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ANNUAL SUMMARY REPORT

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Author/s: Anthony Germanchev

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R34 Review of In-service Test for Road Friendly Suspensions

SUMMARY

The project was commissioned under the TMR/ARRB Agreement. The current project contract is for year 1 (problem definition and scoping) with potential for subsequent funding in 2015/2016 (proof of concept) and 2016/2017 (field testing and reporting).

This report summarises the preliminary review of materials relevant to the development of an in-service testing mechanism for road friendly suspension (RFS) systems conducted as Stage 1 of this project.

The common understanding held by road managers is that road-friendly suspensions (RFS) reduce pavement damage, thus heavy vehicles fitted with RFS are afforded mass and access benefits. However, to continue to derive the benefits of RFS throughout its service life, it is necessary to monitor and correct the in-service degradation. Despite this understanding there are no in-service performance requirements for RFS.

The review has identified the next steps required to evaluate an in-service test method via a proof-of-concept and field testing program of work. In addition to this ARRB has highlighted limitations and the corrective measures to address and potentially overcome them for the proposed work program. A summary of key findings is listed below.

- The concept of road-friendly suspensions and the understanding that they are less damaging to pavements is well founded. The key performance characteristics that define road-friendliness are damping ratio and frequency.
- There are still knowledge gaps in the relationship between RFS systems (in particular varying the suspension characteristics of damping and frequency) and pavement wear. If not addressed these will prevent the development of performance requirements that differ from the existing requirements documented in VSB11.
- Computer modelling of vehicle and pavement interaction has advanced in recent years and offers potential for use in addressing the existing knowledge gaps.
- Developments in on-board mass monitoring technology, vehicle telematics and the increased sophistication of heavy vehicle braking systems provide options for cost effectively monitoring suspension performance of a number of vehicles during their normal operation.
- The key requirements for developing an in-service compliance standard have been identified and the potential for a cost effective solution through the use of new technology and on-board sensors warrants further investigation as a viable measurement method.
- The recommended next step in this program of work is a proof of concept stage to evaluate a method to gather the necessary data within an acceptable accuracy (proximity to true value) and precision (repeatability).

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1 INTRODUCTION

The common understanding held by road managers is that road-friendly suspensions (RFS) reduce pavement damage, thus heavy vehicles fitted with RFS are afforded mass and access benefits not available to vehicles that do not have RFS. Eligible vehicles and individual mass increases vary slightly across each jurisdiction. However, there exists the potential for substantial economic benefits from increased transport efficiency if some of these mass limits are increased.

An obstacle to increased reliance on RFS is that evidence shows that the performance of RFS does degrade over time. As critical components in air-sprung road-friendly suspensions wear or sustain damage through their service life, suspension performance does deteriorate. The result of this deterioration could be such that road-friendly suspensions in service no longer meet road-friendliness requirements. This is dependent upon the performance of the suspension in relation to road-friendly requirements when new, and the magnitude of the effects of wear or damage. For some suspension systems, a significant margin of deterioration may be required before he systems fail to meet road-friendly requirements. If suspension performance is degraded to below road-friendly performance requirements, this will result in increased dynamic forces applied to the pavement, thereby increasing pavement wear compared with a correctly-functioning suspension system. To continue to derive the benefits of RFS throughout its service life, it is necessary to monitor and correct the in-service degradation of RFS.

It has been some time since this issue was first examined. Advancements in telematics, accreditation, software models and technologies now offer new possibilities for in-service testing of RFS. A more current review is necessary to examine the current nature of the problem and the most current options to address the issue. Accordingly, this report has been prepared for Queensland Department of Transport and Main Roads.

2 PROJECT AIM

This project aims to conduct a preliminary review of materials relevant to the development of an in-service testing mechanism for road friendly suspension (RFS) systems.

The scope of this project includes the following tasks:

1. Review of background information
   - (a) list of relevant documents, standards and reports covering previous work in this area
   - (b) review of a selection of the previous work and prepare brief summary (including a PowerPoint presentation).
2. Information sharing
   - (a) circulate summary and other relevant documents to project management team
   - (b) identify suitable candidates for a technical reference group (TRG).
3. Identify and prioritise key issues.
   - (a) list options for project scope and future direction
   - (b) list key requirements/desirables for an in-service RFS engineering solution.
4. Engineering solutions
   - (a) finalise and prioritise list for proof of concept (with input from TRG).

This report draws together the results of the four tasks and proposes a path for the continuation of the project over coming years.

3 BACKGROUND

The development of RFS and its introduction to 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. Introduction of the Higher Mass Limits (HML) scheme, with RFS as a requirement for participation.
4. Investigation of in-service test methods to monitor continuing compliance of RFS equipment.

A brief background to each of these is provided below.

3.1 The Recognition of Road-friendliness

The DIVINE (Dynamic Interaction between the Vehicle and Infrastructure Experiment) project (OECD 1992) is considered the pre-eminent research on the topic of road friendly suspensions. 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.

3.2 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 any two 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 in the Australian Federal regulation *Certification of road-friendly suspension systems* (Vehicle Standards Bulletin 11) (Department of Transport and Regional Services 2004) and subsequently revised in 2004.

3.3 Introduction of Higher Mass Limits (HML)

The maximum load a heavy vehicle can carry is limited and enforced by the state road authorities. Mass limits are based on an economic evaluation of the asset wear resulting from axle loads. In 1998, the NRTC investigated the end economic effects of allowing axle load increases for vehicles with road-friendly suspension (at the time considered to be solely limited to air suspension types). Subsequently the higher mass limits (HML) scheme was adopted by most state and territory jurisdictions. These axle loading schemes apply to most types of heavy vehicles provided that necessary conditions are met.

Required conditions for heavy vehicles to operate at HML vary across different jurisdictions but all include 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.

3.4 Investigation of In-service Compliance of RFS

The current standard (VSB11) defines the requirements for certifying a new suspension as road friendly. Once approved, the suspension make and model is given a RFS number. 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 Road Friendly Suspensions. A technical assessment of the management of in-service performance of road friendly suspensions 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.

4 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 4.1.

Table 4.1: Summary of reviewed documents

	Document Name	Author(s)	Date	Report Section
▪ 1	▪ Mass limits review – Technical supplement No 2 – Road and Bridge Impacts	▪ National Road Transport Commission	▪ 1996	▪ Section 4.1
▪ 2	▪ OECD DIVINE programme – Final report – Dynamic interaction of heavy vehicles with roads and bridges	▪ Organisation for Economic Co-operation and Development (OECD)	▪ 1997	▪ Section 4.1
▪ 3	▪ OECD cooperative international research into vehicle-road interaction – DIVINE project	▪ K Sharp, P Sweatman, ▪ R Addis	▪ Nov. 1998	▪ Section 4.1
▪ 4	▪ In-service assessment of road-friendly suspensions	▪ P Sweatman, ▪ S McFarlane, ▪ J Komadina, D Cebon	▪ Jan. 2000	▪ Section 4.1
▪ 5	▪ Evaluation of in-service compliance of road-friendly suspensions	▪ MM Starrs, Ian Wright & Assoc., ARRB Transport Research	▪ Aug. 2000b	▪ Section 4.1
▪ 6	▪ Air suspension code: guidelines for maintaining and servicing air suspensions for heavy vehicles, ARTSA Code 01	▪ Australian Road Transport Suppliers Association	▪ May 2001	▪ Section 4.1
▪ 7	▪ The benefits of road-friendly suspensions	▪ A Collop, D Cebon	▪ 2002	▪ Section 4.1
▪ 8	▪ Impacts of vehicles with higher mass limits on NSW roads	▪ D Cebon	▪ Jun. 2004	▪ Section 4.1
▪ 9	▪ Certification of road-friendly suspension systems Vehicle Standards Bulletin No 11	▪ Department of Transport and Regional Services	▪ Jul. 2004	▪ Section 4.1
▪ 10	▪ Analysis of heavy vehicle suspension dynamics using an on-board mass measurement system	▪ L Davis, R Sack	▪ Oct. 2004	▪ Section 4.1
▪ 11	▪ Testing of heavy vehicle suspensions – Proof-of-concept: 'white-noisy road test' and 'pipe test' to determine heavy vehicle suspension parameters	▪ L Davis	▪ Dec. 2005	▪ Section 4.1
▪ 12	▪ An in-service survey of heavy vehicle suspensions	▪ C Blanksby, R George, ▪ A Germanchev	▪ Jun. 2006	▪ Section 4.1
▪ 13	▪ Determining heavy vehicle suspension dynamics using an on-board mass measurement system	▪ L Davis	▪ Nov. 2006	▪ Section 4.1
▪ 14	▪ Further development of in-service suspension testing for heavy vehicles	▪ L Davis, S Kel, R Sack	▪ Sep. 2007	▪ Section 4.1
▪ 15	▪ Heavy vehicle suspensions – testing and analysis - a literature review.	▪ L Davis, J Bunker	▪ Dec. 2007	▪ Section 4.1
▪ 16	▪ In-service Performance Assurance for Road Friendly Suspensions	▪ National Transport Commission	▪ 2008	▪ Section 4.3
▪ 17	▪ Measuring heavy vehicle wheel loads dynamically	▪ Austroads	▪ Mar. 2009	▪ Section 4.4

	Document Name	Author(s)	Date	Report Section
▪ 18	▪ Heavy vehicle suspension- testing and analysis PHD thesis	▪ L Davis	▪ 2010	▪ Section 4.4
▪ 19	▪ Measurement and analysis of dynamic wheel loads	▪ Austroads	▪ May 2012	▪ Section 4.4
▪ 20	▪ Vehicle pavement interaction modelling	▪ RL Roebuck et al.	▪ 2012	▪ Section 4.4

The aim of the review is 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.

A brief summary of the findings of the literature review is provided below in which each of these topics outlined above is discussed in relation to in-service compliance of road-friendly suspensions.

The findings of the literature review are grouped into the following three sections:

- Summary of the development of RFS requirements – this includes research conducted between 1996 and 2008
- Development of a low-cost method for measuring dynamic wheel loads
- Summary of findings from the NTC review conducted in 2008
- Current and ongoing research.

4.1 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 had 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 road-friendly suspension 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 et al. (1998) 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. (1998) 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 road-friendly suspensions compared with the continued absence of concessions to encourage road-friendly suspensions. 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 road-friendly suspensions 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 road-friendly suspension 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 road-friendly suspension 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 tri-axle 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. Table 4.2 summarises the suspensions surveyed, separated into columns for the 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.

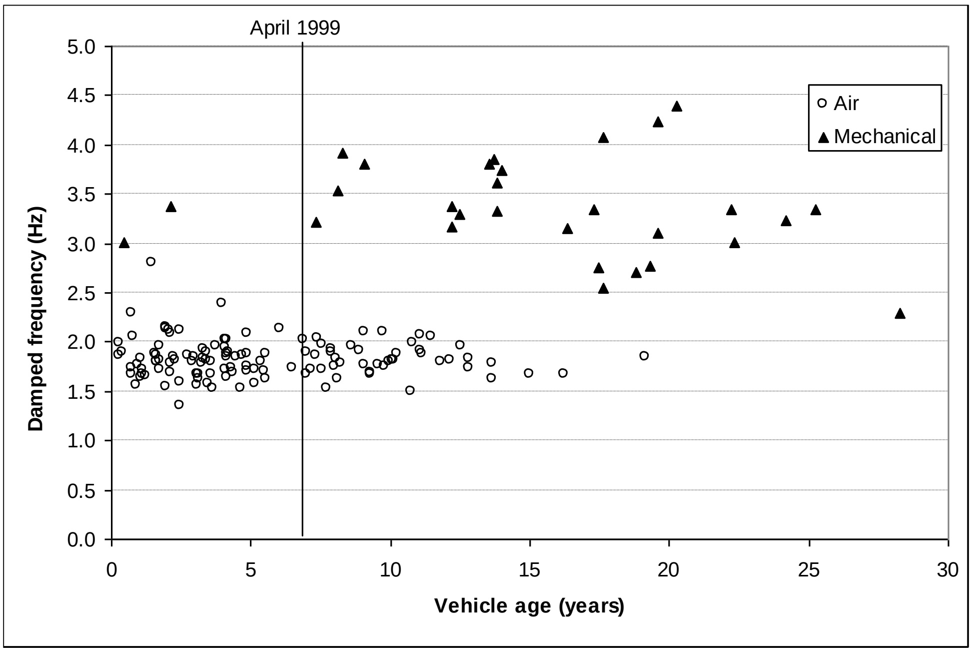
Table 4.2: Summary of RFS survey results

Type	Air suspension	Mechanical	Total
Total	121	29	150
> 20 t	26 (21.4%[1])	16 (55%)	42 (28%)
Non-compliant (less than 15%)	7 (26.9%)	14 (87.5%)	21 (50%)
Non-compliant (between 15% - 20%)	5 (19.2%)	1 (6.25%)	6 (14.3%)
Compliant (greater than 20%)	14 (53.9%)	1 (6.25%)	15 (35.7%)

1 Percentages calculated based on the previous subset of sampled suspensions.

Figure 4.1 compares suspension damped frequency and trailer age; it shows that there is no apparent relationship between the damped frequency and the age of the trailer.

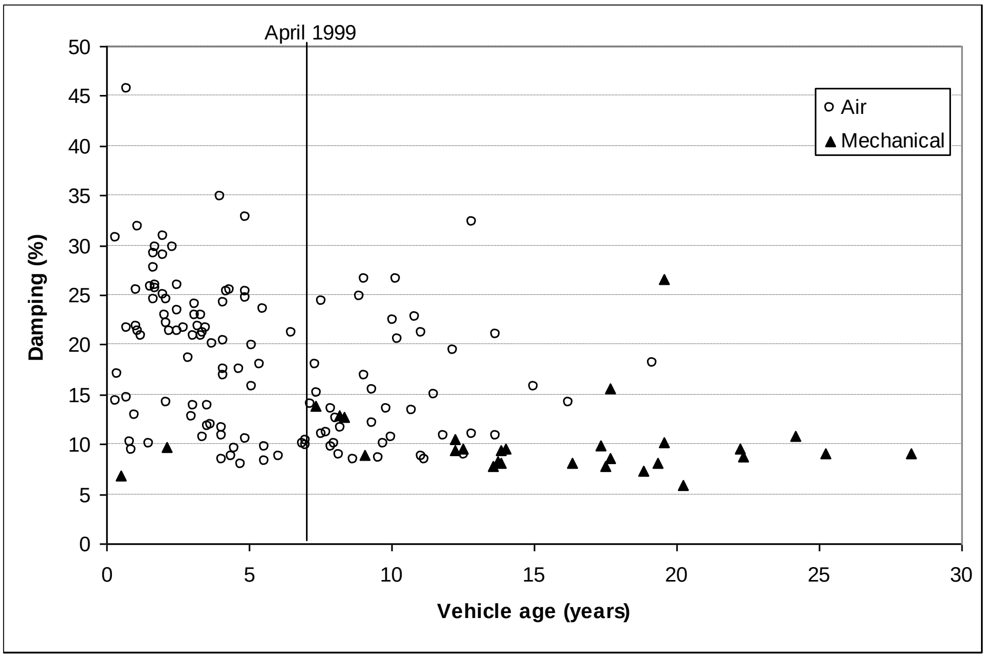
Figure 4.1: Suspension damped frequency vs trailer age



Source: Blanksby et al. (2006).

Figure 4.2 compares 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.

Figure 4.2: Suspension damping vs vehicle age



Source: Blanksby et al. (2006).

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 (2000b) 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 road-friendly suspensions 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 road-friendly suspensions 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 (2000b) was incorrect due to the assumption that poorly-maintained road-friendly suspensions 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% road-friendly suspensions, the cost of road maintenance would decrease by 14%. However, with the increased loads available for vehicles with road-friendly suspensions, the reduction in road maintenance costs would only be 6%. A fleet with 75% effective road-friendly suspensions and 25% ineffective road-friendly suspensions 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.

4.2 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. Figure 4.3 shows a hub-mounted not contact sensor under assessment.

Figure 4.3: Laser mounted hub for measuring dynamic wheel loads

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. This research program is continuing and is discussed further in section Section 4.4.

4.3 Summary of the NTC Investigation

The NTC (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 VSB-11 tests in the field, it is considered that a roadside, in-service test based on VSB-11 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 VSB-11, it would be effective in detecting the most damaging vehicles.

A number of non VSB 11 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-VSB-11 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.

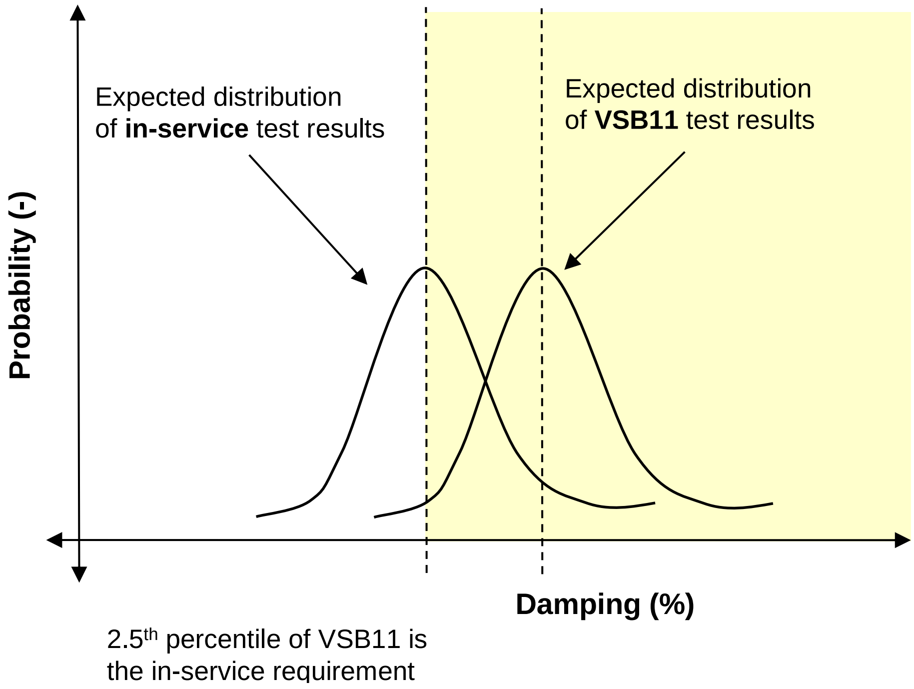
In the absence of an established relationship between these factors and wear, the VSB11 requirements for the certification of RFS systems has been used as a benchmark to establish effective road friendliness requirements, identified during the literature review. It was decided that at this time, in-service 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 2.5^{th} percentile value, and will also meet the requirements of an in-service test.

This is illustrated in Figure 4.4 which compares the expected distribution of the results obtained using the VSB11 and an in-service test which has the damping requirement set at the 2.5^{th} percentile of the expected range of results from VSB11 tests.

Figure 4.4: VSB11 and in-service testing tolerances



Using VSB11 as the basis for in-service testing limits the options available for selection and imposes limitations on the implementation of this option and impractical test methods. The option of pursuing an alternative path to VSB11 remains 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 provides flexibility that could allow for a viable solution.

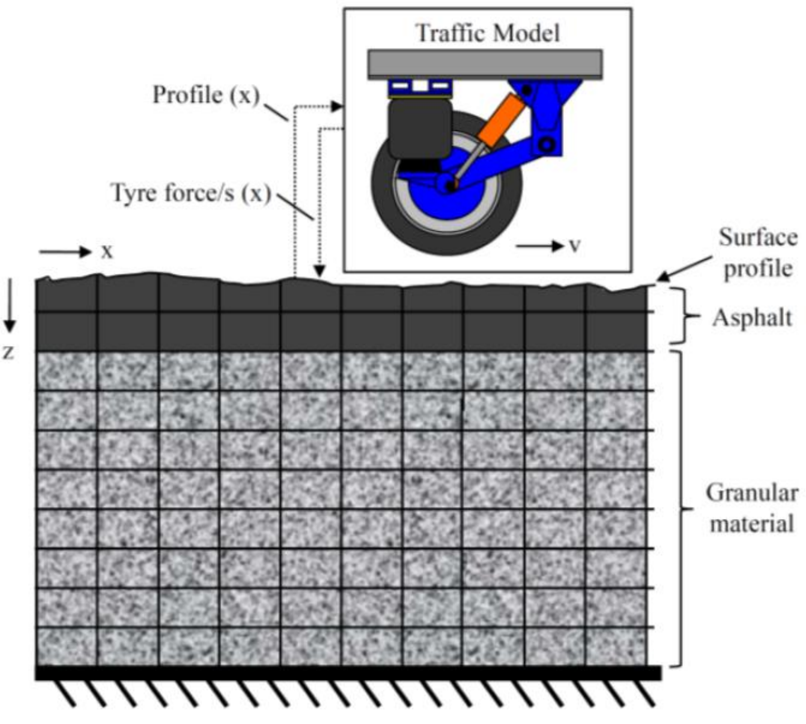
4.4 Current and On-going Research Related to RFS

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 is provided below.

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 tri-axle 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.

Figure 4.5: Interaction between truck model and road profile



A case study was presented showing comparison between steel, air and defective air suspensions, under Higher Mass Limits (HML) and General Mass Limits (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 10 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 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

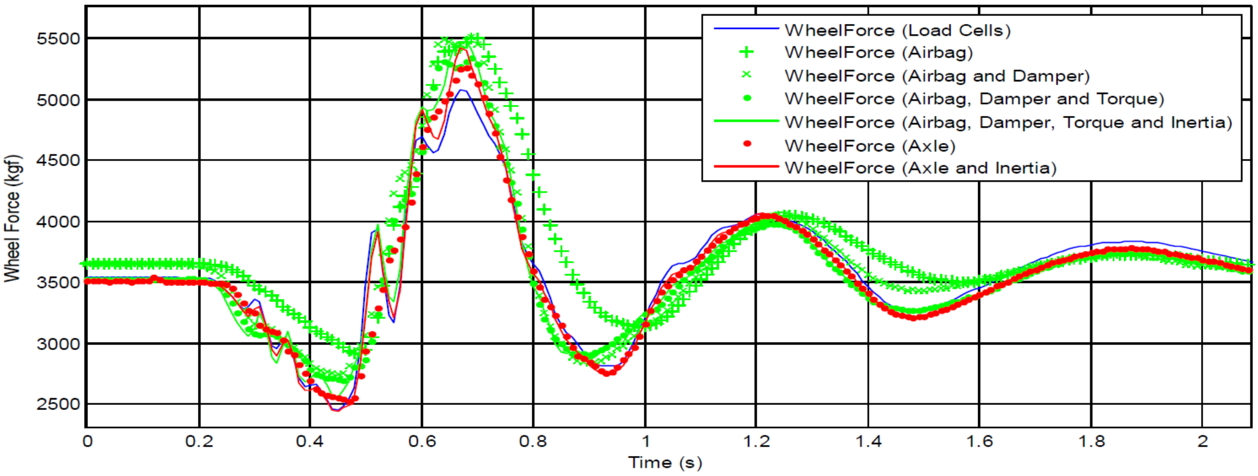
Estimating dynamic wheel loads from airbag pressure requires additional sensors compared with the strain gauge approach, which only requires the strain gauge and outboard mass acceleration to be measured. The measurements required for both approaches are summarised in Table 4.3 .

Table 4.3: Requirements of alternative measurement methods

Measurement approach	Required measurements	Sensors
Airbag pressure	Airbag pressure, damper velocity, relative position of left and right trailing arms, outboard mass acceleration.	Pressure sensor, linear voltage displacement transducers, and accelerometer.
Axle strain	Strain and outboard mass acceleration	Strain gauge and accelerometer

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. Figure 4.6 shows a time history of the dynamic forces for each technique.

Figure 4.6: Wheel force measured during drop test



The accuracy of the measurement options is summarised in Table 4.4. The results include comparisons based on two references: 1) the drop test (shown in Figure 4.6) 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.

Table 4.4: Accuracy of airbag and strain gauge

Measurement approach	RFS drop test data	On-road test data
Airbag pressure (airbag only)	0.815	0.512
Airbag pressure (airbag, damper and axle torque)	0.937	0.777
Airbag pressure (airbag, damper, axle torque and inertia)	0.971	0.926
Axle strain	0.992	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.

4.5 Summary of Literature Review Findings

The literature review highlighted that there are still knowledge gaps in understanding the relationship between RFS systems and pavement wear. While considerable research had been conducted in this area, the review highlighted that the following areas represent opportunities for future study:

- 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 suspension 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 of particular importance, as the relationship between suspension frequency and damping, and the resulting dynamic loading applied to the pavement, cannot be defined at this time.

The research conducted in the area of measuring dynamic wheel loads has not resulted in an on-board sensor that can accurately measure the dynamic loads required for determining in-service compliance. This research is ongoing but has led towards a solution that involves a model of the truck that is validated using in-field data. It is envisaged the use of a truck model will be able to utilise data gathered from a number of sources. This could include vehicle-based input data readily available such as air bag pressures, shock absorber temperatures, tyre pressures, wheel speeds and road surface input data which can be sourced from road surveys. A truck model will provide a simulation platform that can be utilised as part of the final solution. Modelling the performance of components that can’t be measured during field testing provides options of overcoming practical limitations.

The practical issues of conducting a roadside test that strictly adheres to the requirements of VSB11 render such options unviable. The practical issues that were identified by MM Starrs (2000b) and during the NTC review (2008) relate to the costs associated with conducting tests, in particular the requirement to remove shock absorbers and load the vehicle to the specified test weight. These requirements are unlikely to be overcome by advancements in technology, conversely the costs associated with each are more likely to increase as they depend on labour rates and require the freight vehicle to be off the road for some period of time. Alternative options that utilise on-board technologies provide a most cost effective solution.

The option of pursuing an alternative path to VSB11 remains 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 provides flexibility that could allow for a viable solution.

5 REQUIREMENTS FOR AN IN-SERVICE SOLUTION

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

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

The key requirements of the solution include a technical and functional specification. These are listed below as an example but require further verification via testing. The assessment method can excite the suspension system by:

- imposing an impulse via a purpose-built test rig the same or similar to those currently used to perform VSB11 certification tests, such as the drop test method, pull-down method, step test; or,
- driving the vehicle over a section of road sufficient to excite the suspension system via a bump or series of bumps, similar to the step test.

The system should measure:

- oscillations of the suspension system at a sampling frequency twice that of the natural frequency of the system
- the test mass within a tolerance of +/–5%
- the magnitude of oscillations to sufficient accuracy and resolution in order to determine damping ratio of the system (this will depend on the test conditions, which can be determined via testing)
- the test conditions in order to quantify their effect on the test results.

The analysis method should be robust and repeatable, ideally using a larger number of peaks and averaging the result. It is also important to set a threshold below which peaks cannot be counted. This is because the relative error (due to measurement error, noise, rounding off, etc.) for small peaks is much greater than for large peaks and when averaging, this error can distort the results. Generally, a threshold of around 5–10% of the magnitude of the first peak is used.

The assessment method should also meet a functional specification to ensure the system performs the function intended and without negatively impacting other operations. As an example the functional specification will include but not be limited to the following:

- assure data security and be protected against manipulation, tampering and vandalism
- not interfere with normal operation of the vehicle
- not impair vehicle or traffic safety
- not cause undue harm to the environment or others.

5.1 Practical Limitations of In-service Testing

The ideal in-service test method should replicate the results of the existing certification test method. In order to achieve this aim, the in-service test method must excite the system under test, measure its performance and analyse the data collected. The current certification standard (VSB11) permits a range of test approaches (e.g. drop test method, pull-down method, step test) and a test weight. The in-service method must produce an output that is comparable with certification results regardless of the original method used. It is likely that the results obtained during certification testing will vary in accuracy and repeatability; these variations must be first quantified before any comparison can be made with in-service requirements. It is anticipated that this will determine the performance requirements and tolerance of the in-service test method, and thus be more lenient than those required for certifying a new suspension. If the in-service requirement is considerably less stringent; the effectiveness of a lesser performance requirement to achieve the desired aim of minimising pavement wear must be considered.

6 FUTURE DIRECTION

A project scope and the future direction for the research required to develop an in-service compliance standard for road-friendly suspensions has been prepared and included in a proposal for completion in 2015/16.

The preliminary findings of this current project indicate that the major obstacles to an in-service test for RFS have been:

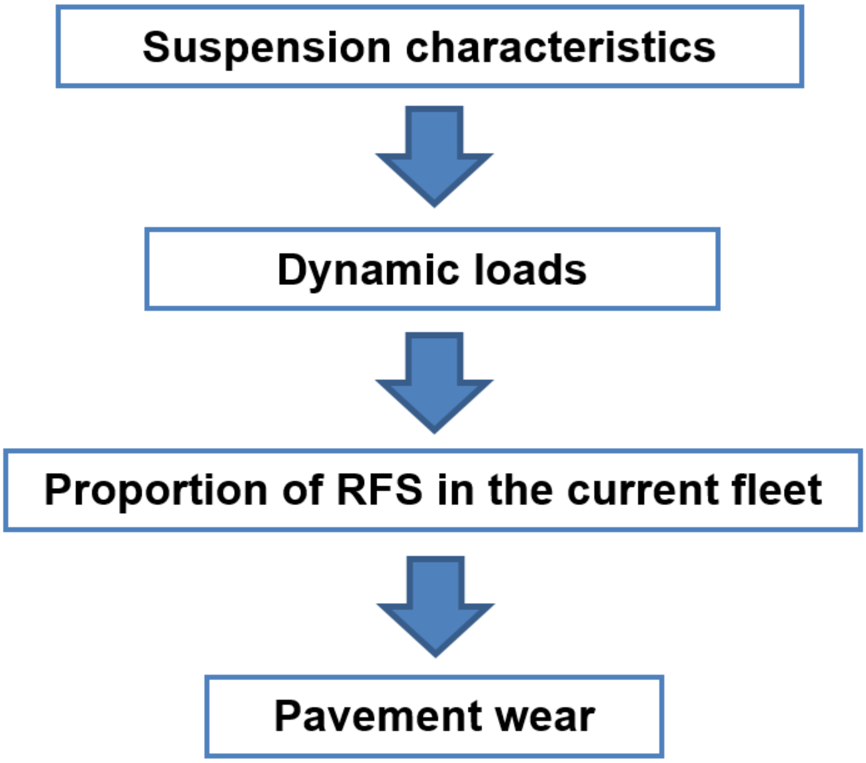
1. identifying a cost-effective approach that doesn't involve removal of components or major interruption to the vehicle
2. knowledge gaps and disagreement on the link between performance characteristics of a suspension, road friendliness and the amount of pavement wear.

These obstacles have prevented development of an in-service RFS compliance standard.

Any subsequent research project must either acknowledge these knowledge gaps addressing them directly or alternatively identify an innovative solution that is not hindered by these obstacles.

The path for understanding the relationship between suspension characteristics and pavement wear is shown in Figure 6.1.

Figure 6.1: Links between suspension and pavement wear



The current project has identified an innovative option of utilising on-board sensors. The use of on-board sensors addresses the first issue by providing a means of measuring suspension performance characteristics.

In order for knowledge gaps identified to be addressed data must be gathered and analysed and compared with data obtained from vehicles compliant with the RFS certification standard.

6.1 List of Engineering Solutions

The following engineering solutions have been identified for further investigation:

- on-board scales (high and low frequency)
- commercially available products for measuring shock absorber performance
- tyre pressure sensors
- Electronic Braking System (EBS) control modules.

Figure 6.2 shows two after-market 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 6.2: After-market on-board scales

Figure 6.3 shows a linear displacement transducer fitted to a vehicle to measure displacement between the chassis and axle. Instrumentation such as the linear transducer requires that the transducer be securely mounted to the chassis and the extension cable fitted to the axle. A sensor similar the one shown here is required to measure axle displacement.

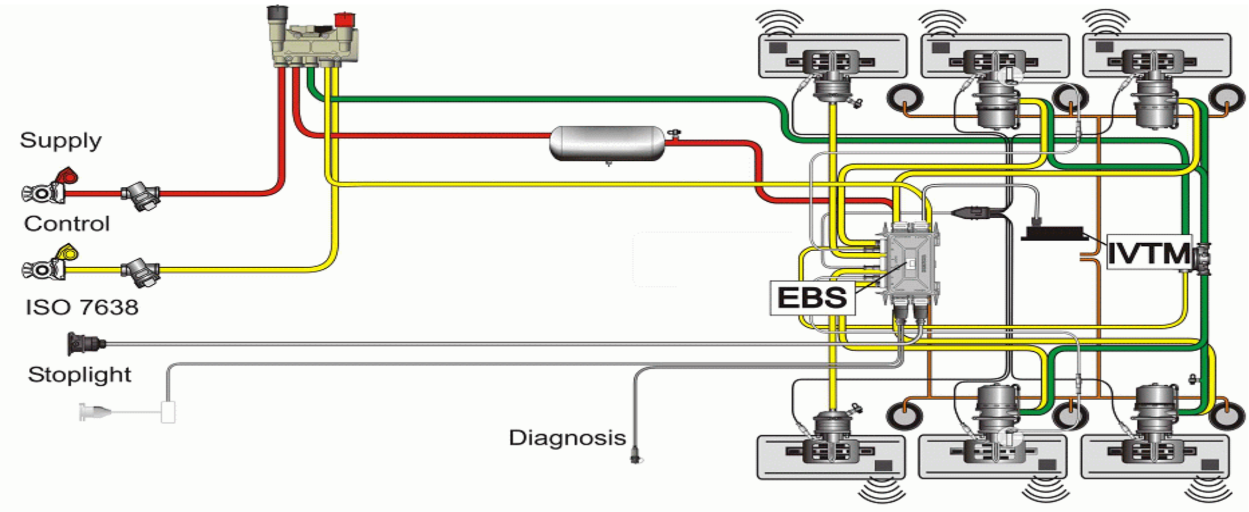
Figure 6.3: Linear displacement transducer fitted to axle

An electronic braking system (EBS) module is shown Figure 6.4. Such technology is common on trucks and prime movers but also is becoming increasingly common on new trailers. This module is the basis for any electronic braking system, can include sensors to record wheel speeds and air bag pressure and can 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 6.4: Electronic Braking System module

A schematic for a tri-axle semi-trailer fitted with an EBS module, ABS braking and air suspension is shown in Figure 6.5.

Figure 6.5: Schematic for a semi-trailer fitted with EBS



6.2 Proof-of-concept work program

A proof-of-concept work program has been proposed as the next stage of this research project with the aim to assess which of the selected the engineering options are viable as a method for monitoring in-service road friendly suspension performance. The work program will require instrumentation and calibration of the subject vehicles. Data will be gathered from the subject vehicles during normal operation. Prior to commencing the in-field tests, each vehicle will be tested as per the requirements of VSB11 at a load or loads representative of normal practice. The data from these tests will be used a reference for comparison with in-service data. The ARRB RFS analyser will be used to perform the VSB11 tests using the approved 'drop test' method. ARRB's RFS analyser is shown in Figure 6.6.

Figure 6.6: ARRB RFS analyser

The ARRB RFS analyser is a portable test rig and can be located for testing by the road side at a suitable inspection area in Queensland. Figure 6.7 show the test rig in use at the heavy vehicle inspection bay at Marulan, NSW.

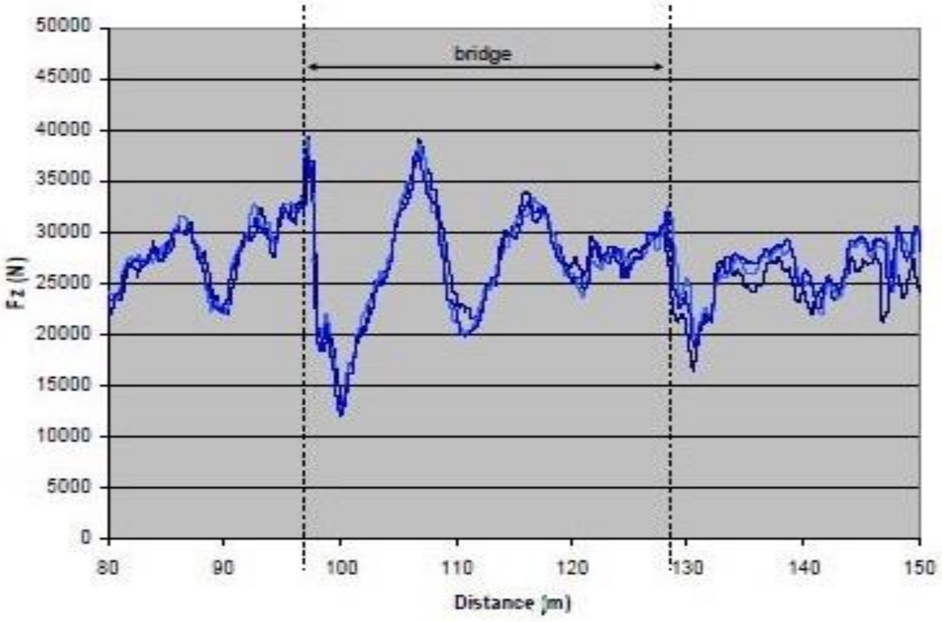
Figure 6.7: RFS testing on site using ARRB RFS analyser

Following the in-field testing a further VSB11 test will be conducted to verify if the performance of the suspension has changed during the testing period.

6.3 Impact on Bridges

It is proposed that the dynamic loading of bridges will be investigated during this project. Test routes can be selected to include bridges of interest. Figure 6.8 shows an example of test data collected during trials (Austroads 2009), in which a semi-trailer traversed a bridge. The location of the bridge is shown beginning at approximately 96 m and ending at 128 m in the figure. The beginning of the bridge imparts an impulse (most likely due to the bridge joint) on the trailer suspension; the subsequent oscillation in dynamic load is clearly evident in the data trace, particularly at 100 m. Strain gauge on-road repeatability.

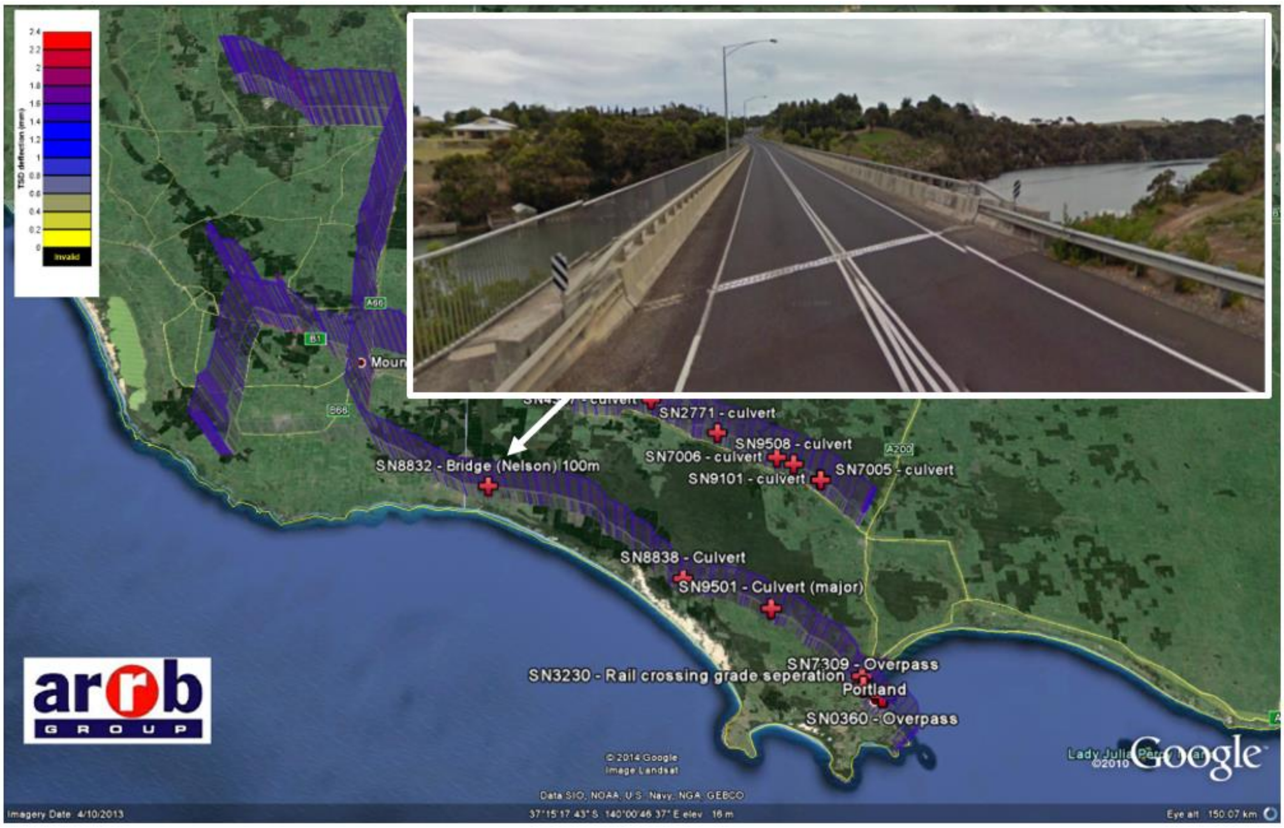
Figure 6.8: Strain gauge on-road repeatability



The oscillations resulting from the impulse imparted on the vehicle from crossing the bridge joint are similar to the oscillations which occur from the impulse in a VSB11 test. An example of this is shown in Figure 4.6, which shows the data trace resulting from the ‘drop’ impulse. Locations similar to the example shown in Figure 6.8 offer the possibility of providing a sufficient impulse to excite all relevant modes of oscillation necessary for analysis. This phenomenon is also an example of spatial repeatability, which is the repeated occurrence of high dynamic loading of the pavement or bridge in the same location. This can lead to increased deterioration of the infrastructure. The increased rate of pavement wear due to spatial repeatability is potentially exacerbated by the concentration of air suspensions with a similar a resonant frequency.

In order to investigate the concept of a spatial repeatability thoroughly and efficiently, it is proposed that the locations of bridges be mapped and then compared with the data recorded at these locations. An example of this process is shown in Figure 6.9. This example uses telematics data which includes GPS co-ordinates and mass data, recorded on the same time domain. The purple extrusions shown on the map in the figure represent the mass recorded from a vehicle fitted with on-board scales. The red markers indicate the location of bridges.

Figure 6.9: Location of bridges and telematics data



6.4 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 aim of the next stage of this project is to utilise technology that is commercially available. This means the use of methods that utilise existing devices and their 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.

7 CONCLUSIONS

ARRB has completed a review of in-service compliance for road friendly suspensions. The review has identified the next steps required to evaluate an in-service test method via a proof-of-concept and field testing program of work. In addition to this ARRB has highlighted limitations and the corrective measures to address and potentially overcome them for the proposed work program.

Limitations and corrective measures

- There are still knowledge gaps in the relationship between RFS systems (in particular varying the suspension characteristics of damping and frequency) and pavement wear. If not addressed these will prevent the development of performance requirements that differ from the existing requirements documented in VSB11.
- Computer modelling of vehicle and pavement interaction has advanced in recent years and offers potential for use in addressing the existing knowledge gaps.
- The inherent variability of performing a physical test (i.e. test weights, vehicle condition, temperature, etc) reduces the accuracy and repeatability of both the certification and the in-service test method and may result in a different performance requirement for each.
- Applying an acceptable tolerance to the in-service performance requirements can overcome the limitations of performing an accurate and repeatable test.
- Computer modelling of suspension performance can be used to understand and minimise the effect of external influences and variations in test conditions.
- Previously conducted cost benefit analyses indicate that vehicle tests, both those performed at the roadside and those requiring component testing in a workshop, are not viable options.
- Suspension performance can be measured by a variety of tests that utilise existing on-board technology or require minimal instrumentation during an inspection.

Basis for further work

- The concept of road-friendly suspensions and the understanding that they are less damaging to pavements is well founded. The key performance characteristics that define road-friendliness are damping ratio and frequency.
- Developments in on-board mass monitoring technology, vehicle telematics and the increased sophistication of heavy vehicle braking systems provide options for cost effectively monitoring suspension performance of a number of vehicles during their normal operation.
- Gathering data from on-board sensors will provide insight into the operation of suspensions as well as the capability of the sensors to adequately monitor suspension performance.
- The key requirements for developing an in-service compliance standard have been identified and the potential for a cost effective solution through the use of new technology and on-board sensors warrants further investigation as a viable measurement method.
- The recommended next step in this program of work is a proof of concept stage to evaluate a method to gather the necessary data within an acceptable accuracy (proximity to true value) and precision (repeatability). It is proposed that this be followed by a field testing program involving deployment on a range of heavy vehicles selected from an operational fleet. Field testing should provide additional learnings of a practical nature.

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