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Heavy Vehicle Suspensions - Testing and Analysis.

Phase 3 - Eigenfrequency peak loads: measuring suspension health from wheel loads.

Preliminary test report

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Version no.	Mk V
Revision date	April 2009
Status	final, save for dynamometer results (to follow)
DMS ref. no.	890/00037
File/Doc no.	890/00037

File string: C:\masters\suspension tester report preliminary Mk V.doc

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Executive Summary

One response to requests from the transport industry to allow more “freight efficient” heavy vehicles (HVs) onto the road network has been that road authorities have allowed higher axle loads in return for HVs being equipped with “road-friendly” suspensions. These suspensions (particularly those with air springs) are critically dependant on shock absorber health for proper operation. These suspensions are only certified, however, as “road-friendly” at the time of manufacture and this via a type-test. Once in service, the “road-friendliness” is determined solely by the maintenance regime of the transport operator.

One of the triggers for shock absorber replacement in the road transport industry is tyre wear. Blanksby *et al*., (2006) showed that this was not a good determinant of damper wear as over 54% of a statistically significant sample of "road-friendly" HVs did not meet at least one of the criteria in the Australian standard for "road-friendly" HV suspensions (Blanksby et al., 2006). Previous reports on the prevalence of, and increased damage done by HVs with worn, out-of-specification or defective suspension dampers have been commissioned and published (Blanksby et al., 2006; Cebon, 2004; Costanzi & Cebon, 2005, 2006). The results in this report align with the conclusions of that work and indicate that Qld Main Roads could save approximately $76M/annum were HV operators to maintain their shock absorbers to manufacturers' specifications.

There is no in-service test for HV suspensions in Australia yet. In-service testing for “road-friendliness would advantage the transport industry and road asset owners. The former because worn dampers could be replaced before vehicle and payload damage occurs; high-mileage but still serviceable shock absorbers need not be replaced (saving labour and equipment costs). The latter through reductions in road and bridge asset rehabilitation costs through less wear-and tear from HVs with out-of-specification or deficient shock absorbers. That a test would be advantageous has been recognised by the Australian Government, the States of New South Wales and Queensland. These organisations are funding a programme to develop an in-service suspension test for HVs. The expansion of higher mass limits (HML) routes across Queensland and New South Wales was made conditional on such a test being developed (Australia Department of Transport and Regional Services, 2005a, 2005b). The National Transport Commission (NTC) is the project manager for the development of this test.

This report examines a test methodology involving a moderate-cost test bed that provides a low-cost-per-test methodology for an in-service HV suspension test. The results are presented

within the context of a "proof-of-concept" test programme. The preliminary results indicate that low-cost-per-test suspension testing is possible with a moderate-cost testing rig.

Under the joint QUT/MR project *Heavy vehicle suspensions – testing and analysis* a test bed has been developed by modifying the roller from a HV brake tester. This test bed was designed to impart a known vibration to the wheel of a HV under test. This by having flat portions machined into the roller that, when the roller was spun, imparted a cyclic vibration to the wheel of the HV under test. The modified brake-testing machine was instrumented with load cells at the bearings of the roller. No instrumentation was installed, nor required, on the HV. A wheel load approximating full load was used. Damping on the wheel of the test HV was varied in three stages:

- ☞ none (no shock absorbers);
- ☞ worn to the point of tyre wear; and
- ☞ meeting the manufacturer's specification (i.e. new shock absorber).

The preliminary results from this test programme show that:

- the dynamic signals from the load cells may be used to determine the threshold beyond which HV suspensions cause tyre wear and road damage compared with when they are new; and
- a moderate-cost testing machine to perform bulk, low-cost HV suspension testing is possible at the "proof-of-concept" level.

This is a preliminary report covering only one test load and three different shock absorber conditions. The timing of the NTC project, the delivery schedule of the NTC's consultant's report and the timetable for the tests outlined herein has necessitated that this report has had to be truncated with respect to the level of detail that should be supplied in an ideal situation. This report and other reports (available as analysis continues) will be sent to the National Transport Commission (NTC) as a contribution to the in-service suspension test project and will also form part of the final output in the QUT/Main Roads project *Heavy vehicle suspensions – testing and analysis*.

1. Introduction

The conclusions from DIVINE project (OECD, 1998) were used in Australia to justify the introduction of air-suspended heavy vehicles (HVs) carrying more mass. DIVINE (OECD, 1998), amongst others (de Pont, Thakur, & Costache, 1995; Woodroofe, 1996), noted the results of suspension testing using a shaker bed imparting sinusoidal inputs to determine suspension characteristics. These shaker beds, whilst valuable tools for experimental and other laboratory-level testing, are expensive items to deploy for mass testing programmes (Cebon, 1999).

Under the joint QUT/MR project *Heavy vehicle suspensions – testing and analysis* it was proposed to develop a low-cost test bed made from a modified heavy vehicle (HV) brake tester (Davis & Bunker, 2008a). This by making one of the rollers eccentric. It was hypothesised that, by rotating the wheels of a HV under test using an eccentric roller, a known vibration could be imparted to the wheel under test. It was proposed that measurement of the forces at the bearings of the roller should provide an indication of the HV wheel-forces and, were the level of serviceability of the shock absorbers varied; any differences in wheel-load should provide a quality indicator corresponding to a change of damper characteristic.

The testing has been carried out. Preliminary results are presented in this report. Conclusions regarding:

- the levels of damper maintenance beyond which HV suspensions cause road damage; and
- dynamic wheel forces at the threshold of tyre wear at which HV shock absorbers are normally replaced

are presented.

The Australian Government and the States of New South Wales and Queensland are funding a programme to develop an in-service suspension test for HVs. The expansion of higher mass limits (HML) routes across Queensland and New South

Wales was made conditional on such a test being developed (Australia Department of Transport and Regional Services, 2005a, 2005b). The National Transport Commission (NTC) is the project manager for that development. This is a preliminary report covering only one test load and three different shock absorber conditions. The timing of the NTC project, the delivery schedule of the NTC's consultant's report, other commitments within the QUT/Main Roads project *Heavy vehicle suspensions – testing and analysis* and the timetable for the tests outlined herein has necessitated that this report has been truncated from the level of detail that might have been supplied in an ideal situation. This report and other reports (available as analysis continues) will be sent to the National Transport Commission (NTC) as a contribution to the in-service suspension test project and will also form part of the final output in the QUT/Main Roads project *Heavy vehicle suspensions – testing and analysis***.**

1.1. Aims and objectives

The results from this test programme are proffered to inform the issue of the threshold at which HV shock absorbers should be replaced compared with when they are usually replaced due to tyre wear. The aim of this approach is to assist the National Transport Commission (NTC) as a contribution to the in-service suspension test project (Australia Department of Transport and Regional Services, 2005a, 2005b). Accordingly, a heavy vehicle brake-test roller machine was instrumented and modified. It was used to provide a cyclic loading into a HV suspension under test using eccentricity in a roller.

In addition, the use of the modified roller-brake machine yielded:

- a “proof-of-concept” of moderate-cost testing machine to perform low-cost HV suspension testing; and
- conclusions on levels of maintenance beyond which HV suspensions move outside the envelope of “road friendliness”.

For the purposes of this report, the results for a wheel load of approximately full load have been used. Results for other wheel loads will be reported as time and resources for analysis permit.

Three shock absorber condition-states were tested:

- ☞ no shock absorber (i.e. simulating the presence of a shock absorber worn to the point where its damping function had become totally ineffective);
- ☞ a shock absorber worn to the point where it was taken off a donor vehicle because tyre wear had become apparent and was therefore due for replacement under the conventional approach of the road transport industry. This shock absorber was the reference for the "used to the point of tyre wear" condition state in our testing; and
- ☞ a fully-functional shock absorber (i.e. within specification) for the suspension being measured.

This document sets out the equipment, procedures and preliminary results from modification of the HV brake test unit and the experimental methodology to determine HV wheel-forces therefrom, particularly for the different damping values used.

1.2. Rationale

By placing a HV's wheel on a roller, a known vibration can be imparted to that HV wheel as a test. Sweatman used a modified drum on a roller-dynamometer to create an input signal to a HV suspension (Sweatman, 1983). This for purposes of cross calibration of instrumentation and to characterise the input function on that suspension. One of the proposed methods that Gyenes *et al.*, (1992) summarised for determining axle hop and damped fundamental frequency of body-bounce was by performing a low-amplitude (1mm) sinusoidal sweep excitation (that is, a frequency scan). It was postulated that the eigenfrequencies of the sprung (body) and unsprung (axle hop) components could be found by the highest amplitude wheel-forces measured after such a sweep.

Cyclic inputs to test HV suspensions using simulators have been well documented (Hoogvelt, van Asseldonk, & Henny, 2004; Woodroofe, 1996). Prem *et al.*, concluded that constant amplitude sinusoidal sweeps and increasing-force frequency sweeps were of use in characterising suspensions for road-friendliness and in-service testing provided the latter was used in conjunction with type-test data (Prem, George, & McLean, 1998). Ahmadian (2003) noted that using this method on complete HVs in a reaction frame allowed the resonant frequencies of individual HV components to be found, particularly suspension components and the beams of the chassis.

The DIVINE (OECD, 1998) project showed the results of ineffective shock absorbers on HV wheel loadings. Woodrooffe (1996) reported on dynamic loading tests where the wheels of a loaded HV were subject to a 1mm sinusoidal sweep frequency input. The control case for dampers in good condition then was compared with two test cases of ineffective shock absorbers.

The methodology used for the testing in this report allowed the recording of wheel-force data for varying levels of shock absorber maintenance and differing loads. Analysis of this data indicates that the wheel-forces vary proportionally with damper performance.

2. Background

2.1. “Friendliness” of “road-friendly” suspensions

Road authorities and transport regulators are under continuous pressure, internally and externally, from the transport industry to allow “freight efficient” vehicles onto the road network. Outputs from the final report of the DIVINE project (OECD, 1998) were used in Australia to support the argument that air-sprung heavy vehicles (HVs) should carry greater mass under the micro-economic reform popular in the 1980s and 1990s in Australia. One of these reforms was the mass limits review (MLR) project as implemented under the 2nd heavy vehicle reform package (National Transport Commission, 2003). It was concluded that HVs operating at higher mass limits (HML) and equipped with “road friendly” suspensions (RFS) would be no more damaging than conventional heavy vehicles (HVs) operating at statutory masses with

conventional steel springs (Pearson & Mass Limits Steering Committee, 1996). This resulted in the implementation of higher mass limits (HML) schemes in various guises in all Australian States. HML allows HVs to carry greater mass in return for, amongst other requirements, being equipped with “road friendly” suspensions (RFS). The documents leading to the introduction of HML noted that suspension damper (shock absorber) health was crucial to RFS being no more damaging to pavements at HML loadings than conventional steel-suspended HVs at statutory mass.

If transport operators were maintaining their vehicles to specification and regulation then there would be no need for concern on the part of road authorities and transport regulators. However, work in NSW has indicated (Blanksby et al., 2006) that 54% of HVs in a statistically valid survey did not meet at least one of the requirements of VSB 11, the Australian standard for heavy vehicle suspension "road-friendliness”. The possible scenario of non-standard MCVs with more than statutory mass (at or higher than HML loadings) on axles or axle groups with worn or out-of specification suspension dampers has now become a better than even-money probability. This is of concern to Australian road authorities and transport regulators.

The anecdotal HV transport industry view of worn shock absorbers and the attendant issue of air suspension health is that the resultant tyre wear is detected quickly. This is then rectified to prevent further increased tyre wear and the associated costs of premature tyre replacement. Despite this view, the Marulan survey (Blanksby et al., 2006) showed that more than half the HVs equipped with "road-friendly" suspensions sampled on the Hume Highway did not meet at least one VSB 11 suspension parameter. This result was somewhat expected since Sweatman *et al.,* (2000) found that:

- quantitative evaluation of shock absorbers did not usually take place in most fleets; and
- the trigger for replacement of shock absorbers was visible leakage or lack of heat after a trip.

From this empirical evidence, it may be inferred that the industry indicators of using tyre wear, leakage or temperature to detect out-of-specification or deficient shock absorbers is too late in the maintenance cycle to be effective at meeting the Australian

requirements for "road-friendly" HV suspensions. Compounding this issue is the fact that there are no recognised low-cost in-service HV suspension tests in Australia. This has been discussed previously (Starrs *et al.,* 2000, Sweatman *et al.,* 2000) without decisive action by regulators until recently. That action is now occurring on this issue is due to agreement between two Australian States and the Commonwealth (Australia Department of Transport and Regional Services, 2005a, 2005b).

Within the framework described above and its indeterminacy with respect to RFS health, regulators and road authorities have not been able to be certain that air-sprung heavy vehicles (HVs) with RFS are having their "road friendliness" maintained as the suspension dampers wear from normal service.

Costanzi & Cebon (2005) modelled a fleet of HVs with 50% ineffective dampers. That report concluded that, at Higher Mass Limits loadings, pavement and surfacing damage would be 20 - 30% greater than for a comparable freight task with a fleet equipped with dampers in good condition. The Costanzi & Cebon study was for HVs on the Newell Highway. The Newell has considerably thicker pavements than those found in Queensland (Queensland Department of Main Roads, 2007). If the figure of 50% poorly maintained suspensions modelled by Costanzi *et al*., is equated to the actual status found at Marulan then a HV fleet with 100% functional shock absorbers would save Queensland Main Roads' maintenance budget $76M/annum in 2008 dollars (Queensland Department of Main Roads, 2008); a saving going forward every year. This is essentially "free money" to government since HV suspensions should be maintained as a matter of course.

The order of magnitude of these savings indicates that the previously estimated benefit to pavement rehabilitation costs of $14M in 2000 dollars across Australia (Starrs Pty Ltd, Ian Wright and Associates, & ARRB Transport Research Ltd, 2000) was low, even allowing for cost escalation and inflation with the effluxion of time.

Further, the consideration of well-maintained dampers does not include the road safety, Local Government asset impact or workplace health and safety aspects of a HV fleet with in excess of 50% sub-optimal shock absorbers.

2.2. Summary

Shock absorber wear in HVs is not detected quickly nor in a timely manner (Blanksby et al., 2006). Transport industry indicators of tyre wear, shock absorber oil leakage or lack of heat arise too late to be effective in keeping a RFS suspension within the Australian "road friendly" suspension specification. In-service testing has not been explored in Australia with a definitive way forward until the bilateral infrastructure funding agreements between two Australian States and the Commonwealth (Australia Department of Transport and Regional Services, 2005a, 2005b). Such testing could save Queensland approximately $76M/annum.

The testing outlined in this report and the preliminary results therefrom address these issues in part by:

- testing a typical HV suspension with shock absorbers at different levels of utility; and
- developing a "proof-of-concept" for a moderate-capital-cost, high-volume, low-cost-per-test HV suspension testing methodology and associated equipment.

3. Experimental procedure

3.1. General

The following section outlines a portion of the test programme. Other tests were carried out and will be detailed in future papers and reports. The HV under test was a semi-trailer equipped with standard Meritor 9000 axles without modification, save for changing the shock absorbers as mentioned.

3.2. HV brake tester modifications

HV brake testing machines are generally configured as two or four rollers in a rigid frame. The wheels of the vehicle under test are placed between the rollers (Davis & Bunker, 2008a). For normal operation to test the brakes on a vehicle, the vehicle's wheels are spun under the power of the tester. The brakes of the test vehicle are applied. A dynamometer then measures whether the retardation force present from the braking effect of the test vehicle's wheels is adequate.

The brake testing functions of the roller brake tester were not used for this test programme. The only features of the roller brake tester used were two rollers and the frame.

The test rig used was modified from the original roller-brake tester in that the wheel under test sat on top of one roller only. A general view of the test rig used is shown in Figure 1. In this figure, the power unit is in the foreground and the roller is mounted at the end of the frame furthermost from the viewer.

The roller used had two diametrically opposed flats 4 mm deep (Figure 2). The amount of material removed to create the flats was chosen to provide sufficient depth of eccentricity so that results could be compared with similar research (Woodroofe, 1996). The eccentricity created provided repetitive input to the test vehicle's wheel.

Figure 1. End view of modified roller brake tester.

The brake tester's original drive motors and ancillary devices such as the arm on the idler roller and the testing control console were discarded. A 22 kW capacity electric motor driving a hydraulic pump (Figure 3) which, in turn, drove a hydraulic motor (Figure 5) was used as the power unit for the testing. The hydraulic motor was connected to the roller via a coupling (Figure 4). To eliminate any effect of motor torque altering the readings on the load cells, the motor was mounted on a plate attached to a torque arm. This torque arm and arrangement to allow the motor to float is shown in Figure 5. In this way, we ensured that vertical loads presented to (and measured by) the load cells were from the wheel without influence from motor torque.

Figure 2. Roller with 4mm flats.

Figure 3. 22 kW motor (blue fins), coupled to hydraulic pump in the hydraulic fluid reservoir.

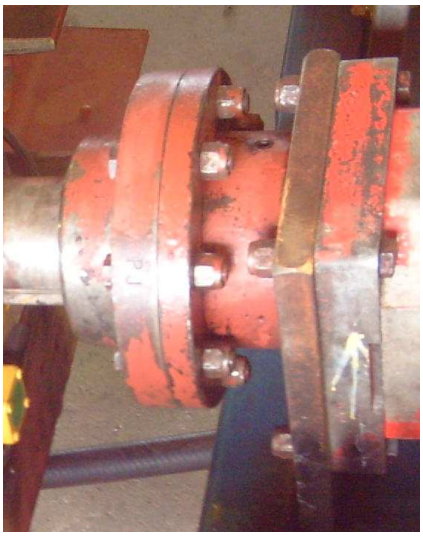

Figure 4. Hydraulic motor (right) and coupling to roller shaft (left).

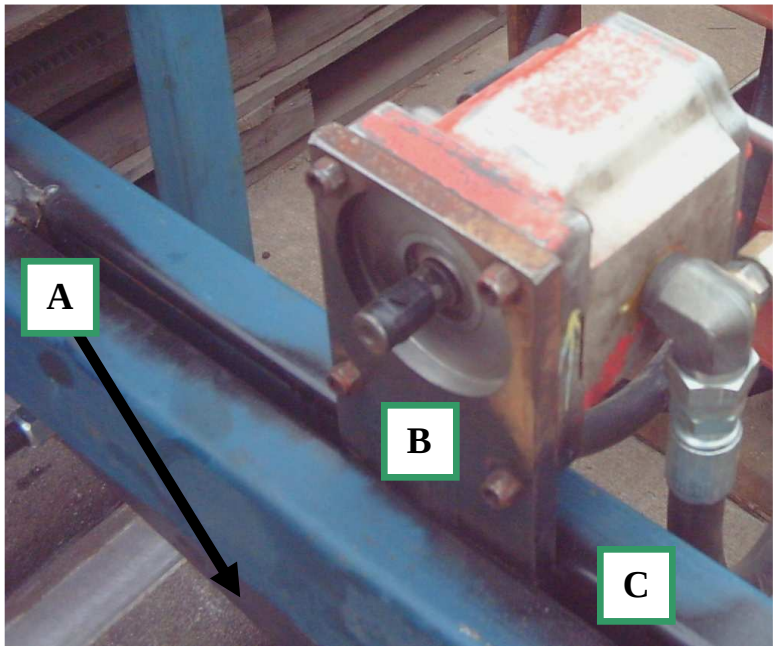

Figure 5. Hydraulic motor with roller and coupling removed. Note torque arm, slightly obscured (arrow A) was connected to hydraulic motor mounting plate, B. Locating frame (C) allowed motor mount to float.

The hydraulic motor was controlled via valves and a safety switch. The safety switch is shown (Arrow "A") in Figure 8. The speed of the roller was controlled via a coupling to the hydraulic bypass valve shown (arrow "C") in Figure 9.

3.3. Roller-bed installation

The modified test rig retained the overall frame dimensions of the original tester from which it was made. Brake testers are designed to be installed in roadside pits during HV interceptions by regulatory authorities or in pits as part of a HV service facility. A pit was constructed according to the manufacturer of the roller tester (FKI Crypton Ltd, 1990). It is shown in Figure 6.

Figure 6. Pit used for test rig.

The test rig was manoeuvred as shown in Figure 7. It was positioned and installed as shown in Figure 8 and Figure 9.

Figure 7. Manoeuvring the test rig.

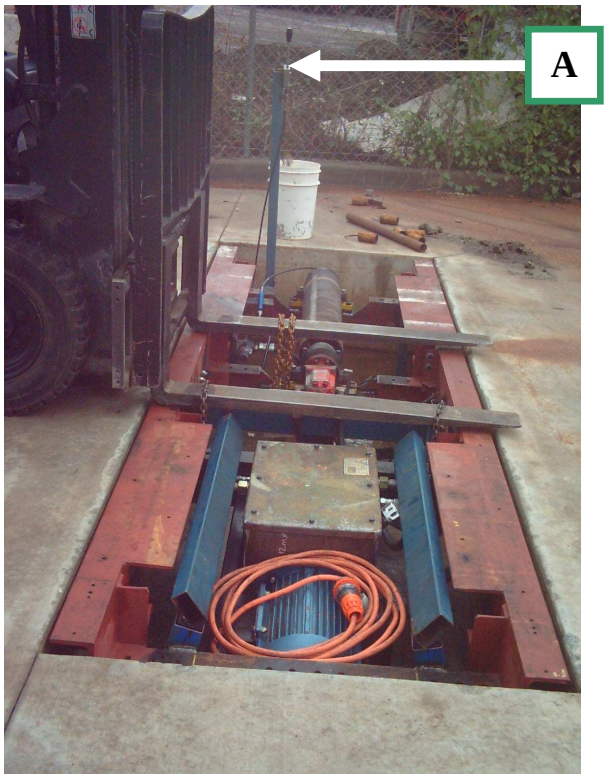

Figure 8. The test rig in the pit. Arrows A shows hydraulic safety cut off switch.

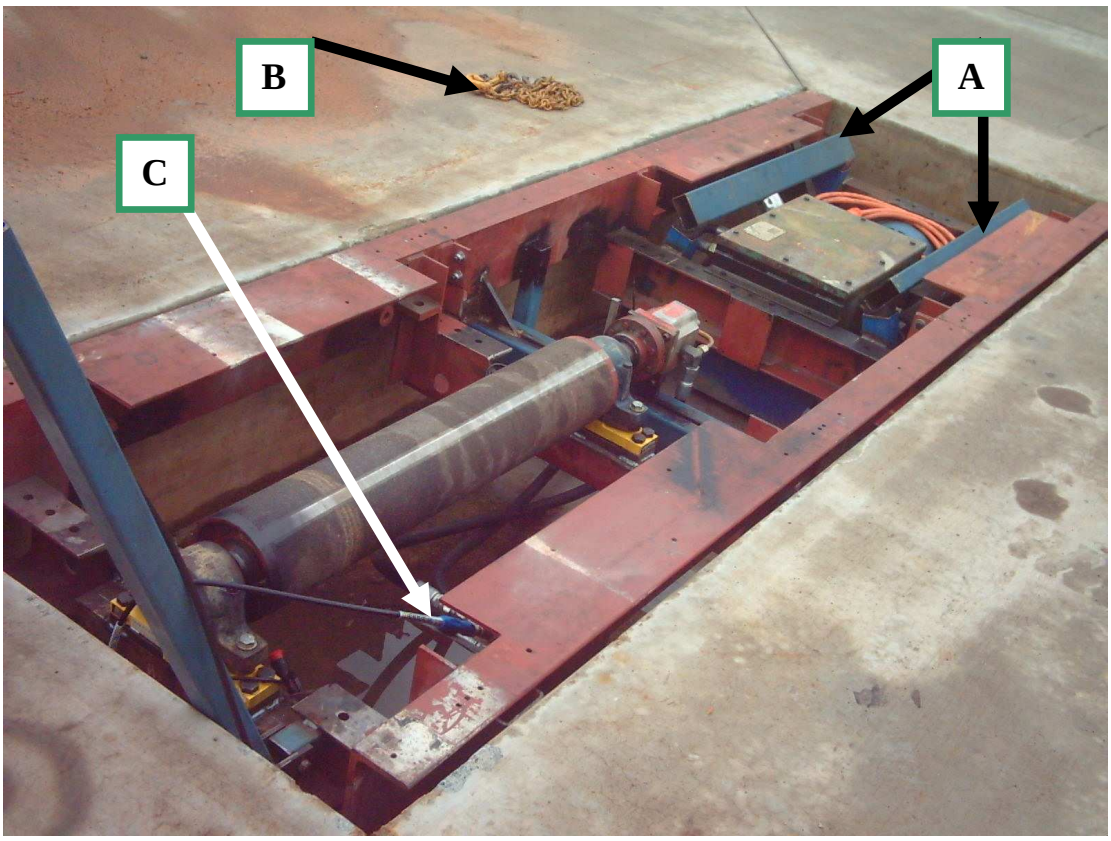

Figure 9. The test rig in the pit. Arrows A show extendable wheel restraints and arrow B shows hold-down chain. The arrow C indicates the speed control coupling.

3.4. Positioning the trailer on the roller-tester

The test HV (a semi-trailer) was positioned such that the RHS middle wheel of the tri-axle group was on the roller. The LHS wheel of the middle axle was constrained using extendable retaining frames (indicated by arrows "A", Figure 9) and chained down (arrow "B", Figure 9) as an added precaution. The brakes on the trailer were applied except for the brake on the wheel under test. These measures were a safety precaution due to the uncertain nature of any testing. It is expected that this level of restraint would not be necessary should this test procedure be implemented commercially.

The final arrangement of the wheel and its relationship with the drive roller is shown in Figure 10.

Figure 10. The final position of the roller in relation to the HV wheel under test.

3.5. Instrumentation

Commercial load cells (strain gauges attached to a steel block) were installed under the bearings at each end of the roller. Figure 11 and Figure 12 show this detail. The

dynamic wheel force was found from the sum of the forces on the load cells. This was then calibrated as wheel force in kilograms.

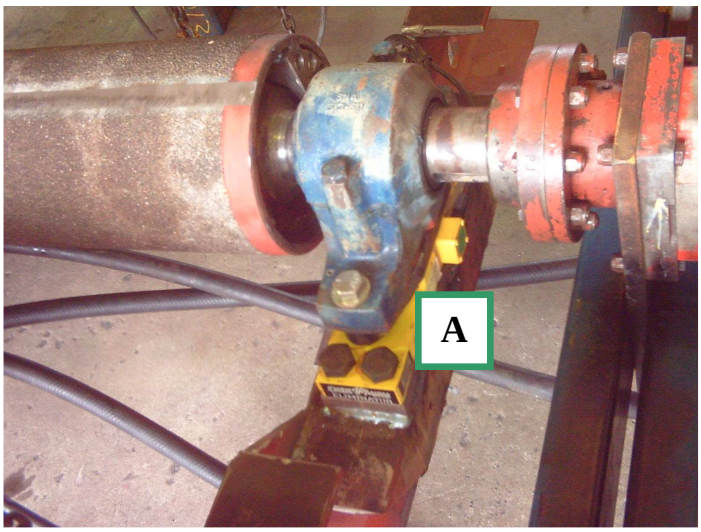

Figure 11. Load cell (indicated A) under roller LHS bearing.

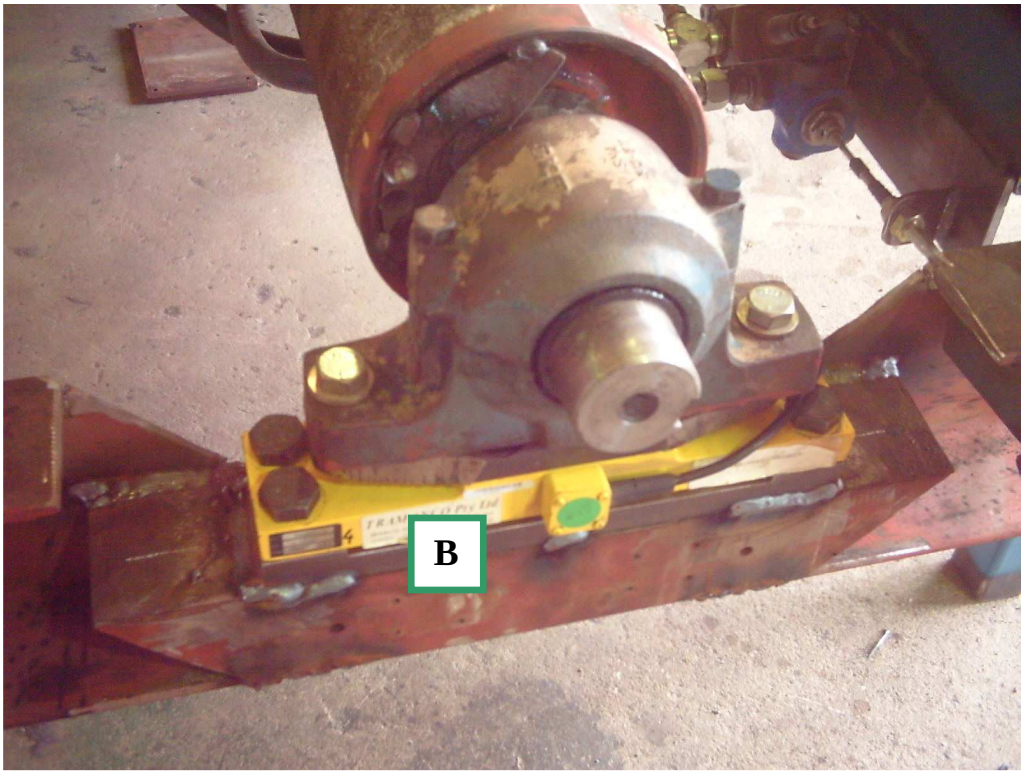

Figure 12. Load cell (indicated B) under roller RHS bearing.

An advanced version of the TRAMANCO P/L on-board CHEK-WAY® telemetry system was used to measure and record the dynamic signals from the outputs of the strain gauges. Figure 13 shows the CHEK-WAY® recording system and Figure 14 shows the system management computers. The data sets were recorded in the memory of the CHEK-WAY® units (boxes indicated "A" in Figure 13). The data sets were recorded in 10 s blocks. A system management computer, Figure 14, was used to manage the data capture timing and post-test data downloads.

The CHEK-WAY® system is subject to Australian Patent number 200426997 and numerous international application numbers and patents that vary by country.

3.5.1. Sampling frequency

The telemetry system-sampling rate was 1 kHz giving a sample interval of 1.0 ms. Note that the natural frequency of a typical heavy vehicle axle is 10 - 15 Hz (Cebon, 1999) compared with a relatively low 1 - 4 Hz for sprung mass frequency (de Pont, 1999). Any attempt to measure relatively higher frequencies (such as axle-hop) using time-based recording will necessarily involve a greater sampling rate than when relatively lower frequencies (such as the body-bounce frequency) are to be determined (Houpis & Lamont, 1985). Since axle-hop was the highest frequency of interest for the analysis undertaken, the sampling frequency used by the CHEK-WAY® system was more than adequate to capture the test signal data since its signal sample rate was much greater than twice any axle-hop frequency. Should this test be implemented commercially, a data logger with sampling frequency of (say) 100 Hz would suffice. Accordingly, and to check the validity of the choice of sampling frequency, the Nyquist sampling criterion (Shannon’s theorem) was met (Houpis & Lamont, 1985) for our testing.

Figure 13. Data recording and capture system.

Figure 14. Computer used for data capture management.

3.6. Final operation

Figure 15 shows the test HV wheel run up on the roller with a roller rotational speed of 360 revolutions per minute. This resulted in a cyclic loading from the two flats on the roller.

Figure 15. Test HV wheel rotating at speed.

3.7. Tested conditions

The following section outlines a portion of the test programme. The test cases detailed in this report are shown in Table 1.

Table 1. Shock absorber condition and test loading for the tests as documented herein.

Condition	4mm flats on roller Full Load
No shock absorbers	√
Worn shock absorbers (see section 1.1)	√
New shock absorbers	√

For the three condition states of:

- ☞ no shock absorber;
- ☞ a shock absorber that had worn to the point where it removed from its donor vehicle because tyre wear had become apparent; and

- ☞ a fully-functional shock absorber (i.e. within specification) for the suspension being measured

at a load approximating full load (3 t) on the wheel, the test HV wheel was spun up using the powered roller of the test rig.

The worn shock absorber used for the testing will be dynamometer tested and the results of that testing, when available, will be published in augmented versions of this report in future.

For the data presented in this report, the hydraulic valves of the test rig were set so that the final speed of the roller reached 360 revolutions per minute. This meant that, with two flats per revolution, the frequency of the forcing function from the flats of the roller was 12 Hz. This was at or above the highest axle-hop frequency measured for this trailer and suspension (Davis & Bunker, 2008b). Other speeds were used and data recorded for these. The results of that analysis will be reported in future papers and at other fora.

4. Results

4.1. General

The signals from the load cells under the roller bearings were conditioned and filtered with a 25 Hz low-pass filter to remove noise. Time-series and peak-to peak values are shown in the following section.

4.2. Time series of wheel force signals

Portions (and representative samples) of the time series of the wheel-force signals for the three states of shock absorber health are shown in Figure 16 to Figure 18. As reported by other researchers such as Woodrooffe (1996), resonance occurred during the transients from starting the roller compared with the steady-state running dynamic forces. This may be seen in the starting transients for the worn and no shock absorber cases in the 0.5-1.0 s or so before the signal settled down to fairly even excursions.

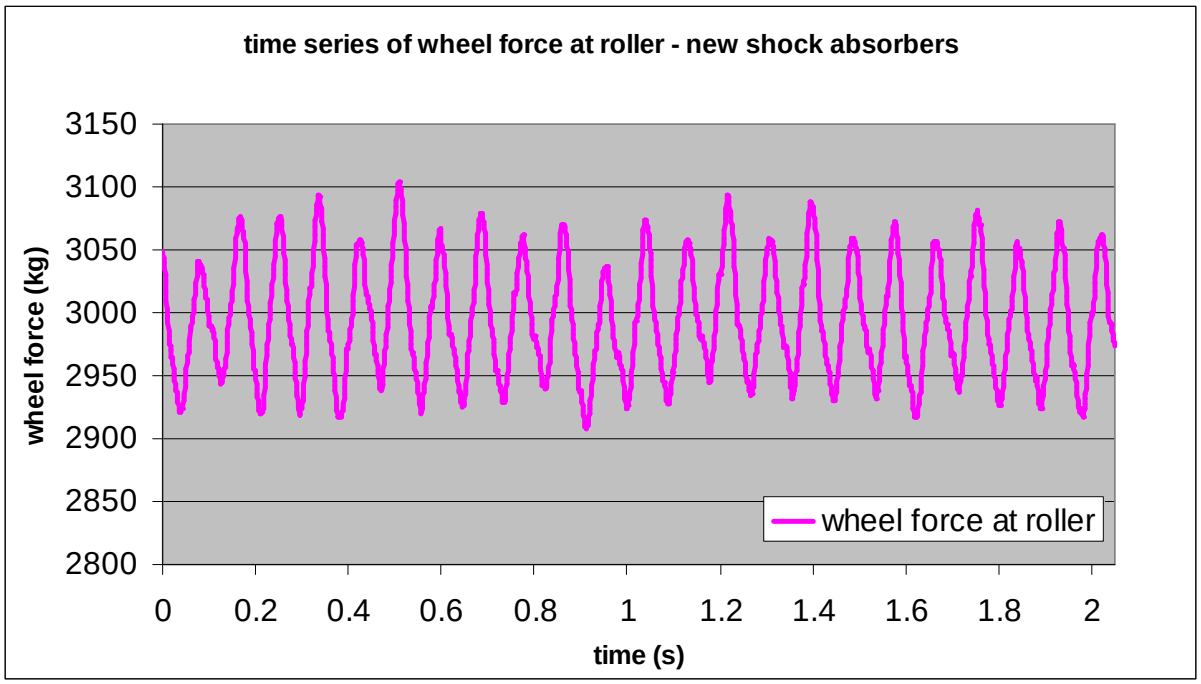

Figure 16. Time series of the wheel forces for new shock absorbers.

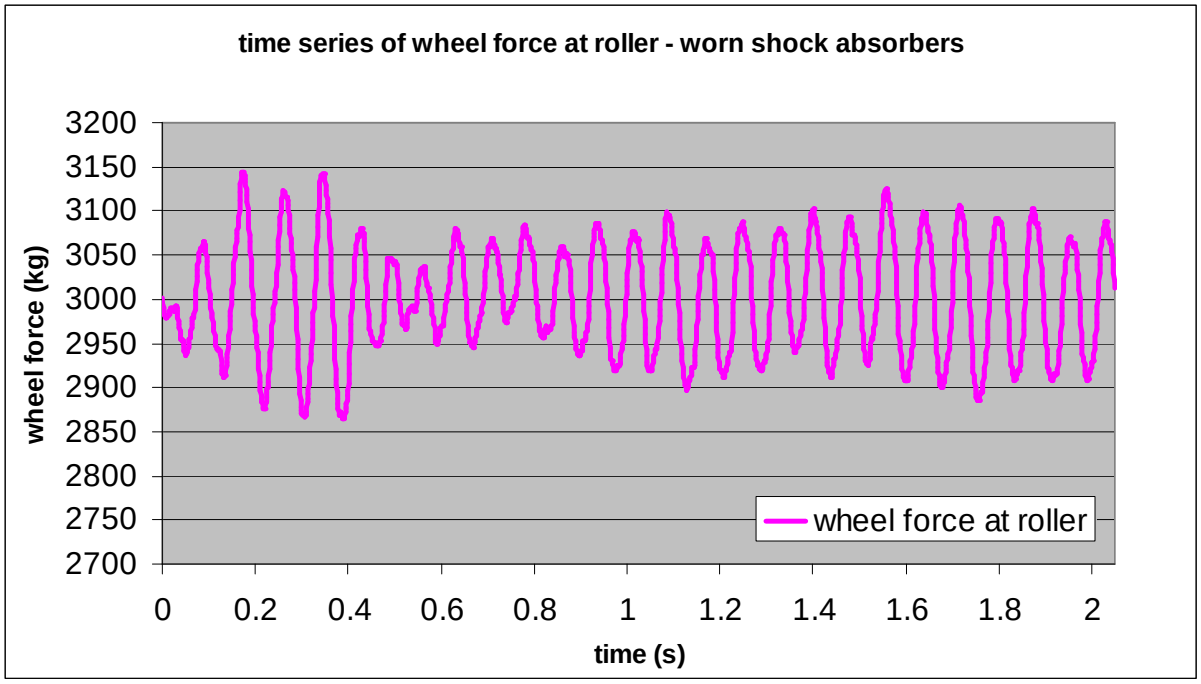

Figure 17. Time series of the wheel forces for worn shock absorbers.

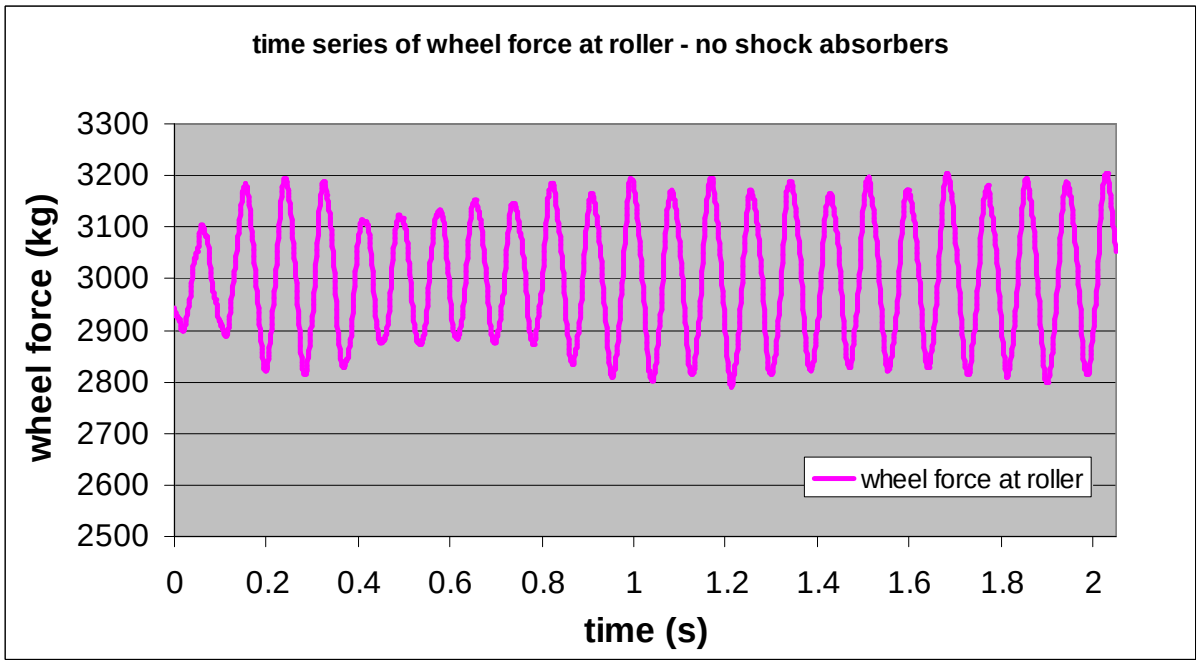

Figure 18. Time series of the wheel forces for no shock absorbers.

4.3. Dynamic range of signal

The peak-to-peak value (i.e. the dynamic range) of the wheel-force signal was derived for the three cases of shock absorber health. This concept is illustrated in Figure 19.

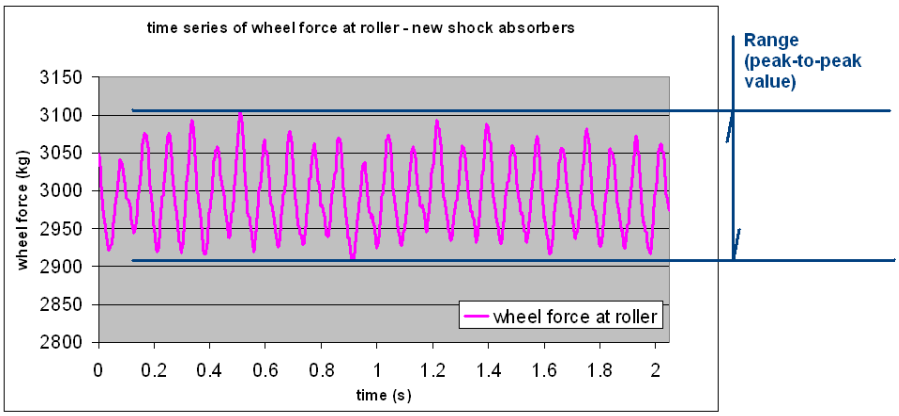

Figure 19. Example of dynamic range (peak-to-peak value) of the wheel forces.

The values of dynamic range[1] for wheel forces with the three conditions of shock absorber health are shown in Table 2. These values were derived from the dynamic data shown in graphical form in Figure 16 to Figure 18.

Table 2. Shock absorber condition for the tests as documented herein.

Condition at 3t static wheel loading	Peak-to-peak value of wheel force (kg) for flats with 4 mm excitation	Difference compared with new shock absorber case (%)
No shock absorbers	415	97.6
Worn shock absorbers (see section 1.1)	280	33.3
New shock absorbers	210	n/a

[1] Calibration data to translate the load cell signals into wheel force had not been finalised when developing earlier drafts of this report. Revised, updated and final calibration values have been used to develop the data presented here.

5. Discussion

5.1. General

The delivery schedule of the NTC's project to find and/or develop an in-service suspension test for HVs has, unfortunately, clashed with other commitments within the joint QUT/Main Roads project *Heavy vehicle suspensions – testing and analysis***.** This tension has necessitated that a preliminary set of results be issued in the format of this preliminary report. Nonetheless, the programme of analysis and further results from the testing outlined in this report will continue and further reports will be issued.

5.2. Difference in wheel-forces for shock absorber health

With 4 mm flats on the roller, the dynamic wheel forces above static were approximately doubled when comparing the case of new shock absorbers *vs.* no shock absorbers. Further, dampers worn to the point where they would be replaced because the tyres were starting to wear provided approximately 33% more dynamic loading to the pavement compared with dampers in the new condition when the wheel was excited by 4 mm excursions. It will be for future research to determine what level of increase in dynamic wheel forces occurs when wheels damped with worn, ineffective or out-of-specification shock absorbers encounter pavement and bridge irregularities with magnitudes greater than the excursions used for these tests. Even so, the figures herein and their orders-of-magnitude are indicative, at least, of the increases to the road and asset damage from HVs with worn, ineffective or out-of-specification dampers.

Previous research (Davis & Bunker, 2008b) has shown that HV wheel loads at highway speeds resonate continuously at axle hop frequencies in the range 10 Hz to 12 Hz. For the exercise described in this report, a 4mm excitation was used to induce axle-hop in a HV wheel. For the case of worn shock absorbers, this resulted in an increased peak wheel-load of 70 kg more than for the case for new shock absorbers. The axle-hop excitation for the case no shock absorbers resulted in a peak wheel load of 205 kg more than for the case for new shock absorbers.

Let us estimate that, conservatively, road excitation has a 4mm range (in reality, a low estimate). Even so, these results indicate that HVs with worn shock absorbers, with condition-states somewhere between tyre wear being apparent to totally ineffective, are imposing peak loadings on the pavement and bridges between 2.3% and 6.8% higher than for the case of well-maintained shock absorbers. Applying a conservative 4th-power rule for the relationship between pavement loading and pavement damage, this result indicates that instantaneous loading from worn, out-of specification or defective shock absorbers on HVs is creating instantaneous loading damage increases in the range of 9.7% to 30.2% when compared with well-maintained dampers. This exercise does not account for the 12th-power rule for concrete pavements where the increase in damage would be proportionally worse; nor does it account for excitation due to road irregularities of greater than 4mm. From the work of Costanzi & Cebon (2005) who modelled a fleet of HVs with 50% ineffective dampers, the conclusion arose that, at Higher Mass Limits loadings, pavement and surfacing damage would be 20 - 30% greater than for a comparable freight task with a fleet equipped with dampers in good condition. We see here a confluence of figures with respect to rectification costs from the approach developed above and that of Costanzi & Cebon (2005).

Main Roads' budget for maintenance in the 2007-2008 financial year was $253M (Queensland Department of Main Roads, 2008) or 11% of total expenditure of $2.3B spent on maintenance. It is not unreasonable to propose that road asset damage is due to heavy vehicles compared with the damage from any other form of road traffic. From the indicative exercise on increased instantaneous pavement loadings above, a potential saving of up to 30.2% of the maintenance portion of Main Roads' budget, or $76.4M/annum could be gained from the simple expedient of road transport operators testing their HVs and replacing worn shock absorbers. This would then obviate the situation (Blanksby et al., 2006) where over 54% of the heavy vehicle fleet does not meet the provisions of VSB 11, the Australian standard for HV suspension "road-friendliness”.

5.3. Wheel-forces as an indicator of shock absorber health

The generally accepted practice and anecdotal evidence in the road transport industry is for tyre wear to be used as an indicator that suspension dampers are worn. Blanksby *et al*., (2006) showed that this is not a good determinant of damper wear. The testing as outlined in this report has gathered data on wheel-forces present when a shock absorber was worn to the point that tyre wear was evident. When compared with the forces for the case where the shock absorber was in good condition, there was a clear distinction both in shape of dynamic signal at the roller and the range of that signal. For the case where the shock absorber was removed entirely, the comparison was even more striking.

5.4. Test rig and the future

The use of the modified roller-brake machine has shown, at the "proof-of-concept" stage, that wheel-forces can be used to determine damper health. Should additional analysis of the test data from this test programme further validate the methodology described herein, the next step is to consider the cost of such testing. The modified test rig used for these tests cost approximately $AUD10,000 for the initial purchase of a second-hand roller brake tester and the modifications to it. The instrumentation used cost approximately $AUD5,000 but this could be lower if a simple 100 Hz data logger were used. The analysis would, on the commercial market, cost approximately $100 per axle group. The brake testing machine from which our test rig was made was a standard unit that was not altered with respect to its original overall dimensions. A commercial variant of it should therefore be able to fit into existing infrastructure at roadside interception sites or vehicle maintenance facilities where brake testers were designed to fit. Accordingly, a moderate-cost testing machine could perform low-cost-per-test HV suspension testing in a high-volume application.

6. Conclusion

Using tyre wear as an indicator that suspension dampers are worn is not an indicator that results in timely shock absorber replacement. This report shows that wheel forces from a suspension with worn shock absorbers at the point where tyre wear was apparent were clearly distinguishable from the forces present when new or no dampers were present. The dynamic component of these forces ranged from 33% to approximately double those of the dynamic forces present in a HV suspension in good condition. Other research, such as that by Blanksby *et al*., (2006) has shown that the philosophy of damper replacement predicated on tyre wear is unreliable. This since over 54% of the HVs surveyed in that work had worn, ineffective or out-of-specification dampers without noticeable tyre wear. Deployment of regular damper testing and resultant replacement of worn, out-of-specification or defective shock absorbers has the potential to save Main Roads up to $76M/annum. This figure aligns well with the figure derived from earlier work by Costanzi & Cebon (2005). This saving could then go forward every year to fund other programmes instead of rectifying road asset damage from heavy vehicles that should be maintained as a matter of course. This approach does not account for any safety benefits of heavy vehicles with well-maintained suspensions, nor does it consider, except for noting and future research, the benefits to Local Governments in potential savings to their works budgets.

The testing as outlined in this test plan has gathered data on dynamic wheel-forces present with varying shock absorber health levels. The results in this preliminary report indicate that, for a very small (4 mm) excitation signal, the dynamic range (over and above the steady-state) of the wheel forces for the case where the shock absorbers were totally inoperable was higher, by about twice, than that for the case of new shock absorbers. The results also showed that, for a 4mm excitation and damper condition starting to wear the tyres, the dynamic pavement forces were 33% higher than for new shock absorbers.

The results indicate that a “proof-of-concept” for a moderate-cost testing machine to perform low-cost-per-test heavy vehicle suspension testing has been achieved with the

use of a modified roller-brake tester. Further work will now be undertaken on the data recorded during the test programme including frequency-domain analysis to determine further insights into eigenfrequency phenomena other than reported here. These results will be reported in future.

Appendix 1.

Dynamometer results of dampers to be inserted when available.

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