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Dynamic Load Effects of Heavy Vehicles on Pavement Performance – Stage 1

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Dynamic Load Effects of Heavy Vehicles on Pavement Performance – Stage 1

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for Main Roads Western Australia

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DYNAMIC LOAD EFFECTS OF HEAVY VEHICLES ON PAVEMENT PERFORMANCE – STAGE 1

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SUMMARY

Dynamic loading is the constantly varying load of a vehicle due to internal and external factors while moving along a road. Consideration of the dynamic effect of heavy vehicles on pavement performance is a complex issue. This report presents the literature review conducted to investigate the many factors involved, including:

- variations in the load magnitude imparted on the pavement, which varies with:
  - road geometry
  - pavement roughness
  - heavy vehicle properties (axle and tyre types, tyre pressure, suspension etc.)
  - traffic movement (straight traffic, turning, accelerating or braking)
  - traffic speed
- the effect of dynamic load magnitudes on the pavement
- accumulation of pore water pressure
- the viscoelastic behaviour of bituminous materials
- principal stress rotation
- surface damage due to horizontal shear stresses
- tyre contact area and pressure.

Several studies have been conducted to understand the increase in load magnitude that is imparted to the pavement due to dynamic effects. The literature review highlighted that there are still knowledge gaps in understanding the effect that heavy vehicle suspension characteristics and dynamic wheel loads have on pavement wear.

This report concludes with a list of ideas for further studies to allow better understanding of the relationship between suspension characteristics and dynamic loading, the relationship between suspension frequency and damping, and the resulting dynamic loading applied to the pavement.

However, accepted pavement design procedures are calibrated for the current assumptions made in the design. For example, the Austroads design procedure makes use of empirical charts and laboratory to field shift factors that correlate assumed static load calculations with observations in the field.

Any changes to the design methodology, including those related to the consideration of dynamic loading effects on pavement responses and performance, would need to be validated by observed performance in the field.

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1 INTRODUCTION

1.1 Background – General

Many countries have developed sophisticated means of designing, monitoring, maintaining and managing pavements, supported by the availability of improved data on heavy vehicle traffic and axle loads generated by increased use of weigh-in-motion (WIM) systems. The adoption of mechanistic procedures for the design of pavements, and the increasing use of Pavement Management Systems (PMS), has resulted in a strong focus being placed on pavement response to load, design life, maintenance intervention strategies and the strong influence of heavy vehicle loadings on the initial calculated life and remaining life of pavements (Organisation for Economic Co-operation and Development (OECD) 1998).

Similarly, bridge design methods are based upon the number and magnitude of heavy vehicle loads. Size and weight limits in all countries contain important requirements for controlling the gross weight of heavy vehicles and the manner in which this load is distributed over the vehicle's axles (OECD 1998).

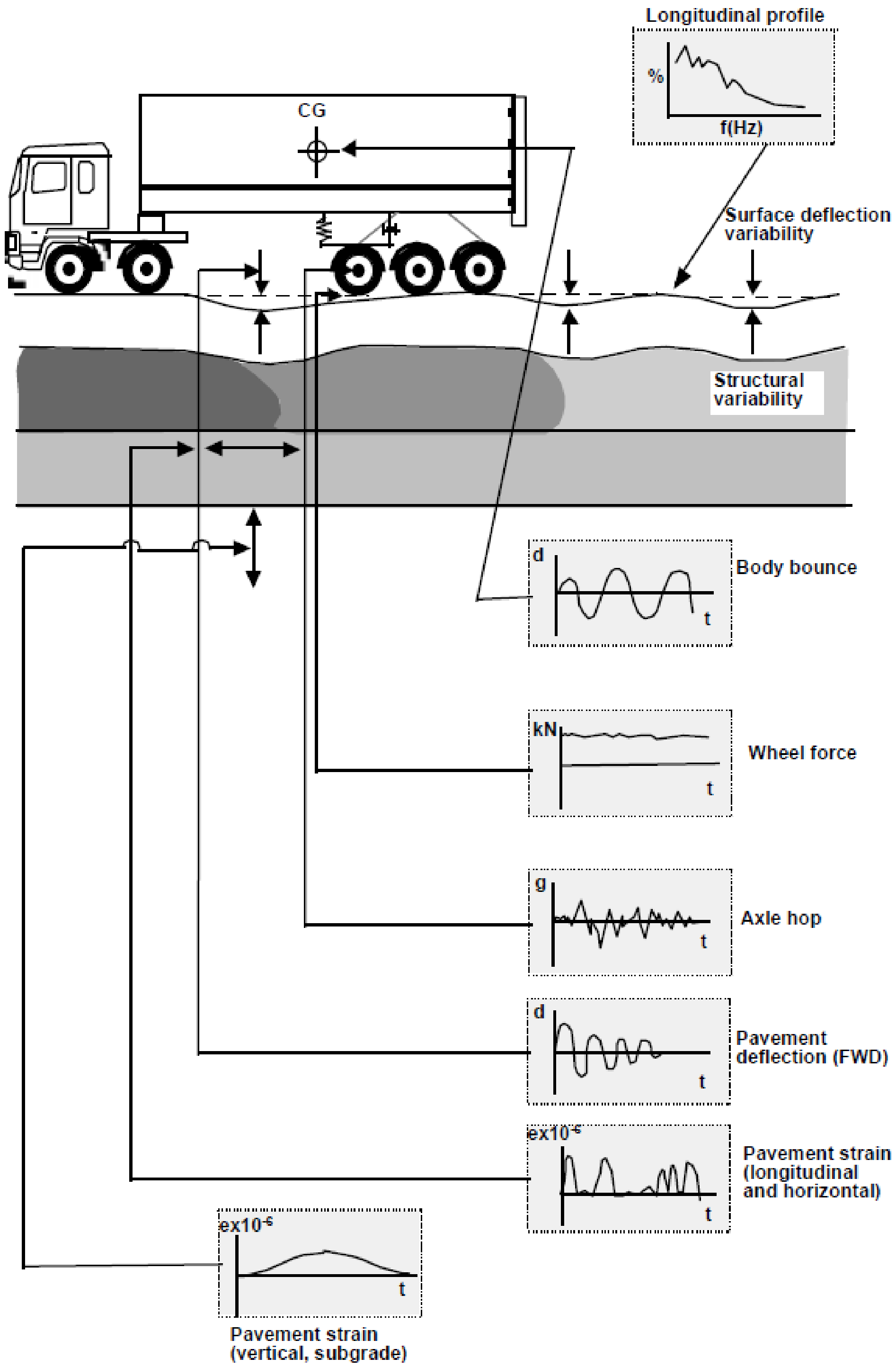
However, these activities are based on simple models of vehicles, pavements and bridges, and do not provide adequately for the interactive nature of the infrastructure-vehicle system (OECD 1998). The effect of dynamic loading, where a vehicle's load constantly varies due to internal (vehicular) and external (road roughness) inputs, is not incorporated in the design philosophy (Steyn 2001).

The current Austroads flexible pavement design method (Austroads 2017d) does not explicitly consider dynamic load effects. The design method is based on traffic data from WIM sites, which are usually collected in smooth profiles, representative of newly constructed pavements. Therefore, consideration of dynamic load effects with length of pavement, or elapsed time, is not considered by the current Austroads design method. Dynamic effects are only considered indirectly through the laboratory-to-field shift and reliability factors and by adjusting asphalt modulus as a function of traffic speed.

Figure 1.1 illustrates the interacting components and key performance characteristics of the vehicle-pavement system in which a truck travels over a flexible pavement with certain characteristics of surface roughness and structural strength. A full physical description of all the relationships involved is challenging due to the complexity of the dynamic systems involved and the fact that some behaviour is spatially related, some is time-related, and some is cumulative with regard to repeated passes of the vehicle (OECD 1998).

In simple terms, the pavement roughness initiates the vertical dynamics of the moving vehicle and the resulting dynamic wheel loads cause pavement responses which contribute to pavement distress. The pavement responses depend on the combination of dynamic wheel load, speed and local pavement strength. This relationship is compounded by the depth at which the pavement response is measured and the influence of the tyre contact patch in distributing the dynamic wheel load to the pavement structure. Over time and with repeated loading by heavy vehicles, the profile changes due to vertical surface deformations, which are partly influenced by the accumulation of pavement rutting. In turn these profile alterations then change the dynamic wheel loads. Also, over time, the pavement structural strength changes due to the accumulated effects of pavement responses as well as environmental influences. The net effect on pavement response and distress will depend on the spatial relationship between dynamic wheel load, pavement profile change and pavement structural strength variations (OECD 1998).

Figure 1.1: Vehicle-pavement system



Source: OECD (1998).

1.2 Background – Western Australia

The design methodology for flexible pavements in WA takes into consideration the effects of currently permitted axle loads on pavement performance. The loads are considered to be static. The only consideration of dynamic effects in the current pavement design methodology is expressed indirectly when defining the modulus of asphalt layers based on design vehicle speed. The current models do not consider the effect that closely spaced axles travelling at a certain speed have in conjunction with pavement material viscosity and the dissipation of pore water pressures.

The trend in heavy vehicle axle configurations and loads is leading to more closely spaced axles and increasing axle loads. The maximum permitted individual axle load in WA is 6 tonnes for steering axles and 9 tonnes for other axles (based on a single axle dual tyre). In Europe, the permissible maximum axle loads can be up to 13 tonnes. Discussions with Main Roads indicate that heavy vehicle operators are seeking permission to operate with more closely spaced and heavier axles. A standard methodology to assess the impact of dynamic axle loads on long-term pavement performance does not currently exist.

The mechanism of pavement deterioration when an axle loads the pavement prior to it being able to completely recover from the stresses and strains induced by the previous axle on granular and bound materials are not fully understood. In addition, there is limited understanding of the effect of surface shearing forces, wheel bouncing and uneven pavements on pavement performance.

The distribution of loads in an axle group can be extremely irregular between axles of a double, tri- or quad-axle. Depending on the road geometry and pavement roughness, there are occasions where not all the tyres within the axle group are in contact with the pavement. When this happens, all the load is concentrated on a reduced number of tyres, which does not represent the load configuration that was assumed in the pavement thickness design.

1.3 Objectives

A brief literature review indicates that there are a number of studies aimed at identifying the loads that are imparted to the pavement by the dynamic effects of heavy vehicle axles. A correlation between dynamic loads and International Roughness Index (IRI) has been explored.

However, there is limited information on how dynamic loads combined with the viscoelastic nature of pavement materials translate to stresses and strains in the pavement and how shorter recovery periods affect the damage caused by these strains.

The objective of the project is to assist Main Roads in understanding how new axle configurations and loads translate into damage to the pavement so that Main Roads can have a consistent and informed approach for assessing requests from heavy vehicle operators to operate with more closely spaced and heavier axles.

1.4 Scope

The scope of this study includes the following:

1. Literature review aimed at understanding the current state of knowledge on the following topics related to the effect of heavy vehicle dynamic loads on pavement performance:
   (a) existing information on performance changes when loaded by closely spaced axles
   (b) the effect of road geometry and pavement unevenness leading to uneven distribution of load magnitudes within an axle group and wheel bouncing
   (c) the effect of non-traditional tyre configuration loads on pavements
   (d) the effect of surface shearing forces caused by heavy vehicle turning movements on pavements.

2. Preparation of a draft report with the findings of the literature review and recommendations for further studies.
3. Workshop with ARRB's and Main Roads WA's pavement and heavy vehicle teams to disseminate the findings of the literature review and agree on a scope of work for further studies.
4. Preparation of a final report and, if agreed, proposal for a subsequent stage of this study.

1.5 Report Structure

This report comprises a literature review from a combined pavement and vehicle engineering viewpoint. Section 1 describes the purpose of the study. Section 2 and Section 3 examine heavy vehicle dynamic loading from a heavy vehicle perspective, as relevant to pavement engineering. Subsequent sections examine heavy vehicle dynamic loading from a pavement response, damage and modelling perspective. Section 4 presents the response to moving loads. Section 5 discusses the effects of horizontal shear stresses on pavement surfacing. Section 6 includes a discussion on tyre contact area and pressure. A summary of the findings is presented in Section 7. Finally, suggestions for further studies are included in Section 8.

2 HEAVY VEHICLE DYNAMIC LOADS

This section of the report presents the outcomes of the literature review specific to dynamic loading generated by heavy vehicles.

2.1 Dynamic Interaction Between the Vehicle and Infrastructure Experiment (DIVINE)

The DIVINE project (Dynamic Interaction between the Vehicle and Infrastructure Experiment) (OECD 1997) is regarded as the most comprehensive study of heavy vehicle dynamic loading. The findings from this research was the genesis of road-friendly suspension (RFS) requirements and the subsequent introduction of the higher mass limits (HML) for heavy vehicles in Australia.

A summary of the key technical findings from the DIVINE project has been included as part of this review. The DIVINE projects' research elements included:

- accelerated dynamic pavement testing
- pavement primary response testing
- road simulator testing
- computer simulation of heavy vehicle dynamics
- evaluation of spatial repeatability of dynamic loads
- bridge dynamic loads.

2.1.1 Research Findings

In terms of pavement loading, the key findings of the DIVINE research were as follows:

- The dynamic component depends on the vertical dynamics of the vehicle – including such factors as the mass and stiffness distribution of the vehicle's structure, payload mass distribution, suspension and tyres – and on the road surface's longitudinal profile and the speed of the vehicle.
- Typical magnitudes of dynamic wheel loads, when expressed statistically as a standard deviation, ranged between 5 and 10% of the static load for well-damped air suspensions and for soft, well-damped, steel leaf suspensions. They ranged between 20 and 40% of the stationary constant load for less road-friendly suspensions.
- Using conventional pavement wear and fatigue relationships, the results suggested that dynamic loading introduces a 30 to 50% increase in damage as compared with that for static loading.
- For rough roads, dynamic loads can be substantially higher.
- There was a direct and proportional relationship between primary pavement response and the instantaneously applied load for bituminous pavements approximately 150 mm thick (not common in Australia).
- For pavements thinner than 80 mm (typical sprayed seal surfaces common in Australia (sprayed sealed pavements were not considered in the project)) the relationship was not as clear. The lack of test results for Australia cast some doubt on the true benefits of RFS; however, the general concept that RFS reduces dynamic loading of pavements is well accepted by road managers.

- The use of an air suspension, particularly on the class of vehicle responsible for the greater part of pavement damage (often the 5-axle semi-trailer), could reduce dynamic loads by 10 to 12% and therefore lead to significantly reduced pavement damage. This finding substantiates the increases permitted under HML.

In terms of bridge loading, the key findings of the DIVINE research were as follows:

- In the case of a smooth bridge and approach profile on medium-span bridges, the influence of the vehicle suspension on dynamic wheel load and bridge response magnitudes was not very significant.
- For these test conditions, neither the mechanically- nor the air-suspended vehicles induced significant dynamic responses in the bridges.
- Heavy vehicles fitted with air suspension did not generate excessive vibrations on bridges (with smooth pavements) and impart loads at low body bounce frequencies (f = 1.5 to 1.8 Hz). Most air suspensions fitted to heavy vehicles oscillate at this frequency, which supports the theory that RFS reduce dynamic loads applied to pavements and bridges.
- At axle hop frequencies (f = 10 Hz), excessive bridge vibrations can be expected with both mechanically- and air-suspended vehicles operating on bridges with average to rough pavement conditions. The situation is especially severe if the shock absorbers on an air-suspended vehicle are ineffective.
- Air suspensions with inadequate damping are potentially damaging to short-span bridges. When air-suspended vehicles travelled at critical speeds over axle-hop-inducing features, large dynamic responses and multiple fatigue cycles were observed. These responses were up to 4.5 times the dynamic load allowance specified in bridge design, but only if the bridge has a natural frequency corresponding to the body bounce frequency or if it has a short-span (natural frequency corresponding to axle-hop) and exhibits short wavelength roughness. The quality of the road profile is an important parameter in determining the dynamic bridge response.
- The effective damping of soft suspensions is essential. Further understanding of the effectiveness of dampers fitted to both new and used air-suspensions is required. This finding highlights the need for an in-service performance requirement.

2.1.2 Key Recommendations of DIVINE

Demands for the transport of more goods, by both weight and volume, and for greater responsiveness to customer needs, result in the consideration of larger and heavier trucks, as well as increased efficiency and diversity of truck configurations (OECD 1997). The recommended policy options included:

- increase the gross combination mass (GCM) of road-friendly vehicles; this can be done by adding axles rather than increasing individual axle weights (e.g. increased use of triaxle groups in place of tandem groups)
- an increase in axle group weights on proven road-friendly tandem and triaxle groups
- implementing a sound means for measuring and assessing the road-friendliness of heavy vehicle suspensions (including the dynamic and load-sharing performance of suspensions).

2.2 Australian Policy

The DIVINE project team consisted of experts from 17 countries, including Canada, France, Germany, New Zealand and Australia. Australia had a leading role in the DIVINE study, with ARRB conducting the research for one of the project elements. The ARRB researchers were led by

Dr Peter Sweatman and supported by others such as Kieran Sharp, Geoff Jameson and Dr Michael Moffatt.

The Australian research included in DIVINE, confirmed the following key findings:

- 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 (Coulomb) friction in (mechanical) suspension systems increased dynamic loads (National Road Transport Commission (NRTC) 1996).
- Dynamic load reducing properties were unlikely to be found in mechanical suspensions but were generally found in air suspensions (Sharp, Sweatman & Addis 1997). This led to the introduction of an RFS test method based on achieving performance equivalent to air suspension.
- There would be little effect on the rehabilitation cost of arterial and local roads with an increase in mass limits and the use of RFS, compared with a continuation of the absence of any concessions to encourage RFS (NRTC 1996). This was concluded after much research was devoted to estimating the overall effects of increasing mass limits and allowing RFS, including cost-benefit studies. A procedure for estimating loading changes due to the introduction of HML for RFS is presented in NRTC (1996).

This work ultimately led to the development of the Vehicle Standards Bulletin 11 (VSB11) first published in 1999, later amended in 2004 (Department of Transport and Regional Services 2004), in which the certification requirements for road-friendliness were defined.

2.2.1 Development of a Performance Standard for RFS

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 (NRTC 1996).

The defined performance criteria are:

- static load sharing between axles in a group (≤ 5% variation between any two axles)
- frequency of oscillation of sprung mass (≤ 2.0 Hz)
- damping capability (≥ 20% of critical damping)
- damping capability (≤ 50% of total damping due to friction damping).

Despite the understanding that the performance of a suspension degrades over time, mainly due to shock absorber wear, there was no in-service compliance as part of the of RFS standard.

2.2.2 Introduction of Higher Mass Limits (HML)

The maximum load a heavy vehicle can carry is limited and enforced by the state road agencies. Mass limits are based on an economic evaluation of the asset wear resulting from axle loads. In 1998, the 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 HML scheme was adopted by most state and territory agencies. 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 specify that the vehicle must be fitted with a certified RFS system. The inclusion of RFS as an operational requirement of HML is based on the understanding that RFS allows a greater mass to be carried for a similar overall effect on infrastructure.

2.3 Recommendations for Improvement of Australian Policy

2.3.1 The Importance of In-service Suspension Maintenance

Cebon (2004) quantified the effect of worn air suspensions on road damage through road maintenance costs by analysing six theoretical fleets, with combinations of steel and air suspensions and well- and poorly-maintained suspension systems. The results of this analysis are presented in Table 2.1, which express the road damage caused based on suspension typed in terms of pavement maintenance costs.

Table 2.1: Calculation of relative road damage based on suspension type and maintenance

Suspension	Fleet composition scenarios					
	1	2	3	4	5	6
Conventional steel leaf springs	100%	0%	0%	0%	0%	0%
Air springs with well-maintained shock absorbers	0%	100%	0%	75%	50%	25%
Air springs with poorly-maintained shock absorbers	0%	0%	100%	25%	50%	75%
Pavement maintenance cost charge						
General Mass Limits (GML)	0%	–14%	7%	0%	–3%	2%
Higher Mass Limits (HML)	10%	–6%	19%	0%	6%	12%

Source: Based on Cebon (2004).

The results show that fleet scenario 4, in which 75% of the HML fleet is well maintained, is equivalent to GML with the entire fleet operating on conventional steel leaf springs. A greater than 25% proportion of poorly-maintained suspension increases maintenance costs above the base scenario. This result supports the importance of maintaining suspension performance to maintain the benefits of RFS.

Blanksby, George and Germanchev (2006) presented results from a survey of 150 in-service triaxle trailers, including 121 units with air suspensions and 29 units with mechanical suspensions. The survey included an inspection of the vehicle and an assessment of suspension damping and frequency characteristics using an RFS test facility temporarily located at the Marulan heavy vehicle inspection site in New South Wales.

Table 2.2 summarises the suspensions surveyed, separated into columns for the 121 air suspensions and 29 mechanical suspensions. It is important to note that only 26 of the air suspensions surveyed were loaded to greater than 20 tonne and, therefore, within the test weight tolerance requirement for vehicles (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 to 20% or greater than 20%. The suspensions with a damping ratio greater than 20% are listed as compliant; however, they must also meet the load sharing and frequency requirements of VSB11 to be RFS compliant. 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.

Table 2.2: Summary of RFS survey results

Type	Air suspension	Mechanical	Total
Total units	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% and 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.

Source: Based on Blanksby, George and Germanchev (2006).

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 Pty Ltd (2000) conducted an extensive review of several 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 Starrs (2000) 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.

Costanzi and Cebon (2007) 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 by 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 to 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, Kel and Sack 2007, Davis & Sack 2004, Davis & Sack 2006).

2.3.2 Investigation of In-service Compliance for 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 an 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 titled '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 (NTC 2008).

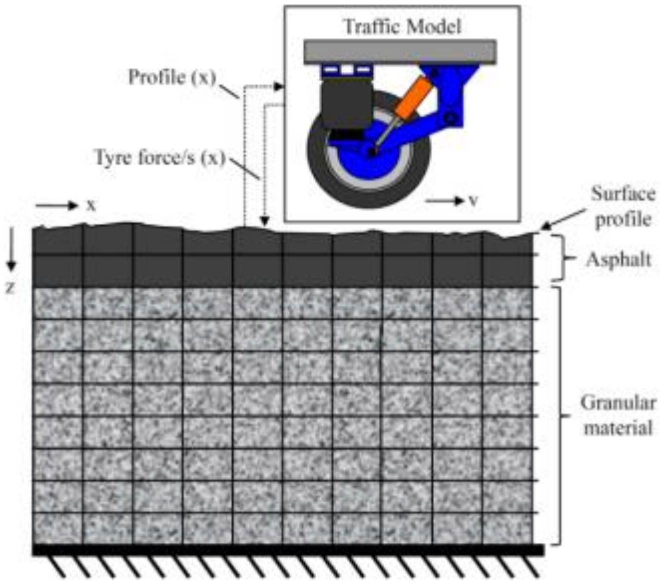
The costs and benefits of the tests were estimated. It was concluded that the costs exceeded the benefits under a range of assumptions and that in-service compliance options therefore could not be justified on economic grounds. Consequently, there is currently no in-service test for RFS. Instead, visual 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.

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 of the previous work documented in Davis (2005). Davis (2005) explored the viability of measuring suspension performance using two different and independent methods referred to as a 'pipe test' and a 'white-noise-road-test'. In his most recent work, Davis focuses on developing a method based on driving a vehicle on a section of (rough) road in preference to the 'pipe test' method. Tests were undertaken using an instrumented triaxle semi-trailer to determine the forces exerted on pavements by this vehicle. Accelerometers and strain gauges were fitted to the axles of the vehicle and used to determine dynamic wheel forces. A roughness value of the roads during testing was derived. Dynamic pavement forces were presented according to the range of roughness values encountered during testing along the test section of road. The report states that the mean and standard deviation of heavy vehicle wheel forces did not correlate with pavement roughness, however peak wheel forces did. Davis (2010) reports promising results; however, the concept of using a test road for comparison of suspension performance between different vehicles needs to be explored further 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; the concept is shown in Figure 2.1. This software tool provides a simulation environment that can be used to investigate several issues relating to vehicle-pavement interaction, including the effect of suspension characteristics on the loading of the pavement.

Figure 2.1: Interaction between truck model and road profile



Source: Roebuck et al. (2012).

A case study was presented by Roebuck et al. (2012) showing comparison between steel-, air- and defective air-suspension, under Higher Mass Limits (HML) and General Mass Limits (GML). The model was calibrated to Australian (New South Wales) conditions. The design pavement structure was a 300 mm thick 'full-depth' asphalt layer over a 200 mm granular base layer. Four different vehicle fleets, consisting of 6-axle tractor-semi-trailers and 9-axle B-doubles, were simulated. The progression of the International Roughness Index (IRI) with time was simulated up to a limit of 3.7 m/km. The case study showed 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.

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

Austroads (2012) investigated the use of strain gauges with accelerometers, which was initially only intended as a reference system for the laser-based method, 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 technique 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.

The most recent work completed on this topic was a review of the in-service requirements for RFS. This was commissioned under the National Asset Centre of Excellence (NACoE) research agreement between the Queensland Department of Transport and Main Roads (TMR) and ARRB (Germanchev 2015, Germanchev et al. 2016). A primary focus of this work was to identify and evaluate emerging technologies with the potential to measure and quantify suspension road-friendliness. The findings relating to emerging technologies is summarised in Section 2.5. The most recent studies confirmed that the variability of external factors (particularly road surface geometry and roughness) prevented air bag pressure from being a viable option for monitoring suspension road-friendliness.

The key findings were:

- Knowledge gaps exist in the relationship between RFS systems and pavement wear. In particular, the relationship between varying suspension characteristics and the loading of pavements is not adequately quantified to develop a new standard that differs from the existing RFS requirements (air suspension equivalency) documented in VSB11.
- Due to the openness for interpretation in the test methods documented in VSB11, it is possible for identical suspensions to achieve vastly different results when tested.
- A review of VSB11 is recommended as a necessary step prior to implementing an in-service requirement.

2.4 Recent Heavy Vehicles Research

The Austroads 2016–17 research program included four projects related to heavy vehicle loads and axle limits; these are:

1. AP-R541-17 – *Reassessment of the Benefits and Impacts of the Use of High Productivity Vehicles on Australian Highway Pavements*
2. AP-R555-17 – *Development of National Mass Assessment Procedures for Oversize Overmass* (OSOM) *Vehicles*
3. AP-R505-16 – *National Steer Axle Mass Limits*
4. AP-R325-17 – *Heavy Vehicle Horizontal Stresses and Pavement Surface Performance*.

2.4.1 Pavement Impacts of High Productivity Vehicles

Austroads commissioned a reassessment of the benefits and impacts of high productivity vehicles (HPV). This study focused on HPVs that are assessed under the Australian Performance-Based Standards (PBS) scheme, which was formalised in 2007. The project outcome was a proposed method for comparing the relative pavement impacts of HPVs with those of reference vehicles that might be used to accomplish the same freight movement task. To this end, the project arrived at a process which takes into account the potential benefits or costs of HPVs in terms of its productivity, safety, environmental and pavement effects. The proposed method for quantifying vertical pavement loading was to address the absence of a performance-based requirement for pavement vertical loading in the current PBS rules.

Three options for quantifying pavement impacts were proposed by Austroads (2017b), each of which is based on the marginal cost principles supported by Austroads for the determination of the cost of road wear. The three options proposed were:

1. A relative comparison of case-by-case subject vehicles against either prescriptive or HPV alternatives using the Freight Axle Mass Limits Investigation Tool (FAMLIT).
2. An approach based on the Western Australia Local Government Association’s (WALGA) User Guide (WALGA 2015).
3. A Table of Values approach as adopted by TMR to assess the transport impacts. The application includes both long-term changes in loading, including the introduction of HPVs, and the impacts of significant, additional short- to medium-term loading.

The above options are all based on existing equivalent standard axles (ESA) calculations to determine the wear caused by the axle group, relative to the wear caused by a standard axle.

In Australia, the predominant method used between 2004 and 2017 to evaluate traffic-induced pavement wear was through the number of standard axle repetitions (SARs) calculated by treating each axle group separately. This method uses a load damage exponent (LDE), which is based on the type of pavement being trafficked.

Austroads (2017b) only considered sealed unbound granular pavements for the analysis as a large proportion of Australian highway pavements consist of a thin bituminous sprayed seal over an unbound granular base; therefore, the LDE used was the 4^{th} power.

The scope of the project was to review the input data requirements and propose a method for quantifying the vertical loading impacts of heavy vehicles. It was identified that there are many vehicle characteristics that are known to affect pavement vertical loading, but for varying reasons the scale of the impact has not been fully understood. The areas in which knowledge gaps exist are: road-friendly suspensions, dynamic loading, tyre size and inflation pressures, and horizontal tyre forces. Investigating these topics was not within the scope of the project. Austroads (2017b) did not investigate them in any detail but highlighted the requirement for future work in these areas that would address the limitations of the proposed method. These knowledge gaps were identified as longstanding issues known at the formation of the PBS rules in 2007 and were cited as to the reason why the infrastructure standards were established at prescriptive standards, with no performance requirements inclusive of these topics.

As a consequence, the project highlighted the opportunity to gain a clear understanding of pavement vertical loading and to develop a model that estimates deterioration based on vehicle characteristics.

2.4.2 Development of National Mass Assessment Procedures for OSOM Vehicles

Austroads (2017c) conducted a field testing program to measure the axle group loads of a range of oversize overmass (OSOM) vehicles. The aim of the project was to develop a nationally-consistent procedure for weighing OSOM vehicles. The vehicle combinations included low loaders and platform trailers designed for transporting large, indivisible loads. The field trials involved the static weighing of vehicles using portable scales and weighbridges at a range of sites with varying road geometry. The purpose of the study was to determine the measuring tolerance for these vehicle types and subsequently recommend mass measurement adjustment values to include in a weight procedure. The project did not investigate the dynamic loading of these vehicles; all tests related to the static mass only. The testing program was designed to investigate the load transfer between axles and axle groups on uneven surfaces and on and off scales and to quantify the amount of measurement error associated with each scenario.

The vehicle combinations used in the field tests were:

- a 2x4 dolly and a 4x4 low loader with mechanical load-sharing suspension,
- a 2x4 dolly with mechanical suspension and a 4x4 low loader with hydraulic load-sharing suspension,
- a 2x8 dolly with no suspension, a 4x8 low loader with hydraulic load-sharing suspension, and
- 6x8 load platform with hydraulic load-sharing suspension.

The weighing methods covered a range of combinations using blocks and portable scales, including:

- fully blocked – scales under some axles, blocks of scale height under all other wheels of all vehicle units;
- partially-blocked – scales under some axles, scales or blocks of scale height under other wheels of the same vehicle unit, wheels of other vehicle units on the ground; and
- unblocked – scales under some axles, other wheels on the ground.

The aim of these tests was to understand the effect of suspensions being raised and lowered as they were driven on to the scales for measurement. This assessment was only made in static conditions. A total of 852 vehicle movements were performed, facilitating 6624 measurements. The results of the testing were used to develop mass measurement adjustment values.

The mass measurement adjustment values ranged from 0.3 t to 1.3 t depending on the site and axle type. The largest adjustment value to account for errors for a single axle on a trailer in the worst-case measurement site was 4.5%. This variation in static mass does not provide any useful insight regarding dynamic loads other than the peak dynamic variations are expected to be considerably higher.

2.4.3 Investigation of Optimum National Steer Axle Mass Limits

Austroads (2016) determined the optimum steer axle mass limits for road trains operating in remote and regional areas. The motivation for this research was to accommodate the needs of the transport industry, particularly in response to the increase in steer axle loads for prime movers delivering freight long distances in remote areas. The reason being that this particular freight task requires prime movers to be fitted with additional equipment including heavy-duty bullbar, tool boxes, additional spare-wheel carriers and higher capacity fuel tanks which increase the load on steer axle.

The major task to be undertaken was to use a detailed load wear cost (LWC) model to determine the pavement maintenance costs associated with increased steer axle limits.

The analysis was conducted based on a selection of sealed unbound granular pavement segments (6 in WA, 6 in NT, 6 in NSW, 4 in QLD and 3 in VIC). A total of 30 loading scenarios were conducted for the 25 road segments. Sealed unbound granular pavements were analysed, as they constitute the roads that road trains predominantly use and make up the majority of sealed roads in Australia. Across all road segments analysed, it was found that the rate of deterioration that a pavement experienced was sensitive to the width of the tyres used by the heavy vehicles. This occurs due to differences in tyre contact profile shape and stress distribution, and because of these factor, wider tyres were less damaging to the pavements analysed. This means that the wider tyres supported heavier steer loads in the tests conducted before matching the deformation caused by lighter steer loads on narrow tyres. There was consideration of dynamic wheel loads as part of this research.

2.4.4 Quad Axle Groups and Wide Tyres

The axle loads for a range of axle group types and tyre widths normalised against a standard load are shown in Table 2.3 and Table 2.4. ARRB considers that further research is required to better understand the impacts of these tyre sizes prior to the development of a policy for quad-axle groups and wide tyres.

Table 2.3: Loads on axle groups with single tyres which cause the same wear as a standard axle

Axle group type	Nominal tyre section width	Load (kN)	Load (t)[(1)]
Single axle with single tyres (SAST)	Less than 375 mm	53	5.41
	At least 375 mm but less than 450 mm	58	5.92
	450 mm or more	71	7.24
Tandem axle with single tyres (TAST)	Less than 375 mm	89	9.08
	At least 375 mm but less than 450 mm	98	10.00
	450 mm or more	119	12.14
Tri-axle with single tyres (TRST)	Less than 375 mm	121	12.34
	At least 375 mm but less than 450 mm	132	13.46
	450 mm or more	162	16.52

1 Conversion factor 1 t = 9.807 kN

Source: Austroads (2017d).

Table 2.4: Loads on axle groups with dual tyres which cause same wear as a standard axle

Axle group type	Load (kN)	Load (t)[(1)]
Single axle with dual tyres (SADT)	80	8.16
Tandem axle with dual tyres (TADT)	135	13.77
Tri-axle with dual tyres (TRDT)	182	18.56
Quad-axle with dual tyres (QADT)	226	23.05

1 Conversion factor 1 t = 9.807 kN

Source: Austroads (2017d).

The current axle group mass limits for HML are listed in Table 2.5.

Table 2.5: Current HML by axle groups

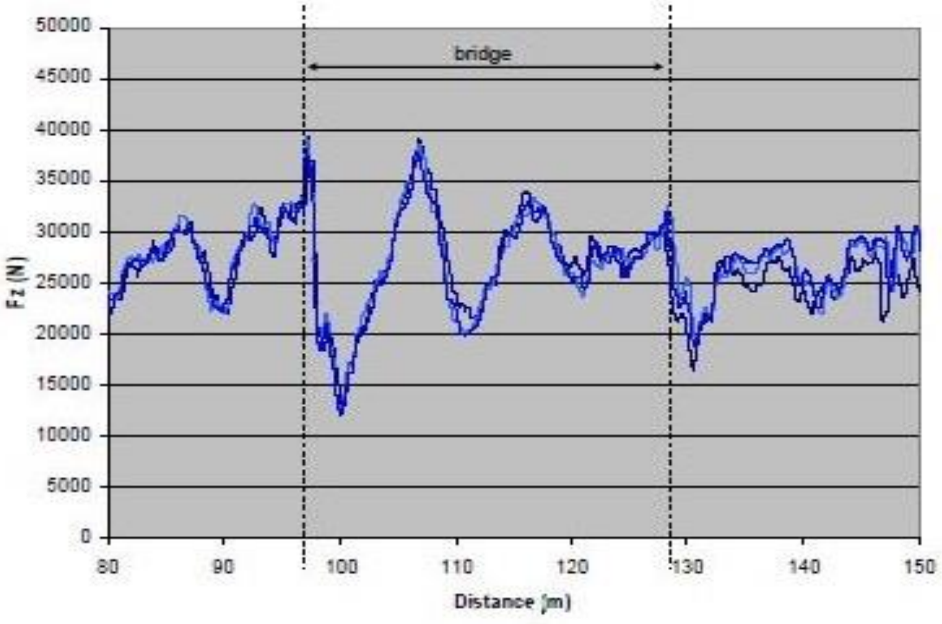
Axle groups	HML (tonne)
Single drive axle on a bus (dual tyres)	10.0
Tandem axle group (dual tyres)	17.0
Tandem axle group (with six tyres)	14.0
Triaxle group (dual tyres)	22.5

Currently, there is no national provision for HML to be applied to quad-axle groups or wide tyres. Presumably this is because these axle groups and tyres widths were not included in the original research and a relationship between the reduction in pavement and these axle and tyre configurations has not been established. Research, most likely including field testing, is required prior to the development of a policy for quad-axle groups and wide tyres.

2.4.5 Impact on Bridges and Spatial Repeatability

Dynamic loading of bridges was briefly investigated by Austroads (2009a). During field trials, test routes were selected to include bridges of interest. Figure 2.2 shows an example of test data collected during trials 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.

Figure 2.2: Strain gauge on-road repeatability crossing a bridge joint



Source: Austroads (2009a).

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. 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 resonant frequency.

No further analysis was conducted (Austroads 2009a). In order to investigate the concept of a spatial repeatability thoroughly and efficiently, it has been 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 2.3. This example used telematics data which included 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 2.3: Location of bridges and telematics data

Source: Germanchev and Roper (2017).

The spatial repeatability demonstrated using strain gauges was investigated by testing conducted under the NACoE research program (Germanchev & Roper 2017). On-road testing was conducted on the section of road shown in Figure 2.4.

Figure 2.4: Map showing bridge location for on-road testing

Source: Germanchev and Roper (2017).

The vehicle was fitted with a GPS receiver to record speed and location and an on-board mass monitoring to record dynamic axle group loads. The vehicle was driven repeatedly along this section of the road identified as suitable to excite the suspension. The testing proved there was difficulty with the repeatability of test data. To achieve repeatability, it is necessary to excite the vehicle consistently with a known or unchanged input and then to eliminate any subsequent inputs. This was proven to be practically impossible under the normal driving conditions of the field test. The variables that were found to affect repeatability included: vehicle speed, traffic conditions as it related to maintaining a steady speed (not braking or accelerating during the test) and lateral position in the lane. Other variables such as suspension condition, tyre pressure and tyre run-out may also affect repeatability but were not the subject of this on-road testing program.

Figure 2.5 shows the triaxle semi-trailer during the on-road tests conducted by Germanchev and Roper (2017).

Figure 2.5: Triaxle semi-trailer during on-road testing

Source: Germanchev and Roper (2017).

2.5 Emerging Technologies for Measurement

The accuracy and resolution of the data available from in-field measurements using cost-effective sensors were identified in the preceding research (NTC 2008 and Austroads 2009a) as limitations for understanding dynamic wheels loads. One of the aims of the NACoE research programs', project R34 (Germanchev and Roper 2017) investigating RFS compliance, was to identify and utilise technology that is commercially available for measuring heavy vehicle suspension performance. The key data requirements were:

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

The following engineering solutions were identified as suitable for measuring suspension performance:

- on-board scales (high and low frequency)
- linear displacement sensors

- accelerometers
- tyre pressure sensors
- Electronic Braking System (EBS) control modules.

Figure 2.6 shows two on-board scale devices that can be fitted to a vehicle to measure mass, using an air pressure transducer (left) and load cells (right).

Figure 2.6: Examples of on-board scales

Source: Germanchev and Roper (2017).

An EBS module (shown Figure 2.7) is a technology commonly fitted on trucks and prime movers, and it is also becoming increasingly common on new trailers. This module is the basis for any electronic braking system; it can include sensors to record wheel speeds and air bag pressure and communicate with other devices via the controller area network (CAN). Data can be sent to the vehicle's telematics device and communicated via the mobile network or other wireless platforms.

Figure 2.7: Electronic Braking System (EBS) module

Source: Germanchev and Roper (2017).

This device was identified as a potential method for measuring dynamic wheel loads; however, based on industry consultation it was not included in the evaluation. Consultation with EBS manufacturers and suppliers advised that the technology was capable of measuring suspension performance but was limited by other variables such as vehicle payload, road surface, speed, etc. These limitations were discussed in Section 2.4.5 and were identified as limitations for on-board monitoring technologies.

Accelerometer technology has advanced predominantly through the wide adoption of smart phones, but accelerometers alone are not able to measure dynamic wheel loads. However, if combined with either linear displacement or pressure sensors it could come close to an accurate measurement.

The DynaSses (Dynamic Assessment) system (shown in Figure 2.8) is a commercial system comprising hub-mounted sensors (temporarily fitted) at each end of the axle, and custom software serving as the data logger and user interface. This system was evaluated by field testing and was found to be the most accurate and repeatable of the systems assessed including air pressure sensors, linear displacement transducers and load cells.

Figure 2.8: DynaSses test system (Dynamic Assessment)

The system is still limited by the variations in on-road data collection, but these are reduced by a calibration process in which the vehicle is driven over ramps, dropping from a fixed height sufficient to excite the resonant frequency of the suspension. Details of the sensors used as part of this system were not disclosed to protect the intellectual property of the system owner. However, it is expected that due to the low-cost and ease of installation that a vast quantity of data can be gathered for a wide range of vehicles and conditions. It is expected that analysis of this big dataset will allow for the variations due to speed and conditions to be isolated from the dynamic wheel load data.

3 IMPACT OF MAGNIFIED LOADS ON PAVEMENTS

Cole et al. (1992) measured dynamic load caused by 15 articulated vehicles with a variety of suspension designs, tyre types, payloads and speeds by driving them on a portable mat 56 m long with capacitive strip sensors. The study found that for the three typical articulated vehicles considered, the average asphalt fatigue damage caused by dynamic loads (calculated by applying the 4^{th} power law to the measured dynamic loads normalised by the same law applied to static loads) is approximately 7 to 25% greater than the damage caused by static loads; and the 95^{th} percentile damage is 2 to 3 times the damage caused by static loads. It is noted, however, that these tests were limited to 56 m of a given road geometry, and it is known that dynamic load effects are highly dependent on the road profile.

Gillespie et al. (1993) analysed the effect of different axle loads, suspension types and vehicle speeds, concluding that rutting is mainly a function of the gross vehicle weight. Suspension types and dynamic loading only have a minor effect on rutting (about 10 to 20%). On the other hand, in relation to fatigue damage, dynamic loading can increase it to a factor of 5 to 6 times compared to fatigue damage due to static loads.

According to Collop and Cebon (1995), consideration of dynamic loads can result in a pavement life 48% shorter in terms of subgrade rutting and 91% shorter in terms of fatigue damage. Whereas Bilodeau, Gagnon and Dore (2017), based on a multibody dynamic truck model with a vehicle at 100 km/h, reported reductions of 20 and 29% respectively for the rutting failure criteria and for bottom-up fatigue cracking.

The sections to follow will review the impact of road roughness, vehicle speed, road geometry and manoeuvring, spatial repeatability and the effect of uneven distribution of loads within an axle group on magnification of dynamic loads and its effects on pavement performance.

3.1 Roughness

Pavement roughness increases pavement damage by increasing the magnitude of loads imparted on the pavement. Austroads (2012) reports a high degree of correlation for a linear relationship between dynamic load coefficient (DLC – ratio of the root mean square dynamic wheel force to the mean wheel force) and the International Roughness Index (IRI).

Therefore, pavement damage can be reduced if the road is maintained in a smooth condition. Gillespie et al. (1993) mentioned, for instance, a damage increase by a factor of 3 on rough rigid pavements (Pavement Serviceability Index of 2.5).

Potter et al. (1996) measured the dynamic loading of about 1500 heavy vehicles on a British road. For most of the vehicles measured, the damage at the worst 5% of the road resulted in 1.5 to 2.5 of the damage of a static load (calculated using the 4^{th} power law). Drive axles were in general more damaging than trailer axle groups.

Lee and Chatti (2002) developed a roughness index called dynamic load index (DLI), which correlates relative damage from the 95^{th} percentile dynamic load at different roughness index values and the corresponding percent reduction in life. According to the authors, there is a level of roughness for which a sharp increase in dynamic load occurs. Their analysis consisted of applying the 4^{th} power damage law using dynamic axle loads obtained from the TruckSim^{TM} program to calculate relative damage for different roughness levels. The DLI allows differentiation between profiles with the same ride quality index generating different levels of dynamic loading. The authors concluded, based on the 333 pavement sections investigated, that smoothing the pavement surface (milling, grinding or applying a thin overlay) as a preventative maintenance to extend pavement life is most effective in rigid pavements, followed by flexible pavements. For composite pavements, however, the authors concluded that smoothing actions might not be as effective (Lee & Chatti 2002, Chatti & Lee 2002, Chatti, Lee and Baladi 2001).

3.2 Vehicle Speed

As vehicle speed increases, the following occurs in respect to dynamic loads:

- In rigid pavements: the increase in peak dynamic wheel loads results in increased fatigue damage (Gillespie et al. 1993).
- In asphalt pavements: the increase in dynamic loads is compensated for by the shorter duration of the load, giving less time for the pavement to respond, with asphalt fatigue damage remaining fairly constant (Gillespie et al. 1993 and Gillespie & Karamihas 1992).
- Rutting decreases as loading time decreases (although some localised deformations may occur at points of high dynamic load) (Gillespie et al. 1993).

3.3 Road Geometry and Manoeuvring

Findings from Gillespie et al. (1993) in respect to load increase and pavement damage due to manoeuvring are summarised below:

- Where heavy vehicles brake, load transfer to front axles can result in increased localised asphalt fatigue damage by 100 to 1000%.
- In concrete pavements, front axles are much less damaging than rear axles, and therefore, braking decreases rigid pavement fatigue damage for this type of pavement.
- Heavy vehicle acceleration can increase rear axle load by about 10%, increasing fatigue damage at these locations but decreasing it in the front axle.
- Rutting does not seem to be affected by accelerating movements.
- Cornering manoeuvres can typically increase the load on one side of an axle by 20% on individual wheels, resulting in a 100% increase in fatigue and 20% increase in rutting.

For a symmetrical vehicle on a turn with superelevation, the load on the outside wheels of the vehicle can be calculated by Equation 1 and illustrated in Figure 3.1.

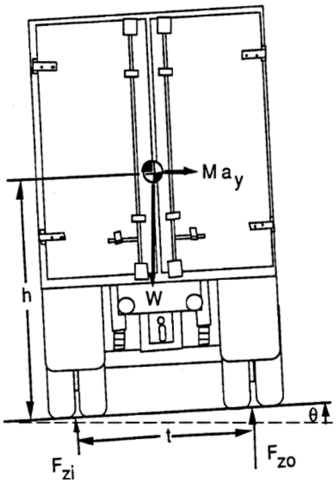
$$F_{ZO} = W\left[\frac{1}{2} + \frac{h}{t}\left(a_y - \theta\right)\right] \qquad 1$$

where

F_{ZO}	=	load on the outside wheels of the vehicle
W	=	gross vehicle weight
h	=	centre of gravity height
t	=	track width
a_y	=	lateral acceleration (in g's)
θ	=	superelevation angle of the road surface (positive inward)

Source: Gillespie et al. (1993).

Figure 3.1: Forces acting to produce a moment balance on a vehicle



Source: Gillespie et al. (1993).

Vuong and Blanksby (2008) conducted a study to analyse the damage impact of triaxles and quad-axles undertaking a 90º turn of 15 m radius at 5 km/h. The analysis used the 3-D vehicle model AutoSim to model the heavy vehicles and a 3-D finite element pavement model to simulate pavement responses. The Shell asphalt fatigue model was used to predict pavement damage. The pavement cross-section analysed comprised 65 mm of dense graded asphalt on 300 mm of crushed rock. The relative damage encountered for different triaxle and quad-axle loads are summarised in Table 3.1. It is noted by the authors, however, that relative damage could vary with loading limits and pavement configuration.

Table 3.1: Relative damage between trailer triaxle and quad-axle loads

Performance parameter	20 tonne triaxle of A123-GML	22.5 tonne triaxle of A123-HML	20 tonne quad-axle of A124-GML	22.5 tonne quad-axle of A124-HML	24 tonne quad-axle of A124-NEW1	27.5 tonne quad-axle of A124-NEW2
Axle group allowable loading (cycles)	4.6E + 03	1.96E + 03	4.47E + 04	2.31E + 04	2.31E + 04	2.73E + 03
Relative damage as compared to the 20 tonne triaxle of A123-GML	1.00	2.35	0.10	0.20	0.20	1.69

Notes: A123 – a six-axle vehicle
A124 – a quad-axle vehicle
GML – general mass limit
HML – higher mass limit
NEW1, NEW2 – to other loads
Source: Vuong and Blanksby (2008).

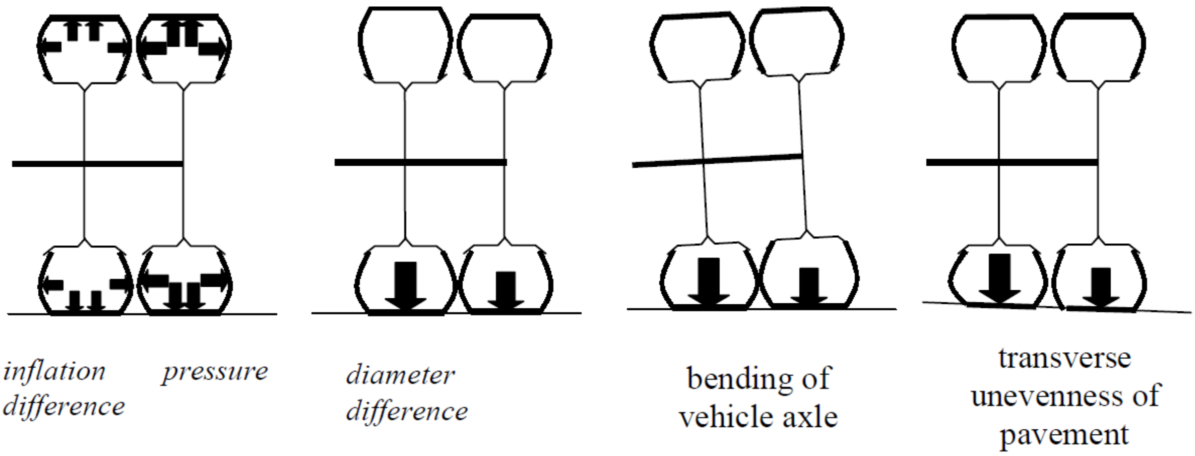
3.4 Spatial Repeatability

Spatial repeatability is the phenomenon, observed in several studies, where for a given speed the dynamic wheel loads generated by a heavy vehicle are repeated closely on successive runs over a given stretch of road. This phenomenon results in the accumulation of peak loads within certain locations in the road, leading to localised large damage. Spatial repeatability is a function of the road surface roughness, truck regulations and the homogeneity of the vehicle fleet (Gillespie et al. 1993). It can be measured by the 'Spatial Repeatability Index' (SRI), which is defined as the correlation coefficient between an aggregate tyre force history and a reference aggregate force history. The aggregate force is defined as the sum of the dynamic forces applied at each point along the wheel path by all of the axles of a vehicle (Cole et al. 1996).

3.5 Uneven Distribution of Loads within an Axle Group

Potential causes for uneven load sharing between tyres in a dual tyre assembly are illustrated in Figure 3.2. As shown in the figure, not all of them are necessarily related to dynamic effects.

Figure 3.2: Causes for unequal load sharing between tyres in a dual tyre assembly (load imbalance)



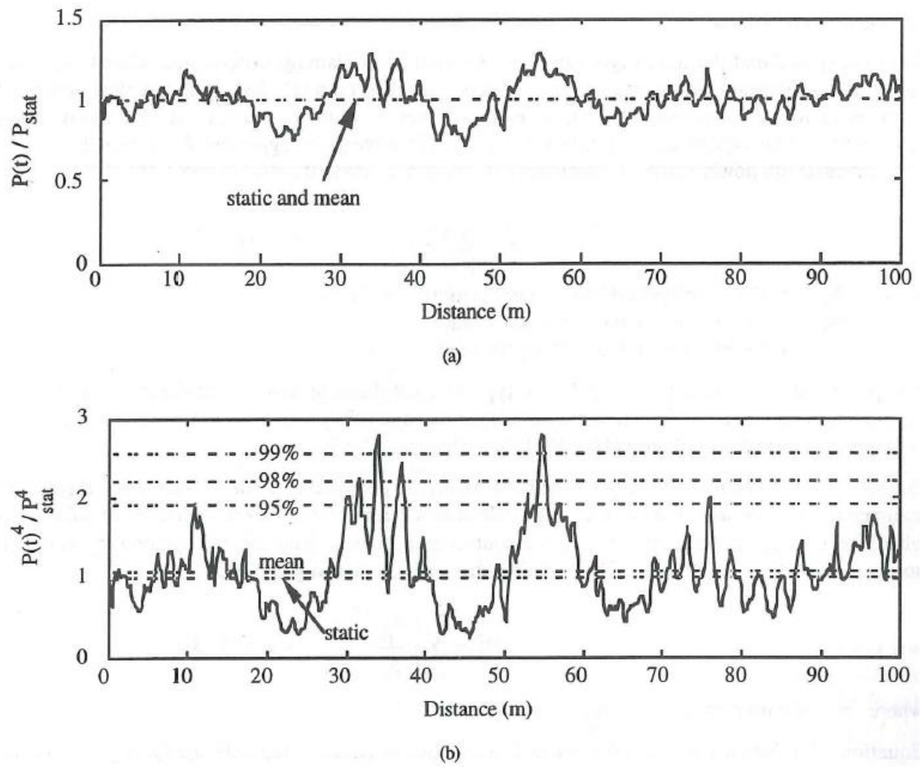
Source: European Commission Directorate General Transport (COST) (2001).

The European Co-operation in the Field of Scientific and Technical Research (COST 2001) Action 334 report ('Effects of Wide Single Tyres and Dual Tyres') estimated the damage caused by single tyres due to dynamic loading to be slightly less than that caused by dual tyres, which is partly due to the possibility of the dual tyres being unbalanced (Austroads 2008).

The ability of an axle group to distribute loads among its individual axles has a direct effect on pavement damage. The increase in damage caused by heavier tyres/axles leads to more damage than the reduction in damage that is observed with the reduction in other tyres/axles loads (Brademeyer, Delatte and Markow 1986).

As damage is correlated with load by a power-law, damage is accentuated by greater load magnitudes. This is illustrated by Cebon (1999) in Figure 3.3.

Figure 3.3: Dynamic tyre forces generated by a quarter-car model on a 'good' road at 100 km/h



Note

(a)) Normalised dynamic tyre forces

(b) Normalised dynamic tyre forces, raised to the 4th power

Source: Cebon (1999).

The European Commission Directorate General Transport (COST 1999) Action 333 recommended calculating damage caused by individual axle configurations until failure, respectively for fatigue (5th power) and rutting (4th power), using the power-law, resulting in Equation 2 and Equation 3.

$$Fatigue\ EALF_i = \left(\frac{Fatigue\ strain_{i-th\ axle\ load}}{Fatigue\ strain_{ESAL}}\right)^5 \qquad 2$$

$$Rutting\ EALF_i = \left(\frac{Rutting_{i-th\ axle\ load}}{Rutting\ strain_{ESAL}}\right)^4 \qquad 3$$

where

$EALF_i$	=	equivalent axle load factor for the ith-axle load
$ESAL$	=	80 kN equivalent standard axle load

Austroads (2015a) analysed required pavement thickness using the Austroads (2017d) pavement design method for flexible pavements by considering amplification of loads by dynamic effects. The increase in load magnitude was considered through the Load Sharing Coefficient (LSC), first proposed by Sweatman (1983). The LSC equation, as typically expressed in modern times, is presented in Equation 4.

$$LSC_i = \frac{n \times F_i}{F_{group}} \quad (4)$$

where

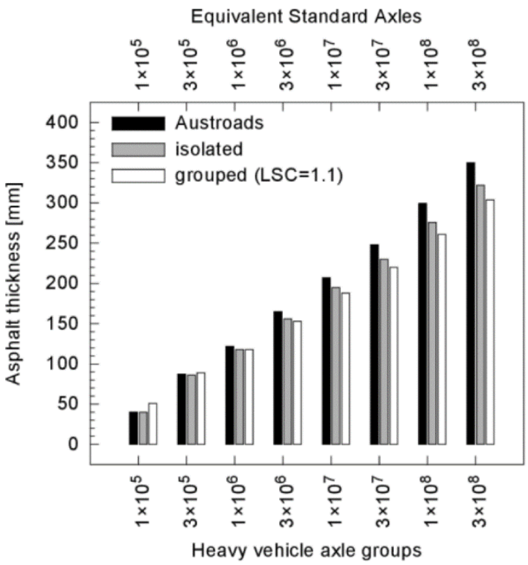
LSC_i	=	load sharing coefficient for axle i
F_i	=	load on axle i (kN)
F_{group}	=	total load on axle group (kN)
n	=	number of axles within group

LSC values used in Austroads (2015a) were taken from six months of WIM site data around metropolitan Melbourne. Assuming a 90th percentile value of LSC of 1.1, the author obtained thicknesses of up to 4 mm higher in the case of asphalt pavements and up to 16 mm higher for cemented materials. By modelling the full spectrum of maximum LSCs, he reported that the increase in thickness would correspond to modelling the asphalt pavement with a maximum LSC of 1.05 and the cemented material pavement with a maximum LSC of 1.07. Modelling of the isolated axles within an axle group generally resulted in thicker pavements than modelling grouped axles with an LSC of 1.1 (Austroads 2015a).

Therefore, the current Austroads design method (Austroads 2017d) conservatively considers axle groups with multiple axles as isolated single axles. Design asphalt thicknesses considering the Austroads (2017d) design method, isolated axles within an axle group (i.e. Austroads (2017d) method) and grouped axles with an LSC of 1.1 for Kwinana Freeway are illustrated in Figure 3.4.

It is noted, however, that this approach does not consider that stresses and strains need some time to recover after the passing of a single axle, due to the viscoelastic behaviour of bituminous materials (COST 2001). A discussion on the viscoelastic behaviour of asphalt pavements is discussed in more detail in Section 4.3.

Figure 3.4: Minimum thickness of 3000 MPa asphalt for different design traffic levels, Kwinana Freeway



Source: Austroads (2015a).

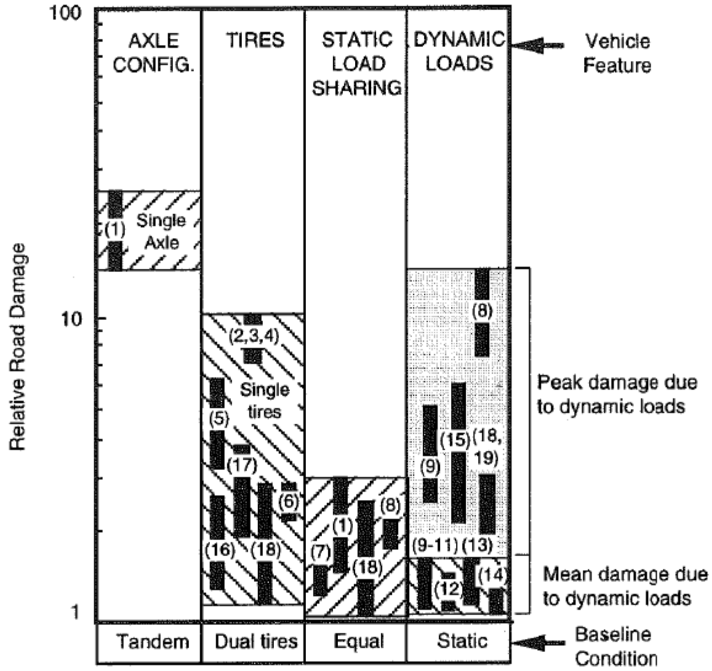
A summary of calculated damage increase due to uneven distribution of loads within an axle group by several authors is presented in Table 3.2.

Table 3.2: Increase in pavement damage due to uneven distribution of loads within an axle

Authors	Axle type	Load	Increase in damage
Gillespie et al. (1993)	Tandem	LSC between 0.95 and 1.05	Fatigue hardly affected
		LSC = 1.2	40–50% (fatigue)
Gordon (1988)	Tandem	LSC = 0.8	100% (rutting)
O'Connell, Abbo & Hedrick (1988)	Tandem	LSC = 0.8	23% (cracking) 43% (rutting)
Southgate and Deen (1984 & 1985)	Tandem	13 combinations of uneven load distribution	40% (fatigue)
	Triaxle		130% (fatigue)

Cebon (1999) summarises the importance of various considerations on relative road damage as reported in Figure 3.5. This figure shows that uneven load sharing contributes to more damage than the mean damage due to dynamic loads. Cebon (1999) notes that fatigue failure is likely to occur at specific locations of the road where peak dynamic loads occur, so peak forces should be considered rather than average dynamic forces.

Figure 3.5: Summary of literature on the effects of various vehicle features on road damage



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5 Huhtala, Finland, (1988), [248]
6 Anon (OECD) (1982), [16]
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9 Sweatman, Australia (1983), [443]
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14 Papagiannakis et al, Canada, (1989), [365]
15 Cebon, UK, (1985), [91, 93]
16 Addis, UK, (1991), [2]
17 Bonaquist, USA, (1992), [64]
18 Gillespie et al USA (1992) [192]
19 Cole et al, UK, (1992) [129]

Source: Cebon (1999).

It should be noted that the effect of dynamic loading considerations is expected to be different for different pavement configurations and depending on the main mode of failure expected. According to Collop, Cebon and Cole (1996), for example, thinner asphalt pavement where fatigue is the main mode of failure is more sensitive to dynamic load effects than thicker pavements where rutting is the main mode of failure.

3.6 Software Packages

COST (1999) summarise a list of pavement modelling software packages in Table 3.3, including some that allow consideration of dynamic loading due to vehicle suspension and uneven road surfaces.

Table 3.3: Preliminary inventory of pavement design models

Name	Method used as response model	Issues covered													
		Non linearity	Rheology	Anisotropy	Interface	Climatic effects	Dynamic loading	Axle spectrum	Tire characteristics	Stochastic	Crack propagation	Thermal effects	Cumulated damage	Fatigue	Permanent deformation
APAS-WIN	Multi-layer					x		x	x			x		x	
AXIDIN	Axisymmetric FEM						x								
BISAR/SPDM	Multi-layer				x	x		x						x	x
CIRCLY	Multi-layer			x	x			x	x				x	x	
CAPA-3D	3D-FEM	x	x	x	x		x		x		x	x			
CESAR	3D-FEM	x	x	x	x	x	x		x	x	x		x	x	x
ECOROUTE	Multi-layer				x				x				x		
ELSYM 5	Multi-layer														
KENLAYER	Multi-layer	x	x		x		x		x				x	x	x
MICHPAVE	Axisymmetric FEM	x												x	x
MMOP	Multi-layer	x				x	x	x	x	x	x				
NOAII	Multi-layer			x	x	x		x		x				x	x
ROADENT	Multi-layer				x	x		x	x						
SYSTYS	3D-FEM	x	x	x	x		x		x		x				
VAGDIM 95	Multi-layer					x						x	x	x	x
VEROAD	Multi-layer		x					x	x						x
VESYS	Multi-layer					x		x	x	x			x	x	x

Source: COST (1999).

4 PAVEMENT RESPONSE TO MOVING LOADS

4.1 Introduction

This section discusses the mechanic behaviour of the pavement subjected to the effect of moving loads other than the increase/decrease in load magnitude. More specifically, it discusses the effect of load dwelling and recovery time on pavement deterioration, as well as the effect of principal stresses rotation. Longer load dwelling is expected when vehicles travel at low speeds or are stationary. Recovery time (or rest period) corresponds to the interval of time between axle loads. More closely spaced axles result in shorter rest periods between axle loads.

There are contradictory conclusions in the literature on whether higher vehicle speeds increase or decrease pavement responses. While the increase in load caused by dynamic effects of heavy vehicles at higher speeds results in increased stresses in the pavement, the higher speeds also give the pavement less time to respond to the loads (Cebon 1999).

Mechanistic empirical pavement thickness design methods usually comprise the following stages:

- mechanistic modelling: modelling of the pavement structure subjected to a static load representing the heavy vehicle axles to obtain stresses and strains at certain locations of the pavement (commonly tensile strain at the bottom of bound layers and compressive strains at the top of granular layers)
- empirical modelling: translating critical strains to a number of allowable traffic load repetitions by using a transfer function (empirical equation relating material properties, strains and number of allowable load repetitions)
- comparing the allowable number of load repetitions to the expected number of load repetitions within the design period.

The transfer function is calibrated based on field and laboratory observations. Current pavement thickness design methodologies are based on static loads. However, with the changes in axle configurations, spacing and loadings, there is a need to understand how the new generation of heavy vehicles may impact pavement deterioration mechanisms. The advent of closely spaced axles and automated vehicles, with less wander between axles, is one of the factors that may have significant impact in the performance of the pavement. More closely spaced axles and less wander will result in less rest period between loads. The impact of that in different materials is investigated in Sections 4.2 (granular materials), 4.3 (asphalt) and 4.4 (concrete).

4.2 Granular Materials

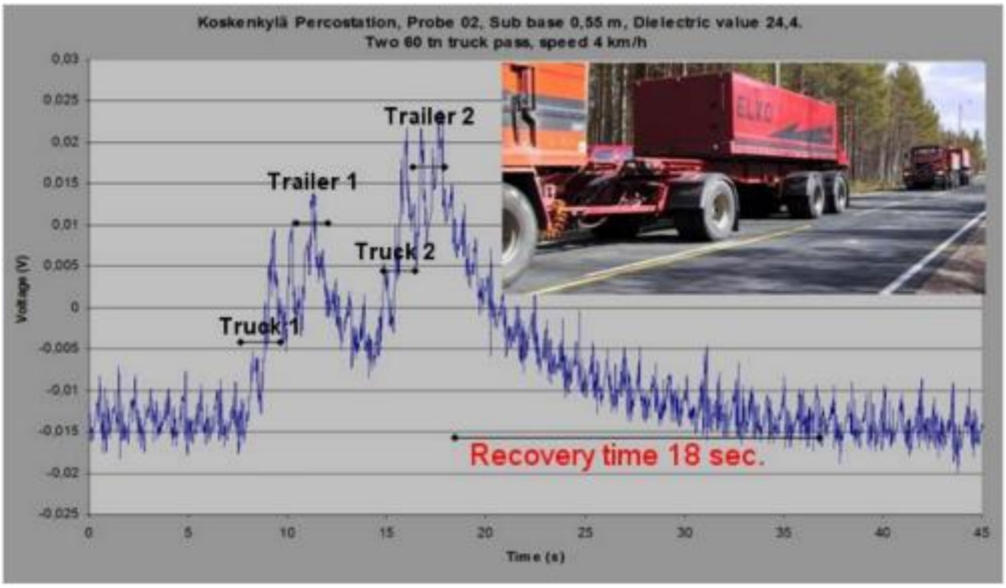
4.2.1 Pore Water Pressure Accumulation

Cyclic loading can lead to two phenomena not considered in a static load analysis: the accumulation of plastic strain and the potential build-up of pore water pressure (O'Reilly & Brown 1991).

Partially saturated granular materials can develop positive pore water pressure when subjected to repeated loads without allowance for sufficient recovery time between loads (Cary 2011, Saarenketo et al. 2012, Varin & Saarenketo 2014, Krechowiecki-Shaw et al. 2016, Lei et al. 2017). The development of pore water pressure in granular materials leads to a decrease in effective stresses in saturated soils and a decrease in matric soil suction in unsaturated soils. Both lead to a decrease in soil stiffness and an increase in degradation (Cary 2011).

Varin and Saarenketo (2014) present an example from Koskenkylä Percostation in Finland where two trucks drove close to each other on the same spot. The rise in the pore water pressure at the subbase layer is illustrated in Figure 4.1.

Figure 4.1: Koskenkylä Percostation pore water pressure development with several consecutive axles passes



Source: Varin and Saarenketo (2014).

According to Saarenketo et al. (2012), heavier trucks leads to higher displacement in the subgrade, resulting in increased recovery times of the subgrade. To avoid issues with pore water pressure build-up in the subgrade, the authors proposed that the distance between trucks should be controlled and convoy driving forbidden, as well as the distance between combination axles groups should be at least 3 m (Varin & Saarenketo 2014). This could be done, for instance, using GPS and mobile data transfer technologies as an alternative to load restrictions in the future.

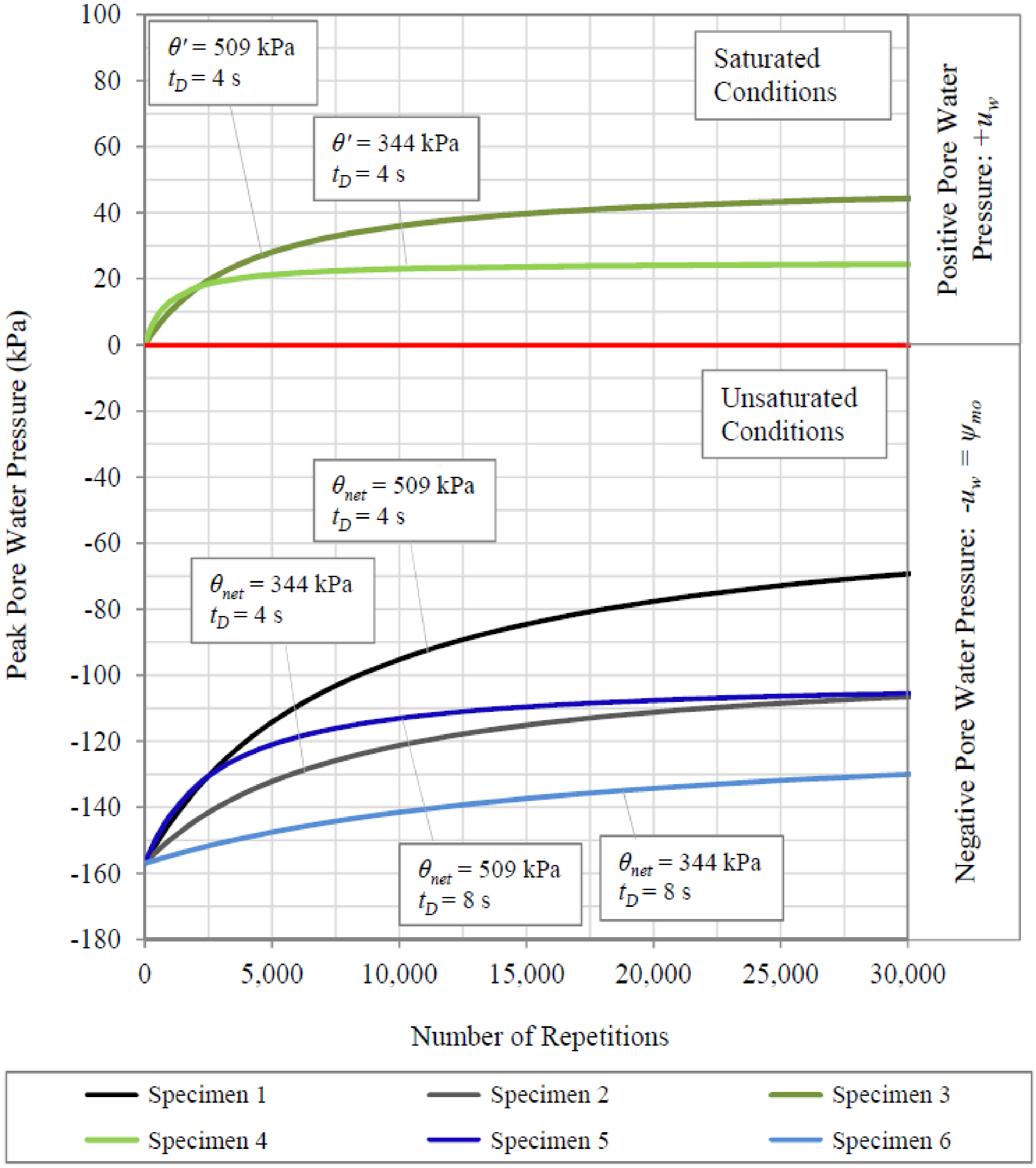
Krechowiecki-Shaw et al. (2016) proposed monitoring of excess pore water pressures in saturated subgrades to provide a useful indication of the proximity to failure, and therefore, to be used as a trigger for intervention.

In railways, where the cyclic loading is more accentuated, special attention is given to the sub ballast to be able to provide a permeable layer capable of dissipating excess pore water pressure. The excess pore water pressure developed with load cycles can become high and result in pumping issues (Indraratna, Salim and Rujikiatkamjorn 2011).

The accumulation of pore water pressure depends on the particle size distribution, Atterberg limits and hydraulic conductivity of the granular material. Materials that allow more drainage between loads can dissipate more pore water pressure, which reduces the loss of strength with cyclic loading. Soils with more plastic components present higher potential for developing high excess pore pressure. Cumulative pore water pressure build-up can reduce resilient modulus to critical values not considered by pavement designers (Cary 2011).

Cary (2011) conducted dynamic loading laboratory tests with unsaturated and saturated soil specimens and, contrary to expected, reported higher excess pore water pressure for unsaturated soil specimens than for saturated specimens. He also concluded that longer rest period between loads reduces loss of stiffness. Figure 4.2 illustrates how different net bulk stresses and rest periods between loads affected the peak pore water pressure development in his experiments.

Figure 4.2: Results from regression analysis for the global peak pressure curves

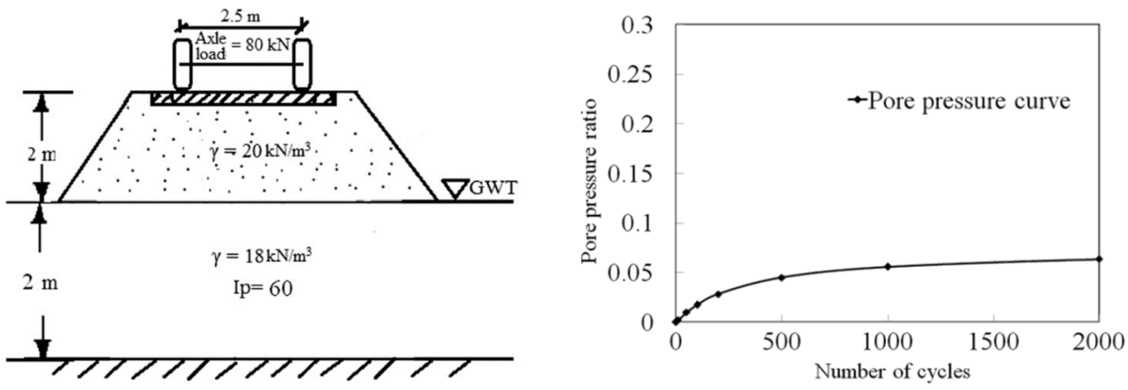


Source: Cary (2011).

In regard to the duration of stress application in repeated load triaxial tests, most investigators concluded that the effect of this variable on the resilient response is negligible for the range of load durations expected in the field (Young & Baladi 1977).

Paul, Sahu and Banerjee (2015) developed a model for prediction of pore pressure in cohesive soil under cyclic loading in an undrained condition using triaxial and torsional tests. The results of pore pressure accumulation with number of cycles for an 80 kN single axle single tyre load with tyre pressure of 552 kPa at a frequency of 0.1 Hz (i.e. one vehicle every 10 s) and at a location 3 m deep at the centre of the load is presented in Figure 4.3. The pore pressure ratio corresponds to the ratio between the induced pore-water pressure and the effective confining pressure. The authors proposed hyperbolic pore pressure generation models under cyclic loading.

Figure 4.3: Pore pressure generation curve at the centre of the clay layer under traffic loading



Source: Paul, Sahu and Banerjee (2015).

Some authors note that although cyclic loading increases pore water pressure and decreases granular material stiffness, low cyclic stress can also provide a beneficial fabric rearrangement, leading to an increase in resilient modulus of saturated soils (Ward 1983, Ng & Zhou 2014).

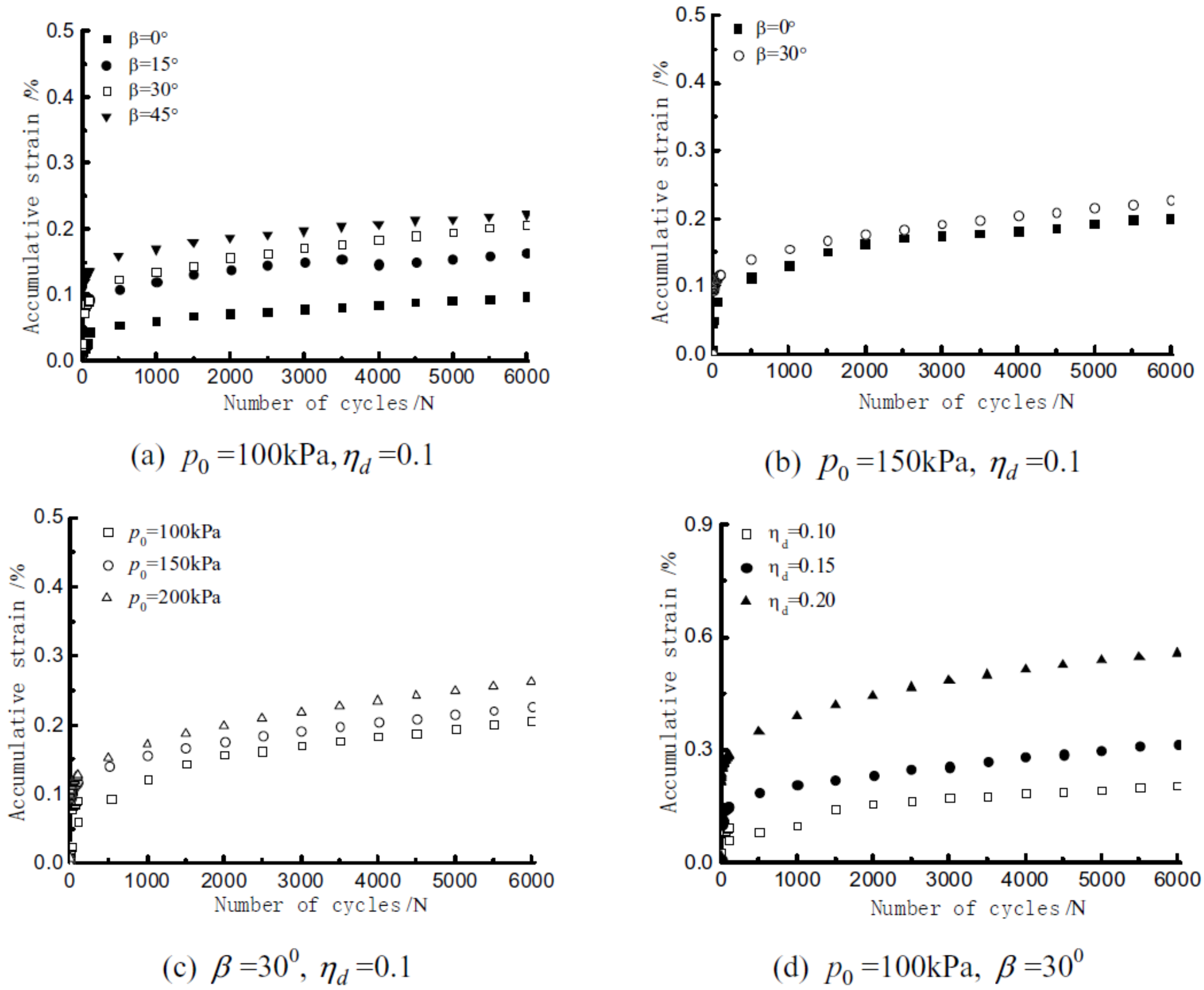
4.2.2 Principal Stress Rotation

Ishikawa, Sekine and Miura (2011) conducted small-scale model testing of cyclic deformation of granular material subjected to moving (i.e. simulated by varying the principal stress direction for each load) and single-point wheel (simulated by a single principal stress direction for each load) loads. The tests were set up to simulate the mechanical behaviour of a railroad ballast subjected to repeated train passages on ballasted track. The results indicated that the cumulative residual settlement of a railroad ballast caused by moving-wheel loading is much greater than the one caused by single-point loading, suggesting that the principal stress axis rotation plays an important role in the development of cyclic plastic deformation.

This agrees with the findings of Xiao et al. (2014) and Huang and Yao (2016), who performed a series of undrained cyclic tests on soft clay samples varying the principal stress direction. Their results indicate that both the accumulative strain and accumulative pore water pressure increase with principal stress rotation and with load frequency.

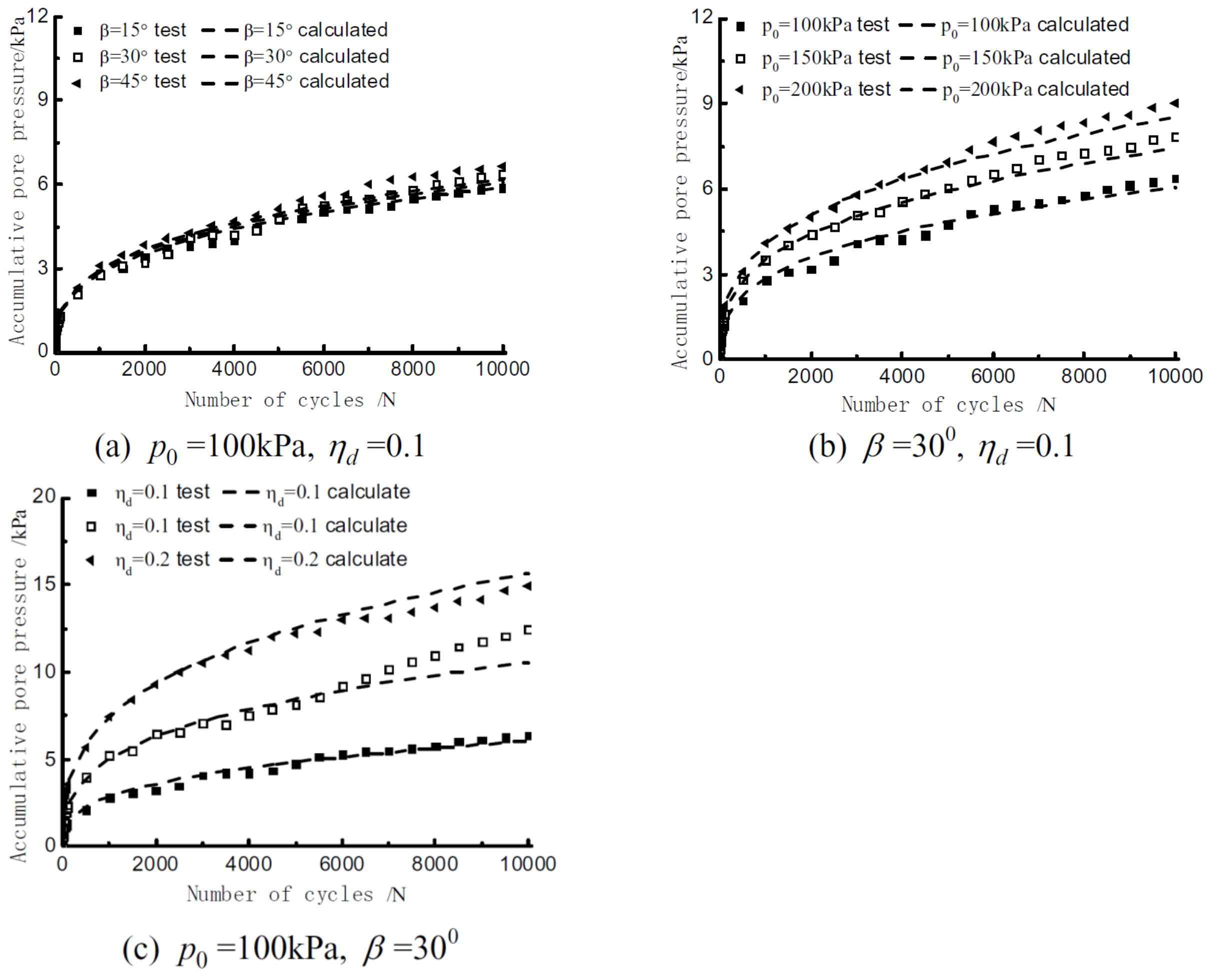
Huang and Yao (2016) performed undrained cyclic tests on soft clay samples. Their test results, for varying isotropic consolidated pressures (p_0), rotational angle of principal stress axes (β) and dynamic stress (η_d), are summarised in Figure 4.4 – accumulative strain vs. number of cycles – and Figure 4.5 – accumulative pore pressure vs number of cycles. Dynamic stress (η_d) is defined as the ratio of the deviatoric stress and the isotropic consolidated pressure (q_d/p_0). The results show that both the accumulative strain and accumulative pore water pressure increase as the angle between the major principal stress direction and the vertical axis (β) increases from 0º to 45º and with increasing confining pressure and dynamic stress ratio.

Figure 4.4: Relationship between axial cycle cumulative strain and number of cycles



Source: Huang and Yao (2016).

Figure 4.5: Relationship between cyclic cumulative pore water pressure and number of cycles



Source: Huang and Yao (2016).

A repeated load triaxial test (RLTT) is the most common test used to determine design modulus of granular materials for the mechanistic pavement design procedure. This test does not allow for a rotation in principal stresses. Therefore, the stress condition in the RLTT only represents the instant when the load is directly above the element, with principal stresses oriented horizontally and vertically (Young & Baladi 1977).

4.3 Asphalt

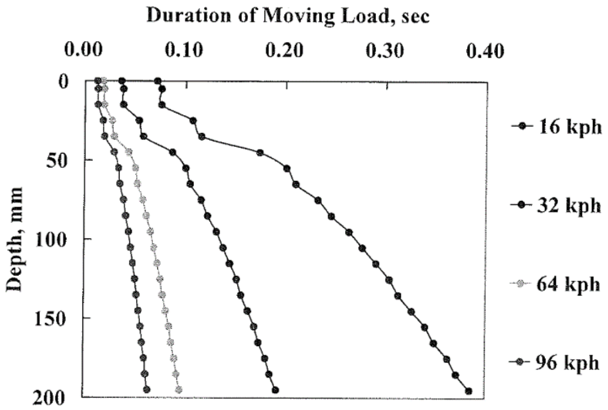
4.3.1 Viscoelastic Behaviour

Closely spaced axles result in the overlap of strain patterns, which results in a longer load period and consequent reduction in the asphalt mix stiffness (Peattie 1984).

The current Austroads asphalt thickness design method (Austroads 2017d) only considers magnitude of load, temperature and vehicle speed as input parameters. The effect of vehicle speed and temperature are only considered by a change in the asphalt design modulus. Once the asphalt modulus is adjusted for temperature and vehicle speed, the model simulates a static scenario, where the material is considered to be linear elastic. The responses do not depend on the frequency of the load pattern and do not consider the effect of rest periods between loads.

Yin et al. (2007) note that the effect of loading time varies at different depths. Deeper layers are generally loaded for longer periods, as illustrated in Figure 4.6. The current modulus adjustment factor, considered in the Austroads design method (Austroads 2017d), however, does not consider layer depth when assigning the asphalt modulus adjusted for vehicle speeds.

Figure 4.6: Duration of moving loads at different pavement depths



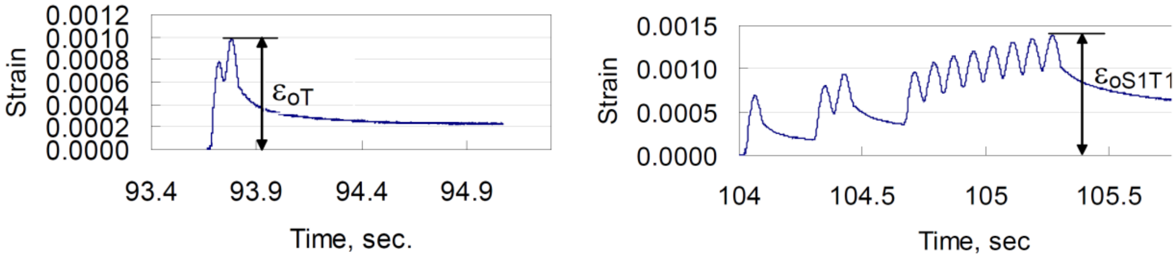
Source: Yin et al. (2007).

Shafiee (2016) suggests that the use of Fast Fourier Transforms (FTT) in frequency domain results in a more accurate and reliable prediction of dynamic modulus values associated with vehicle speeds. However, his results using FTT are similar to those obtained using the Austroads method (Austroads 2017d).

Salama and Chatti (2008) conducted unconfined compression cyclic load testing simulating different axle and truck configurations to investigate the effect of multiple axle groups on the development of asphalt permanent deformation. In their testing procedure, the authors used a constant ratio of loading/unloading duration of 1:9. Axle factor (AF) was defined as the damage of an axle group normalised to that of a single axle carrying the same load as any of the individual axles within the axle group. Their results indicated that AFs were proportional to the number of axles within an axle group, although for larger axle groups, the damage was slightly less than the damage of the same number of single axles (i.e. an eight-axle group was found to be about seven times more damaging than a single axle). AFs obtained by Chatti and El Mohtar (2004) through indirect tensile cyclic load laboratory testing, showed that compared to asphalt fatigue, the damage caused by multiple axle groups in the development of permanent deformation of an asphalt mix is higher. For fatigue, AF values of 1.59, 2.08, 2.52 and 3.99 were found for, respectively, tandem, tridem, quad and eight-axle groups, whereas rutting damage appeared to be relatively proportional to load (Chatti, Salama & El Mohtar 2004).

Salama and Chatti (2008) suggest three methods for considering pavement rutting damage under multiple axles: (1) cumulative peak strain, (2) initial dissipated energy and (3) strain area (impulse). In the first method, the cumulative peak strain value, obtained through a viscoelastic analysis, is correlated to the number of allowable repetitions of load. The cumulative peak strain value (ε_0) is illustrated in Figure 4.7 for a tandem axle and for a truck composed by one single axle, one tandem axle and one eight-axle group. The initial dissipated energy method correlates initial dissipated energy density of a truck or axle to the number of allowable repetitions of load. The dissipated energy density corresponds to the area within the stress-strain hysteresis loop under cyclic loading. This methodology would also require a viscoelastic analysis. In the third proposed methodology (strain area), the area under the initial strain curve is correlated to the number of allowable repetitions of load. This methodology resulted in the poorest correlation with the laboratory results obtained by the authors (Salama & Chatti 2008).

Figure 4.7: Examples of the cumulative peak of the initial strain pulse



(a) *Tandem axle* (b) *Truck S1T1E1*

Source: Salama and Chatti (2008).

Machemehl and Lee (1974) observed that repeated loading, in asphalt, retards age hardening and prevents thixotropic viscosity increases. Contrary to other findings, the authors experienced beneficial effect of concentrated dynamic wheel loads, with less water intrusion and freeze-thaw damage.

A number of authors have proposed theoretical models to investigate viscoelastic behaviour of asphalt pavements in response to moving loads. These are summarised in Table 4.1.

Table 4.1: Theoretical asphalt pavement models and main findings

Authors	Model	Main findings
Govind et al. (1987)	Finite element developed at the University of Texas at Austin used to simulate the dynamics of vehicles moving on different pavement profiles calibrated using the AASHTO Road Test Data	▪ higher rate of change of stress (i.e.: vehicle speed) leads to higher fatigue damage ▪ fatigue failure is a function not only of the load magnitude but also of the rate of change of the load, which means that higher loads at low speeds are not necessarily critical if the load is within the elastic limits of the material ▪ closely spaced axles generally result in less pavement damage compared to axles far apart
Sousa et al. (1988)	SAPSI software (linear viscoelastic layered model with surface circular loads) used to simulate pavement damage of load histories for three tandem-axle suspensions compared to the same axle with a uniform static load	▪ consideration of dynamic effects results in reduced pavement life ▪ the reduction in pavement life depends on the tandem-axle suspension
Zaghloul and White (1994)	Three-dimensional dynamic finite element program (3D-FEM) simulating trucks at different speeds. Asphalt was input as a viscoelastic material; granular pavement materials were input following the Drucker-Prager model (elastic-plastic model) and clay was input using the Cam-Clay model. (Amplification of load magnitude due to dynamic effects on rough surfaces or road geometry was not considered.)	▪ the results obtained with the proposed model agreed with predicted field measurements of pavement deflections from loads moving at different speeds ▪ the elastic strain is relatively constant after the first loading cycle, while the plastic strain accumulates with each loading cycle ▪ pavement deflection and rut depth reduce with increasing vehicle speed ▪ temperature, loading time and rate of loading have a significant effect on pavement response
Cebon (1999)	VESYS model (semi-infinite linear elastic layered structure) supplied with viscous equivalents of Young's modulus and Poisson's ratio. Model accounted for different vehicle speed (loading times) and dynamic loads. Rutting model validated with full scale accelerated wheel tracking tests.	▪ after an initial compaction period, asphalt rutting increases with static load and decreases with increasing vehicle speed ▪ the proposed methodology needs to be validated for a wider range of asphalt materials

Authors	Model	Main findings
Yin et al. (2007)	Finite element analysis using a single factor ('pseudo temperature') to simulate the effect of load time and temperature and a 'relaxation moduli' to characterise the viscoelastic behaviour of asphalt	▪ pavement response to loading time reduces at colder temperatures ▪ loading time can result in increases in tensile strain and compressive strain of respectively 300% and 350% in hotter temperatures
Al-Qadi and Wang (2009)	3-D finite element model with measured 3-D tyre-pavement contact stresses. Model considers asphalt as a linear viscoelastic material as well as moving loads.	▪ damage in thin and medium thickness asphalt layers is governed by the longitudinal tensile strain developed at the bottom of the asphalt layer ▪ damage in thick asphalt layers is governed by the vertical shear strain at 75–200 mm below the asphalt surface, which results in near-surface fatigue cracking and rutting ▪ wide-based tyres perform better at pavement near the surface, but cause more damage at higher depths ▪ the effect of vehicle speed and load magnitude is greater at deeper depths than at the pavement surface ▪ wide-based tyres develop higher longitudinal tensile strain at the bottom of the asphalt and compressive strain at the top of the subgrade than dual-tyres ▪ wide-based tyres develop less vertical shear and compressive strains near the surface than dual-tyres ▪ the difference in pavement responses when loaded by a dual-tyre, compared to a wide-based tyre, is not significantly dependent on vehicle speed ▪ wide-based tyres are more effective in interstate roads, becoming costlier on primary roads and local roads
Khavassefat, Jelagin & Birgisson (2014)	Finite element analysis considering the viscoelastic behaviour of the asphalt layer through a Prony series formulation of the shear relaxation modulus	▪ horizontal stress at the surface and the bottom of the asphalt layer found to be approximately 50% higher in the majority of the frequency ranges for rough pavement profiles

4.3.2 Pore Water Pressure Accumulation

Repeated traffic loading can cause an increase in pore water pressure in asphalt mixes, which can result in stress concentration, emulsification, loss of cohesion at the interface between the binder film and the aggregate, hydraulic scouring and growth of microcracks in the asphalt mastic (Little & Jones 2003, Karlson 2005, Zaniewski & Viswanathan 2006, Varveri et al. 2014, Weldegiorgis 2014, Huang et al. 2015, Yang 2017, Shakiba, Darabi & Little 2017, Guo, Sun & Dai 2017).

Novak, Birgisson & McVay (2003) and Cui et al. (2009) note that high pore water pressures (up to 0.1 MPa) are expected at the bottom of a permeable asphalt surface layer where water accumulates. This may explain Karlson's (2005) observation of field specimens, which concluded that stripping begins at the bottom layer interfaces and works its way up.

Frank (2004) performed resilient and dynamic modulus testing of drained and undrained saturated samples at different temperatures. The main findings of his study relating to the behaviour of asphalt under cyclic loading are summarised below:

- Resilient modulus (repeated load indirect tensile test):

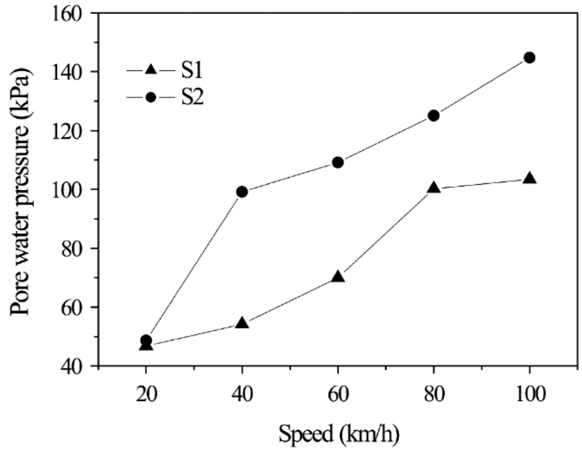
    - drained tests: the modulus increased and then stabilised, there was no notable increase in pore pressure or change in volume of water within the specimen
    - undrained tests: residual pore-pressure developed with cyclic loading, which is believed to be due to the reduction in interconnected voids and/or insufficient time (0.9 seconds) between loads to allow dissipation of pore-pressure
    - the drained resilient modulus was higher than the undrained, which is believed to be due to an increase in pore-pressure in the latter.
- Complex modulus (obtained by applying a sinusoidal vertical load at different frequencies and correlating it to the vertical strain):
    - drained tests: results seem to be independent of the load frequency, negligible pore-pressure response with cyclic loading
    - undrained tests: a cyclic pore-pressure response was observed with cyclic loading for lower load frequencies (1 Hz and 4 Hz) but not for higher frequencies (10 Hz and 16 Hz), which the author attributed to the reduced time that the pore water pressure had to develop due to the short load contact time
    - there is a time lag between the load application and the pore-pressure response
    - the modulus increased with cyclic load frequency
    - complex modulus values at undrained and drained conditions were found to be similar
    - saturated drained and undrained tests resulted in higher modulus than a dried specimen.
- At low temperatures, higher loads are required for the specimens to develop the same pore-pressure of high temperature specimens.

Based on the findings above, it can be concluded that the development of pore water pressures within an asphalt mix is not only dependent on load magnitudes, but also on temperature, vehicle speed, moisture and drainage/permeability conditions. Frank's (2004) study did not correlate the observed increase in pore water pressure with the development of moisture related damage in the asphalt.

Roque et al. (2012) performed cyclic pore pressure conditioning of laboratory samples using a triaxial cell chamber to investigate moisture damage to asphalt mixes. The conditioning consisted of inducing cyclic pore pressure at a constant rate by a sine wave (0.33 Hz frequency and a total of 5800 cycles) to simulate a portion of the pumping action that can occur in the field when vehicles travel over a wet pavement. The authors found that cyclic pore pressure conditioning resulted in a reduction of fracture energy (more embrittlement), permanent damage and less healing potential.

Gao, Guo and Liu (2015) measured pore water pressure through a fibre optic hydraulic pressure sensor installed in the field. They concluded that the pore water pressure increases with vehicle speed, but its lifetime decreases with increasing speed. The relationship between vehicle speed and pore water pressure is illustrated by the authors in Figure 4.8, where S1 represents the measurements from a sensor 100 mm below the surface and S2 the sensor 40 mm below the surface.

Figure 4.8: Relationship between vehicle speed and pore water pressure in pavement



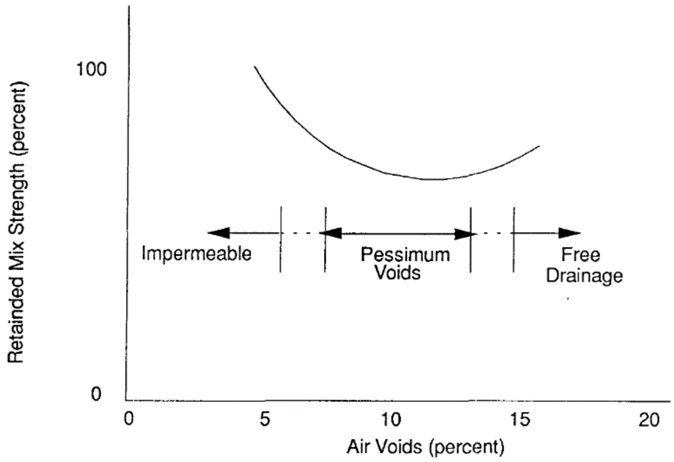
Source: Gao, Guo and Liu (2015).

These findings agree with laboratory experimental results obtained by Yang (2017), who conducted cyclic dynamic triaxial tests on asphalt mixes to investigate the development and effects of excess pore water pressure. His experiments indicate that excess pore water pressure and, therefore, moisture damage increase with an increase in:

- air void (based on tests carried out with 8% and 12% air voids)
- external load, which indicates that overweight vehicles result in higher moisture damage in asphalt mixes
- load frequency.

It is noted that for air voids lower or higher than the values indicated above, moisture damage is expected to decrease. This is illustrated in Figure 4.9 by Terrel and Al-Swailmi (1994), which indicates the 'pessimum voids', which is the air void content range for which the worst behaviour in the presence of water occurs.

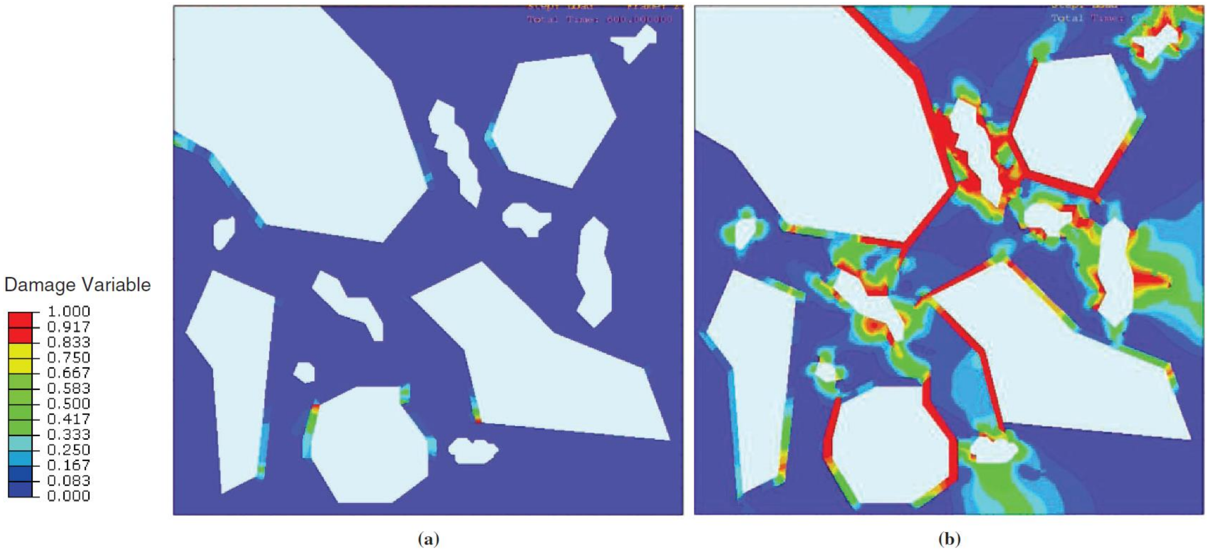
Figure 4.9: Relationship between strength of mixtures and air void content



Source: Terrel and Al-Swailmi (1994).

An illustration of damage with and without consideration of pore pressure effects based on a finite element study performed by Shakiba, Darabi and Little (2017) is included in Figure 4.10. More details on this study can be found in Table 4.2.

Figure 4.10: Damage distribution in finite element (FE) representation of asphalt concrete without (a) and with (b) consideration of pore water pressure effect



Source: Shakiba, Darabi and Little (2017).

A number of authors have proposed theoretical models to estimate the effect of load induced pore water pressure within an asphalt mix. These are summarised in Table 4.2.

Table 4.2: Theoretical asphalt pavement models and main findings

Authors	Model	Main findings
Novak, Birgisson and McVay (2003)	Finite element analysis based on the theory of mixtures for simulating saturated coarse-graded asphalt pavement	▪ coarse-graded asphalt mixes can develop significant pore pressures as a function of permeability and vehicle speed (rate of loading) ▪ asphalt develops positive pore pressures as the wheel approaches and negative pore pressures when the wheel passes ▪ pore pressure variation within the asphalt can result in stripping and hydraulic scouring ▪ pore pressure dissipates faster where the permeability is higher ▪ pore pressures at the interface between asphalt layers increase with faster rate of loading, due to the reduced time available for the pore pressures to dissipate
Cui et al. (2009)	Fast Lagrangian finite difference method and Biot dynamic consolidation theory, fluid-solid coupling analysis to simulate saturated asphalt mixture. An elastic constitutive model was used for the surface course and basecourse. A Mohr-Coulomb elastic-plasticity model was used for the embankment soil. Material damp was considered using Rayleigh linear combination.	▪ pore pressure increases with increasing vehicle speed ▪ pore pressure reduces effective stress and pavement deflection ▪ as the traffic load passes, water is pumped out and sucked into the pavement surface course ▪ the maximum dynamic pore pressure occurs at the bottom of the surface layer ▪ repetitive seepage forces result in scouring of damage
Huang et al. (2015)	Finite element model of saturated asphalt pavement using ANSYS. Model considers pavement layers to be linear elastic and isotropic, a vehicle speed of 90 km/h, load time of 0.05 s and load of 0.7 MPa.	▪ the maximum positive and negative pore water pressure occurs at the bottom of the lower layer

Authors	Model	Main findings
		▪ the pore water pressure mix behaves in a sinusoidal way (positive and then negative), resulting in scouring of the asphalt mix
Shakiba, Darabi and Little (2017)	Effective stress concept inside a deformable media using Biot's approach coupled to the nonlinear viscoelastic and viscodamage (moisture and mechanical) constitutive relationships. Model implemented in PANDA (finite element code developed at Texas A&M University).	▪ pore water pressure induces stress concentrations and damage around and near air voids, which can lead to damage propagation through interfaces and can induce stripping of mastic from aggregate particles ▪ experiments should be developed to measure Biot's coefficient of asphalt concrete material, so it can be incorporated into pavement studies and designs.

4.4 Concrete

Contrary to flexible pavements, concrete behaves essentially in an elastic way, so the effects of speed and frequency on primary pavement responses are considerably smaller (Cebon 1999). Stoner and Bhatti's (1994) experimental results showed that rest periods between load cycles are unlikely to significantly affect concrete fatigue performance.

Several authors reported that for single axle single tyres, the tensile stress considering static and dynamic loads are comparable (Darestani et al. 2006 and Chatti, Lysmer & Monismith 1994). However, other studies indicated that stresses decrease with vehicle speed (Zaghloul & White 1994). Experiments conducted on instrumented rigid pavement sections in Illinois indicated that in the interior of the slab strains diminish with increasing traffic speed but near cracks strains may increase (Cebon 1999).

Chatti, Manik & Brake (2008) performed flexural concrete beam fatigue tests simulating different multiple load pulses corresponding to single, tandem, tridem, quad, six and eight axle groups. The results indicated that the normalised fatigue damage per axle for larger axle groups is less than the single axle under identical stress ratios.

Table 4.3 summarises studies that included modelling of rigid pavements, taking into consideration dynamic effects related to material behaviour and strain time history.

Table 4.3: Theoretical concrete pavement models and main findings

Authors	Model	Main findings
Zaghloul and White (1994)	Three-dimensional dynamic finite element program (3D-FEM) simulating trucks at different speeds. Three stages were modelled: elastic, plastic and after failure stages	▪ dynamic responses obtained using the model agreed with the measured pavement deflections from loads moving at different speeds ▪ pavement response reduces with increasing vehicle speed
Chatti, Lysmer and Monismith (1994)	Finite element using DYNA-SLAB. The foundation support was represented by the damped Winkler model or by a viscoelastic layered system on a rigid or deformable half-space. The model accounted for inertial and viscous effects.	▪ consideration of dynamic effects on the design of rigid pavements usually leads to decreased pavement response, and is therefore, not generally necessary ▪ the quasi-static analysis is usually conservative if the wheel loads are adjusted for the effects of vehicle speed, truck suspension and pavement roughness ▪ Table 4.4 shows a comparison of measured deflections, deflections calculated considering dynamic effects

Authors	Model	Main findings
		(DYNA-SLAB) and deflections from the static analysis (ILLI-SLAB).
Darestani et al. (2006)	Finite element model using ANSYS software. Drucker-Prager material properties used to simulate subgrade soil behaviour.	▪ dynamic loads can be considerably different to static loads especially in the case of axle groups with multiple axles (tandems, triples and quad-axles) and jointed plain concrete pavements ▪ Table 4.5 was developed for consideration of dynamic analysis for jointed plain concrete pavements

Table 4.4: Comparison of DYNA-SLAB predictions with Waterways Experiment Station (WES) experimental results

Site no.	Foundation parameters				Maximum deflection		
	Dynamic (15 Hz)			Static			
	Stiffness coeff. k (MPa/m)	Damping coeff. c (sec.MPa/m)	Damping ratio, β	Coeff. subgrade reaction, Kp (MPa/m)	Measured	DYNA-SLAB	ILLI-SLAB
3[b]	20.3	0.36	1.33	81.3	0.132 0.212	0.137 0.197	0.146 0.209
7[c]	8.9	0.34	2.74	22.2	0.203 0.329	0.238 0.349	0.509 0.748
11[d]	42.5	0.48	1.03	21.9	0.070 0.099	0.055 0.078	0.121 0.172

Reported results were converted to using 1 mm = 39.37 mil and 1 MPa/m = 3.69 pci

[b] Pensacola Naval Air Station: 10 in portland cement concrete (PCC) + 4 in Base

[c] Birmingham: 7 in PCC

[d] Sheffard Air Force Base: 21 in PCC + 6 in Base

Source: Chatti, Lysmer and Monismith (1994).

Table 4.5: Type of required analysis in jointed plain concrete pavement for each axle group

Types of axle group	Required analysis	Velocity (km/h)	Global dynamic amplification (%)	Local dynamic amplification (%)	Location of severe damage
SAST	Static or dynamic	45	6	0	Near transverse joint
SADT	Static or dynamic	45	1.7	11.1	Near transverse joint
TAST	Static or dynamic	45 110	0.4 –1.2	0 11.4	Near transverse joint Quarter point of slab*
TADT	Dynamic	110	12.11	58	Midpoint of slab
TRDT	Dynamic	80	24	35	Quarter point of slab*
QADT	Dynamic	80	41	45	Quarter point of slab*

* From transverse joints.

Source: Darestani et al. (2006).

5 SURFACE DAMAGE

5.1 Introduction

There is a global trend towards increasing freight efficiency, with heavy vehicle operators increasing the use of heavier vehicles with more axles, which in turn leads to a greater contribution to transverse shear forces on pavements. The magnitude of shearing forces applied to the pavement depends on different factors, such as the number of axles and tyres within the axle group, axle spacing, the number of steering axles, tyre model and vehicle geometry (de Pont & Taramoeroa 2008, Neaylon, Harrow & van den Kerkhof 2017).

Heavy vehicle turning, braking and accelerating movements can generate considerable shearing forces, leading to pavement surfacing damage. Pavement design methods do not quantitatively consider these forces. As there is currently no widely accepted and validated model to determine vehicle wear from horizontal shear forces, the pavement designer usually applies engineering judgement and experience to choose appropriate pavement types, surface treatments and materials to minimise the risk of damage from the expected shearing forces.

From the heavy vehicle perspective, state road agencies usually have prescriptive requirements to minimise damage due to horizontal forces, which are interim measures until further work is conducted to develop a performance-based standard.

The pavement surfacing type most affected by horizontal shear stresses are sprayed seals. Australia, New Zealand and South Africa are three countries with the most experience in this type of surfacing. Neaylon, Harrow & van den Kerkhof (2017) roughly summarise guidelines for the selection of sprayed seals (chip seals) in these three countries as shown in Table 5.1.

Table 5.1: Summary of guidelines for the selection of sprayed seals in Australia, New Zealand and South Africa

Resistance to horizontal shear	Chip seal treatment	Binder
Least	Single seal	Bitumen
	Racked-in (single/double)	Bitumen
	Double seal	Bitumen/bitumen
	Double seal	PMB/bitumen
	Double seal	PMB/PMB
Greatest	Double seal	Higher % PMB

PMB – Polymer Modified Binder

Source: Neaylon, Harrow & van den Kerkhof (2017).

This section of the report concentrates on sprayed seal damage caused by horizontal shear stresses from turning movements. However, it is noted that horizontal shear stresses can also result in increased cracking and ravelling on asphalt surfaced pavements (Jacobs & Moraal 1992).

Analysis by Austroads (2015b) of accelerated loading facility (ALF) testing carried out using single, tandem and triaxial groups indicated that surface texture decay is increasing in the following order: single 40 kN, triaxle 90 kN, tandem 60 kN, tandem 80 kN. According to the findings of the Austroads report, ESAs do not adequately characterise the influence that heavy vehicle loading has on sprayed seal performance. ESAs are based on a load damage exponent of 4, whereas this study indicates a load damage exponent of 1 is more appropriate for use in a seal design method.

According to Neaylon (1996), it is believed that the decay of the surface texture of sprayed seals is mainly due to aggregate reorientation, which is dependent on the proportion of elastic and viscous behaviour caused by different vehicle speeds (shear rates) and vertical axle loads. One pass of a triaxle, for instance, represents a rapid succession of shear loadings, whereas three passes of a single axle permits a much larger recovery period between successive loadings.

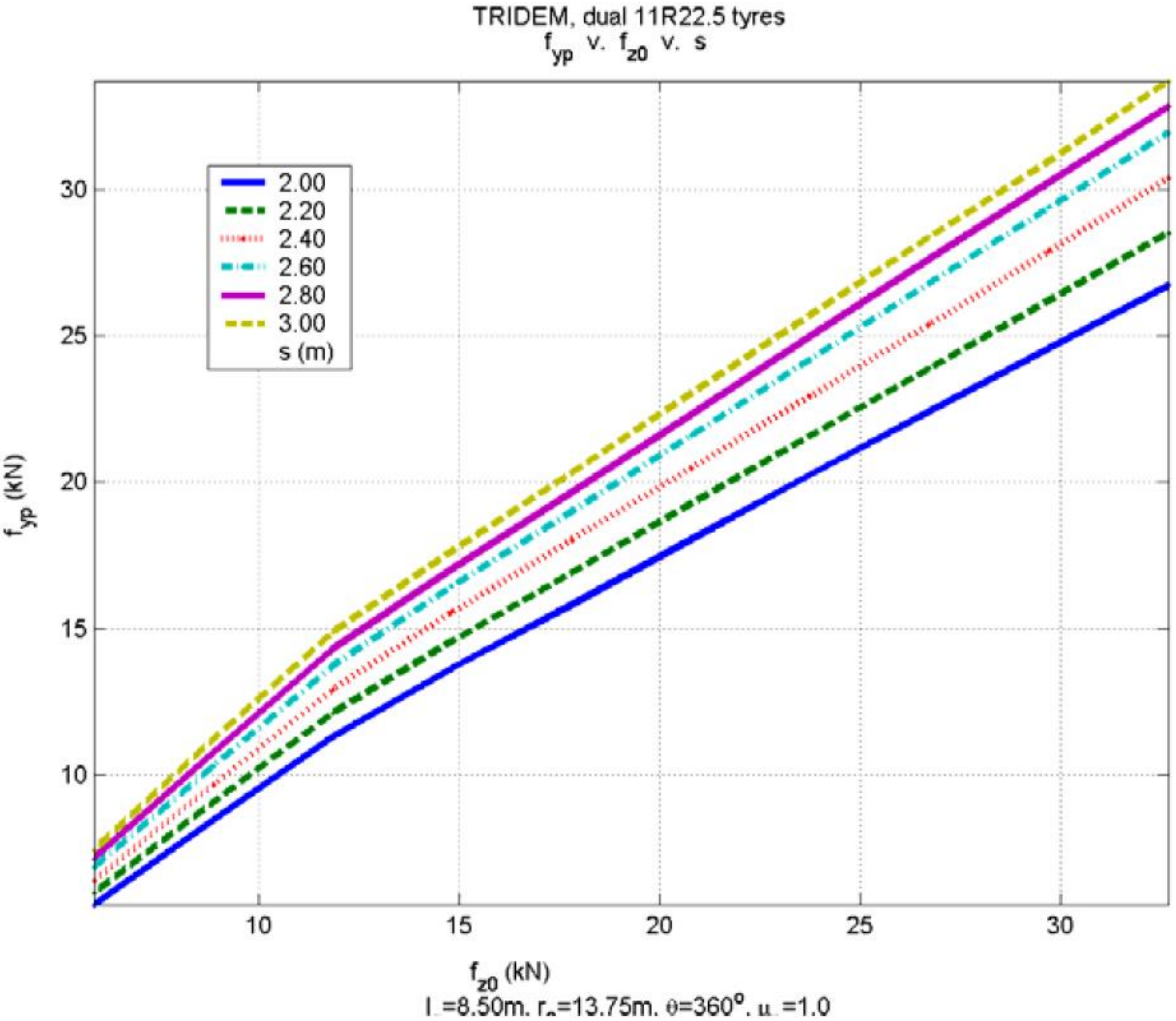
The following factors were found to contribute to the development of horizontal shear stresses: wheel movement (braking, accelerating, turning), wheel configuration (loading, tyre type, inflation pressure) and friction between the pavement surface and the tyre rubber (Austroads 2009b).

5.2 Effects of Different Axle and Truck Configurations

Prem et al. (2000) conducted a study based on computer modelling to understand the effects of combined vertical, horizontal and moment loading imposed by different load configurations on the pavement. The authors used a computer software called ADAMS (Mechanical Dynamics Inc) to estimate pavement loading at different conditions, including acceleration from rest, constant speed and turning movements. They found that seal damage at start-up and up-hill grades are almost entirely due to drive axle groups. Additionally, they found that for low-speed turn movements, the maximum horizontal forces applied to the pavement are generally generated by the front axle of triaxle groups, which apply about 50% of the available drive torque. The force increases with decreasing turn radius and axle group spread.

Taramoeroa and de Pont (2008) simulated the effect of different axles and vehicle configurations using the Yaw-Roll multi-body software developed by the University of Michigan Transportation Institute. Figure 5.1 illustrates how, in their simulations, the peak scuffing force increases with static load and axle spacing for a tridem axle turning 360º with a 13.75 radius. Figure 5.2 shows the peak scuffing force as a function of angles of turn for different wheelbases.

Figure 5.1: Peak scuffing force against static load for different axle group spacing



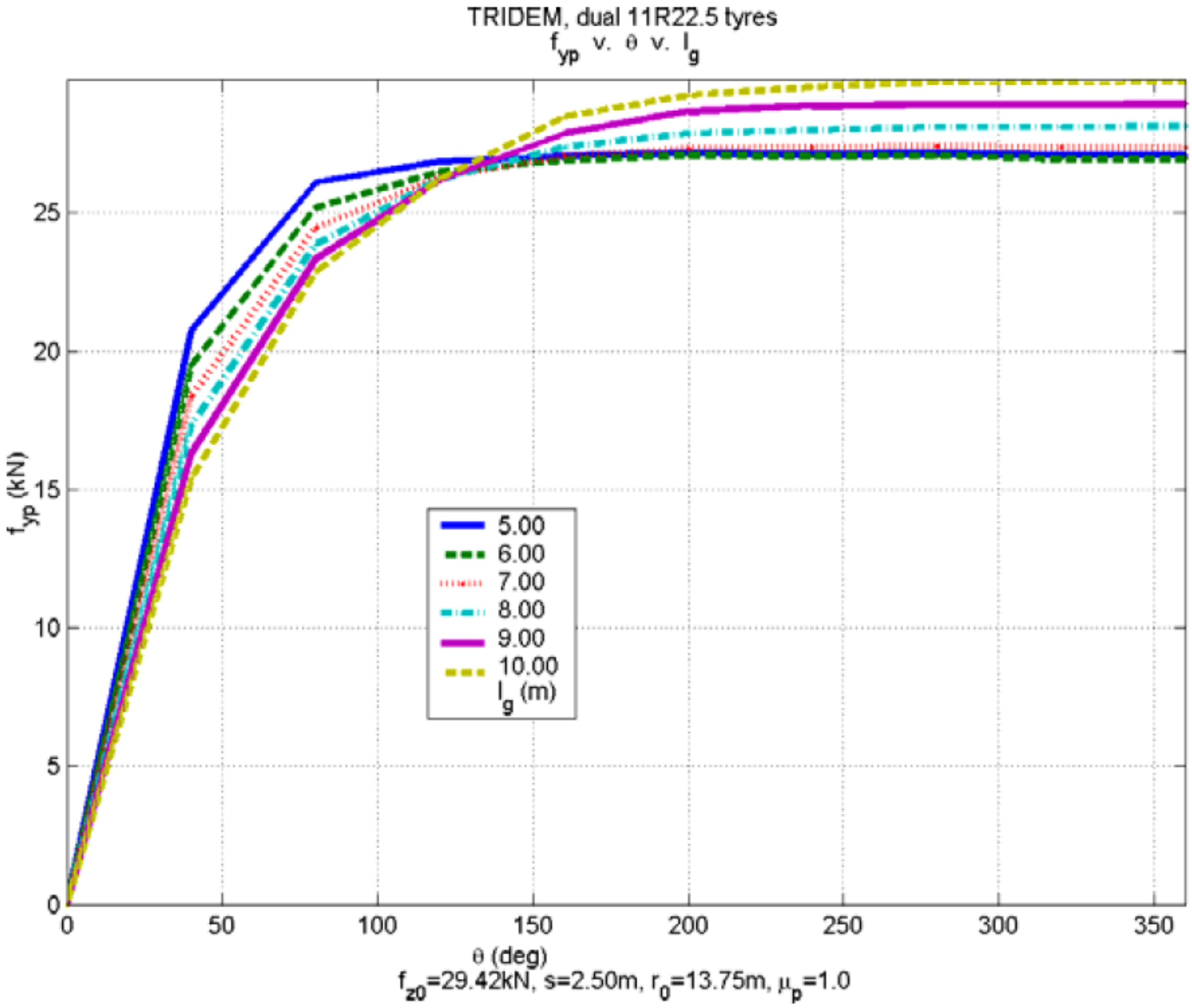
Turn radius = 13.75 m

f_{yp} = peak scuffing force

f_{z0} = vertical force on the tyre group

Source: de Pont and Taramoeroa (2008).

Figure 5.2: Peak scuffing force against angle of turn for different wheelbases



Turn radius = 13.75 m

Static wheel load = 29.42 kN

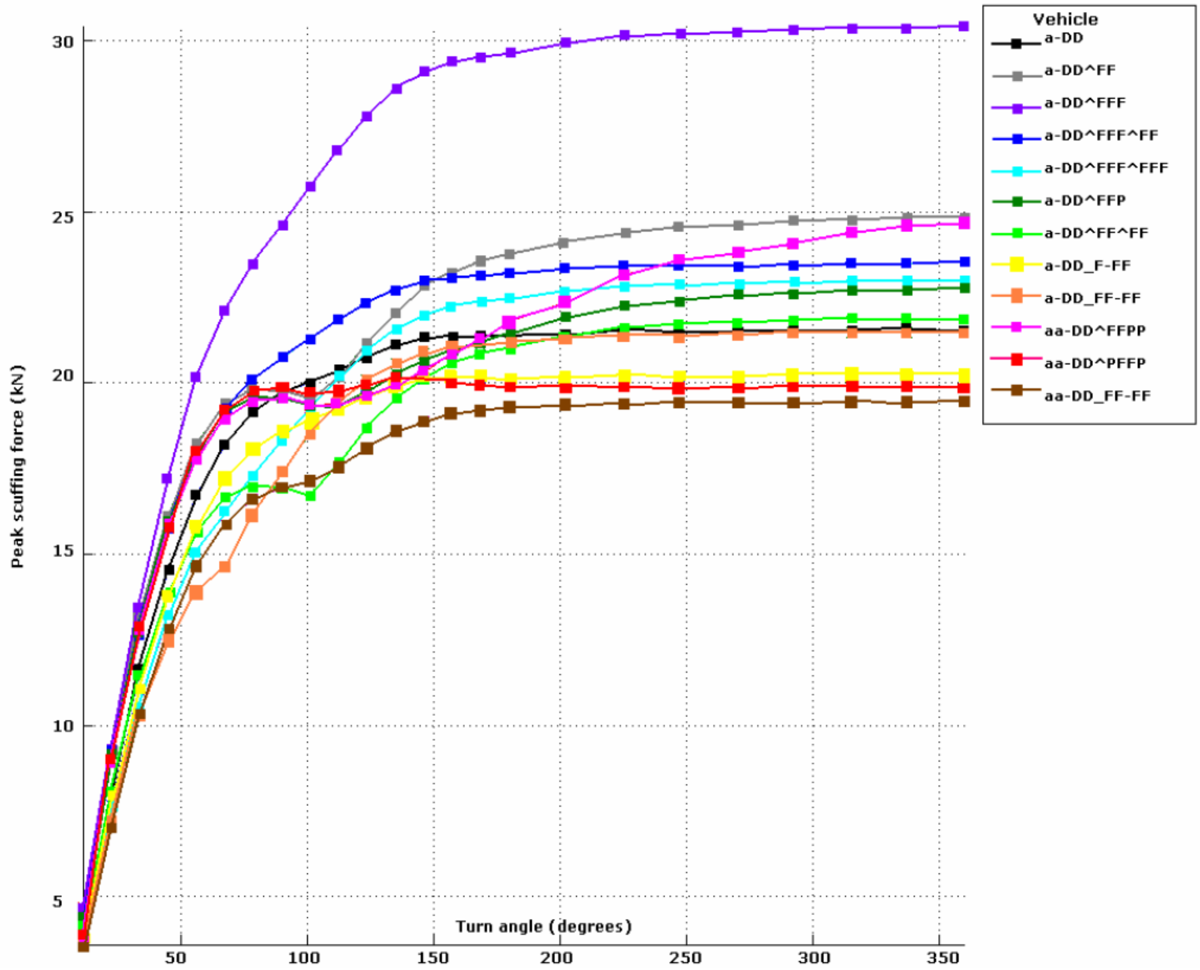
f_{yp} = peak scuffing force

Θ = angle of turn

Source: de Pont and Taramoeroa (2008).

Figure 5.3 shows the results of computer simulations on the effect of different axle types and vehicle configurations on scuffing forces by Taramoeroa and de Pont (2008). The description of axle types, tyre configurations and coupling types are included in Table 5.2 and Table 5.3. The vehicle description is included in Table 5.4.

Figure 5.3: Peak scuffing force vs turn angle by vehicle type (11R22.5 tyres)



TAC = tyre-axle-coupling

Source: Taramoeroa and de Pont (2008).

Table 5.2: Description of axle types and tyre configurations with the designated tyre-axle-coupling characters

Axle type	Tyre configuration	
	Single	Dual
Actively steered axle	a	A
Passively steered axle (self-steering axle)	p	P
Non-steering drive axle	d	D
Non-steering fixed axle	f	F

Source: Taramoeroa and de Pont (2008).

Table 5.3: Description of coupling types with the designated tyre-axle-coupling character

Coupling type	Coupling
Chassis	–
Fifth wheel, kingpin, and semi-trailer chassis	^
Tow-eye, drawbar, and turntable (dooly)	_

Source: Taramoeroa and de Pont (2008).

Table 5.4: Tyre-axle-coupling (TAC) sequence and vehicle description

TAC sequence	Vehicle description
a-DD	Three-axle truck
a-DD^FF	Five-axle tractor semi-trailer (tandem-semi)
a-DD^FFF & a-DD^fff	Six-axle tractor semi-trailer (tridem-semi)*
a-DD^FFF^FF & a-DD^fff^ff	Eight-axle B-train*
a-DD^FFF^FFF	Nine-axle B-train
a-DD^FFP	Six-axle tractor semi-trailer (tridem-semi) with a single rear-mounted self-steering axle
a-DD^FF^FF	Seven-axle B-train
a-DD_F-FF	Six-axle truck and full-trailer
a-DD_FF-FF	Seven-axle truck and full-trailer
aa-DD^FFPP & aa-DD^ffpp	Eight-axle tractor semi-trailer (quad-semi) with twin rear-mounted self-steering axles*
aa-DD^PFFP	Eight-axle tractor semi-trailer (quad-semi) with front rear-mounted self-steering axles
aa-DD_FF-FF & aa-DD_ff-ff	Eight-axle truck and full-trailer*

* Reference vehicles.

Source: Taramoeroa and de Pont (2008).

Table 5.5 shows the effects of different tyre configurations on the trailers of the four reference vehicles on a 360º steady-state low-speed turn with a turn radius of 18.75 m.

Table 5.5: Effects of different trailer tyres on the reference vehicles undergoing a 360º steady-state turn at a radius of 18.75 m

Tyres	Vehicle description	F_{yp}	F_{zp}	F_{yp}/f_{zp}	Δ_{ypt} (%)	Δ_{zp} (%)	a_p (deg)	Axle
11R22.5	aa-DD_FF-FF	13.2	36.4	0.362	0	24	2.8	7
245/70R19.5	aa-DD_FF-FF	12.9	35.3	0.366	–2	20	2.8	7
385/65R22.5	aa-DD_ff-ff	13.1	35.6	0.367	–1	21	2.8	7
11R22.5	a-DD^FFF^FF	18.1	32.7	0.554	0	36	5.2	4
245/70R19.5	a-DD^FFF^FF	18.5	31.6	0.584	2	32	5.2	4
385/65R22.5	a-DD^fff^ff	20.1	32.3	0.622	11	35	5.2	4
11R22.5	a-DD^FFF	22.8	40.3	0.567	0	37	5.7	4
245/70R19.5	a-DD^FFF	23.8	39.1	0.608	4	33	5.7	4
385/65R22.5	a-DD^fff	26.1	40.1	0.651	14	36	5.7	4
11R22.5	aa-DD^FFPP	17.1	33.1	0.518	0	35	4.4	5

Tyres	Vehicle description	F_{yp}	F_{zp}	F_{yp}/f_{zp}	Δ_{ypt} (%)	Δ_{zp} (%)	a_p (deg)	Axle
245/70R19.5	aa-DD^FFPP	17.1	31.6	0.541	0	29	4.6	5
385/65R22.5	aa-DD^ffpp	17.0	31.9	0.534	–1	30	4.2	5

Notes:
- 11R22.5 and 245/70R19.5 tyres are in dual configuration, 385/65R22.5 tyre is configured as wide-singles.
- Single and dual 11R22.5 tyres are used on the steer and drive axles of all the powered units.
- f_{yp} = peak scuffing force.
- f_{zp} = vertical force on the tyre group.
- Δ_{ypt} = percentage change in peak scuffing force of a tyre configuration relative to dual 11R22.5 tyres.
- Δ_{zp} = lateral load transfer expressed as a percentage of the static vertical force.
- a_p = slip angle of the tyre group on which the peak scuffing force occurred.

Source: Taramoeroa and de Pont (2008).

The main findings from the work Taramoeroa and de Pont (2008) performed are summarised below.

- Shearing forces are directly proportional to vertical load.
- For typical in-service angles of turn (up to about 110º), the highest scuffing forces are generated by shorter wheelbase vehicles, because the longer wheelbase vehicles need a greater turn angle to reach steady state off tracking. For large turn angles, highest scuffing forces are generated by larger wheelbase vehicles.
- Self-steering axles can significantly reduce scuffing forces for smaller angles of turn but for large angles of turn, they are likely to reach their steer angle limits at which time they respond like non-steering axles.
- For the same axle group weight and spread, wide-single tyres generate higher scuffing forces than dual tyres.
- Scuffing forces increase with increasing axle group spread.
- For vehicles without self-steering axles, the highest steady-state scuffing forces are generated by tractor semi-trailers followed by B-trains, then truck and full-trailers, and then single-unit trucks (refer Figure 5.3).
- Cornering stiffness (‘*the negative of the slope of the transverse force versus slip angle curve*’) and scuffing forces increase with increasing tyre width of rim diameter for the same tyre height, as the profile of the tyre is lowered.
- The influence of inflation pressure on cornering stiffness varies as a function of the carcass design.
- The slip angle and cornering force on the lead axle of a group are greater than in other tyres in the group.

5.3 Measuring Horizontal Stresses and Quantifying its Detrimental Effects

Austroads has recently published a report entitled *Heavy Vehicle Horizontal Stresses and Pavement Surface Performance* (Austroads 2017a). This report presents the findings of an Austroads project (AT1540) aimed at studying failure mechanisms of pavement surfacings resulting from horizontal stresses generated by heavy vehicle turning, acceleration and braking movements. The project included development and commissioning of a mobile tyre force and surface wear test rig (or Surface Wear Trailer – SWT). It consists of

> a semi-trailer that was: capable of applying any desired combination of vertical and horizontal stresses to real pavement surfacings; capable of replicating the stresses applied to the pavement surface by any single or dual tyre from any steer, drive or trailer wheel from any heavy vehicle combination undertaking any manoeuvre in an accurate and, most importantly, repeatable manner.

As part of the project, field trials were conducted in Victoria, New South Wales and the Australian Capital Territory using the SWT, with follow-up field trials in Victoria and Queensland.

The main findings of Austroads(2017a) are listed below:

- The main factors contributing to horizontal stresses are wheel loading, strain at the tyre-pavement interface imposed by the motion of the wheel, coefficient of friction between the pavement surface and the tyre.
- ‘A horizontal force of 12 kN per (standard trailer) tyre for surfaces in the range 25 °C to 50 °C represents a threshold, below which all surfaces demonstrated adequate resistance to wear
- Temperature is an important factor; when the surface temperature was below 40 °C there was less damage
- As expected, surfacings containing PMBs were more resistance (sic) to wear than surfacings containing Class 170 bitumen’.

It is noted that the horizontal force of 12 kN is based on a limited set of data. The authors recommend its application to a wider range of sprayed seal surfacings and that operating conditions are further investigated.

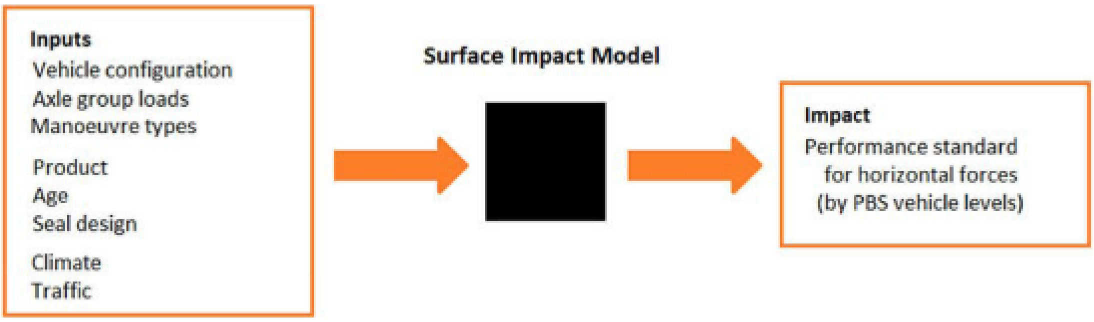
The report includes a few prescriptive requirements to minimise damage from turning movements, as listed below. The first two requirements are already part of the Main Roads Performance Based Standards (PBS) Scheme (Main Roads Western Australia 2016):

- ’tandem axle groups with an axle spacing of more than 2 m must have at least one steerable axle
- for axle groups with three or more axles and a spread of greater than 3.2 m all axles beyond the 3.2 m spread must be steerable.’
- ‘entrance-to-roadway requirements to force heavy vehicles to have passed the peak impact point of the turning manoeuvre before entering the roadway (e.g. for the angle of entry to be no greater than, say, 40 degrees), placing the peak impact on the property; or
- if no ‘soft’ entry as described above is possible, then ‘hard’ entries are allowed by permit only, with appropriate pricing to provide for the costs of installing a section of asphalt or concrete and its ongoing maintenance.’

The authors also suggest limiting heavy vehicle traffic in hot days, and the use of stronger seals (PMBs or bitumen with added crumb rubber), asphalt or concrete in areas of high stress.

Finally, the authors suggest the development of a surface impact model, as illustrated in Figure 5.4, which would provide further knowledge to verify (and potentially improve) current guidelines such as illustrated in Figure 5.5.

Figure 5.4: Inputs and outputs of a desired surface impact model



Source: Austroads (2017a).

Figure 5.5: Preliminary seal selection guide

<table>
<tr><th rowspan="2"></th><th>Design traffic v/l/d</th><th colspan="4">< 200</th><th colspan="4">201–750</th><th colspan="4">–2000</th><th colspan="4">2001–5000</th><th colspan="4">> 5000</th></tr>
<tr><th>Equivalent heavy vehicles %</th><th>< 15</th><th>15/26</th><th>26/45</th><th>> 45</th><th>< 15</th><th>15/26</th><th>26/45</th><th>> 45</th><th>< 15</th><th>15/26</th><th>26/45</th><th>> 45</th><th>< 15</th><th>15/26</th><th>26/45</th><th>> 45</th><th>< 15</th><th>15/26</th><th>26/45</th><th>> 45</th></tr>
<tr><td rowspan="3">Rural: roads, highways and freeways – no high stress areas</td><td>Climate* – hot</td><td colspan="3">S/S</td><td colspan="9">D/D
HSS1</td><td colspan="3">HSS2</td><td colspan="4">XSS</td><td>XSS^</td></tr>
<tr><td>Temperate</td><td colspan="5">S/S</td><td colspan="10">D/D
HSS1</td><td colspan="2">HSS2</td><td colspan="3">XSS</td></tr>
<tr><td>Cold</td><td colspan="8">S/S</td><td colspan="5">D/D
HSS1</td><td colspan="6">HSS2</td><td>XSS</td></tr>
<tr><td rowspan="3">High stress locations</td><td>Small radius curves, roundabouts, driveways, turning lanes, intersections</td><td colspan="3">D/D</td><td>HSS2</td><td colspan="2">D/D</td><td colspan="5">HSS2</td><td colspan="3">XXS</td><td colspan="6">NO SEAL SUITABLE^</td></tr>
<tr><td>Grades# > 5%</td><td colspan="2">S/S</td><td colspan="11">D/D
HSS1</td><td colspan="3">HSS2</td><td colspan="3">XSS</td><td>XSS^</td></tr>
<tr><td>Cracked pavements</td><td colspan="20">• SAM – preferred SAM is a S/S (14 or 10 mm) but a D/D may be required where there are also high stress conditions
• Minimum binder rate for SAM application is 1.5 L/m^2
• GRS – C170 with D/D is preferred type of GRS (14/7 mm)</td></tr>
</table>

Legend:

(green)	S/S: Single/single with C170, C320 or M500/170 binder
(yellow)	D/D: Double/double with C170, C320 or M500/170 binder
(orange)	HSS1: Single/single seal with PMB for moderately severe sites (M500/170, S10E, S15E, S35E, S45R or S15RF) and severe sites (S20E, S45R or S15RF)
(light pink)	HSS2: Double/double seal with PMD in first or both applications for medium traffic loading (M500/170, S10E, S15E, S35E, S45R or S15RF) and heavy traffic loading (S10E, S15E, S20E, S35E, S45R or S15RF)
(red)	XSS: Double/double seal with PMB in both applications (S15E, S20E, S45R or S15RF) for high stress areas. Seal performance may be inadequate under these conditions and may require alternative treatments
(grey)	Asphalt generally DGA 10 or 14 mm where and XSS sprayed seal cannot be expected to cope

*Climatic conditions are determined as per AP-T235-13 *Guide to the Selection and Use of Polymer Modified Binders and Multigrade Bitumens* (Austroads 2013b)

^Seal performance may be inadequate under these conditions and may require alternative treatments.

#Considerably steeper grades or combinations of extreme events may lead to unsatisfactory performance and may require alternative treatments.

Source: Austroads (2013a).

A research study currently being conducted by Opus Research and the NZ Transport Agency aims at understanding how sprayed seals can be improved to resist increases in horizontal shear forces. The scope of work consists of carrying out laboratory simulation of traffic shear forces by changing the following variables: treatment type (single seal, two-coat seal, racked-in seal), and pavement temperature (0 °C, 25 °C and 45 °C). The tests are conducted in the Opus circular accelerated surfacing tester (CAST), which simulates traffic shear forces in an insulated enclosure. The authors expect to assess seal volume changes, aggregate loss and reorientation, location and quantum of plucking or stripping for the different combinations of seal type and temperature (Neaylon, Harrow & van den Kerkhof 2017).

De Beer, Fisher and Sadzik (2008) measured forces and stresses of a slow-moving, free-rolling pneumatic rubber tyre with a Stress-In-Motion (SIM) measuring device and found stresses on rough textured surfaces to be 16 to 32% higher than on a relatively smooth surface.

5.4 Software Packages

There are a few software packages encountered in the literature for modelling the development of horizontal stresses in the pavement, as summarised in Table 5.6.

Table 5.6: Summary of software packages to model the development of horizontal stresses in the pavement

Reference	Software packages
Neaylon, Harrow and van den Kerkhof (2017)	▪ Pavement Analysis Using Nonlinear Damage Approach (PANDA): developed at the University of Illinois – Champaign, simulates the complex thermos-viscoelastic-viscoplastic-viscodamage responses of the pavement to mechanical and environmental loads, based on a database of tyre contact areas and stresses obtained from tyre finite element simulations (Shakiba et al. 2016). ▪ TyreStress: developed by CSIR to provide estimations of tyre contact stress distributions in the longitudinal, lateral and vertical directions. ▪ Tyreview, developed by the Texas Transportation Institute, similar to TyreStress (Fernando et al. 2006).
Prem et al. (2000)	▪ Multi-body dynamic systems simulation package ADAMS (Mechanical Dynamics Inc) – allows modelling pavement loading for different vehicle configurations and situations, including acceleration from rest, constant speed and turning.

6 TYRE CONTACT AREA AND PRESSURE

Tyre contact area and pressure vary with dynamic tyre forces, temperature and speed (Gillespie et al. 1993, Cebon 1999, Neaylon, Harrow & van den Kerkhof 2017). The contact area increases with temperature and decreases with vehicle speed (Neaylon, Harrow & van den Kerkhof 2017).

The Austroads pavement design guide (Moffatt 2017), considers a simplified circular contact area with a constant pressure. The net contact area (area between tyre rubber and pavement excluding grooves) is assumed to be 69% of the gross contact area. Load radii is assumed based on data collected by a COST project (COST 2001), which represent average values for several manufacturers' representative of the European truck fleet in 2000. COST (2001) notes that the values recorded can vary for the same type of tyre with different manufacturers, over the years, with different measurement methods and due to measurement variability.

Although pavement design methods often consider a simplified circular load with constant pressure, the tyre contact area shape can be circular, elliptical or rectangular depending on the tyre type and inflation; and the pressure applied by the tyre varies over the contact area. In general, overloaded and underinflated tyres result in the highest contact stresses at the edge of the contact area, whereas high inflated tyres concentrate the loads in the centre of the contact area (De Beer et al. 2012).

It has also been observed that axle and tyre types influence the magnitude of the dynamic load. Several authors report that wide base single tyres result in lower dynamic load coefficients than dual tyres. Additionally, the lack of maintenance can lead to unequal tyre pressures within an axle group. In extreme cases, tyres with lower pressures may not even be supporting the load (COST 2001).

Although it is often assumed that the contact pressure between the tyre and the pavement is equal to the inflation pressure of the tyre, this is frequently not the case. Mean contact pressures are usually higher than the tyre inflation pressures (COST 2001, Pezo, Marshek & Hudson 1989). According to De Beer, Fisher and Kannemeyer (2004), the maximum vertical stress exceeds inflation pressure by approximately 30% for normal loading conditions and can be as high as twice the inflation pressure for extremely high levels of loading.

Some of the methods for measuring or estimating contact pressure in the tyre footprint encountered in the literature are summarised in Table 6.1.

Table 6.1: Summary of methods for measuring or estimating contact pressure and tyre footprint

References	Method	Description
COST (2001) Pezo, Marshek and Hudson (1989) Hansen et al. (1989)	Fuji-foil	Two foils placed on top of a sheet metal place, one foil has microscopic small bubbles filled with ink and the other foil acts as blotting paper; the tyre footprint for different contact pressures is observed as different shades of red colour, which are then scanned and scaled. This method only measures static load.
COST (2001) Rose and Guenther (2009)	Tekscan	Piezoelectric pressure sensors measuring 0.5 cm x 0.5 cm with measurements taken 127 times a second. This method can measure static and dynamic loads.
De Beer, Fisher and Kannemeyer (2004) Fernando et al. (2006)	Stress-in-Motion (SIM)	Measuring pad developed by CSIR composed by an array of tri-axial load cells at 17 mm centre-to-centre measuring vertical, lateral and longitudinal loads. This method can measure static and dynamic loads.

References	Method	Description
Fernando et al. (2006)	TireView	Computer software that provides estimates of tyre contact area and stress distribution at the tyre-pavement interface as a function of tyre type, load and inflation pressure based on a database of measured tyre contact stresses. It is noted that the predictions are specific to the tyres tested as part of the development of the software.

De Beer et al. (2012) investigated the effect of considering actual observed distribution of stress underneath a tyre instead of the traditional assumption that the tyre load is equally distributed over an area. Tyre-pavement contact stresses were quantified using the SIM technology (refer Table 6.1). The study concluded that consideration of the actual distribution of stresses can result in up to 94% reductions in predicted asphalt life. The authors stress the importance of better representing actual tyre contact stress in pavement design procedures.

The effect of tyre contact pressure distributions is likely to have greater effect near the surface and diminish with depth (Fernando et al. 2006).

7 SUMMARY OF LITERATURE REVIEW

Consideration of the dynamic effect of heavy vehicles on pavement performance is a complex issue. This report presents the literature review conducted to investigate the many factors involved, including:

- variations in the load magnitude imparted on the pavement (Section 2), which varies with:
  - road geometry
  - pavement roughness
  - heavy vehicle properties (axle and tyre types, tyre pressure, suspension etc.)
  - traffic movement (straight traffic, turning, accelerating or braking)
  - traffic speed
- the effect of dynamic load magnitudes on the pavement (Section 3)
- accumulation of pore water pressure (Section 4.2.1 and Section 4.3.2)
- the viscoelastic behaviour of bituminous materials (Section 4.3.1)
- principal stress rotation (Section 4.2.2)
- surface damage due to horizontal shear stresses (Section 5)
- tyre contact area and pressure (Section 6).

Several studies have been conducted to understand the increase in load magnitude that is imparted to the pavement due to dynamic effects. The literature review highlighted that there are still knowledge gaps in understanding the relationship between heavy vehicle suspension characteristics, dynamic wheels loads and pavement wear.

The lack of knowledge regarding the relationship between suspension characteristics and dynamic loading, the relationship between suspension frequency and damping, and the resulting dynamic loading applied to the pavement, cannot be defined at this time.

Most of the research conducted in measuring dynamic wheel loads has found that traditional on-board sensors are not able to 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 several 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 cannot be measured during field testing provides options of overcoming practical limitations.

The research has confirmed that the practical issues of conducting a roadside test that must adhere to the requirements of VSB11 has rendered such options unviable. The practical issues relating to removal of shock absorbers and loading the vehicle to the specified test weight are unlikely to be overcome, 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 a period. Alternative options that utilise on-board technologies provide a most cost-effective solution.

Many authors have investigated the effect of dynamic load magnitudes on pavement damage. These studies consider existing relationships between stresses and strains caused by a load magnitude and pavement damage (usually a power-law relationship). The mechanical behaviour of the pavement materials subjected to dynamic load effects other than the change in load magnitude is often not considered.

Limited studies have investigated the effect of pore water pressure build-up, principal stress rotation, rest periods and the viscoelastic behaviour of the pavement when subjected to different axle types and spacing (Section 4). Although there are several models and software packages that allow modelling of viscoelastic materials, there is no widely accepted methodology for taking into consideration these effects on pavement deterioration models and pavement design.

The effect of dynamic loads on pavement surfacing has been a topic of different studies (Section 5). There are a few software packages available that can estimate the magnitude of the horizontal loads imparted on the pavement; however, there are no readily available methodologies to predict the damage caused by these loads. The current state of knowledge in this area only allows for prescriptive requirements to be imposed on heavy vehicle operators and general guidelines to be available for pavement designers. There is no quantitative method for the design of seals based on expected shear stress magnitudes.

Regarding tyre contact area and pressure, a few studies emphasise the importance of modelling the actual contact area and distribution of stresses rather than assuming the loads to be circular/rectangular with a constant stress distribution. Different methods of measuring or estimating tyre contact area and pressure distribution are available, but there is no established procedure for their consideration in pavement design analysis.

8 FURTHER STUDIES

As previously mentioned, there are many different aspects involved in considering the effect of heavy vehicle dynamic loading on pavements. A list of ideas for further studies to allow further understanding of these aspects and potential implementation of learnings is presented below:

1. Load magnitudes imparted on the pavement due to dynamic loads:
   - Development of a method for estimating the dynamic loads under trucks tyres, including the variation in applied wheel loads due to interactions between axles as axle spacing varies for different axle configurations/tyre types/suspension.

     This will address one aspect of the existing knowledge gaps required to understand dynamic wheel loads and the relationship with pavement wear. These gaps are:
     - existing knowledge gaps and disagreement on the link between performance characteristics of a suspension, road-friendliness and the amount of pavement wear
     - lack of a cost-effective approach that does not involve removal of components or major interruption to the vehicle.

     Any subsequent research project must either acknowledge these knowledge gaps, address and resolve them directly or alternatively identify an innovative solution that is not hindered by these obstacles.
2. Pavement damage caused by dynamic loads:
   - Development of pavement damage models based on predicted dynamic loads using accepted pavement damage relationships (4^{th} power of the dynamic load for wear/damage due to rutting and 5^{th} power of the dynamic load for wear/damage due to asphalt fatigue (COST 1999) for inclusion in FAMLIT (Freight Axle Mass Limits Investigation Tool) software.
   - This would allow quantification of costs of pavement damage caused by the increase in load magnitudes caused by dynamic effects.
3. Pore water pressure accumulation due to cyclic loading:
   - Laboratory testing to investigate the effect of different axle spacing on the development of pore water pressures for different granular and asphalt materials.
   - Testing at the accelerated loading facility for different axle and pavement configurations/materials (including different spacing between individual axles of an axle group) with pore water pressure measurements.
   - Development of models to predict pore water pressure accumulation and correlate those to pavement damage based on the observations of the accelerated load testing.
4. Viscoelastic behaviour of asphalt pavements:
   - Modelling of different scenarios using a software package that allows consideration of the viscoelastic properties of asphalt varying vehicle speed and axle configurations to determine relative pavement responses.
   - Testing at the accelerated loading facility for different axle and asphalt pavement configurations, including different spacing between individual axles of an axle group.
   - Development or calibration of pavement deterioration models correlating the response obtained from the modelling with the pavement responses and deterioration observed in the accelerated loading testing.

5. Horizontal/shear forces on pavement surfacing damage:
   - Testing of a wider range of sprayed seal surfacings (including binder types) and operating conditions (following Austroads No. AP-T325-17).
   - Development of a surface impact model to predict seal performance of different surfacing types as a function of vehicle configuration, axle group loads, manoeuvre types, age, seal design, climate and traffic.
   - Development of a mechanistic performance model relating horizontal shear forces to seal performance.
6. Tyre contact area and pressure:
   - Measuring of contact area and pressure distribution for different expected scenarios (tyre types, axle types, vehicle speeds and movements).
   - Modelling of measured contact area and pressure distribution to quantify its effects on typical pavement responses.
   - Development of a methodology or interim measure to account for refined contact area and pressure distribution in pavement design procedures.

The findings of the literature review, as well as these future study ideas, will be discussed with Main Roads. If required, a more detailed scope of work to pursue some of these studies can be developed.

It should be noted, however, that accepted pavement design procedures are calibrated for the current assumptions made in the design. For example, the Austroads design procedure makes use of empirical charts and laboratory-to-field shift factors that correlate assumed static load calculations with observations in the field. These are discussed and agreed based on practitioners' experience. Any changes to the design methodology, including those related to consideration of dynamic loading effects on pavement responses and performance, would need to be validated by observed performance in the field. Empirical charts and laboratory-to-field shift factors need to be reassessed to ensure that additional considerations in the design methodology provide realistic results in terms of pavement damage. This process takes a long time and involves considerable costs.

Based on our understanding of Main Roads requirements in developing this project, the ideas that are expected to provide more benefits and be implemented faster are listed as 1 and 2 above.

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