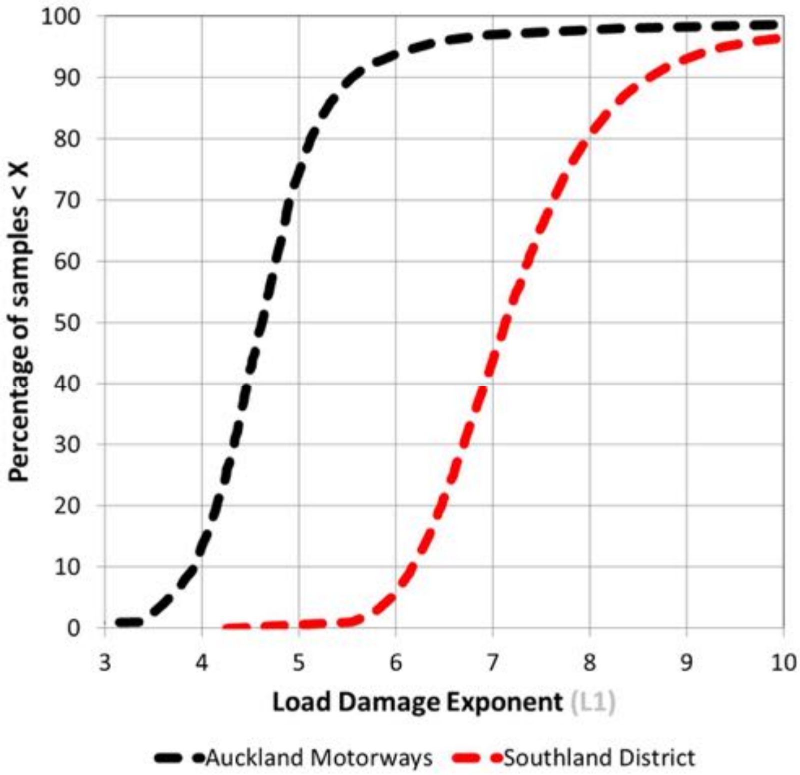
Pavement Structural Damage from Single versus Twin Tyres

Pavement Analytics Group 2016
GeoSolve

AT A GLANCE

A detailed study of the performance of low-volume roads in New Zealand has been carried out, using in situ testing of in-service roads and an evidence based procedure for the practical evaluation of pavement structural damage from alternative tyre configurations and loadings. The issues studied are the effects of increasing loads on specific axles or using single instead of twin tyres as those changes tend to be more significant than increasing the gross mass of vehicles where the number of axles can be increased also.

The study is different in that it uses in situ testing of in service local roads in their exposed environments rather than accelerated testing of artificial test tracks. It systematically quantifies the substantial increase in damage that can be expected on unbound granular basecourses with thin seal surfacing where pavement deflections are moderate or high. It is not appropriate to draw on overseas studies of pavements with low deflections or where thick structural asphalt is used for surfacing.



One key factor for determining the relative damage imposed by a given increase in load on a single tyre is the "load damage exponent" from which the increased cost of structural wear is readily quantified.

The load damage exponent must relate to the layer which will govern the pavement life (first to reach a terminal condition) and the distress mode occurring in that layer.

The cumulative distribution curves for load damage exponents for the Auckland Motorways and all Southland District Roads tested over the last two decades, provide definitive evidence that the load damage exponents for each network differ substantially. Advanced statistical analysis methods developed and refined very recently, for the first time enable RCA's to readily quantify cost implications of any proposal for increased loading on the entire network, or on individual roads, in a rigorous and justifiable manner.

Pavement Structural Damage from Single versus Twin Tyres

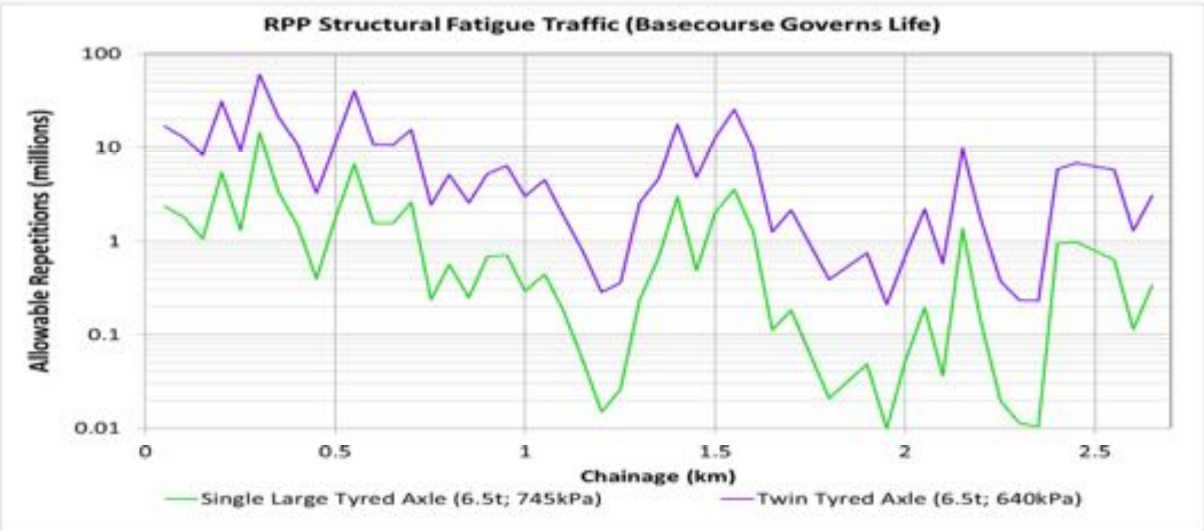
ABSTRACT

An issue arising for local authority asset managers is whether the same axle load with customary tyre pressures, results in more damage from single large tyres than from twin tyres.

Detailed analysis of local roads has been carried out for Southland District, to establish a reliable pavement life model for its unbound granular pavements, using regional precedent performance (RPP) of the entire network. This calibrated mechanistic model enables comparison of the damage from alternative axle configurations, and one road, nominated as a representative case for local low volume unbound granular pavements has been examined in detail.

Structural analysis of this road, when considering only the subgrade (as with the Austroads method), indicates there is little difference between the two axle configurations (single 7.2 t versus twin tyres with 8.2 t) in terms of expected number of axle load repetitions until a terminal condition is reached.

However, the basecourse of this road is only of moderate quality and forms the critical layer (governing pavement life as it has the capacity for lesser load repetitions than the subgrade). Much of this specific road indicates a tenfold decrease in pavement life when changing to a single large tyred axle as shown below:



In Southland's low volume unbound granular pavements where the critical layer may be either the subgrade or one of the aggregate layers, the decrease in allowable repetitions for a single tyre will alternate between a factor of about 1 and 20 or more. The calculations are straightforward for this network because a calibrated mechanistic model has been developed. These graphs (or an average damage factor and/or cost consequence for each road) can now be readily generated for the entire network, allowing informed assessment of single tyre damage or any other set of vehicle/tyre configurations, from first principles, rather than empirically.

The prediction of pavement performance based on mechanistic structural analysis provides reliability that cannot be obtained using the empirical "Structural Number" approach now discouraged by US authorities (NCHRP).

Summary

Various studies have concluded there are only minor differences in pavement wear for single large tyres versus the same load on twin tyres. However these studies mostly relate to (i) accelerated trafficking in protected environments (ii) thick structural asphalt pavements and (iii) subject to heavy traffic loading. Because few existing pavements in Southland District are in these categories, a study has been carried out on what is expected to be a representative, in-service unbound granular pavement with thin seal surfacing designed for low-volume traffic.

The study, comparing damage from a standard twin tyred axle to a single large tyre, has been carried out using state-of-the-art mechanistic analyses to determine what impact this arrangement (and others like it) will have on the deterioration rate for a given pavement. The proposed technique (using stresses and strains in each pavement layer) reliably quantifies specific load damage exponents and consequent pavement wear under the prescribed axle load(s) or load combination. Pavement fatigue parameters have been calculated based on regional precedent performance of the network. Variables including relevant heavy vehicle types, lane-width, climate, subgrade characteristics, aggregate sources, as well as customary construction and maintenance practices, are all inherently taken into account to some degree with this method. The distinct advantage of this technique over traditional methods (such as accelerated test track loading in the CAPTIF environment) is the ability to incorporate in-service precedent performance of all roads in any given region, for more reliable forecasting of future performance. The internationally peer-reviewed and endorsed methodology is the first of its kind globally, and provides an economic, rapid, and sound basis for HPMV decision making.

The calculations confirm that for many roads (particularly where there is thick structural asphalt and where the subgrade governs the life of the road) it can be reliably established that for the same axle load, the number of passes, before structural rehabilitation will be required, changes minimally when using single large tyres compared to standard twins with similar axle loads. (Damage ratio of about 1).

However, in a flexible granular pavement where the subgrade is deep and an unbound basecourse with thin surfacing forms the top layer (and governs the life of the pavement), the damage ratio can easily reach 4 or more. The increase in cost from road damage will not be to the same ratio. For example, if the subject road has over 100 years structural life with the twin tyre loading, net present value cost consequences of a change to single large tyre with the same load are minimal. However if pavement life is only 20 years, the Forward Work Programme will be significantly affected. (Costs of structural rehabilitation in this case will be "brought forward" from 20 years to 5, hence NPV cost consequences will be substantial.)

For this reason the cost consequences of two alternative tyre configurations (twin versus single) cannot be computed in isolation. The tyre condition, route and traffic intensity, are critical inputs. The tyre inflation pressure is also a key factor and the other parameters required for each treatment length on the route are (i) the mode of distress that will cause a terminal condition, (ii) the layer that first reaches that terminal condition, (iii) the pavement layer fatigue criteria and load damage exponent for that layer/ distress mode (iv) the life of the entire treatment length under both loading scenarios. Most of the necessary input data for this region are readily available in RAMM and this can now be used with specifically developed software to readily compute the cost consequences of any alternative loading/tyre configuration scenario.

Homestead Rd, nominated as a representative unbound granular pavement, gave a damage ratio of 3.7 (for 7.2 tonne single versus 8.2 tonne twin tyred axle) using customary tyre pressures for trucks. If the same load is used on each axle, the damage ratio is 10 or more. The high values are primarily due to the unbound basecourse being the critical layer (governing pavement life). If the subgrade happened to be the critical layer, the difference in damage imposed by either axle at the same load would be much less.

Introduction

Single axles with "single large" tyres[1], or "super-single" tyres[2], are used by heavy commercial vehicles (HCVs) as a more economical alternative to standard twin-tyred axles. Concerns have been raised on appropriate road user charges or weight limits for such tyres in view of perceived higher rates of pavement deterioration[3] expected from their use.

For unbound granular pavements, Austroads determines the equivalency of various axle types from the relative deflection induced under the respective loads and inflation pressures, assuming each footprint will exert uniform stress, and using a load damage exponent of 4.

Using Weigh-in-Motion data located on Auckland's southern motorway and applying Austroads power laws, Hudson & Wanty[4] concluded that heavy commercial vehicles with 6 or more axles using single tyres could cause damage up to 60% more when the 4th power law is used[5] and up to 180% more when a 7th power law is considered, compared to the same load on twin tyres.

However, those exponents apply only for specific forms of pavement. A more detailed assessment of damage caused by single tyres using in situ testing from a New Zealand network which has suitably comprehensive information on pavement structural capacity, is provided in this article.

Previous Work

A major European study (COST 334) was carried out over a decade ago comparing large singles and twin tyred axles subject to the same load. However for European pavements the average thickness of structural asphalt is 119 & 218 mm for design traffic loadings of 1 & 10 MESA respectively. Unsurprisingly that study found that for a given total load, varying the contact area (wide single versus thinner twin tyres) on such a stiff load-spreading layer caused only minor change in pavement wear. A summary by Cebon[6] indicates a range of results for the relative damage of single to twin tyres under the same load (the second column in the following figure). This indicates a wide range, for which the median appears to be a factor of about 2.5 for structural asphaltic pavements.

[1] Single large tyres are defined by NZTA as having width of at least 330mm and a rim diameter of at least 24 inches, or width of at least 355mm and a rim diameter of at least 19.5 inches

[2] NZTA refers to super-single tyres as those larger than 450 mm width. However, US and South African sources refer to "wide base tyres" or "super singles" as all tyres of at least 330 mm width. https://www.jiscmail.ac.uk/cgi-bin/webadmin?A3=ind1111&L=ROAD-TRANSPORT-TECHNOLOGY&E=base64&P=3315266&B=--_006_703D07875540E04F978A674C36D0FA580136F945AUSP01DAG0101co_&T=application%2Fvnd.openxmlformats-officedocument.wordprocessingml.document;%20name=%22CSIR-Study_FinalReport_20101020.docx%22&N=CSIR-Study_FinalReport_20101020.docx&attachment=q&XSS=3

[3] The use of super-single tyres requires a lower maximum axle load of 7200kg for a single axle set compared to 8200kg allowed for twin-tyred axles (NZ Transportation Agency, 2013).

[4] (Hudson & Wanty, 2014) highlighted a discrepancy in the maximum loads for super-single tyres in the tri-axle and quad-axle configuration set by NZTA (NZ Transportation Agency, 2013), where the same limit is used for both twin and super single tyres (therefore assuming the same damage for both axle types).

[5] Austroads Guide to Pavement Technology – Part 2 Appendix I.

[6] Cebon, D 1999, Handbook of vehicle-road interaction / David Cebon ... - Trove

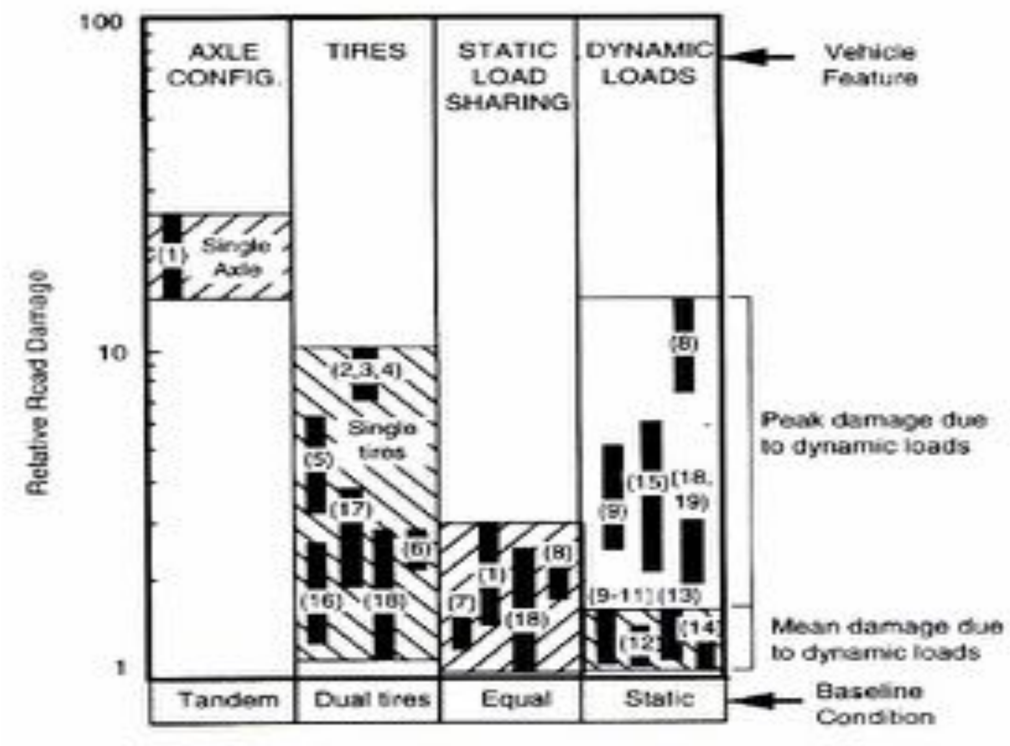


Figure 1 - Damage ratios from the same load applied to different axles, from previous studies. (Structural asphaltic pavements)

Damage ratios are largely controlled by load damage exponents for which values of 4 to 7 are indicated by Austroads for unbound granular pavements. Accelerated pavement trafficking trials[7] have reported load damage exponents in the range of 1.1 to 3.4 for local materials. These trials used (i) an artificial environment (ii) only one measure of distress (vertical surface deformation) and (iii) deformation was extrapolated rather than taken to a terminal condition. Because such low results are not consistent with internationally recognised ranges, and were not consistent with findings for in service pavements, detailed re-analyses of the raw data from the same trials were carried out using (i) widely used software that correctly accounted for non-linearity of layer moduli (ii) recognised modular ratios between successive unbound granular layers, and (iii) non- linear projection to a terminal rutting condition. This procedure resulted in a range of load damage exponents with an average of about 8, for the same data[8]. Subsequently, various other independent reviewers advised NZTA of their similar reservations for the same basic reasons: "*those findings involving the load damage exponent cannot be relied upon*" [9,10]. Further support for the reservations, is given in an LTNZ research report[11], and also in an extensive summary of load damage exponents from in situ testing of New Zealand in-service roads, showing results from all state highways and a large database of local roads[12].

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[7] Arnold G, Steven B, Alabaster, Fussell A (2005). Effect of pavement wear of increased mass limits for heavy vehicles- Concluding Report Land Transport New Zealand Research Report 281,

[8] Tonkin & Taylor (2006). LTPP Study Section 6: Re-analyses of Permanent Deformation at CAPTIF. Report to Chris Parkman, NZTA.

[9] TERNZ (2008) Methodology for Calculating the Exponent in a Pavement Wear Model, John de Pont, TERNZ Ltd,

[10] SKM Road User Charges Review Group. (2009) http://www.transport.govt.nz/assets/Import/Documents/SKM20Engineering20Advice.pdf

[11] Bailey Patrick & Jackett. Opus. (2006). Relationship between design and predicted performance of New Zealand pavements. LTNZ RR 259. https://www.nzta.govt.nz/assets/resources/research/reports/259/docs/259.pdf

[12] GeoSolve (2016). Discussion document on load damage exponents nationally. PPT to NZTA Wtn February 2016

A concise and very pertinent overview of twin-single tyre configuration effects is contained in Attachment 2, from the footnote reference.[13] Key findings are summarised in the conclusions below.

Other relevant research is an Austroads study[14] of damage from single versus twin tyres which was carried out in an ALF trial using unbound granular pavements with thin seal. The accelerated trafficking used vertical surface deformation as the primary measure of wear and a single pavement type under controlled Australian conditions with new high quality basecourse, the same material as subbase and compacted sand subgrade. These favourable conditions produced a moderately low deflection (0.7-0.8mm) under a 40 kN FWD load. Similar deflections are obtained in many of the highways in New Zealand, but much higher values are common in Southland District.

Deflection versus Stresses and Strains

The Austroads method for determining damage uses standard axle repetitions (SAR), defined as the ratio of applied axle loads to reference load is presented below.

$$SAR = \left(\frac{Load_{axle\ group}}{Load_{reference\ load\ for\ axle\ group\ type}}\right)^{load\ damage\ exponent}$$

On linear elastic unbound granular materials, Austroads considers that the above load ratio, can be determined from the ratio of pavement deflections under the corresponding loads. However, (Ullidtz, 1987) demonstrates with worked examples that deflection criteria, although simpler, are not compatible with the more fundamental strain criteria, stating: *"The process of calculating the stresses or strains complicates the structural evaluation compared to just using the deflections directly. But with the availability of modern micro computers, there is really no excuse for not doing it."*

Although contrary advice is given by Austroads for unbound pavements, Austroads does at least require comparison of strains in the critical layers of pavements with bound layers.

Damage by Single Tyres

The structural damage imposed by single tyres on pavements was assessed by comparing the vertical strains at the top of the subgrade and within the basecourse and subbase layers under the two axle types. This was done using University of Sydney's Finite Layer Elastic Analysis (FLEA5) software and DynELMOD. The DynELMOD program is basically the ELMOD engine (which has the advantage of modelling the non-linear elastic response of the pavement subgrade under given loadings) but allows more generalised treatment of dynamic response and non-linear moduli as they may be either stress or strain dependent as well as allowing the dependency to be either hardening or softening.

Falling-weight deflectometer (FWD) testing data from a section of Homestead Road nominated by local Council representatives was chosen for the study.

Tyre Size and Pressure

One implication of the use of the stress and strain criteria for pavement damage is the effect of tyre pressure on pavement damage, which is ignored in the Austroads deflection based method, but in

[13] NVF Committee Vehicles and Transports, 2008. Road Wear for Heavy Vehicles. Report 08/2008 http://www.nvfnorden.org/lisalib/getfile.aspx?itemid=261

[14] Yeo, R. (2008). Relative Pavement Wear of an Unbound Granular Pavement due to Dual Tyres and Single Tyres

mechanistic analysis 80 kN axle with twin tyres at 750 kPa are standard. The South African design standard is 80kN axle twin tyres at 520kPa. NZ Benkelman Beam is 80 kN, 420 kPa (implicit from contact area, and preferred tyre is 10x20). Australia models the 80kN Benkelman Beam tyres at 580kPa.

Typical tyre pressures (customarily reported in psi within the tyre service industry) were found to be highly variable across various provinces, with enquiries from the service providers returning customary inflation ranges between 586kPa (85 psi) to 620kPa (90 psi) for twin tyres and 648 kPa (94 psi) to 724 kPa (105 psi) for single large tyres in Otago and Southland. Milk tankers, because they have no backload, use slightly lower pressure (586 kPa). Some logging trucks adjust pressures (Bigfoot Pressure Adjustment) on their driving wheels. Some buses adopt single large tyres at the rear beneath the engine, and these are typically at 830kPa (120psi with typical tyre size 385 65 R 22.5). This is a substantial increase. Additionally, industry advice is that 20 kPa (3 but up to 5 psi) should be added for in-service temperature conditions. The pressures modelled in this assessment are shown in Table 1.

Table 1 –Tyre pressures used in our analysis

Tyre Type	Tyre Size	Tyre Pressure (kPa)
Single Large – (Trucks)	(385 65 22.5)	745
Single Large – (Buses)	(385 65 22.5)	850
Twin	(11 R 22.5)	640

Maximum Axle Loads

Maximum legal axle loads of 8.2T and 7.2T apply for twin tyred and single-large tyre axle configurations respectively. Models have been run with these limits and also, with the same load on each. (Enforcement allows a weighing tolerance of 0.5T on any one axle, so in a competitive industry the effective axle loads in practice often may be 85 kN per twin tyred or about 75 kN per large single). Of concern for near surface shear stability therefore is the comparison of the ratio of the individual effective wheel loads: the large single applies a contact pressure that is significantly (a factor of about 1.2-1.3) greater than the pressure from a standard twin tyre configuration. Of much more concern is the individual wheel load that is 75/(85/2) ie 1.76 times greater than either of the twin wheels. In combination therefore, the stresses and strains in the basecourse will increase by a factor of nearly 2. This increase is imposed in immediate proximity to the surface layer, and the forces can be accommodated effectively with a thick structural asphaltic layer which is stronger and stiffer by a factor of about 4 or more. But it is clearly a massive imposition on an unbound granular basecourse with thin chip seal surfacing, (before applying any damage exponent). This supports the observations from many experienced practitioners who have observed what is actually happening on our roads: it is neither reasonable nor realistic to apply overseas research results from twin tyres on thick structural asphaltic pavements to large single tyres on unbound granular pavements with chip-seal surfacing.

Load Damage Exponents

A recent network-wide study regional precedent performance (RPP) of Southland pavements has been undertaken, resulting in well-defined fatigue parameters and associated load damage exponents being established for each pavement layer, hence there is no need for arbitrary exponents relating to other forms of pavement. The RPP study collated the historic structural analyses carried out through New Zealand (with some regions, including Southland having close to 100,000 structural analyses). Pavement layer profiles collected from rehab related test pitting, FWD and additional sensor recordings over the last two decades were statistically analysed to establish relevant characteristics for each region, rather than defaulting to criteria derived by Austroads for Australian roads, practices and environmental conditions. An example of the effects of load damage exponent on relative damage (damage ratio) of pavement under the two axle combinations are shown in Figure 7 below.

Analysis under Design 25 year ESA.

The methodology used in this study follows state-of-the-art mechanistic analyses incorporating the latest features of European, US (MEPDG) and South African (SAMDM) practices, The state-of-the-art design from all 3 of the sources mentioned is not to rely on ESA or other “fixed equivalencies”, per se, and “each vehicle is considered with its full axle/tyre configuration (i.e. tyre/axle loading and its associated tyre inflation pressure) as input into the SAMDM. From this input, the total “life” of each layer in the pavement is calculated under static loading conditions, and the pavement life is equal to the critical layer life (i.e. lowest life found for a particular layer in the pavement). The stresses and strains (i.e. mechanistic pavement response parameters) under each wheel of the vehicle are calculated and then directly related through the associated transfer functions for pavement damage to layer life”. In all of these methodologies “the vehicle or combination of vehicles are therefore not reduced to an equivalent axle load of 80 kN, based on the crude 4th power law of relative pavement damage.”

Some departures for this study from the above recognised state-of-the-art have been:

(i) specific axle/tyre configurations have been used where possible but calibration has also called on ESA from RAMM
(ii) rather than using transfer functions from heavy vehicle simulators for accelerated pavement testing, all transfer functions have been derived from analysis of regional in situ measurements and observations of distressed treatment lengths (FWD RPP)
(iii) load damage exponents have been regionally evaluated (RPP) with multiple distress modes considered for each layer, and the specific distress mode, which is predicted to bring the critical layer to its terminal condition, is used to assign the governing load damage exponent.

A detailed analysis of Homestead Rd has been carried out (Attachment 1), and a summary of the relevant load damage exponents is shown below. Figure 2 shows the remaining life of this section of road and the exponents in Figure 3. The basecourse, also with the higher load damage exponent, is shown to be the critical layer.

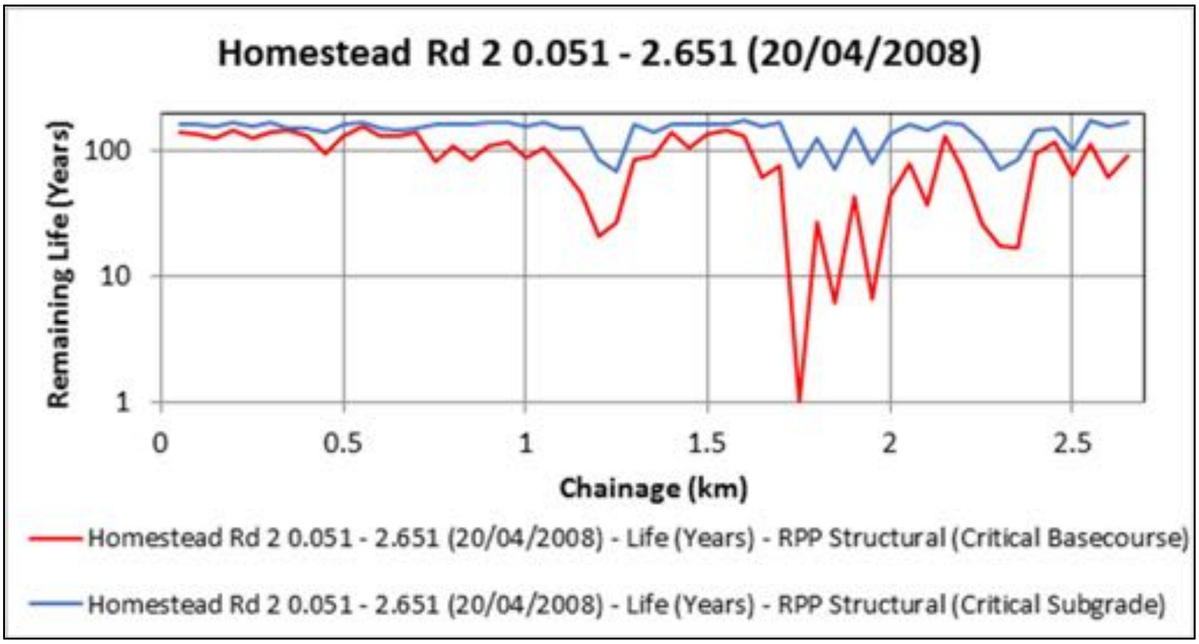

Figure 2 - Remaining life of the basecourse and subgrade for Homestead Rd. The lower of the two values (basecourse in this instance) governs the pavement life.

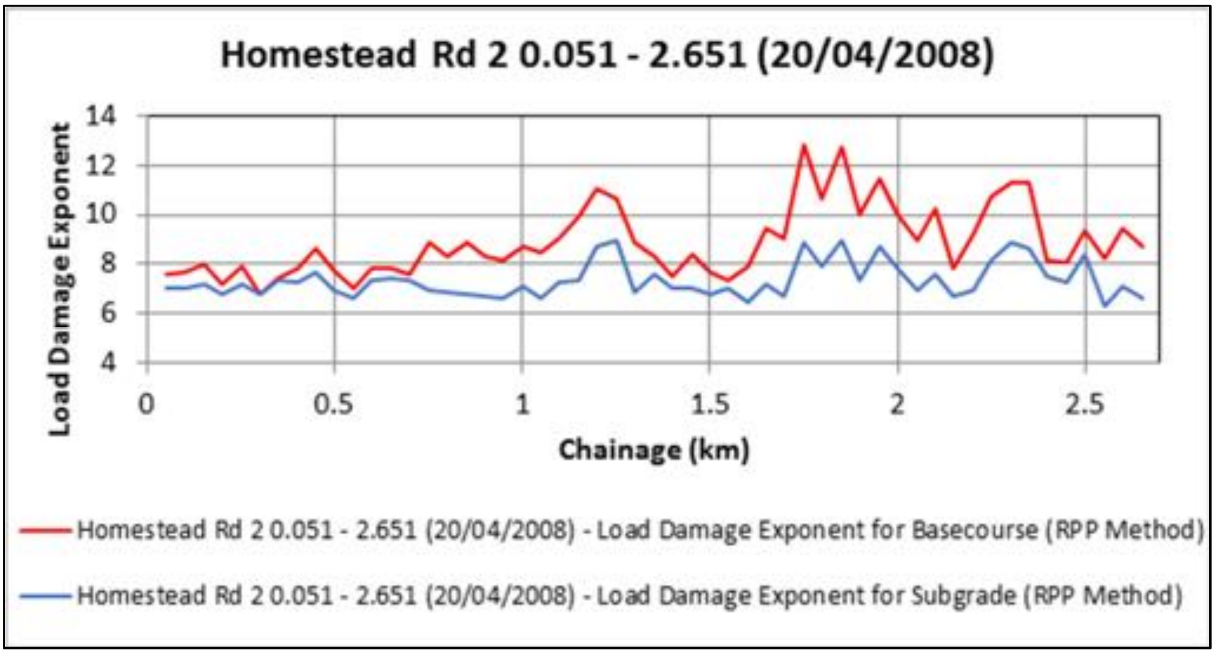

Figure 3 - Load damage exponents for basecourse and subgrade for Homestead Rd, showing that LDE's of mostly 8 to 12 (for basecourse) apply typically on this road.

Normally the characteristic points on the road in the vicinity of the 10th percentile structural capacity, are used to determine the pavement life and relevant critical layer, in this case being the basecourse (although the same layer is critical for full length here).

Damage applied to a single (characteristic) point on Homestead Rd.

The single to twin tyre damage ratio is calculated using the formula below. Table 2 shows the damage ratio between single large and twin tyred axles at the characteristic point. The results show similarity in the increase in damage by the single tyre except for the subgrade layer, where the non-linearity of the subgrade modelled by DynELMOD shows a reduction in damage to the subgrade for single large tyred axles (being a reflection of the reduced axle load from 8.2 to 7.2 t.) FLEA5 on the other hand cannot handle non-linearity, and gives a contrary result.

$$Damage\ Ratio = \left(\frac{vertical\ strain_{single\ large\ tyre}}{vertical\ strain_{dual\ tyre}}\right)^{load\ damage\ exponent}$$

Table 2 – Damage ratio using FLEA5 and DynELMOD software packages

	FLEA5				DynELMOD			
Layer	**Single Large Tyre Vertical Micro strain**	**Twin Tyre Vertical Micro strain**	**Damage Exponent**	**Damage Ratio**	**Single Large Tyre Vertical Micro strain**	**Twin Tyre Vertical Micro strain**	**Load Damage Exponent (RPP)**	**Damage Ratio**
Base-course	2340 (2740)	2050	9.7	3.7 (16.9)	2960 (3410)	2580	9.7	3.7 (14.5)
Top of Sub-grade	3240 (3260)	2960	9.4	2.4 (2.5)	3540 (3570)	3740	9.4	0.6 (0.6)
Note: Values in brackets () show microstrains and damage under loading from a super-single tyre as used for buses (inflated to 850kPa).								

The above results indicate marked additional damage can be expected with higher inflation pressure on this particular road, where the basecourse is the critical layer.

A preliminary consideration of the intermediate (subbase) layer(s) indicated damage ratios even greater than those for the basecourse, so the damage ratios should be regarded as a lower bound.

Analysis of the Full Length of Homestead Rd with Nominated Vehicles

A 9 axle truck-trailer combination was nominated as a trial case for comparing damage between use of single and twin tyred axles on a 50MAX vehicle, (where the gross weight is constant) as shown in

Figure 4 below.

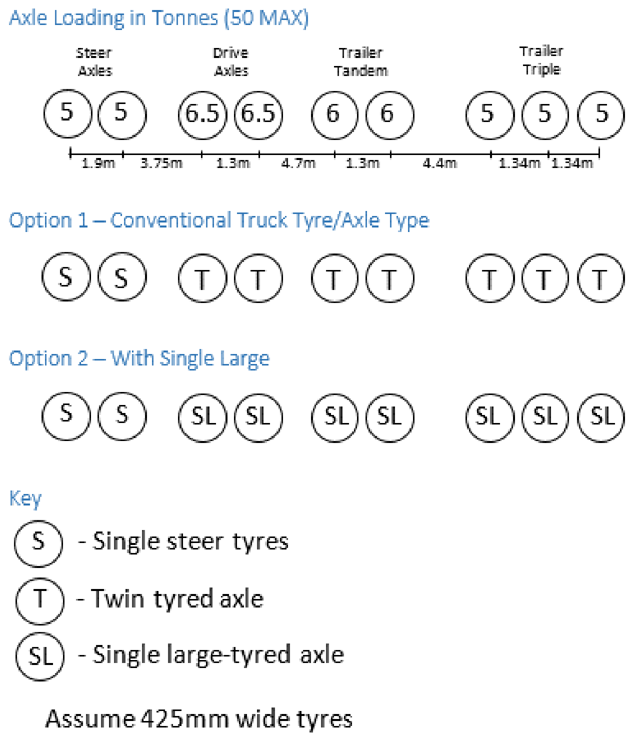

Figure 4 - Axle loads and axle/tyre combinations used in the comparative scenario. (It should be noted that narrower tyres with the same load will cause greater damage.)

The methodology using the mechanistic approach involves several steps but each is straightforward, and readily computed as follows:

1. Input each loading including tyre pressures into the mechanistic model that has the layer moduli defined from FWD backanalyses for each test point on the road.
2. Sub-section each road into relevant treatment lengths. Using relevant fatigue criteria (preferably established for the specific region), calculate the damage factors for each axle load at each FWD test point, for all layers and distress modes, for both the twin and single tyre vehicles.
3. Calculate the life of each treatment length by establishing the number of passes of each vehicle type (summing the damage factors for each axle) to first develop a cumulative damage factor greater than 1, for 10% of each treatment length (or other defined level of service).
4. Calculate the most effective treatment and rehabilitation cost for each treatment length.
5. Plot the cost versus year cumulative curve for each of the two loading scenarios
6. Calculate the net present value for the two loading scenarios.

This routine provides a rational basis for quantitative evaluation of twin tyre loading relative to single. For the case of Homestead Rd, Figure 5 below presents the remaining traffic in million equivalent standard axles (MESA) under the two axle types when the same 6.5 tonne axle load is applied. If only the subgrade is considered (standard Austroads criterion) there is little difference in the remaining traffic that can be applied, for either tyre configuration.

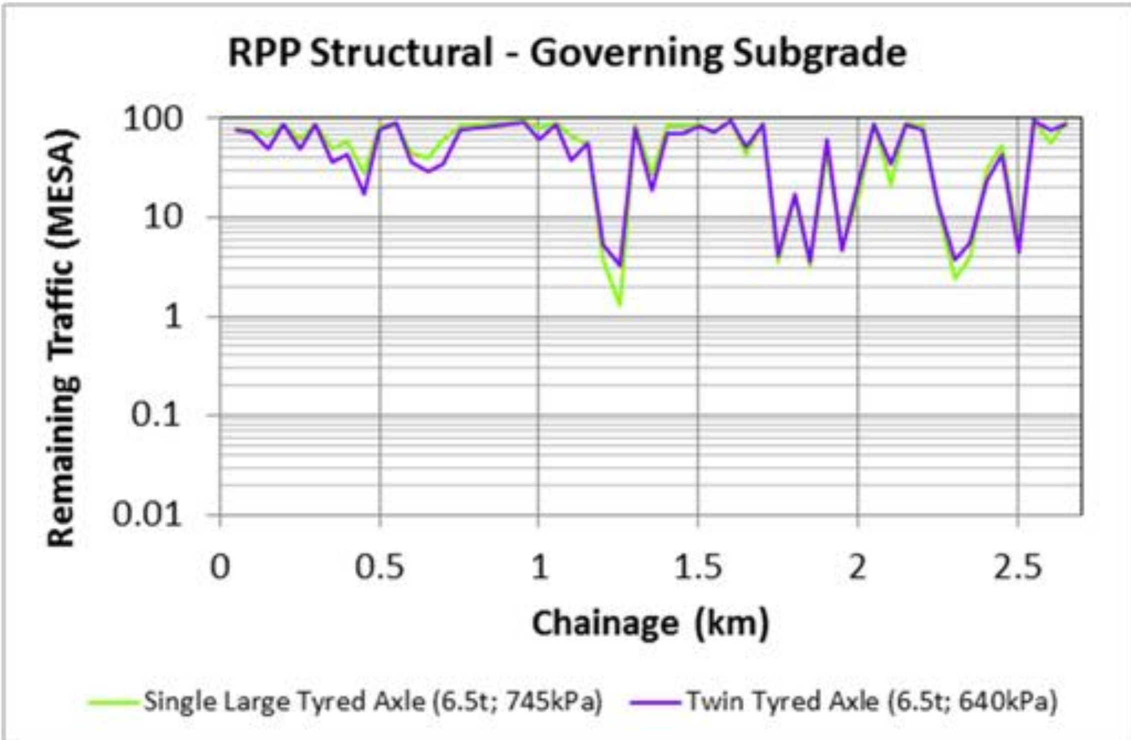

Figure 5 - Remaining traffic (subgrade governing) under loading by single large and twin tyred axles

However, for Homestead Rd, the calibrated mechanistic model indicates that the relatively weak basecourse, not the subgrade will govern pavement life. Furthermore the basecourse life itself is on average about 10 times shorter when the single large tyred axle is used in place of the customary twin tyred option.

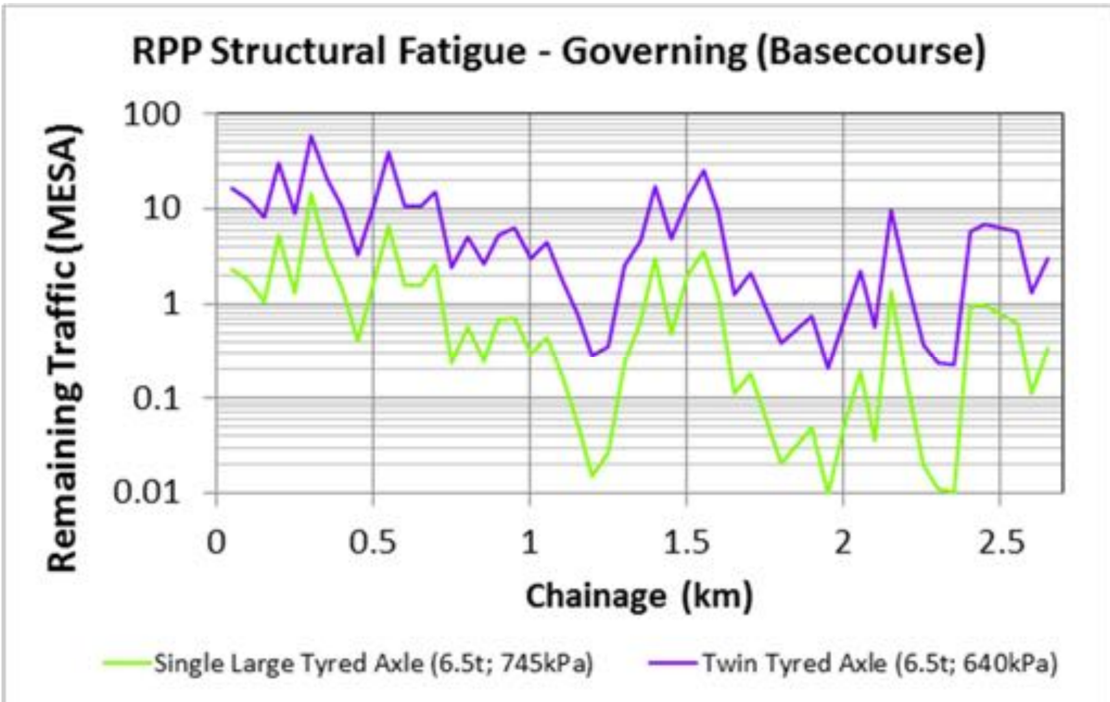

Figure 6 - Remaining traffic (basecourse) for Homestead Road under loading by single large and twin tyred axles.

The damage ratio can vary significantly depending on the load damage exponent for the basecourse (using mechanistic analysis calibrated from the regional precedent performance model). Figure 7 shows increased pavement damage ratios from 1.5 to more than 20 times, where singles are used instead of twin tyres depending on the applicable basecourse damage exponents. The total overall damage ratio of the nominated 50MAX truck-trailer combinations above (see Figure 4) remains high after taking account of the steering axles because only a small proportion of the total weight is on the steering axles which are the same on both vehicles, as shown in Figure 8.

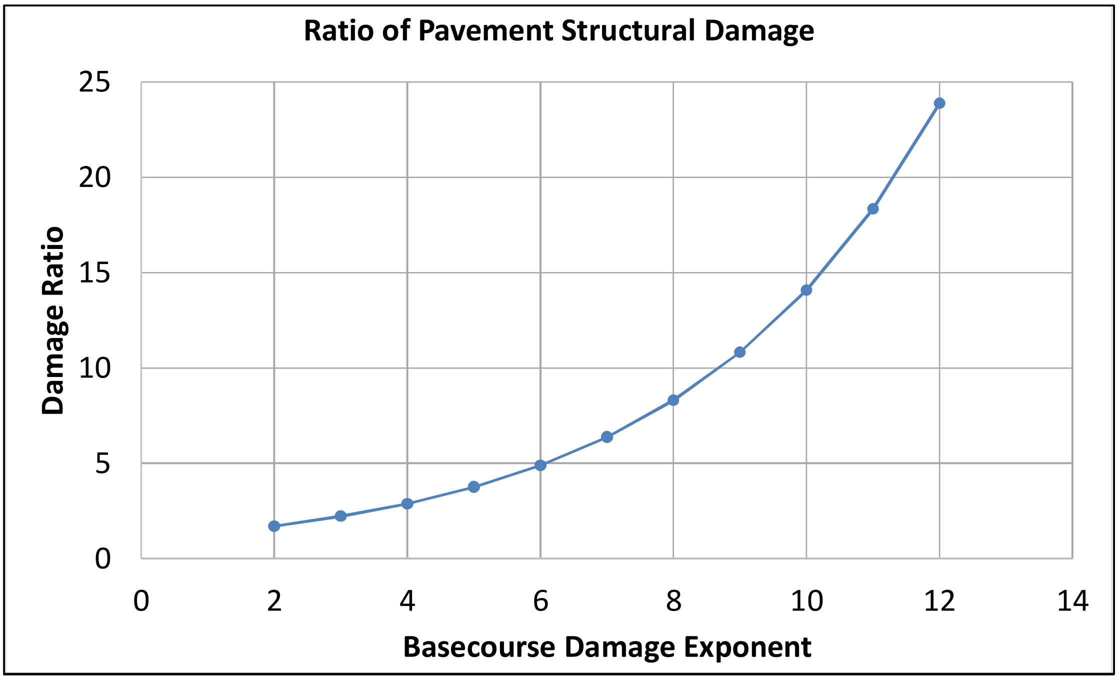

Figure 7 - Ratio of pavement structural damage (in the basecourse) for different LDEs at a 10th percentile characteristic point on Homestead Rd

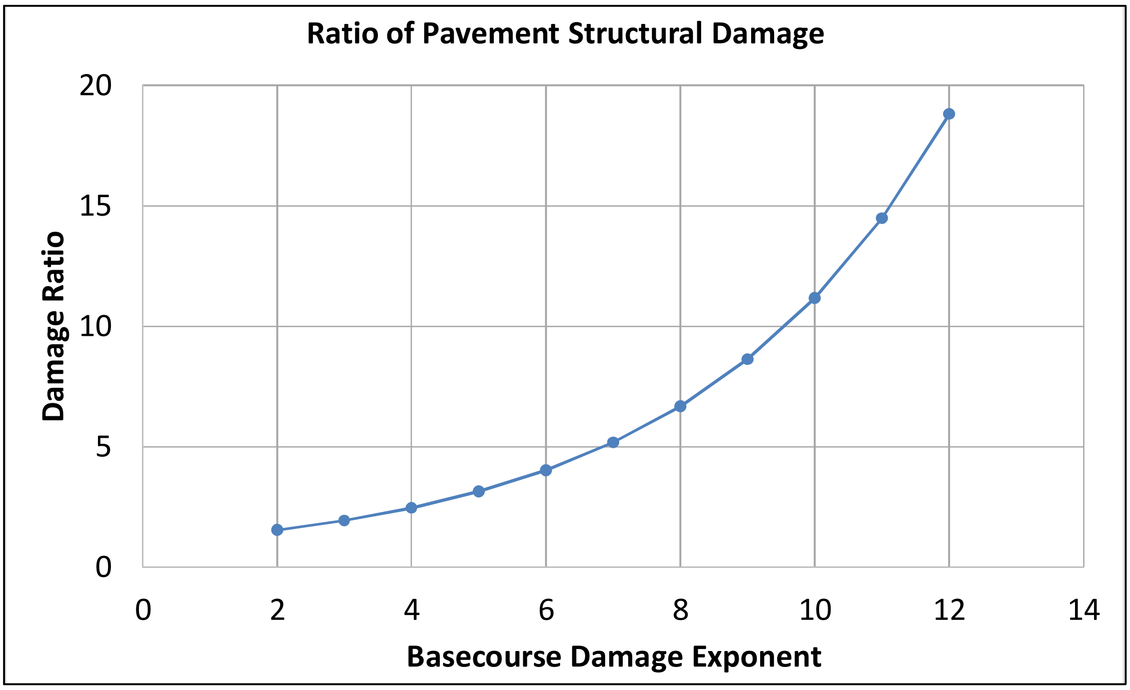

Figure 8- Overall ratio of pavement structural damage (in the basecourse) by the 50MAX truck-trailer combination for different LDEs.

Results are provided in graphical form in Attachment 1, showing the various distress modes for

(i) ESA loading (ii)Twin tyred axle (III) Single large tyred axle

Tyre Pressure Considerations

Tyre pressure is now a specific input for pavement design for US designers using the M-EPDG[15]. Traditional ESA concepts are convenient, but rely on invalid assumptions[16]. The M-EPDG inputs include the full spectrum of traffic parameters:

- Base year truck-traffic volume (the year used as the basis for design computations).
- Vehicle (truck) operational speed.
- Truck-traffic directional and lane distribution factors.
- Vehicle (truck) class distribution.
- Axle load distribution factors.
- Axle and wheel base configurations.
- Tire characteristics and inflation pressure.
- Truck lateral distribution factor.
- Truck growth factors.

This more fundamental approach allows a substantially more meaningful quantification of pavement wear. The "one size fits all" ESA approach used in RAMM 4th power calculations is an over simplification that can give approximate results for a network which has (i) been designed for traffic of at least 10 MESA and (ii) a limited allowable ESA range (less than a factor of 2). Southland local roads are poorly suited to ESA methods. Examples are given in a subsequent section.

The issue of tyre pressure was examined closely in the COST 334 study (Attachment 2) in determining the TCF (Tyre Configuration Factor) – being damage ratio of a given tyre compared to a standard tyre- as follows:

On tyre inflation pressure and contact stress distribution:

11. The tyre inflation pressure is not a direct parameter in the TCF formulae. For the same load and tyre, higher inflation pressures generally result in a smaller tyre-pavement contact area, and thereby increased surface stress in the pavement As a consequence, higher inflation pressures generally result in higher pavement wear, especially on thin pavements.

12. The ratio of actual to recommended inflation pressure was shown to be influential for the cases of primary rutting on thick (and probably medium) pavements and secondary rutting on thin and medium pavements. An inflation pressure 10% higher than that recommended for the actual tyre load results in about 15% increase in pavement wear. In such a case of over-inflation, the contact stress distribution is non-uniform and the load is concentrated on a smaller area.

13. The detailed contact stress distribution within the contact area is probably relevant for distress modes whose origin is at or close to the pavement surface, such as ravelling

[15] NCHRP 2004. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. http://onlinepubs.trb.org/onlinepubs/archive/mepdg/Part2_Chapter4_Traffic.pdf

[16]

Because the COST 334 study addressed only thick structural asphaltic pavements, it follows that somewhat higher damage ratios should apply when unbound basecourse with thin seal forms the critical layer (governing pavement life).

Consistency with Other Studies

The accelerated trafficking of a relatively strong pavement at ALF, reported by Yeo[17] is relevant to some degree as it uses an unbound granular pavement with chip seal. This used accelerated trafficking of an artificial chip seal unbound granular pavement with 40 kN plate load deflections of 0.7-0.8 mm after bedding-in. “Structural Number” SNP values were about 4.0-4.2. Poor correlations with pavement life are commonly reported[18],[19] for central deflection and SNP. However, the ALF pavement structural capacity was more representative of high volume highways, than local roads ie there are significant differences between that new pavement and the in-service existing pavements in Southland District, so the same conclusions are not appropriate.

Load damage exponents for the basecourse layer are primarily dependent on their support from the underlying layer(s). The stiffness of the subbase plays a governing role, as shown in the following network comparisons from recent studies of regional precedent performance.

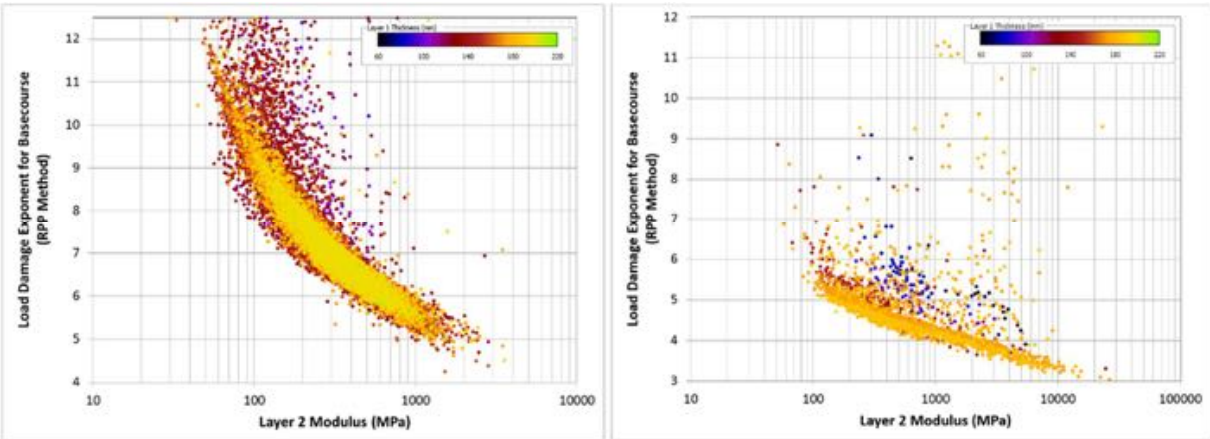

Figure 9. Load Damage Exponents for Southland District versus Auckland Motorways (AMA).

These extremes show the dramatic differences in susceptibility of different networks to increased loading, now that recent advances have established a reliable statistical analysis methodology for quantifying load damage exponents for each layer and each relevant distress mode. To consider only one layer or one distress mode is no longer acceptable. More rational design has long been in practice with other engineering disciplines, as for example the multiple checks made for design of a reinforced concrete beam. The rationale for pavement design has lagged severely in comparison, probably because of the lesser consequences, but needless cost continues to be the outcome.

Comparisons of the composite cumulative distribution curves of all load damage exponents (many tens of thousands of in situ measurements) from various networks are given below, showing that ranges

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[17] Yeo, R. (2008). Relative Pavement Wear of an Unbound Granular Pavement due to Dual Tyres and Single Tyres
[18] REAAA Working Group (2015). REAAA Technical Report TC-5. Pavement Durability.
[19] Salt, Henning, Stevens & Roux (2010) Rationalisation of the structural capacity definition and quantification of roads based on falling weight deflectometer tests. https://www.nzta.govt.nz/assets/resources/research/reports/401/docs/401.pdf

are commonly 4 to 9, and reinforcing the general trend for higher exponents in a region where lower structural capacity is required.

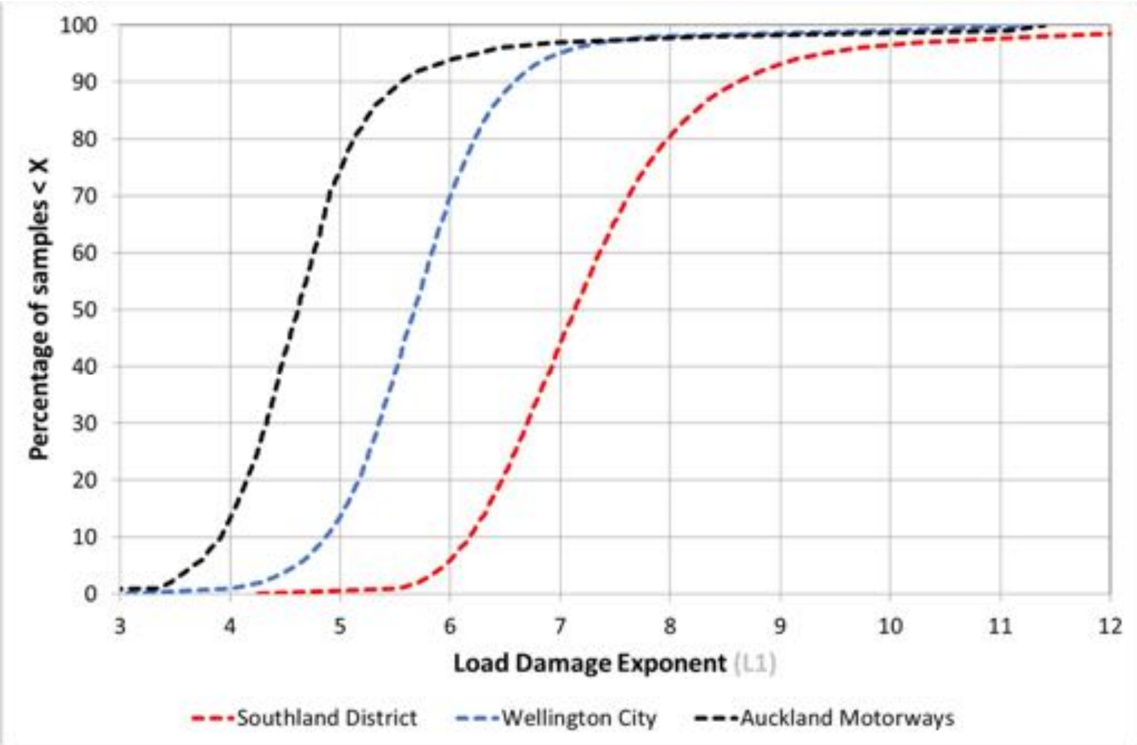

Figure 10. Comparison of the Composite Cumulative Distributions of Load Damage Exponents

It is important to note, that the higher values apply to the weakest parts of each road, and those parts in turn govern pavement life. Depending on ONRC category, the percentile of the treatment length in a terminal condition that triggers rehabilitation is likely to be about 10% for highways but as much as 30 or 50% on some local roads. For that reason, the characteristic load damage exponent for each treatment length should be selected towards the upper end of the range.

Conclusions

1. The current Austroads simplified approach of comparing deflections imposed by different axle load configurations to calculate pavement damage is no longer state-of-the-art, nor is it supported by leading authorities internationally. Stress or strain based [mechanistic] approaches using structural analysis have been promoted internationally for many years, and suitable software is now widely available. Use of the obsolete "structural number" or SNP concept (the basis of which was officially dismissed as nebulous[20] by its US originators (NCHRP) in 2004 when they shifted to mechanistic methods), can no longer be supported for any structural evaluation.
2. Using calibrated structural analysis of the stresses and strains in each layer under standard twin tyred axles and then single large tyred axles enables the critical layer to be determined (ie basecourse versus subgrade) which is then used to rationally and reliably evaluate the relative pavement wear for the different loading regimes.
3. Use of a single large tyred axle under maximum legal axle loading (7.2 tonne) will tend to impose an increase in strains in the basecourse and usually a decrease in strains at depth when compared to an 8.2 tonne standard twin tyred axle.
4. Even though the axle load is less, the single tyre is likely to reduce pavement life substantially. Normally, heavily loaded singles will be in a minority, but it is important to appreciate that comparing only one 7.2 tonne single large tyred axle with one 8.2 tonne twin tyred axle, the truck single modelled will impose 3.7 times the damage of the twin while the bus single will impose 14.5 times the damage. This applies specifically to the case of Homestead Rd at the characteristic (10 percentile structural capacity) location where the basecourse is the critical layer governing the pavement life.
5. If both the twin and single tyre axles carry the same load, at customary tyre inflation pressures for trucks, the effect is compounded because the tyre pressure increases and the effective width decreases so both act to concentrate the load. The damage imposed if the subgrade is the critical layer is not high, but in the case considered, where the basecourse is the critical layer, the pavement wear increases by 10 fold or more under the single.
6. Software has now been developed so that a network wide evaluation can be carried out very quickly, on this basis, once two sets of axle load configurations are defined for comparison, on any network where a calibrated mechanistic model has been established. The same process can be used to quickly assign the cost of running any spectrum of fleet loading. (This could readily be established as a fully automatic user-queried internet based service to automatically quantify and assign road user charges transparently and equitably for any nominated route, based on structural damage.)
7. Load damage exponents are higher for structurally weak pavements compared to those that have high capacity. Values much higher than typically assumed (Austroads uses 4, 5 or 7) apply in many secondary roads where the unbound granular basecourse is the layer that will govern pavement life, rather than the subgrade where the additional damage caused by single large tyres is less marked (often similar if the current maximum loads are applied in each case).

[20] NCHRP (2004). Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Report. "Nothing could be more nebulous than this parameter" http://www.trb.org/mepdg/guide.htm

8. The initial results confirm the expectation that for certain roads, (and these are predominantly local roads rather than highways) evidence based calculations show that road user charges should be much higher for single large tyres than for standard twin tyres, if both are loaded to their legal maxima. This presents an issue for the local authority, (i) because road user charges customarily relate to the vehicle, not the specific road or route, and (ii) at present, there is no enforcement of tyre pressure and that is a very significant wear factor as far as basecourses on low volume roads are concerned. COST[21] 334 (Attachment 2) specifically recommends that in order to reduce wear, legislation should be promoted for tyre pressure regulation.
9. Future proposals for increasing HPMV traffic may have much more adverse impacts than intended unless calculations are based on observed in-service performance (considering all pertinent distress modes) of similarly constructed pavements. Some specific roads, which can now be readily identified, should be avoided otherwise budget will be required for upgrades. LTNZ Report 281 based on an artificial track, is inappropriate for such decisions because "*those findings involving the load damage exponent cannot be relied upon.*"
10. Damage in the subgrade is highly affected by non-linearity of the subgrade, as strains in highly non-linear elastic subgrades were found to decrease under single tyre loadings (i.e. calculations ignoring non-linearity characteristics of subgrades can be misleading).
11. Rational determination of appropriate weight limits and/or road user charges, necessarily requires consideration of the axle configuration, loads, tyre pressure, and pavement structure (including identification of the layer and governing distress mode which will cause the pavement to reach a terminal condition). Where proper mechanistic calibration (a regional precedent performance study) of any road network has been carried out, as implemented with Southland District, state-of-the-art mechanistic analyses (using stresses and strains in each pavement layer) are now available to reliably and quickly quantify specific load damage exponents and consequent pavement wear under any given axle load(s) or load combination, enabling rational evaluation of any HPMV impacts. The procedure is very straightforward and enables decisions to be technically based on real (in-service) precedent performance of roads in any given region, necessarily giving due regard the wide range of important controlling parameters that cannot be practically replicated in a test track, including climate, subgrade characteristics, aggregate sources, lane width (wheelpath wander), as well as customary construction and maintenance practices. The internationally peer-reviewed methodology provides a sound basis for HPMV decision making as well as documented evidence in the event of any challenge.
12. Although pavement wear evaluation necessarily includes (i) the load, (ii) the detailed axle/tyre/pressure configuration and (iii) the pavement structure, Road User Charges currently give due consideration to less than half of these relevant inputs. Therefore allowing general access of all heavy vehicles to any local road network, provides minimal incentive to operators and leads to open-ended cost increases for road maintenance and rehabilitation. Advances in structural analyses and technology in the last three years, now enable equitable and economic allocation of the costs of pavement wear in direct proportion to the damage imposed by each vehicle. Upgrading the current web-based system to include all necessary inputs and a mechanistic structural model would now be straightforward, driving operator behaviour to deliver cost savings for all parties.

GeoSolve Ltd Pavement Analytics Group 2016

[21] COST 334 Effects of wide single tyres and dual tyres

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Attachment 1. Mechanistic Analysis of Homestead Rd

Distress mode analysis of Homestead Rd and load damage exponents.

The first sequence of blue graphs (pavement life) goes to full scale if there is 25 years for each distinct RPP distress mode, ie black shows problem areas and distress modes. The RPP overlay graph above shows however, very minor overlay would fix the various issues.

The lines beneath them give the load damage exponents for basecourse and subgrade and the subsurface drainage priority

The second sequence of blue graphs give the Austroads models, which generally tend to be too conservative for Southland. Overlays are just above the life graphs.

The graphs (PEGrapher) use the following model scenarios:

1. ESA loading as advised.
2. The proposed twin tyre load, (with 640 kPa tyre pressure) with number of passes increased to create similar damage to the ESA loading.
3. The proposed super-single tyre load (with 745 kPa tyre pressure), and same number of passes as (2).

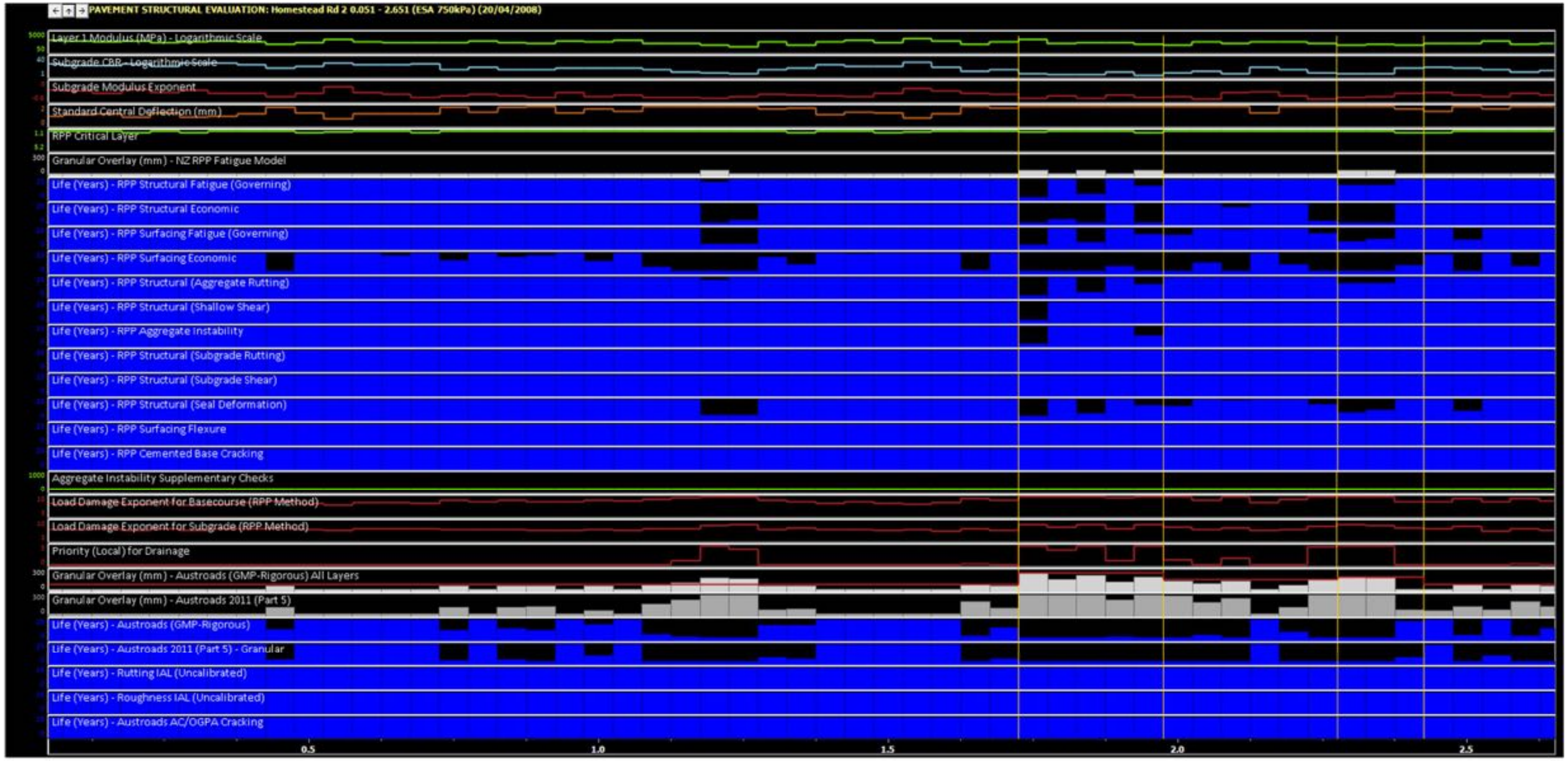

Figure A1 – Homestead Rd. Chainage versus for pavement life for each distress mode, and other parameters, 1 ESA Loading Case

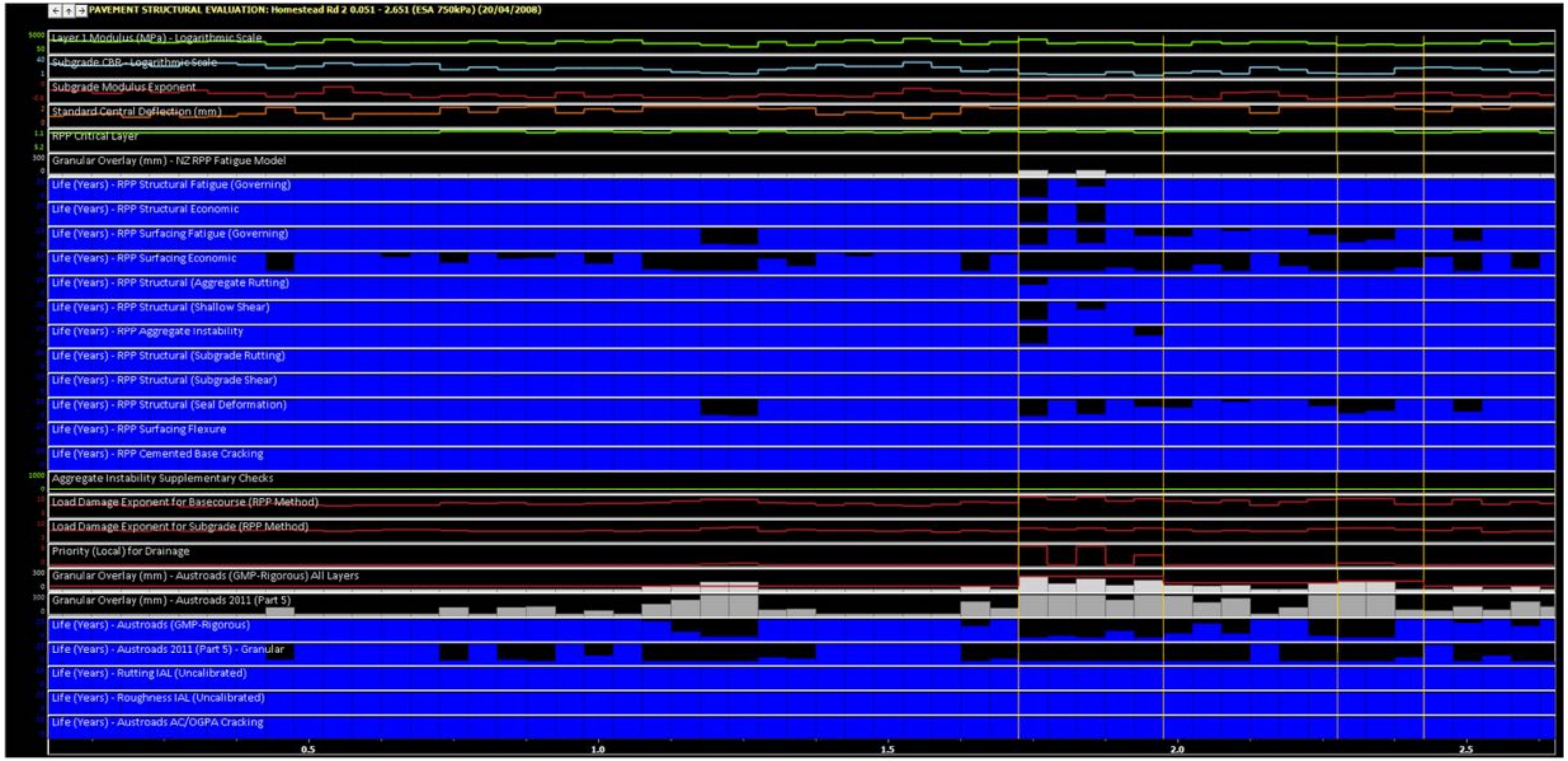

Figure A2 - Homestead Rd. Chainage versus for pavement life for each distress mode, and other parameters, Twin tyred axle (640 kPa tyre pressure and 6.5t axle load)

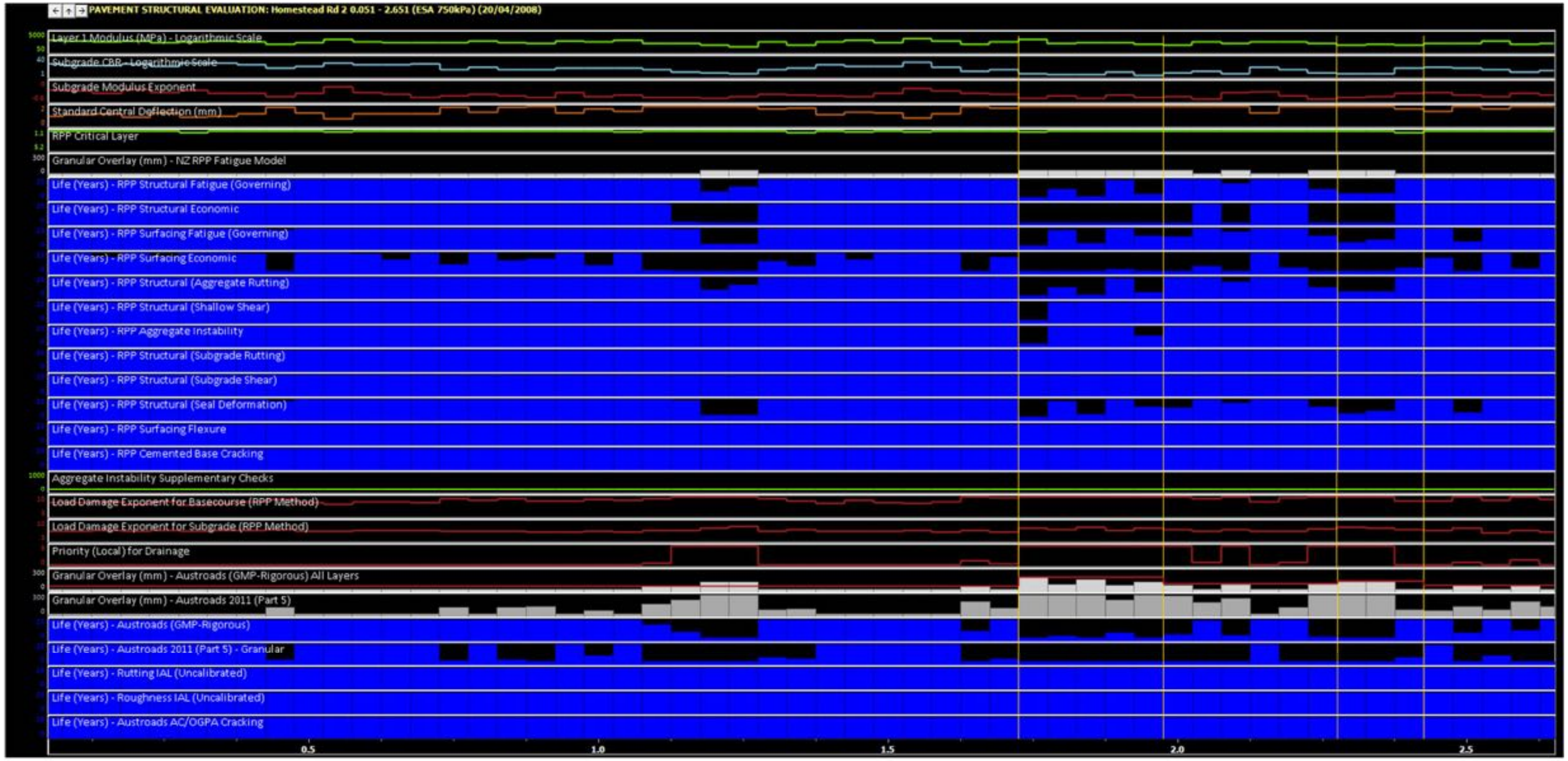

Figure A3 - Homestead Rd. Chainage versus for pavement life for each distress mode, and other parameters, Single large tyre load (745 kPa tyre pressure and 6.5t axle load)

Attachment 2. COST 334 Conclusions and Recommendations

4.9.2 Conclusions

The conclusions of the work carried out by TG3 are confined to the relative damaging effects of different tyre sizes on road pavements. Many different complex and inter-related factors have been identified as contributing to pavement distress, and these have been described earlier. In the following paragraphs, therefore, an attempt has been made to separate the overall conclusions of the work into general conclusions, those related to the tyre concept and tyre width, size of contact area, tyre inflation pressure and contact stress distribution and those related to the relative pavement wear of the current tyres. The interaction between many of these conclusions should, however, be remembered.

The work of the Task Group was confined to bituminous pavements. For concrete pavements, TG3 expects only small influences of differences in tyre configurations on pavement wear. For bridges, viaducts, etc. no conclusions were drawn.

General

1. Large differences in relative pavement wear exist among dual tyre assemblies and among wide-base single tyres. Therefore, a single factor for the difference between wide-base single and dual tyres is not applicable. Comparisons between pavement wear effects can only be made if the detailed characteristics of the tyre fitments are taken into account.
2. The pavement wear effects of different tyres vary according to the types and thickness of pavement, as well as their associated distress modes. For this reason COST 334 developed the concept of the Tyre Configuration Factor (TCF). The TCF of a tyre expresses the amount of pavement wear, depending on the pavement thickness and distress mode considered, relative to an arbitrarily chosen reference tyre. In use, the higher the TCF value, the higher the pavement wear (with the same axle loads, suspension type, etc.).
3. The TCF formulae developed from the work enable the quantification of the pavement wear effects of current and future different tyre fitments and sizes. The derivation of TCF formulae for all pavement thicknesses was not possible in all cases, however, because of insufficient data.
4. On the basis of the TCF formulae, the main influencing factors for pavement wear are the width (see Conclusions 6 and 7) and size of the tyre-pavement contact area, and the ratio of the actual inflation pressure over the recommended inflation pressure for the actual load (hereafter referred to as the pressure ratio).
5. It was found that the thinner the pavement, the stronger was the influence of differences in tyre configurations on pavement wear.

On the tyre concept (one or two contact areas) and the tyre width parameter:

6. For primary rutting (mainly on thick and medium pavements) the main width parameter is Width, being the footprint width for wide base singles, and for dual tyres twice the footprint width of the individual tyres. (All width values consider footprint (tyre contact area envelope) width, not tyre section width.) As a consequence, for this distress mode, pavement wear due to wide base single tyres or dual tyre assemblies does not differ significantly, when the axle load, tread pattern width, contact area, tyre diameter and pressure ratio are equal.

7. For secondary rutting and fatigue cracking on thin and medium pavements the main width parameter is the Total Width of the footprint of the tyre assembly. [For dual tyre assemblies this includes the distance (100mm) between the footprints of the individual tyres.] As a consequence, single and dual tyre assemblies will produce equal TCF values indicating equal pavement wear, when the Total Width is equal (all other factors being equal). Usually, however, for the same axle load, current dual tyres will have a greater Total Width than a current wide single tyre.

8. For secondary rutting and fatigue cracking on thick pavements there is little difference between different fitments and sizes of tyres, as the pavement wear is dominated by the overall magnitude of the load carried in these cases.

On size of contact area:

9. In addition to its width, the length of the tyre-pavement contact area was shown to be influential in the cases of primary rutting on thick (and probably thin and medium) pavements and fatigue on thin and medium pavements. Combined, this signifies the influence of the size of the tyre-pavement contact area, and hence the average contact stress. Sensitivity analysis showed that a decrease of 10% in contact area results in a 9-39% increase in pavement wear for these cases. No similar conclusion could be drawn for secondary rutting because of a lack of data.

10. The tyre diameter can also be taken as an indicator for the contact area length and the related pavement wear. A reduced tyre diameter will lead to increased pavement wear (when all other tyre parameters remain constant). This is important in the context of a trend towards the use of smaller-diameter tyres in Europe, to allow the lower platform heights that will accommodate volume-limited loads to be carried, rather than mass-limited loads.

On tyre inflation pressure and contact stress distribution:

11. The tyre inflation pressure is not a direct parameter in the TCF formulae. For the same load and tyre, higher inflation pressures generally result in a smaller tyre-pavement contact area, and thereby increased surface stress in the pavement. As a consequence, higher inflation pressures generally result in higher pavement wear, especially on thin pavements.

12. The ratio of actual to recommended inflation pressure was shown to be influential for the cases of primary rutting on thick (and probably medium) pavements and secondary rutting on thin and medium pavements. An inflation pressure 10% higher than that recommended for the actual tyre load results in about 15% increase in pavement wear. In such a case of over-inflation, the contact stress distribution is non-uniform and the load is concentrated on a smaller area.

13. The detailed contact stress distribution within the contact area is probably relevant for distress modes whose origin is at or close to the pavement surface, such as ravelling (loss of aggregate in the pavement surfacing) and surface cracking. Although COST

334 established good techniques for the measurement of these distributions, insufficient data was obtained to draw robust conclusions.

On the effect of dynamic loading and load imbalance

14. By comparison with other effects, tyre fitment does not significantly affect the dynamic loading of the road pavement.

    Experimental work reported by COST 334 shows that, for the tyre fitments tested, the dynamic loading applied by the truck is not changed significantly by the choice of tyre fitment. Dynamic loading can significantly increase pavement damage, and it had been thought that the contribution of tyre stiffness to the suspension characteristics controlling the phenomenon may be a significant factor. On the basis of the work carried out, this appears not to be the case.

15. By comparison with other effects, the effect of load imbalance between tyres on a dual assembly was found not to significantly affect pavement wear or other aspects.

    Load imbalance between tyres on a dual tyre assembly is brought about primarily by different inflation pressures in each of the tyres, and by truck axle geometry and pavement profile. Surveys have shown that this difference (in relation to the recommended inflation pressure) can be large, but is confined to a small proportion of the truck fleet. The work of COST 334 has shown that load imbalance effects on pavement wear and other aspects is negligible in comparison with other effects.

On TCF values for current common tyre fitments and possible future tyre fitments

As stated earlier, TCF values vary according to the pavement thickness and distress mode under consideration. For practical use, values for the current common and possible future tyres (rim sizes 19.5 and 22.5 inches) were determined for the European primary road network (based on primary rutting in the bituminous layers of thick pavements) and the European secondary road network (based on a weighted average of the three distress modes on medium pavements, namely primary rutting, secondary rutting and fatigue cracking). Most road freight in Europe is carried on the primary networks, however, and greater importance is attached to these.

16. Common current and possible future dual tyre assemblies for towed axles have TCF values for primary roads ranging from 1.5 to 1.7 and for secondary roads TCF values of 1.3 to 1.5. Current common and possible future wide base single tyres for towed axles have TCF values for primary roads ranging from 1.5 to 2.2 and for secondary roads TCF values ranging from 2.2 to 3.6. On average the use of current common or possible future wide base singles on towed axles, instead of dual tyre assemblies, increases the contribution of these axles to pavement wear on primary roads and secondary roads by 17% and 97%, respectively.

17. Common current and possible future dual tyre assemblies for driven axles have TCF values for primary roads ranging from 0.9 to 1.3 and for secondary roads TCF values ranging from 0.9 to 1.2. The prototype extra-wide base single tyre 495/45R22.5 for use on drive axles has a TCF value of 1.2 on primary roads and 1.6 on secondary roads. On average, the use of wide base singles on driven axles, instead of common current dual tyre assemblies, increases the contribution of these axles to pavement wear on primary roads and secondary roads by 17% and 64%, respectively.

18. Conventional single tyres for steering axles have TCF values for primary roads ranging from 2.8 to 4.0 and for secondary roads TCF values ranging from 5.0 to 8.0. Current common and possible future wide base single tyres (from the 385 - fitment

and wider) for steering axles have TCF values for primary roads of 1.9 to 2.2 and for secondary roads TCF values of 2.8 to 3.6. On average the use of current common and possible future wide base singles on steering axles reduces the contribution of this axle to pavement wear on primary and secondary roads by 36% and 45% respectively.

19. Conventional single tyres for steering axles are relatively more damaging than the common dual tyre assemblies for driven and towed axles, and wide single tyres for towed axles. This is partly alleviated by lower loads on the steering axles, but in practice the steering axle still may cause more pavement wear than a driven or towed axle.

4.9.3 Recommendations

On the basis of the conclusions noted above, a number of recommendations can be made. These apply to the use of the experimental and analytical results obtained on the relative pavement wear effects of different tyres in the wider work of COST 334, and to the specific case of those effects as they arise in practice.

1. *On the use of results in the further work of COST 334*

   TG3 recommends the use of the TCF formulae it has developed, to quantify the relative effects of different tyre load configurations on the wear of pavement structures. These factors may be used to calculate the contribution of pavement wear of different tyre types in the overall assessment of the use of wide single and dual tyres.

The development of the Tyre Configuration Factor allows discrimination between different tyre fitments based on the corresponding damage they cause to road pavements. It is recommended, therefore, that the TCF should be used by national road authorities in the design process to better estimate the damaging effect of the traffic that roads are designed to carry.

Implementation of this recommendation will require that the design authority undertakes appropriate surveys of the national fleet of road transport vehicles, to establish the numbers and types of vehicle, their tyre equipment, and other factors. Approximations can of course be made by the judicious use of sample surveys, the results of which are extended to the national situation. Alternatively, specific surveys may be carried out for the design of a given road.

3. *On the application of the Tyre Configuration Factor to tyre design and use*

The results of the COST 334 work show that the use of a limit on TCF can be used to guide the design of new tyre sizes, and the further development of existing tyre sizes. It is recommended, therefore, that limiting values of TCF be placed on new and developing tyre fitments.

4. *On Maximum Designed Operating Tyre Inflation Pressure*

In addition to the proposed limits on TCF value of the tyre, it is also recommended that a maximum limit be placed on the manufacturer-recommended inflation pressure of the tyre (measured cold) according to the allowable load level of the specific axle on which the tyre is mounted. This will ensure that the TCF limits cannot be inadvertently exceeded by the use of increased inflation pressure.

The proposed maximum designed operating tyre inflation pressure (measured cold) is 9 bars.

Much progress has been made in recent years on the development of on-board systems for the measurement and control of tyre inflation pressures. It is further recommended, therefore, that consideration is given to introducing legislation requiring the use of such systems on the largest (5 and 6-axle) vehicles, in order to ensure compliance with tyre manufacturer's recommended inflation pressures for given loads and duty cycles. This will produce benefits to operators in terms of improved tyre performance (tyre wear and rolling resistance), and to society in terms of minimised pavement wear and reduced safety risks.