty with obtaining data which was 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 roads 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 in Figure 7.6. Due to the (uncongested) 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; however, it was still likely to vary between passes. All other variables remained unchanged. The data trace bears very little resemble 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 7.6: Air pressure data trace from on road tests – first pass

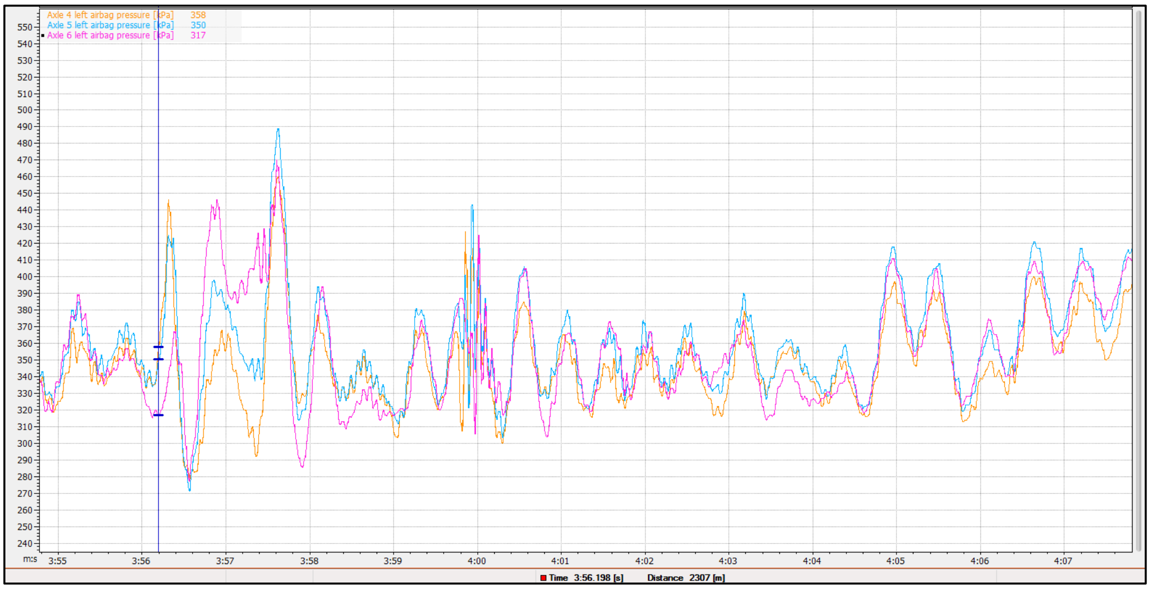


Figure 7.7 shows the triaxle semi-trailer during the on-road tests. The repaired section of the road is in the foreground. In this photograph the vehicle is travelling on the return trip, in the opposite direction as tested.

Figure 7.7: Triaxle semi-trailer during on-road testing

7.2 Results of Stage 2 of Testing

7.2.1 Open Road 'Pothole' Method (CHEK-WAY® Eliminator System)

The data logged during the on-road testing demonstrated that this method did not provide a single impulse sufficient to excite the natural frequency followed by a period free from interference (as required by VSB11) such that the damping of the suspension could be measured.

7.2.2 Pipe test (CHEK-WAY® Eliminator system)

The test results showed that a speed of 20 km/h was not an effective method for exciting the suspension. The speed was later reduced for subsequent testing 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. Variations in speed of approximately 3-4 km/h from the target speed affected the results significantly.

7.2.3 RFS analyser (RFSA)

Tests conducted using the RFSA highlighted the importance of an experienced driver to position the vehicle and release the brakes as well as trained and experienced staff to achieve an even load distribution of the vehicle's payload. The results were highly sensitive to the operation of the rig; a satisfactory level of repeatability cannot be expected when testing vehicles in-service.

7.2.4 DynaSses

The results showed that the DynaSses system produced the most accurate and repeatable results. This is most likely due to the excitation method which reduces the effect of driver errors associated with aligning the tyres with the ramps and maintaining a correct and steady speed. Testing was conducted with a single axle only during Stage 2. The test results obtained for a tandem and triaxle group necessary to confirm if this method reduces the errors associated with the axles not falling simultaneously are presented in the following section.

7.3 Results of Stage 3 of Testing

Stage 3 testing was conducted using the DynaSses system on a triaxle semi-trailer and a 6x4 rigid truck (see Figure 6.6 and Figure 6.7). As described earlier, the test system includes custom designed ramps, temporarily-fitted sensors, data logging and a tablet-based user interface. This system provided the excitation, measurement and analysis method required. As the capability of the DynaSses system was established during the Stage 2 tests, a comparison between it and the reference system was not required during Stage 3. The purpose of these tests was to demonstrate the ability of the system to deal with a triaxle group, and to test the system's ability to detect a suspension's non-compliance with road-friendly requirements.

The data from the DynaSses system was provided to ARRB by FormulaSpec.

7.3.1 Triaxle Semi-trailer Laden to 20 tonne

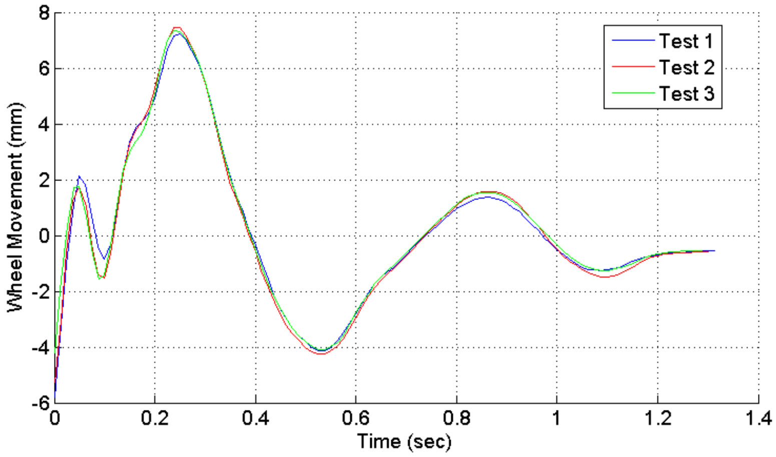
The triaxle semi-trailer was loaded with steel weights to bring its axle group load to 20 tonnes. While lower than the HML limit of 22.5 tonnes, for which RFS would ordinarily be required, a load of 20 tonnes was consistent with the load used in the Stage 2 testing and is representative of common operational conditions.

A summary of the results is presented in Table 7.2 and the recorded data traces are shown in Figure 7.8. The DynaSsess device was fitted to the rear axle of the triaxle group for the first three tests shown in the Table. A fourth test was performed with the device fitted to the front axle of the triaxle group.

Table 7.2: Summary of results: DynaSses – triaxle semi-trailer

	Damping (%)	Frequency (Hz)
Test 1	22.32	1.624
Test 2	21.13	1.621
Test 3	20.63	1.613
Averaged result (%)	**21.4**	**1.62**
Test 4 (front axle mounting)	21.91	1.59

Figure 7.8: Data for DynaSses test method – triaxle semi-trailer (provided by FormulaSpec)



Commentary

The repeatability of the results measured across the three successive tests was similar to that found in the Stage 2 testing. This indicates that the excitation of the suspension was consistent across the three tests, and across all of the wheels in the axle group. This consistency was due to the fact that all of the wheels dropped to the ground within a very short period of time.

Observation of the tests, both in real time and from video recordings, showed that the ramps were able to slide along the ground after being run over by the wheels. This sliding ensured that contact with the ramps after the initial drop of the axles did not interfere with the measured suspension performance.

In an earlier test, one ramp had been observed to slip instead of grip the ground; this delayed the wheel running over it and hence invalidated the results. This slippage was found to have been caused by mud on the painted concrete floor of the test venue. After the mud was removed, the slip did not recur. It is highly unlikely that similar slip would occur on a non-painted floor or a typical road surface.

7.3.2 6x4 Rigid Truck – Tandem Drive Group: Lightly Loaded

Three tests were conducted on the tandem drive axle group of an Isuzu 6x4 rigid truck with mechanical (leaf spring) suspension (Figure 6.7) (see close-up suspension image in Figure 7.9). The axle group was loaded to 10.92 tonnes instead of the 6.5 tonnes at which this axle group would usually be permitted to operate. The intention of this testing was to gauge the effect of using a lightly-loaded, non-road friendly suspension. The results of the testing are presented in Table 7.3 and the data traces are shown in Figure 7.10.

Figure 7.9: Close-up image of Isuzu leaf spring suspension

Figure 7.10: FormulaSpec data from DynaSses test method – 6x4 rigid truck

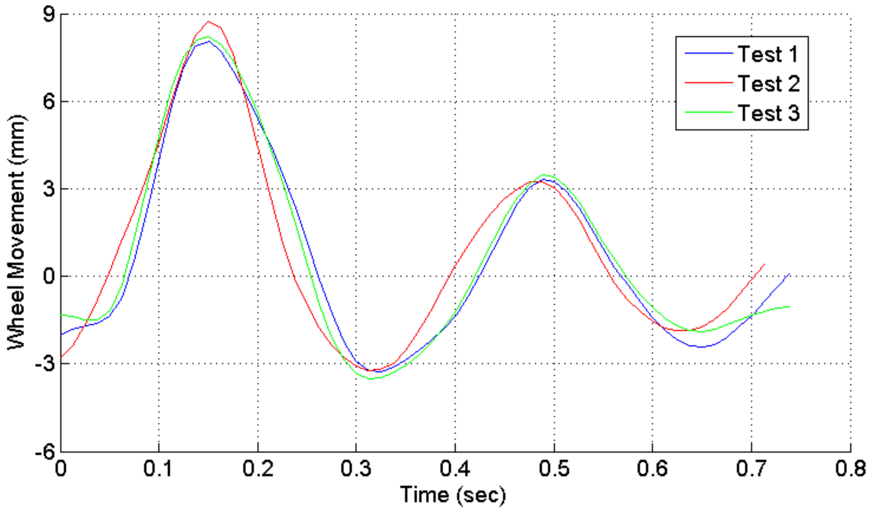


Table 7.3: Summary of results: DynaSses – tandem drive axle, mechanical suspension

	Damping (%)	**Frequency (Hz)**
Test 1	11.88	2.97
Test 2	10.45	3.02
Test 3	11.76	2.95
Averaged result (%)	**11.4**	**3.0**

Commentary

The data recorded over the three tests showed that the oscillation frequency of the suspension was too high, and the damping ratio too low, to satisfy road-friendly requirements. Consistent results across the three tests indicated that the system was able to produce a repeatable determination that the suspension was not road-friendly.

In each test, the ramps failed to eject properly after the wheels dropped onto the ground. This phenomenon has been shown to occur with lightly-loaded axles. As the axles of this vehicle were loaded to only 5.46 tonne each, they were not able to exert enough force on the ramps to cause them to eject fully. Nevertheless, the measured results were useful in identifying the suspension's characteristics.

7.4 Discussion of Stage 3 Test Results

This section reviews the results of the new tests performed during Stage 3 (Section 7.3). A recap of the details of the DynaSsess system is provided as an introduction to the findings.

7.4.1 DynaSsess Operation

The measurement method employed by the DynaSses system requires two sensors to be temporarily fitted to the wheel hubs on both sides of the vehicle, and then removed at the completion of the test. To protect the intellectual property of the system owner, details of the sensors used as part of this system were not disclosed. Processed data was provided to ARRB for review and analysis. The measurement system includes allowance for axle hop and the results were shown to be accurate and repeatable.

Rather than requiring the user to select points and a baseline for input into a formula, the DynaSsess analysis method employs a multi-body dynamic model representing the various modes of suspension behaviour, which can include axle hop, roll and bounce. This model is fitted to the measured test data and its parameters are adjusted automatically until the model output closely matches the measurements. 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. The 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.

7.4.2 Testing of Triaxle Trailer

The use of the DynaSsess system on the triaxle semi-trailer suspension demonstrated that it is able to determine the oscillation frequency and damping ratio of a multi-axle suspension, regardless of which axle the system's sensors are fitted to. Further, the excitation mechanism employed by the system, being the individual ramps placed in front of each wheel, is capable of causing all wheels of the axle group to drop to the ground in unison. This simultaneous generation of impulse was shown to be repeatable across multiple tests.

The movement of the excitation ramps after being run over was predictable and consistent across the three tests. Each ramp was flipped over by the force of the wheel traversing it. It was then pushed along the road surface by the following wheel, causing no hindrance to the wheel and applying no further input to the suspension. This behaviour ensured that the suspension was able to oscillate as a result of only the initial impulse.

7.4.3 Testing of Rigid Truck with Tandem Drive Group

An essential requirement of a road-friendly test system is its ability to detect and reject a suspension that does not meet road-friendly requirements. To ascertain the ability of the DynaSses system to function in this way, tests were performed on a 6x4 rigid truck with leaf spring suspension (Figure 6.7).

The DynaSsess system reliably measured the oscillation frequency and damping ratio of the rigid truck's drive group suspension, with all results showing that the suspension was not a road-friendly unit. An important finding of the testing was that the excitation ramps were not properly ejected from beneath the wheels. Tests on other tandem-axle drive suspensions have been conducted in the past using the same excitation ramps. This demonstrated that the failure of the ejection process was not related to the drive torque applied by the wheels. It was concluded that the ejection failure was caused by the light load on the suspension, with each axle of the rigid truck imposing only a 5.46 tonne load on the road, compared with the usual 8.25 tonne load applied by such axles.

As the DynaSsess analysis method applies a consistent method, can resolve the effects of roll, pitch and axle hop, is automated to eliminate the chance of human error and is able to function on single, tandem or triaxle groups, it is strongly recommended for use in an in-service compliance test.

8 REVIEW OF ON-BOARD MASS DATA

The test results obtained from Stage 2 showed that the CHEK-WAY® Eliminator system (an on-board mass monitoring device) was not sufficiently repeatable with either the pipe test or on-road excitation methods. Based on this finding the operational evaluation that was proposed for completion during Stage 3 was revised. The revised task undertaken during Stage 3 was a review of a sample of data collected by the CHEK-WAY® Eliminator system when it was fitted to a B-double during normal operation[2].

An example of the header file, including the description of for each data packet, is shown in Figure 8.1.

Figure 8.1: Example of on-board mass header file

```
CWGI,ZA63456,08,10,01,45,6D,A,17795,07122014,225914,-33.796385,151.086383,0250,
0000,18859,07,GRP1 Data
```

`CWGI` = Prefix for automated Inscom transmission
`ZA63456` = Start of Inscom header / channel / amp identity
`08` = record number within this Smart Amp (hex)
`10` = Inscom Control flags
`01` = Age of GPS data (bit marker moves left each second there is no gps)
`45` = Preset Trigger threshold for Inscom (hex)
`6D` = Maximum level within the captured data (hex)
`A` = Trigger source = Auto (M = manual by driver)
`17795` = DCU number
`07122014` = International date
`225914` = International time
`-33.796385, 151.086383` = Latitude / Longitude
`0250,0000` = Speed and direction (to 1 decimal point)
`18859` = Current steady weight (in Kg - damped)
`07` = Marker flags for enabled Inscom Smart Amps. (7 = 3 channels A,B,C.)
`GRP1 Data` = indicates which side the sensor is on. (GRP1 is passenger side, GRP2 is driver side)

The mass data follows on immediately from the header information as shown in Figure 8.2.

Figure 8.2: On-board mass header and data file

```
CWGI,ZA63456,08,10,01,45,6D,A,17795,07122014,225914,-33.796385, 151.086383,0250,
0000,18859,07,GRP1 Data,056,056,056,056,056,056,056, 056,056,056,060,060,060,060,
060,060,060,060,060,060,060,060,060,059,059,059,059,059,059,059,059,059,059,059,059,05
9,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,
059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,059,05
9,059,059,060,061,066,080,100,109,109,107,102,097,092,086,079,070,059,057,057,
057,057,
```

Each reading relates back to that portion of the 'Current Steady Weight' that is supported by the air bags and shows the variation from steady weight. The readings have been converted from 1 byte hexadecimal for convenience and can have a decimal value of 000 to 255.

An explanation of the values is as follows:

2 ARRB was supplied with 2 weeks of data from September/October 2016 for the B-Double operated by Mr Rod Hannifey.

- 030 equates to a halving of supported weight
- 060 equates to no variation in supported weight
- 090 equates to 1.5 times the supported weight
- 120 equates to 2 times the supported weight
- 150 equates to 2.5 times the supported weight.

The readings are spaced at 24 milliseconds, providing 417 data points per 10 seconds of data recorded.

Analysis of the data was conducted and the visualisation shown in Figure 8.3 was produced to show the location of the vehicle during normal operation.

The arrows indicate the direction of travel as the vehicle travels south from Bundaberg while unladen and north when laden. The arrows are coloured from green to red depending on the weight range of the vehicle.

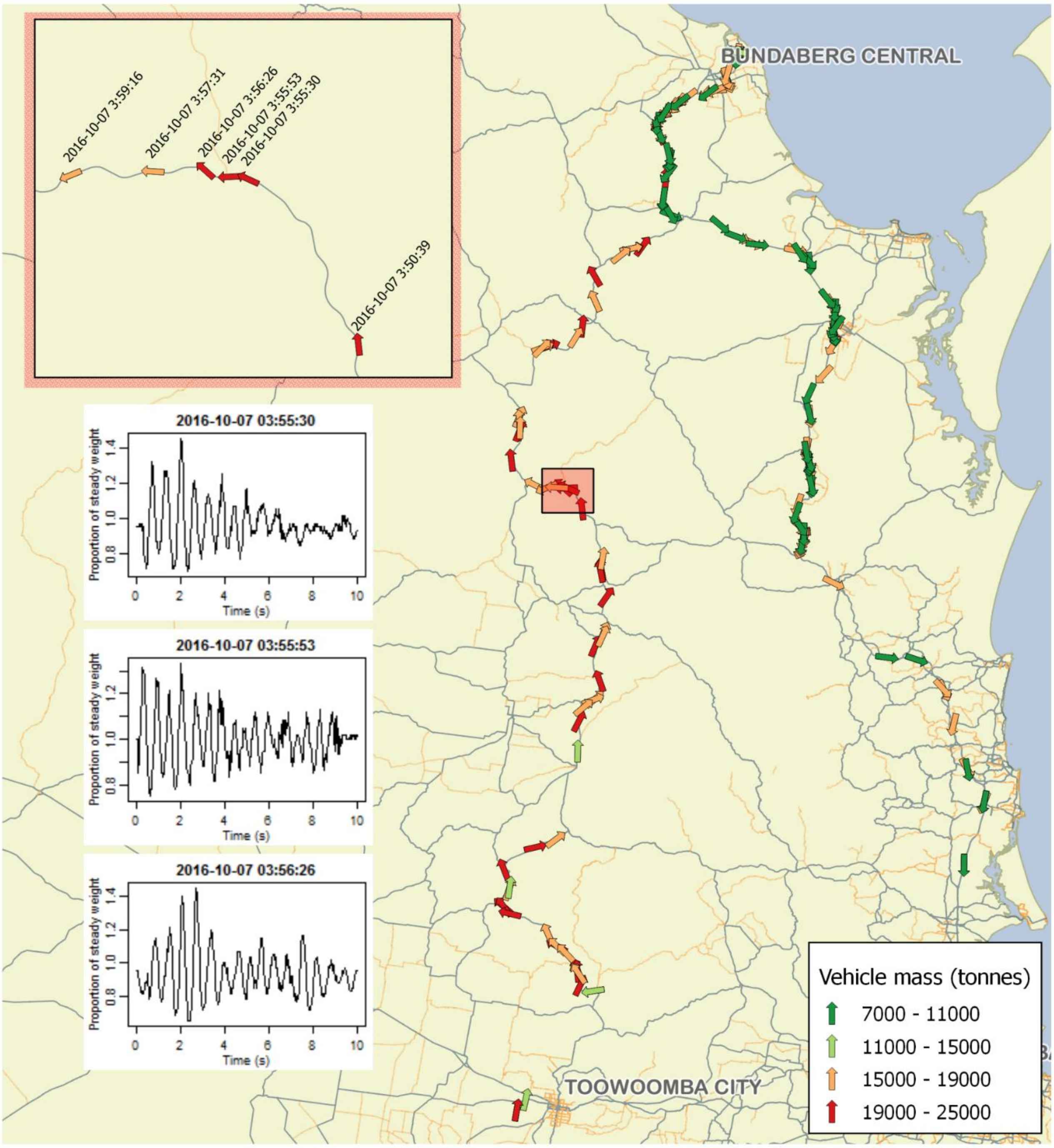
The inset map shows six locations where the logging system was triggered to record a 10 second sample of data. It can be observed that the first four data points are red (indicating the scales are reading between 19-25 tonnes) and the subsequent two data points are orange (indicating the scales are reading between 15-19 tonnes). There is approximately 9 minutes between the first sample and the sixth sample and the vehicle is travelling at a steady speed between these two points; the variation in mass cannot therefore be due to the vehicle stopping and unloading a portion of its payload. The reason for this variation in static load is not apparent, but can be observed for the duration of the journey.

Further analysis of the dynamic loads at three successive data points (within the same data range, i.e. 3:55:30, 3:55:53, 3:56:26) was conducted. The data traces for these are shown below the inset map in Figure 8.3. For each of these examples the peak loads were between 1.3 and 1.5 times the static load. The damping ratio of the suspension could not be calculated such that it aligned with expected VSB11 performance.

Based on these datasets there was no correlation between the damping rates in each of the three examples. These findings are consistent with the controlled on-road tests conducted during Stage 2 which found that variations in speed and road surface prevented the quantification of variations in suspension performance.

The analysis of this (on-board scales) dataset differed from the analysis conducted during Stage 2; as it included a larger number of samples over a wider portion of the road network. The analysis was undertaken to investigate if the limitations identified in Stage 2 could be overcome by collating information from a much larger dataset. Despite the dataset including a number of trips repeated over the same route, the data was not sufficient to determine suspension performance or any trends relating to suspension damping that could provide insight into the road-friendliness of the suspension as it relates to VSB11.

Figure 8.3: Visualisation of data obtained from on-board scales



9 RESEARCH FINDINGS

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

- excitation
- measurement
- analysis.

9.1 Excitation Methods

The following excitation methods were evaluated and for each method a summary of the key findings is provided:

- rolling 80 mm step method (VSB11 method)
- open road ‘pothole’ method (CHEK-WAY® Eliminator)
- pipe test (CHEK-WAY® Eliminator)
- RFS analyser (RFSA)
- stationary rocker mechanism (DynaSsess).

9.1.1 Rolling 80 mm step method (VSB11 method)

This method generates an impulse as the wheel rolls off the step and drops to the ground. 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, resulting in measurement errors.

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, then other (asymmetric) modes may be excited and analysis becomes complicated. As shown in Figure 9.1, to achieve this the vehicle must be positioned on sets of blocks. In this case, and in 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. Testing 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. Whilst this method was acceptable to complete the testing, it 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 9.1: Demonstrating practical issues with step method during test 3

The vehicle should be travelling at 5 km/h when it falls off the step. This 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 a 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.

The VSB11 ramp excitation method causes disturbances (as the wheels mount the steps and as they fall off the step) which invalidates the response. It is not considered to be suitable excitation method for in-service testing.

9.1.2 Open Road 'Pothole' Method (CHEK-WAY® Eliminator System)

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 investigated the relationship between dynamic pavement forces and road roughness according to the range of roughness values encountered during testing along a section of road. The report states that the mean and standard deviation of heavy vehicle wheel forces did not correlate with pavement roughness; however, peak wheel forces did.

Despite the limitations identified during the literature review, this method offers great potential and an ideal solution when using existing on-board technologies fitted to vehicles. The benefits include the ability to obtain live data during a journey which could be potentially uploaded to a remote server for review at any time. The development of the CHEK-WAY® Eliminator system was based on providing this remote and automated compliance solution. It offers many advantages, most importantly eliminating the need to conduct road side inspections.

The method of excitation was assessed during Stage 2 of the testing and the 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 the wheel paths. The result of this is that the suspension continues to receive impulses, thus introducing other effects such as body pitch and roll, and this makes analysis difficult.

The data logged during on-road testing demonstrated 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.

The open road 'pothole' excitation method does not sufficiently excite the suspension and is not repeatable (due to variations in speed and road surface). It is therefore not a suitable excitation method.

9.1.3 Pipe Test (CHEK-WAY® Eliminator System)

The pipe test aims to address the deficiency of the on-road testing method. The pipe test generates an impulse by driving the vehicle over a rigid steel pipe of nominal outer diameter 48 mm. It is located on a smooth road surface such that the suspension is free from interference.

The pipe test was evaluated during Stage 2 at speeds between 3 and 5 km/h. Initially tests were conducted at 20 km/h as per the procedure for the system. The results showed that a speed of 20 km/h, it was not an effective method for exciting the suspension.

Further test were conducted at lower speeds. The lower speed produced much better results, as the suspension was able to be excited at the natural frequency of the suspension. However, the driver was not able to maintain a steady speed and small variations in speed (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 pipe test generated results which consistently underestimated the damping performance of the suspension system when compared with the VSB11-approved excitation methods.

The pipe test excitation method generates a considerably different excitation impulse compared to VSB11 methods. This invalidates any comparison of performance between the two methods. The pipe test is not a suitable excitation method.

9.1.4 Road-friendly Suspension Analyser (RFSA)

The RFSA excites the vehicle by raising a platform (by 80 mm via a pneumatic system) upon which the vehicle is positioned, air is then exhausted from the system, which allows the raised vehicle to drop.

This excitation method eliminates tyre enveloping problems that exist with alternative methods that involve driving a vehicle over a step or pipe. The vehicle does not roll forward but it drops vertically over a longer period of time causing the impulse to be less than the other methods. The creation of two or three impulses (an issue for tandem or triaxle groups when using the step or pipe method) is also an issue for this method. A repeatable and simultaneous drop of all axles is not easily achieved. The load distribution of the vehicle can affect the drop as the vehicle may pitch or roll depending on whether the load is biased to the front or rear or left or right. These effects prevent an accurate assessment of the suspension performance to be made.

There are four major practical disadvantages with this method associated with the need for the vehicle to be driven onto the rig and positioned accurately on the load plates:

- care must be taken to ensure there is suitable clearance between the vehicle and rig and some vehicles with underslung suspensions may not be suitable

- the driver must position the vehicle precisely on the load plates (within 10-20 mm)
- the brakes must be released prior to the vehicle being dropped and then re-applied
- the position of the rigs must be adjusted to suit variations in axle spacing and wheel bases, as each platform weighs approximately 800 kg; this requires a forklift.

When used for VSB11 certification these practical issues are managed by using experienced drivers and test engineers. 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 highly repeated 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 RFS analyser excitation method has a number of practical limitations that prevents it from being a suitable excitation method for in-service testing.

9.1.5 Stationary Rocker (DynaSsess System)

The excitation method used for DynaSsess system is similar to the VSB11 ramps. It is based on providing an impulse from the vehicle dropping off a fixed height sufficient to excite the resonant frequency of the suspension. It differs in that the vehicle begins from a stationary position, thus eliminating the issues associated with variations in approach speeds and tyre enveloping.

Tests were conducted with a single axle and later with a tandem and triaxle group. The results confirmed that this method reduces the errors associated with the axles not falling simultaneously.

The stationary rocker excitation method was shown to produce the most consistent impulse and subsequently the most repeatable test results. This excitation method is considered suitable for both VSB11 certification testing and in-service testing.

9.1.6 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 synchronization. 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. It is considered to not be feasible as an in-service compliance test method.

The RFSA proved to be reliable producing highly repeated drops, in a highly controlled test environment. However, it is not expected that this level of repeatability will be achievable when used for roadside testing as part of an in-service compliance solution. The practical issues associated with this method are prohibitive to successful implement it 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 and this has contributed to the variability of the certification results. Despite the chassis pull up/pull down method being permitted under VSB11, these were not included in this study based on the findings of a review of in-service test methods (NTC 2008) which rated the practicality of these methods as very low and unsuitable as an option 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. However, these methods are not repeatable (due to variations in speed and road surface) and pipe test method in particular generates a considerably different excitation impulse when compared to VSB11 methods which invalidates any comparison of performance between the two methods.

Testing involving the use of individual rocker-action ramps was designed to address these practical issues. The results were shown to be the most repeatable and consistent. This excitation method is considered suitable for both VSB11 certification testing and in-service testing.

9.2 Measurement Methods

The following measurement methods were evaluated and for each method a summary of the key findings is provided:

- air pressure sensors (APS)
- linear displacement transducers (LDT)
- on-board scales (CHEK-WAY® Eliminator)
- load cell platforms (RFSA)
- hub-mounted sensors (DynaSsess).

9.2.1 Air Pressure Sensors

APSs were used as the reference measurement system and fitted to the triaxle semi-trailer used in Stage 1 of testing. Six pressure sensors were fitted to air bags of the triaxle trailer to measure the variations in pressure due to roll (left and right) and pitch (between fore and aft axles). It was found that there were small variations between the left and right side of the vehicle due to body roll. The analysis method must consider these effects and compensate for it by summing the signals from both sides. For a three-axle suspension it is sufficient to measure the air pressure of the middle axle only as the suspension will typically pitch about the middle axle.

Air pressure sensors were shown to be suitable for measuring oscillation and subsequently suspension performance.

9.2.2 Linear Displacement Transducers

LDTs are the measurement sensors required by VSB11. They 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 during the pipe test at low speed.

As with measuring suspension performance via pressure sensors it is necessary to compensate for roll and pitch. A total of six sensors were fitted to the triaxle. The difference between axles was 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 LDTs. The damping results calculated using the front, middle and rear axles with medium damping shock absorbers were 4%, 9%, and 13% respectively. For the results obtained from the VSB11 ramp tests the damping ratio calculated using the LDTs was less than the results obtained using the APSs.

Further analysis is required to understand this result; 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 LDTs 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 were comparable and both sensors were able to measure both damping and frequency. This assumes that they are fitted correctly and that the data obtained from them is analysed correctly.

9.2.3 On-board Scales (CHEK-WAY® Eliminator)

This system typically utilises two air pressure sensor 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 and number of sensors may influence the latency of the signal. For example if positioned far from the air bag, the connecting hoses could act as pneumatic means of averaging the signal – 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 confirm 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 that 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.

This system uses air pressure sensors as the measurement device, as does the reference system; therefore, the findings for APSs are applicable to this system. APSs were proven to be less responsive and not contain all the frequency modes present in the suspension. Nonetheless, the results are comparable to the results obtained by LDTs in terms of measuring damping and frequency. The limitation of this system is that it does not 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 a degradation in the suspension system.

9.2.4 Load Cell Platforms (RFSA)

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 measurement 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 hop, the consequence can be worse than not measuring it all, resulting in significant errors.

9.2.5 Hub-mounted Sensors (DynaSsess)

The measurement method employed by this system requires two sensors to be temporarily fitted to the wheel hubs on both sides of the vehicle; they are removed at the completion of the test. Details of 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 includes 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 in order to gain a better understand of the capability of this system.

9.2.6 Summary of Findings

The measurement methods assessed included air pressure sensors, linear displacement transducers and load cells. The measurement method used as part of the DynaSsess system was not disclosed to ARRB. All systems proved 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; however, must be resolved during the analysis.

9.3 Analysis Methods

The analysis method required by VSB11 is considered a critical step in ensuring the correct assessment of the health of the suspension.

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. In cases where the oscillation continues to occur for an extended period of time due to poor damping, the baseline value is selected before oscillations begin.

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

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

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) occurs and the time when the following peak (T2) occurs. The following equation was then applied to calculate the frequency.

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

where

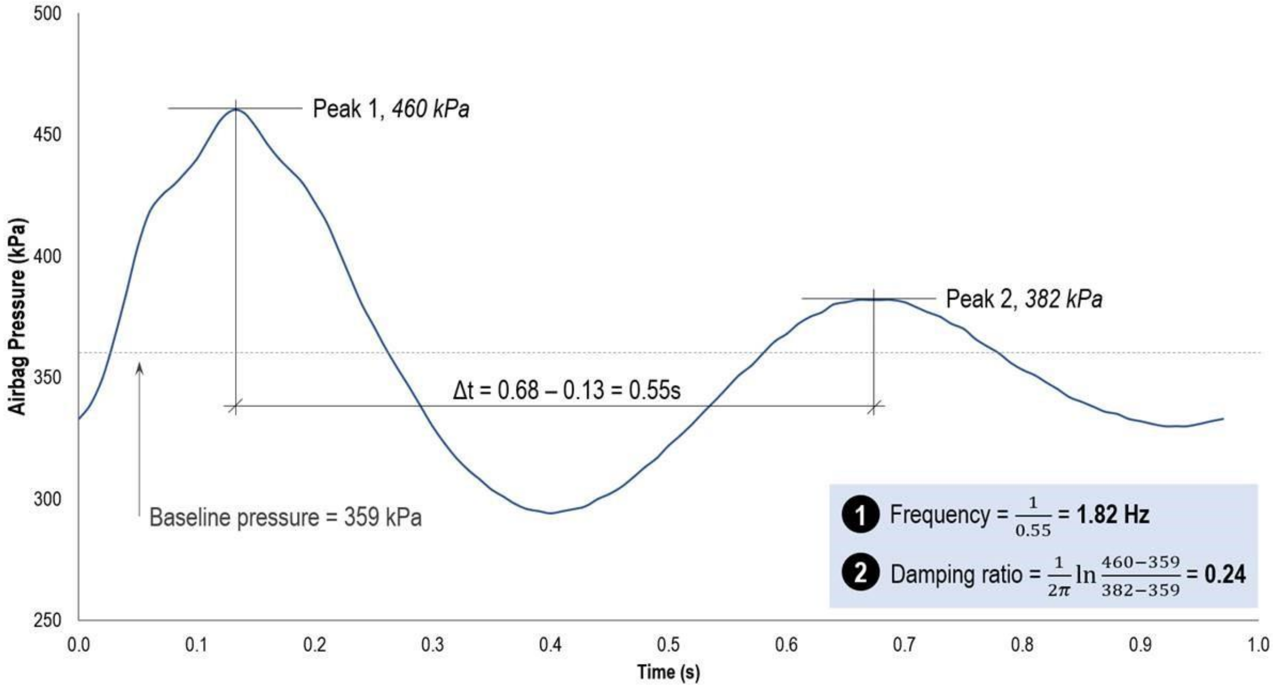
T1 = Time at which peak amplitude of the first cycle of oscillation occurs.

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

9.3.1 Manual Selection of Two Consecutive Points (VSB11)

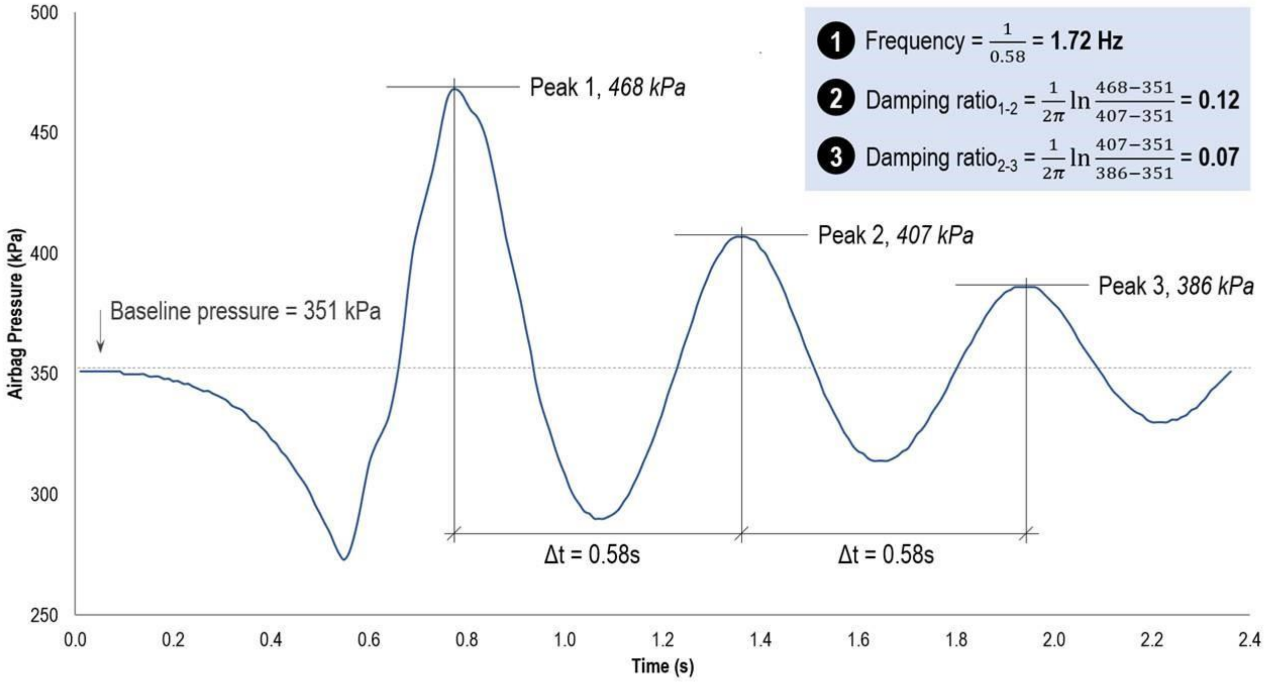
As previously discussed, the method for calculating the damping ratio in line with VSB11 is to identify two successive peaks. This process is demonstrated in Figure 9.2. In this example, Peak 1 (460 kPa) is the first peak in magnitude upon compression after dropping off the 80 mm step. Peak 2 (382 kPa) is the next successive peak. A baseline value of 359 kPa was 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 the RFSA as this system does not include its own analysis method.

Figure 9.2: Example of calculating damping ratio using successive points



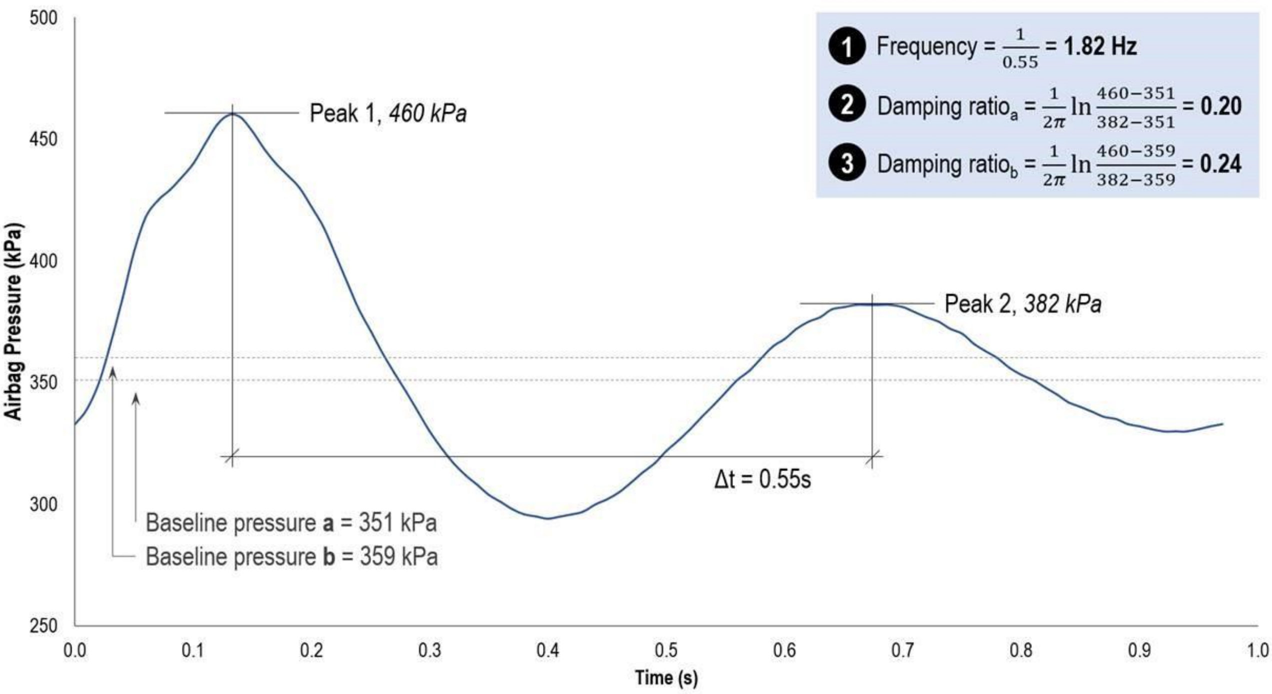
This means that the selection of which two successive peaks to use for the calculation is open to the interpretation of the user. This method produces consistent results only if every peak declines at the same rate from the first to the last. This is not the case for a number or reasons; it is the responsibility of the user to select two points that best represent the response of the suspension and to use those two points consistently across all tests. The selection of peaks can result in significant differences in damping ratio. Figure 9.3 shows an example data trace from Stage 1 of testing where he difference in results if the first and second peaks are compared with the second and third peaks. The damping was calculated to be 12% or 7% depending on what peak was selected, despite the fact that the frequency does not change.

Figure 9.3: 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 a different positions following the test. Figure 9.4 shows the variation in damping depending on the baseline value selected. This example is based on data from Stage 1 testing; a damping ratio is 20% or 24% depending on which baseline value is used.

Figure 9.4: Variation in damping due to selection of baseline value



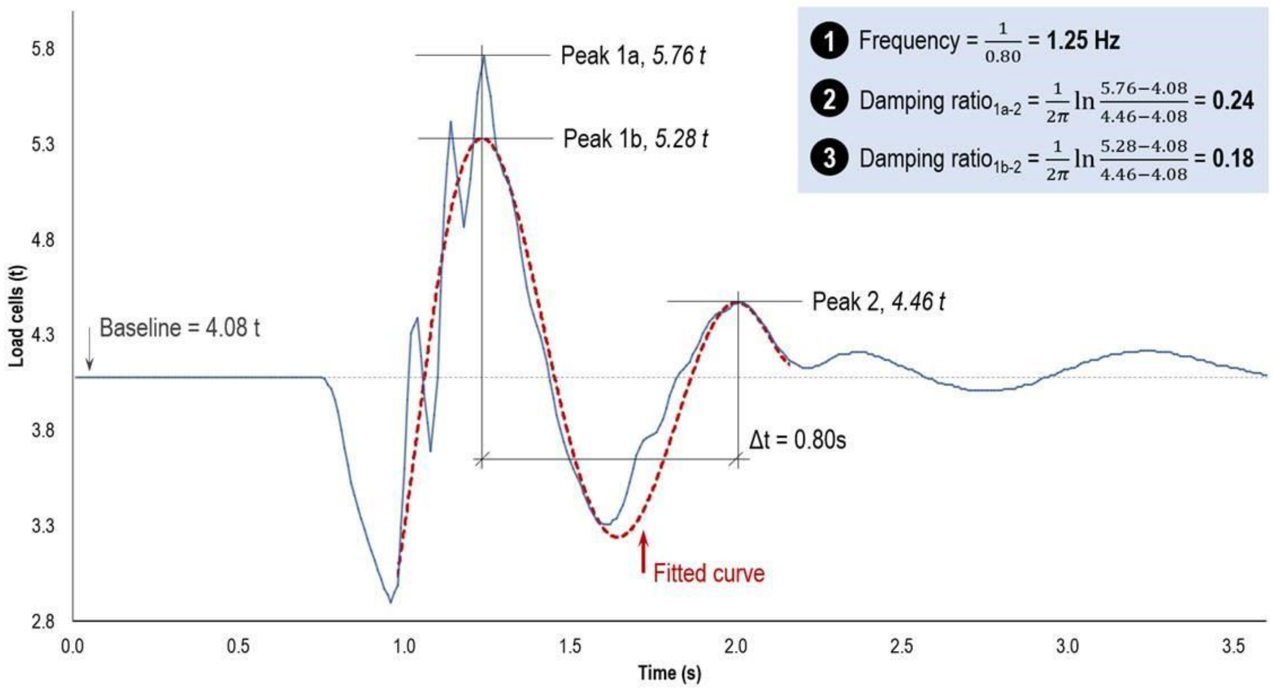
9.3.2 CHEK-WAY® Eliminator System

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 this system is propriety and was unable to be reviewed in detail. However, based on the similarity of the results it is likely that the analysis method was the VSB11 method 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.

9.3.3 RFSA

As the RFSA does 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 9.5 shows an example of the variation possible due to axle hop if it is not resolved correctly during analysis. The data trace used in this example is from Stage 2 of testing. The axle hop is present throughout the first oscillation, immediately after the drop is complete, and when the vehicle is bouncing on its tyres. As this dissipates more quickly than the suspension oscillations it 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 9.5: Example of calculation with and without resolving axle hop



9.3.4 DynaSsess

This system employs a different approach to data analysis. 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 the user selecting 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.

9.3.5 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 depending 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 Stage 2 of the testing program, 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 is consistent, that can resolve the effects of roll, pitch and axle hope, and is preferably automated – thus eliminating the chance of human error – is strongly recommended for an in-service compliance test.

10 INDUSTRY CONSULTATION

Consultation with the major Australian suspension and suspension parts manufacturers was undertaken during Stage 3 of the project. The aim of this consultation was to determine the views of industry, in particular the level of understanding of RFS performance and the expected impact of adopting of an in-service testing regime based on the preliminary findings from Stages 1 and 2 of this project. Consultation was conducted in person or via teleconference with three suspension manufacturers and two brake component manufacturers. The anonymity of the participants has been maintained at their request. The consultation was based on a series of questions that led to a general discussion. S summary of each major topic discussed follows. The two brake manufacturers consulted were not actively involved in RFS certification or in-service testing; their views are only included where relevant. The summary is therefore largely based on the views of the suspension manufacturers.

10.1 Current RFS Performance Requirements as Defined in VSB11

All the suspension manufacturers held concerns about the current requirements of VSB11. The major reason given was the need for re-design and the provision of shock absorbers specific to the Australian market simply to comply with the RFS requirements. It was explained that Australia is a relatively small market and it is not cost-effective to invest in the design and development of new components for these unique performance requirements. A consequence of this is that manufacturers are sourcing alternative and typically more expensive shock absorbers that are designed to have high damping characteristic *'The RFS requirements are such that the shock absorbers must continue to maintain the same durability at high loads and with a much higher stiffness. The result is a more expensive and more difficult to source shock absorber.'*

Another suspension manufacturer raised concerns that the VSB11 requirements are too flexible, offering a number of options for testing and recording: *'they are too open to interpretation and this can lead to ambiguous overall results. When called to compare results at a later date or possibly in service the validity of the initial or in service test could be raised'.*

One manufacturer explained: *"Typically we see suspensions that are within our own product range which are more road-friendly than others. We are of course trying to use common parts to create a wide range of options/flexibility for trailer builders and operators. With the current VSB11 requirements not all of our range can be offered. In particular there are limitations or additional demands on shock absorbers; the number of shock absorbers we offer in Australia is limited and the demands on the performance specification for the Australian shock absorbers is often unnecessarily over and above what we use for other developed countries.'*

10.2 Current RFS Testing and *Certification Pro*cesses

Two suspension manufacturers outsource their RFS testing services to their own preferred suppliers; one uses the pull-up-and drop method while the other uses the pull-down-and-release method.

The same measurement method – linear displacement transducers fitted between the body and axles – were used by both manufacturers.

The analysis methods differ between manufacturers, with one manually selecting any two consecutive peaks as per VSB11 and the other relying on software (developed by the certifying agent) to interpret the displacement peaks and troughs as well as the frequency of the suspension.

The other suspension manufacturer advised that they conduct their testing in-house predominantly using the chassis-drop method but have used other methods in the past including the drive-over-step method. They both use LDTs as the method and manually selecting successive peaks to calculate damping and frequency analysis.

One manufacturer noted the importance of selecting a centreline for the trace and the considerable effect this can have on the final result. The manufacturer was aware that VSB11 is open to interpretation and depends on symmetrical the compression and rebound part of the traces in order to make a fair and correct assessment.

10.3 Need for a Review of VSB11

All manufacturers supported a review of the current certification requirements defined in VSB11. Suspension manufacturers demonstrated a good understanding of the issues relating to VSB11 and justified their position by listing the following limitations or gaps in the current VSB11 standard:

- load sharing (dynamic or static) requirements are not clear
- there is no reference to testing and certifying axle groups; for example, current practise is to extrapolate from single axle tests, which is not robust
- there are no test conditions specified for quad-axle groups within VSB11 even though there is a requirement for road-friendly certified suspensions to be used in quad-axle groups
- there is considerable variability in test methods and analysis techniques.

Manufacturers raised concerns that these three issues may render products non-compliant if an in-service standard is introduced without these issues being first addressed. It was noted that a review of VSB11 that changed the certification requirements could create legacy issues of previously-tested suspensions being found to be non-compliant even if in-service testing is not adopted.

Regarding test conditions, one manufacturer explained the test weight requirements differ for each axle group type (single/tandem/triaxle and quad-axle); however, the shock absorbers are, where possible, the same. Therefore a single-axle suspension will be more heavily damped compared to the quad-axle. This manufacturer highlighted: 'from a test point of view we don't see why if you test a single (axle) and a quad (axle group) that then the tandem and triaxle groups should be covered as their performance is in between. Similarly if we test a shocker in a given position relative to the spring eyebolt once we establish a minimum radius/line of action for the shocker that a larger radii should be acceptable.'

10.4 Introduction of an In-service Test or Performance Requirement?

The three manufacturers were not in agreement about whether in-service testing should be introduced.

Manufacturer 1 stated: *'We do not support in service testing due to the issues discussed previously (documented above). The concept is a good one but it appears there are too many potential issues for it to be practical. Allowing a range of test and analysis methods for initial compliance and then re-testing suspensions when in-service with a single test methodology is likely to produce different results between initial and in service tests.'*

Manufacturer 2 supported in-service testing with the following statement: *'If it is required to further productivity then Manufacturer 1 will work with customers.'*

Manufacturer 3 stated: *'If there is a simple reliable method to check in-service road-friendliness then something should be adopted. Currently there are just subjective checks regarding shock absorber condition or sometimes people use a comparative temperature check by using an infra-red temperature gun to see if the temperature of all shock absorbers on the trailer are* *approximately equal. If they are then usually it is concluded that the suspension is working satisfactorily but it could be that all are good or that all are bad.'*

10.5 Readiness to Provide Solutions to Determine In-service Road-Friendliness

None of the suspension or brake manufacturers consulted had a readily available product or solution that could be used to determine *in-service road-friendliness.* The comments from the suspension manufactures are as follows:

'We don't have one that would be practical and cost affective to implement at this stage.'

'We don't have a system solution ourselves. The requirements for this seem to be fairly targeted to the Australian market. I'm not sure what happens when such a solution is found. You could argue then that operators could mix and match componentry that hasn't otherwise been tested under VSB11 or similar and could still pass a "road-friendly" in-service performance test. This would require a rethink from the point of view of up-front (VSB11) certification and the expense that is involved along with the current mass management type schemes.'

'No readily available solution but are exploring options with existing suppliers.'

One brake manufacturer explained that they had explored the possibilities that air pressure sensors could offer but found that the repeatable measurements were not possible across a range of vehicle types including variations in suspensions, tyres, payloads, and environments.

Their reasons for not pursuing the commercialisation of an in-service testing solution were consistent with the findings from the on-road tests conducted during Stage 2 and the analysis of on-board scale data during Stage 3.

11 SUMMARY OF KEY FINDINGS

The findings of all three stages of the project are summarised in this section. They have been grouped under the following topic areas:

1. **Literature review** findings relating to the theory of dynamic loads and pavement wear
2. **Emerging technologies** and their potential to determine in-service compliance
3. **Field test results** and analysis of selected technologies
4. **Industry consultation**.

11.1 Literature Review

The literature review highlighted the knowledge gaps in the relationship between RFS systems and pavement wear. While considerable research had been conducted in this area, the review highlighted that the following is not known:

- the relationship between pavement type and pavement wear resulting from RFS
- the relationship between suspension characteristics and dynamic loading
- the level of compliance of in-service suspensions with current RFS requirements.

While each of these knowledge gaps has an effect, a lack of knowledge regarding the relationship between suspension characteristics and dynamic loading is critical and prevents a new in-service standard from being set. This is because the relationship between suspension frequency and damping, and the resulting dynamic loading applied to the pavement, cannot be defined at this time.

The practical issues of conducting a roadside test that strictly adheres to the requirements of VSB11 render many options unviable, in particular those that require shock absorbers to be removed or those that require the vehicle to be loaded to a specified test weight.

Despite this notable knowledge gap, the option of pursuing an alternative path to VSB11 remains available if the relationship between suspension characteristics, dynamic loads and pavement wear is better understood. An alternative to directing addressing this knowledge gap is to apply a tolerance for acceptable in-service performance which was explored in this project.

11.2 Emerging Technologies

A survey of emerging technologies was conducted and three products were deemed suitable for subsequent testing and evaluation.

One of these products (CHEK-WAY® Eliminator) was a commercial (on-board scale) system commonly fitted as an after-market option to measure the mass of a vehicle. This product was modified specifically to monitor the health of the suspension and, although it was found to measure suspension oscillations, the system was not able to determine road-friendliness. The other two products evaluated were developed as a part an engineering consulting services required for RFS certification.

The RFSA was found to be not practical for in-service testing.

The DynaSsess system was found to be the most suitable option. The system specifically addressed the limitations associated with repeatable excitation and analysis methods.

Despite no other submissions being receiving, industry consultation was undertaken to determine the readiness of the major suspension and brake manufacturers to provide an in-service solution. It was found that none offered an on-board vehicle technology suitable for determining in-service RFS compliance.

Developments in on-board mass monitoring technology, vehicle telematics and the increased sophistication of heavy vehicle braking systems continue. As these systems become more advanced they may in the future provide options for cost-effectively monitoring suspension performance of a number of vehicles during their normal operation. However, the test results (summarised in the following section) showed that the limitations do not lie in the accuracy of the technology but rather the need to control the variations in the test conditions.

11.3 Results of Field Testing

The test results showed that excitation, measurement and analysis were critical steps in accurately determining suspension road-friendliness. It was found that the measurement method could be achieved by air pressure sensors and this offers the potential for on-board systems to monitor suspension health. However, the excitation and analysis methods were shown to cause significant sources of error.

11.3.1 Excitation Methods

- Test results conducted on-road, over ramps, steps or pipes showed that these excitation methods produced significant sources of error due to variations in speed and the roughness of the road surface. These sources of error were shown to be difficult to control in a roadside environment, thus rendering them unsuitable excitation methods.
- VSB11 ramps proved to be suitable for single axles, but when used for more than one axle they were susceptible to the errors caused by the wheels dropping at different times and impulses being out of synchronization. The practicality of this method was another prohibitive limitation.
- 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 most repeatable excitation method was the cantilever ramps developed as part of the DynaSses system. These were shown to sufficiently reduce the effects of tyre enveloping, speed and road surface. Tests with tandem and triaxle suspensions confirmed its suitability for these suspension groups.

11.3.2 Measurement Methods

- The measurement methods assessed included air pressure sensors (APSs), linear displacement transducers (LDTs) 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
- Despite the sufficient measurement accuracy, current on-board technologies lack the ability to isolate the effects of variations in the road surface, vehicle dynamics and environmental factors.

11.3.3 Analysis Methods

- The analysis method stipulated in VSB11 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 showed significant errors due to the analysis method alone.
- The most repeatable analysis method used a multi-body model and limited user-interface. The DynaSsess analysis software which employed this method produced the most consistent results and included functionality to resolve the effects of roll, pitch and axle hope. The analysis software was fully automated, thus eliminating the chance of human error.

11.4 General Findings

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. This project revealed that there are consistency issues associated with existing certifications while still complying with the current test methods. The variations possible under current certification methods for new suspensions as documented in VSB11 prevent comparison with in-service test results. The result is that in-service test results cannot be compared to certification results with any more accuracy than the accuracy of the original tests.

11.5 Industry Consultation

- All the suspension manufacturers consulted held concerns about the current requirements of VSB11.
- Some manufacturers conducted testing in-house while others used external engineering services. The methods employed differed between manufacturers. The issues regarding repeatability and consistency were well understood by the manufacturers and their service providers and were being managed to maintain consistent results.
- All manufacturers supported a review of VSB11 but expressed concerns that, if the review resulted in changes to the certification requirements, then it would create legacy issues with previously-tested suspensions and this must be managed.
- The suspension manufacturers consulted were not in agreement about whether in-service testing should be introduced. The practical issues were considered by some as prohibitive in terms of introducing an effective in-service compliance standard.

12 RECOMMENDATIONS

The work program undertaken during this project was aimed at developing a better understanding of the challenges associated with in-service compliance of RFS and exploring the options to address this issue, including technologies offering potential solutions for in-service testing.

A fundamental problem to implementing any changes to the current RFS requirements is the lack of knowledge regarding the relationship between pavement wear, suspension characteristics and dynamic loading. At the completion of Stage 1 of this project the following two options were available: 1) to proceed with an in-service standard by applying a tolerance to mitigate legacy issues with existing RFS requirements, and 2) develop an in-service standard that determines suspension health independent of the existing VSB11 requirements.

The findings from Stage 2 showed that the variations in suspension performance possible under the existing VSB11 test method were such that the tolerance required would need be in the range of 30-50%. This tolerance would be required to avoid failing a newly-certified suspension (with no wear); however, such a tolerance would prevent the detection of worn shock absorbers. This renders the introduction of an in-service compliance standard relatable to VSB11 (Option 1) as futile; the remaining option is to develop a standard independent of VSB11 requirements.

An in-service standard that determines suspension health independent of the existing VSB11 requirements is a feasible option but the practical issues of conducting a roadside inspection were found to be largely prohibitive. It was found that the on-board vehicle scales have sufficient measurement accuracy but the lack of a suitable excitation method prevents this being a viable solution. Current technologies lack the ability to isolate the effects of variations in the road surface, vehicle dynamics and environmental factors. A preferred RFS test method (based on the DynaSsess system) was identified that limits these variations to an acceptable level. However, this project has revealed that there are consistency issues with existing certifications that must be overcome first. The variations possible under current certification methods for new suspensions as documented in VSB11 prevent comparison with in-service test results. Because of this, it is recommended that the development of an in-service RFS compliance standard not be pursued in the immediate future.

The issues associated with the current VSB11 certification standards must be addressed prior to the introduction of an RFS in-service compliance standard. It is recommended that a review of VSB11 be conducted and that this be done at a national level. The review of VSB11 should include the following technical considerations:

- Detailed technical requirements must be defined for sufficient excitation of the suspension, accurate measuring systems and the analysis of the results.
- A single excitation method should be defined in the standard that limits the effects of tyre enveloping and vehicle speed and minimises the likelihood of body roll and pitch.
- A single analysis method needs to be developed that uses a multi-body model to determine the damping properties of the suspension and can produce consistent performance results. The analysis method should resolve the effects of roll, pitch and axle hop by measuring and compensating for it. Note that his step is not required if these effects have been eliminated as a part of testing method. Preferably the process should be automated, thus eliminating the chance of human error.

The review of VSB11 must engage actively with industry, in particular through discussions with the ATA, as well as key national stakeholders including DIRD and the NHVR.

REFERENCES

Australian Road Transport Suppliers Association 2001, 'Guidelines for maintaining and servicing air suspensions for heavy vehicles', *ARTSA, Hawthorn,* Vic, viewed on 24 June 2007, <http://www.artsa.com.au/RFSWorkbookReadOnly.pdf>

Austroads 2009, 'Measuring heavy vehicle wheel loads dynamically', *AP-T129-09*, prepared by C Blanksby, A Germanchev, A Ritzinger & R George, Austroads, Sydney, NSW.

Austroads 2012, 'Measurement and analysis of dynamic wheel loads', *AP-R406-12*, prepared by N Trevorrow, L Callaway & C Blanksby, Austroads, Sydney, NSW.

Blanksby, C, George, R & Germanchev, A 2006, 'An in-service survey of heavy vehicle suspensions', *ARRB conference, 22nd, Canberra, ACT,* ARRB Group, Vermont South, Vic, 12 pp.

Cebon, D 2004, 'Impacts of vehicles with higher mass limits on NSW roads', *report 03392/I, Roads and Traffic Authority, Sydney, NSW.*

Collop, A & Cebon, D 2002, 'The benefits of road-friendly suspensions', *International conference on asphalt pavements, 9th, 2002, Copenhagen, Denmark,* Danish Road Directorate, Ministry of Transport, Copenhagen, Denmark, 11 pp.

Davis, L 2005, 'Testing of heavy vehicle suspensions: proof-of-concept: 'white-noisy road test' and 'pipe test' to determine heavy vehicle suspension parameters', *Australian Institutes of Transport Research conference, 27th,* Brisbane, Queensland, Monash University, Institute of Transport Studies, Clayton, Vic., 21 pp.

Davis, L 2010, 'Heavy vehicle suspensions – testing and analysis', *PhD thesis, Queensland University of Technology, Brisbane, Qld.*

Davis, L & Bunker, J 2007, Heavy vehicle suspensions: testing and analysis: a literature review, Queensland Department of Main Roads & Queensland University of Technology, Brisbane, Qld.

Davis, L & Sack, R 2004, 'Analysis of heavy vehicle suspension dynamics using an on-board mass measurement system', *Australasian Transport Research Forum, 27th, Adelaide, South Australia*, University of South Australia, Transport Systems Centre, Adelaide, SA., 19 pp.

Davis, L & Sack, R 2006, 'Determining heavy vehicle suspension dynamics using an on-board mass measurement system', *ARRB conference, 22nd, Canberra, ACT,* ARRB Group, Vermont South, Vic., 12 pp.

Davis, L, Kel, S & Sack, R 2007, 'Further development of in-service suspension testing for heavy vehicles', *Australasian Transport Research Forum, 30th, Melbourne, Victoria*, ETM Group, Melbourne, Vic., 16 pp.

Department of Transport and Regional Services 2004, 'Certification of road-friendly suspension systems', *Vehicle standards bulletin no. 11,* DOTARS, Canberra, ACT.

European Union 1996, Laying Down for Certain Road Vehicles Circulating Within the Community the Maximum Authorised Dimensions in National and International Traffic and the Maximum Authorised Weights in International Traffic, Council Directive 96/53/EC of July 25, 1996, http://www.interregs.com/catalogue/details/eec-9653/directive-no-96-53-ec/weights-and-dimensions/?ref=eec-12.

MM Starrs Pty Ltd, Ian Wright & Associates & ARRB Transport Research 2000, 'Evaluation of in-service compliance of road friendly suspensions', National Road Transport Commission, Melbourne, Vic.

National Road Transport Commission 1996, ‘Mass limits review: technical supplement no. 2 to the steering committee report: road and bridge impacts’, NRTC, Melbourne, Vic.

National Transport Commission 2008, ‘In-service performance assurance for road friendly suspensions’, NTC, Melbourne, Vic.

Organisation for Economic Co-operation and Development 1997, ‘OECD DIVINE programme: final report: dynamic interaction of heavy vehicles with roads and bridges’, OECD, Paris, France.

Organisation for Economic Cooperation and Development 1998, ‘Dynamic interaction between vehicles and infrastructure experiment (DIVINE): technical report’, OECD, Paris, France.

Roebuck, RL, Isola, R, Goodrum, WJ, Cebon, D & Collop, AC 2012, ‘Vehicle-pavement interaction modelling’, *International symposium on heavy vehicle transportation technology (HVTT12), 12th, 2012, Sweden*, Conference Committee, Stockholm, Sweden, 12 pp.

Sharp, KG, Sweatman, PF & Addis, RR 1997, Results and major implications of the OECD DIVINE project: OECD co-operative international research into vehicle-road interaction: DIVINE project, *Proceedings 10th AAPA International Flexible Pavements Conference,* Perth, Western Australia, 9 pp. (Paper 36), Australian Asphalt Pavement Association (AAPA), Hawthorn, Vic.

Sweatman, P, McFarlane, S, Komadina, J & Cebon, D 2000, ‘In-service assessment of road-friendly suspensions: for information’, National Road Transport Commission, Melbourne, Vic.

APPENDIX A LITERATURE REVIEW

A.1 Summary

A.1.1 Summary of the Development of RFS requirements

The DIVINE study (Dynamic Interaction between Vehicle and INfrastructure Experiment) conducted by the Organisation of Economic Collaboration and Development (OECD 1997) is the definitive research project on the issue of the dynamic loading of pavements and bridges resulting from heavy vehicles. Research into dynamic loads was conducted via a number of research elements which included the use of accelerated load facilities, in-field testing and computer simulation. Australia played a leading role in the DIVINE study, with ARRB conducting the research for one of the project elements. In particular, Peter Sweatman and Kieran Sharp, research engineers at ARRB, participated in the Project Working Group. The concept of a RFS originated from this research.

Suspension type and characteristics were identified as key factors in relation to dynamic loads. Studies found that ‘soft’ springs, low vertical stiffness tyres and viscous (hydraulic) damping reduced dynamic loads, while friction in the suspension system increased dynamic loads (NRTC 1996). Sharp, Sweatman and Addis (1997) agreed with this, adding that dynamic load-reducing properties were unlikely to be found in mechanical suspensions, but were generally found in air suspensions. These findings supported the common understanding that, due to the inherent properties of the two suspension types, air suspensions offered advantages over mechanical suspensions in terms of dynamic loading.

Sharp et al. (1997) noted that, for the same static load, the dynamic forces generated were greater for a vehicle with mechanical suspensions than for air suspensions. For these reasons, air suspension systems were largely considered to be road-friendly and understood by the majority of industry and regulators to limit infrastructure wear and damage.

It was stated that there would be little effect on the rehabilitation cost of arterial and local roads with an increase in mass limits and the use of RFS compared with the continued absence of concessions to encourage RFS. It was concluded that, in terms of the comparative performance of suspension types, air systems dynamically load-shared better than mechanical systems at low speeds (NRTC 1996). Accelerated pavement testing conducted during the DIVINE project suggested that the rate of increase in pavement wear under a mechanical suspension was about 25% faster than under an air suspension (OECD 1997).

These findings led to subsequent research devoted to estimating the overall effects of increasing mass limits and allowing RFS for the purpose of improved freight productivity. This work included cost-benefit studies and ultimately led to the development of Vehicle Standards Bulletin 11 (VSB11) in 1999, later amended in 2004 (DOTARS 2004), in which the certification requirements for road-friendliness were defined.

Sweatman et al. (2000) investigated the comparative effects of air and mechanical suspensions on bridges and pavements and identified that the main cause of high dynamic loading in air suspensions was shock absorber degradation. Sweatman et al. suggested that road-friendliness related to suspension condition and maintenance, and recommended that in-service suspension testing be conducted and that a guideline for the maintenance of suspension systems be developed. Subsequently, a guide which provides advice for the maintenance and servicing of suspension components was published (Australian Road Transport Suppliers Association 2001). The guide covers the maintenance of shock absorbers, suspensions and axles, the air system and valves and suspension bushes.

Studies conducted by Sweatman et al. (2000) and Cebon (2004) have indicated that having malfunctioning air suspension components, primarily shock absorbers, can lead to high dynamic forces. It was initially proposed by Sweatman et al. (2000) that there was no reason to believe that having a totally ineffective shock absorber on a RFS would cause an increase in the dynamic forces transmitted to the pavement compared with a non-road-friendly mechanical suspension. This view was challenged by Cebon (2004), who suggested that damage due to vehicles fitted with ineffective shock absorbers as part of a RFS was greater than the damage caused by vehicles fitted with conventional mechanical suspensions.

Based on this research, several in-service assessments of heavy vehicle suspension systems were conducted. A survey conducted by Sweatman et al. (2000) found that approximately 80% of in-service shock absorbers remained within 50-100% of their original effectiveness.

Blanksby et al. (2006) presented results from a survey of 150 triaxle trailers, including 121 units with air suspensions and 29 units with mechanical suspensions. The survey included an inspection of the vehicle and an assessment of suspension damping and frequency characteristics using an RFS test facility temporarily located at the Marulan heavy vehicle inspection site in New South Wales. The suspensions surveyed comprised 121 air suspensions and 29 mechanical suspensions. It is important to note only 26 of the air suspensions surveyed were loaded to greater than 20 t and therefore within the test weight tolerance requirement for VSB11. The suspensions within the test weight tolerance were tested and separated into the categories based on the measured damping ratio; either less than 15%, 15-20% or greater than 20%. The suspensions with a damping ratio greater than 20% are listed as compliant, however must also meet the load sharing and frequency requirements of VSB11 to be RFS compliant.

A comparison was made between suspension damped frequency and trailer age; it was shown that there is no apparent relationship between the damped frequency and the age of the trailer.

A comparison was made between suspension damping and vehicle age. Whilst there is a wider spread of suspension damping for newer vehicles (similar to the damped frequency) there is no clear, continuous relationship between vehicle age and suspension damping.

Neglecting any maintenance, trailer age may provide an indication of the condition of the suspension – specifically the shock absorbers. The findings of Blanksby et al. (2006) did not support or refute the need for in-service RFS testing. While it was not identified in the previous work, the existence of a strong relationship between trailer age and deterioration in suspension performance would have supported the introduction of an in-service scheme. It is important to note that this survey was conducted on a GML route and, as a result, no HML vehicles required to be fitted with RFS were included in the study. A survey and assessment of HML vehicles fitted with RFS would provide valuable data necessary for defining the in-service testing requirement.

These studies indicate that in-service performance assurance may be required to ensure that shock absorbers remain effective throughout their service life. However, a comprehensive survey collecting suspension data would be required to support the need for an in-service scheme. The survey would need to evaluate the level of deterioration and its effect on suspension performance.

Sweatman et al. (2000) proposed that an in-service test should include shock absorber dynamometer testing, a visual inspection of suspension components and a direct test of suspension road friendliness via a mobile drop test device.

MM Starrs et al. (2000) conducted an extensive review of a number of options for the in-service performance measurement of RFS. The study found that the analysis of the benefits and costs of any of the schemes did not support proceeding with in-service analyses of RFS based purely on the cost-benefit analysis. It should be noted that none of the options calculated a saving in pavement wear which outweighed the other costs involved.

Collop and Cebon (2002) conducted a related study pertaining to the United Kingdom, using a deterministic pavement performance model. The study found that the change to RFS would result in a significant increase in the life of thin asphalt pavements. An increase in the life of thin asphalt pavements of between 40% and 90% – depending on the characteristics of the lower pavement layers – is particularly relevant to the Australian road network, which has predominantly thin pavements.

Further work in this area performed by Cebon (2004) suggested that the economic evaluation performed by MM Starrs et al. (2000) was incorrect due to the assumption that poorly-maintained RFS were no more damaging to pavements than mechanical suspensions. The analysis conducted by Cebon found that, by changing the fleet from 100% mechanical suspensions to 100% RFS, the cost of road maintenance would decrease by 14%. However, with the increased loads available for vehicles with RFS, the reduction in road maintenance costs would only be 6%. A fleet with 75% effective RFS and 25% ineffective RFS at the higher mass limits produced an equivalent cost to the fleet as 100% mechanical suspensions operating at standard mass limits.

Further work by Costanzi and Cebon (2006) found that, if the road fleet was to have 100% poorly maintained shock absorbers, this would result in an increase in road maintenance costs at the higher mass limits of 46%. The study showed that the level of compliance of a road friendly-suspension was critical to the accuracy of a cost-benefit analysis. Davis and Bunker (2007) suggested that VSB11 be updated to include levels of compliance with the standard.

Including levels of compliance with VSB11 offers the benefit of flexibility in enforcement, as compliance with the standard can be based on the performance level achieved. However, the levels of compliance can only be set based on an understanding of the relationship between suspension characteristics and pavement wear.

Davis and Bunker (2007) also suggested that VSB11 be updated to include criteria for axle hop and dynamic load sharing. They reviewed various methods of in-service performance assurance. A grading system was used to describe the methods, but no recommendations were provided. Davis has also conducted multiple investigations into various in-service methods involving simple apparatus and on-board air-bag pressure measurement systems, quoted accurate results, and promoted the use of these measures (Davis 2005; Davis et al. 2007; Davis and Sack 2004; Davis and Sack 2006).

The research conducted in these areas is dependent on understanding the characteristics of the suspension that influence road-friendliness, and the level of compliance with road-friendly performance requirements that are critical to pavement wear. The relationship between suspension characteristics, road-friendliness and pavement wear needs to be understood, as this will form the basis for in-service compliance test criteria.

A.1.2 Methods for Measuring Dynamic Wheel Loads

Austroads (2009) describes the process of developing a wheel load measuring system in order to improve knowledge of in-service dynamic wheel loads and load sharing of axle groups. This research is vital for understanding the relationship between suspension characteristics and dynamic wheel loads. The aim of this research program was to develop a low-cost device for measuring dynamic loads that could be fitted to a number of heavy vehicles.

A number of methods of measuring dynamic wheel loads were identified during a literature review, including tyre pressure transducers, wheel hub force transducers, instrumented axle casings and non-contact optical sensors.

The wheel load measuring system was designed to measure the load on each wheel and be easily transferred to different vehicles with a range of different suspension types. The development of the wheel load measurement tool was intended to provide information on the magnitude of the wheel loads transmitted to pavements, the distribution of the loads within the axle groups (including dynamic 'impulse' load sharing) and a comparison of the performance of a number of suspension types.

The non-contact optical sensor was chosen for this project as a potential simple and cost-effective method. This method directly measured the compression of the tyre and therefore the load at the road surface based on the relationship between load and tyre compression and has the limitation that the tyre stiffness parameters are a necessary input for every tyre to be tested, at a range of operating conditions, if the system is to be used successfully.

A static calibration of the wheel load measuring system was conducted using a six-axle articulated vehicle after a trial run on a rigid vehicle. The static calibration was conducted by loading the test vehicle at a number of test weights and measuring the tyre deflection from the optical sensor. These values were compared with known wheel loads measured by a testing platform. The calibration tests were conducted at two tyre pressures and showed that a linear relationship exists between tyre deflection and load for each tyre pressure.

A series of on-road tests were then performed and data collected during this study provides strong evidence that longitudinal dynamic load sharing in an axle group does not occur to any significant extent at speeds greater than 20 km/h. This supports expert opinion that dismisses the concept of dynamic 'impulse' load sharing. Dynamic load was shown not to increase with speed for a single feature (bump) but to increase with speed for continuous random input (on-road). Road roughness was shown to cause a considerable increase in dynamic wheel load, causing approximately double the static loads on a very rough road but only about 20% above static loads on a smooth road. The effects of removing shock absorbers on the second axle were seen to be small (no greater than the variation in wheel loads measured during identical repeat runs) for the suspension type considered, but the report qualifies this finding by recommending further testing in this regard.

The evaluation of the dynamic data showed that the system effectively measured dynamic wheel loads at speeds up to 80 km/h. The accuracy of the system was sufficient to meet the objectives of the project and the findings summarised above. However, the data collection methods were not pursued further for measuring dynamics loads, due to practical limitations.

A.1.3 Summary of NTC Investigation

NTC (2008) commissioned a review of in-service test methods. As opposed to investigating a method for measuring dynamic wheel loads, this review focused on a test that would determine RFS compliance in accordance with the requirements of VSB11.

Based on the VSB11 assessment criteria, the drop-test method was considered to be the most accurate method of impulse delivery; load cells mounted in the test apparatus would be the most suitable sensor type, and fitting a theoretical curve to the recorded data plots was the most accurate data analysis method. However, none of the fully developed methods evaluated could be termed low cost or practical to be deployed as a roadside test. This is particularly due to the need to be able to load the test vehicle up to the required test mass.

In the majority of cases this would require tens of tonnes of mass to be transported along with the test rig and added to trailers of varying configurations (such as fuel tankers or curtain-siders) prior to testing, without damaging the vehicle, its load or posing a health and safety risk.

In light of the high expense and practical issues associated with conducting VSB11 tests in the field, it is considered that a roadside, in-service test based on VSB11 test could not be justified from a cost and benefit perspective.

As an alternative to a physical test it was recommended that visual inspection of the suspension system and review of the vehicle's maintenance logs would provide the most cost effective roadside method at the time. While visual inspection may not detect slight breaches of VSB11, it would be effective in detecting the most damaging vehicles.

A number of non VSB11 tests in development however these tests are not ready to be deployed at this time and are contingent on further research to correlate results to pavement wear rates (see further research section). Should these test methods be validated then they may provide an effective roadside test in the future.

The review highlighted that knowledge gaps exist and that these must be address in order to develop an in-service test method that deviates from adhering to the requirements of VSB11. The review recommends the following tasks be undertaken:

- investigate the relationships between pavement type and pavement wear attributed to poorly-functioning RFS
- quantify the relationship between suspension characteristics and pavement wear, as this could form the basis for a non-VSB11 in-service compliance test criteria
- a survey and assessment of HML vehicles fitted with RFS should be conducted in order to achieve the following aims:
  - determine the current level of proliferation of RFS, and the level of in-service suspension compliance with current RFS requirements
  - evaluate the level of deterioration and its effect on suspension performance
  - determine the 'level of redundancy' in the road-friendly performance of suspensions which may be poorly maintained
  - determine the proportion of vehicles operating under HML which operate at the maximum axle group limits allowable under HML.

In the absence of an established relationship between these factors and wear, the VSB11 requirements for the certification of RFS systems has been used as a benchmark to establish effective road friendliness requirements, identified during the literature review. It was decided that at this time, in-service compliance requirements should be based on the current RFS certification requirements.

The report also explored options in terms of the calculation of tolerances for in-service tests, discussion centred on the importance of setting appropriate levels on suspension damping and frequency, and ensuring the prevention of situations where certified suspensions do not pass in-service test requirements, or vice-versa. Based on statistical analysis of VSB11 test data and RFS capabilities, the recommended minimum performance level values for an in-service scheme are 17.8% damping and 2.2 Hz frequency of oscillation of the sprung mass.

Using this approach, it could be reasonably assumed that any suspension that passes a VSB11 test (e.g. measured damping of 20% or above) will have a true damping higher than the 2.5th percentile value, and will also meet the requirements of an in-service test.

A.1.4 Current and On-going Research Related to RFS

Research into the area of heavy vehicles and the loading of pavements continues. Particularly, following the NTC investigation in 2008 there has been further research conducted relevant to in-service compliance of RFS. A summary of this work follows.

The work presented in Davis (2010) is a continuation on the previous work documented in Davis (2005). Davis (2005) explores the viability of measuring suspension performance using two different and independent methods referred to as a 'pipe test' and a 'white noisy road test'. In his most recent work he focuses on developing a method based on driving a vehicle on a section of (rough) road in preference to the 'pipe test' method. Tests were undertaken using an instrumented triaxle semi-trailer to determine the forces exerted on pavements by this vehicle. Accelerometers and strain gauges were fitted to the axles of the vehicle and used to determine dynamic wheel forces. A roughness value of the roads during testing was derived. Dynamic pavement forces were presented according to the range of roughness values encountered during testing along the test section of road. The report states that the mean and standard deviation of heavy vehicle wheel forces did not correlate with pavement roughness, however peak wheel forces did. Davis (2010) reports promising results; however, the concept of using a test road for comparison of suspension performance between different vehicles needs to be explored further in order to determine if the approach is suitable for monitoring road-friendliness.

Roebuck et al (2012) documents the development of a new user-friendly software tool that can be used to model the interaction between vehicles and pavements. This software tool provides a simulation environment that can be used to investigate a number issues relating to vehicle-pavement interaction including the effect of suspension characteristics on the loading of the pavement.

A case study was presented showing comparison between steel, air and defective air suspensions, under HML and GML which is particularly relevant to the Australian axle mass limits and road friendliness of suspension. The case study shows that road lifetime until resurfacing could be reduced by as much as ten years if the air suspension vehicle fleet had 50% malfunctioning hydraulic dampers. It is worth noting that this simulation study, as with all computed simulated studies, requires accurate input data representative of the components under assessment.

Austroads (2012) is the most recent publication of the research conducted under the Austroads program investigating a method for measuring dynamic wheel loads. The laser transducer based method for estimating dynamic wheel loads identified in Austroads (2009) was suitable as a first-order estimate of dynamic wheel loads, but there are limitations relating to its practicality and accuracy. Significant efforts were made to overcome the limitations of the laser method. However, these ultimately made the system too expensive and complex to warrant its use, in comparison with the traditional and accepted method of using strain gauges with accelerometers, which offers relatively high accuracy.

Use of strain gauges with accelerometers was initially only intended as a reference system but in the absence of a viable low cost method, strain gauges and accelerometers were used as the only means of collecting data in the subsequent field tests. This well established and proven method was effective as an accurate method for acquiring the required data on a limited number of vehicles, although fewer than originally intended. Nonetheless, the data gathered for a smaller sample of vehicle and roads was adequate for the development and validation of the computer model, which became the focus of the research program as it approaches its completion.

The use of airbag pressure as an alternative measurement was investigated. It was found that by measuring airbag pressure, damper velocity, relative position of left and right trailing arms (for torque), and outboard mass acceleration, reasonably accurate results could be achieved. Requirements of alternative measurement methods.

Estimating dynamic wheel loads from airbag pressure requires additional sensors compared with the strain gauge approach, which only requires the strain gauge and outboard mass acceleration to be measured.

Both approaches include the outboard mass acceleration. However, the airbag approach relies on an additional measurement (trailing arm vertical motion as measured by the linear displacement transducer), which is needed to derive forces associated with axle torque during body roll, and damper force. This initial investigation into using airbag pressures as an alternative has indicated some potential but there is a need for considerably more research to fully understand the influencing factors. The airbag pressure approach was not pursued any further in this project as the strain gauge approach was more accurate and more suitable for achieving the project aim of validating a computer model. To compare the accuracy of different measurement techniques dynamic forces were measured during the certified RFS drop test.

The results include comparisons based on the drop test and on-road tests. The accuracy is reported as an R^2 value relative to the calibrated load cells fitted to the RFS drop test rig. The reference for the on-road tests used the strain gauge hence the value of R^2 value of 1.

A limitation of the airbag approach was identified in the need to physically test the shock absorber to obtain its damping coefficient values. Understanding the sensitivity of such values and of the influences of shock absorber conditions and their interplay within a suspension group was recommended in order to improve confidence in an airbag pressure-based system.

The research program is now in its final year and the final technical report is due to be published towards the end of 2015. The work to be completed in this final year is expected to validate a computer model which can be used to estimate the dynamic loading resulting from heavy vehicles. This work is expected to complement the findings of Roebuck et al (2012), which has a similar aim of providing a simulation platform to investigate vehicle-pavement interaction.

APPENDIX B IN-SERVICE RFS SYSTEMS REVIEWED

B.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 are shown in Figure 5.1. 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 B 1: CHEK-WAY® Eliminator components

This system was evaluated during test program 1 (described in the Stage 2 report), conducted at Tramanco workshop facility in Brisbane on 16-18 May 2016.

Table B 1 provides a summary of the details of the CHEK-WAY® Eliminator.

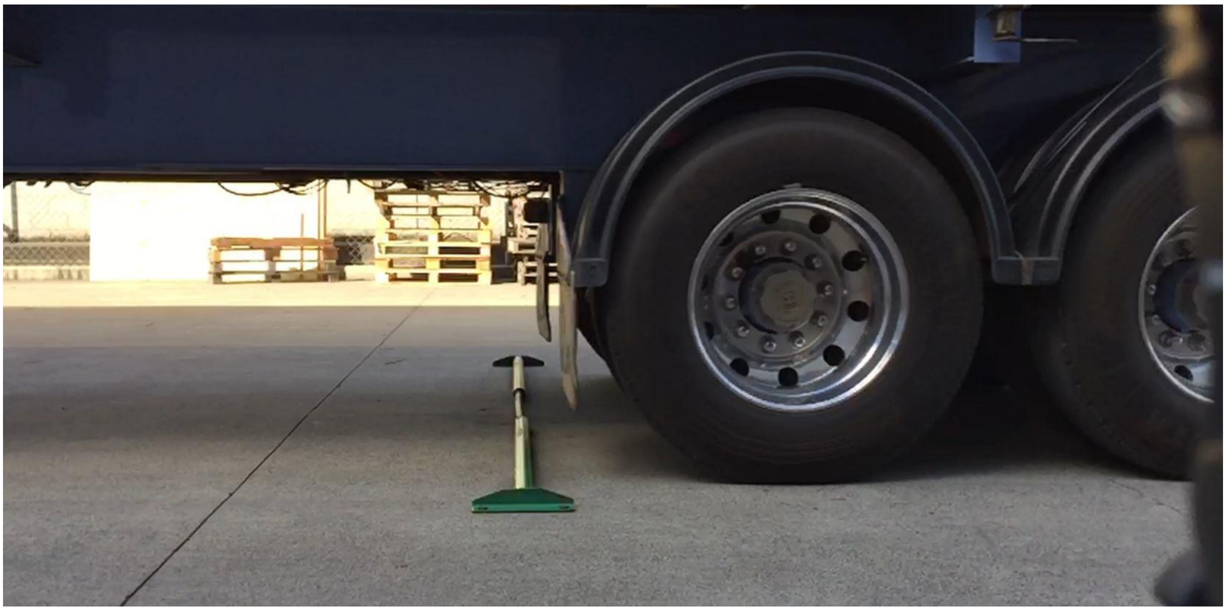
Table B 1: Details of CHEK-WAY® Eliminator

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

B.1.1 Excitation Method

The excitation method for this system is the pipe test (Figure B 2) or any road section sufficient to excite the suspension. The pipe is 58 mm in diameter and the vehicle is driven over the pipe at speed.

Figure B 2: Pipe test used as excitation



B.1.2 Measurement Method

The measurement method comprises two air pressure transducers (APTs). Figure B 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 its on-board scale system; an additional sensor was added for the test to function as a system to measure damping and frequency.

Figure B 3: Measurement comprising two air pressure transducers

B.1.3 Analysis Method

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

B.2 RFS Analyser

The RFSA is a purpose-built rig designed 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. Load cells in the platforms measure the weight imposed by 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 the device. Figure B 4 shows the RFSA with ramps in position.

Figure B 4: Road Friendly Suspension Analyser (RFSA)

The RFS Analyser was evaluated during test program 2 (described in the Stage 2 report), completed at the DECA facility in Shepparton, Victoria, on 26-27 May 2016.

Table B 2 provides a summary of the details of the RFSA.

Table B 2: Details of RFSA

Name:	Road Friendly Suspension Analyser
Company	Australian Road Research Board
RVCS No.	T9872
Patent No.	None
Business type	Research & Consulting
Contact	Anthony Germanchev, HV Team Leader
Email	anthony.germanchev@arrb.com.au
Website:	www.arrb.com.au
Office	500 Burwood Hwy, Vermont South, Vic 3133

B.2.1 Excitation Method

The excitation method for this system is the rig itself which raises a platform upon which each axle is positioned. Figure B 5 shows the vehicle in the raised position. The rig is installed with air bags on each side of the rig, which are filled with compressed air from an external source.

Figure B 5: RFSA used as the excitation method

B.2.2 Measurement Method

The measurement method is the load cells positioned beneath each tyre. Data is logged at 100 z via an independent data acquisition system. Figure B 6 shows the three platforms connected to a laptop computer.

Figure B 6: Measurement method comprising load cells for each wheel

B.2.3 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 from plots of logged data.

B.3 DynaSses

The DynaSses system is shown in Figure B 7. The system comprises custom designed ramps (four are required for a single axle with dual tyres), hub mounted sensors (temporarily fitted) at each end 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 analysis is via custom software which can be installed on a tablet or PC.

Figure B 7: DynaSses test system

The DynaSses system was evaluated during test program 3 (described in the Stage 2 report), completed at the ARRB test site in Vermont South, Victoria, on 7-8 June 2016.

Table B 3 provides a summary of the details of the DynaSses test system.

Table B 3: Details of DynaSses test system

Name:	DynaSses
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

B.3.1 Excitation Method

The excitation method for this system is an 80 mm ramp positioned in front of each tyre prior to the test. Figure B 8 shows the vehicle in the raised position, immediately prior to dropping off the ramp.

Figure B 8: Individual 80 mm ramps used as excitation

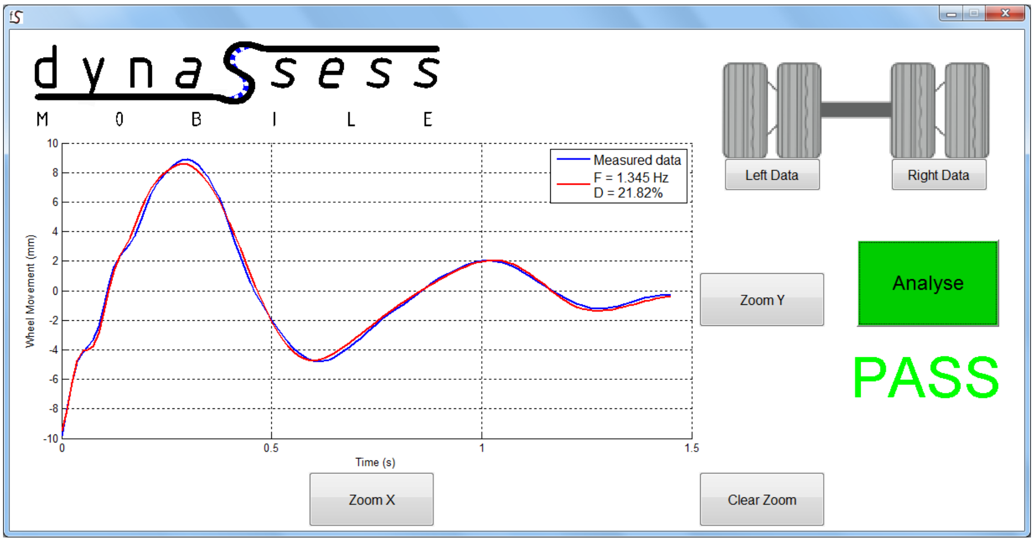
B.3.2 Measurement Method

The measurement method comprises sensors that are temporarily mounted to each end of the axle. The sensors send data wirelessly to a laptop or tablet. Data is logged at 85 z.

B.3.3 Analysis Method

The analysis is an automated process which doesn't require the user to select points or 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 B 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 B 9: Screen capture of software used for analysis

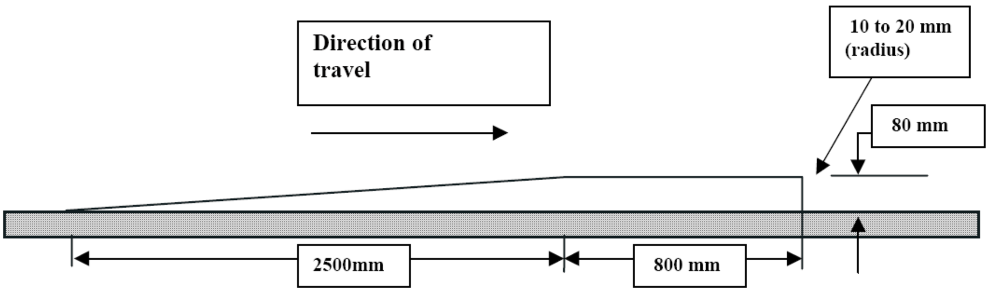


B.4 Reference System

B.4.1 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 shown Figure B 10.

Figure B 10: VSB11 ramp test



Source: Council of the European Union (1996); Department of Transport and Regional Services (2004).

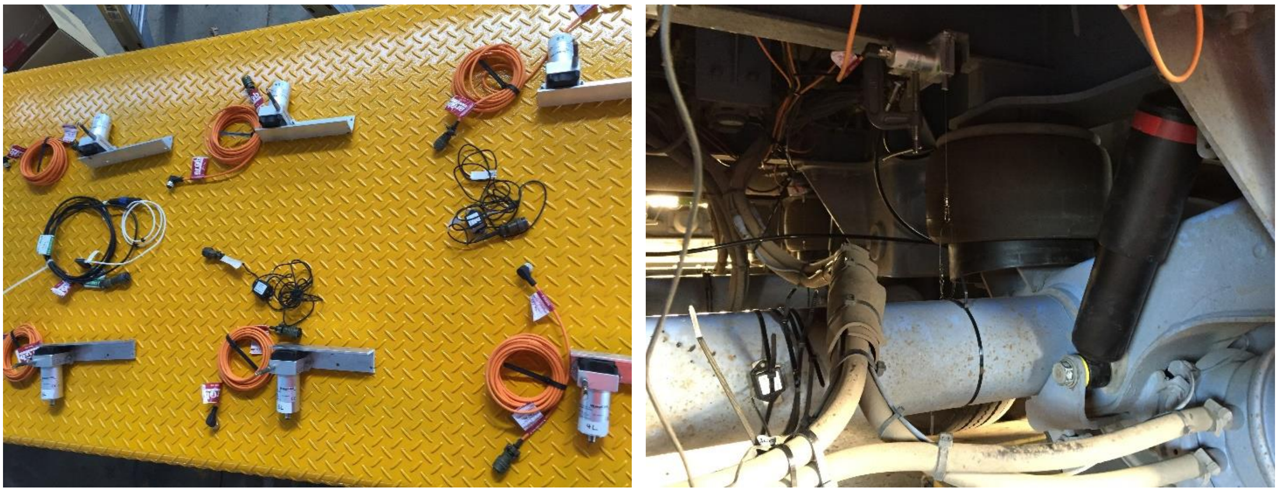
The VSB11 ramps were used as part of test program 1 and 3. Figure B 11 shows the VSB11 ramps being used with a 4x2 rigid truck and a triaxle trailer suspensions. Note that the 2500 mm length of the ramps required by VSB11 is not compatible with testing multi-axle groups.

Figure B 11: VSB11 ramps used for RFS testing

B.4.2 Measurement method

The reference system included linear displacement transducers and air pressure sensors shown in Figure B 12. These sensors were fitted to each vehicle and data was logged at 100 Hz using customised MOTEC software.

Figure B 12: VSB11 ramps used for test program 3 with a 4x2 rigid truck



B.4.3 Analysis Method

To calculate the damping ratio, the 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 over the time when the oscillations had settled down. The following equation was then applied to calculate the damping ratio:

$$Damping\ ratio = \frac{1}{2\pi}\ln\frac{A1}{A2} \qquad 5$$

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

$$Frequency = \frac{1}{(T2 - T1)} \qquad 6$$

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.

The low and medium duty shock absorbers were tested at 8 speeds whereas the heavy duty shock absorber was only tested at five speeds. The three 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 five speeds used for testing covered the range of speeds the shock absorbers would be expected to operate at during the testing program. Table B 4 shows the test speeds used for testing. It is expected that the shock absorbers will operate below 2.0 Hz.

Table B 4: Speeds for shock absorber tests

Test rig		Shock absorber		
Speed (m/s)	Frequency	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	☑	☑	☒
1.00	6.370	☑	☑	☒

The shock absorber performance was quantified using force vs velocity and force vs displacement charts. Figure B 13, Figure B 14 and Figure B 15 shows the force vs displacement characteristics of the heavy duty, medium and low damping shock absorbers respectively.

Figure B 13: Force vs displacement test results for a heavy duty shock absorber

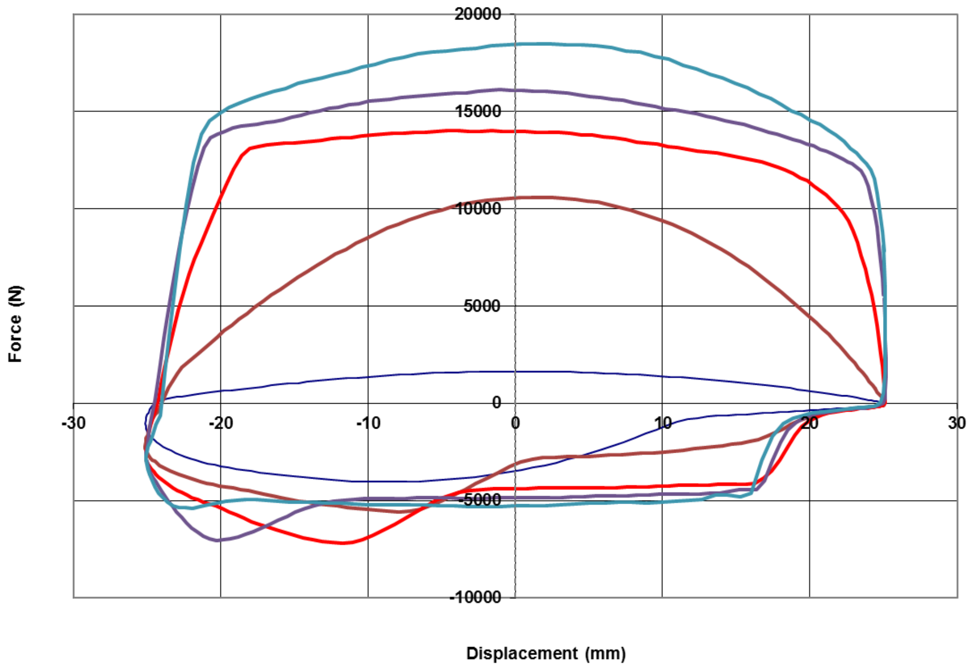


Figure B 14: Force vs displacement test results for a medium duty shock absorber

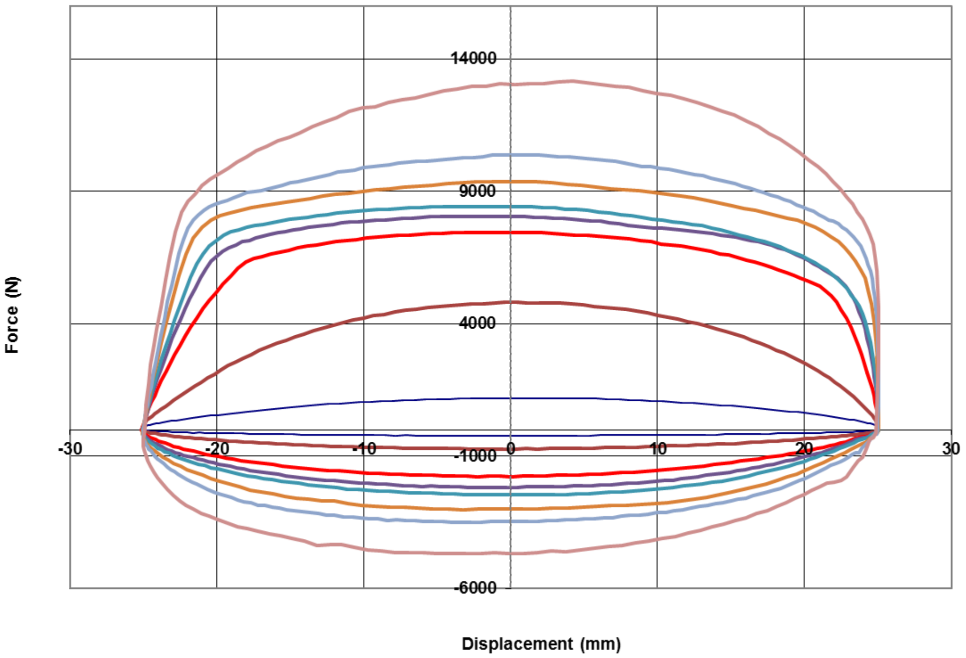


Figure B 15: Force vs displacement test results for a low damping shock absorber

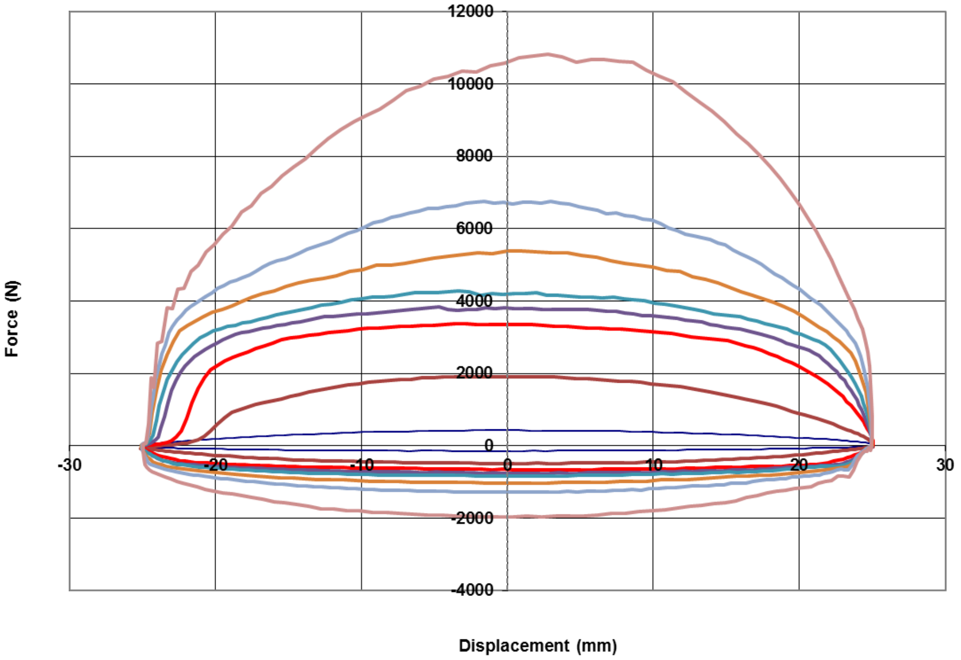
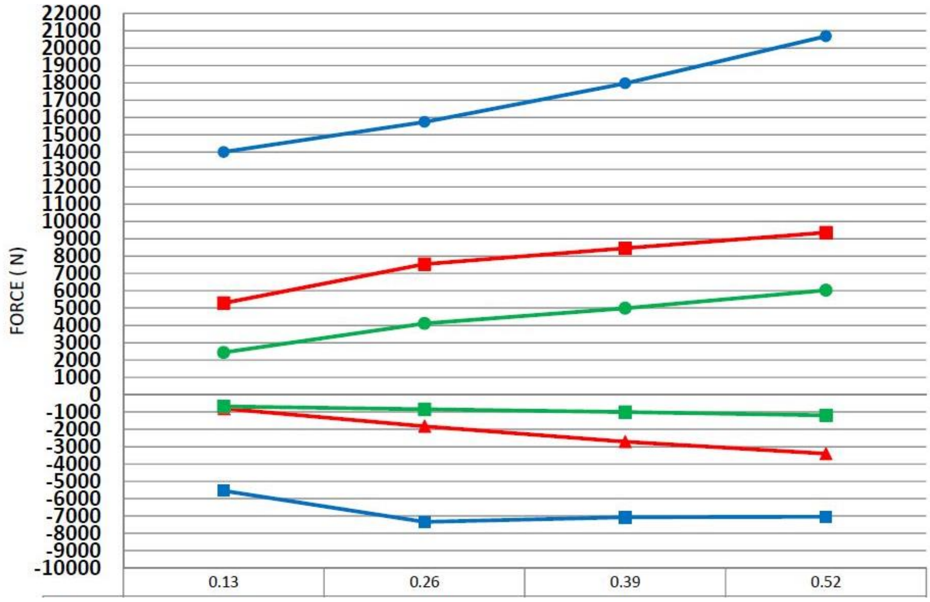


Figure B 16 shows a summary of the peak forces values for each shock absorber at four test speeds, for both the extension stroke and the compression stroke. The data points shown in the positive range of the y-axis represents the damping force in the extension stroke and compression stroke force is shown in the negative range. The four data points are four speeds at which the test were conducted: 0.13 m/s, 0.26 m/s, 0.39 m/s and 0.52 m/s.

Figure B 16: 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 B 5, Table B 6 and Table B 7 for the low, medium and high damping shock absorbers.

Table B 5: 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	1919	2360	2269	2221	2274	2282	1919	2360	**19%**
0.26	3377	3747	3459	3027	3693	3657	3027	3747	**19%**
0.33	3831	4232	3868	3421	4128	4034	3421	4232	**19%**
0.39	4278	4576	4324	3831	4545	4417	3831	4576	**16%**
0.52	5377	5424	5472	4852	5566	5343	4852	5566	**13%**
0.66	6749	6523	6742	5988	6841	6419	5988	6841	**12%**
1.00	10813	10114	10690	10070	11128	10210	10070	11128	**10%**

Table B 6: 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	1188	1508	1710	1470	1696	1330	1188	1710	**31%**
0.13	4805	4808	5140	5082	5679	4874	4805	5679	**15%**
0.26	7458	6830	7305	7634	7950	7607	6830	7950	**14%**
0.33	8059	7402	7897	8200	8465	8158	7402	8465	**13%**
0.39	8433	7857	8252	8565	8839	8535	7857	8839	**11%**
0.52	9377	8796	9184	9508	9737	9445	8796	9737	**10%**
0.66	10374	9851	10150	10550	10610	10378	9851	10610	**7%**
1.00	13164	12672	12673	13406	13106	13024	12672	13406	**5%**

Table B 7: Summary of peak damping forces for high damping shock absorbers

Test speed (m/s)	Medium damping shock absorber						Lowest peak force (N)	Highest peak force (N)	Variability
	1	2	3	4	5	6			
0.05	1635	5687	1070	4150	3089	2774	1070	5687	**81%**
0.13	10597	13397	13106	13813	13014	13123	10597	13813	**23%**
0.26	14011	15129	14957	15692	14872	15181	14011	15692	**11%**
0.39	16144	17451	16991	17764	17175	17233	16144	17764	**9%**
0.52	18499	20085	19460	20506	19840	19736	18499	20506	**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, this 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 B 17 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 B 17: Shock absorber sets for field tests with high, medium and low damping

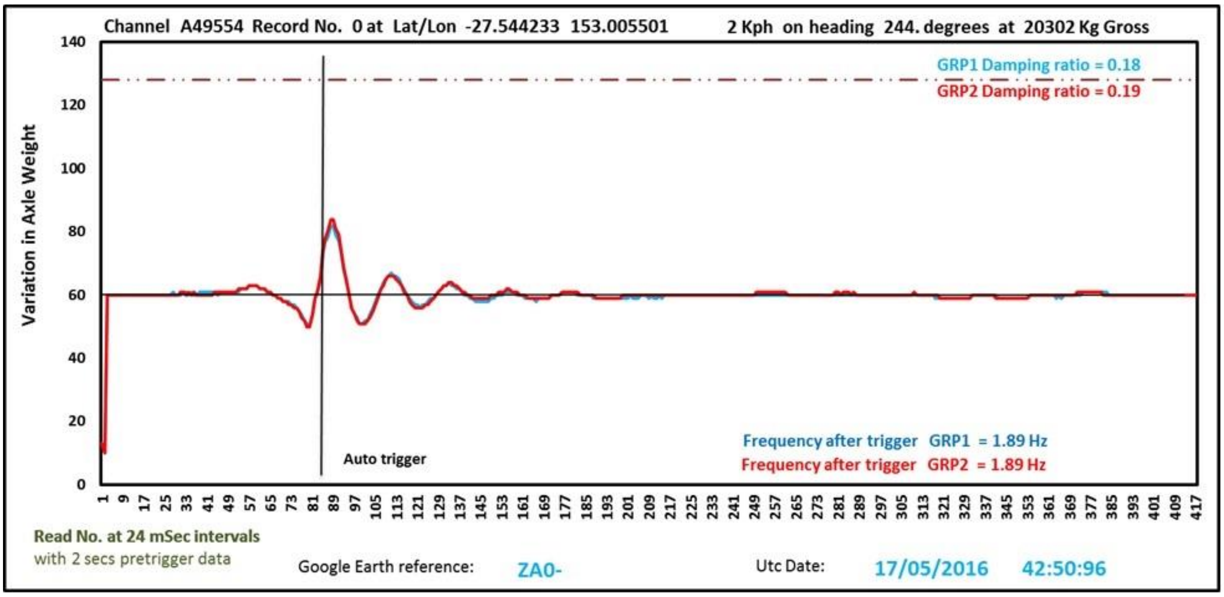
APPENDIX C TEST RESULTS

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

C.1 Results from Stage 1

Figure C 1 shows the data trace supplied by Tramanco for VSB11 ramp test number 1 with heavy duty shock absorbers. The y-axis is a unit-less output from the air pressure sensors and the x-axis is number of samples each at an interval of 24 milliseconds. The vertical black line located between 81 and 89 samples is an indication of an event trigger, signifying that data logging commenced approximately 2 seconds prior to this point for a total of 10 seconds.

Figure C 1: Data trace from triaxle semi-trailer (Test 1 HD ramp test fitted to triaxle semi-trailer a 9:09:52)



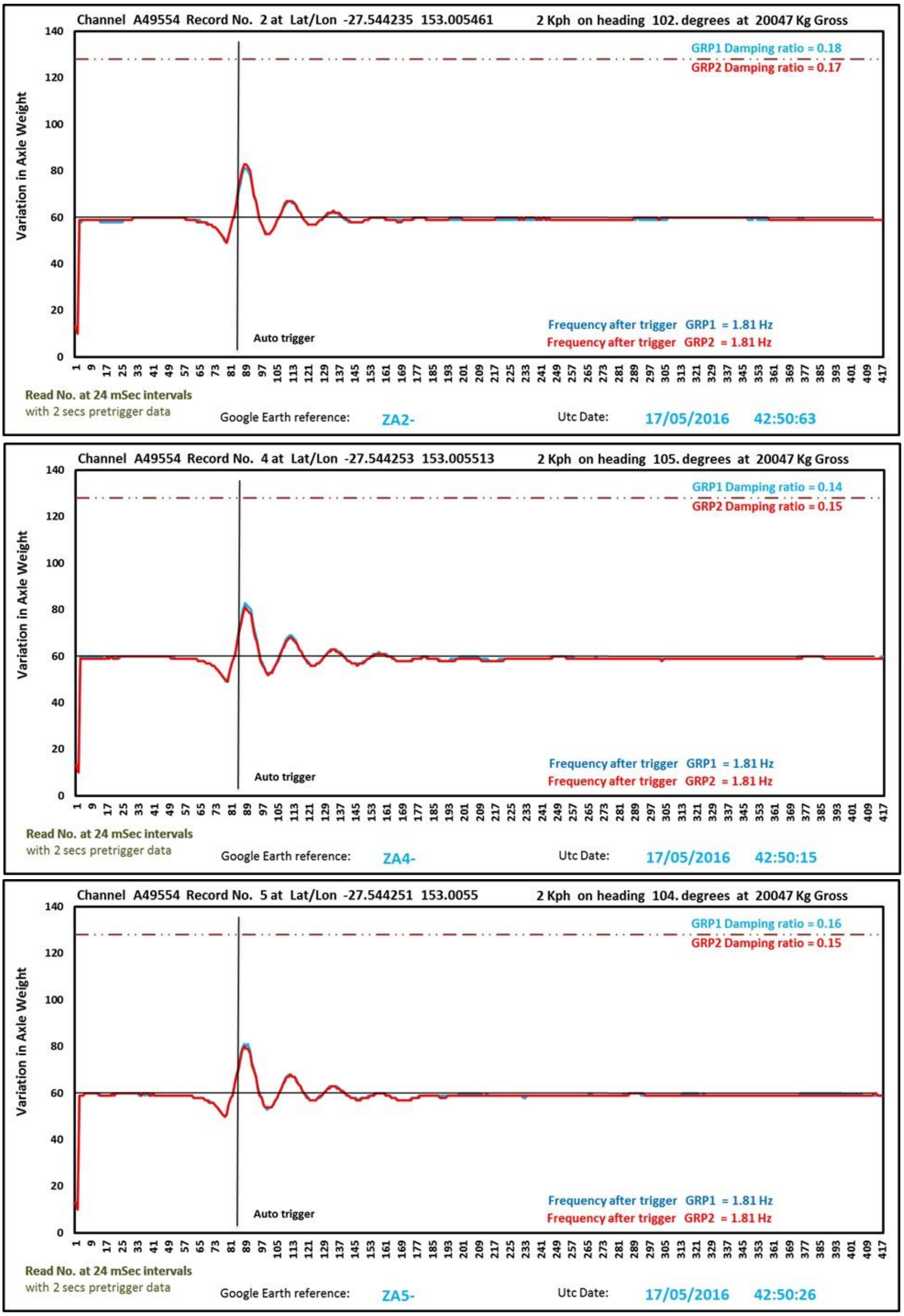
The processed data is 'zeroed' at a baseline value of 60 units. Therefore, this value of 60 represents zero vertical displacement between the axle and the body. It should be noted that air pressure transducers measure a voltage linearly proportional to the pressure, not displacement so this is not a 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 addition 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 C 2 shows the results obtained from three consecutive ramp tests with the vehicle in the same configuration. These results can be compared for repeatability.

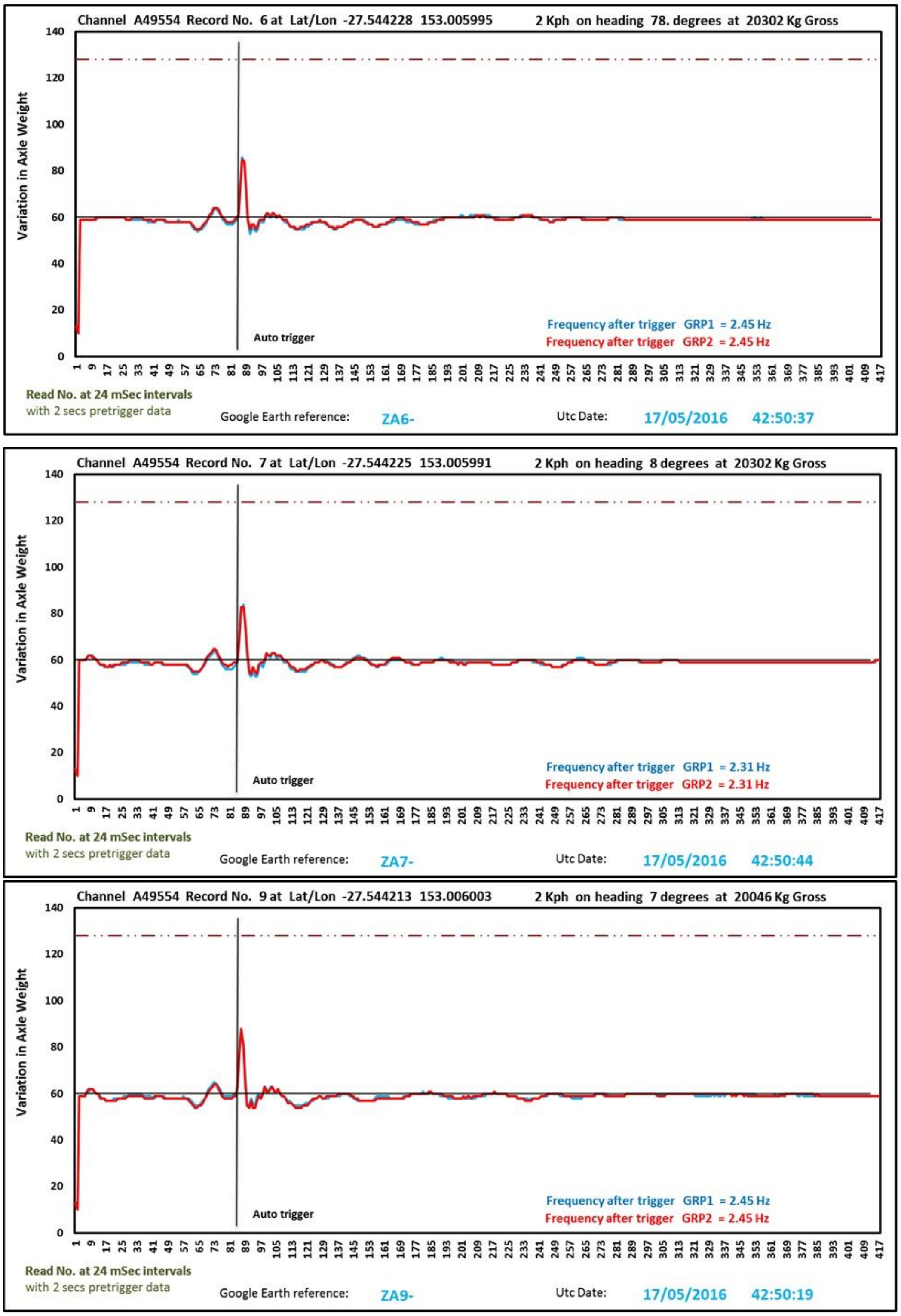
Figure C 2: Data trace from triaxle semi-trailer: 3 consecutive ramp tests: Test No. 3, 4 and 5)



The frequency of each test is identical at 1.81 Hz, this is expected as the frequency of the suspension (which acts as a spring with constant stiffness) should not change. The damping ratio varies between left and ride sides and between tests. The damping ratio varies between 0.14 and 0.18, which is an increase of 28.5%.

Figure C 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, however the frequency is calculated to be either 2.45 Hz (Test 1 and 3) or 2.31 Hz (Test 2) both are considerably different from the 1.81 Hz calculated from ramp tests. No damping ratio has been provided for these tests, assumingly it was not possible detect subsequent peaks from this over damped response.

Figure C 3: Data trace from triaxle semi-trailer: 3 consecutive pipe tests (Test No. 6, 7 and 9)



The tests conducted as part of Stage 2 are listed in Table C 1.

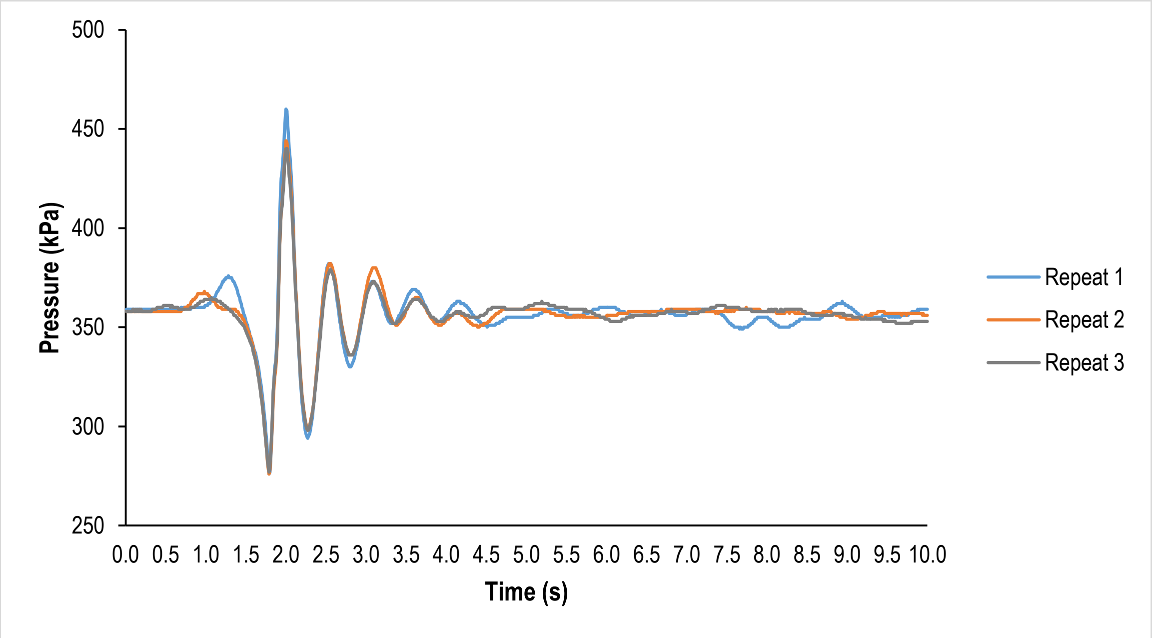
Table C 1: Tests conducted during Stage 2

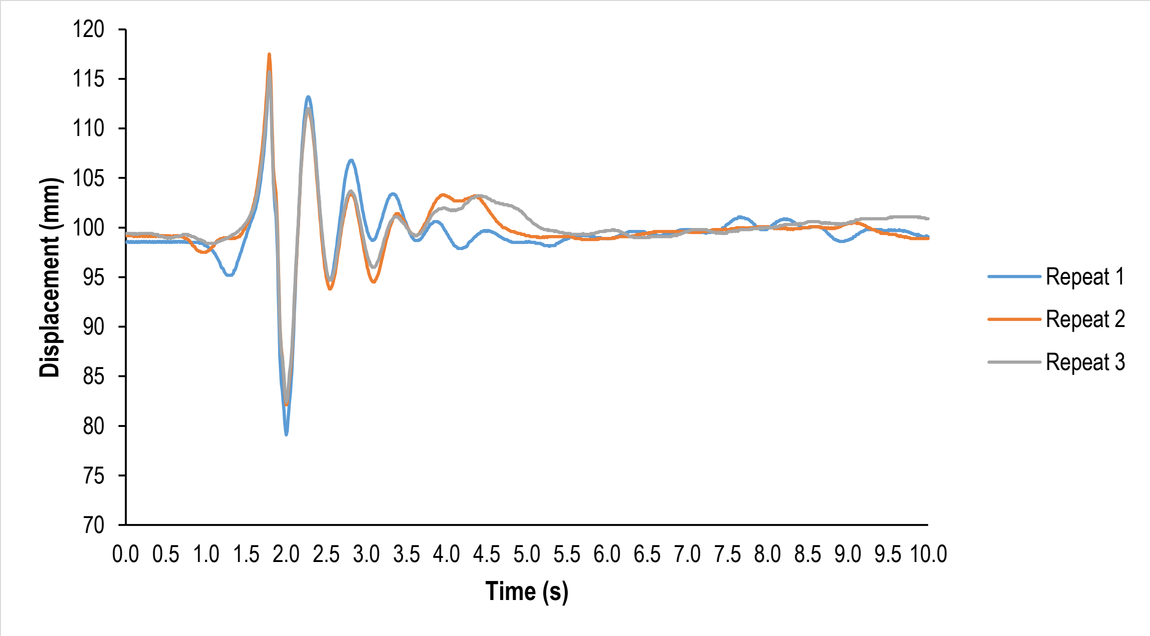
Test No.	Subtitle
1	Repeatability of ramp tests: Fully laden with HD shock absorbers
2	Repeatability of ramp tests: Fully laden with MED shock absorbers
3	Repeatability of ramp tests: Fully laden with LOW shock absorbers
4	Repeatability of pipe tests: Fully laden with HD shock absorbers
5	Repeatability of pipe tests: Fully laden with MED shock absorbers
6	Repeatability of pipe tests: Fully laden with LOW shock absorbers
7	Summary of repeatability test results
8	Repeatability tests: Fully laden with NO shock absorbers
9	Comparison of pipe vs ramp tests: Fully laden 6 LOW
10	Comparison of ramp tests: Fully laden 6HD vs 5HD vs 4HD
11	Comparison of pipe tests: Fully laden 6HD vs 5HD vs 4HD
12	Comparison of ramp tests: Fully laden HD vs MED vs LOW
13	Comparison of pipe tests: Fully laden HD vs MED vs LOW
14	Comparison of ramp tests: Fully laden MED vs 3 OFF
15	Comparison of pipe tests: Fully laden MED vs 3 OFF
16	Comparison of ramp tests: Fully laden MED vs No RHCV
17	Comparison of ramp tests: Fully laden MED vs half laden MED
18	Comparison of pipe tests: Fully laden MED vs half laden MED
19	On road test: Fully laden with MED shock absorbers

C.1.1 Repeatability of Ramp Tests: Fully Laden with Heavy Duty Shock Absorbers

Figure C 4 shows the three repeat tests for the vehicle fully laden and fitted with heavy duty shock absorbers.

Figure C 4: Repeatability of ramp tests (HD shocks – fully laden)





A summary of the results is presented in Table C 2.

Table C 2: Summary of results: fully laden with HD shock absorbers

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

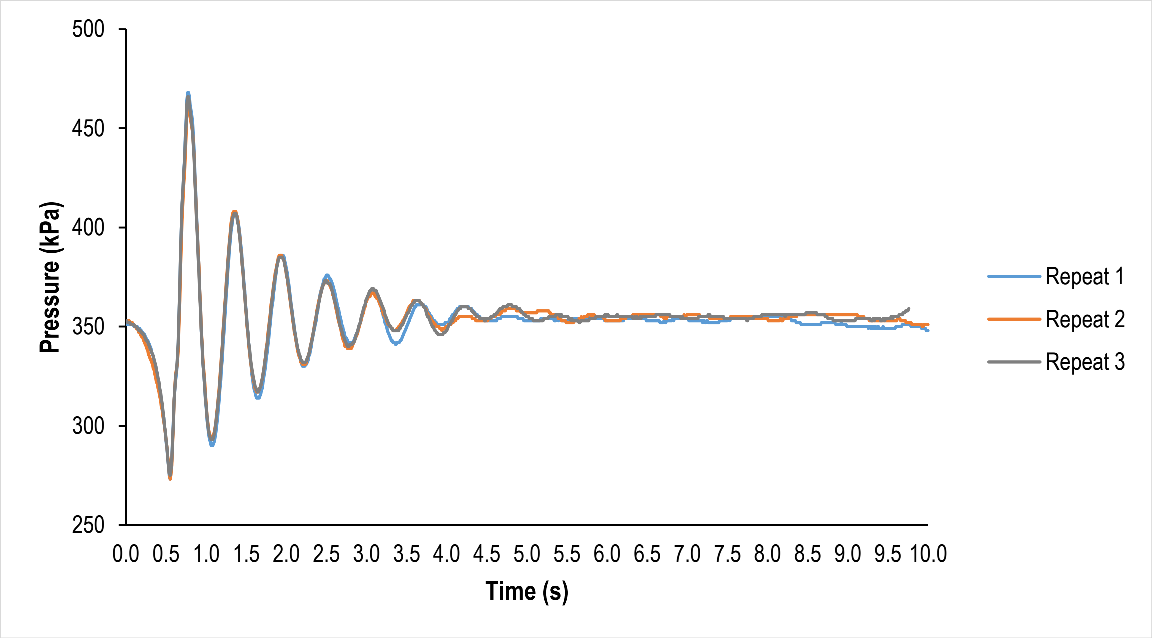
Commentary

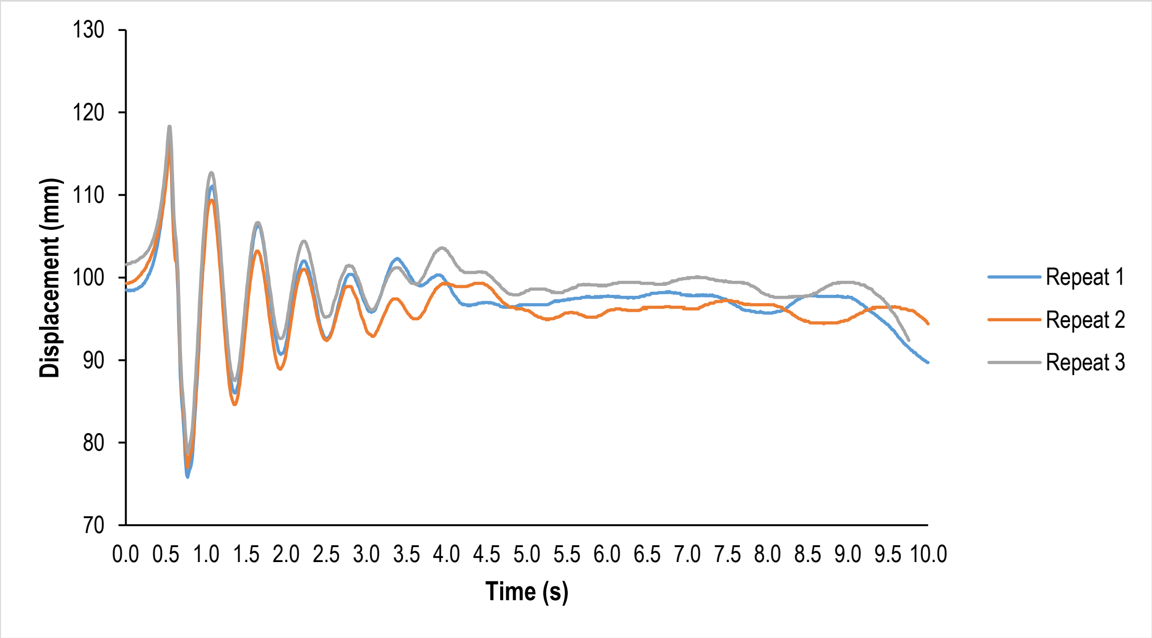
This test has produced a similar results for the APT and LDT sensors. Despite this the variation between the left and right sides of axle and between repeat tests when measured by the LDT is much greater compared with APT. This result implies that the axles are rolling or the wheels are dropping off 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, this movement not being registered by the APT, most likely due to either a low latency in the air bag suspension itself or slow response rate in air pressure sensors.

C.1.2 Repeatability of Ramp Tests: Fully Laden with Medium Damping Shock Absorbers

Figure C 5 shows the three repeat tests for the vehicle fully laden and fitted with medium damping shock absorbers.

Figure C 5: Repeatability of ramp tests (MED shocks – fully laden)





A summary of the results is presented in Table C 3.

Table C 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	*Right*	*Left*	*Right*	*Left*
Test 1 - Damping ratio (%)	12	10	13	10
Test 2 - Damping ratio (%)	11	9	8	6
Test 3 - Damping ratio (%)	12	9	10	8
Averaged result (%)	**11**		**9**	
Standard deviation	**1.37**		**2.40**	
Frequency (Hz)	**1.76**		**1.72**	

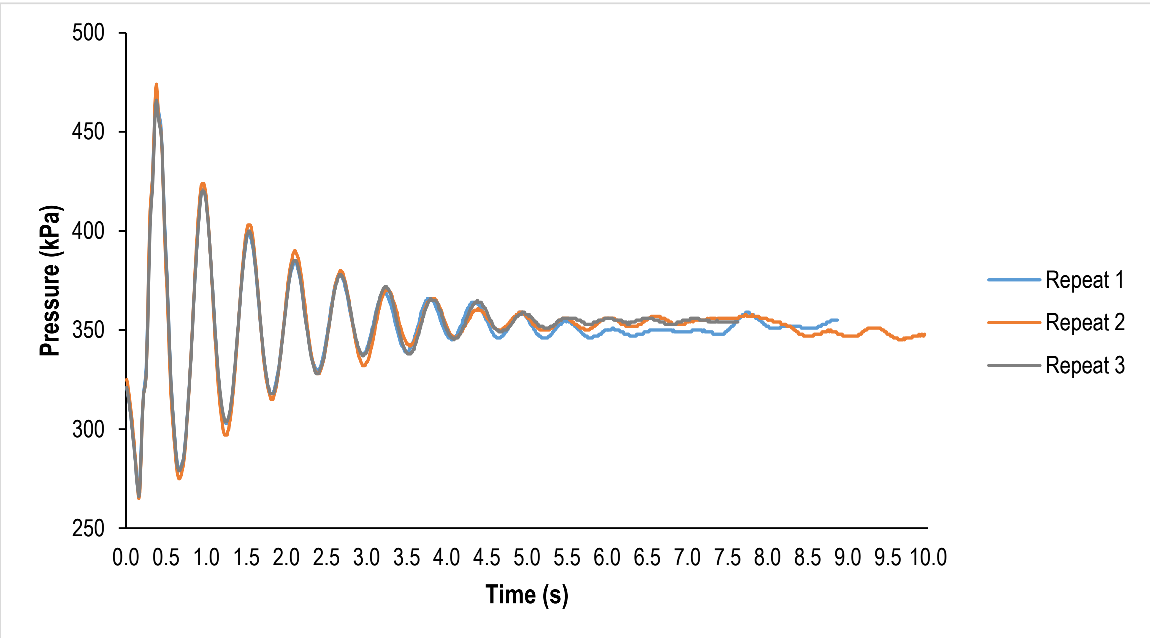
Commentary

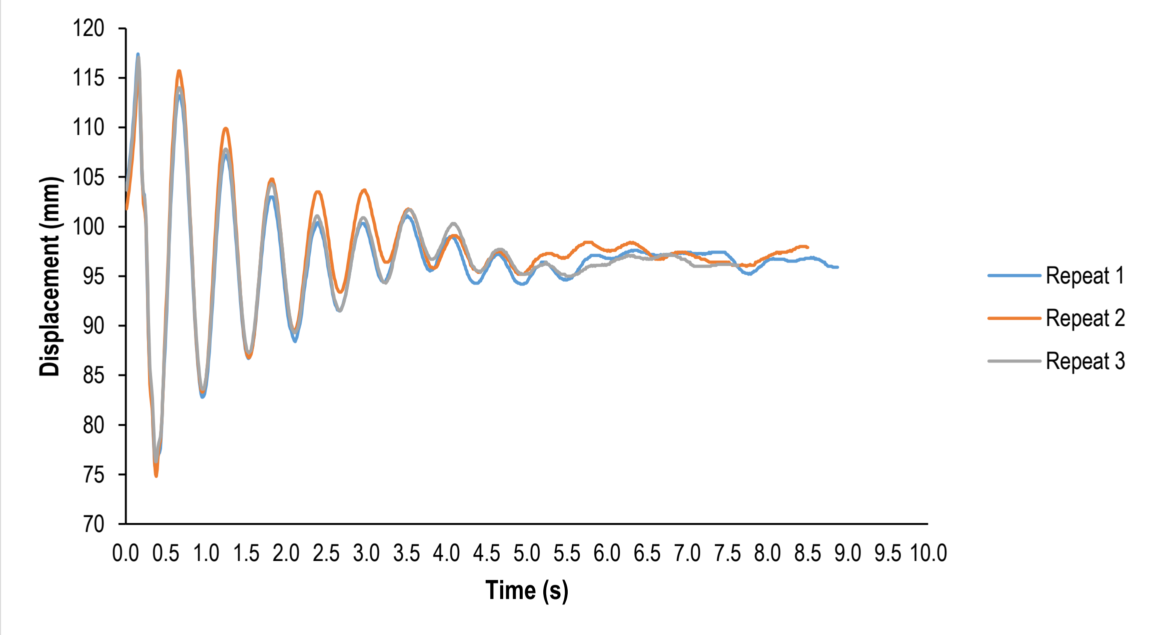
These results are consistent with the previous results, indicating a similar averaged results for damping (11% – 9%) and frequency (1.76 Hz – 1.72 Hz). A similar observation can be made for these results where the variation between left and right side and between repeats is greater for LDT than APT.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

C.1.3 Repeatability of Ramp Tests: Fully Laden with LOW Shock Absorbers

Figure C 6 shows the three repeat tests for the vehicle fully laden and fitted with LOW shock absorbers.

Figure C 6: Repeatability of ramp tests (LOW shocks – fully laden)





A summary of the results is presented in Table C 4.

Table C 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	*Right*	*Left*	*Right*	*Left*
Test 1 - Damping ratio (%)	8	8	7	7
Test 2 - Damping ratio (%)	8	9	8	7
Test 3 - Damping ratio (%)	8	7	7	6
Averaged result (%)	**8**		**7**	
Standard deviation	**0.63**		**0.63**	
Frequency (Hz)	**1.80**		**1.74**	

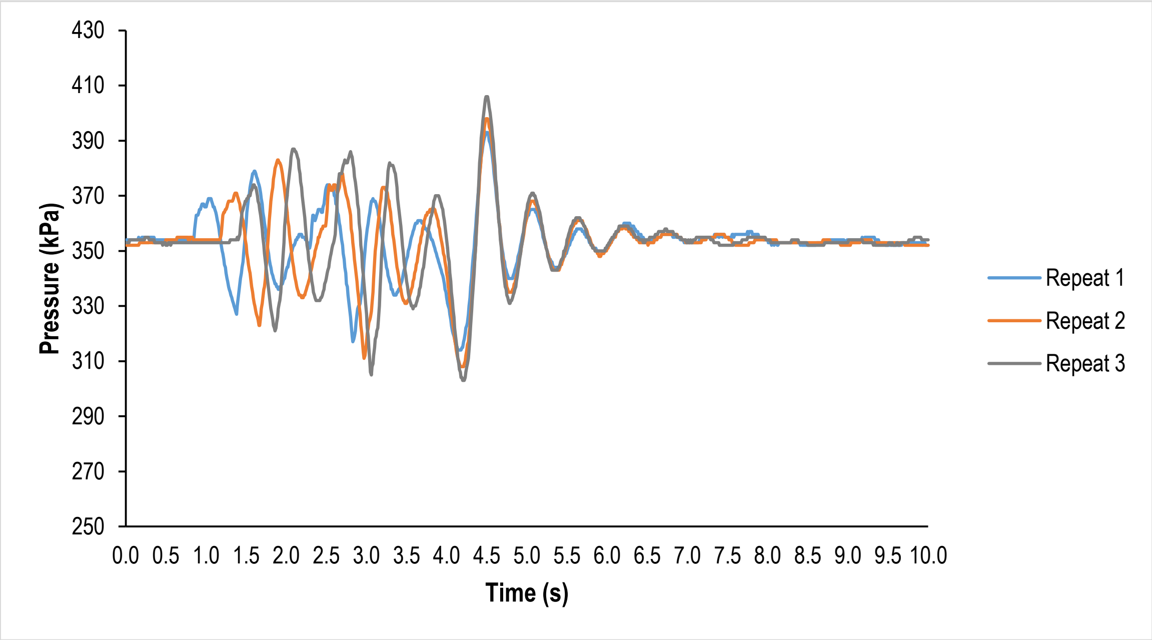
Commentary

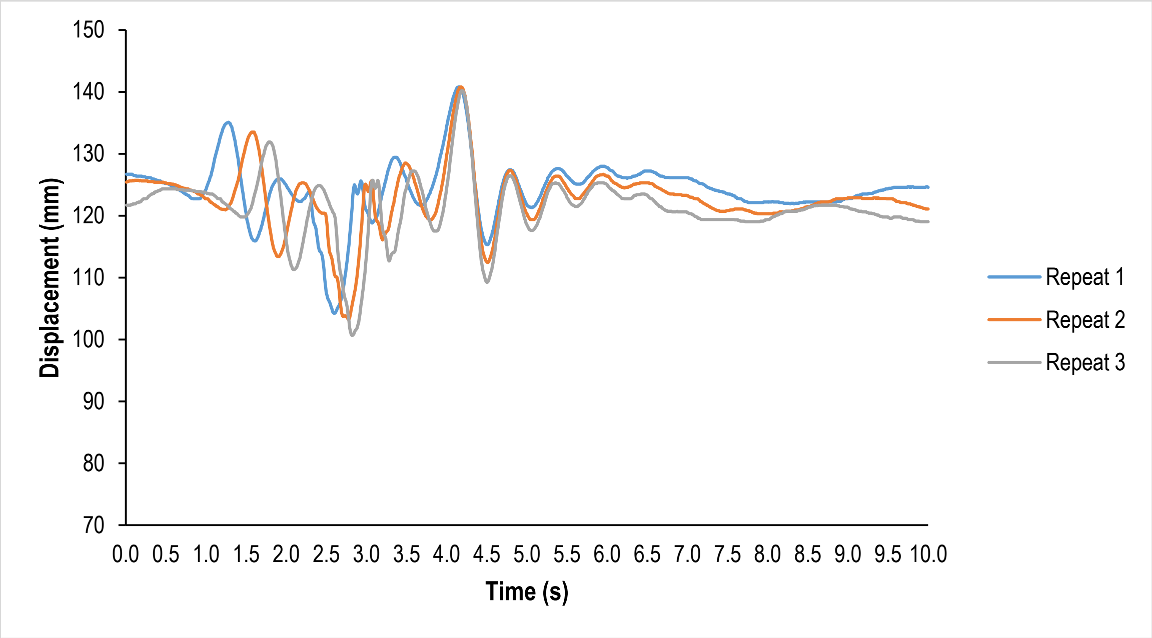
A clear reduction in damping is evident and was able to be detected by both systems. For the low damping shock absorber, the variations between axle sides and repeats is less, due to the system as whole being less damped, resulting in less potential for variability.

C.1.4 Repeatability of Pipe Tests: Fully Laden with HD Shock Absorbers

Figure C 7 shows the three repeat tests for the vehicle fully laden and fitted with HD shock absorbers.

Figure C 7: Repeatability of pipe tests (HD shocks – fully laden)





A summary of the results is presented in Table C 5.

Table C 5: Summary of results: fully laden with HD shock absorbers

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

Commentary

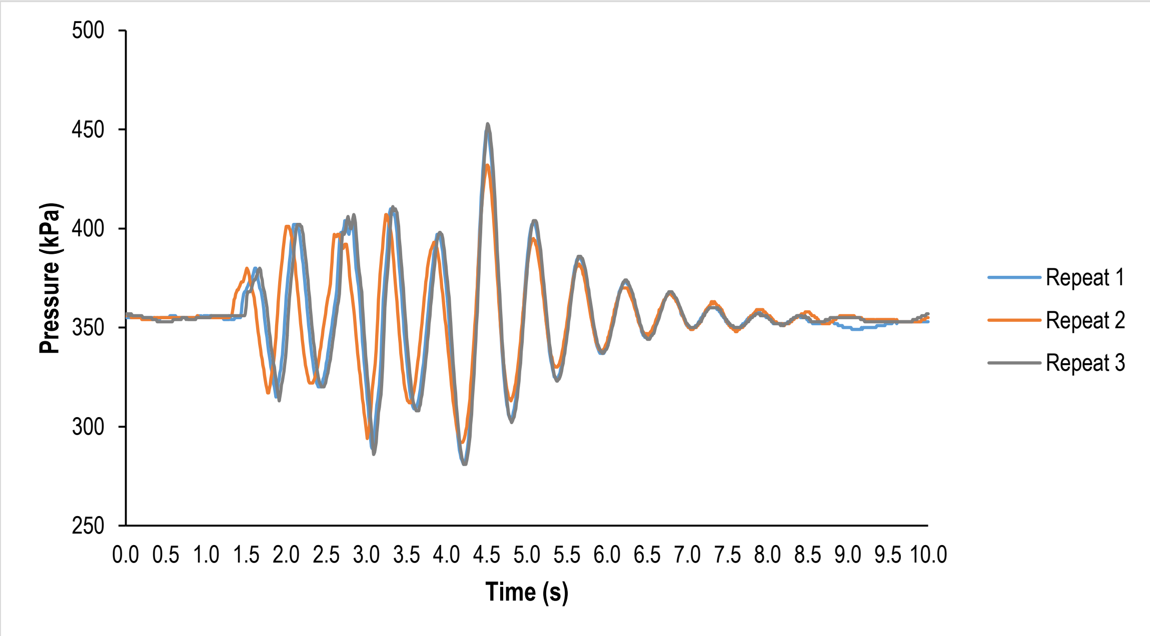
The results from the pipe test show significant variation across the side of the axles and between repeat tests; 17% compared with 27%, between test 1 and test 3, for the right side. Unlike previous results obtained from the ramp test, these variations were also recorded by the APT, confirming that the 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 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.

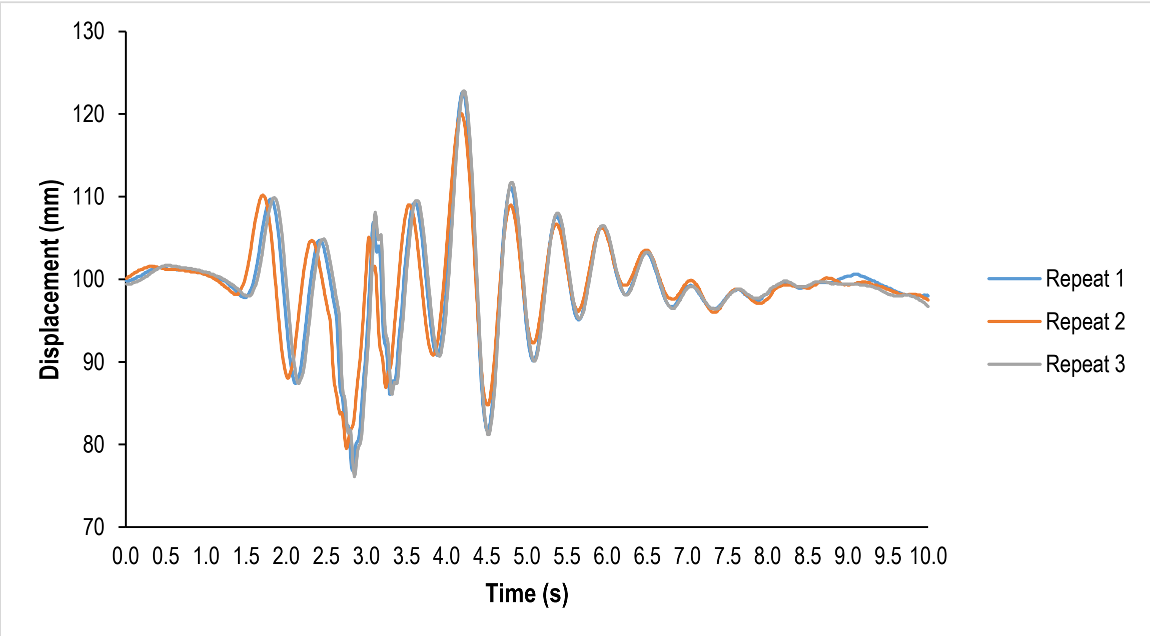
The results obtained from pipe tests overestimate the damping when compared with the ramp test, from the APTs the averaged result was 21% for the pipe compared with 20% for the ramp, and from LPTs it was 22% for the pipe with 18% for the ramp.

C.1.5 Repeatability of Pipe Tests: Fully Laden with MED Shock Absorbers

Figure C 8 shows the three repeat tests for the vehicle fully laden and fitted with MED shock absorbers.

Figure C 8: Repeatability of ramp tests (MED shocks – fully laden)





A summary of the results is presented in Table C 6.

Table C 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	*Right*	*Left*	*Right*	*Left*
Test 1 - Damping ratio (%)	11	12	10	9
Test 2 - Damping ratio (%)	11	12	11	10
Test 3 - Damping ratio (%)	11	12	11	10
Averaged result (%)	**12**		**10**	
Standard deviation	**0.54**		**0.75**	
Frequency (Hz)	**1.72**		**1.74**	

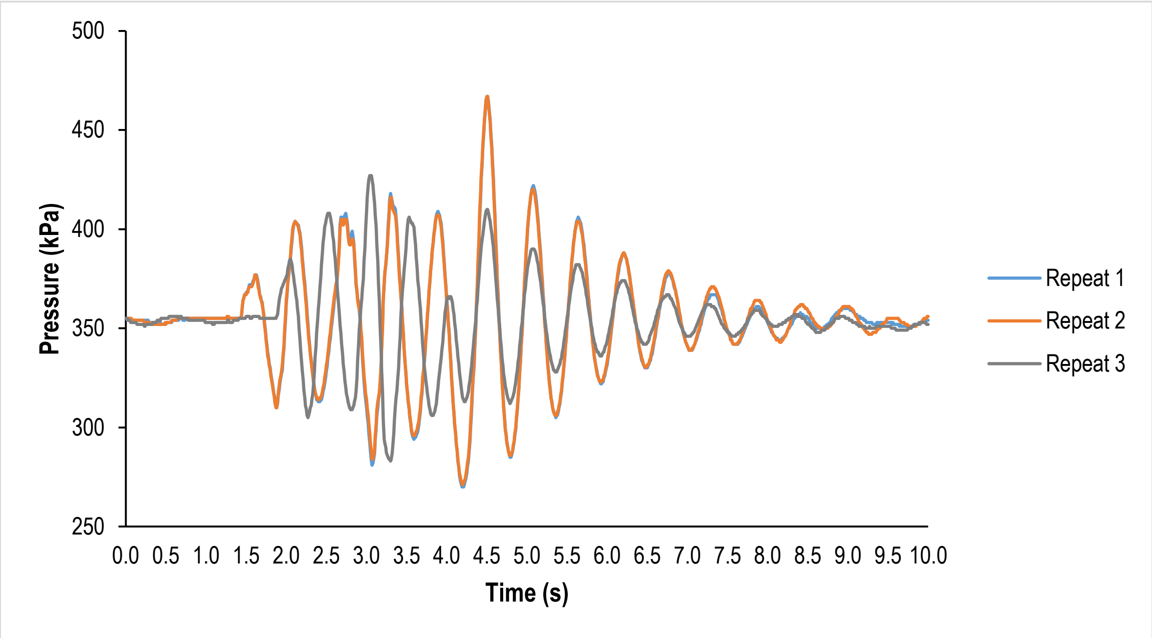
Commentary

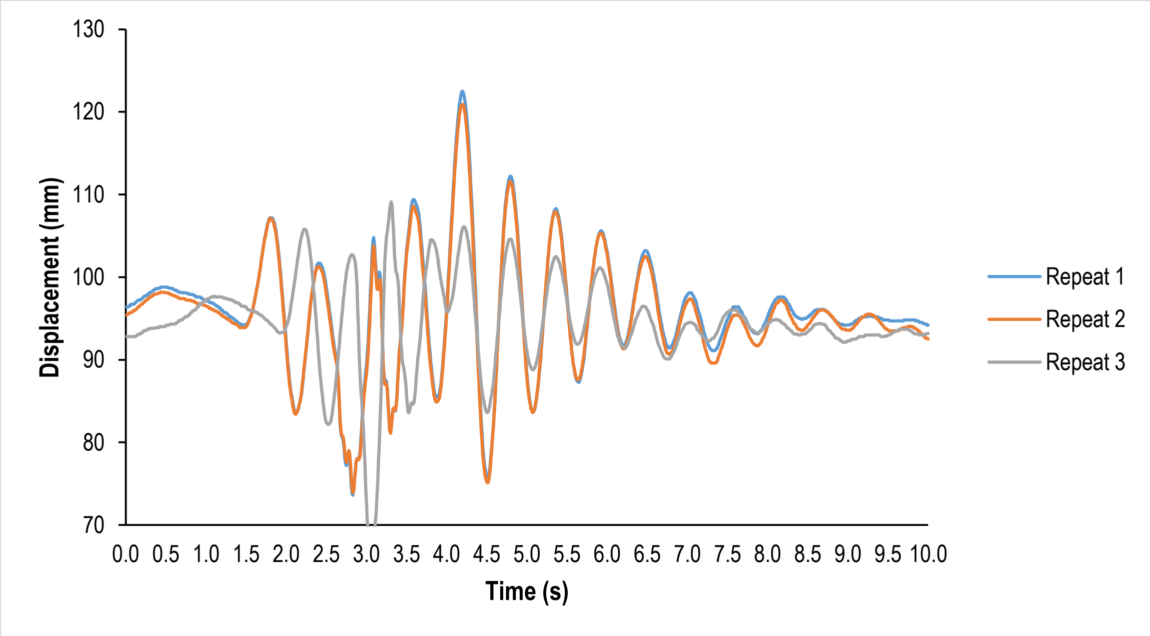
The results obtained for the medium damping shockers are very similar to the results obtained by the ramp tests for the same shock absorber set up. The visual appearance of the data trace indicates high repeatability with consistent magnitude and frequency. This implies that the driver has chosen the correct speed for these tests and the correct approach angle resulting 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.

C.1.6 Repeatability of Pipe Tests: Fully Laden with LOW Shock Absorbers

Figure C 9 shows the three repeat tests for the vehicle fully laden and fitted with LOW shock absorbers.

Figure C 9: Repeatability of ramp tests (LOW shocks – fully laden)





A summary of the results is presented in Table C 7.

Table C 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	*Right*	*Left*	*Right*	*Left*
Test 1 - Damping ratio (%)	8	8	8	7
Test 2 - Damping ratio (%)	9	8	8	8
Test 3 - Damping ratio (%)	7	7	7	12
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.

C.1.7 Summary of Repeatability Test Results

A summary of the results is presented in Table C 8.

Table C 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.

C.1.8 Repeatability Tests: Fully Laden with NO Shock Absorbers

Figure C 10 and Figure C 11 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 C 10: Repeatability of ramp tests (NO shocks – fully laden)

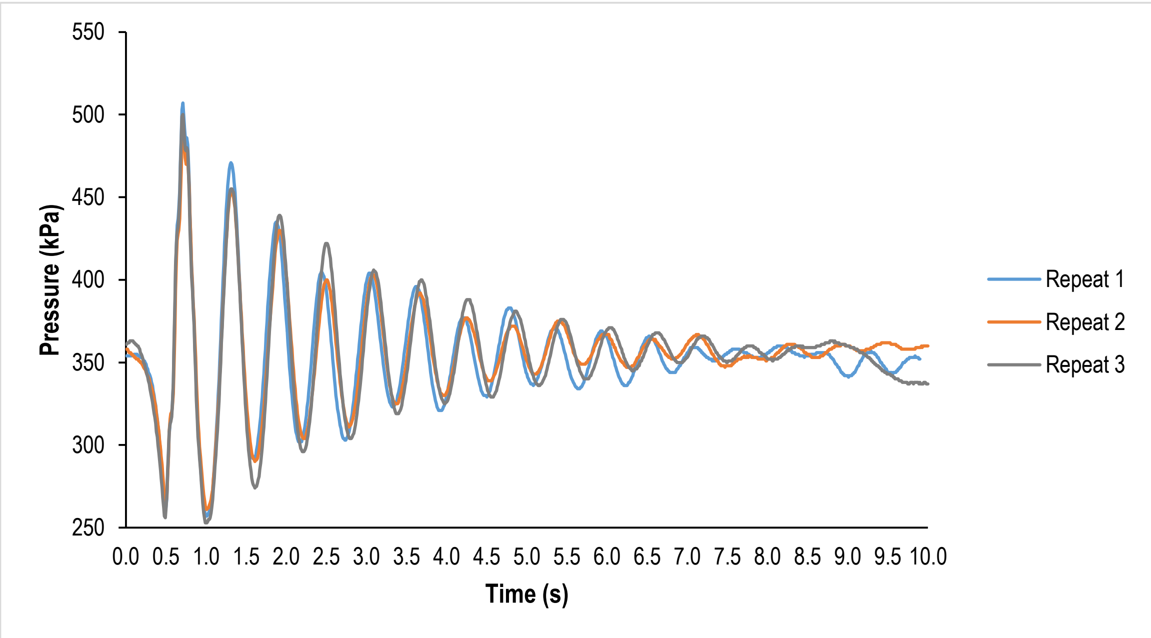
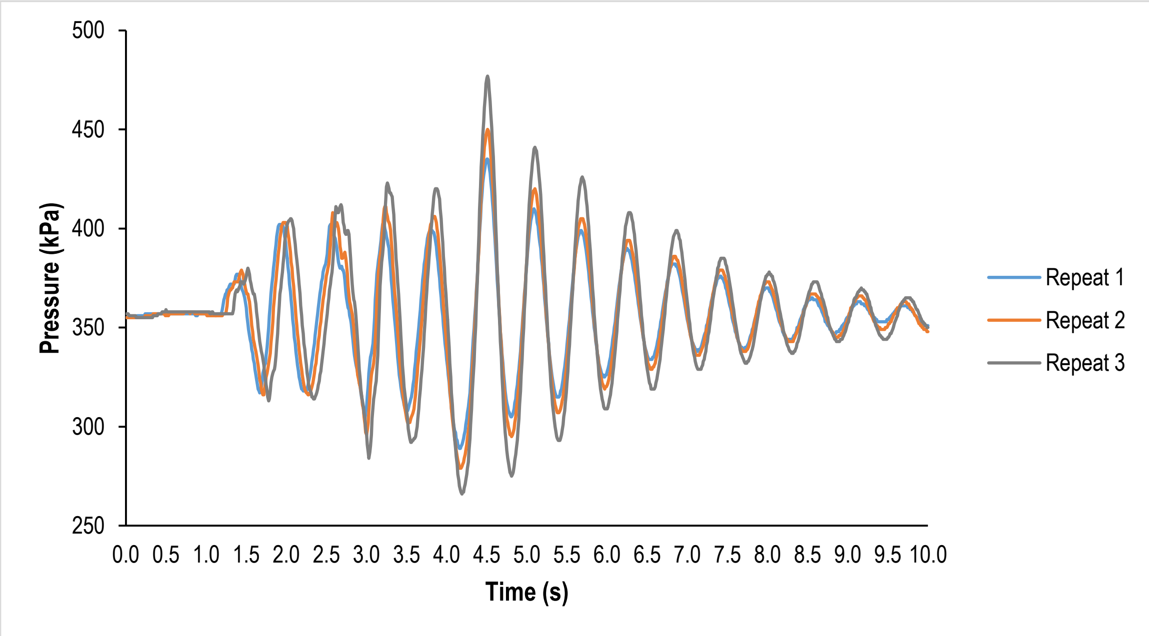


Figure C 11: Repeatability of pipe tests (NO shocks – fully laden)



A summary of the results is presented in Table C 9.

Table C 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	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*
Test 1 - Damping ratio (%)	8	8	6	8	7	5	6	7
Test 2 - Damping ratio (%)	10	10	6	7	7	5	5	5
Test 3 - Damping ratio (%)	8	7	6	6	5	5	6	5
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 wearing 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 shock absorbers removed.

C.1.9 Comparison of Pipe vs Ramp Tests: Fully Laden & LOW

Figure C 12 and Figure C 13 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 C 12: Comparison of pipe and ramp tests using APTs (LOW shocks – fully laden)

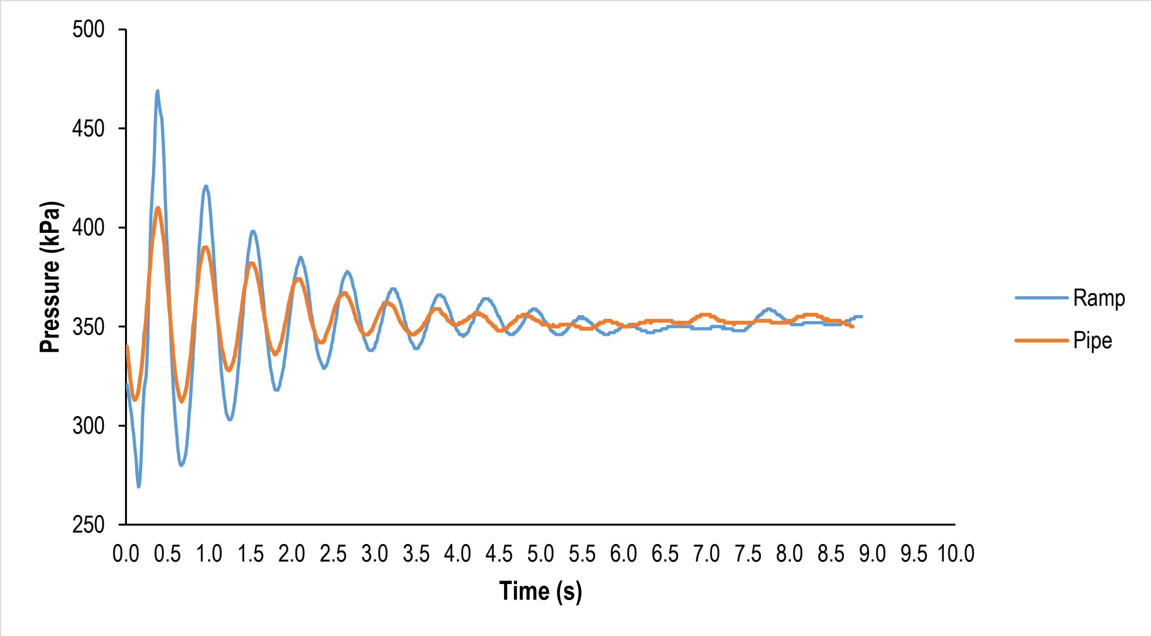
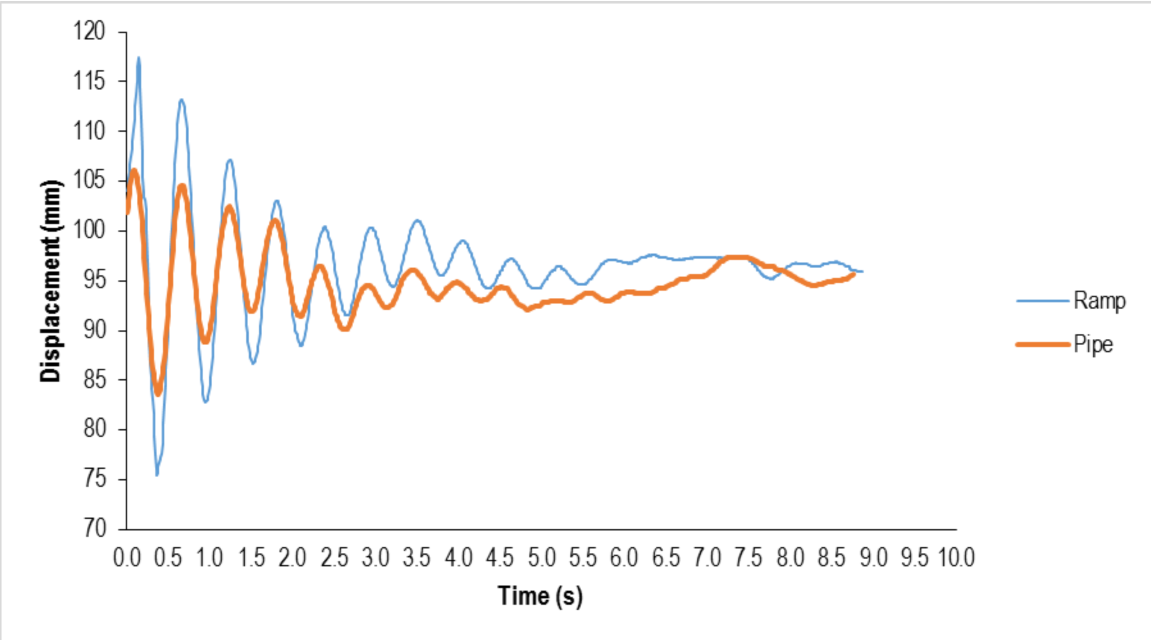


Figure C 13: Comparison of pipe and ramp tests using LDTs (LOW shocks – fully laden)



A summary of the results is presented in Table C 10.

Table C 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*

Load	*Fully laden*							
Shock absorbers	*All low damping*							
Analysis	*VSB11 ramp test and Pipe test*							
Axle	*Centre*							
Excitation method	*VSB11 ramps*				*Pipe*			
Left/right sensor	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*
Test 1 - Damping ratio (%)	8	8	7	7	7	7	4	6
Test 2 - Damping ratio (%)	8	7	7	7	8	8	4	5
Test 3 - Damping ratio (%)	8	7	5	7	8	8	4	6
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**	

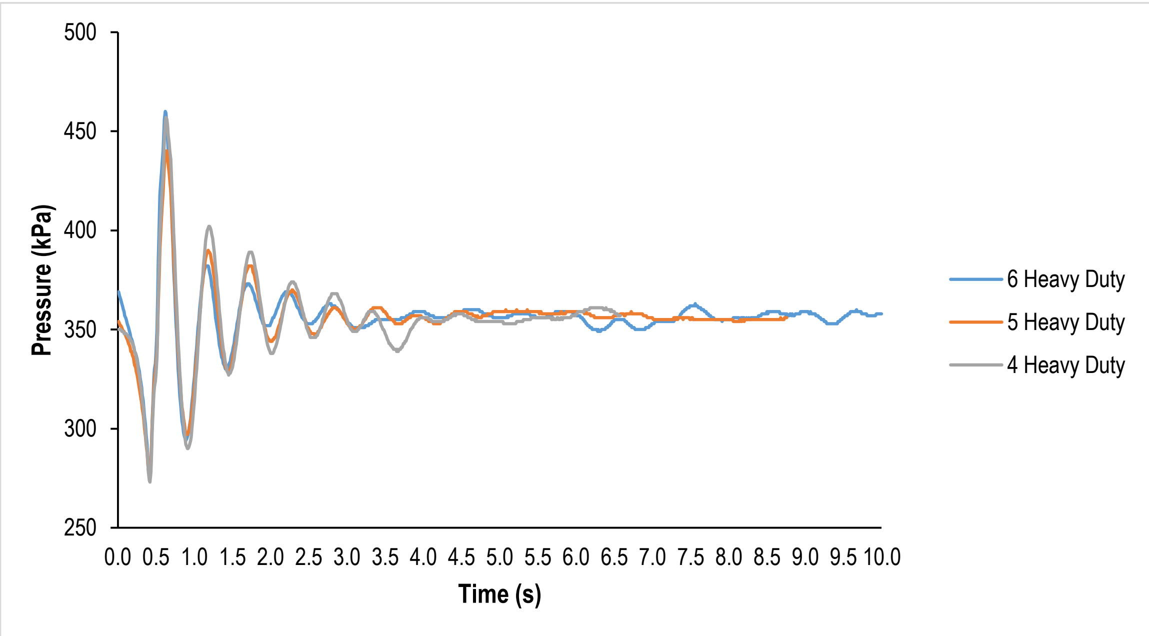
Commentary

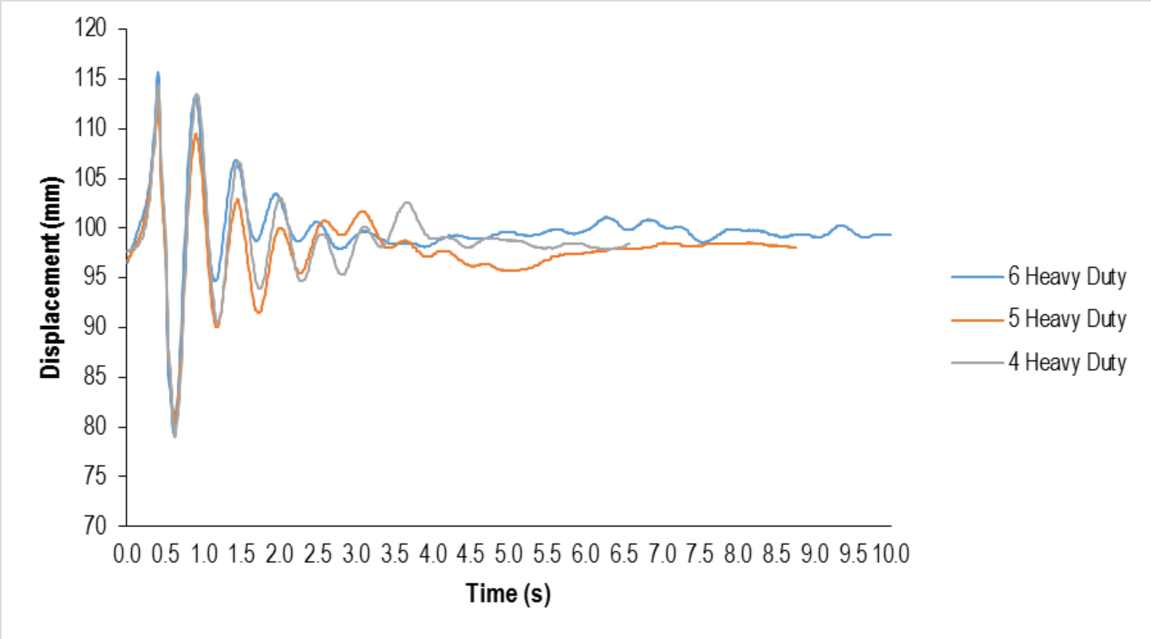
The pipe test results are marginally lower than the ramp tests for these tests.

C.1.10 Comparison of Ramp Tests: Fully Laden 6HD vs 5HD vs 4HD

Figure C 14 shows 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.

Figure C 14: Comparison of ramp tests (6HD, 5HD and 4HD – fully laden)





A summary of the results is presented in Table C 11.

Table C 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	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*
Test 1 - Damping ratio (%)	22	19	14	13	13	12	10	13	13	17	9	8
Test 2 - Damping ratio (%)	20	19	14	13	11	10	19	24	24	28	13	11
Test 3 - Damping ratio (%)	21	20	11	9	12	12	20	26	20	42	10	11
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**	

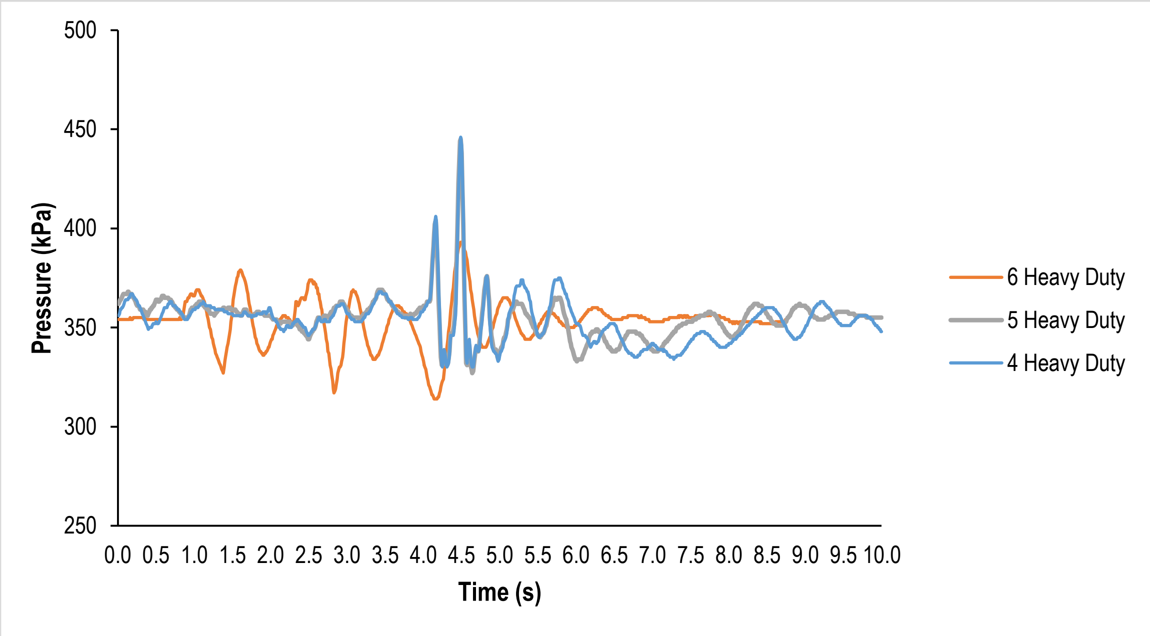
Commentary

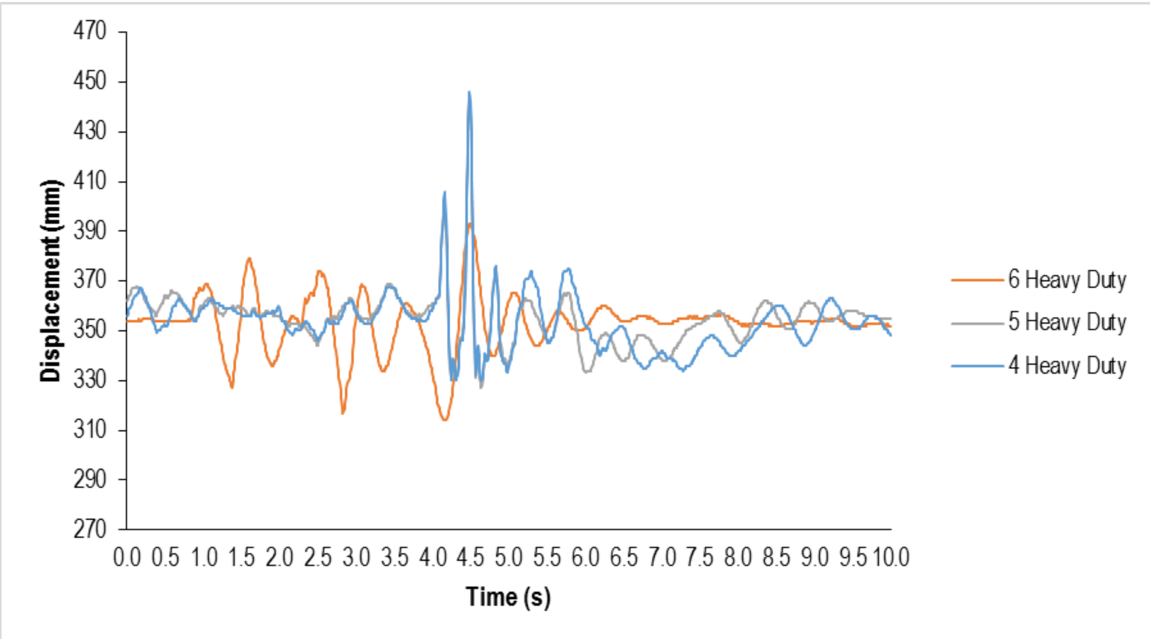
The intention of these tests were to determine if a small change in damping could be detected by the systems. Removing one shock absorber from the triaxle suspension represents a reduction in damping of 16.67%, removing two shock absorbers represents a reduction in damping of 33.34%. Reductions are expected as each shock absorber is removed, however the results did not fall with the expected range. This is due to the variations in the excitation method and measurement method being greater than the difference 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 robust conclusion on the ability for this system to detect the absence of a single shock absorber.

C.1.11 Comparison of Pipe Tests: Fully Laden 6HD vs 5HD vs 4HD

Figure C 15 shows 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.

Figure C 15: Comparison of pipe tests (6HD, 5HD and 4HD – fully laden)





A summary of the results is presented in Table C 12.

Table C 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	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*
Test 1 - Damping ratio (%)	24	26	NA*	NA	6	NA	0	4	17	12	2	1
Test 2 - Damping ratio (%)	18	22	NA	25	7	8	3	6	12	10	3	1
Test 3 - Damping ratio (%)	19	22	NA	NA	21	21	4	6	15	NA	2	NA
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**	

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

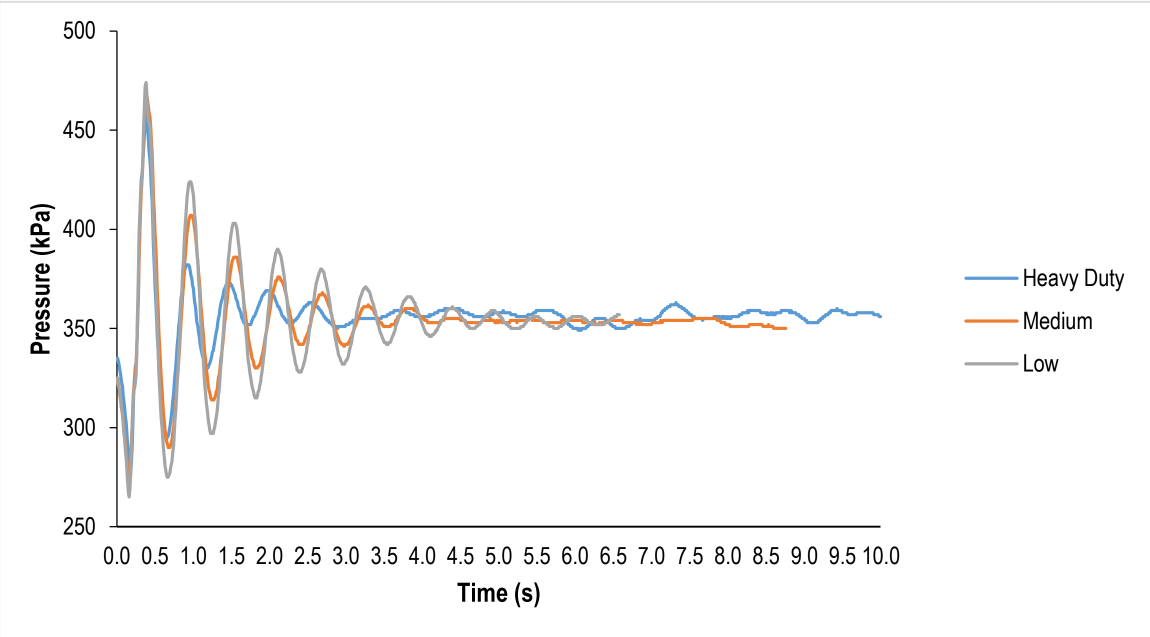
Commentary

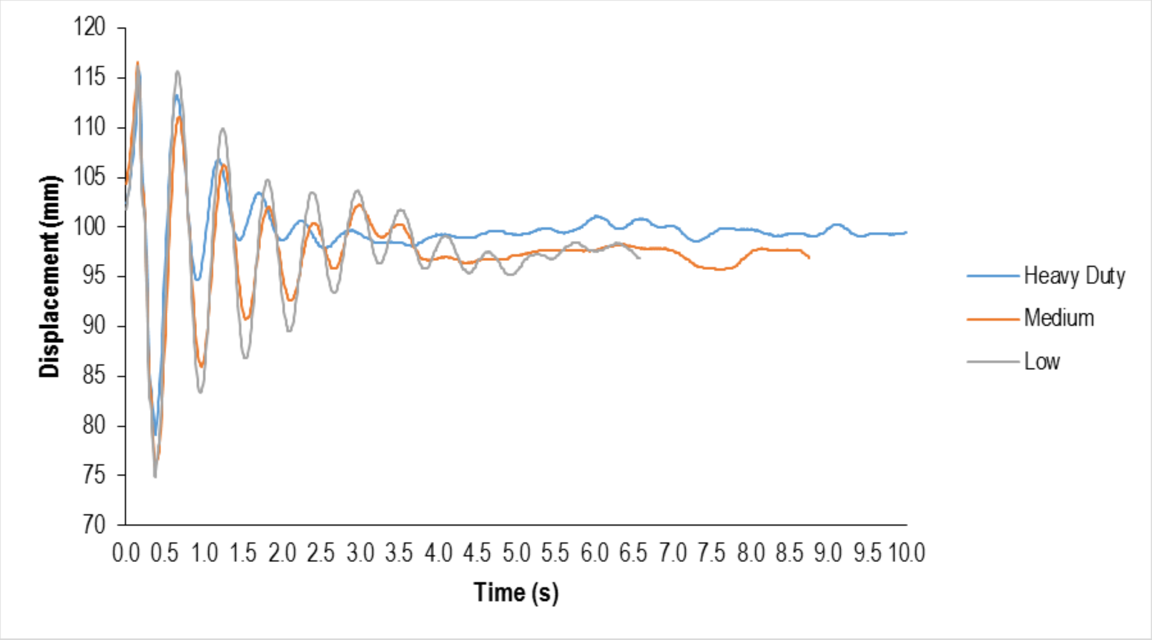
These tests were conducted prior to adjusting the test speed for the pipe test from high to low. In some instances no peaks can be identified, and those that were detected produced unreliable results.

C.1.12 Comparison of Ramp Tests: Fully Laden HD vs MED vs LOW

Figure C 16 shows the data traces from the ramp test for the tests with high, medium and low damping shock absorbers.

Figure C 16: Comparison of ramp tests (HD, MED and LOW – fully laden)





A summary of the results is presented in Table C 13.

Table C 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	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*
Test 1 - Damping ratio (%)	22	19	12	11	8	7	10	13	6	8	5	10
Test 2 - Damping ratio (%)	20	19	11	10	8	7	19	24	10	12	7	9
Test 3 - Damping ratio (%)	21	20	12	10	9	8	20	26	9	11	8	12
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**	

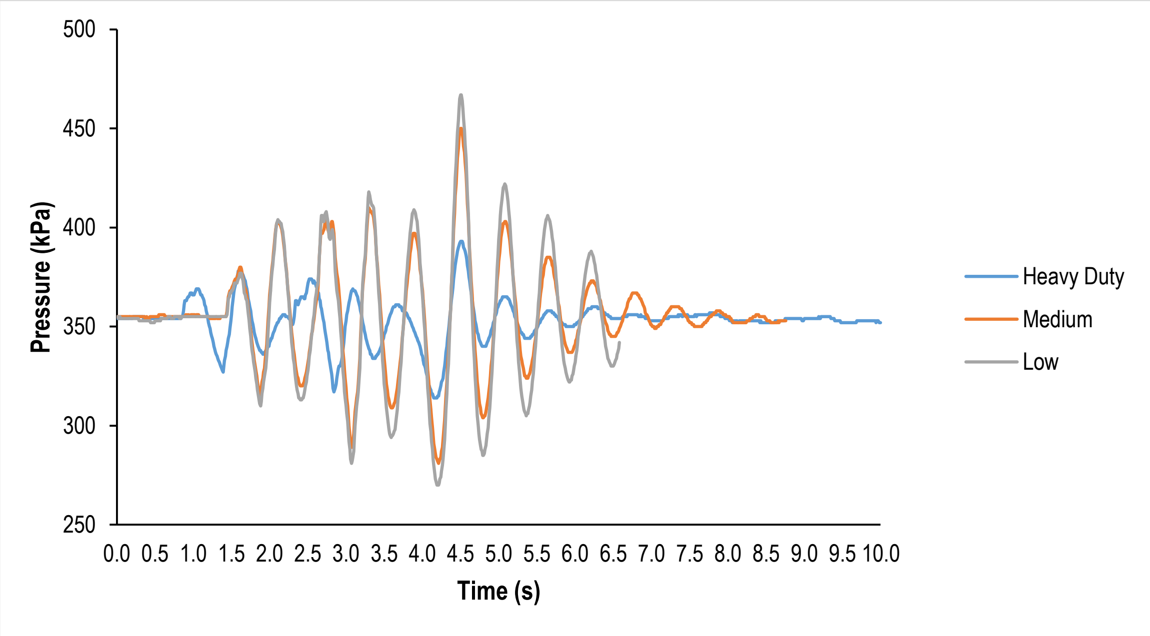
Commentary

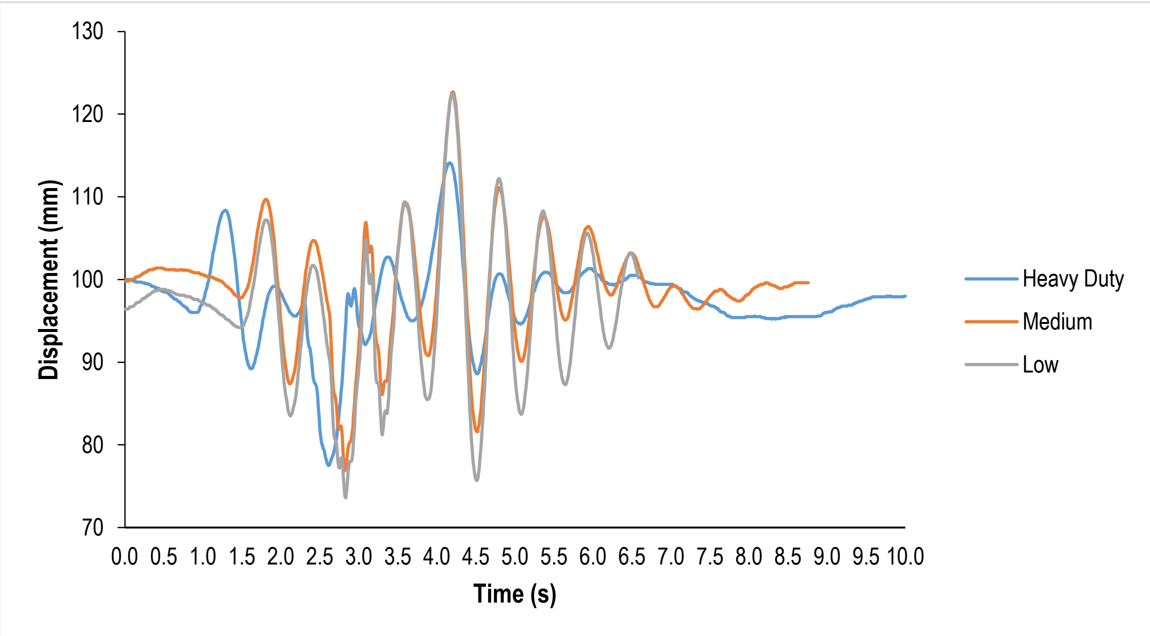
A clear reduction in damping was detected by the APTs and LDTs between the high damping and medium damping tests, but less when changing between the medium and low dampers for the APTs and no change was detected by the LDTs between these two dampers. The frequency varied inconsistently for both sensors, 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.

C.1.13 Comparison of Pipe Tests: Fully Laden HD vs MED vs LOW

Figure C 17 shows the data traces from the pipe test for the tests with HD, MED and LOW shock absorbers.

Figure C 17: Comparison of pipe tests (HD, MED and LOW – fully laden)





A summary of the results is presented in Table C 14.

Table C 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	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*
Test 1 - Damping ratio (%)	22	25	11	12	8	8	17	19	10	09	8	7
Test 2 - Damping ratio (%)	17	22	11	12	9	8	21	23	11	10	9	8
Test 3 - Damping ratio (%)	18	21	11	12	7	7	27	26	11	10	13	12
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**	

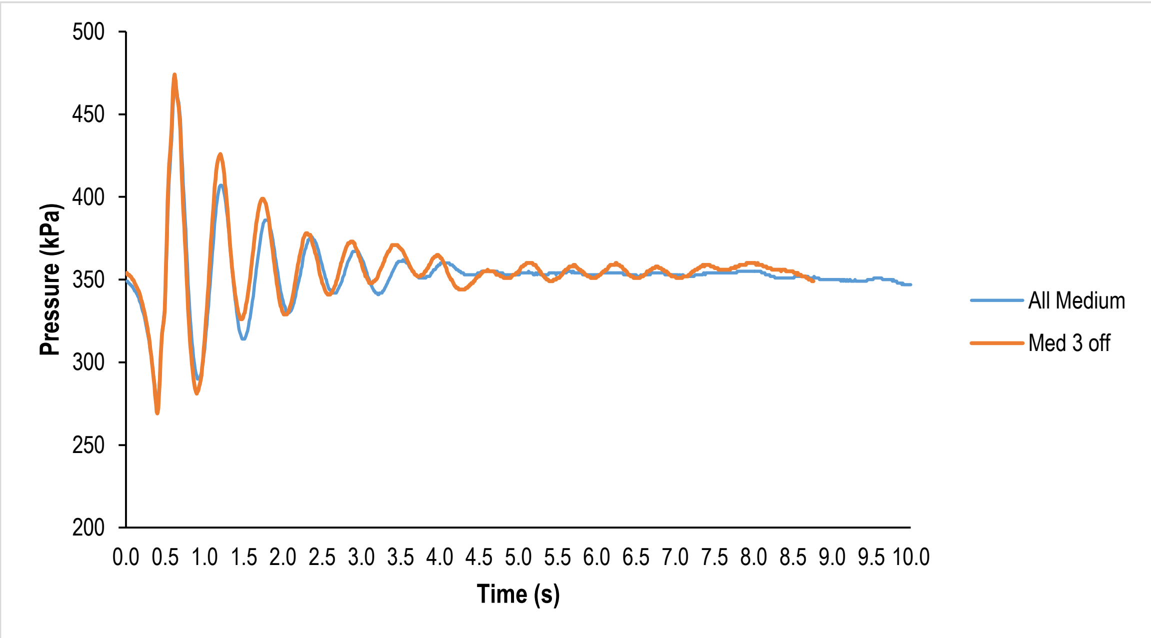
Commentary

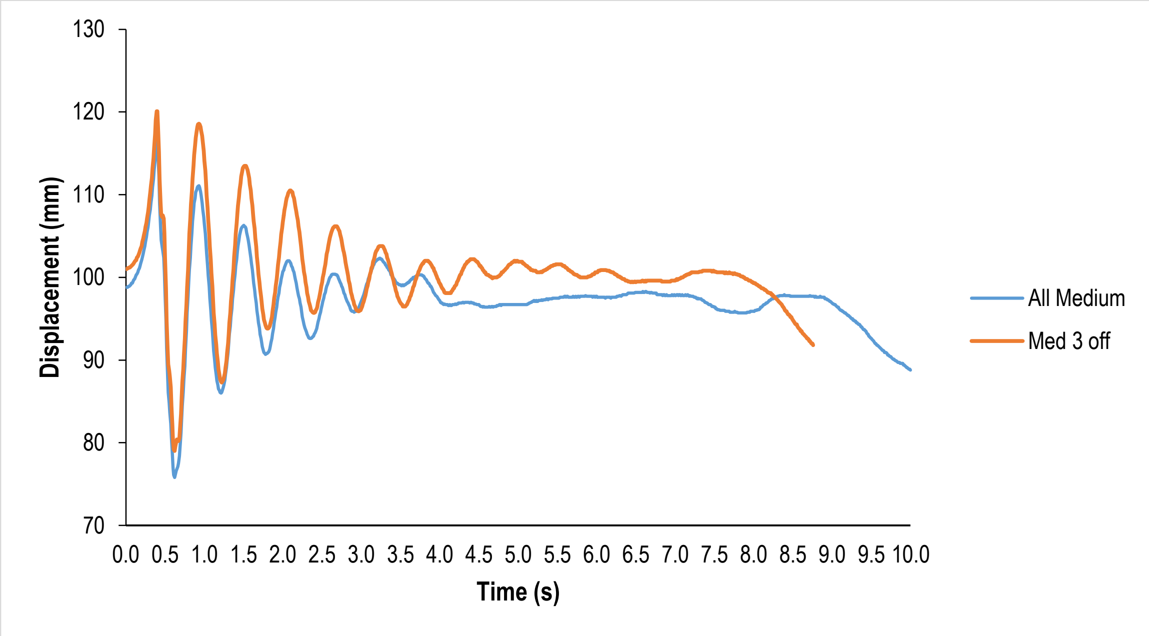
Similar to the ramp test results, the pipe test results indicate an approximate 50% reduction in damping between the high damping and medium damping shock absorbers, but much less change between the medium and low damping shock absorbers.

C.1.14 Comparison of Ramp Tests: Fully Laden MED vs 3 OFF

Figure C 18 shows the data traces from the ramp test for the tests with 6 MED shocks and fitted and 3 removed from the left (passenger) side of the vehicle.

Figure C 18: Comparison of ramp tests (6MED and 3 removed – fully laden)





A summary of the results is presented in Table C 15.

Table C 15: Summary of results: fully laden 6MED 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	*6MED*		*3 removed*		*6MED*		*3 removed*	
Left/right sensor	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*
Test 1 - Damping ratio (%)	12	10	8	7	13	10	6	5
Test 2 - Damping ratio (%)	11	9	8	8	8	6	6	6
Test 3 - Damping ratio (%)	12	9	7	6	10	8	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

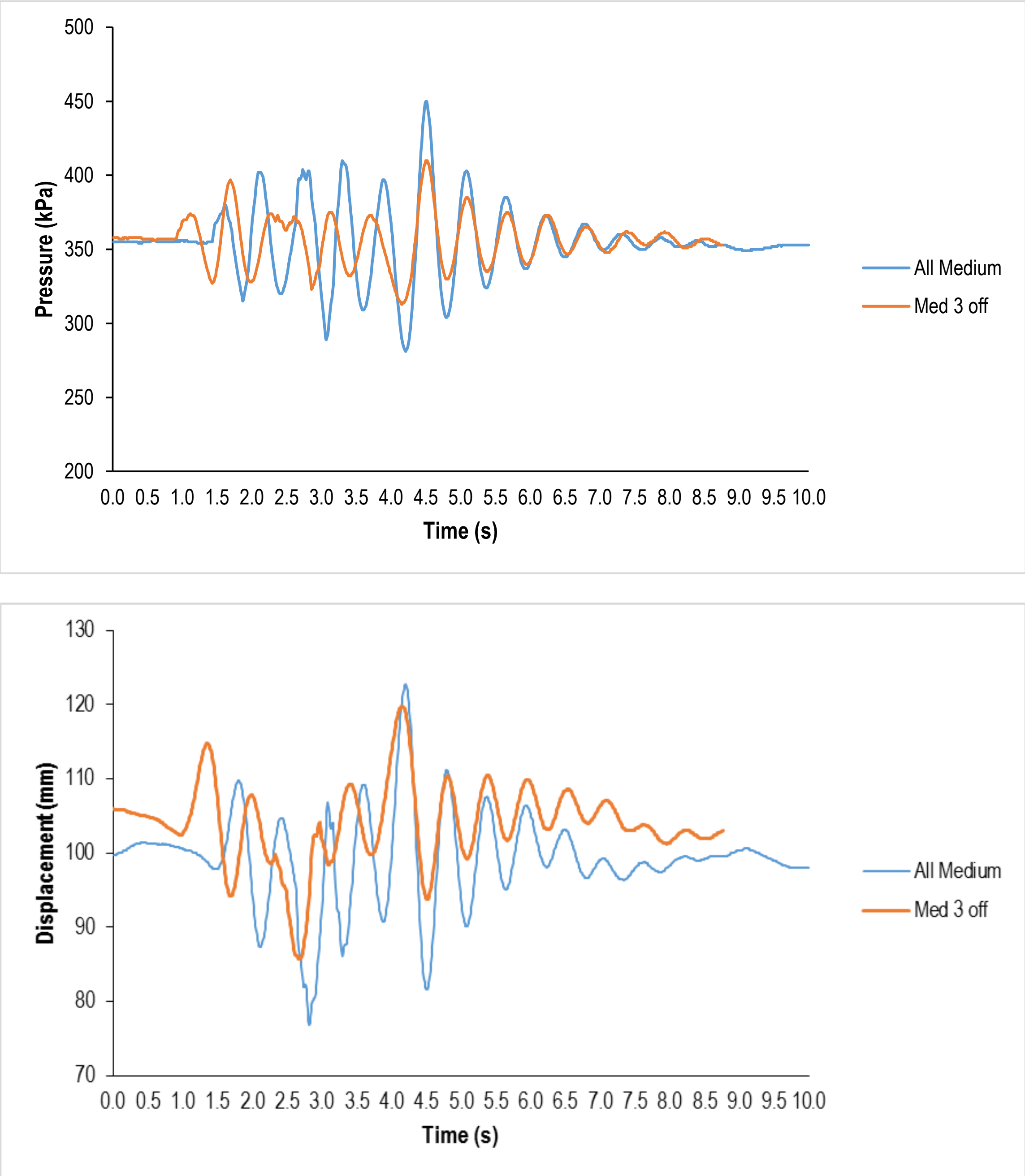
The intention of this test was to determine if a larger change in damping can be detected by removing all three shock absorbers on the left side of the triaxle suspension group. It was also expected that this test would generate body roll, the effects of which would be assessed during this test. However, no evidence of body roll was noticeable in these tests.

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.

C.1.15 Comparison of Pipe Tests: Fully Laden MED vs 3 OFF

Figure C 19 shows the data traces from the pipe test for the tests with 6 MED shocks and fitted and 3 removed from the left (passenger) side of the vehicle.

Figure C 19: Comparison of ramp tests (6MED and 3 removed – fully laden)



A summary of the results is presented in Table C 16.

Table C 16: Summary of results: fully laden 6MED 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	*6MED*		*3 removed*		*6MED*		*3 removed*	
Left/right sensor	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*
Test 1 - Damping ratio (%)	11	12	10	13	10	9	0	6
Test 2 - Damping ratio (%)	11	12	9	11	11	10	3	5
Test 3 - Damping ratio (%)	11	12	9	8	11	10	4	7
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**	

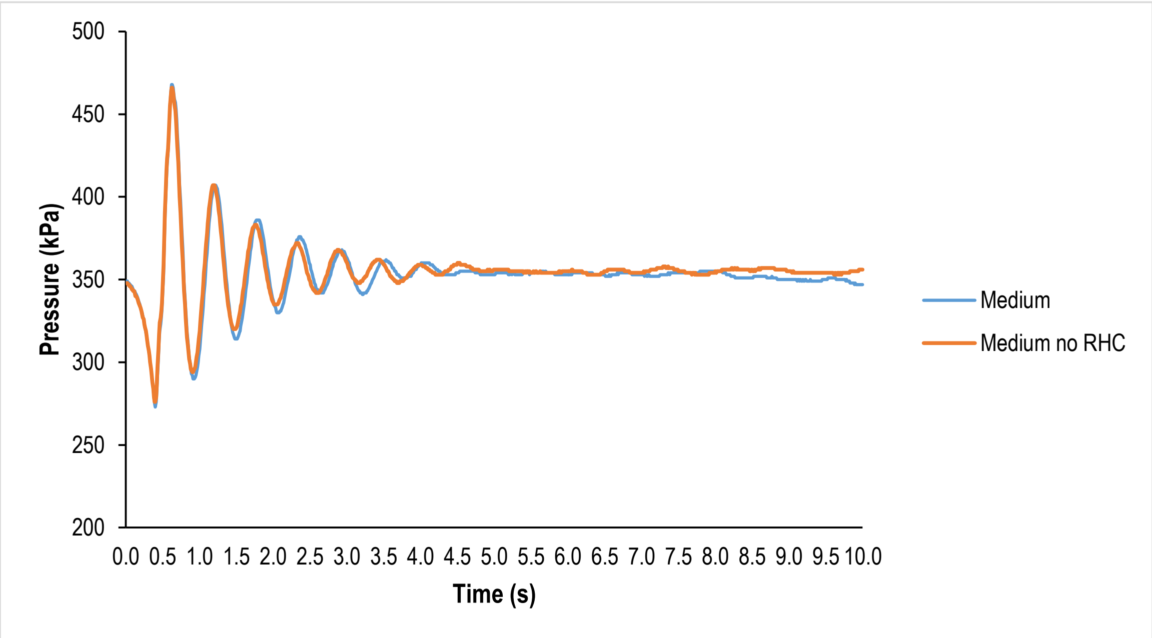
Commentary

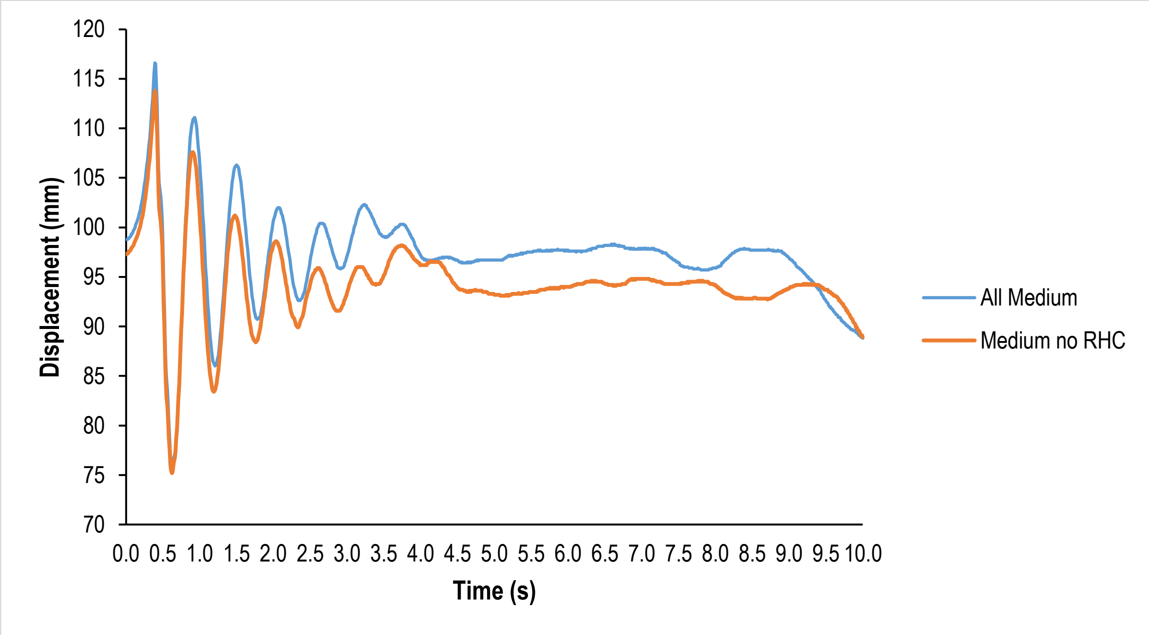
The pipe test produced significantly different results from the ramp tests, for the first time during the test program, other than those tests affected by speed. There is a large variation between the repeat tests with three shock absorbers removed for both the APTs and LDTs. The averaged results from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

C.1.16 Comparison of Ramp Tests: Fully Laden 6MED vs 6MED with no RHC

Figure C 20 shows the data traces from the ramp test with the vehicle fitted with 6 MED damping. Tests were conducted with the ride height control valve was in place and then with it disconnected.

Figure C 20: Comparison of ramp tests (6MED with and without RHC – fully laden)





A summary of the results is presented in Table C 17.

Table C 17: Summary of results: fully laden 6MED 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

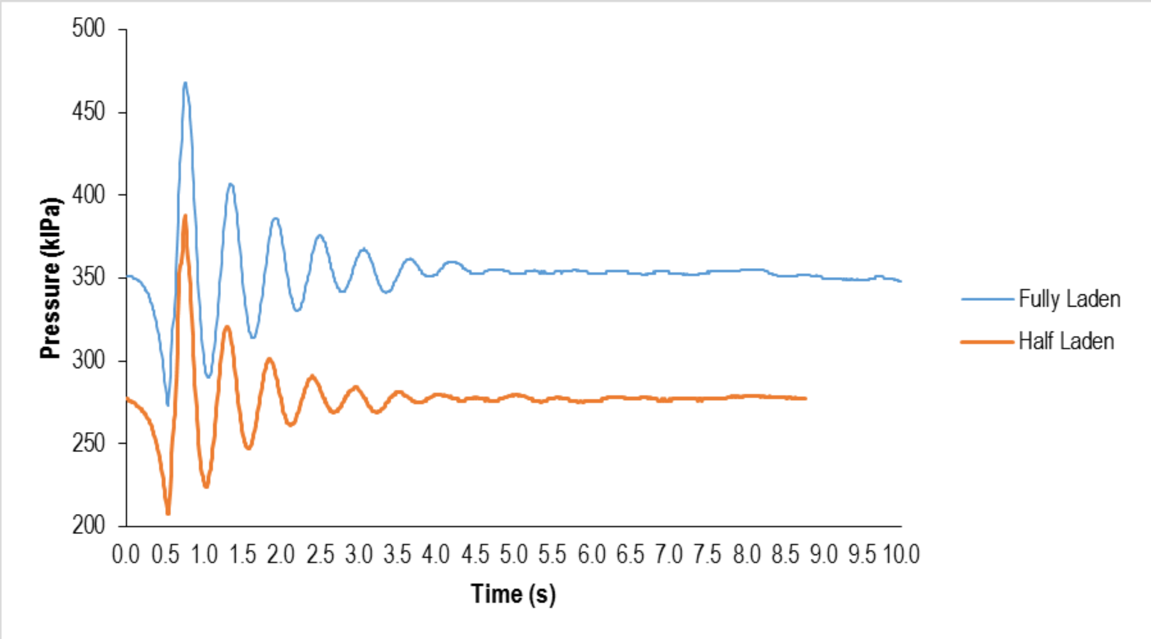
The intention of this test was to quantify the effect of the ride height control (RHC) valve. Tests were conducted with RHC connected and disconnected. The averaged results indicate that this had no effect on the damping of the suspension.

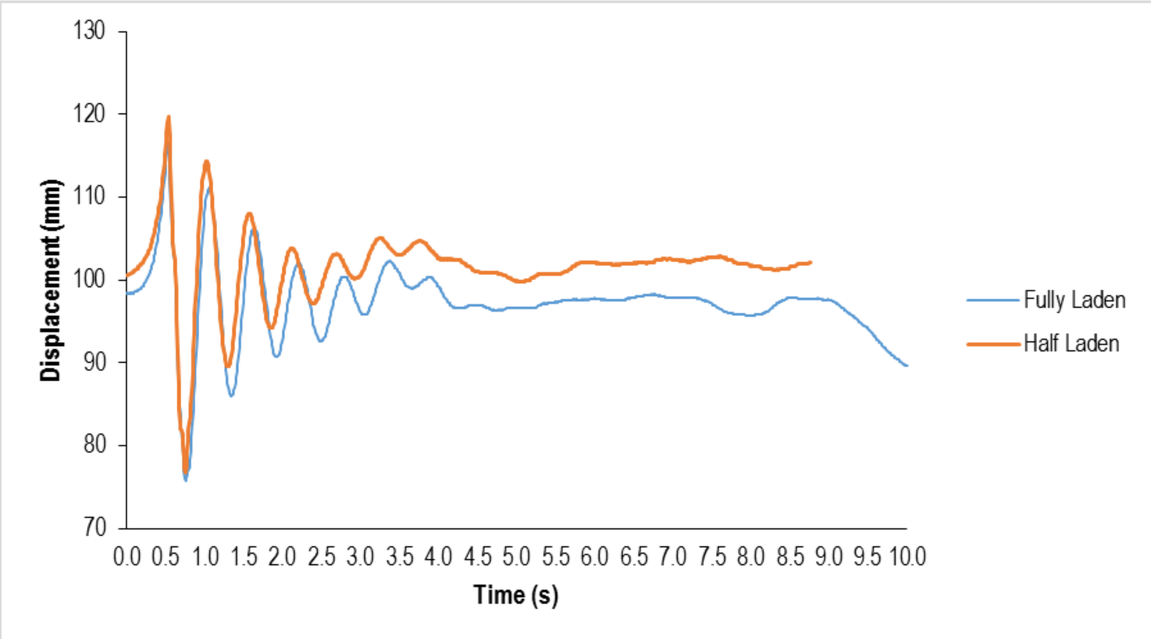
The RHC valve when disconnected did cause the final position (the vertical height) at which the suspension settles following the tests, to vary by approximately 5 mm. There is often some variation in this final position, even for those tests where the RHC valve was operating normally, although the difference was greater for the tests with it disconnected. The difference in final position must be removed prior to calculating the damping, and can affect the results if not compensated for during the analysis.

C.1.17 Comparison of Ramp Tests: Fully Laden MED vs Half Laden MED

Figure C 21 shows the data traces from the ramp test with the vehicle fitted with 6 MED damping. Tests were conducted with the vehicle full laden and then again approximately half laden.

Figure C 21: Comparison of ramp tests (6MED – fully laden and half laden)





A summary of the results is presented in Table C 18.

Table C 18: Summary of results: 6MED 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	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*
Test 1 - Damping ratio (%)	12	10	15	14	13	10	12	15
Test 2 - Damping ratio (%)	11	9	16	13	8	6	12	15
Test 3 - Damping ratio (%)	12	9	16	14	10	8	12	16
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

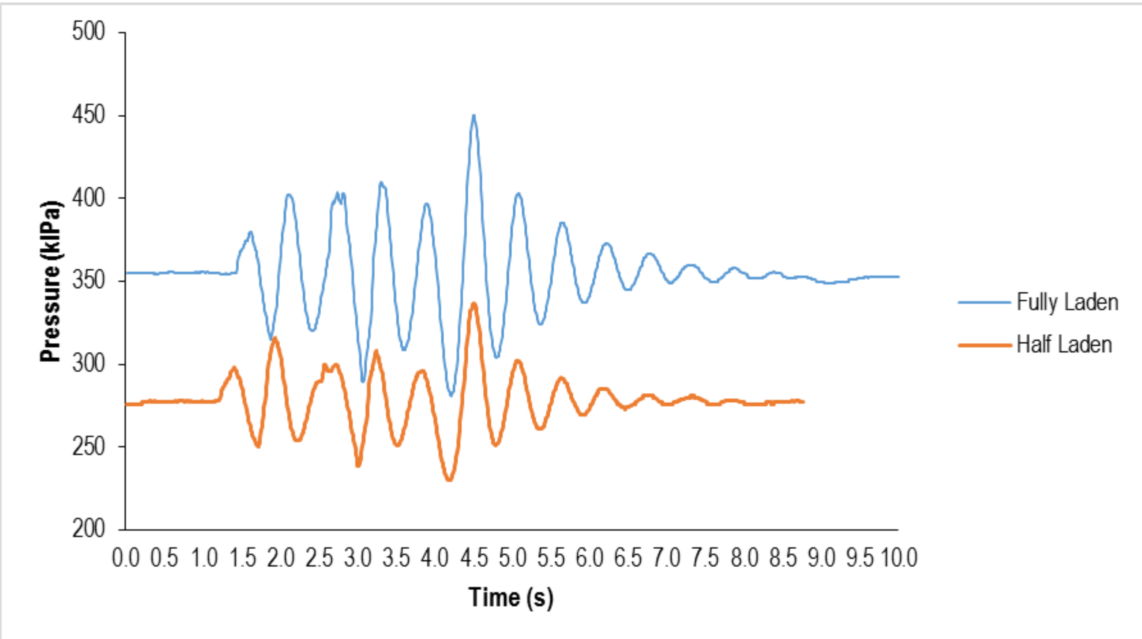
The intention of this test was to quantify the difference between testing the vehicle laden and approximately half laden. It is clear that the results are affected by the change in load.

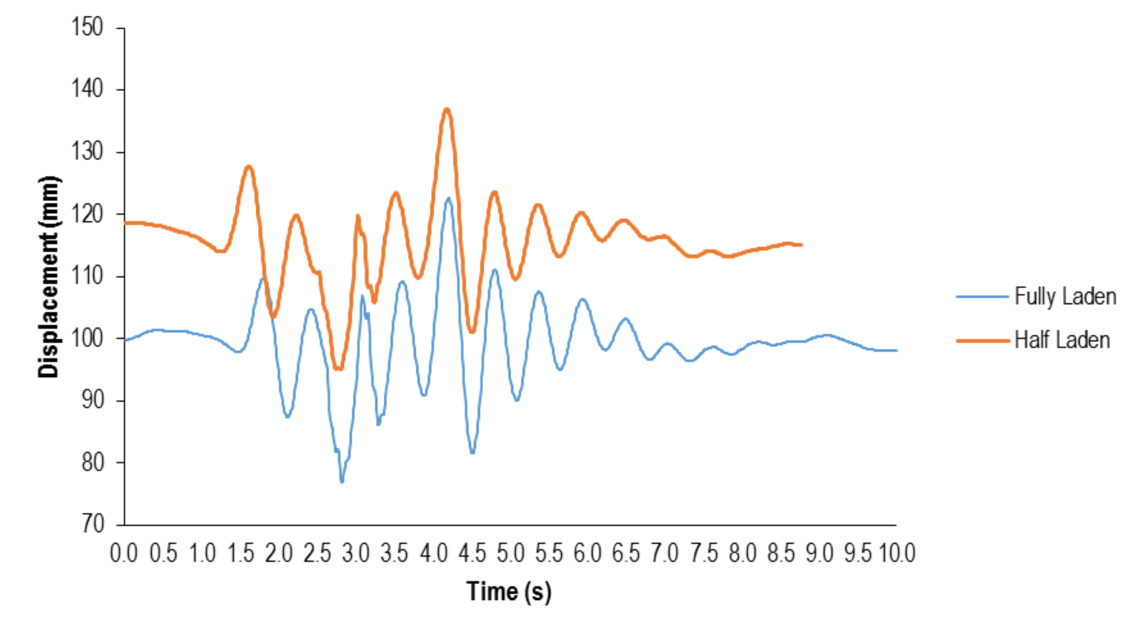
No change in damping should occur as the vehicle was fitted with the same shock absorbers for both tests, however the results have increased significantly. It can be concluded that tests must be conducted within a mass tolerance. The VSB11 mass tolerance is +/-5%.

C.1.18 Comparison of Pipe Tests: Fully Laden MED vs Half Laden MED

Figure C 22 shows the data traces from the pipe test with the vehicle fitted with 6 MED damping. Tests were conducted with the vehicle full laden and then again approximately half laden.

Figure C 22: Comparison of pipe tests (6MED – fully laden and half laden)





A summary of the results is presented in Table C 19.

Table C 19: Summary of results: 6MED fully laden and half laden – pipe test

Load	*Fully laden and half laden*							
Shock absorbers	*6 MED 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	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*
Test 1 - Damping ratio (%)	11	12	14	16	10	9	9	13
Test 2 - Damping ratio (%)	11	12	13	15	11	10	8	10
Test 3 - Damping ratio (%)	11	12	13	14	11	10	7	10
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 test produced inconsistent results across the APTs and LDTs when compared with the ramp test.

The APTs followed a similar trend to the ramp tests, whereas the PDTs did not. Despite the inconsistency, the results confirm that tests must be conducted within the axle group mass tolerance.

C.2 Results from Stage 2

Stage 2 of testing was conducted using the Road Friendly Suspension Analyser and a 6x4 prime mover. The test system is 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 vehicle and data obtained from both measurement systems were compared. For test program 2 the data presented was logged by ARRB for both the test system and the reference system.

C.2.1 Repeatability of RFSA Tests: Fully Laden with HD Shock Absorbers

Figure C 23 and Figure C 24 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 C 23: Load cell data trace from RFSA – HD shock absorbers

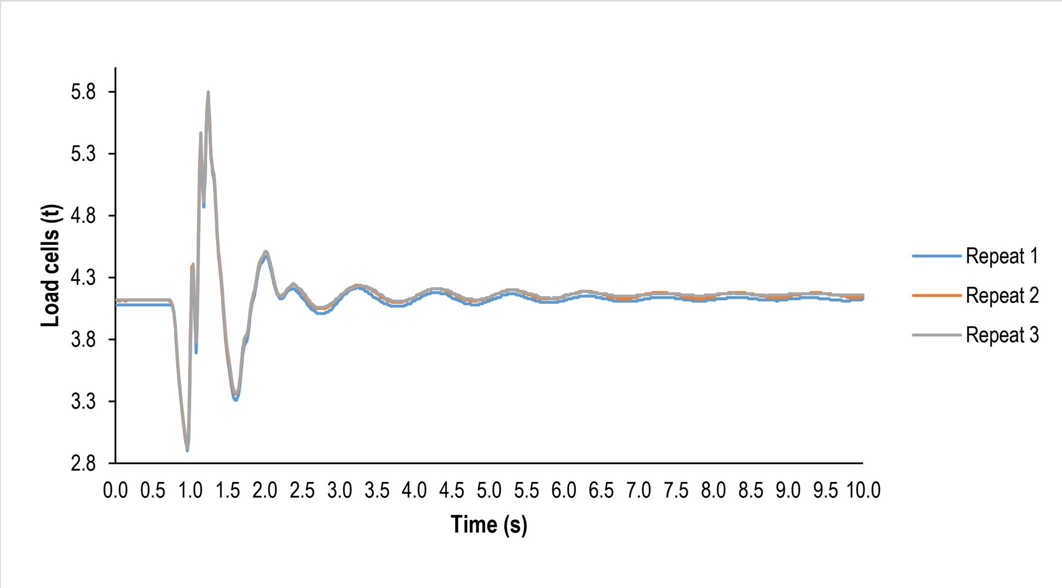


Figure C 24: Reference system (linear displacement) data trace from RFSA – HD shock absorbers

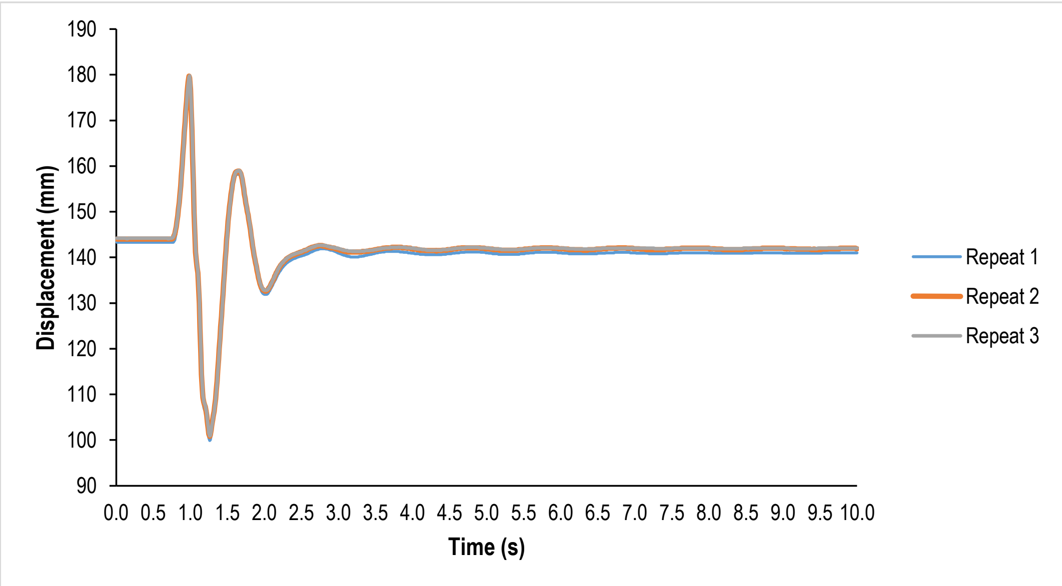


Figure C 25 and Figure C 26 shows the data traces of both the first and second axles.

Figure C 25: Load cell data trace from RFSA – HD shock absorbers

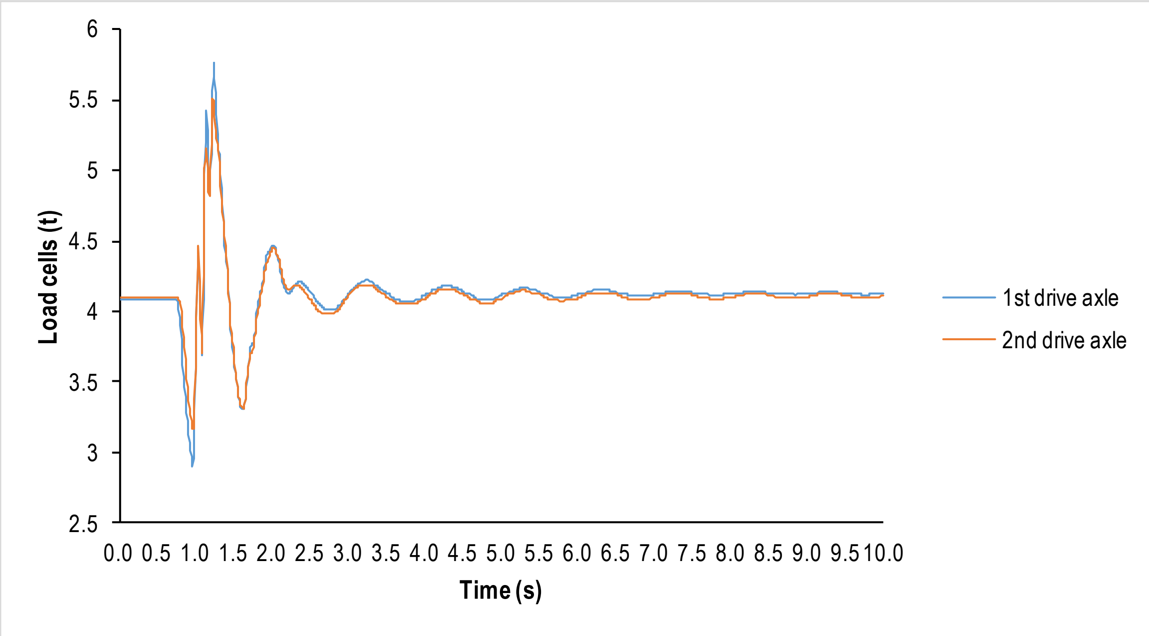
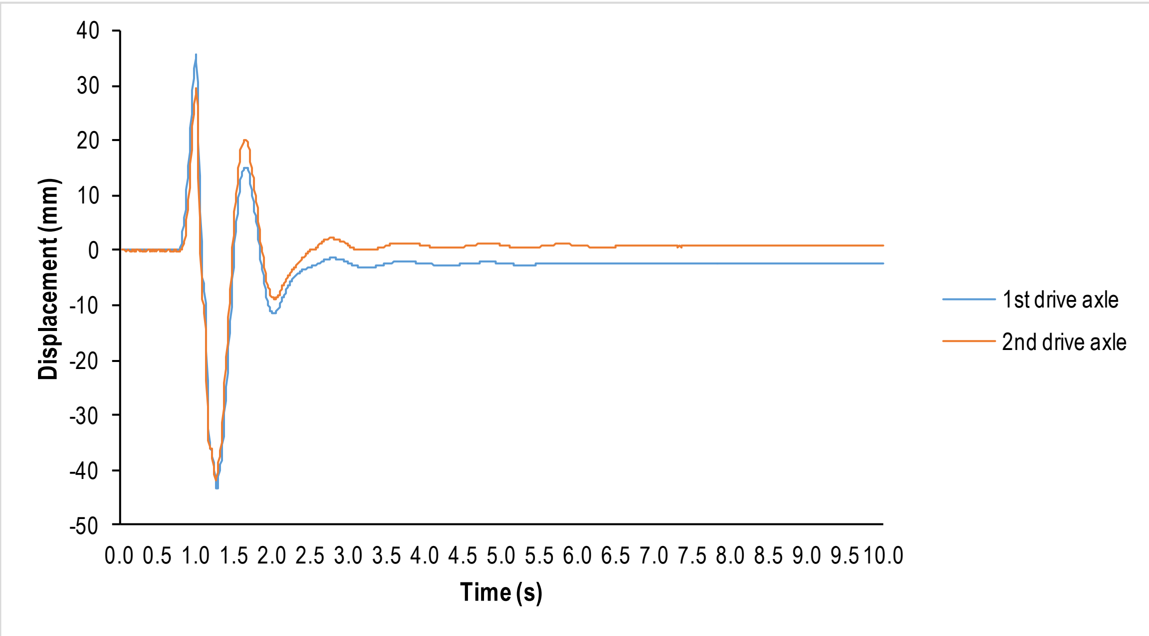


Figure C 26: Reference system (linear displacement) data trace from RFSA – HD shock absorbers



A summary of the results is presented in Table C 20.

Table C 20: Summary of results: RFSA – HD shock absorbers

Load	*Fully laden*							
Shock absorbers	*HD Damping*							
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	Right	Left	Right	Left	Right	Left	Right	Left
Test 1 - Damping ratio (%)	25	26	23	19	25	25	25	26
Test 2 - Damping ratio (%)	26	25	26	18	24	25	24	24
Test 3 - Damping ratio (%)	25	24	24	19	24	25	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, as this axle is not affected by pitch unlike the front and rear axles of the group, and would need 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 so the effects of pitching compensated for via calculation. The pitching effect is evident during this test as the data traces 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 follow 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.

The results obtained from the RFSA are very consistent. The calculating damping is higher than that from the LDTs and the frequency is much lower. The lower than expected frequency is a result of an analysis error due to the additional higher frequency of oscillation present due to axle hop.

The RFSA data trace is a true representation of modes of oscillation present during a 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.

C.2.2 Repeatability of RFSA Tests: Fully Laden with 1 HD OFF

Figure C 27 and Figure C 28 shows the data traces for the RFSA test with the vehicle fitted 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 are shown.

Figure C 27: Load cell data trace from RFSA – 1 shock absorber removed

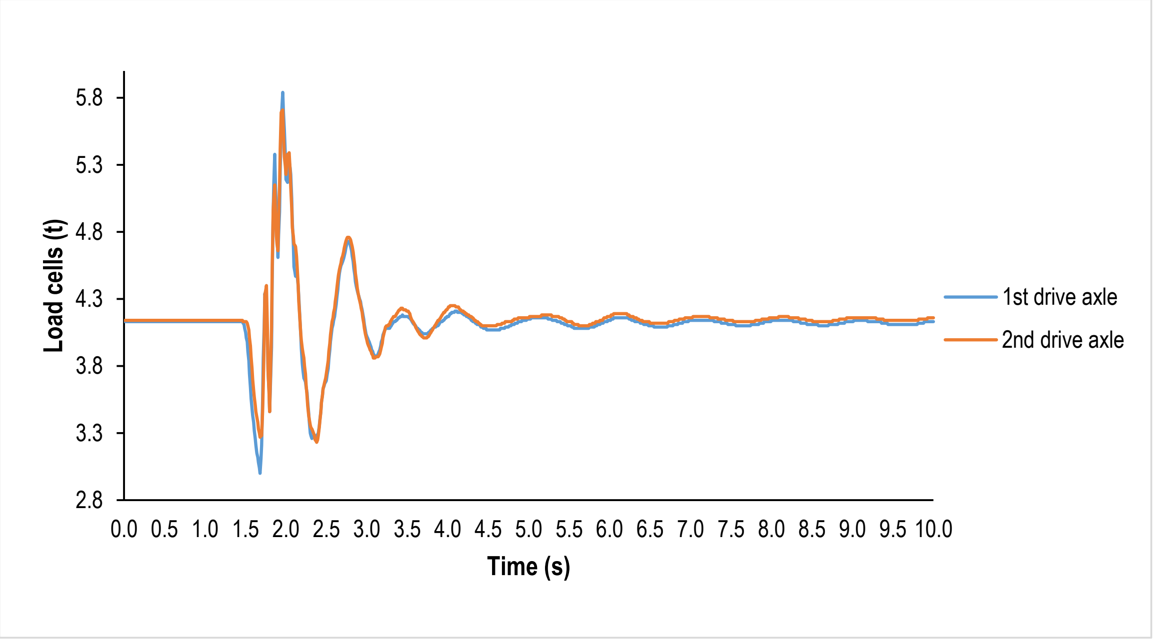
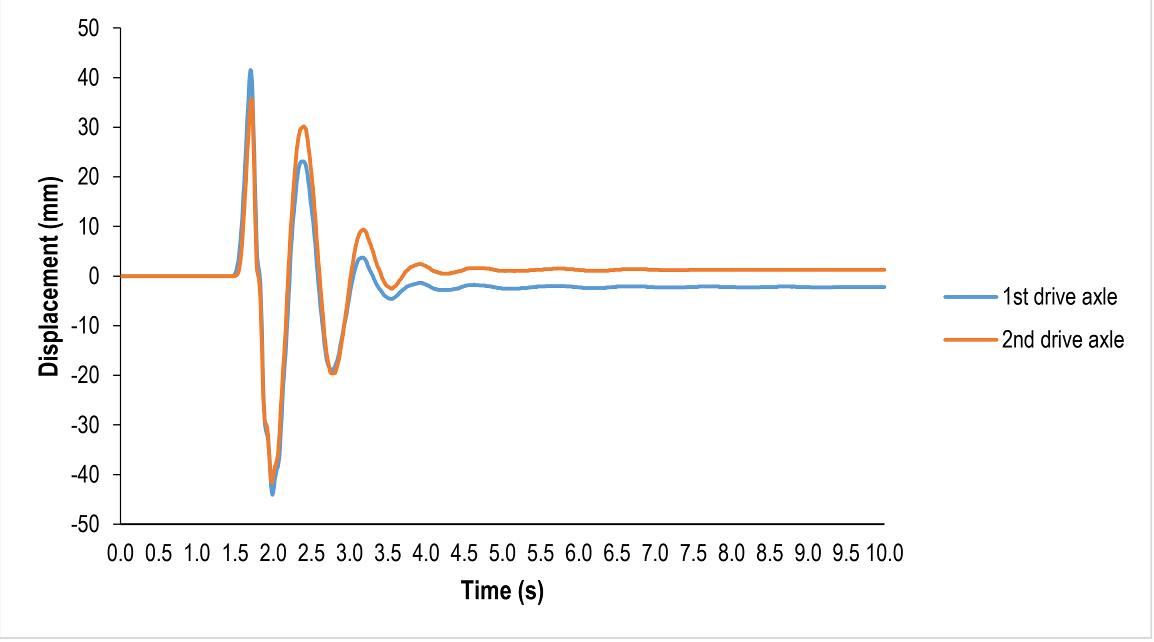


Figure C 28: Reference system (linear displacement) data trace from RFSA test – 1 shock absorber removed



A summary of the results is presented in Table C 21.

Table C 21: Summary of results: RFSA – both 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	*Right*	*Left*	*Right*	*Left*
1st drive - Damping ratio (%)	19	20	20	21
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.

C.2.3 Repeatability of RFSA Tests: Fully Laden with 2 HD OFF

Figure C 29 and Figure C 30 shows the data traces for the RFSA test with the vehicle 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 were recorded.

Figure C 29: Load cell data trace from RFSA – 1 shock absorber removed

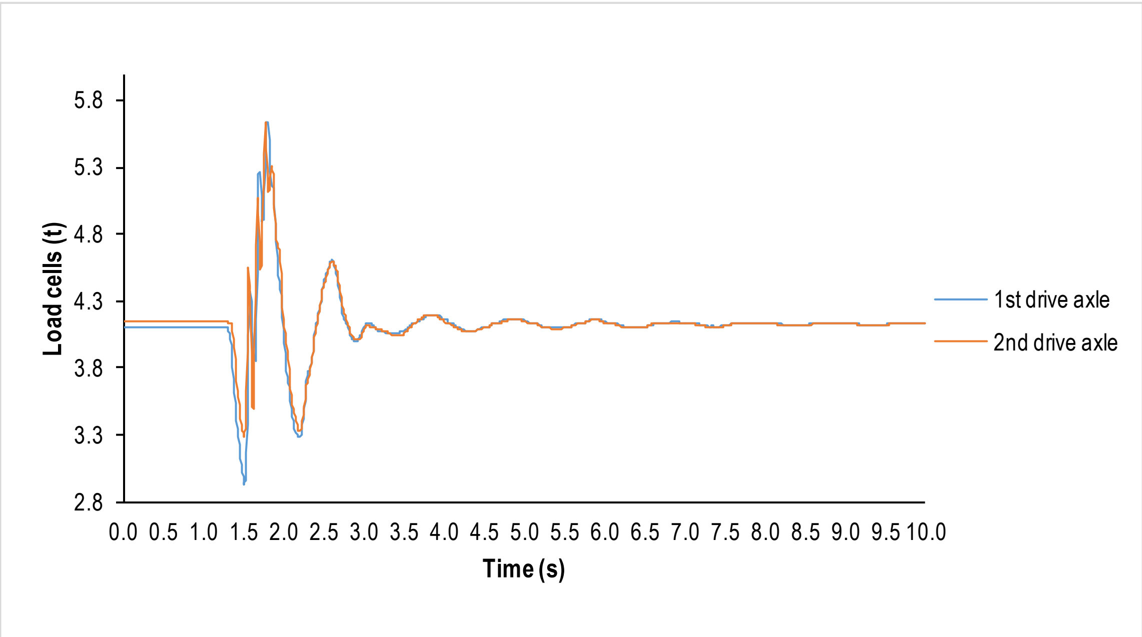
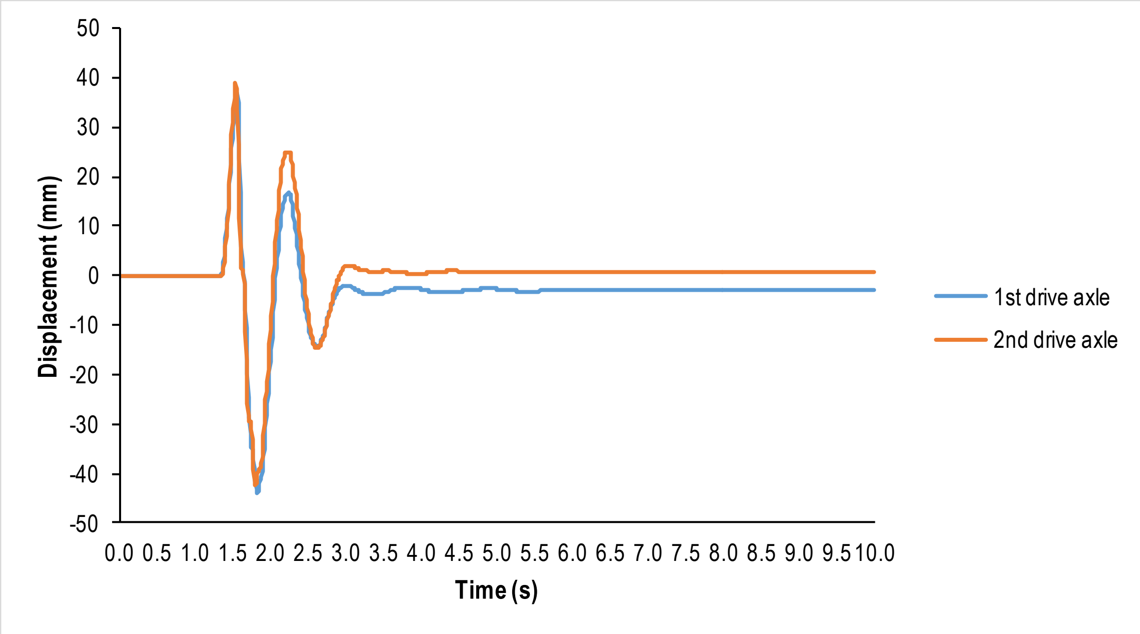


Figure C 30: Reference system (linear displacement) data trace from RFSA test – 1 shock absorber removed



A summary of the results is presented in Table C 22.

Table C 22: Summary of results: RFSA – both shock absorber 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	*Right*	*Left*	*Right*	*Left*
1st drive - Damping ratio (%)	18	15	15	15
2nd drive - Damping ratio (%)	16	13	11	12
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%.

C.2.4 Repeatability of RFSA Tests: Fully Laden with ALL OFF

Figure C 31 (RFSA load cells) and Figure C 32 (LDTs) shows the data traces (first drive axle only) for the RFSA test with all shock absorbers removed from the drive axles.

Figure C 31: Load cell data trace from RFSA – all shock absorbers removed

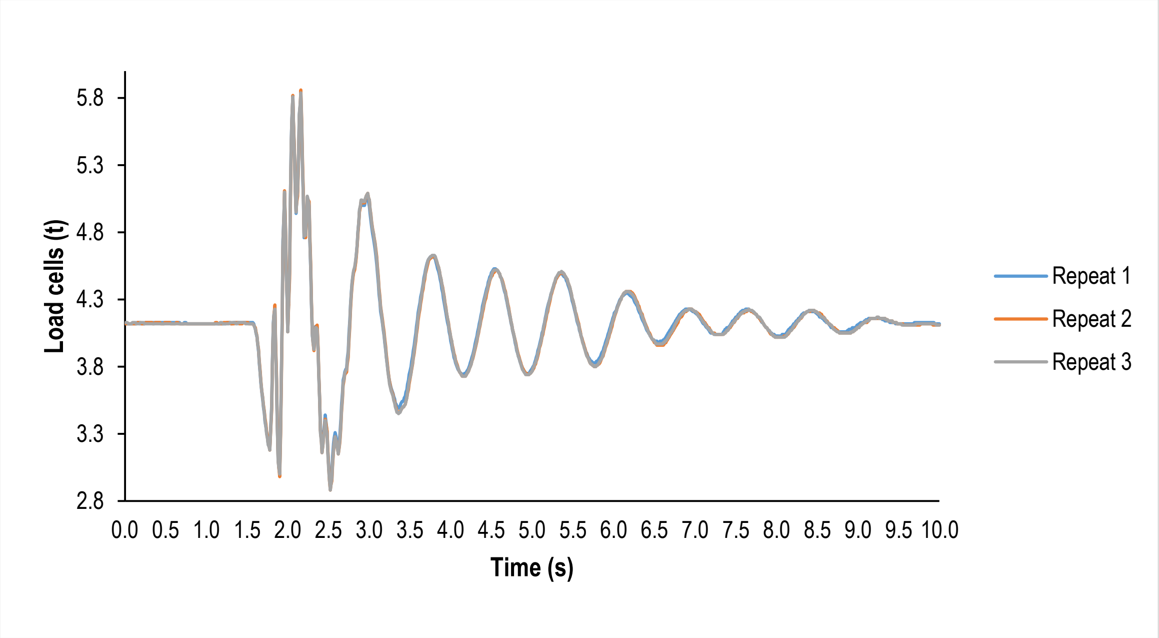
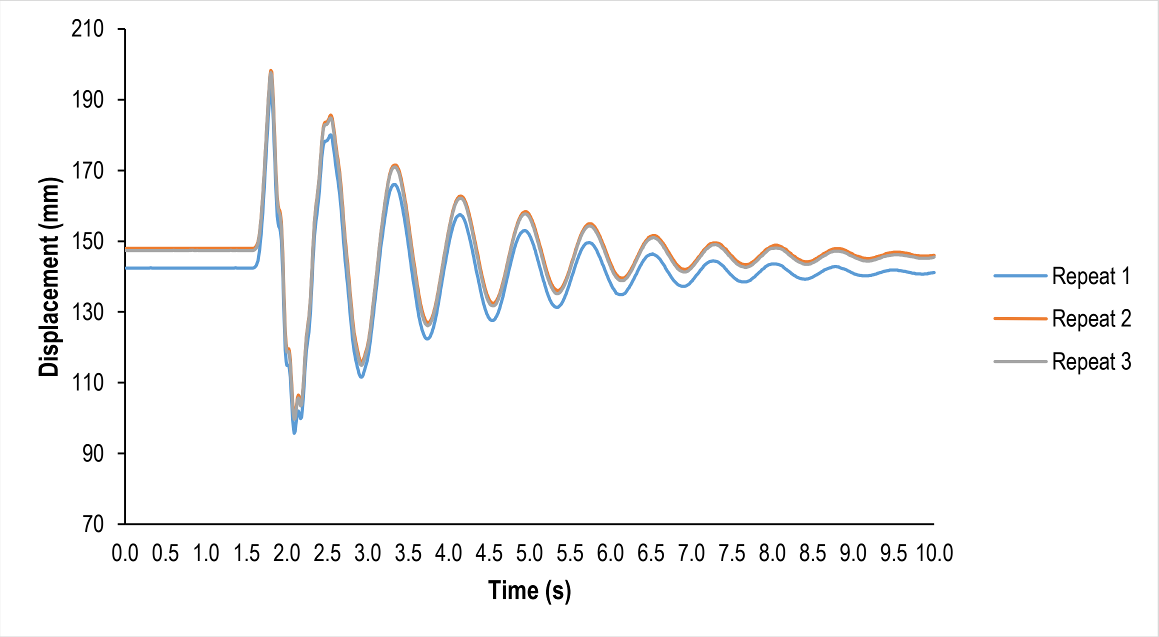


Figure C 32: Reference system (linear displacement) data trace from RFSA test – all shock absorbers removed



A summary of the results is presented in Table C 23.

Table C 23: Summary of results: RFSA – all shock absorber 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	Right	Left	Right	Left	Right	Left	Right	Left
Test 1 - Damping ratio (%)	11	13	8	6	5	7	6	4
Test 2 - Damping ratio (%)	10	9	8	7	5	7	4	6
Test 3 - Damping ratio (%)	9	6	8	7	5	7	6	4
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 and done so 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 sooner than the other causing pitching and rolling moments.

C.3 Results from Stage 3

Stage 3 testing was conducted using the DynaSsess system on a 4x2 rigid truck. Test system 3 includes 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. The data for test system 3 was provided to ARRB by FormulaSpec and two examples are presented in Figure C 33 and Figure C 34. The reference data is shown in Figure C 35.

C.3.1 Repeatability of DynaSsess Tests: Fully Laden with HD Shock Absorbers

Figure C 33: FormulaSpec data from DynaSses test method with all shock absorbers in place

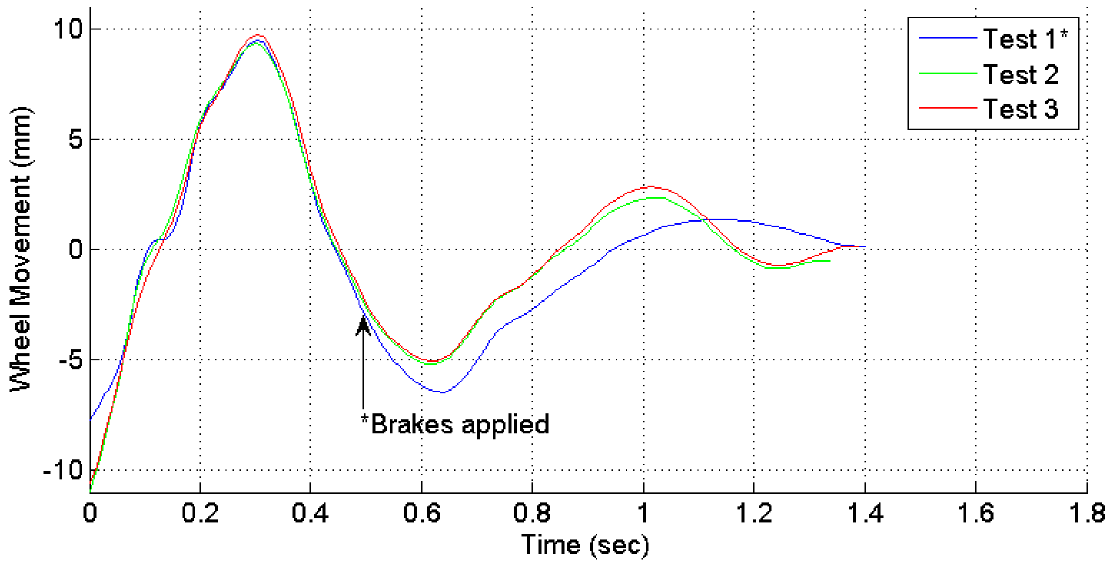


Figure C 34: FormulaSpec data from DynaSsess test method with all shock absorbers in place (flat road)

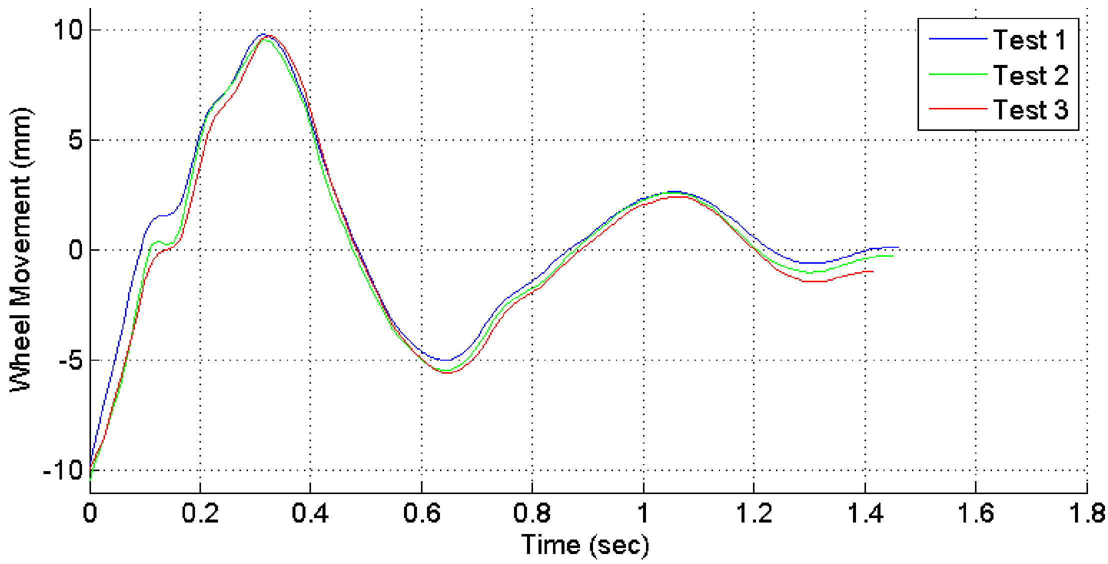
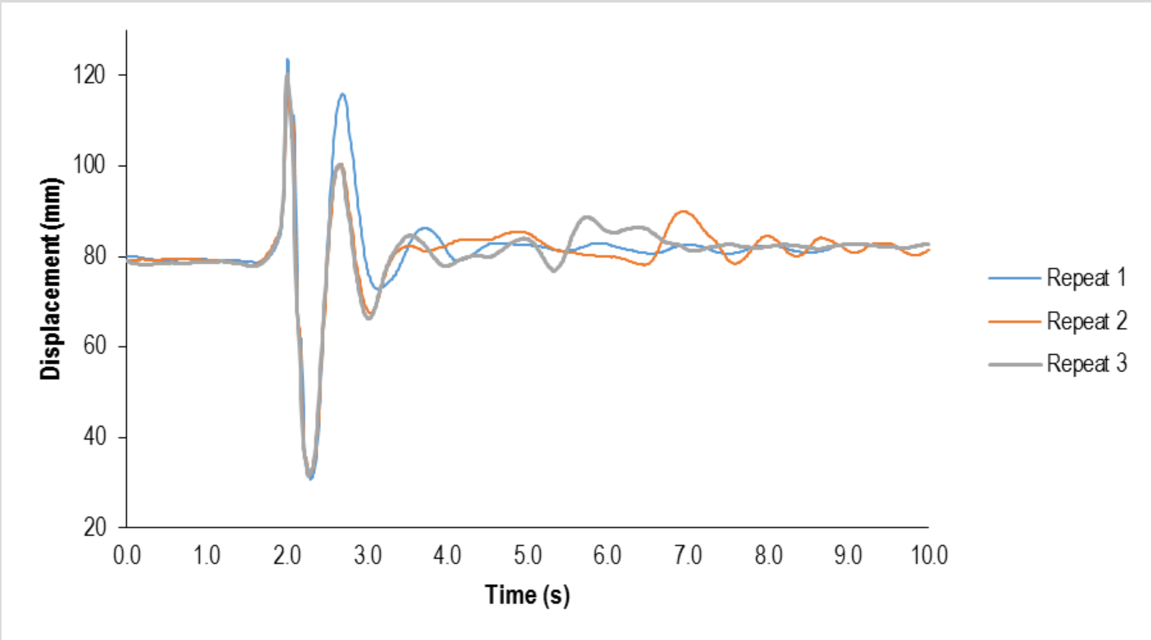


Figure C 35: Reference system data from DynaSsess test method with all shock absorbers in place



A summary of the results is presented in Table C 24.

Table C 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****		*Asphalt*		*Concrete****	
	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)
Test 1*	23.67	1.161	22.34	1.320	18	38	–	–
Test 2	22.64	1.353	21.82	1.345	22	20	–	–
Test 3	22.37	1.367	22.16	1.331	21	19	–	–
Averaged result (%)**	**22.5**		**22.1**		**21**		-	
Frequency (Hz)	**1.36**		**1.33**		**1.28**		-	

*Brakes were applied prior to second peak which affected results.

**Averaged result excludes the first test.

***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 higher accuracy and repeatability than the previous test systems.

C.3.2 Repeatability of DynaSsess Tests: Fully Laden with 1 HD OFF

Figure C 36: FormulaSpec data from DynaSsess test method with one shock absorber removed

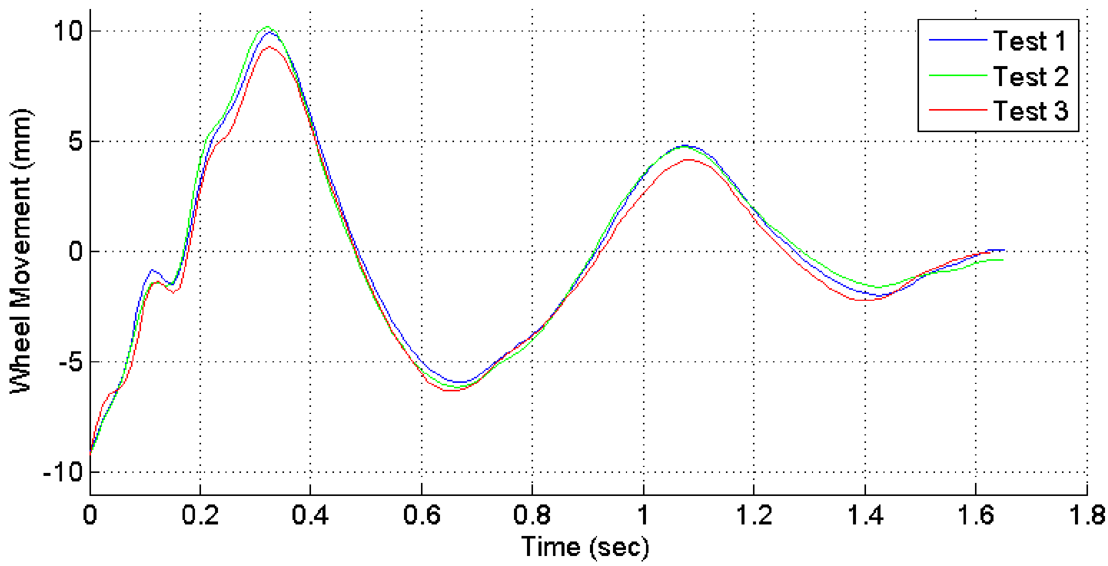
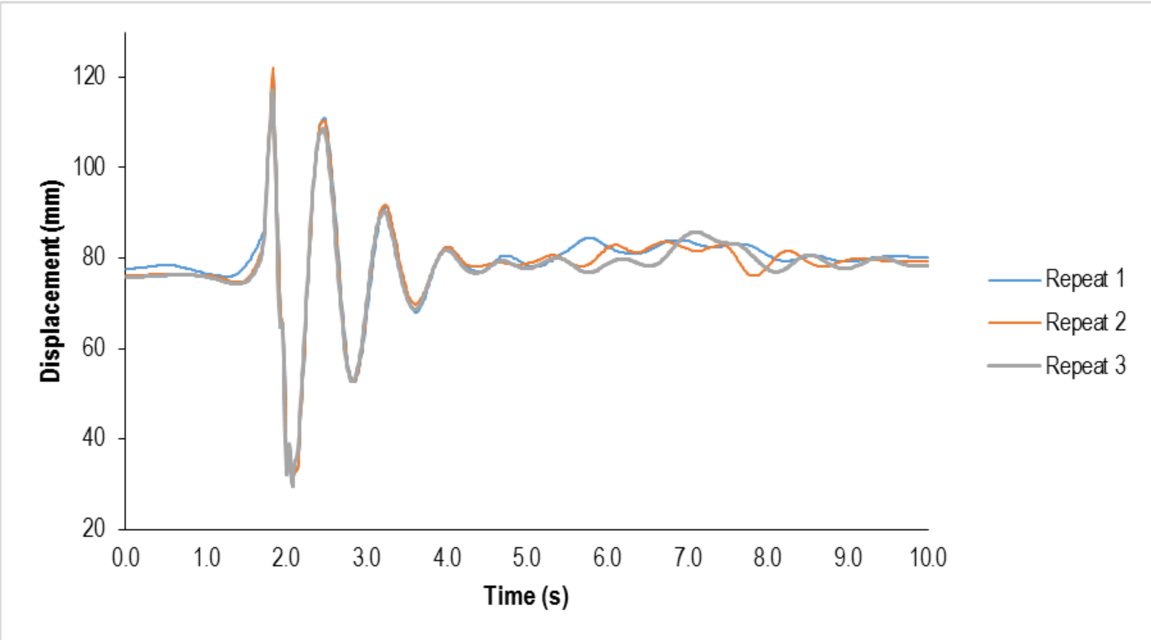


Figure C 37: Reference system data from DynaSsess test method with one shock absorber removed



A summary of the results is presented in Table C 25.

Table C 25: Summary of results: DynaSsess – all shock absorbers 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 results and reference system results indicated a reduction in damping within the expected range due to removing a single shock absorber.

C.3.3 Repeatability of DynaSsess Tests: Fully Laden with all Shock Absorbers OFF

Figure C 38: FormulaSpec data from DynaSsess test method with all shock absorbers removed

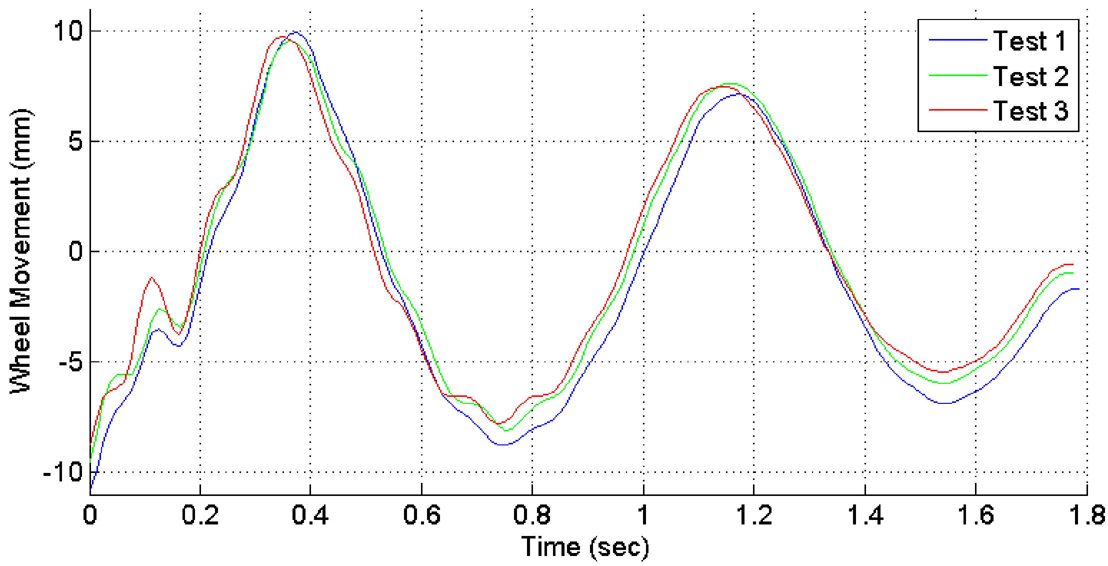
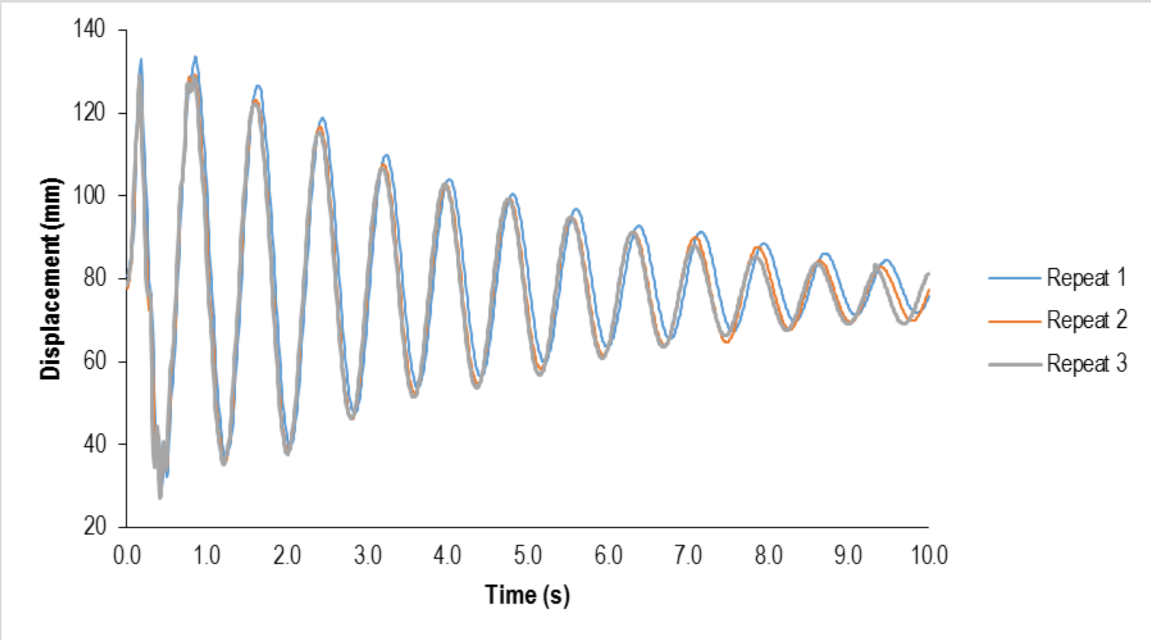


Figure C 39: Reference system data from DynaSsess test method with all shock absorbers removed



A summary of the results is presented in Table C 26.

Table C 26: Summary of results: DynaSsess – all shock absorber 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 results and reference system results indicated a reduction in damping within the expected range from removing a single shock absorber. The damping results are much lower for the reference system, most likely due to the inaccuracy of the analysis method which uses the first two successive peaks (which may not be representative of the system).

A summary of the results for test system 3 is presented in Table C 27.

Table C 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* – 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**

**Brakes were applied prior to second peak which affected results, excluded from average.

C.3.4 Repeatability of VSB11 Tests: Fully Laden with all HD ON

Table C 28: FormulaSpec data from VSB11 ramp test method with all shock absorbers in place

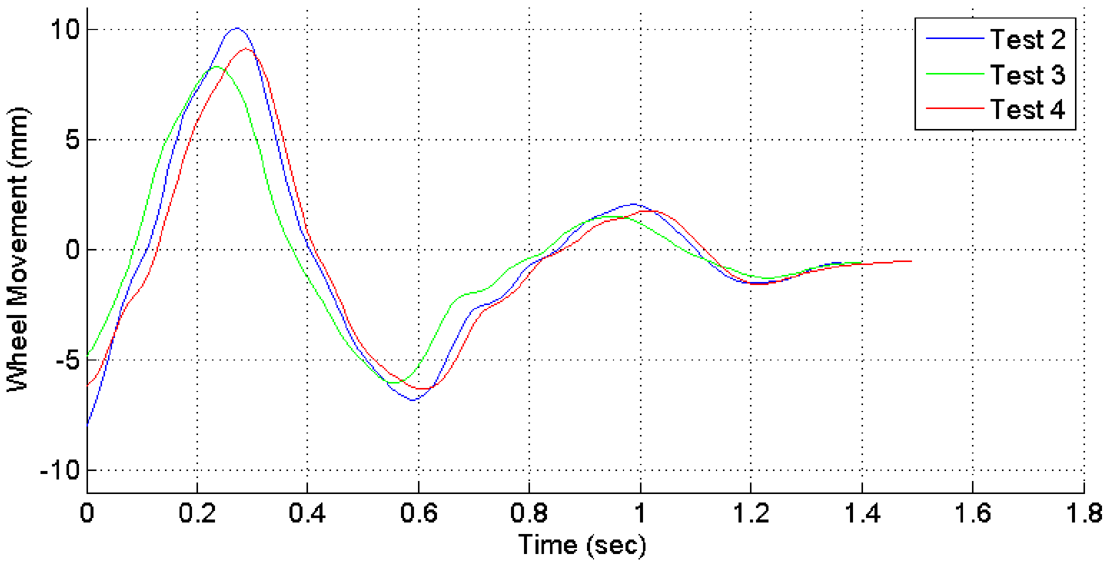
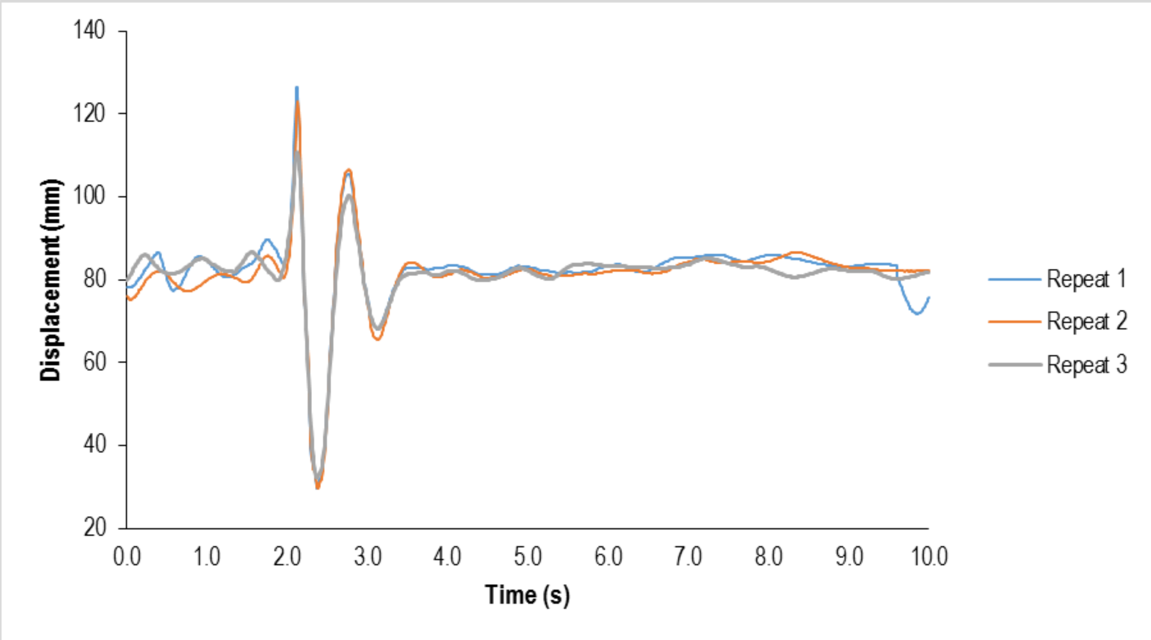


Table C 29: Reference system data from VSB11 ramp test method with all shock absorbers in place



C.3.5 *Repeatability of VSB11 Tests: Fully Laden with 1 HD OFF*

Figure C 40: FormulaSpec data from VSB11 ramp test method with one shock absorber removed

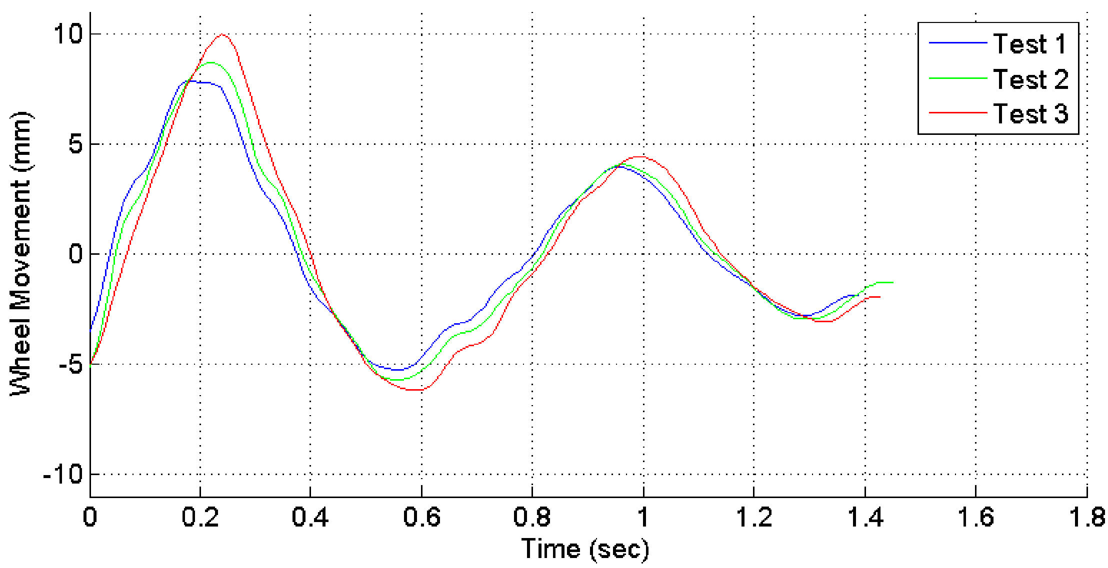
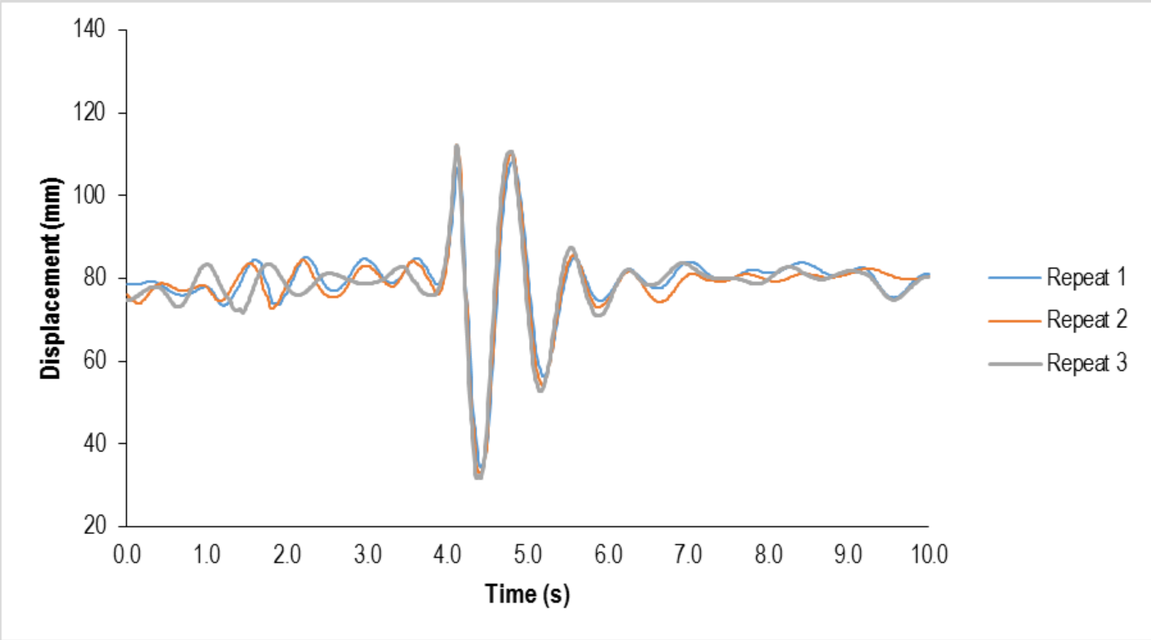


Figure C 41: Reference system data from VSB11 ramp test method with one shock absorber removed



C.3.6 Repeatability of VSB11 Tests: Fully Laden with all shock absorbers OFF

Figure C 42: DynaSsess system data from VSB11 ramp test method with all shock absorbers removed

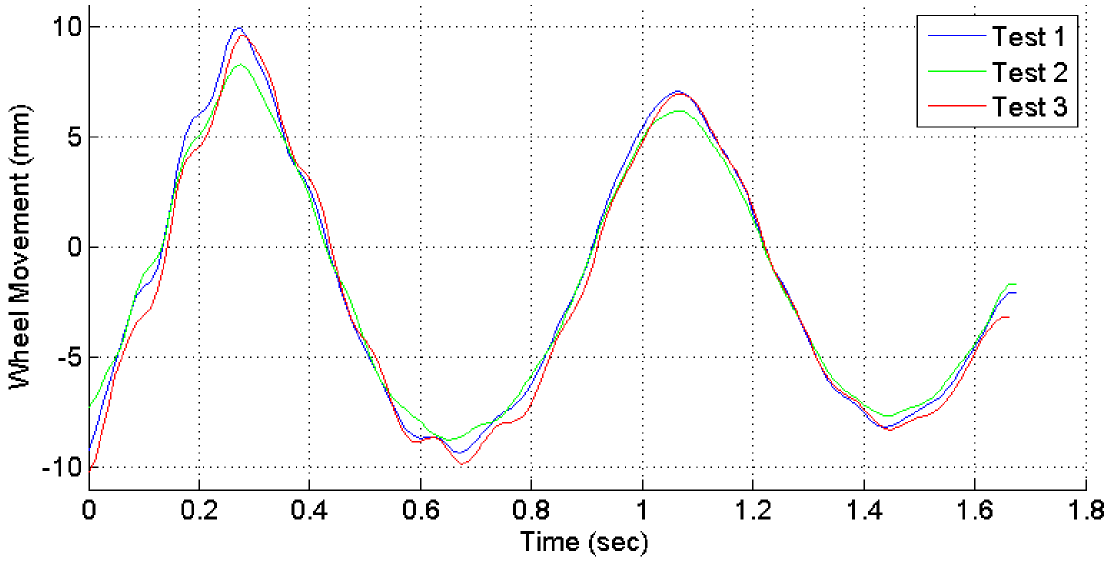
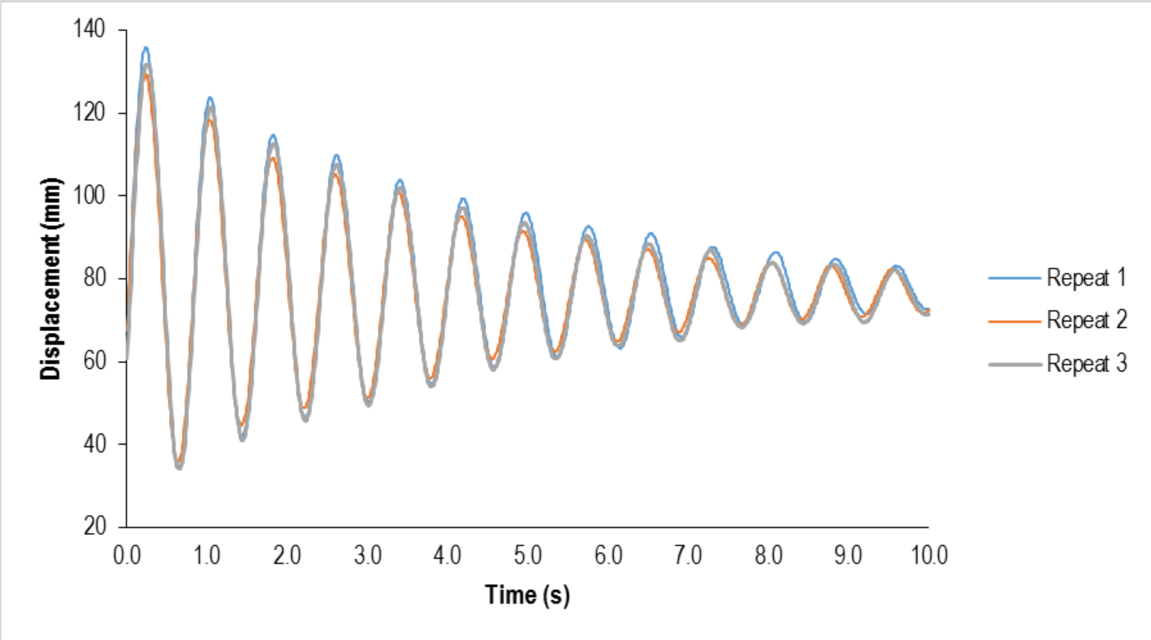


Figure C 43: Reference system data from VSB11 ramp test method with all shock absorbers removed



A summary of the results is presented in Table C 30.

Table C 30: Summary of results: DynaSsess – all test

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* – Damping ratio (%)	22.00	13.27	4.37	20	11	4
Test 2* – 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**

*left wheel was driven off the edge of the ramp.

Commentary

The results obtained from test system 3 using the VSB11 ramps as the excitation method 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. Whereas, the reference system showed considerable variation in results particularly for the low damping tests with results 14%-10% and 2%-4%.

This confirmed the repeatability of test system 3 but also may be a reflection the tests with 4x2 vehicle being more repeatable compared with the tandem and triaxle groups used in test programs 1 and 2.