Road Users Charges Review Group

ENGINEERING ADVICE

- 23 February 2009

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Sinclair Knight Merz
ABN 37 001 024 095
100 Christie Street
PO Box 164
St Leonards NSW
Australia 1590
Tel: +61 2 9928 2100
Fax: +61 2 9928 2500
Web: www.skmconsulting.com

Sinclair Knight Merz (SKM)

Sinclair Knight Merz is an Australian based international Consulting Group with offices in Wellington, Auckland and Christchurch.

The Group provides transport engineering and planning services to a wide range of international clients including policy advice to government transport agencies.

Authors

This report was prepared by Gabriel Tooma and Peter Prince of SKM.

For further information on aspects of this report, contact the authors at gtooma@skm.com.au or pprince@skm.com.au.

Disclaimer

The focus of this report is the engineering relationships in the Road User Cost (RUC) model allocation to vehicle classes for the purpose of the cost recovery of New Zealand road use.

The content of this report is based on existing information and on the information and documents made available to the authors. The independent views expressed are those of the authors.

The findings and conclusions do not necessarily represent the views of the New Zealand Ministry of Transport or the New Zealand Transport Agency.

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Executive Summary

Introduction

This report presents findings of an independent review of the engineering relationships within the Road User Cost (RUC) model currently being investigated by the Road User Charges Review Group. It has been prepared by consultants Sinclair Knight Merz (SKM), based on existing technical reports and findings from relevant research work and reviews undertaken by others.

The main findings are presented below.

Fourth Power Rule

The fourth power rule, relating thin flexible pavement damage to vehicle axle loads, which forms an important pavement wear cost within the RUC, continues to be used in road design in all comparable and relevant countries, including Australia.

It represents a proven relationship applied to a wide range of pavement strengths and conditions. There is no intention of State road authorities within the Austroads membership to change this relationship. The latest Austroads research into cost allocation suggests flexible pavement damage and changes should be based on a net tonne kilometre using the fourth power rule.

Evidence available suggests that road pavements on generally low trafficked and weak road pavements are on average subject to higher damage than on national roads under the same axle load.

The recent Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) research indicates a lower power rule than four would more accurately represent equivalent pavement damage to the point of pavement failure. The definition of failure (15mm deformation over 10% of the pavement surface) used in the laboratory is far different from pavement conditions in practice.

A large part of the New Zealand network (National and Local roads) operates at levels of deformation in excess of 15mm before renewal.

A lower power rule would greatly increase the risks of both higher pavement damage and rehabilitation costs over the life of pavements across the network.

A change towards a lower road damage power would significantly put at risk the integrity of the road network and the ability of government to afford the resulting pavement rehabilitation upkeep programs especially in respect to local roads. Furthermore, such a change would unfairly in our view, pass user fees from large vehicles to smaller vehicles. For these reasons the power law should not be changed.

Vehicle Dynamics

There is sufficient evidence (from Austroads tests) to support the case that air suspensions (called road-friendly suspensions) reduce pavement deformation. Road-friendly suspensions should be recognised in the RUC model provided vehicles with road-friendly suspensions are monitored through a third party system.

Reference Loads

Reference loads in the RUC model should be aligned with Austroads and current road design practice in New Zealand. A consistent approach should be taken.

Vehicle Types

New vehicle types should be investigated and included in the RUC model to better represent the current vehicle fleet.

Vehicle Loading and Utilisation

In the absence of evidence and information on actual distances travelled, the current assumption (55% of vehicles travelled at full load) should be maintained until new data is available.

Large Single Tyres

Single wide tyres should be recognised in the RUC model as vehicles fitted with these tyres increase pavement stress compared with twin standard tyres. Vehicles fitted with wide single tyres should have a different vehicle classification and corresponding RUC rates schedule.

Weight Distribution

Averaging out of ESA’s per axle as in the RUC model, disadvantages some vehicle types. The effect of vehicle weight distribution on road pavement wear is not as significant however (in terms of wear and tear costs) as the other above factors which should be addressed first.

Diesel Excise

A diesel excise is not related to pavement wear whatsoever.

1. Introduction and Scope of Works

1.1. Introduction

Ministry of Transport, New Zealand (MoT) has engaged SKM to provide engineering advice to the Road User Charges Review Group late November 2008.

Sinclair Knight Merz (SKM) understands that the Road User Review Group is an independent committee, appointed by the Minister of Transport to undertake a review of the Ministry's road user charges cost allocation model and of the method of collecting the proportion of transport network costs attributable to diesel vehicles.

The Ministry specifically required in its brief the following topics to be addressed:

"

- *whether the assumptions about the impacts of vehicle weight and axle configuration in the Cost Allocation Model appropriately reflect road engineering practice and road network conditions in New Zealand. This will be informed by:*
  - *theoretical context on the nature of the relationship between road construction and maintenance costs and vehicle weight and axle loadings; and in particular*
  - *an assessment of the relative merits of the different points of view on the relationship between axle weight and road wear and the relationship between axle configuration and road wear.*
- *the extent of correlation between fuel consumption of heavy vehicles and their road network costs."*

SKM has prepared this report to provide professional engineering opinion as required above in the following chapters:

Chapter 2	Describes an outline of the RUC, for the purpose of investigating vehicle wear effects.
Chapter 3	Discusses the fourth power rule.
Chapter 4	Briefly reviews the effect on road wear from vehicle dynamics.
Chapter 5	Briefly provides commentary on Reference Loads and the effects on road wear.
Chapter 6	Summarises the effect on road wear from vehicle weight distribution across axle groups.

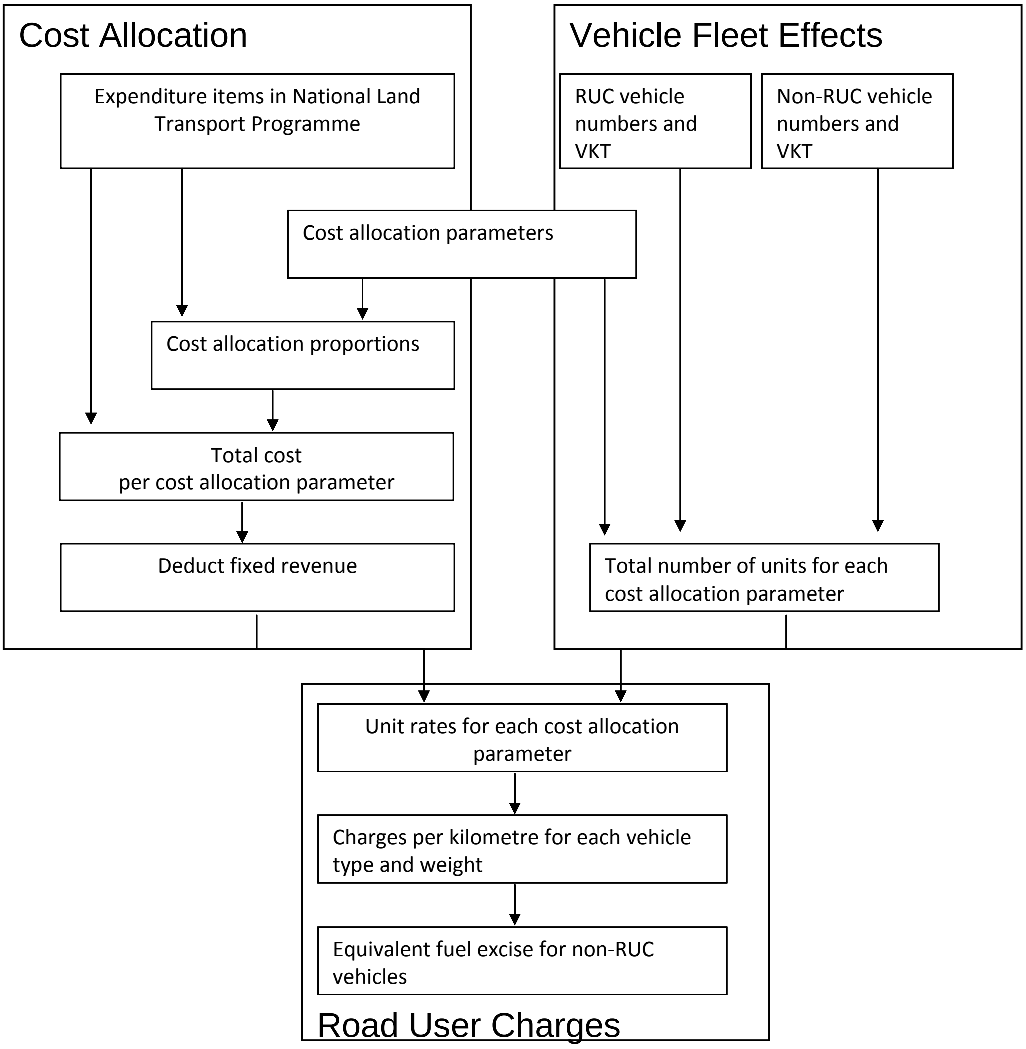
- Chapter 7 Briefly comments on the effect on road wear from vehicle types.
- Chapter 8 Summarises the main points in respect to road wear from vehicle loading and utilisation.
- Chapter 9 Briefly summarises views on the effect of large single tyres on road wear.
- Chapter 10 Discusses the appropriateness of a diesel excise, in respect to road wear.

2. The New Zealand Road User Cost (RUC) System

This section briefly describes the current RUC model in respect to vehicle wear effects. Figure 1 - Overview of NZ RUC, shows the overall outline of the current RUC model.

From Figure 1 it can be seen that the actual costs are allocated to the different road vehicle types and these costs are recovered through the Road User Charges.

- **Figure 1 - Overview of NZ RUC[1]**



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[1] Heavy Vehicle Road User Charges Investigation, February 2008, TERNZ COVEC

2.1. Road costs and vehicle weight and axle loading

The theoretical relationship between road construction and maintenance costs, vehicle weight and axle loading is based on the use of fatigue laws. The fatigue law is a mathematical relationship between a road pavement structural strength and the number of allowable load repetitions.

The fatigue damage model is considered through Miner’s hypothesis which assumes that each axle load application “consumes” a part of the life of the pavement equal to the inverse of the allowable load repetitions.

The key is to determine an equivalence between the different axle loads and axle groups such that the cumulative damage can be estimated and compared to the allowable load repetitions.

This is where the Fourth Power rule was developed to enable different axle groups and axle loads to be converted to an Equivalent Standard Axle (ESA).

The Fourth Power Rule is discussed further in Chapter 3, as to its origins and its applicability to New Zealand roads.

The ESA or “wear effect” of a vehicle is calculated in the CAM using the following:

Wear = (Maximum Gross Weight/Sum of Axle Reference Loads)^4 *x Number of Axles x 0.55*[2]

Where the Axle Reference Load depends on:

- • the number of axles;
- • the number and arrangement of tyres on each axle, ie the axle type;
- • tyre sizes, or more specifically the tyre contact areas; and
- • axle spacing.

Additionally the “wear” formula above assumes through the 0.55 factor, that the vehicles will be loaded about half (55% of the time) the time.

Table 1 below shows the Axle Reference Loads for standard tyres and various spacing.

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[2] Review of the Road User Charges Cost Allocation Model, Report to MoT, Allan Kennaird Consulting 29 January 2007

Table 1 - Axle Reference Loads For Standard Tyres (tonnes/axle)

	Single Tyred	Twin Tyred	Four Tyred	Eight Tyred
Spaced axles	6.70	8.20	13.00	14.90
In close group of two axles	7.05	8.62	13.70	15.69
In close group of three axles	7.17	8.77	13.91	15.94
In close group of 4 or more axles	7.26	8.88	14.08	16.14

Hence for a 3 axle truck, single steer and twin driven axle with 21 gross weight the “wear” using the above formula is :

$$= (21/(6.2+23.92))^{\wedge 4} \text{ x } 3 \text{ x } 0.55 = 0.98 \text{ ESA}$$

In the following chapters we review the impacts of:

- Reference Loads;
- Vehicle Loading and Utilisation;
- Vehicle Weight Distribution; and
- Large Single tyres.

3. The Fourth Power Rule

3.1. Introduction

The Fourth Power Rule was mainly based on performance data derived from the American Association of State Highway and Transportation Officials (AASHTO) Road Test (Highway Research Board, 1962).

Some key features and findings of the trials were:

- Conducted in Ottawa, Illinois between 1958 and 1961;
- The temperature range was between 24.5°C in summer and -2.8°C in winter, and with average rainfall of 864mm;
- Used various pavement sections with flexible pavement section consisting of various thicknesses of asphalt surfacing, basecourse , subbase and subgrade;
- Some sections had asphalt surfacing of 25mm which is equivalent to NZ thin road surfacings;
- All had the same subgrade with a value of CBR 3;
- Failure was defined through a Present Serviceability Rating (PSR) which was defined as " The judgement of an observer as to the current ability of a pavement to serve the traffic it is meant to serve";
- The PSR had a scale of: (0–1) very poor, (1–2) poor, (2–3) fair, (3–4) good, and (4–5) very good;
- Using regression analysis the subjective PSR could be correlated to Present Serviceability Index based on physical road wear measurements such as roughness , cracking, patching and rutting;
- From the analysis they developed Load Equivalence Factor (LEF) which is basically the number of axles passing a point to generate the same pavement wear as the standard axle (a standard axle is defined as 8 tonnes);
- The LEF derived from AASHTO are complex and depend upon axle load, axle configuration, pavement type, pavement strength (structural number) and the value of failure as defined by PSR;
- LEF could be expressed as:

  $$LEF_{PSI} = N_0 / N_x \mid_{PSI}$$

  where:

  - N_0 : Number of 80-kN single axle loads to produce a limiting value of PSI

  - N_x : Number of repetitions of selected axle configuration (single or tandem) of load x to produce the same limiting value of PSI

- In 1970, Scala observed that the AASHTO LEFs derived from above equation are approximately equal to the fourth power of the ratio of the actual loads.

  $LEF_{PSI} = (L_x/L_0)^4$ where:
  L_x : Arbitrary axle load
  L_0 : Standard axle load (18 kips for single axles, 30 kips for tandem axles)

3.2. Review of Recent NZ Research

The most recent research in New Zealand on the LDE was conducted at CAPTIF between 2000 and 2004. The following reports were the output of the research:

- Report No. 214, by Arnold et al., 2001: Prediction of pavement performance from repeat load tri-axial tests on granular materials;
- Report No. 207, by de Pont et al., 2001: Effect on pavement wear of an increase in mass limits for heavy vehicles [Stage 1];
- Report No. 231, by de Pont et al., 2002: Effect on pavement wear of an increase in mass limits for heavy vehicles – Stage 2;
- Report 279, by Arnold et al., 2005a: Effect on pavement wear of increased mass limits for heavy vehicles – Stage 3;
- Report 280, by Arnold et al. 2005b. Effect on pavement wear of increased mass limits for heavy vehicles – Stage 4; and
- Report 281, by Arnold et al. 2005: Effect on Pavement Wear of Increased Mass Limits for Heavy Vehicles.

The CAPTIF facility is circular track where a rotating arm moves in a circular direction mimicking the loadings that can be applied to a pavement to assess the relative damaging effect i.e. the LDE.

The CAPTIF is capable of having different loads applied to the pavement in different wheel paths.

The comments in this section are based on the final concluding Report 281.

Table 2 shows the different test segments, base course materials, subgrade and relevant reports applicable to those tests.

- **Table 2: CAPTIF Test Segments and attributes[3]**

Pavement Segment ID	Pavement Thickness (mm)	Gravel Source	Description	Report	Subgrade
Cptf_A03	320	Montrose Class 2	20mm max size rhyolite from Montrose, Victoria, Australia	Arnold et al. (2005a) [Stage 3, RR279] Test 40 kN compared to 60 kN	Silty clay CBR=11%
Cptf_B03	250				
Cptf_C03	250	AP40 TNZ M/4	40mm max size alluvial gravel, greywacke from Canterbury, NZ		
Cptf_D03	320				
Cptf_E03	320	Rounded AP40 TNZ M/5	40mm max size uncrushed rounded river gravel from Canterbury, NZ	de Pont et al. (2001) [RR207] Test 40 kN compared to 50 kN	
Cptf_A01	300	AP40 TNZ M/4	40mm max size alluvial greywacke gravel from Canterbury, NZ		
Cptf_B01	300	AP40 TNZ M/4 + fines	40mm max size alluvial greywacke gravel, deliberately contaminated with 10% by mass silty clay fines from Canterbury, NZ		
Cptf_C01	300	Montrose Class 2	20mm max size rhyolite from Montrose, Victoria, Australia		
Cptf_D01	300	Recycled concrete	Recycled crushed concrete from Auckland building demolition sites		

As with all research not all combinations and variables can be studied at the same time in the available timeframe, hence certain assumptions had to be and made some key ones are:

- The “vertical surface deformation (VSD) was used as the main measure of pavement wear”[3];
- The end of life of pavement is defined as “the number of wheel passes when 10% of the area has a VSD greater or equal to 15 mm”[3]; and
- The pavement base course material was placed on an identical subgrade for all test segments and it “was a silty clay with a CBR of 11%,”[3].

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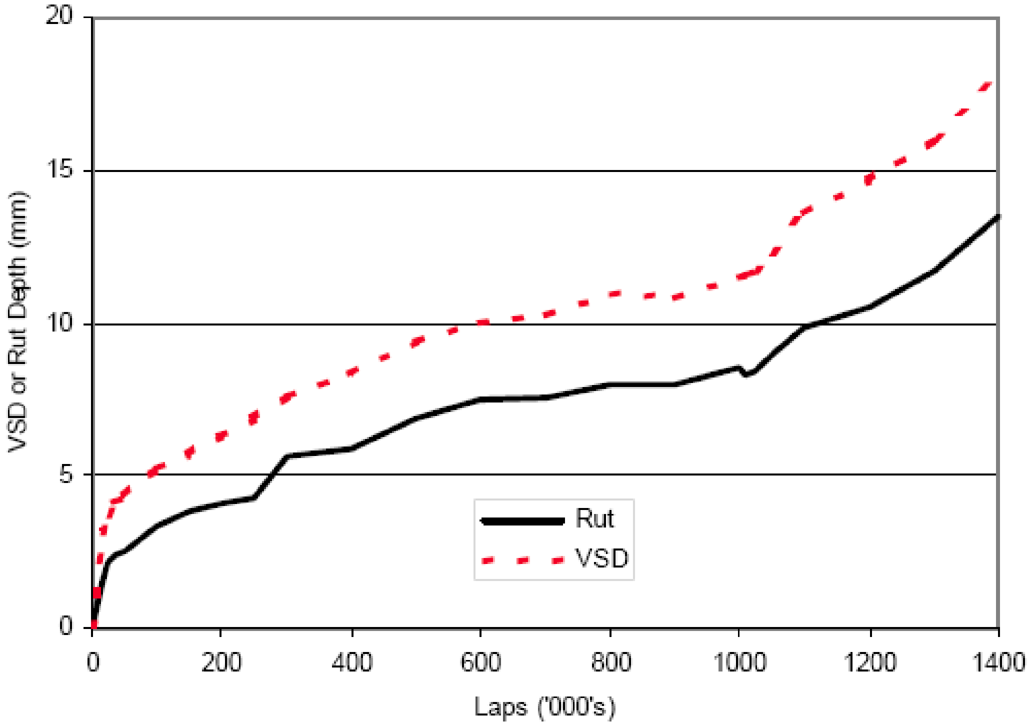
[3] Report 281 by Arnold et al. 2005: Effect on Pavement Wear of Increased Mass Limits for Heavy Vehicles

3.2.1. Vertical Surface Deformation

The use of VSD as a surrogate to rutting and roughness (longitudinal unevenness) is sound although there are some basic differences which the report recognises.

Firstly in the CAPTIF test it is shown that VSD is greater than rutting as can be seen in the **Figure 2**.

- Figure 2: Comparison of VSD and rut measurement at CAPTIF[3]



It is not clear from the report as to why this is the case apart from the statement that the “for this is related to the initial reference level taken for calculating the VSD values and how the edges of the ruts at CAPTIF move downwards during the testing which affected the straight-edge rut depth”[3].

From the above figure it can be suggested that rutting is generally 20% less than VSD, this is important as it can affect the comparison to the existing road network and other accelerated pavement loading trails, eg ALF and AASHTO.

3.2.2. End of life criteria

The definition adopted is “when 10% of the area has a VSD greater or equal to 15 mm”[3], this is justified by considering six factors of which the 3 that are of concern are:

- The level of rutting has no impact in determining the LDE;
- This level of rutting is currently applied to the state highway network in NZ; and
- By adopting a medium level of rutting as end of life then there is less likelihood of the need to extrapolate the results as compared to adopting a worst level of rutting (this would indicate time was limited for the research project and hence a low value was chosen).

The first assumption in the report is backed by the figure below. It is stated that “Figure 2.3 shows the marginal effect of the chosen VSD value on the damage law exponent"[3].

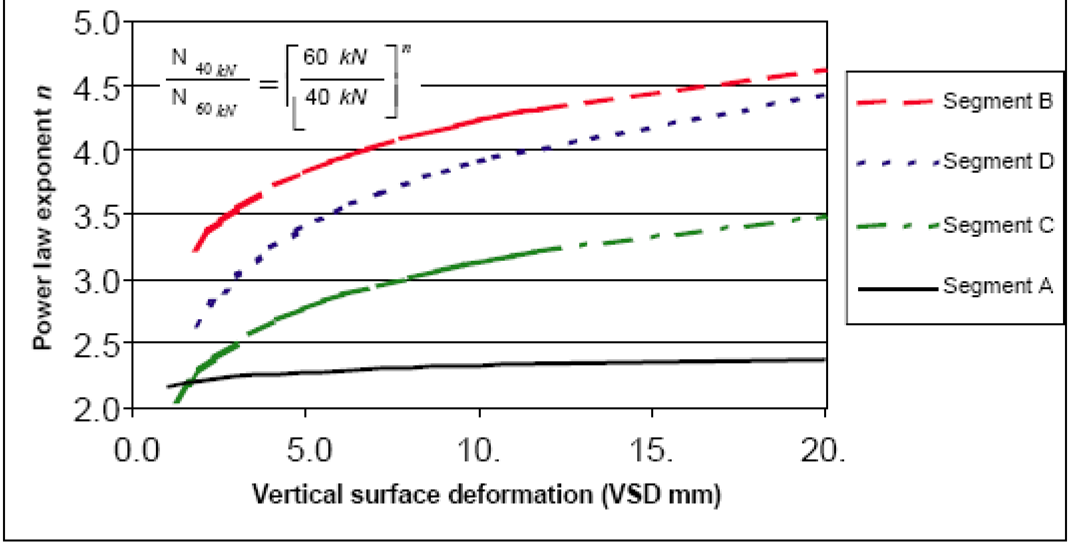
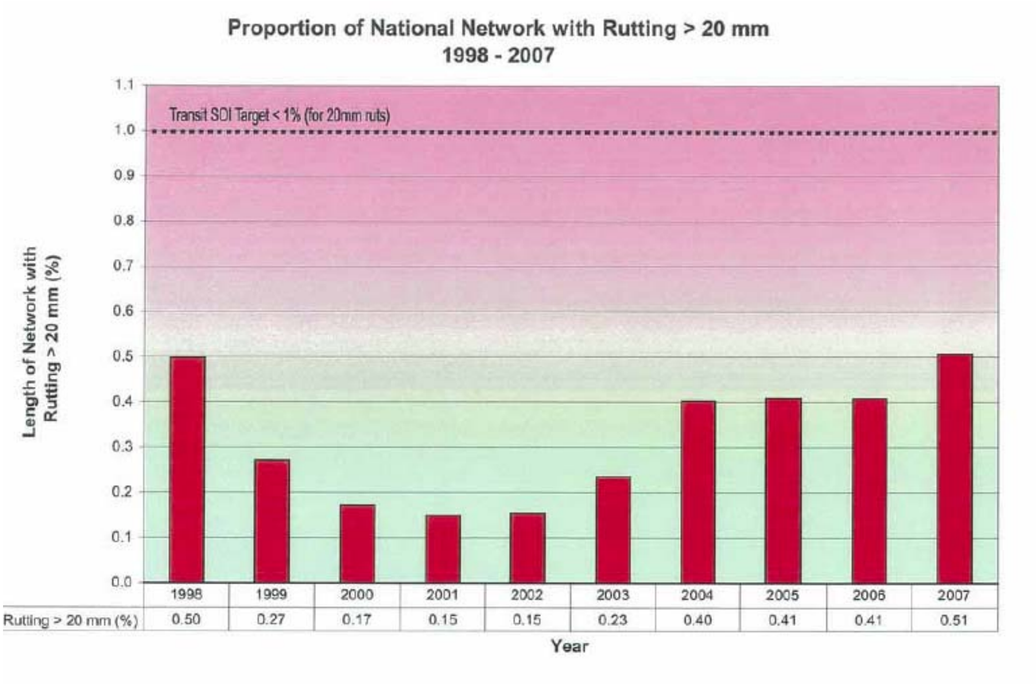


Figure 2.3 Power law exponent *n* determined for a range of vertical surface deformation (VSD) values (after Arnold et al. 2005a).

However when examining the above figure it is clear that in 3 of the 4 segments the LDE increases as the VSD measurement increase. This change is significant i.e. for a 30% increase in VSD there is a 10% increase in exponent value. This is not unexpected as the ASSTO trials showed for different end of life definitions i.e. PSI the load equivalencies factors for the same axles groups were different.

When considering the end of life as being 15mm of VSD on 10 percentile of the segment as being representative of current practices is it important to reflect that the RUC wear component is applied to actual costs and not theoretical costs so a direct comparison to actual pavement performance is warranted.

The 2007 Condition report[4] states with regards to rutting that “The network, shows signs of deterioration, with 0.51% of the network having rutting > 20mm compared with 0.41% last year, but this is still within Transit’s SOI target of < 1%”. See figure below from the 2007 Condition Report[4].



Hence the failure / end of life is considered to be 20mm of rutting but there is no indication of 10% of the segment, it is simply a percentage of the network i.e. length of network which exceeds 20mm of rutting.

Assuming the 20% difference from Figure 2: Comparison of VSD and rut measurement at CAPTIF[3]is correct, then an end of life of 20mm of rutting translates to 24mm of VSD measurement, which is far different from the 15mm adopted in the CAPTIF trails. This difference is important as it has an impact on the LDE derived.

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[4] Transit New Zealand State Highway National Pavement Condition Report 2007

The other key consideration in choosing the VSD of 15mm was to pick a vertical displacement low enough such that the end of life is reached during the testing phase. This would negate the need to post-extrapolate the results to determine the number of passes at the end of life stage.

It is clear from the past research i.e. ASSHTO, that the defined terminal level of distress has an influence of the number of cycles and the LDE derived.

Even though a low VSD level was chosen for end of life definition the majority of the test segments required to be post-extrapolated. This is another avenue for introducing errors in the final conclusions.

In comparison during the recent Accelerated Loading Facility (ALF)[5] trials in Australia of unbound granular pavement with thin surfacing failure was “defined as 25 mm maximum mean surface deformation” or “until the deformation reached such a magnitude that trafficking was no longer possible”. This is more consistent with road practitioners’ definition and of note is the use of the *mean* measurement and not the *10 percentile* of the segment.

3.2.3. VSD Extrapolated to end of life

The researchers considered two methods to extrapolate the VSD measurement to 15mm to estimate the end of life of the pavement segments. They were principally linear and a power model. **Figure 3** shows how the two models were applied to one station reading.

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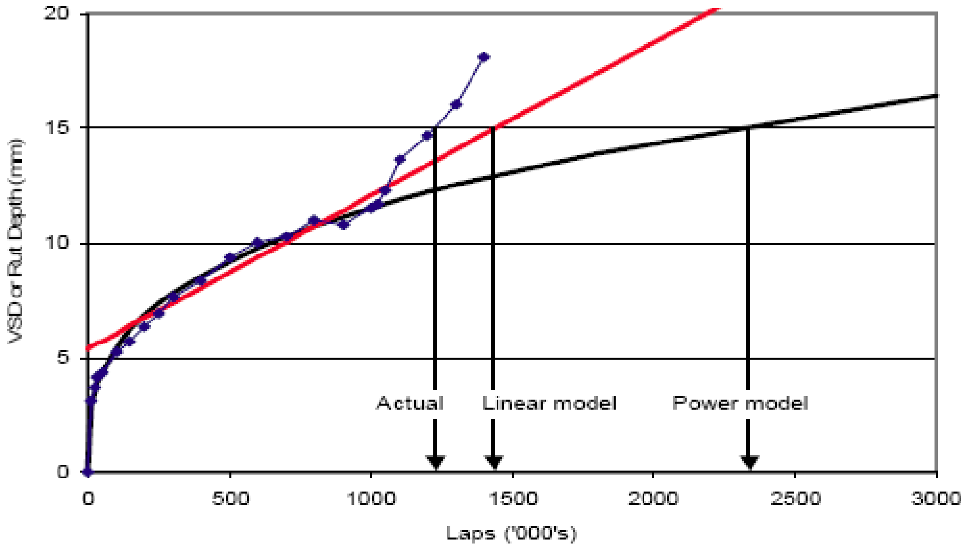
[5] AP-T104/08 Relative Pavement Wear of an Unbound Granular Pavement Due to Dual Tyres and Single Tyres, by Richard Yeo, Siew Leng Koh, Kieran Sharp, August 2008

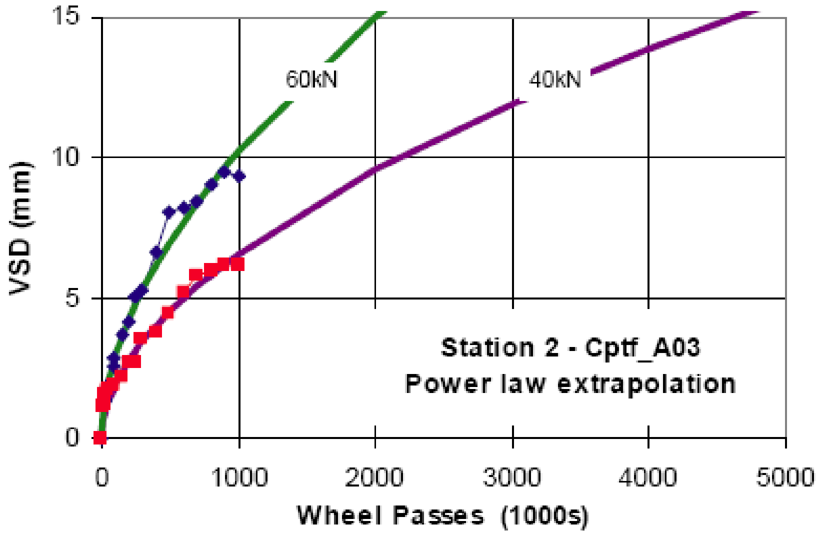
- **Figure 3: Linear and power model extrapolation methods compared to actual results**



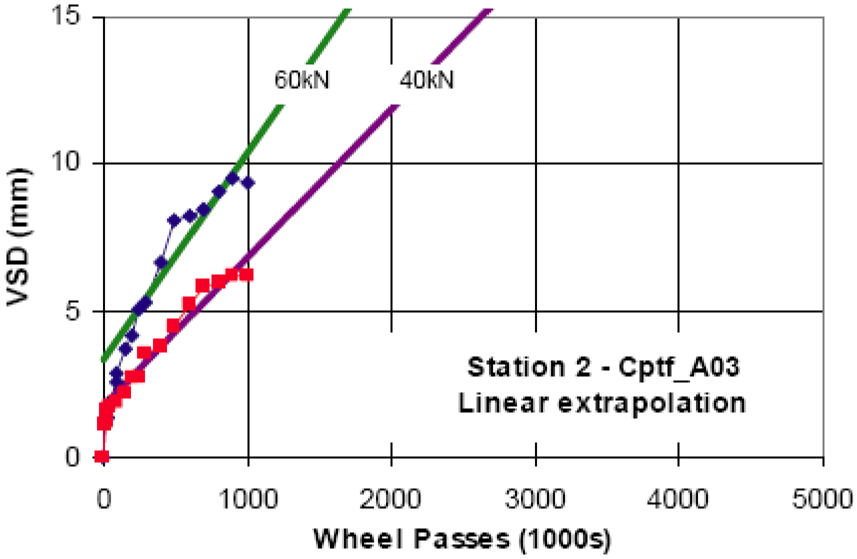
The report concludes that even though the power model is a better fit to the data, that the linear model is more appropriate for thin surfaced pavements.

The impact of which model is chosen for extrapolating the VSD has a significant influence on the outcome of the LDE. The report states that using the power model as compared to the linear model results "in a higher damage law"[3].

- **Figure 4: Extrapolation of VSD data using the power model**



- **Figure 5: Extrapolation of VSD data using the linear model**



By examining **Figure 4** and **Figure 5** it clearly shows the impact of using the different extrapolation models on the LDE. Note the difference between 60kN and 40kN for power and linear in terms of the number of wheel passes.

This difference is further reinforced by **Table 3** and **Table 4** below.

- **Table 3: LDE using Linear model for extrapolation to end of life**

ID	Load (KN)	Pavement Life in Wheel passes (10^6) – Extrapolated by Linear model			LDE Report 281
		Average	10th %ile	90th %ile	10th %ile
Cptf_A03	40	2.9	2.4	3.4	
Cptf_A03	60	1.7	1.3	2	1.5
Cptf_B03	40	3	2.8	3.3	
Cptf_B03	60	1.4	1.2	1.6	2.0
Cptf_C03	40	2.8	2.4	3.2	
Cptf_C03	60	1.4	1.1	1.5	2.0
Cptf_D03	40	3.2	2.6	3.8	
Cptf_D03	60	1.5	1.2	1.9	1.9
Cptf_E03	40	0.8	0.4	1.4	
Cptf_E03	60	0.2	0.1	0.3	3.2
Cptf_A01	40	4.5	2.5	7.7	
Cptf_A01	50	2.3	1.1	3.4	3.4
Cptf_B01	40	4.8	2.4	7.8	
Cptf_B01	50	2.4	1.3	3.4	2.7
Cptf_C01	40	6.4	4.5	8.3	
Cptf_C01	50	4.7	2.2	7.5	3.2
Cptf_D01	40	6.2	4.3	9.4	
Cptf_D01	50	4.2	3.4	5.1	1.1
				Average ->	2.3

Table 4: LDE using Power Model for extrapolation to end of life

ID	Load (KN)	Pavement Life in Wheel passes (10^6) - Power			LDE calculated from adjoining figures by SKM
		Average	10th %ile	90th %ile	90th %ile
Cptf_A03	40	5.7	3.9	8.2	
Cptf_A03	60	1.9	1.4	2.2	3.2
Cptf_B03	40	7	5.7	8.2	
Cptf_B03	60	1.5	1.3	1.8	3.7
Cptf_C03	40	6.1	4.6	9.5	
Cptf_C03	60	1.7	1.2	2	3.8
Cptf_D03	40	11.9	5.2	16.3	
Cptf_D03	60	2	1.4	2.6	4.5
Cptf_E03	40	0.5	0.2	0.8	
Cptf_E03	60	0.2	0.1	0.3	2.4
Cptf_A01	40	41.9	4.1	135.5	
Cptf_A01	50	4.7	1.3	9.6	11.9
Cptf_B01	40	62.7	3.6	89.6	
Cptf_B01	50	10.1	1.8	22.3	6.2
Cptf_C01	40	72.1	14.5	213.1	This segment data was ignored as the number of passes for 40KN is less than 50KN in the 90th percentile which is counterintuitive.
Cptf_C01	50	88.8	2.6	226.3	
Cptf_D01	40	85.6	18.8	211.8	
Cptf_D01	50	14.1	7.4	23	9.9
				Average	5.7

From the above tables it is shown that the linear extrapolation method leads an average LDE of 2.3, whereas a power model extrapolation on the 90h percentile data results in an average LDE of 5.7.

Furthermore the Report 281 states that during the development of a deterioration model based on material properties from Repeated Load Triaxial (RLT) that “The extrapolation method used was a power model as this provided the best fit”[3]. It is clearly inconsistent to use different extrapolation methods in the same research project.

3.2.4. Subgrade strength

The research at CAPTIF limited the CBR value to 11% for all subgrades in all segments. This subgrade is relatively high and would contribute significantly to the pavement strength.

Clearly the strength of the subgrade has had an impact on the pavement strength and this is recognised in the research report.

From **Table 5** a pavement with 300mm of basecourse similar to the CAPTIF pavement trails and a weaker subgrade CBR of 5% there is a 3 fold increase in the LDE. Clearly the subgrade contributes to the pavement strength and has a greater impact on thin weak pavements as compared to thicker pavements.

- **Table 5: Effect of subgrade on SNP and LDE[3]**

Pavement Thickness & Subgrade CBR	SNP (estimated)	LDE(derived from pavement model)
300 mm/CBR10%	3.5	1.5
300 mm/CBR5%	2.8	4.8
700 mm/CBR10%	4.9	1.1
700 mm/CBR5%	4.3	0.9

3.2.5. Summary comments on Report 281

In reviewing the Report 281 with reference to the 4th power rule the following can be summarised:

- The LDE can be shown to be between 2.9 and 11.9 if you adopt a Power Model to extrapolate the VSD until the end of life instead of the Linear Model adopted in the report;
- Assuming that the 10th percentile of the segment as the basis for measurement is not based on any pavement condition reported by the roading authorities;
- The VSD measurement in CAPTIF is actually a higher measurement than rutting. Hence a VSD of 15mm for terminal stage of a pavement is equivalent to 11mm which is well below the actual level used and reported by roading authorities being 20mm of rutting;
- The strong subgrade contributes to the pavement strength and in turn reduces the power law exponent;

In concluding there does not seem to be sufficient evidence to change the power rule from the 4th to a lower level.

3.3. Review of other relevant reports

3.3.1. Ternz and Covec[6]

This report was commissioned by the Ministry of Transport NZ. Amongst its objectives was a requirement to obtain further information on the "fourth power rule for allocating axle weight related roading expenditure to vehicle use".

Their literature search is present in **Table 6**.

- **Table 6: LDE from various researchers**

Pavement type	Test conditions	Exponent	Reference
Flexible	Modelling with validation	1.3-4.1	(Cebon 1999)
Flexible	Modelling using AASHO results	2-6	(Addis and Whitmarsh 1981)
Rigid	Reported values from OECD members	8-12	(OECD 1982)
Rigid	Reported values	11-33	(Cebon 1999)
Thin surface granular	Accelerated pavement testing in Australia	1.8-5.9	(Yeo, Sharp et al. 2004) (Martin 2005)
Thin surface granular	Accelerated pavement testing in New Zealand	1.3-3	(de Pont 2001; de Pont 2002; Arnold 2005; Arnold 2005; Arnold 2005)

In summary the report's literature search suggests that:

- No universal fourth power relationship exists and that there are many variables at play;
- The exponent value was dependent upon pavement type, the pavement strength, the type of distress chosen for end of life determination, for example rutting compared to roughness, the terminal value chosen, and the analysis methodology.

3.3.2. Arnold et al.[7]

The CAPTIF research concluded amongst other items:

- "The exponent for the power law ranged from 2 to 4 for Segments A, B, C and D.";

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[6] Heavy Vehicle Road User Charges Investigation, February 2008, TERNZ COVEC

[7] Effect on pavement wear of increased mass limits for heavy vehicles – stage3, by G. Arnold, B. Steven, D. Alabaster & A. Fussell, Land Transport New Zealand Research Report 279,2005

- "The value of the exponent depended on the pavement type and the value of VSD taken to be the end-of-pavement life."
- "The result of this accelerated pavement test principally provides an indication of the performance of a relatively strong pavement, on a strong dry subgrade, in ideal dry environmental conditions. The behaviour of weaker or saturated subgrades has not been investigated, nor have the effects on older and/or poorly maintained surfaces where moisture may be entering the base."

So the findings above are no different to the ASSHTO trials in that they confirm:

- the Exponent is dependent upon the terminal / failure definition, that strong pavement provide values of 2 to 4 in ideal conditions and that it would not be unexpected to have higher exponent values for weaker pavements.

3.3.3. Sharp and Vuong[8]

Reported on ALF test trails conducted to test thin surfacing on unbound crushed rock pavement typical of pavements used in arterial roads (i.e. total pavement thickness of 200 mm on a subgrade) they conclude "The load damage exponent (LDE) value determined for this pavement was about 7.5, which is similar to the LDE values of 6-8 estimated from a previous ALF trial, much higher than the LDE of 4 obtained from the AASHO Road Test, but similar to the "subgrade damage" exponent of 7.14 recommended in the Austroads Pavement Design Guide".

3.3.4. Yeo, Martin and Koh[9]

They reported on ALF trials of unbound granular material with thin surfacing as shown in **Figure 6**. Three materials were tested including New Zealand M4 material.

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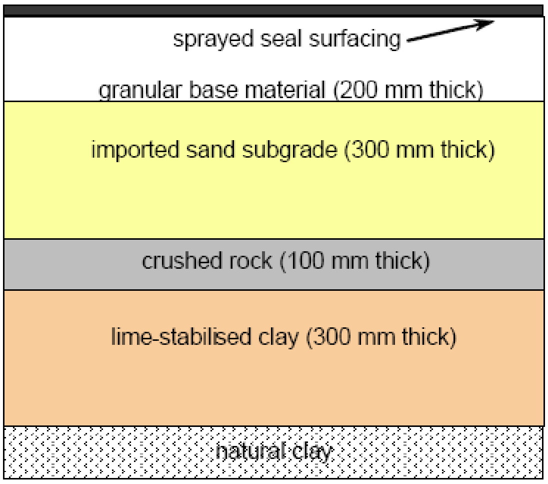
[8] Characterisation and Axle Load Equivalency of Unbound Granular Pavements by K.G. Sharp and B.T. Vuong 2000

[9] Investigation of the Load Damage Exponent of Unbound Granular Materials under Accelerated Loading, AP-T73/06, by Richard Yeo, Tim Martin and Siew Leng Koh, 2006

- **Figure 6: Typical pavement structure**



Their analysis of the results is shown in **Table 7**.

- **Table 7: LDE**

Material	Deformation	Roughness
CC blend (50% / 50% blend of recycled crushed concrete and quarry product)	3.2	4.8
Montrose (high quality material - an Australian rhyolite / rhyodacite, crushed rock)	3.8	3.4
NZ M4(high quality gravel- a New Zealand crushed alluvial gravel)	2.0	-

One of their key conclusions is:

"Overall it was considered that the 4th power law (LDE = 4) was adequate for the types of pavements studied and under the test conditions".

3.3.5. Chen et al[10]

This research paper outlines the performance of thin surfaced pavements in an instrumented full-scale test pavements when built inside a temperature-moisture controlled environment, and subjected to accelerated traffic by means of a heavy vehicle simulator (HVS).

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[10] Analysis of Overload Damages in Thin Flexible Pavements by Chen, Dar-Hao ; Cortez, Edel R; Petros, Katherine A; Zhou, Fujie ; Yang, Wei-Shih Transportation Research Board Annual Meeting 2006 Paper #06-0391

A LDE was found to be higher than 7.8, they believe that the high exponent values obtained were attributable to low structural capacity (SN) of the test pavements.

They consider that the well known 4th-power rule is too conservative for low SN pavements.

This is in line with NZ research which shows that low strength pavement will have an exponent value greater than the fourth power rule.

3.3.6. Johnsson 2004[11]

Johnsson examined other researcher's data and stated that for flexible pavements the fourth power law seems to be justified.

3.3.7. De Pont [12]

De Pont reviewed the methodology for calculating the exponent by Arnold et al. in the Report 281 and found "some inconsistencies in the method used by Arnold et al to determine the power law exponent in the pavement deterioration model. This does not necessarily mean that all Arnold's findings are wrong. However, those involving the power law exponent cannot be relied upon."

3.3.8. Austroads[13]

The Austroads pavement design guide recognises the different failure mechanism and suggests different damage exponents for each pavement type and failure mode. **Table 8** shows values from 4 to 12.

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[11] .The cost of relying on the wrong power – road wear and the importance of the fourth power rule, by Johnsson, R. 2004, Transport Policy 11 Issue 4, October 2004:

[12] Methodology for Calculating the Exponent in a Pavement Wear Model, by John de Pont, TERNZ Ltd, February 2008

[13] Austroads 2004 Pavement Design Guide

- **Table 8: LDE from Austroads Pavement Design Guide**

Design method	**Pavement type**	**Damage type**	**Damage designation** **k**	**Damage exponent** **m**
Empirical *(Figure 8.4)*	Granular pavement with thin bituminous Surfacing	Overall pavement damage	e	4
Mechanistic	Pavement containing one or more bound layers	Fatigue of asphalt Rutting and shape loss Fatigue of cemented materials	a s c	5 7 12

3.4. Fourth Power Rule Conclusions

The fourth power rule has been used extensively around the world and there has been significant body of research into the robustness of the rule. It can be concluded that the research points to the following:

- There is no unique value of the LDE for all pavements and this is recognised in current Austroads pavement design guide;
- All research confirms the existence of damage power relationship with a standard 8 tonne axle;
- Most research indicates that the value of the power exponent varies with:
  - The pavement type i.e. weak or strong, and rigid or flexible;
  - The subgrade strength;
  - The environmental factors which will influence the pavement strength;
  - The type of distress chosen for the definition of end of life egg rutting compared to roughness, or the PSR used in the original AASHTO trials;
  - The terminal value chosen;
  - The method of analysis of the data; and
  - The material properties of the pavement.

With regards to New Zealand’s recent research results from the CAPTIF trials it can be concluded that:

- The tests were done on specific pavement types (strong pavements) and the results cannot be applied to the entire road network of national and local roads;

- The definition of terminal value adopted of 15mm VSD (which is about 20% less than rutting measurement in the CAPTIF setup) seems on the low side as compared to road practitioners definition i.e. 20mm of rutting;
- The use of the 10 percentile measurements as the terminal value is not in line with other accelerated pavement trials such as the ALF which uses the mean value;
- The majority of the pavement segments did not fail and had to have their VSD values post-extrapolated using a linear relationship even though they state that the power relationship has a better data fit. This has a significant effect on the reported values from an average exponent value of 2.3 for linear model extrapolation to 5.7 for power model extrapolation;
- The predictive modelling calibrated against the CAPTIF results show that for a weaker subgrade (CBR =5%) in lieu of CBR of 11% in the trials that there is dramatic increase in the exponent value, from 1.5 to 4.8; and

In conclusion from the above research there is insufficient robust and clear evidence to change the RUC model for road wear by changing the fourth power rule. To apply a different LDE over different parts of the network would be complex and administratively difficult to implement.

Changing the fourth power rule to a lower power value over the entire New Zealand road network would be a risky strategy, and one in our view which should be avoided.

4. Vehicle Dynamics and Its Effect on Road Wear

4.1. RUC Model

The vehicle dynamics has an important effect on pavement deterioration due to the dynamic loads that can be generated from stiff spring suspension systems.

From the previous section the “wear” formula does not include any explicit factors for dynamic loading of heavy vehicles. However the Fourth Power rule implicitly includes this dynamic loading effect as it is derived from field trials in the early sixties where the heavy vehicle suspensions would have been stiffer than today’s vehicles.

4.2. Effect on Road wear

The summary of research shows:

- The measured dynamic wheel forces vary with suspension type, road roughness and vehicle speed;
- On moderately rough roads vehicles travelling at highway speed and poorer performing suspensions can have up to double the wheel loads than those of the better suspensions systems;
- On smooth roads there is less difference between suspension types hence the specification for new roads works to have low roughness values;
- General road-friendly suspensions systems have low vertical stiffness and high levels of dampening;
- Air suspensions tend to have better dynamic performance than mechanical suspensions but their maintenance is vital to ensure continuity of their road friendliness;
- Air suspensions with poor damping can produce higher levels of dynamic loading as mechanical suspensions; and
- As most heavy vehicle suspensions have similar stiffness they tend to respond in a similar manner when they encounter a particular road profile and this is exhibited in a spatial repeatable pattern causing localised pavement failure rather than a general pavement wear.

Currently in Australia and in other EU countries there is recognition of the different suspension effects by allowing higher mass vehicles for road-friendly suspensions. In Australia and in particular in NSW there is a required for the transport operator to have a maintenance quality system to ensure the road friendliness of the suspension system before they are allowed the higher mass.

4.3. Other Views

The BCA believes that airbag suspensions should obtain a discount as:

"Most buses and coaches have airbag suspension which reduces road wear, but the RUC scale, developed in the late 1970s has failed to recognise these improvements"

OPUS 1999 recommends in their report that "alternative sets of RUC rates for vehicles fitted with road-friendly suspensions" be developed.

4.4. Conclusion

SKM is of the opinion in keeping with Australian practice, that the effects of road-friendly suspensions should be recognised by a new vehicle type in recognition of their road friendliness, provided the suspension system is monitored through a third party system.

5. Reference Loads

5.1. RUC Model

The RUC model assumes a “wear” ESA as discussed in Chapter 2. The maximum gross weight of the vehicle is divided by the reference load as part of that formula. In other words the Reference Load is the base line from which other loads are compared against to estimate their relative road wear effects.

The RUC Reference Loads are shown in Table 1 - Axle Reference Loads For Standard Tyres (tonnes/axle).

5.2. Effect on Road wear

The Reference Load reflects the ESA of the different axles and axles groups which is directly related to the cumulative ESA that a pavement can withstand during it service life.

5.3. Other Views

It has been suggested that the Reference Loads used in the cost allocation model for determining the number of ESA associated with a particular axle should be the same as those values used in the Austroads pavement design guide. This guide is used in the design and rehabilitation of pavements in New Zealand.

The Austroads design loadings are shown in the Table 9: Austroads axle group reference loads for pavement design.

- **Table 9: Austroads axle group reference loads for pavement design**

Axle group type	Load (kN)
Single axle with single tyres (SAST)	53
Single axle with dual tyres (SADT)	80
Tandem axle with single tyres (TAST)	90
Tandem axle with dual tyres (TADT)	135
Triaxle with dual tyres (TRDT)	181
Quad-axle with dual tyres (QADT)	221

Hence, consider a 3-axle truck (RUC type 6) at 21 tonnes gross weight. It will have 6 tonnes on the steer axle and 15 tonnes on the drive axle group.

- Under RUC pavement wear model the steer axle generates 0.64 ESA and each drive axle generate 0.57 ESA, giving a total of 1.78 ESA;
- Whereas using the Austroads Reference Loads (**Table 9**), the steer axle generates 1.52 ESA while the drive axle group generates 1.41 ESA, giving a total of 2.93 ESA.

It would seem from the above simple example that the RUC Reference loads are less conservative than the Austroads Reference loads.

5.4. Conclusion

SKM is of the opinion that the Reference Loads in the RUC model should be changed to align with Austroads as they are currently being used in pavement design. A consistent approach should be taken.

6. Vehicle Weight Distribution

6.1. RUC Model

The RUC model assumes that the loads are equally distributed between all the axles as evidenced by the “wear” formula and the Reference Loads are per axle.

In the above example (Chapter 5) of the 3-axle truck (RUC type 6) with 6 tonnes on the steer axle and 15 tonnes on the drive axles, the respective ESAs are 0.64 ESA and 0.57 ESA. Whereas the RUC model assumes each axle to be 0.59 ESA giving a total of 1.77 ESA as compared to 1.78 ESA.

This difference is small but does increase slightly as the vehicle is partially loaded as is shown by the example below:

- Assume 3-axle truck (RUC type 6) with 5 tonnes on the steer axle and 12 tonnes on the drive axles the respective ESAs are 0.31 ESA and 0.235 ESA. Whereas the RUC model assumes each axle to be 0.25 ESA giving a total of 0.75 ESA as compared to 0.78 ESA.

6.2. Effect on Road wear

Calculating the right ESA is important to road wear as an increase in ESA increases the road wear over the lifetime of the pavement.

6.3. Other views

It has been suggested that this averaging out of ESA per axle in the RUC model is disadvantages to certain vehicle types. In particular, powered vehicle loads on the front do not increase with payload as much as the loads on the drive axles, however trailers the loading is more proportional.

Hence assuming “uneven load distribution into account will lead to proportionately more RUCs being attributed to powered vehicles and less to trailers particularly at lower levels of loading.”

6.4. Conclusion

SKM is of the opinion that the manner in which the RUC model currently treats the load distribution is not as significant as the other issues raised in this report. The impact is marginal and other more influential factors (vehicle dynamics and reference loads) should be addressed first.

7. Vehicle Types

7.1. RUC Model

The RUC model classifies the vehicle fleet into different vehicle types depending upon the number of axles configurations. Almost 50 percent of RUC vehicle types have a one to one relationship to the vehicle configuration. The remaining vehicle types have a one to many vehicle configurations.

7.2. Effect on Road wear

The vehicle types have an applicable ESA based on the axle configurations, spacings and number of tyres. Hence if the vehicle type includes several combinations of vehicles then this could lead to under or overestimating the ESA of that vehicle type.

7.3. Other Views

The TERNZ Covec report suggests:

- RUC type 24 possible “one vehicle type for twin-tyred single axle trailers and one for all other single axle trailers”;
- RUC type 28 – “included there is need to subdivide this vehicle type”;
- RUC type 37 – “There should be separate vehicle types for these two configurations”; and
- RUC type 43 – “certainly a case for separating the vehicles with twin tyres from those with wide singles in the RUC schedule and probably a case for separating the semitrailers from the full trailers”.

7.4. Conclusion

The data is improving with greater capability of developing additional vehicle types at minimal administrative cost. It is SKM’s opinion that new vehicle types should be investigated to better represent the current vehicle fleet.

8. Vehicle Loading and Utilisation

8.1. RUC Model

The RUC model assumes a factor of 0.55 to reflect that half the distance travelled (55%) is at maximum gross weight and the other half (45%) is at tare weight. Hence when the vehicle is empty it is assumed to have the wear effect of 1/10 of a full vehicle.

8.2. Effect on Road wear

Clearly the impact of underestimating the proportion of vehicles loaded can have a direct impact on estimating the ESA applied to the pavements.

8.3. Other views

The TERNZ Covec report analysed the WIMs data and found that the assumption in the RUC model are: "Analysis shows that with the current CAM method for calculating ESA a 55% factor for average ESA is reasonable for powered vehicles but the factor for trailers should be 44%."

The Mckenzie Podmore 2008 report[14] points out that some freight operators have specific operations which the average might not be applicable such as:

- "Logging trucks and tankers that are configured for a single commodity with zero backhaul prospects,
- Vehicles engaged in round trip collection and distribution services where maximum weights are achieved for less than half the journey
- Vehicles with full backloads
- Normally lighter vehicles that operate at a constant loading all the time because there is little difference between the tare (or tare plus machinery) and maximum weight.

Failure to recognise these different operational practices or dealing with them on the basis of national averages introduces another source of cross-subsidy into the CAM and undermines the efficiency of vehicle configuration decision making as well as the overall integrity of the user-pays system."

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[14] Efficiency and Equity Issues in the Funding of Roading Expenditures – May 2008 Mckenzie Podmore

The BCA suggests:

"Buses tend to operate at capacity for less than 15% of the time in contrast to freight vehicles on which the 55% loading rate was determined. Bus and coach tare weights are also higher relative to freight."

furthermore

"Bus or coach unladen weights (tare) typically represent around 70% of the total permissible fully laden weight".

8.4. Conclusion

In the absence of other evidence it is SKM's opinion that the 0.55 factor be maintained until better classification between RUC vehicle type and WIM data is available.

9. Large Single tyres

9.1. RUC Model

The RUC axle reference loads assume standard tyres. The RUC model takes into account large single tyres through the gross contact area of the tyre, which is obtained from tyre manufacturer's data.

However the RUC rate schedules do not differentiate between standard tyres and wide single tyres in identifying vehicle types. The classification of vehicles into RUC types is sole based on axle configuration and number of tyres, but not tyres type.

9.2. Effect on Road wear

The replacement of twin standard tyres with large single tyres increases the stress on the pavement and hence the ESA. For example the relative damaging effect of single axle fitted with large tyres as compared with dual tyres is $(8.2t)^4/(7.2t)^4 = 1.68$, an increase of 68%.

9.3. Other views

TERNZ Covec report suggests that “RUC vehicle type classification groups some vehicle configurations together into a single type where it would be more appropriate to distinguish between them because their pavement wear characteristics are quite different”.

OPUS 1999[15] recommended “no change in the RUC model to make allowance for vehicles fitted with single large tyres”. This is based on Table 10: Axle Reference Loads for Large Tyres Compared with those used in Current RUC Calculations, which shows minor differences and where difference exist then the proportion of vehicles are small.

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[15] New Zealand’s Roading Cost Allocation Model Review of Engineering Issues 17 September 1999 Opus International Consultants Allan Kennaird Consulting

- **Table 10: Axle Reference Loads for Large Tyres Compared with those used in Current RUC Calculations**

RUC Vehicle Type No.	**5**	**6**	**28**	**37**	**43**
Sum of Reference Loads currently used in RUC calculation	22.8	23.8	14.1	25.0	34.52
Sum of Reference Loads for single large tyres	22.9(1)	24.4(2)	15.2(3)	23.1(4)	30.3(5)

(1) Single large tyres on rear tag axle in close group with twin tyred axle, single standard tyres on front axle
(2) Single large tyres on front axle and twin tyred rear axles in a close group
(3) Tandem close group of axles both fitted with large single tyres
(4) Tridem close group of axles all fitted with large single tyres
(5) Two close groups of axles all fitted with large single tyres

9.4. Conclusion

SKM is of the opinion that single wide tyres should have different vehicle type classification and a corresponding RUC rates schedule.

10. Diesel Excise

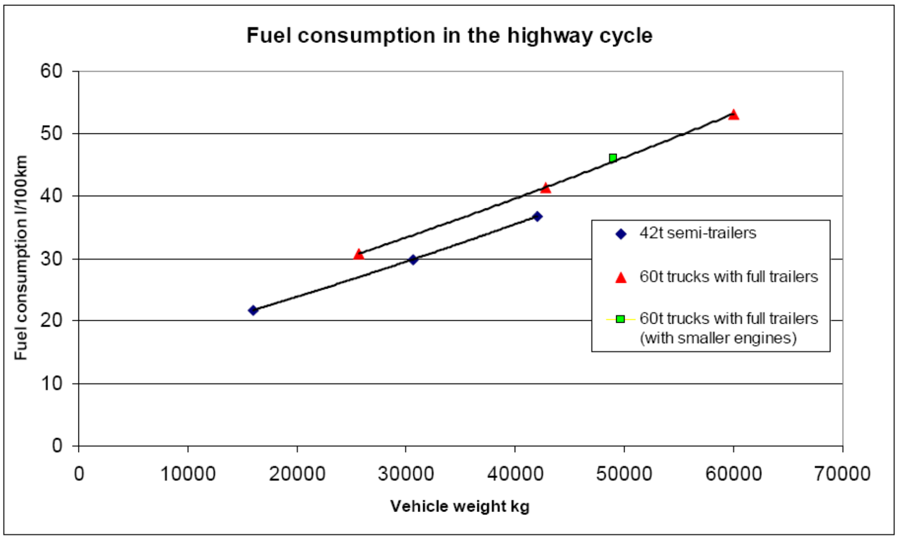
It has been suggested that the use of diesel excise can be used to replace the current RUC method as it does in Australia. This section explores the engineering concepts and validity of such a proposal.

A research report conducted into investigating ways of saving fuels for heavy vehicles[16] concluded "Weight is one of the most essential factors affecting fuel consumption. The dead weight of trailers and vehicles should be minimised. An extra 1,000 kg in weight, either as dead weight or as load, adds some 0.7 l/100 km in fuel consumption for a truck-trailer combination in highway driving. In dynamical urban driving the comparable value for buses is some 2 l/100 km per 1,000 kg".

Hence the application of a diesel excise as a substitute RUC for road wear will not be applied equitably across the heavy duty fleet and network i.e. urban situations with stops and starts will pay a higher level.

Furthermore the study shows how the fuel consumption increases linearly as the load increases, see **Figure 7**.

- **Figure 7: The fuel consumption of heavy duty vehicle as loads increase**[16]



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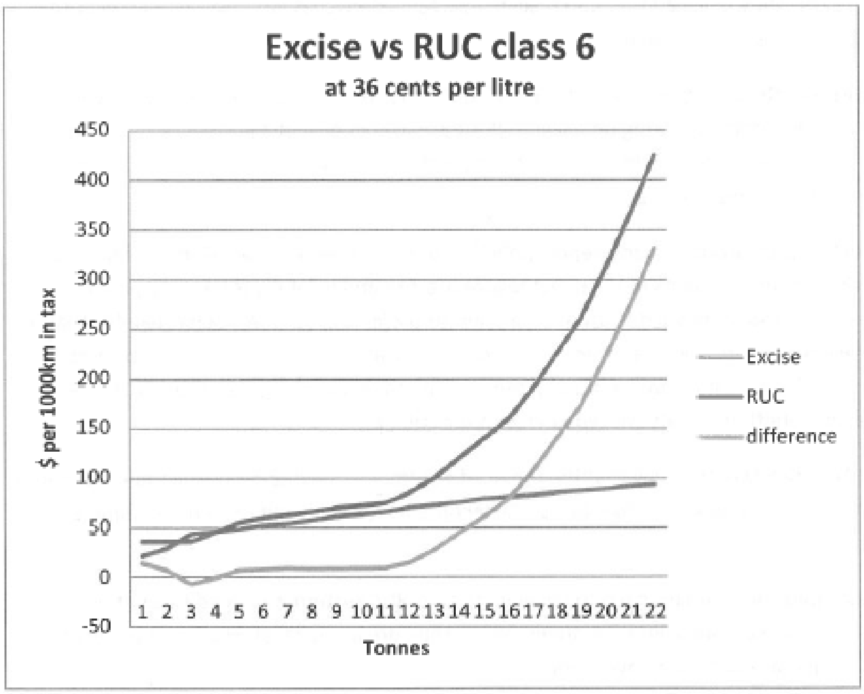
[16] Finish VTT research centre - Fuel savings for heavy-duty vehicles. Summary report 2003 – 2005. English version.

This linear relationship does not match the expected road wear as a consequence of the increase vehicle weight, which is an exponential relationship. A simple illustration is provided by the Automobile Association's submission as shown in **Figure 8**.

- **Figure 8: RUC vs. Excise for Class 6**

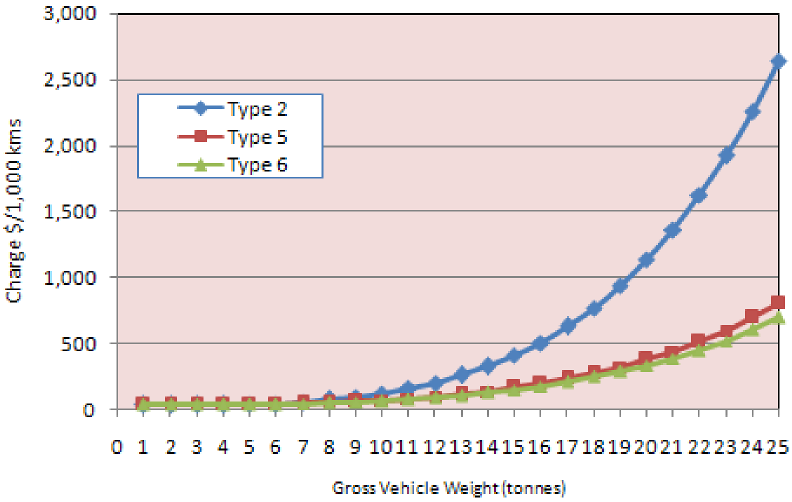


It is clear from the above graph that there is no relationship between fuel consumption of heavy vehicles and the RUC charges and in particular the road wear charges. As the fundamental mathematical relationship of a linear model for fuel consumption and a power model for road wear damage cannot coincide.

Figure 9 shows the RUC charges for the different vehicle types in RUC. Applying a diesel excise which is linear would then favour the heavy duty vehicles at the expense of the light vehicles.

But worst is the fact that high axle loads cause more damage than pavement friendly axle groups which spread the load on the pavement. Currently the RUC charges take care of this impact but a flat diesel excise would simply encourage heavier loads per axle.

- **Figure 9: RUC Charges**



In summary a diesel excise as a replacement for RUC road wear charges would result in:

- Heavier vehicles would pay less than currently under the RUC regime and lighter vehicles would pay more even though they contribute less pavement damage;
- The RUC vehicle classification recognises less damaging axle group classification through the CAM whereas a diesel excise does not;
- Vehicles that are used on private roads would require a rebate scheme of the diesel excise thereby increasing the administrative cost;
- Non road activities egg marine, rail, construction and mining would similarly require a rebate scheme of the diesel excise;
- Vehicles which use fuels other than diesel egg trolley buses, hybrid buses and bio diesel buses would not be covered by the diesel excise and would need some sort of RUC charges to recover their contribution towards of road maintenance and construction costs.

Fundamentally a diesel excise is not related to pavement wear whatsoever.

Appendix A List of References

i. Report 281 by Arnold et al. 2005: Effect on Pavement Wear of Increased Mass Limits for Heavy Vehicles

ii. Transit New Zealand State Highway National Pavement Condition Report 2007

iii. AP-T104/08 Relative Pavement Wear of an Unbound Granular Pavement Due to Dual Tyres and Single Tyres, by Richard Yeo, Siew Leng Koh, Kieran Sharp, August 2008

iv. Heavy Vehicle Road User Charges Investigation, February 2008

v. Effect on pavement wear of increased mass limits for heavy vehicles – stage3, by G. Arnold, B. Steven, D. Alabaster & A. Fussell, Land Transport New Zealand Research Report 279,2005

vi. Characterisation and Axle Load Equivalency of Unbound Granular Pavements by K.G. Sharp and B.T. Vuong 2000

vii. Investigation of the Load Damage Exponent of Unbound Granular Materials under Accelerated Loading, AP-T73/06, by Richard Yeo, Tim Martin and Siew Leng Koh, 2006

viii. Analysis of Overload Damages in Thin Flexible Pavements by Chen, Dar-Hao ; Cortez, Edel R; Petros, Katherine A; Zhou, Fujie ; Yang, Wei-Shih Transportation Research Board Annual Meeting 2006 Paper #06-0391

ix. The cost of relying on the wrong power – road wear and the importance of the fourth power rule, by Johnsson, R. 2004, Transport Policy 11 Issue 4, October 2004:

x. Methodology for Calculating the Exponent in a Pavement Wear Model, by John de Pont, TERNZ Ltd, February 2008

xi. Austroads 2004 Pavement Design Guide

xii. Finish VTT research centre - Fuel savings for heavy-duty vehicles. Summary report 2003 – 2005. English version.