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Technical Basis for Estimating the Cost of Road Wear on Unsealed Local Government Roads in Western Australia

PRA16029-2

AUTHOR: Tyrone Toole and Will Hore-Lacy

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Author	Tyrone Toole and Will Hore-Lacy	**PL**	Tyrone Toole	**QM**	Dr Tim Martin	

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SUMMARY

Western Australian Local Governments face significant costs from road wear as a consequence of unforeseen heavy vehicle traffic triggered by projects, typically in the resources industry. The impacts of additional heavy vehicle traffic on shortening road life and increasing maintenance requirements are greater for roads that were not designed and constructed for this purpose, which is the case for most Local Government roads.

In 2015, the Western Australia Local Government Association (WALGA) published a user guide for estimating the cost of road wear on sealed local roads. The guide was developed using the concept of a marginal cost of road wear attributable to additional freight traffic.

Local Governments have requested the development of a similar tool for unsealed roads. To support this, a methodology has been developed and tested which accounts for the impact of different factors on the cost of road wear for unsealed local government roads. These include the effect of traffic, climate, maintenance and roadbuilding materials related factors on physical performance and location which impacts performance and unit costs.

This report represents the deliverable from Phase 2 of a study aimed at developing a user guide for unsealed roads, and describes the development and application of the methodology, and its application in producing solutions for use in the unsealed roads user guide.

The main achievements and findings of the study include:

- A modelling framework applicable to unsealed roads has been developed and tested, with the analysis covering a comprehensive range of loading scenarios and applications conditions representing roads in Western Australia (WA). The solutions and cases cover three cost zones in WA, with the range of cases and assumptions informed by responses from WA asset management practitioners.
- Results have been presented to illustrate the physical performance of representative unsealed roads sections, in terms of gravel loss, and the financial impact as the marginal cost of road wear, and cover independent variables such as:

  - Additional loading scenarios, ranging from 10,000 tonnes to 500,000 additional loading units (LU) per annum, with the marginal cost expressed as a cost per additional LU, defined as axle pairs
  - Geographical location, representing climate and treatment cost, materials properties and typical operating conditions
  - Impact of compliance with road materials specifications
  - Impact of higher than average costs within a cost zone

- Examples of applying the results to developing and analysing four case studies (similar in scope to the sealed road user guide), including a step-by-step guide to the calculation process, and the sourcing of input data, including example of typical vehicle types and characteristics, and a discussion and interpretation of the results.
- Presentation of solutions in the form of graphical results covering an agreed set of scenarios to be employed in the unsealed roads user guide similar to the sealed road user guide.
- Provision of draft text for inclusion in the unsealed roads user guide.

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1   INTRODUCTION

1.1   BACKGROUND

A key consideration for Local Governments (LG) in Western Australia (WA) is the impact of heavy vehicles on local roads, and the associated cost of road wear. Increasingly over time, there has been greater utilisation of local roads by more significant axle loads. This has had a direct impact on the condition of the roads concerned and, as a consequence, Local Governments are facing significant increases in costs from road wear. In particular, there have been unforeseen increased volumes of heavy and extra-heavy vehicles operated by the freight industry and as a result of resource developments. The impact of heavy vehicles on shortening road life and increasing maintenance requirements is greater for roads that were not designed and constructed for this intended use, which encompasses many Local Government road networks.

To address this challenge, Local Governments have long been seeking mechanisms to quantify the cost of road wear to aid them in effectively negotiating compensation from industry operators. Various methods have been identified by Local Government to evaluate the cost of road wear in the past (Bondietti et al 2014), including routine maintenance determination, evidence-based reporting, pavement design approaches, and the evaluation of single marginal costs. However, a national method based on marginal cost principles has been widely accepted at an Australian Government, State and Local Government level as a reasonable basis for cost attribution, with this providing a consistent basis for estimating load-related impacts on the cost of maintaining road infrastructure using evidence-based deterministic pavement performance models. These estimate the mean-expected future condition of a road in relation to specific inputs, such as the composition (and strength) of the road, current and future traffic, climate and the maintenance regime. They aim to capture the performance impacts and full life-cycle costs of maintaining and rehabilitating road infrastructure over an extended period as illustrated in Figure 1.1. This illustration is typical of a long-term policy change such as allowing a change from gross mass limits (GML) to higher mass limits or a concessional loading arrangement.

Figure 1.1   *Impact of increasing axle load on rehabilitation intervention timing*
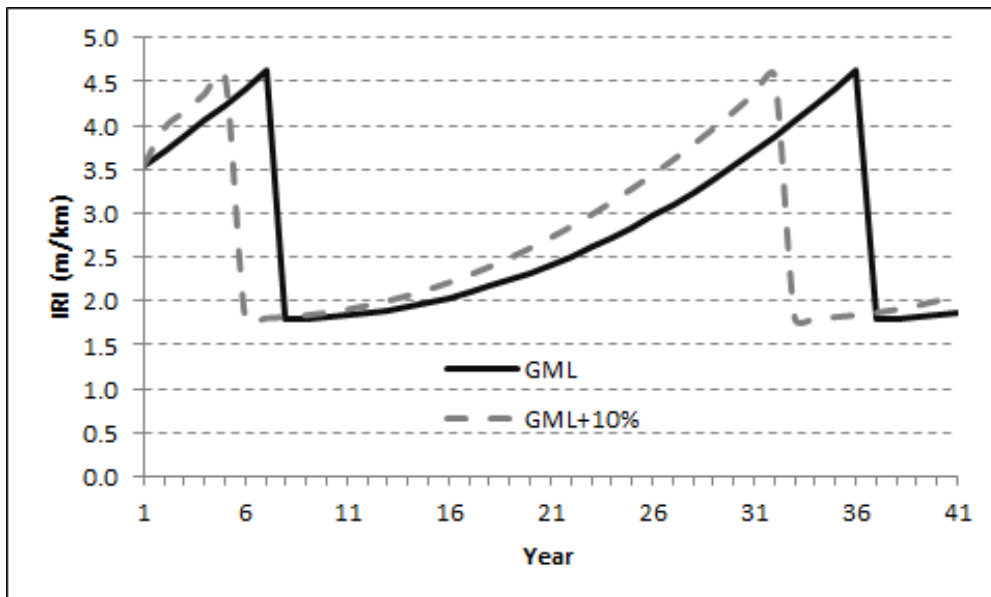
Source: Austroads (2012).

However, the actual loading patterns experienced by LG are often concentrated in time and may be an order of magnitude higher than the current rate of loading. This therefore requires application of a method that is sufficiently flexible to address the variety of circumstances likely to be experienced by local roads. Such a method has been developed for application to sealed local roads in WA, and a User Guide has been developed for application by LG practitioners and industry to determine the incremental cost of load-related road wear (WALGA & ARRB 2015 and Toole et al 2015). However, unsealed roads, which make up a

significant proportion of LG road networks, have not been the subject of such analysis other than in a few exploratory studies (Martin & McLean 2005 and Toole & Sen 2014), and is the focus of this study.

1.2   DEFINITION OF THE MARGINAL COST OF ROAD WEAR AND INFLUENCING FACTORS

The marginal cost of road wear is defined as the difference in the cost of maintaining a road in a serviceable condition arising from an increase in traffic loading above current or base traffic. Algebraically, it is the rate of change of the cost resulting from the incremental change (increase) in the freight task.

For sealed roads, analysis has shown that the marginal cost is mostly dependent on the magnitude and duration of the additional load, the structural strength of the road and its variation, and the additional cost of road maintenance activities to fulfil performance requirements. Consequently, a standard marginal cost based on a network average for all roads is inadequate compensation for the majority of Local Government roads. This is because there is the possibility that they have relatively weak structures in relation to the additional traffic loads they may be subjected to, and in comparison, freeways and highways are designed, built and maintained to higher standards.

For unsealed roads, the subject of this report, the cost of road wear is likely to be primarily a function of the level of traffic and its composition, the surface materials types and location, and the frequency of routine and periodic maintenance requirements. However, as in the case of the sealed roads guide, further information is required on a range of factors to help inform the determination of the cost of road wear. This extends beyond typical vehicles and loading scenarios and includes specific information on the cost of providing and maintaining unsealed roads, the materials and maintenance strategies used, and the physical characteristics of the roads. A greater variation in road standards and history is to be expected, including those specific to metropolitan, rural and remote areas.

Evidence from international studies suggest that the rate of wear of unsealed roads is more associated with the passage of vehicles, or axles, rather than the ESA concept applicable to sealed roads. This means that the denominator in the marginal cost calculation needs consideration, in addition to ensuring an appropriate standard and initial condition to allow trafficking, and the overall structural adequacy to limit vertical deformation or structural rutting primarily in wet conditions.

1.3   PURPOSE AND CONTENTS OF THIS DOCUMENT

This document describes the development and trial application of a methodology to calculate the cost of road wear on unsealed Local Government roads in Western Australia. It represents the deliverable from Phase 2 of a planned three-stage study aimed at developing a user guide for unsealed roads, the scope of which is as follows:

- Phase 1 - An interim report detailing the methodology and approach for developing the user guide including worked examples to test and demonstrate the methodology.
- Phase 2 (this report) - A full technical report detailing background, objectives, methodology, outcomes, conclusions and references, written in a language and style suitable for publication on the WALGA website as the source reference document for the project.
- Phase 3 - A user guide in a similar style to the sealed roads user guide.

The Phase 2 report (this Report) offers solutions to be deployed in a user guide, similar in scope to the existing sealed road user guide. It also contains supporting information on typical operating scenarios and key factors likely to affect the cost of road wear, with this information based on a response to a questionnaire from councils throughout WA. The questionnaire employed is reproduced in Appendix A and a summary analysis of the responses is reproduced in Appendix B. A summary of the background to the road deterioration models employed, and their review and calibration is provided in Appendix C.

Additional information is provided on the results of regression analysis (Appendix D), charts for use in the user guide (Appendix E) and a draft text for the user guide Appendix F).

2 SCENARIOS FOR UNSEALED ROADS

2.1 AIMS AND OBJECTIVES

The principal aim of this project is to inform the development of a catalogue to provide Local Governments with a simple, robust and transparent means of determining an appropriate cost of road wear to end users which represents the cost of additional pavement wear for a wide range of scenarios comprising different loading tasks applied to different parts of the road network.

The objectives the catalogue needs to support include:

1. Provision of a simple, user-friendly methodology for estimating the cost of road wear on unsealed local roads using a marginal cost approach.
2. Account for the range of variables and loadings representative of the range of scenarios likely to be encountered on local roads in WA, and which affect the MC.
3. Allow calculation of the marginal cost of road wear for the range of variables and scenarios.
4. Presentation of the results of the modelling in a catalogue of marginal costs representative of the local road scenarios in WA.

Underpinning the generation of the catalogue is an analytical framework which applies life cycle cost (LCC) principles, with a set of evidence-based performance models, typical intervention strategies, and other input assumptions to inform the generation of marginal costs for the different scenarios represented in the catalogue.

2.2 LIFE CYCLE COSTING BASIS FOR DETERMINING THE COST OF ROAD WEAR

Following initial exploratory work, a method was developed to calculate the cost of road wear arising from additional heavy vehicle usage/loading on sealed roads (WALGA & ARRB Group 2015) by adapting the national approach (Austroads 2012). The method was required to be simple in design to enable it to be applied to a range of industry tasks on different classes of Local Government sealed roads by asset management practitioners. A fundamental requirement of the method was that it should allow for the full life cycle costs arising from the additional loads to be evaluated, thus providing the LG the possibility of maintaining the road in a serviceable state without detriment to other road users. The model therefore employs the analytical framework adopted in HDM-4, the PIARC/World Road Association supported highway development and management suite of tools and knowledge base (PIARC 2006) and other cost-benefit analysis-based tools.

Marginal road wear costs are associated with the difference in expenditure required to maintain a road section (pavement or running surface only) under a different loading scenario. The difference in cost can be determined by comparing the whole of life cycle maintenance cost streams associated with two scenarios, namely a base traffic loading and an alternative traffic loading case representing higher, and heavier traffic applied over short or long-term durations (in years).

To illustrate how the marginal cost is calculated, an example of modelled traffic volumes and cumulative cost profiles is presented in Figure 2.1 and Figure 2.2 for an example scenario. In Figure 2.1 the variation in the traffic volume as a result of an additional loading period over the first 10 years of the analysis is shown, after which the traffic volume is modelled to return to the same value as in the base case.

Traffic over the analysis period

Cost over the analysis period
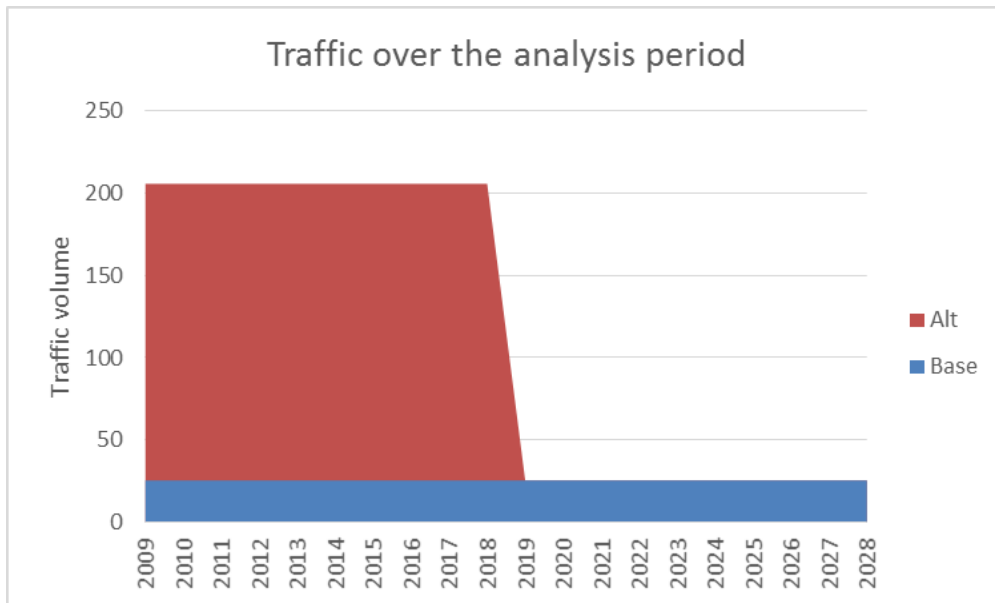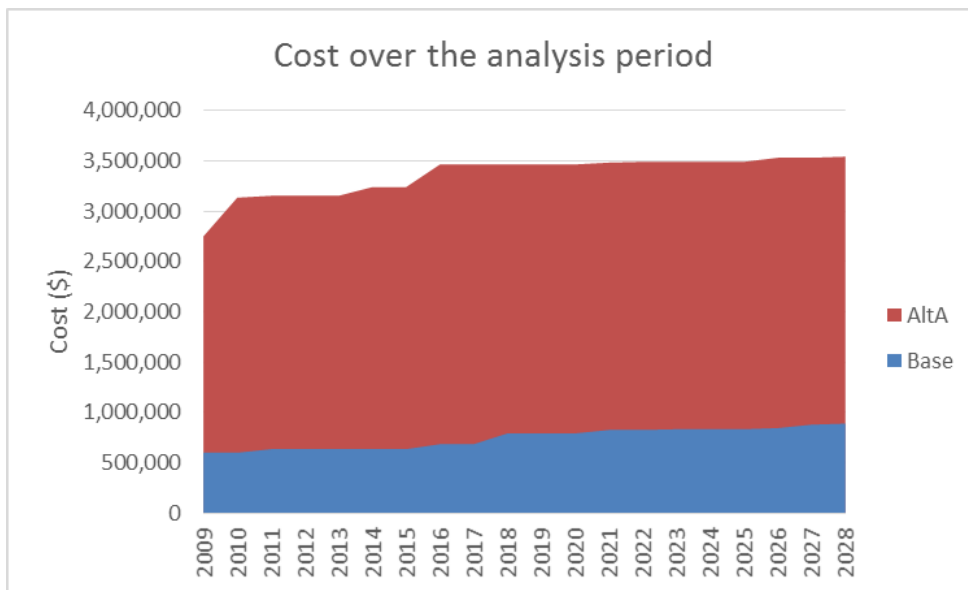
In response to the additional traffic loading requirements shown, the cumulative cost profiles in Figure 2.2 show a greater cost required in the alternative case compared with the base case. The higher costs in the alternative case relative to the base case are due to the higher maintenance needs to deliver the same level of service under the higher loading case relative to normal (or base) loading.

With the modelled year-by-year traffic and cost streams determined, these then need to be discounted as input to Equation 1 to determine the marginal unit cost per loading unit (termed LU). The discounting process simply brings the two modelled streams into present day values and then the ratio of the difference between the two cases facilitates the marginal cost estimate. The basis for the determination of equivalent

loading units for unsealed roads, differs from the ESA-based approach applied to sealed roads, and is explained in Section 2.3.

$$\text{MC per LU.km} = (\text{discounted } RAC_{alt} - RAC_{base})/(\text{discounted } CLU_{alt} - CLU_{base}) \qquad 1$$

where

MC per LU.km	=	marginal cost estimated per LU kilometre
discounted RAC_{alt}	=	discounted road agency costs for the alternative case
discounted RAC_{base}	=	discounted road agency costs for the base case
discounted CLU_{alt}	=	discounted cumulative number of LU's for the alternative case
discounted CLU_{base}	=	discounted cumulative number of LU's for the base case

2.3 SCENARIOS AND LIKELY KEY FACTORS FOR UNSEALED ROADS

2.3.1 GENERAL

Unsealed roads are more variable than sealed roads and are mostly un-designed. They present road asset managers and road users with highly variable surface conditions. These occur in response to the traffic they are subject to, including vehicle numbers, vehicle mix, and speeds, and the effect of these on the running surface construction materials and standards employed in their provision and maintenance, and to the climate and terrain.

Studies in Australia, e.g. the Local Roads Deterioration Study (Martin et al 2013), and elsewhere (Paterson 1987, Paige-Green 1987, Toole et al 2001, Morosiuk et al 2006 and ARRB Group 2009), provide an insight into the factors which affect the performance and costs of providing and maintaining unsealed roads. Those considered of significance to this study are listed below and elaborated in the following text.

- current condition and suitability for carrying significant additional loads, e.g. surface condition, shape and structural adequacy
- surface materials quality/specification, and the availability of different materials
- vehicle types, level of loading and duration of additional loading, and typical base traffic
- maintenance strategies, including the type(s) and frequency of regular maintenance and surface replacement (or regravelling)
- future performance in response to the above factors and climate and terrain, operating speeds, etc.

The effects of a number of these factors can be influenced through deliberate choices, although there will be cost implications, whereas others are location and operating conditions specific. The determination of the relevant marginal cost needs to be based on data and assumptions relevant to a specific project case, and the characteristics of the specific roads and the maintenance options chosen. The potential influence of the various factors, and combinations of these is illustrated below, with this preceded by a general introduction to the types of unsealed roads, deterioration mechanisms and modes of distress.

2.3.2 CLASSIFICATION AND DETERIORATION OF UNSEALED ROADS CLASSIFICATION

A distinction is normally made between engineered unsealed roads, and non-engineered unsealed roads and tracks (Toole et al 2001). Each may have gravel or earth surfaces which influences both the level of service and the deterioration of the road. Engineered roads have controlled alignment, formation width, cross-section profile and drainage, whereas tracks are essentially ways formed by trafficking along natural

contours with or without the removal of topsoil. Unsealed roads incorporated in a classified road network are usually engineered or partly engineered, and tracks are usually not classified.

The distinction between earth and gravel roads is usually on the basis of whether an imported material has been used in the running surface. Therefore, it is possible for perfectly acceptable engineered earth roads to exist alongside gravel roads.

Earth roads are also characterised by seasonal performance, where the presence of moisture can affect trafficability. They are also weak in the presence of water and susceptible to failure, leading to severe rutting under load.

Gravel roads generally have few trafficability problems except where the cover thickness (which provides protection to the subgrade) is inadequate, or where they have deteriorated badly, e.g. if potholes and ruts are extensive and severe. Seasonal performance differences may exist, with moisture from rains aiding dust suppression and enhancing soil binding properties, whereas excessive rainfall can lead to erosion.

2.3.3   DETERIORATION MECHANISMS

The deterioration of unsealed roads is governed by the behaviour of the surfacing material and the roadbed under the combined action of traffic and the environment. The surfacing is typically 100 mm to 300 mm thick and serves as both the wearing course and the base course of the pavement, providing sufficient structural strength and cover thickness to distribute the applied traffic loads to the roadbed material. As the surfacing comprises a natural material, it is usually permeable although in some cases the permeability may be very low, such as in densely graded plastic gravel or naturally cemented material. Thus, material properties, rainfall, and surface drainage influence the behaviour of the surfacing under traffic; likewise, surface water runoff and side drainage usually affect the moisture penetration to the roadbed and thus it's bearing capacity.

There are three fundamental mechanisms of deterioration:

- wear and abrasion of the surface material under traffic
- deformation of the surface and roadbed material under the stresses induced by traffic loading and moisture condition
- erosion of the surface by traffic, water and wind.

Consequently, the modes of deterioration differ in dry weather and wet weather, and also depend on the strength of the surfacing and roadbed material, which are most critical in wet weather. The modes and the approaches for modelling thus can be placed in four categories as described below (Visser, 1981), namely:

- dry weather deterioration
- wet weather deterioration of adequate pavements
- wet weather deterioration with weak surfacing layer
- wet weather deterioration with weak roadbed material.

The most prominent deterioration mechanisms and modes of distress for each category are summarised in Table 2.1. Whereas a focus is often given to the selection of suitable wearing course materials and addressing routine (scheduled) and periodic maintenance requirements, consideration of structural adequacy is necessary particularly where heavy traffic loads already exist or through additional loading. A variety of sources of evidence and procedures for determining structural adequacy exist, including the US Army Corps of Engineers (Webster & Alford 1978 and Giroud & Noiray 1981), TRL (Powell et al 1984) and ARRB Group (2009).

Table 2.1   Description of unsealed road performance categories

Category	Deterioration mechanisms	Modes of distress
Dry weather deterioration	- Wear and abrasion of the surface, which generates loose material and develops ruts and concave shape. - Loss of the surfacing material by whip off and dust. - Movement of loose material into corrugations under traffic action. - Ravelling of the surface, in cases where there is insufficient cohesion in the material to keep the surface intact.	Increased roughness and material loss, the rates of deterioration being primarily a function of the properties of the surfacing material and its moisture condition.
Wet weather deterioration of adequate pavements	- Environmental and traffic influences on surface erosion. - Wear and abrasion of the surface by traffic causing rutting and loss of surfacing material. - Formation of potholes under traffic action, accentuated and accelerated by the presence of free water on the surface and the passage of vehicle.	Increased deterioration (multiple modes including rutting, material loss, loss of shape, potholing and roughness) resulting from erosion, wear and abrasion, and traffic action.
Wet weather deterioration with weak surfacing layer	- Increased risk of shear failure and deformation occur in the upper pavement - Potential for soft and slushy surface conditions in the wet conditions, with increased risk of the road becoming impassable after the passage of even a few heavy vehicles. - Performance expected to vary depending on road geometry, particularly gradient, and the weight and number of vehicles.	Similar to above, but with increased rut depths and poor traction and trafficability in the wet
Wet weather deterioration with weak roadbed material	High likelihood of over-stressing of subgrade or roadbed, with need to protect the roadbed and limit the deformation developing under traffic to acceptable levels with accelerated deterioration in locations of poor surface and subsurface drainage and weak soils.	Similar to above, but with likelihood of severe deterioration in the form of rutting, or permanent deformation in the wheelpaths.

Source: Adapted from Visser (1981).

2.3.4   LIFE-CYCLE PERFORMANCE AND MAINTENANCE EFFECTS

Operating conditions on unsealed roads, such as represented by surface roughness, reflect the variation in longitudinal profile and in transverse profile. These also change over time and respond to maintenance but often in a cyclic manner. That is, the deterioration cycle involves short term changes in surface condition which is then restored by maintenance, and the cycle of deterioration then recommences. The restorative (or works) effect and overall performance trend can be influenced by the choice of maintenance treatment, with some treatments being more effective than others.

A distinction needs to be made between treatments which:

- reprocess and reshape the surface, usually accompanied by watering and compaction, to produce a smooth well-knit surface (referred to as full reprocessing)

- allow some reworking in the presence of natural moisture (recent rainfall) and limited traffic compaction (referred to as heavy grading)
- only respread loose material across the roadway with almost no change in the shape of the underlying surface, with a result that the material will be displaced quickly with surface conditions deteriorating quickly to pre-works levels (referred to as light grading).

The observed trends and response to maintenance and construction activities has led to the following 4-phase model for the progression of roughness for unsealed roads (Morosiuk & Toole 1997):

- Phase 1 – the rate of wear of the original surface before any maintenance is applied
- Phase 2 – the change in roughness as a result of maintenance
- Phase 3 – the rate of wear, or removal of the uncompacted or loosely compacted upper surface layer immediately after maintenance
- Phase 4 – the longer-term rate of wear of the surface once any loose or poorly compacted material is removed.

The model is illustrated in Figure 2.3 and forms a convenient framework for describing the application of current unsealed road roughness progression models in determining life cycle behaviour and, thereafter, optimum maintenance frequencies. Figure 2.3a) represents light grading (or blading) in the absence of water, whereas Figure 2.3b) represents heavy grading or full reprocessing. The costs of these operations differ considerably, and therefore needs to be reflected in any life-cycle cost analysis. At a practical level, location factors may mean that techniques which are feasible are limited due to the lack of water sources, and due to low or unpredictable rainfall.

Figure 2.3   Illustration of the 4-phase roughness progression model for unsealed roads

a) Effect of light grading

b) Effect of heavy grading or full reprocessing
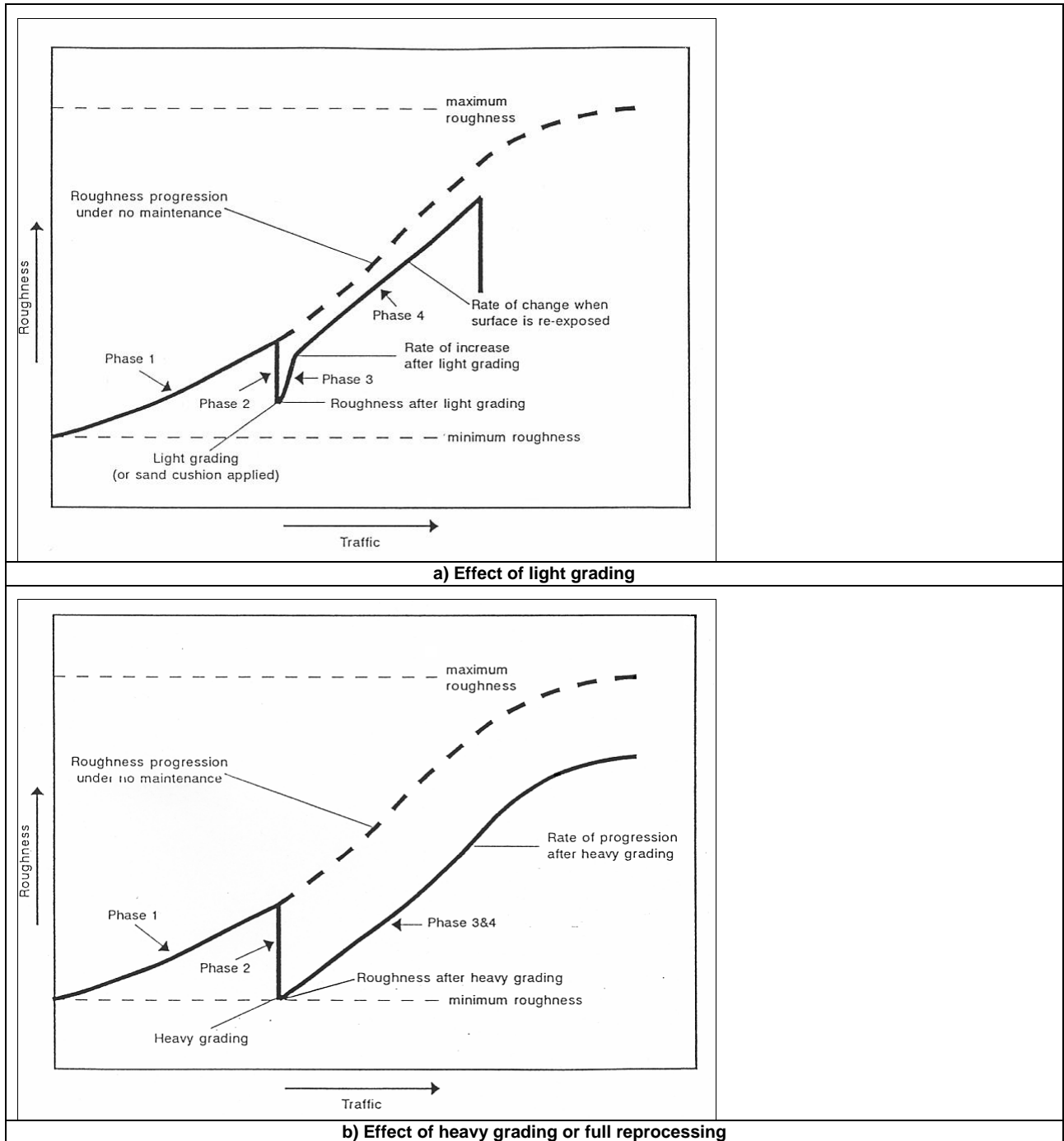
The aim of the 4-phase model is to correctly represent the various levels of improvement which occur as a result of particular operations and the subsequent rates of progression, and use can be made of the model to produce a family of optimum maintenance frequency relationships which relate to specific operations, e.g. light grading, heavy grading and reprocessing. The optimum frequency is chosen by identifying the frequency of each operation which minimises total transport costs (or maximises net present value) for each traffic level, having made assumptions on various parameters, including traffic composition, costs, climate, etc.

An example optimum frequency relationship is shown in Figure 2.4 for a moderately wet tropical climate, and good quality materials (Overseas Centre TRL 1987).

Figure 2.4   Example optimum grading relationship for heavy grading
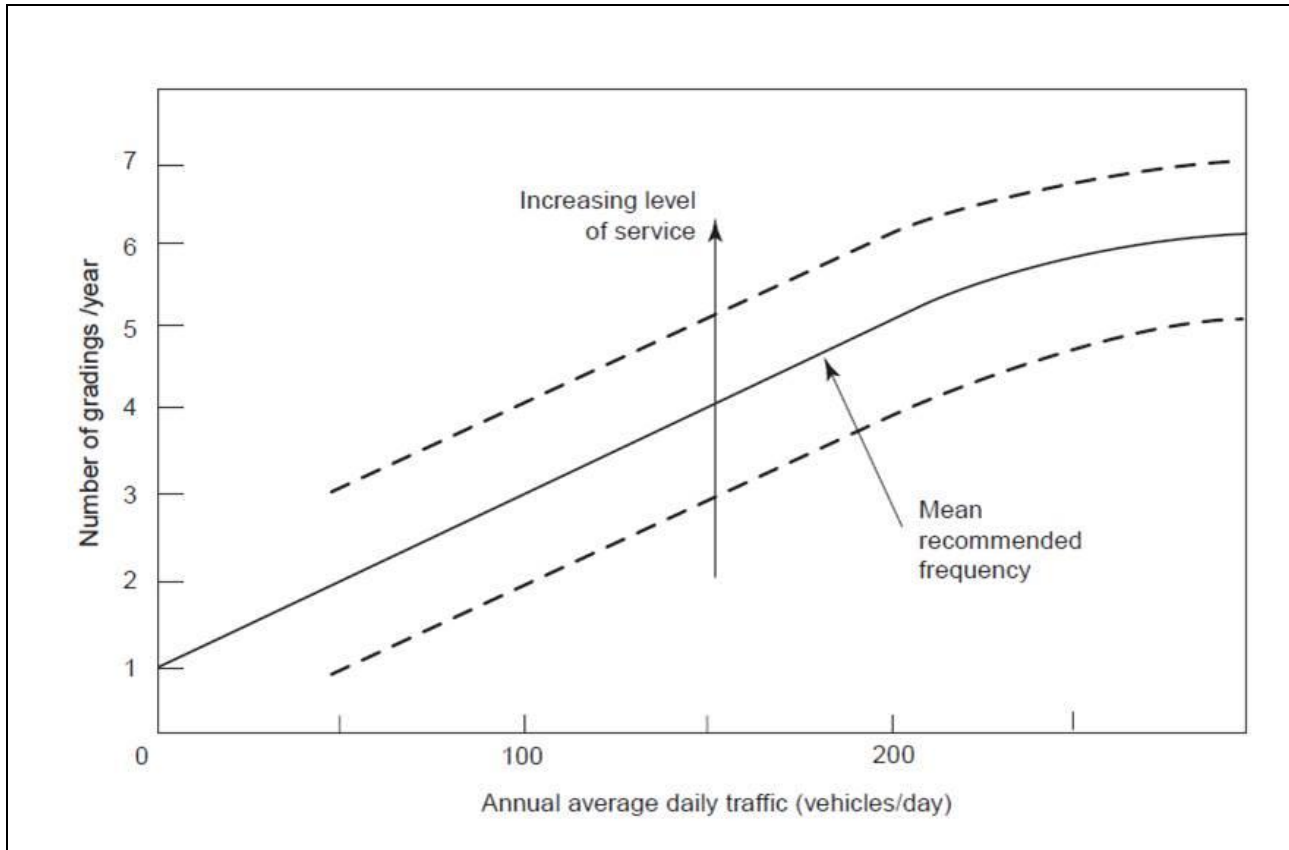
Source: Overseas Centre TRL (1987)

The relationship in Figure 2.4 is based on the economic optimum and, as indicated, an increasing frequency will improve LOS. Higher rainfall would usually warrant an increased frequency to maintain camber and remove ruts, whereas lower rainfall areas may require operations to be concentrated in the wetter parts of the year to minimise damage to the road surface, or for operations to involve the addition of water. If the technique used is light (patrol) grading without compaction, the frequency should be increased since the technique is less effective and pre-maintenance conditions are rapidly restored.

Road deterioration and works effects (RDWE) models for Australian conditions exist as a result of the Local Roads Deterioration Study (LRDS) (Martin et al 2013), and from subsequent studies (Martin et al 2016). The models have also been applied in marginal cost studies for unsealed roads (Toole & Sen 2014). These therefore provide a means for incorporating the above concepts in LCC modelling appropriate to this study.

2.3.5   SURFACE MATERIALS AND CONSTRUCTION QUALITY EFFECTS

Field experience has informed the identification of desirable materials properties and criteria employed in selecting gravel wearing course materials. The characteristics of a surfacing material which contribute to satisfactory behaviour include the following:

1. It should contain a sufficient quantity of binder in the form of fine-grained material to prevent loosening of the surface and dustiness in dry periods and to resist movement of material and thus reduce gravel loss and prevent the formation of corrugations. If the fines content is too high then, in the wet, a substantial loss in bearing capacity will occur, leading to excessive deformation and the surface becoming slippery.
2. The material should not contain a large quantity of coarse particles which can become exposed through trafficking and lead to high surface roughness or create a traffic hazard. Large particles may also prevent efficient reshaping of a road surface and can lead to pothole formation if they are plucked out by traffic or during a grading operation. They can also prevent compaction forces from being transmitted

evenly through a layer, which may result in low densities being achieved with a consequent enhanced risk of potholing.

In summary, the choice of the gravel surfacing material is most often a compromise between a material which possesses sufficiently high plasticity to minimise gravel loss in the dry season and sufficiently low plasticity to prevent serious rutting and deformation in the wet. Specifications in use emphasise the need for these properties combined with a mechanically stable grading suitably modified to give a higher fines content for binding action to result. Selection of a suitable range of plasticity is dependent on climate, with criteria varied as illustrated in Table 2.2.

Table 2.2   *Recommended plasticity characteristics for gravel wearing courses*

Climate	Liquid limit not to exceed (%) 1	Plasticity Index (%) 1	Linear shrinkage (%)
Moist throughout the year	35	4 – 9	2 – 5
Seasonally wet	45	6 – 20	3 – 10
Predominantly dry	55	15 – 30	8 – 15

1   Higher limits may be acceptable for some laterites or concretionary gravels that have structure that is not easily broken down by traffic. Lower limits may be appropriate for some other gravels that are easily broken down by traffic. Any variation from these limits should be based on carefully collated local experience.

Source: Adapted from Toole et al (2001)

Other studies have elaborated on the relation between materials properties and performance, and the performance guide illustrated in Figure 2.5, which is based on South African experience (Jones and Paige-Green 1996), extends the overall concept in terms of expected behaviour.

Figure 2.5   *Relationship between gravel wearing surface properties and performance*
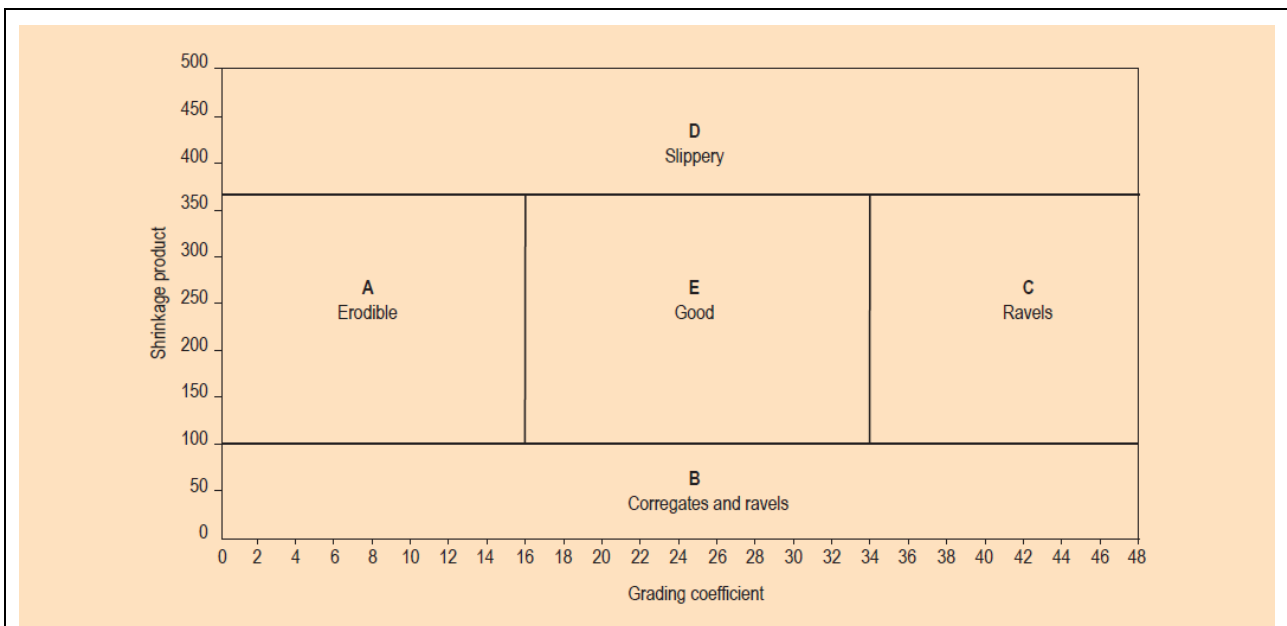
Notes:

1   Shrinkage product = linear shrinkage x %passing the 0.425 mm sieve

2   Grading coefficient = (%passing the 26,5 mm sieve - % passing the 2mm sieve) x per cent passing the 4.75 mm sieve/100

Source: Jones and Paige-Green 1996

RD models also account for materials properties, although few studies have been sufficiently comprehensive to confirm the relative quantitative importance of differences in material properties, although evidence is available from a number of sources, and attempts have been made to accommodate materials properties in both regression type models (Hodges et al 1975, Toole 1987 and Toole et al 1987) and empirical-

mechanistic models (Paterson 1987, Paige-Green 1987 and Martin et al 2013)[1]. However, a review of earlier findings from worldwide studies (Morosiuk & Toole 1997) concluded that materials properties were weakly represented. Other factors, such as rainfall, were also shown to have a beneficial effect from some studies, particularly in arid and semi-arid areas where seasonal rainfall provided a binding effect, whereas in a high rainfall area rainfall was shown to contribute to increased erosion.

In a study from southern Africa, Toole (1987) illustrated the effect of materials properties, with performance dependent on the amount and plasticity of the soil fines, represented by the shrinkage product, and material hardness (Figure 2.6). The effect of mechanical compaction with moisture applied was also illustrated (Figure 2.7), with significantly different rates of deterioration occurring where mechanical compaction or sufficient moisture was absent (Toole 1987 and Morosiuk & Toole 2001).

Figure 2.6   Rate of material loss of calcareous (calcrete) wearing courses under regular maintenance
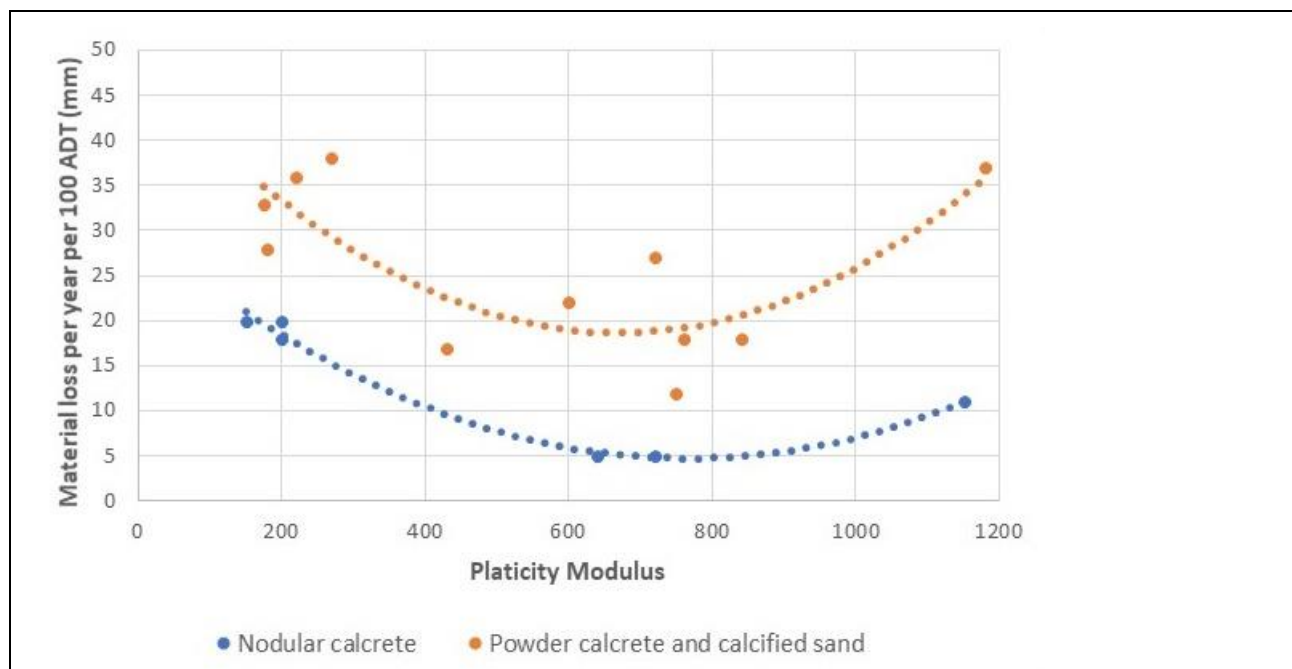
Source: Adapted from Toole (1987)

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[1] Mechanistic-empirical models are based on theoretical postulations about pavement performance, but are calibrated, using regression analyses, by observational data (Lytton 1987). These models must adhere to known boundary conditions and physical limits. These models can incorporate interactive forms of distress near the end of pavement life, such as the interaction of rutting with cracking, when these interactions are well understood. If these models are theoretically sound and correctly calibrated, they may be applied beyond the range of data from which they were developed.

Source: Morosiuk & Toole 2001

The grading (or particle size) characteristics of unsealed road surfacing materials which most affect performance includes:

   a)   the maximum particle size (in mm)
   b)   the percentage oversize material based on the proportion greater than 26.5 mm
   c)   the proportion of material less than 75 micron, with a typical optimum fines content of between 10% and 25%.

Typical particle size distribution and plasticity requirements applied in Australia and New Zealand are shown in Table 2.3. Whereas selection should take account of the availability of materials and local knowledge, compliance will enhance performance.

Table 2.3	Typical gravel wearing course requirements from Australia and New Zealand

Australia		New Zealand	
Sieve size (mm)	% passing for all maximum sizes	Sieve size (mm)	% passing for all maximum sizes
55	100		
37.5	95–100		
26.5	90–100	19	100
19	80–100	6.7	60–80
2.36	35–65	2.36	40–60
0.425	15–50	0.300	25–35
0.075	10–40	0.075	10–20
Plasticity	< 500 mm annual rainfall – max. PI 20 > 500 mm annual rainfall – max. PI 12	Plasticity	PI values 8–12 depending on climatic conditions

Source: NAASRA (1980) and Ferry (1986)

2.3.6   DAMAGING EFFECT OF TRAFFIC ON UNSEALED ROADS

There are limited research results relevant to estimating traffic loading-based cost attribution parameters for unsealed roads with conflicting findings ranging from no attributable costs to separate attributable costs for both light and heavy vehicle usage. The deterioration rates for unsealed roads are also known to vary markedly with factors such as the properties of the gravelling material, climate (rainfall and rainfall intensity) and geometry, as explained above. This contributes to the large variation in research findings. Furthermore, most studies have been conducted on public roads with low proportions of heavy vehicles (HV), and therefore observations are limited with axle loading having not been isolated as a specific parameter.

Drawing on an example from southern Africa (Toole 1987), where directional differences in HV daily ESA varied by a factor of up to 4, the material loss (Figure 2.8) was found to be almost identical for both the loaded and unloaded directions on two sections of road subject to low maintenance and monitored over a 12-month period where traffic was reasonably well separated by direction. Ride quality values were also similar. The reasoning given for the absence of any clear effect of level of loading was that heavy axles may contribute to wear through the application of greater tractive forces and possible dynamic loading, while unloaded axles also damage unsealed roads as the axles tend to lose contact with the road surface and effectively bounce more than loaded axles, leading to surface wear/damage.

Figure 2.8   Comparison of material loss for two directions on an unsealed calcrete surfaced road
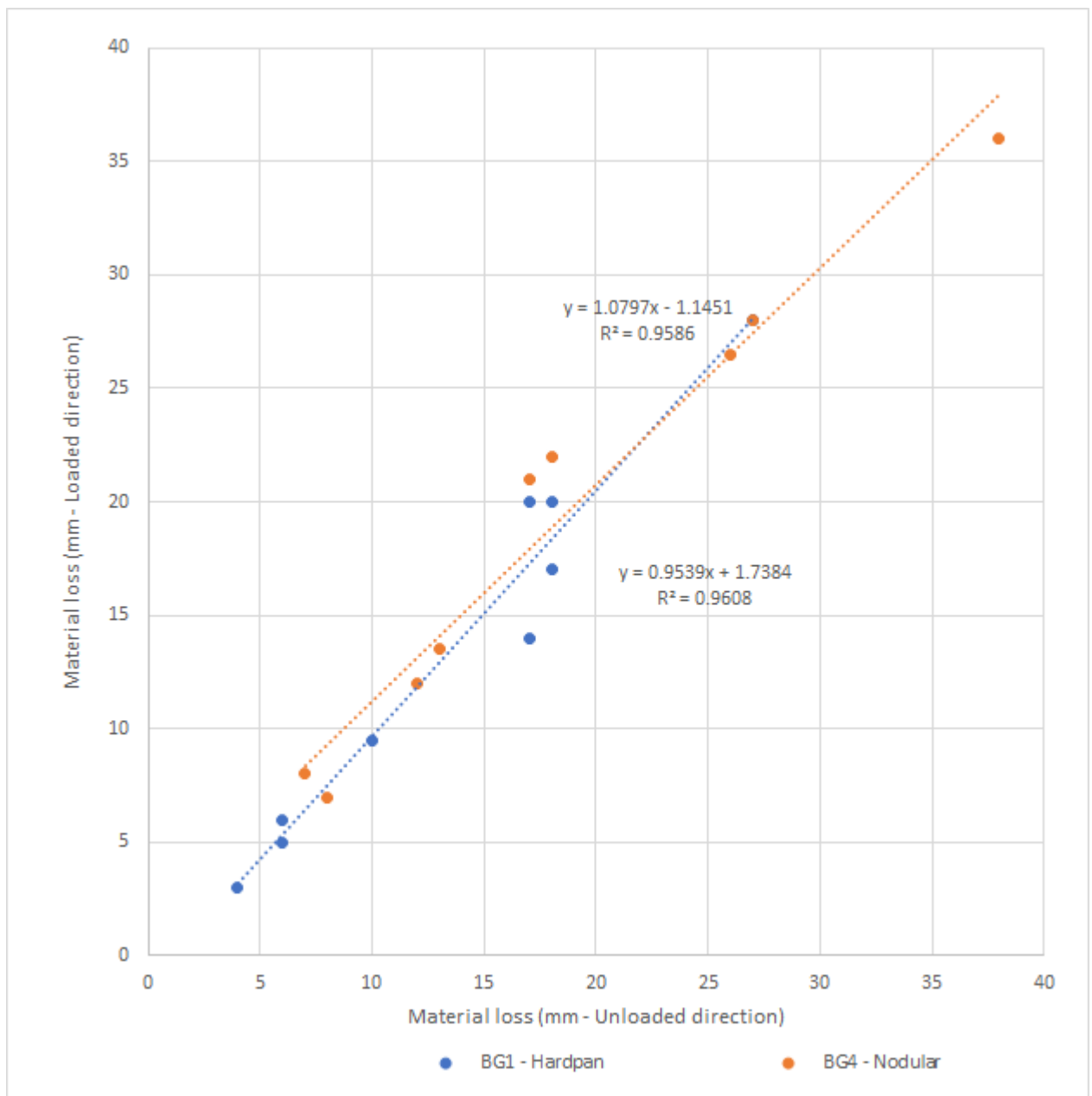
Source: Toole (1987)

In a review of cost attribution for Australia, Martin and McLean (2005) reported that the South African gravel road maintenance cost relationship (Paige-Green 1987) occupies the middle ground within the range of research findings and is approximately equivalent to using passenger car unit (PCU), and therefore PCU-km, as the allocation parameter for unsealed road maintenance costs.

Such an approach was applied in a study of the marginal cost (MC) of road wear for unsealed roads in Queensland, with light vehicle unit (LVU) factors of 1, 2 and 5 applied to heavy vehicles. It was shown that the assignment of an LVU factor to represent heavy vehicles increases the MC in direct proportion to the factor chosen. For example, adopting an LVU of 3 for a 6-axle articulated truck, in proportion to the number of axles, would increase the MC values by a factor of three. An alternative would be to employ a PCU factor, in which case the multiplication factor could be as high as 5 for the same vehicle, or much higher for multi-combination vehicles.

Based on the above evidence an approach whereby the number of axle pairs are used to represent heavy vehicles is recommended.

3 DEVELOPMENT OF THE MODELLING FRAMEWORK AND INPUTS

3.1 GENERAL

The overall modelling framework is illustrated in Figure 3.1 and is consistent with the process employed in LCC analysis for roads, and in the Freight and Mass Limits Tool (FAMLIT) produced by ARRB for the National Transport Commission (NTC) and Austroads over the last decade or so, building on an initial model by Michel & Toole (2005). The method used for determining the long run marginal costs of sealed roads is detailed in a user guide and technical report published in 2015 (Austroads 2015a and 2015b). Using this approach, the output of the analysis process requires determining the marginal cost (per SAR[2].km) by establishing a relationship between successive incremental load increases (in SAR) and the equivalent annual uniform (EAUC) cost of maintenance activities.

Figure 3.1   Flow chart of the life-cycle cost model
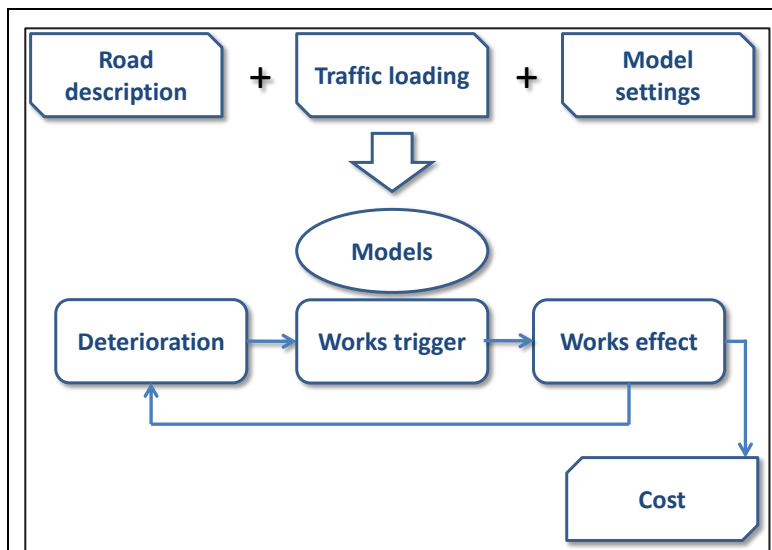
Source: Austroads 2015a

Whereas the framework applied to LG sealed roads in WA employs a similar LCC model, as stated in Section 2.2, the unsealed LCC model differs and is run for a base traffic scenario and an additional traffic scenario with the difference in cost, i.e. the total marginal cost, needing to be allocated to the traffic which contributed to the difference by choosing a suitable metric which represents the traffic applied. For sealed roads this applies the concept of the number of equivalent standard axles at an appropriate load damage exponent for the pavement type concerned. For unsealed roads, this requires the definition and application of Light Vehicle Units (LVU)[3] as described in Section 2.3.6 and the determination of the MC based on the ratio of the NPV of agency costs and traffic loading described in Section 2.2.

The overall process flow for the model is illustrated in Figure 3.2, with further details described below. The process illustrated shows the full LCC modelling adopted in the study to produce a comprehensive set of results. However, for application purposes this was simplified following sensitivity analysis conducted under this study, and choices made by the development team to limit the range of solutions provided. These include factors which can only be assessed on a site-specific basis.

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[2] SAR, Standard axle repetitions, which is the same as the term equivalent standard axle (ESA) based on the 4th power load damage exponent for unbound granular pavements.

[3] Whereas the term LVU has been applied in the preliminary analysis reported here, in the final presentation and discussion of results, vehicles were represented by the number of axle pairs (termed Loading Units (LU)). This is consistent with the South African unsealed road deterioration models (Paige-Green 1987), and the Australian adaptation of these models (Martin et al 2013).
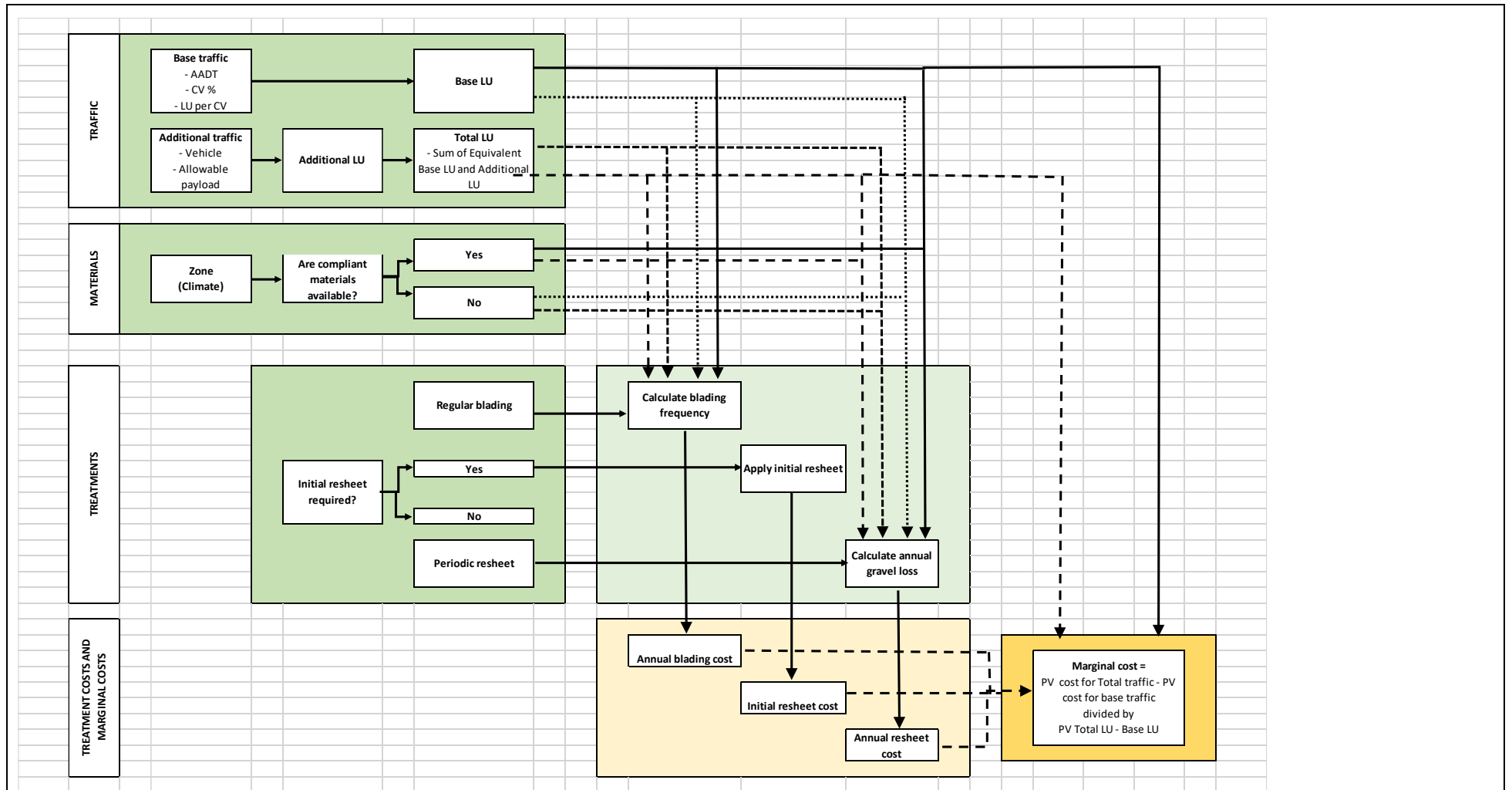
3.2   POPULATION OF THE LCC MODEL FOR UNSEALED ROADS

Population of the LCC model required the supply of the data and models listed Table 3.1, the source of specific information being largely drawn from the responses received to a questionnaire (Appendix A). The deterioration models employed have been adapted from the Australian Local Roads Deterioration Study (Martin et al 2013), with the extent of adaptation described in Appendix C.

Table 3.1   List and sources of required data and relationships

| Type	Input parameters	Values and source(s)
Traffic	BaseADT, base annual daily traffic (ADT)	50, 75, 100, 150, 250, 500 (This study[1])
	BaseHVper, base heavy vehicle percentage	15, 30 (This study)
	Light Vehicle Units (LVU)	1, 3 and 5 (This study)
	AdditionalHV, additional heavy vehicles per day (to reflect additional loading)	Calculated based on additional freight task (in tonnes) (This study)
	Duration, of additional loading (years)	2, 5 and 10 (This study)
	StartTime, of additional loading (year X)	Year 2 (or user specified)
	EquivADT, sum of base traffic and additional traffic (in LVU) by scenario	Calculated (This study)
General road section and location characteristics	Cost zone (as represented in Figure 3.3)	Assigned (WALGA & ARRB 2015)
	Climate classification, as semi-arid, sub-humid	Assigned based on Thornthwaite (1948)
	Climate description, as predominantly dry or seasonally wet	Assigned (This study)
	MMP – mean monthly rainfall (mm)	Assigned by cost zone (BOM 2017)
Materials properties	PF - Plasticity factor (for compliant and non-compliant materials) by climate zone, where PF = amount (%) of material passing 0.075 mm sieve x Plasticity Index	Assigned based on climate description (This study) with five categories applied
Maintenance regime	Grading frequency (GF) (no. per year)	Optimum, 1, 3, 6, 9, 12 (This study)
	Optimum GF for base and additional traffic	Calculated based on TRL (1987)
	Minimum gravel thickness (to trigger regravelling)	50 mm (This study)
	Initial resheet thickness (mm) – to support passability and operation for additional traffic scenario only	150 mm and 300 mm (This study[2])
Road deterioration model	LRDS gravel loss model, and coefficients for ADT, MMP and PF	Assigned based on Martin et al (2013)
	K_{gl} – gravel loss calibration factor	Assigned (This study), accounting for level of compliance and climate classification/description (see basis in Appendix C)
Maintenance costs per cost zone	Grading cost ($/km)	Assigned (Appendix B.3 - this study)
	Resheet/regravelling cost ($/km)	Assigned (Appendix B.3 - this study)
	Initial resheet cost ($/km)	Assigned (Appendix B.3 - this study)
	Remote cost factor (%)	50% (This study, later referred to as 'cost premium')

Notes to Table 3.1
1 The selection of base AADT was proposed during discussions, and covers the range observed during the Australian LRDS for semi-arid and sub-humid climate zones, with the maximum base AADT being above the typical breakeven volume for upgrading to a sealed surface.
2 An initial treatment is needed where there is visible evidence of inadequate cover on the subgrade. The latter can be determined quantitatively by assessing gravel depth and checking this against a suitable thickness design method based on the anticipated freight task (e.g. see ARRB Group (2009)). Otherwise engineering judgement can be applied.

Figure 3.3   Western Australian cost zones
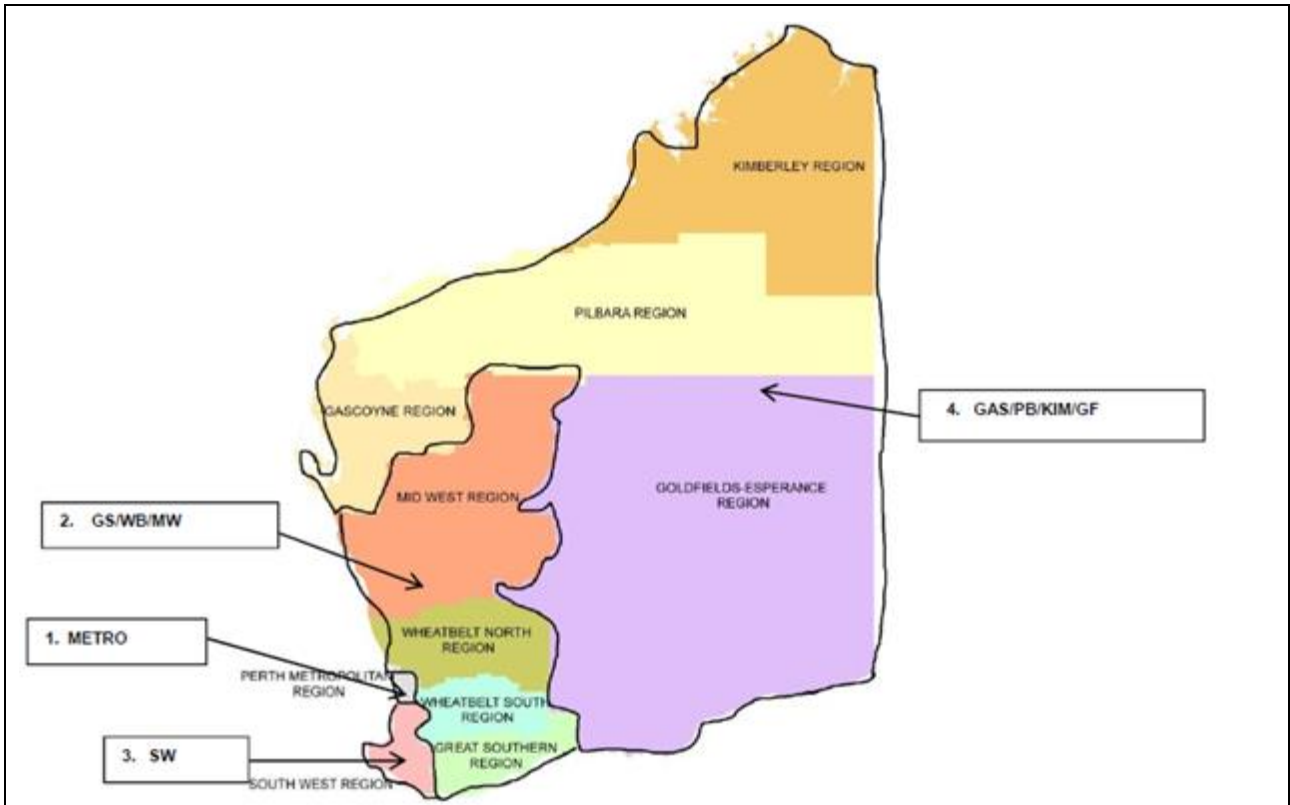
Source: WALGA and ARRB Group (2015).

3.3   ANALYSIS MATRIX

An analysis matrix was developed based on combinations of a selection of the parameters in Table 3.1, with specific choices made based on the impact of possible variables, as described in Section 2, the available data, or assumptions made, and the available models. The matrix was populated by both primary variables, i.e. those which define an analysis case, and secondary variables, these being either supplied input data or calculated values relevant to the analysis. Primary variables also represent the high-level variables which define a scenario, a good example being the combination of cost zone and additional loading (scale and duration) employed. For example, in the sealed roads user guide, a chart exists to provide MC vales for application by end-users and the solutions provided later in this report adopt a similar approach but based on the number of additional loading units per annum.

Table 3.2   *List and number of primary and secondary variables*

Primary variable	Secondary variable (and number)	Associated variables	Combinations
Cost zone	MMP (3 same as number of cost zones) Standard and remote cost, or premium cost factor (2)	Associated unit costs by treatment type	6
Traffic	Base ADT (6) HV (%) (2) LVU (2) Additional annual loading (5) Additional load duration (3)		360
Materials properties	Assigned PF based on compliance level (5)		5
Maintenance	Grading frequency (6) Initial resheet (3)		18

Based on Table 3.2, the full factorial is 194,400 analysis cases (records), which for practical purposes reduces to 10,800 records by selecting a single optimum grading frequency and omitting an initial resheet, or 3,600 records for each cost zone. These were then available for the development of regression models and MC estimates to be applied in producing graphical solutions for users.

4   RESULTS

4.1   SCOPE

The reported results take two forms, namely:

1. Preliminary results which investigated the full set of analysis results and included the modelled results of annual gravel loss for different combinations of parameters for each analysis and the derived marginal cost values for each analysis case.
2. Final results which refined the analysis in several ways, e.g. by accounting for the results of sensitivity testing, setting aside factors which are too site-specific for this study, and for which guidance will be offered in its application, and extending the range and detail of coverage of certain variables.

The results are presented below for selected analysis cases to demonstrate the effect of different factors. These also illustrate the overall magnitude of gravel loss and costs and provide an opportunity to assess the reasonableness of the results and the sensitivity of estimates to changes in inputs. The derived values are then available to illustrate the calculation of total revenue by scenario and location.

4.2   PRELIMINARY RESULTS

4.2.1   ESTIMATED GRAVEL LOSS

The modelled estimates of the annual gravel loss (AGL) examined the following combinations:

- impact of location (and associated climate and materials properties) at different base ADT (100 and 250) and for different additional loading scenarios (base, 100,000 tonnes per year and 1 million tonnes per year)
- impact of compliance (materials properties) for a selected location and base traffic and for different additional loading scenarios (base, 100,000 tonnes per year and 1 million tonnes per year).

The results are presented and discussed below.

4.2.2   IMPACT OF LOCATION

The impact of location on AGL is illustrated in Figure 4.1 for a selection of base ADT and additional loading scenarios, and for compliant surfacing materials. Whereas the examples demonstrate a modest impact of the effect of location and an increased effect of increased base ADT, the effect of additional loading is significant. The two chosen locations cover the spread of climatic conditions in WA, represented by cost zone 3, South West, with a seasonally wet, sub-humid climate, and cost zone 4, Gascoyne, Pilbara, Kimberley and Goldfields-Esperance, where the climate is predominantly dry and semi-arid for the majority of the year. An exception, however, can be the impact of cyclones, although under such conditions road use is often suspended, or greatly reduced.

4.2.3   IMPACT OF COMPLIANCE

The impact of compliance on AGL is illustrated in Figure 4.2 for compliant surfacing materials, and for those with properties above the target optimum and below the target optimum (measured by the PF). A single base ADT and a selection of loading scenarios have been employed.

The examples demonstrate the significance of compliance, with the greatest effect being that for non-compliant materials with properties below those desirable for cost zone 4 (semi-arid). As explained in Appendix C, this is a result of applying a calibration factor of 3 for such conditions to better represent the deterioration mechanism and consequent rate of deterioration under such conditions.

In particular, in predominantly dry areas, there is a significant risk of increased rates of deterioration where materials have low cohesion, either because of their intrinsic properties or because they have not been adequately mixed and compacted with water to mobilise their potential. Furthermore, where gravel is lost from the surface and forms in windrows, or else is loss as airborne dust, there is little opportunity for re-compaction by traffic due to the extensive periods without rain. Research from southern Africa (Toole 1987) illustrated the benefits of frequent light grading (and cushioning operations) under such circumstances leading to a 3 to 4-fold reduction in the AGL. However, this has not been accounted for in this analysis, but is an area deserving attention through further research in support of a later edition of any published guide.

In the example shown, and for the purposes of the preliminary study, the estimated rate of gravel loss for conditions where the material is more plastic than desirable has been left unchanged, i.e. a calibration factor of 1 has been applied. This has also been applied in wetter climates, i.e. in cost zone 3, where water is available through occasional rains to help bind the surfacing material.

Figure 4.2   Annual gravel loss estimates for compliant and non-compliant surfacing materials
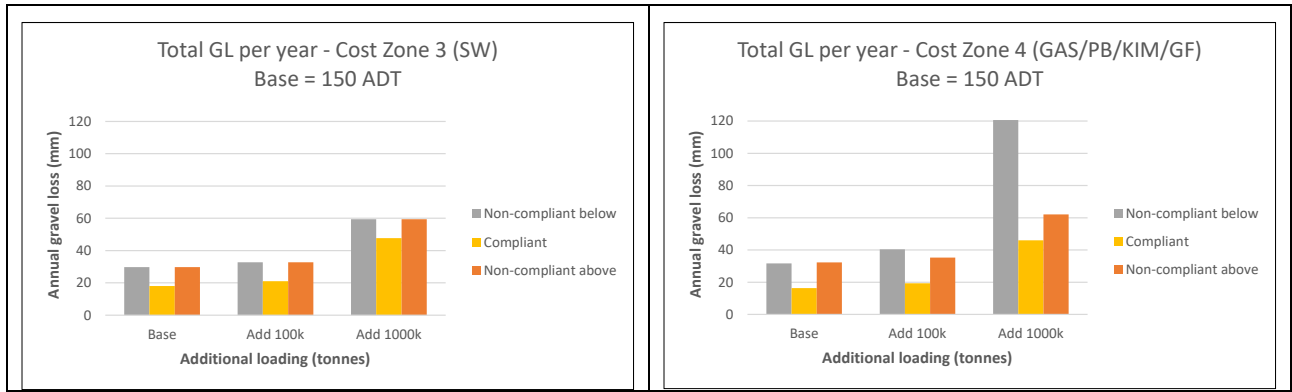
4.2.4   ESTIMATED MARGINAL COSTS

Marginal cost values for a selection of analysis cases are presented below, and examine the following combinations:

- impact of location (cost zone/climate) and the effect of remoteness for different additional loading scenarios (base, 100k tonnes per year and 1 million tonnes per year), and for compliant materials
- impact of the need for an initial 150 mm treatment, using the example of a single location (Zone 4) and for different additional loading scenarios.

The results are presented in Figure 4.3 and Figure 4.1 and discussed below. In the figures, the additional loading scenario is represented by the loading component and the duration, i.e. 100k_2yr represents an additional 100,000 tonnes per annum for a duration of two years, etc.

Figure 4.3   Marginal cost of different loading scenarios for different cost zones and remoteness
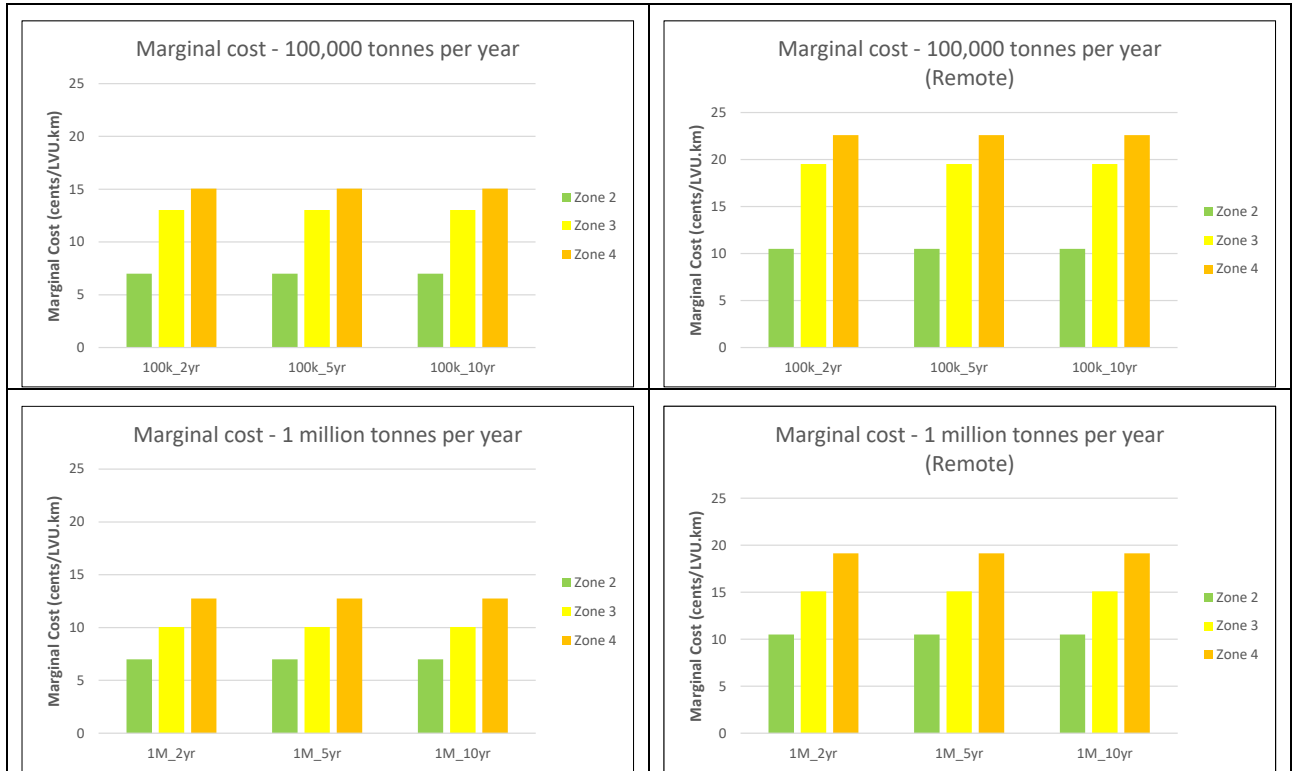
Table 4.1   Impact of an initial 150mm treatment on marginal cost for a base ADT of 100 vpd (cents/LU.km)

Cost zone	Compliance	Additional annual loading (tonnes) and duration (years)					
		100k_2yr	100k_5yr	100k_10yr	1M_2yr	1M_5yr	1M_10yr
4	Compliant (C)	188.5	62.4	19.0	93.8	28.3	16.0
	Non-C Above	165.8	57.0	18.1	84.0	26.1	15.4
	Non-C Below	182.2	72.6	33.5	99.8	41.6	30.8

From the above:

- The marginal cost is in direct proportion to the cost factor employed for remoteness, namely a 50% increase
- The impact of an initial treatment is highest for short term elevated additional loading (2 years), by between approximately 5 and 8 times, and marginal for long term loading (10 years), with an intermediate duration increasing MC by between 1.5 and 3 times. The lower value in each case relates to the higher increase in loading, i.e. 1 million tonnes per year.

Whereas the effect of remoteness is clearly a direct consequence of location, the effect of an initial treatment requires further explanation. The values are affected by the scale and duration of the task, with both of these providing an opportunity to distribute the increased (initial) costs across more or less vehicle units, i.e. high costs are associated with modest levels of additional loading applied over a short period. Whether this is economic is clearly a question for the operator undertaking the task. If the initial treatment is greater, say a 300 mm initial layer, then costs would increase further.

4.2.5   SENSITIVITY ANALYSIS AND IMPLICATION FOR PRESENTATION OPTIONS

The preliminary investigations identified the following key factors which need to be accounted for in the determination of the marginal costs of road wear on unsealed roads, with the number of variations shown in brackets:

- Base ADT (5)
- Base HV (%) (2)
- Cost zone (3)
- Grading frequency (Optimum (1) or all variations (6))
- Materials compliance (3)
- Initial treatment (3)
- Remoteness (2 or 3)
- Additional loading (5)
- Duration(s) (10).

In attempting to reduce the possible number of records relevant to determining an appropriate and practical basis for MC determination, the sensitivity of the model was examined so that appropriate emphasis could be given in a final analysis to important parameters with less emphasis on second or third order effects. The influence of individual parameters differs according to the particular parameter, the particular result being considered, and the values assigned to other parameters in the particular analysis. The sensitivity of results to variations in a parameter therefore varies somewhat under different circumstances.

Sensitivity was examined by determining the percentage increase or decrease in the value of a chosen dependent variable based on a change in input parameters, with marginal cost being selected as key dependent variables, with the central output of this study

The metric **Impact Elasticity** was chosen to assess sensitivity with this defined as the ratio of the percentage change in a specific result to a percentage change of an input parameter, with all other parameters held constant at a mean value. The resulting value may be either positive or negative, this indicating the directional effect of the result, i.e. does it increase or decrease.

For example, when taking a pavement performance example, if a 20 per cent increase in traffic level on an unsealed road causes a 15 per cent increase in roughness development in a single year, the impact elasticity is 0.75. In accordance with the classification in Table 4.2, which is based on the HDM-4 classification system (Bennett & Paterson 2006), this is high.

Table 4.2   HDM-4 sensitivity classes

Impact	Sensitivity class	Impact elasticity
High	S-I	> 0.5
Moderate	S-II	0.2 – 0.5
Low	S-III	0.05 – 0.2
Negligible	S-IV	< 0.05

Source: Bennett & Paterson (2006)

The scenarios tested for each cost zone and for compliant materials included the following:

- Change in Base ADT by up to 2.5 times for two different annual freight tasks representing approximately 10,000 LU per annum and 100,000 LU per annum
- Change in annual freight task, by a factor of ten-fold, for an average Base ADT
- Consideration of compliance and remoteness.

The effect of the following factors was not tested:

- loading duration, which has been shown not to impact total costs using the adopted costing method which ensures that the annual consumption of gravel loss is accounted for year by year
- grading frequency, with this set at an optimum level to reduce impacts on non-freight users
- initial treatment, with this considered to be the responsibility of the operator.

The results are shown in Table 4.3.

Table 4.3   Sensitivity of outcomes to changes in a selection of input parameters

Main parameters tested	Surfacing materials	Impact elasticity	
		Gravel loss	Marginal cost
Zone 3 and change in task from 10k to 100k at 100 Base AADT	Compliant materials	0.16	-0.03
Zone 3 and change in task from 10k to 100k at 250 Base AADT		0.11	-0.03
Zone 4 and change in task from 10k to 100k at 100 Base AADT		0.17	-0.03
Zone 4 and change in task from 10k to 100k at 250 Base AADT		0.12	-0.03
Zone 4 and change in task from 10k to 100k at 150 Base AADT	Compliant and remote	0.15	-0.03
Zone 4 and change in task from 10k to 100k at 150 Base AADT	Non-compliant	0.27	-0.02

Comments on the results are as follows:

- The impact elasticity of a tenfold change in freight task with respect to annual gravel loss (for compliant materials) is greater at lower traffic levels, with this reflecting the increased role of climatic conditions (predominantly rainfall). However, the net effect is relatively 'low' in relation to the HDM-4 sensitivity classes.
- For the same traffic scenarios, the impact elasticity with respect to the marginal cost resulting from a ten-fold increase is negligible.

- Where the cost of supply of compliant materials is increased by applying a remote (or premium) cost factor, the impact elasticity with respect to gravel loss and marginal cost is similar to the cases where a premium cost is not applied.
- Where non-compliant materials are employed, the impact elasticity with respect to annual gravel loss is moderate, whereas the effect on marginal cost is negligible. The latter reflects the higher gravel loss and the greater contribution from traffic-related wear, rather than environmental effects. The former result is consistent with the trends for the cases above with the increased traffic task having a minimal effect on marginal costs.

The results, and in particular the absolute values, confirm the need to account for the effect of materials compliance on marginal costs and cost zone, which should be retained as a key parameter because it reflects the operating conditions and cost structures which cannot be directly controlled, being a consequence of physical location. Retaining the annual freight task is also justified as it helps keep a focus on the overall purpose of the analysis, namely, to determine a gross cost, although its effect in relation to other factors is modest.

4.2.6   OPTIMUM SURFACE MAINTENANCE AND UPGRADING STRATEGIES

The impact of multiple factors on marginal cost suggest that there is a case to provide a more quantitative basis for informing surface maintenance and upgrading strategies. This is because the sum of marginal costs, i.e. the cumulative revenue, could potentially exceed the additional cost of upgrading from unsealed to sealed, using a low-cost treatment. An alternative, optimum maintenance strategy may also be an option, and could significantly reduce the marginal cost even where the road remains unsealed.

A selection of examples, where the estimated revenue for a selection of loading scenarios and analysis cases in Zone 4 and a base ADT of 100, are shown in Table 4.4. They include variations in the following attributes, all for compliant materials:

- remoteness
- initial additional thickness of material, as 0 mm, 150 mm or 300 mm
- different loading scenarios (6 in total).

Table 4.4   Estimated revenue for a selection of loading scenarios and analysis cases in Zone 4 and a base ADT of 100

Additional annual loading and duration						
Load (tonnes per annum)	100,000	100,000	100,000	1,000,000	1,000,000	1,000,000
Duration (Years)	2	5	10	2	5	10
Marginal cost (cents/LU.km) (One-way)						
Analysis case for each loading scenario	Additional thickness (mm)	100k_2yr	100k_5yr	100k_10yr	1M_2yr	1M_5yr	1M_10yr
Compliant	0	15.1	15.1	15.1	12.8	12.8	12.8
Compliant and remote	0	22.6	22.6	22.6	19.1	19.1	19.1
Compliant	150	188.4	89.5	56.8	29.8	20.1	16.9
Compliant and remote	150	282.7	134.3	85.2	44.7	30.1	25.3
Compliant	300	401.6	181.1	108.1	50.7	29.1	21.9
Compliant and remote	300	602.4	271.6	162.2	76.1	43.6	32.8
Estimated revenue ($ per link.km)						
Compliant	0	6,024	15,061	30,122	51,032	127,580	255,159
Compliant and remote	0	9,037	22,592	45,184	76,548	191,369	382,739
Compliant	150	75,374	89,521	113,620	119,120	200,685	337,138
Compliant and remote	150	113,060	134,281	170,429	178,680	301,028	505,707
Compliant	300	160,651	181,082	216,294	202,847	290,582	437,946
Compliant and remote	300	240,976	271,623	324,441	304,270	435,873	656,919

Notes:
- The estimated revenue = annual loading (in tonnes) x duration (in years) / average payload per pair of axles x MC per LU (in $) x 2 (representing a two-way trip)
- For the range of vehicles in Table 5.2 the average payload per pair of axles is 10 tonnes and this has been applied in this example. However, this can vary between approximately 8 tonnes and 11.6 tonnes depending on the particular loading scheme and the configuration of the vehicles used to perform the task.
- The shaded cells represent cases where on the basis of only marginal costs it may be cost-effective to consider sealing the road (see below). Other possible cases for sealing are also discussed below.

For this set of examples, the maximum revenue is shown to be approximately $656,919, which is equivalent to a treatment cost of approximately $82 per sq. m. The quoted revenue is also in addition to the ongoing cost of maintaining the existing road to service the base ADT. The total road upkeep costs are significantly higher, being approximately 1.65 times, the estimated revenue based on the LCC analysis for this example. The question, therefore, is whether it would be more beneficial to upgrade the existing road.

Based on the average unit costs for cost zone 4 used as the basis for the sealed road user guide, the sum of pavement reconstruction and maintenance for a sealed road for a ten-year period including one reseal and annual routine pavement maintenance is approximately $79 per sq. m in present day costs. On this basis, there will be circumstances where an upgrade strategy would be a lower cost option, although a question will be which party or parties pay for the upgrade. In addition, significant road user cost savings would also result due to reduced road roughness levels, with benefits to both heavy vehicle users and other users.

Sealing is also likely to be an economic option where the ADT arising from base traffic and additional traffic is in excess of 150 – 300 vehicles per day, or an equivalent number of loading units. This range, though wide, has been shown in a variety of studies to be appropriate with lower breakeven ADT levels possible where unsealed rod materials are particularly poor and/or costly.

Furthermore, the optimum unsealed road maintenance strategies applied in this study are based on the application of a relationship between traffic level and grading frequency from international studies (TRL Overseas Centre 1987). However, this has not been validated using Australian road deterioration and works effects models and associated road user costs. Whereas the use of the international model is not believed to have significantly affected the outcomes of the current analysis, it would make sense to produce a local set of relationships should the recommended improvements to the unsealed road models be pursued in future. This would also complement the application of a gravel loss model which responds to grading frequency, this having been shown to be a possible means of reducing the costs of road maintenance.

4.3 FINAL RESULTS

4.3.1 GENERAL

Whilst the full set of analysis results were not discarded, the final results concentrated on those factors shown to have greatest impact on the marginal cost bearing in mind the need to present the results to practitioners in a simple chart-based format. This meant that factors which resulted in a relatively minor difference in cost were not isolated but have been used as part of the full dataset employed in the final models.

In reaching a conclusion on what factors to retain, the following questions were posed, and answers developed drawing on the preliminary analysis and the final analysis:

d) Does base traffic and the proportion of commercial vehicles matter, or can it be simplified to additional LU? No, i.e., the effect is insignificant,

e) Does payload matter? No, but this is required in computing the additional LU and the total freight task for cost recovery purposes, but freight operators can choose which vehicles to use to convey a task.

f) Does duration matter? No, based on use of the annual asset consumption-based method of costing.

g) How should compliance be incorporated? This is significant and requires a range of cases to be considered. Provision has been made for up to five examples of compliance in the presented results.

h) Should provision be made for an initial treatment? No, with this considered too site-specific, with judgement needed by the asset manager and the freight operator in assessing the need and agreeing an initial upfront cost.

i) Should climate and cost zones be retained? Yes, as both significantly influence marginal cost.

j) Should a 50% cost loading for remoteness (within a Zone) be included? No, this should be replaced by providing a more flexible basis for computing an actual MC that adjusts the estimated value using the actual costs of material supply (see Section 4.3.2 and Equation 2).

The factors selected to be included are listed in Table 4.5.

Table 4.5   Factors included in final marginal cost estimation

Factor	Inclusion in final MC estimate
Vehicle types, level of loading and duration of additional loading	Yes, based on axle pairs, with the duration of loading accounted for in determining the total cost
Current road condition and suitability for carrying significant additional loads	No, with need to employ an initial treatment not part of the MC determination but to be considered on a case by case basis

Factor	Inclusion in final MC estimate
Surface materials quality / specification	Yes, with five cases of compliance/non-compliance applied covering: ▪ Non-compliant below ▪ Borderline below ▪ Compliant ▪ Borderline above ▪ Non-compliant above
Maintenance effects, including the type(s), frequency and quality	Yes, with optimum grading frequency selected, and re-gravelling at a defined (single) minimum thickness
Climate, terrain, operating speeds	Yes, but climate only employed coinciding with cost zone
Unit costs (and variation in supply cost)	Yes, with a simple equation provided to allow the actual MC to be calculated based on up to date and location specific material supply and treatment costs to cater for the variation in unit costs within each cost zone. This replaces the single 50% premium cost employed to illustrate its impact in the development stages of this study.

4.3.2   DEVELOPMENT OF A FINAL SET OF MODELS AND SOLUTIONS

MODEL DEVELOPMENT

The final results were reviewed and analysed to determine a set of statistical relationships by:

- visualising the data to determine which factors are important to the marginal cost, with a base chart type representing the MC and additional LU units per annum
- producing a set of model relationships using linear and non-linear models, including
- $y = a/x + b$, $y = a.\log_{10}(x) + b$, and $y = a.x + b$ as linear models
- $y = e^{\wedge}(x)$ as a non-Linear Model
- using only the important factors, or using all the factors grouped together either including key factors by filtering the results to suit, e.g.
- MC = function of additional LU for each case with 3 parameter filters (compliance, cost zone and remoteness)
- MC = function of Additional LU + Compliance + RemoteCost (cost zone only filter)
- developing an output matrix/table.

The resulting models and example charts are presented in Appendix D from which the following model form was selected with a separate relationship provided for each cost zone (3 in number) and level of compliancy (5 in number) with the model represented by the following form (Equation 1):

$$MC = a.\log_{10}(x) + b \qquad\qquad 1$$

where

     MC   =   Marginal Cost based on average (supply) cost rates (cents/LU)

     x   =   Additional loading units per annum

     a, b   =   Model coefficients

PRESENTATION OF SOLUTIONS

The presentation of solutions was required to take the form of charts which could be employed by users in a manner similar to that presented in the Sealed Roads User Guide (WALGA & ARRB 2015). Two examples have been developed, comprising:

- a histogram representing a single additional annual LU for each Cost Zone and for five different compliance levels (Figure 4.5). Five separate charts have been produced per cost zone ranging from 5,000 LU to 100,000 LU per year.
- a line graph based on a single solution per Cost Zone using average cost rates with the effect of additional annual LU represented by a single relationship for each level of compliance (Figure 4.4). In this example, only the range of marginal costs is shown, represented by the lowest (compliant) and the highest (non-compliant below).

Figure 4.4   Histogram option - Effect of compliance and additional LU per annum on Marginal Cost
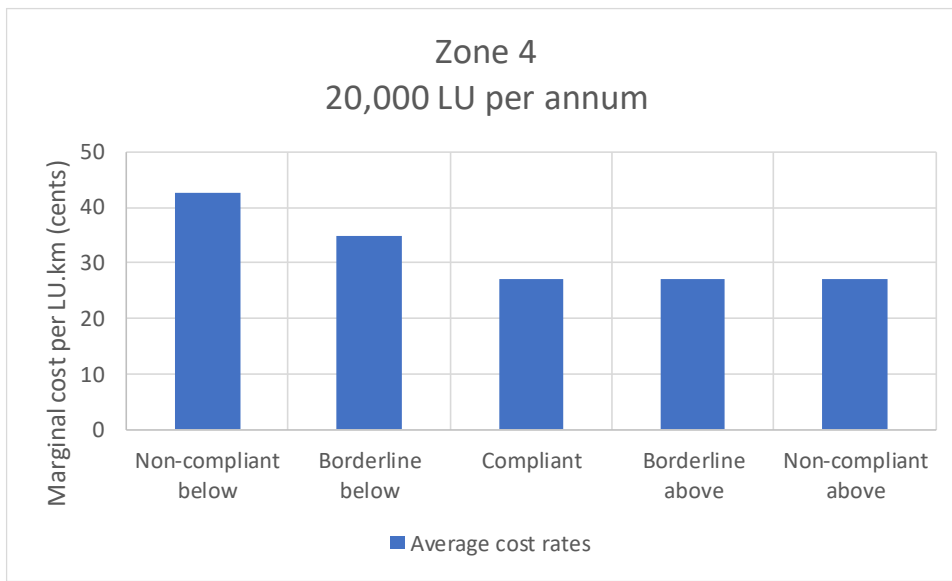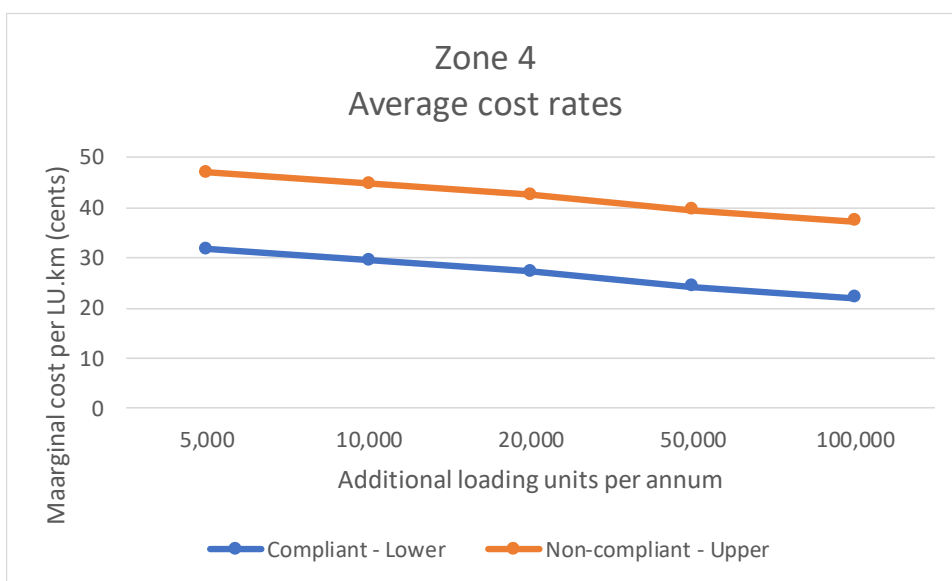

Figure 4.5   Line graph option - Effect of additional LU per annum on Marginal Cost

A comprehensive set of solutions are presented in Appendix E, from which the 'histogram' presentation displaying five levels of compliance is recommended for use in the User Guide. This requires a total of 15 charts (Appendix E.2) based on the following combinations:

- Cost Zone (three)
- Additional LU per annum (five).

Examples of the line-graph option are also presented in Appendix E.3, but these only show the range of marginal costs

EFFECT OF DIFFERENCES IN THE COST OF SUPPLY OF GRAVEL WEARING COURSE MATERIALS

In the preliminary and final analysis, a single premium rate, a 50% increase above average rates, representing an increase in the cost of supply of wearing course materials was applied. This was intended to represent a remoteness factor and its effect on marginal cost is illustrated in Figure 4.6.

Figure 4.6   Illustration of the effect of a cost premium on MC for a single Cost Zone and loading scenario and different levels of compliance.
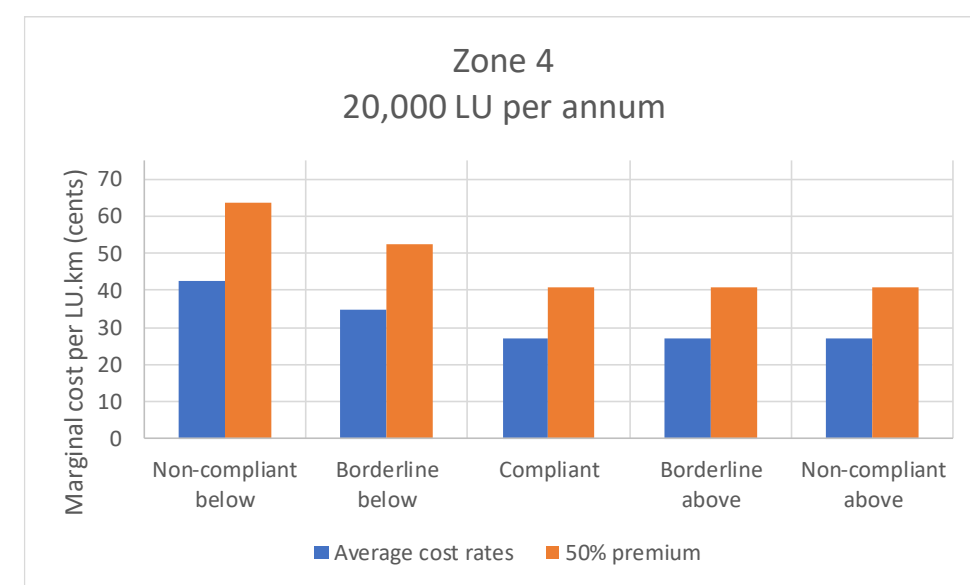
However, for general application, given that the cost of supply may vary within a single region it was decided to develop a simple equation which allowed the marginal cost to be adjusted depending on the supply cost for each case. For all examples tested, which represented the full matrix by Cost Zone, additional LU and compliance level, the marginal cost was found to be directly proportional to the cost increase (or decrease) as illustrated for a single example in Table 4.6.

Table 4.6   Relative marginal cost increase related to increase in supply cost

Cost Zone	Compliance	Average cost ($/km)	Premium cost ($/km)	Additional LU per annum	MC for average cost rate	MC for premium cost rate	Relative marginal cost increase (%)
4	Non-Compliant Above (NCA)	78,133	117,200	5000	31.76	47.53	50
4	NCA	78,133	117,200	20000	27.22	40.74	50
4	NCA	78,133	117,200	50000	24.23	36.24	50
4	NCA	78,133	117,200	100000	21.96	32.84	50

Consequently, the resulting relationship (Equation 2) is as follows:

$$AMC = MC.a/b \hspace{4cm} 2$$

where

AMC	=	Actual Marginal Cost for specific case study
MC	=	Marginal Cost based on average (supply) cost rates (cents/LU)
a	=	Actual cost of supply ($/km)
b	=	Average cost rate per Cost Zone (from Table 4.7) ($/km)

Table 4.7   Unit cost rate for full resheeting used in the development of the user guide

Cost Zone	Average cost rate per Cost Zone ($/km 2017)
2	43,747
3	35,656
4	78,133

5 EXAMPLE APPLICATION

5.1 GENERAL

In order to employ the results in practice, a process for determining the appropriate cost needs to be described. As part of this process, guidance is also required on how to convert a freight task into trips by the vehicle type(s) assigned to the task. This then needs to be followed by the calculation of an appropriate MC value, the calculated revenue and any additional terms as follows:

1. Selection of the applicable Marginal Cost chart and determination of MC per (one-way) LU per km, considering:

    - Cost zone
    - Cost rates (average per zone or user defined)
    - Additional annual LU
    - Compliance of surfacing materials

2. Calculation of annual revenue as:

    Revenue = Annual (two-way) loading units x distance x MC

3. Additional terms, including the suitability of the current infrastructure to carry additional traffic, i.e. does the road possess sufficient structure to carry the expected additional loading, or is the immediate placement of an additional thickness of material necessary to provide a functional running surface and unsealed pavement structure?

This following text describes the process for determining a charge and offers a few examples of its application, and then describes the assumptions employed.

5.2   CALCULATION PROCESS AND INPUT DATA

The calculation process for unsealed roads is illustrated in Figure 5.1. The process is further elaborated below accounting for the information required to complete each step (Table 5.1), which includes:

- a sample set of vehicles and related parameter values (Table 5.2)
- an example set of MC tables which are populated with the attributes which determine the unit MC (Table 5.4). The marginal cost is reported in cents/LU.km, where a loading unit (LU) represents the number of axle pairs[4]
- a basis for determining materials compliance and expected performance is presented in Table 5.3. In wetter climates a slightly lower Shrinkage Product (SP) is likely to provide optimum performance, and in extremely dry climates a higher SP is likely to be suitable. Local experience should be sought to guide performance classification.

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[4] The selection of axle pairs as the 'loading unit' is considered the most suitable to represent both current and future traffic based on available knowledge. It is also consistent with the recommendations on the choice of the unsealed road deterioration model for final analysis, as discussed in Section 2.3.6. The number of LU is determined according to the process in Table 5.4 and involves: a) choosing a vehicle and the allowable payload based on examples in Table 5.2; b) estimating the number of one-way trips as annual loading/allowable payload per vehicle; c) converting the number of trips into a number of pairs of axle passes based on selected vehicle, and assuming single-lane operation. The latter is typical of unsealed roads unless the formation is very wide, and traffic levels are very high.
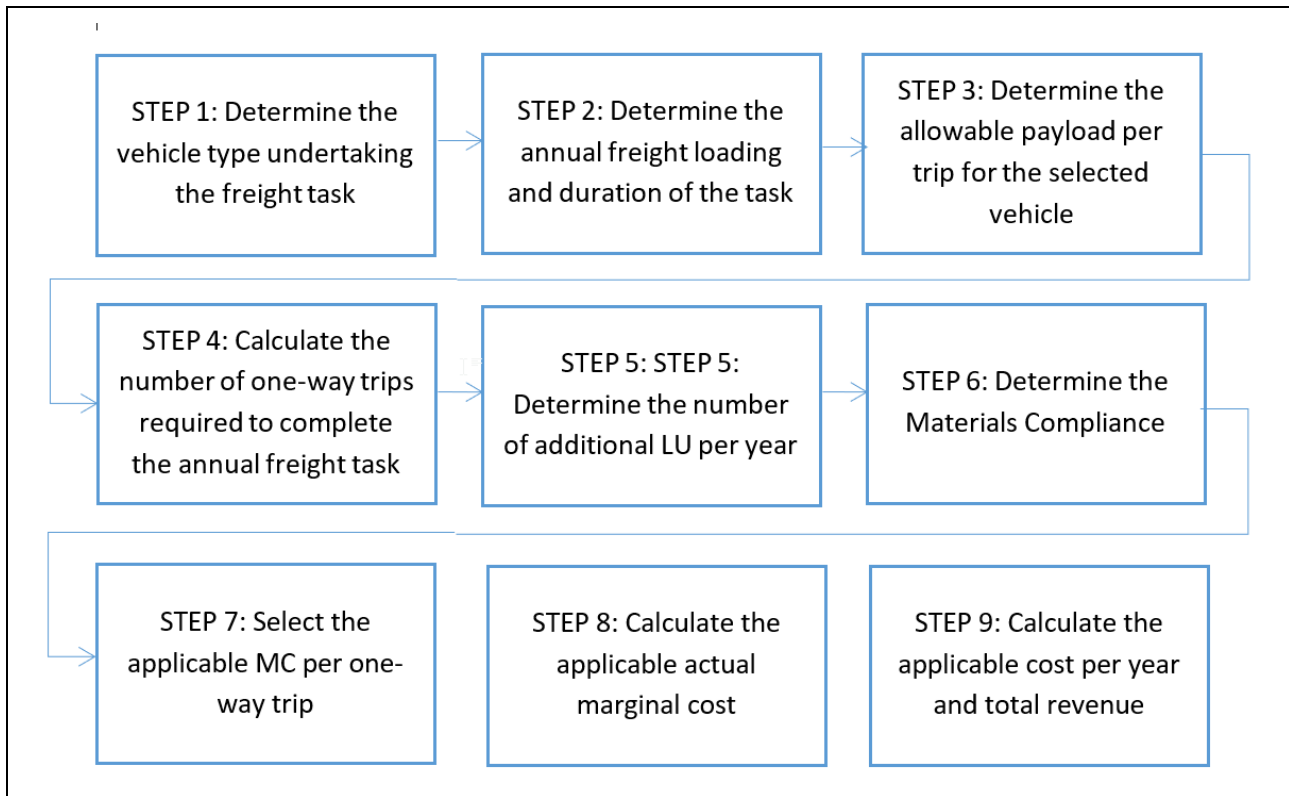
Source: This study

Table 5.1   Step-by-step guide to applying the calculation process

Step	Information and calculations	Example parameter values
STEP 1: Determine the vehicle type undertaking the freight task	▪ Agreed vehicle type and permitted maximum allowable gross mass, and tare weight	▪ Typical values (Table 5.2 by vehicle for: – Maximum permitted load (Tonnes) – Maximum payload (Tonnes) – No. of axle pairs.
STEP 2: Determine the annual freight loading and duration of the task	▪ Agreed annual loading (tonnes) and duration (years)	
STEP 3: Determine the allowable payload per trip for the selected vehicle	▪ Selected from or supplied by the operator	
STEP 4: Calculate the number of one-way trips required to complete the annual freight task	▪ Calculated as: No. of trips = Annual task/allowable payload per trip	
STEP 5: Determine the number of additional LU per year	▪ Calculated as: No. of LU = No. of trips x No. of 2-axle passes per vehicle x 2 ▪ Select the closest level of annual loading: options 5k, 10k, 20k, 50k, 100k LU per annum	

Step	Information and calculations	Example parameter values

STEP 6: Determine the Materials Compliance	▪ Obtain materials test properties and classify performance in relation to Table 5.3 and Figure 2.5:
	  - Shrinkage Product (SP)
	  - Grading coefficient (GC)	

STEP 7: Select the applicable MC per one-way trip	▪ Select MC based on:
	  − Cost zone
	  − Additional loading (from Step 5)
	  − Materials compliance (from Step 6)
		▪ MC graphs (Appendix E)

STEP 8: Calculate the applicable actual marginal cost	This converts the estimated marginal cost to an actual marginal cost accounting for the actual cost of materials supply, where for general application, the MC determined in STEP 7 should be adjusted by applying a simple equation (Equation 2) by using the actual cost of supply for each case	
STEP 9: Calculate the applicable cost per year	▪ Applicable cost (C): C = MC x No. of trips x No. of 2-axle passes per vehicle x route length	

Source: This study

Table 5.2　　　*Examples of typical vehicle types, characteristics and loading*

Western Australia Vehicle1		GCM2 (tonnes)	Estimated payload (tonnes)	ESA3	ESA per payload tonne	No. of axles
Type	Brief description					
3 Axle Rigid	3 Axle Rigid	22.5	13.1	3.54	0.27	3
3 Axle Rigid AMMS L3	3 Axle Rigid AMMS L3 at AMMS L3	23.5	14.1	3.95	0.28	3
RAV 2 B	3 Axle Prime Mover towing a 3 axle Semi-trailer	42.5	24.1	5.06	0.21	6
RAV 2 B AMMS L3	3 Axle Prime Mover towing a 3 axle Semi-trailer at AMMS L3	47	28.6	6.86	0.24	6
RAV 2 C	B-double, with 3 axle Prime Mover and two 3 axle articulated trailers	67.5	44.5	7.57	0.17	9
RAV 2 C AMMS L3	B-double, with 3 axle Prime Mover and two 3 axle articulated trailers at AMMS L3	75.5	52.5	9.98	0.19	9
RAV 3A	3 Axle Prime Mover towing a 3 axle Semi-trailer and a 5 axle dog trailer	84	53.5	9.10	0.17	11
RAV 3A AMMS L3	3 Axle Prime Mover towing a 3 axle Semi-trailer and a 5 axle dog trailer at AMMS L3	93	62.5	12.50	0.2	11
RAV 4A	3 Axle Prime Mover towing a 3 axle Semi-trailer and a 6 axle dog trailer	87.5	56	8.40	0.15	12
RAV 4A AMMS L3	3 Axle Prime Mover towing a 3 axle Semi-trailer and a 6 axle dog trailer at AMMS L3	99	67.5	12.83	0.19	12
RAV 7A	3 Axle Prime Mover towing a 3 axle Semi-trailer, and a B-double trailer	107.5	71.5	10.01	0.14	15
RAV 7A AMMS L3	3 Axle Prime Mover towing a 3 axle Semi-trailer, and a B-double trailer at AMMS L3	122.5	86.5	15.57	0.18	15
RAV 10A	3 Axle Prime Mover towing a 3 axle Semi-trailer, and two 6-axle dog trailers	127.5	83.5	10.86	0.13	18
RAV 10A AMMS L3	3 Axle Prime Mover towing a 3 axle Semi-trailer, and two 6-axle dog trailers at AMMS L3	146	102	17.34	0.17	18

Source: This study adapted from MRWA (2017) and WALGA & ARRB (2015)

Notes to Table 5.2:
1. Western Australia vehicle types and descriptions reproduced in Figure A 1 and Figure A 2 Standard abbreviations include:
2. RAV - Restricted access vehicle network (RAV 1 etc.) and vehicle (RAV 2A etc.)
3. RML – Regulation mass limits
4. AMMS –Accredited Mass Management Scheme, which is a concessional loading scheme with three loading tiers and associated mass limits by axle group (L3 is the third tier and maximum loading). Further information available at HTTPS://WWW.MAINROADS.WA.GOV.AU/USINGROADS/HEAVYVEHICLES/PERMITS/PAGES/AMMS.ASPX and Government of Western Australia Road Traffic (Vehicles) Regulations 2014.
5. GCM – Gross combination mass (tonnes).
6. ESA – No. of equivalent standard axles
7. No. of loading units calculated as no. of axles/2.

Indicative compliance level and performance of unsealed road granular surfacing materials in predominantly dry climatic conditions

Indicative compliance level	Materials and performance attributes
Non-compliant below (NCB)	High rate of material loss (> 20 – 40 mm per year per 100 AADT) with surface ravelling and corrugations under traffic. Shrinkage Product (SP) below 100, whereas the Grading Coefficient (GC) may vary widely. Uniformly graded fine materials with a low GC display low resistance to erosion and coarsely graded higher GC materials tend to ravel badly and are generally unsuitable.
Borderline below (BB)	Moderate rate of material loss (10 – 20 mm per year per 100 AADT), with the surface tending to loosen and corrugate under the action of traffic but may remain tolerable to heavy traffic at low to moderate speeds. SP below 200, whereas GC may vary widely. Performance can improve with regular grading/cushioning operations.
Compliant (C)	Low rate of material loss, typically less than 5 – 10 mm per year per 100 AADT, with a well-knit surface resulting from a mechanically stable particle size distribution with few weak particles and containing a sufficient quantity of plastic fines. Ideal materials typically have a SP greater than 200 with an upper limit of 600 depending on the proportion of heavy traffic and tolerance of dust, and a GC of between 20 and 30. Arm-chair type (or gap) gradings are acceptable with concretionary materials, such as calcretes and laterites.
Borderline above (BA)	Moderate rate of material loss (10 – 20 mm per year per 100 AADT), with the surface tending to rut and become slippery in the wet but may remain tolerable to heavy traffic under wet conditions. SP above 600, whereas GC may vary widely. Performance can improve with regular grading/cushioning operations.
Non-compliant above (NCA)	Moderate to high rate of material loss (> 20 mm per year per 100 AADT) with risk of severe rutting and slipperiness in the wet. SP above 700, whereas GC may vary widely. Uniformly graded fine materials with lower GC display low resistance to erosion and are generally unsuitable, whereas high GC materials tend to be ravel badly leading to extensive potholes.

Source: This study

Notes:

▪ The range of SP used, particularly the lower and upper limits to 'good' performance are based on observations from the Local Roads Deterioration Study (see Appendix C.2 drawing and Figure 2.6), but these should be adjusted based on local experience with reference to the actual rates of material loss and performance characteristics.

5.3   WORKED EXAMPLES FOR UNSEALED ROADS

5.3.1   ILLUSTRATION OF CALCULATION PROCESS

Four worked examples of the calculation of road wear costs for unsealed roads, reported as cents/LU.km values and total charges (as revenue estimates) are presented in Table 5.4. These have been adapted from the examples in the sealed roads user guide (WALGA & ARRB 2015), the exceptions being that example 3 uses cost zone 3 and not cost zone 1 and the level of loading has been reduced to represent loading levels reported by practitioners. The (a) and (b) in each case represents additional variations related to unsealed roads to demonstrate the impact of compliance and a premium cost.

In selecting the applicable MC, the match is made by choosing the closest loading scenario (below or above the actual annual loading). Guidance on populating the actual table (available as a simple spreadsheet) and a description of the calculations involved is provided as notes to Table 5.4.

5.3.2   PRESENTATION OF RESULTS

The results from the four examples (eight including the two variations) are presented in Figure 5.2 (marginal cost comparison), and Figure 5.3 (annual revenue comparison) and the ratios associated with each are presented in Table 5.5, along with the description (text) used to label the examples.

Table 5.4 Example calculation of costs for unsealed roads

Worked example	STEP 1: Determine the vehicle type undertaking the freight task			STEP 2: Determine the annual freight loading and duration of the task		STEP 3: Determine the allowable payload per trip for the selected vehicle	STEP 4: Calculate the number of trips (both directions) required to complete the annual freight task	STEP 5: Select the applicable MC per one-way trip		STEP 6: Determine the Materials Compliance	STEP 7: Select the applicable MC per one-way trip		STEP 8: Calculate the applicable actual marginal cost			STEP 9: Calculate the applicable cost per year and total revenue		
Example	Vehicle description/loading scheme	WA vehicle classification	No. of LU per vehicle (pairs of axles)	Annual freight task (tonnes)	Duration (years)	Allowable Payload per veh (Tonnes)	No. of trips (both directions)/year	Actual LU per year (two-way)	Nearest LU per annum	Compliancy	Cost Zone	Base MC per LU.km (cents)	Average cost	Premium (factor)	Applicable Actual MC per LU.km (cents)	Route-length (km)	Charge per year	Total revenue (add CPI)
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	(q)	(r)	(s)
1 (a)	Prime mover and semi-trailer towing two six axle dog trailers with a concessional loading permit (AMMS Level 3).	RAV 10(A).	9	400,000	5	102	3,922	70,588	50,000	C	2	12.0	yes	1.0	12.0	64	542,118	2,710,588
1 (b)	Prime mover and semi-trailer towing two six axle dog trailers with a concessional loading permit (AMMS Level 3).	RAV 10(A).	9	400,000	5	102	3,922	70,588	50,000	C	2	12.0	no	1.5	18.0	64	813,176	4,065,882
2 (a)	Truck towing two six axle dog trailers operating under the Accredited Mass Management Scheme Level 3 (AMMS L3).	RAV 7(A)	7.5	350,000	5	86.5	4,046	60,694	50,000	C	4	23.0	yes	1.0	23.0	55	767,775	3,838,873
2 (b)	Truck towing two six axle dog trailers operating under the Accredited Mass Management Scheme Level 3 (AMMS L3).	RAV 7(A)	7.5	350,000	5	86.5	4,046	60,694	50,000	NCB	4	39.0	yes	1.0	39.0	55	1,301,879	6,509,393
3 (a)	Prime mover and semi-trailer operating under the regulation mass limit (RML) scheme.	RAV 2(B).	3	75,000	5	24.1	3,112	18,672	20,000	C	3	28.0	no	1.5	42.0	3.8	29,801	149,004
3 (b)	Prime mover and semi-trailer operating under the regulation mass limit (RML) scheme.	RAV 2(B).	3	75,000	5	24.1	3,112	18,672	20,000	NCA	3	28.0	yes	1.0	28.0	3.8	19,867	99,336
4 (a)	Prime movers with a semi-trailer towing two six axle dog trailers The company is operating under the Accredited Mass Management Scheme Level 3.	RAV 10 (a)	9	510,000	6	102	5,000	90,000	100,000	C	4	21.0	yes	1.0	21.0	30	567,000	3,402,000
4 (b)	Prime movers with a semi-trailer towing two six axle dog trailers The company is operating under the Accredited Mass Management Scheme Level 3.	RAV 10 (a)	9	510,000	6	102	5,000	90,000	100,000	BB	4	29.0	yes	1.0	29.0	30	783,000	4,698,000

Source: This study

Notes to Table 5.4:

- Column (a) – aims to closely represent sealed road user guide examples for similar task and vehicles, and cost zone, with two variations employed to test effect of compliance and/or premium cost
- Column (b) – description of loading scheme
- Column (c) – closest match to vehicles (from Table 5.2)
- Column (d) - match to selected vehicle (from Table 5.2)
- Column (e) and (f) – base on chosen examples
- Column (g) – based on selected vehicle (Table 5.2)
- Column (h) – calculated as annual loading/allowable payload per vehicle
- Columns (i) – calculated as no. of trips (both directions)/year (Column (h)) x no. of LU per vehicle (Column (d))
- Columns (j) – round entry in column (i) to nearest annual loading value (above or below) in charts (selected from 5,000, 10,000, 20,000, 50,000 and 100,00 LU per year).
- Columns (k) and (l) – entered for specific example
- Columns (m) – read off from unsealed MC charts in Appendix E
- Column (n) – entered for specific example
- Column (o) – apply premium factor (if any)
- Column (p) – calculated as base MC per LU km x premium cost, i.e. Column (n) x Column (o)
- Column (q) – entered for the case study as round-trip (km)
- Column (r) – calculated as (MC x annual trips x route length (km)) / 100, i.e. as Column (p) x Column (h) x Column (q) / 100
- Column (s) – calculated as sum of annual revenue (with CPI added per year) for duration (yrs)

Figure 5.2   *Comparison of estimated cost per km for unsealed and sealed roads for selected examples*
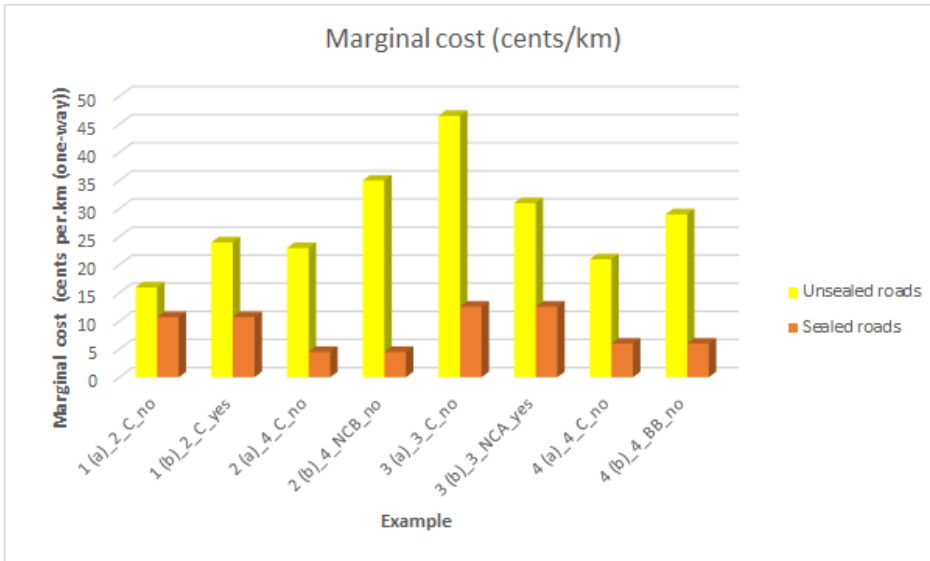
Figure 5.3   *Comparison of estimated annual revenue for unsealed and sealed roads for selected examples*
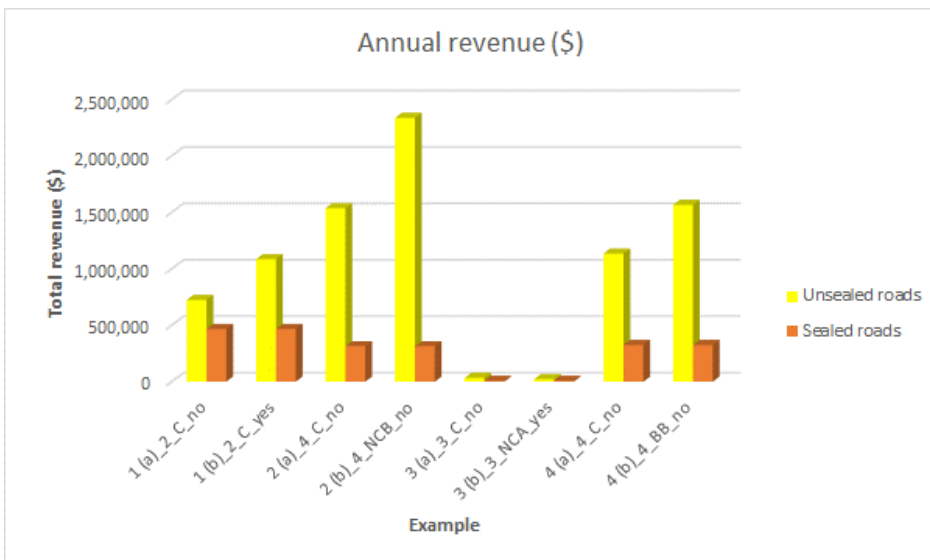
Table 5.5   *Ratio of unsealed and sealed MC and annual revenue*

Example	Description	Ratio of unsealed and sealed marginal cost	Ratio of unsealed and sealed annual revenue
S1	1 (a)_2_C_no	1.5	1.6
S1	1 (b)_2_C_yes	2.2	2.3
S2	2 (a)_4_C_no	5.1	4.9
S2	2 (b)_4_NCB_no	7.7	7.5
S3	3 (a)_3_C_no	3.7	4.4
S3	3 (b)_3_NCA_yes	2.5	2.9
S4	4 (a)_4_C_no	3.5	3.5
S4	4 (b)_4_BB_no	4.8	4.8

Notes to Table 5.5
- Example represents sealed road user guide example #
- Description represents the following (in order)

- Sealed road example #
- (a) and (b) represents alternative unsealed cases
- Cost zone (2, 3 or 4)
- Compliancy (C for compliant, etc)
- Premium cost applied (yes or no)

5.3.3 DISCUSSION OF EXAMPLES

The difference in estimates of MC and annual revenue for unsealed roads are in all cases higher than those for sealed roads for the selected examples, in some cases by a significant amount.

The closest (lowest ratios) is for compliant materials in cost zone 2, with this increasing where a premium cost for extra haulage is applied. The most extreme ratios and corresponding values are for cost zone 4 where a non-compliant below specification material is employed.

In conclusion the examples illustrate that additional loads on unsealed roads lead to significant road wear and therefore relatively high marginal costs. This is a further reason for freight operators and asset managers to carefully consider the viability of unsealed roads where significant freight tasks take place.

Other potential reasons for differences in MC, e.g. due to variations in input costs for major treatments including between cost zones, have not been considered because there is no reason why the relative costs should in fact be close to unity. Furthermore, multiple case specific factors affect the estimates.

However, it is relevant to note that the costs of major pavement/surfacing treatments in the analysis which informed the sealed roads user guide were approximately 30% greater for sealed roads outside the south-west of the State, whereas in this analysis they are between 23% (Zone 2) and 119% (Zone 4) greater. The difference between the minimum and maximum cost in Zone 4 is also different by approximately 8 times. This confirms the need to treat each cost zone differently and justifies the adoption of actual costs of materials supply/resheeting costs as presented in Section 4.3.2 and Equation 2 accounts for circumstances where costs can be substantially lower or higher. The differences between the reported sealed road and unsealed road treatment costs, and the corresponding impacts on performance, also raises the question of the economic viability of unsealed roads. This is discussed in Section 4.2.6.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

1. A modelling framework applicable to the estimation of the marginal cost of road wear unsealed roads has been developed and successfully tested, with the analysis covering a comprehensive range of loading scenarios and applications conditions representative of unsealed roads in Western Australia (WA). In total, approximately 3,800 analysis cases per cost zone were tested to develop the final solutions having selected an optimum grading frequency for each case, with the range of cases and assumptions informed by responses from WA asset management practitioners.

2. Results have been presented to illustrate the physical performance of representative unsealed roads sections, in terms of gravel loss, and the financial impact as the marginal cost of road wear, and cover independent variables such as:

   a) Additional loading scenarios, ranging from 10,000 to 500,000 additional loading units (pairs of axle passes) per annum, and for durations of between 2 years and 10 years
   b) Geographical location, representing climate and treatment cost, materials properties and typical operating conditions
   c) Impact of compliance with road materials specifications, and the need for an initial treatment to support road use.
   d) The effect of remoteness, where treatment costs can increase substantially.

   For the range of examples illustrated in the report, the total annual gravel loss is shown to increase by a factor of up to 3 where compliant materials are used, with this increasing further (to almost 9 times) where non-compliant materials are employed. Marginal costs increase roughly by similar factors, from minimum marginal cost values of approximately 6 or 7 cents/loading unit.km.

3. Examples have been produced of applying the results to developing and analysing four case studies (similar in scope to the sealed roads user guide), including a step-by-step guide to the calculation process, and the sourcing of input data, including example of typical vehicle types and characteristics, and a discussion and interpretation of the results. These have been applied in estimating the total revenue for a trip, and the cost per link.km.

4. Solutions are presented for inclusion in the unsealed roads user guide structured as follows:

   - Cost Zone
   - Annual additional loading units
   - Average or actual cost rates (per zone)
   - Surfacing materials compliance (5 categories)
   - Additional factors have also been identified which require consideration by the asset manager/development proponent, including whether an initial treatment is needed.

5. Whereas the solutions represent application of the best available models, and particular assumptions, future development should consider:

   a) revisions to the road deterioration models to better reflect performance under WA conditions, with a focus on incorporating the effect of grading frequency and improving the response of the model to climatic conditions and materials properties
   b) investigate the possible breakeven point between continuing to maintain an unsealed road or to upgrade to a sealed surface.

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A.1   COMPLETING THE QUESTIONNAIRE

The following questions should be completed by hand with additional information provided as necessary. You may also include a list of reference documents which you regularly refer to.

A.2   CONTACT DETAILS

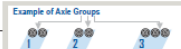Local Government: _____

Name: _____

Email: _____

Phone: _____

A.3   VEHICLE TYPE(S) UNDERTAKING THE FREIGHT TASK

Nominate the vehicle types that typically undertake the freight task in your shire/region by selecting (✓) a maximum of **six** of the vehicles outlined in Table A 1 by referring to Figure A 1 and Figure A 2.

Figure A 1 MRWA RAV Truck, Trailer Combinations

RAV 2015
Heavy Vehicle Operations

Truck, Trailer Combinations

VEHICLE DESCRIPTION AND CONFIGURATION CHART   (RAV) – TRUCK, TRAILER COMBINATIONS EXAMPLES

		Axle Spacing Table	Length (m)	Mass (T) Maximum Permitted Mass	Height (m) ( ) = see NOTES	Axle Groups	RAV Network
Category 1 (A) TRUCK LIVESTOCK OR VEHICLE CARRIER (B) TRUCK TOWING A PIG TRAILER (C) TRUCK TOWING A DOG TRAILER (D) TRUCK TOWING A CAR CARRIER TRAILER	(A)	A	≤12.5	27.5	≤4.6 (4)	2	Network 1
	(B)	B	≤20	45.5	≤4.6 (4)	3	
	(C)	B	≤20	50	≤4.6 (4)	4	
	(D)	A	≤20	42.5	≤4.6 (4)	3	
Category 2 (A) TRUCK TOWING A 6 AXLE DOG TRAILER (B) TRUCK TOWING A CAR CARRIER TRAILER (C) TRUCK TOWING A 2,3,4 OR 5 AXLE DOG TRAILER	(A)	A	≤25	67.5	≤4.6 (4)	4	Network 2
	(B)	A	≤25	42.5	≤4.6 (4)	3	
	(C)	B	≤25	64.0	≤4.6 (4)	4	

Example of Axle Groups

Example of Axle Group with An Optional Axle

Optional Axle

		Axle Spacing Table	Length (m)	Mass (T)	Height (m)	Axle Groups	RAV Network
Category 7 (A) TRUCK TOWING 2 X 5 OR 6 AXLE DOG TRAILERS	(A)	A	>27.5,≤36.5	107.5	≤4.3	6	Network 7
Category 8 (A) TRUCK TOWING 2 DOG TRAILERS	(A)	A	>27.5,≤36.5	107.5	≤4.3	6	Network 8

NOTES

1. Operators using a category of RAV outlined in this document must operate that RAV in accordance with the OPERATING CONDITIONS and only on the network specified.
2. These diagrams are a visual indication of the vehicle only.
3. Operators must refer to the OPERATING CONDITIONS for the full vehicle description.

4. The height of the vehicle can exceed 4.3 m but MUST NOT exceed 4.6 m when it is:
(i) built to carry livestock or; (ii) carrying a crate to carry livestock or; (iii) carrying vehicles on more than one deck or; (iv) carrying a multi modal container or; (v) carrying a large indivisible item or; (vi) When operating with an appropriately licenced over height curtain side or pantechnicon trailer.
5. Maximum height of Pig Trailer only.

Heavy Vehicle Operations
Tel: 138 HVO (138 486)
Email: hvo@mainroads.wa.gov.au
Website: www.mainroads.wa.gov.au

mainroads WESTERN AUSTRALIA

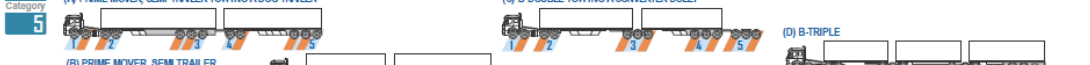*Figure A 2*   *MRWA RAV Prime Mover, Trailer Combinations*

Table A 1   Vehicle combinations and definitions

RAV classification	Reference figure	RAV category	Class	Typical (✓)
Truck, Trailer Combinations	Figure A 1	1	A	
			B	
			C	
			D	
		2	A	
			B	
			C	
		7	A	
		8	A	
Prime Mover, Trailer Combinations	Figure A 2	1	A	
			B	
			C	
			D	
		2	A	
			B	
			C	
			D	
			E	
		3	A	
		4	A	
		5	A	
			B	
			C	
			D	
		6	A	
			B	
			C	
		7	A, B	
		9	A	
			B	
			C, D	
		10	A, B, C	
			D, E	
			F	

A.4   Annual additional freight loading and duration

Nominate (✓) the typical annual additional freight loading (where additional freight loading would represent a specific request from industry to undertake a freight task over and above what is nominally occurring on your network at present) and duration of this task in your shire/region from the choices in Table A 2. Please

provide any relevant additional information.

Annual additional payload (Tonnes per year) 1	Typical (✓)	Duration (Years)	Typical (✓)
100,000		< 2 years	
500,000		2 – 5 years	
1,000,000		5 – 10 years	
2,000,000		> 10 years	
All of the above		All of the above	
Additional information:		Additional information:	

Notes: 1. Determined on the same basis as sealed roads of 0.02, 0.06, 0.1 and 0.2 x 10^6 ESA per annum. For Gross Vehicle Mass (GVM) multiply by 1.5.

A.5   Construction and maintenance costs

Answer the following questions and add any additional information in the box below.

Question	Answer				
A5.1 Identify the unsealed road treatments you commonly apply, and typical cost rates? For definitions, see Section 2.3.4.	Pothole repairs/spot regravelling	Y / N			$/km/yr
	Light grading	Y / N			$/km/cycle
	Heavy grading	Y / N			$/km/cycle
	Regravelling/Resheeting	Y / N			$/km
A5.2 Are the costs for major unsealed road treatments similar across your region? If the answer is No, indicate (✓) the likely difference in costs associated with special factors which affect costs, such as: ▪ Haul distances to obtain suitable wearing course materials ▪ Cost of provision of additional water for compaction ▪ Isolation.	Yes or No. If the answer is Yes, indicate the scale of the additional costs to supply suitable materials and additional water.				
	<20%	20 –50%	50% - 100%	> 100%	
A5.3 On what basis do you undertake unsealed road grading? Typically this is done at regular intervals, but these may vary by road class or Average Annual Daily Traffic (AADT)/traffic use, e.g. see Figure 2.4)	Scheduled by road category	Scheduled by AADT	Scheduled by road category & AADT	Condition responsive (or reactive)	Based on historical deterioration
Other reason/additional information:					

A.6   Road characteristics

Please answer the following questions for your network.

Question	Answer				
A6.1 How would you classify your unsealed network which is likely to be subject to additional loading? If all roads are equally likely, then enter the % network length for each road category.	Road category	Unformed (% by length)	Formed (% by length)		Gravel Roads (% by length)
	Access road				
	Local distributor				
	Regional distributor				

Question	Answer				
A6.2 What deterioration mechanism best represent the performance of your roads? Enter your response with the total equal to 100% per road category.	Road category	Dry weather deterioration (% of year)	Wet weather deterioration/ adequate pavements (% of year)	Wet weather deterioration / weak surfacing (% of year)	Wet weather deterioration/ weak foundation (% of year)
	Access road				
	Local distributor				
	Regional distributor				

A6.3 What proportion of your roads by category fall into single lane operation? This can occur where vehicles straddle the centreline, leading to excessive deterioration and loss of camber.	Road category	Effective single lane operation (% by length)
	Access road	
	Local distributor	
	Regional distributor	

A6.4 What proportion of your engineered gravel roads possess the plasticity characteristics shown opposite?	Road category	Low plasticity relative to climate zone (% by length)	Compliant with desirable specifications (% by length)	High plasticity relative to climate zone (% by length)
	Access road			
	Local distributor			
	Regional distributor			

A6.5 What proportion of your engineered gravel roads possess the particle size characteristics shown opposite?	Road category	Compliant with desirable specification (% by length)	Moderate to high oversize material content (Typically > 15% above 26.5mm and max size 50mm or more) and/or gap graded, with adequate fines (% by length)	Moderate to high oversize material content (Typically > 15% above 26.5mm and max size 50mm or more) and/or gap-graded, with low proportion of fines (% by length)
	Access road			
	Local distributor			
	Regional distributor			

A6.6 What proportion (% by length) of your engineered gravel roads possess initial gravel thicknesses as shown opposite?	Road category	100 mm	150 mm	200mm	250mm	300mm
	Access road					
	Local distributor					
	Regional distributor					

Question	Answer				
A6.7 What proportion (% by length) of your engineered gravel roads fall into the condition categories shown opposite?	Road category	Good (Moderate roughness and good shape)	Fair (Moderate roughness and shape)	Poor (High roughness and adequate shape)	Very poor (High roughness and poor shape)
	Access road				
	Local distributor				
	Regional distributor				
A6.8 To what extent do you apply a formal structural design method in determining the thickness needs for gravel roads?	Always	Never	Significant change in use	Surface upgrading, e.g. earth to gravel	
A6.9 What additional information, not covered above, do you deem relevant?	Additional information:				

A.7   Reference documents

List the documents you regularly consult below.

A.8   Thank you for participating

Question	Answer		
	Yes	No	Maybe
A8.1 Would you be interested in being a member of in the Technical Reference Group (TRG)? Please indicate your preference (✓)			

Appendix B RESULTS FROM QUESTIONNAIRES

B.1 GENERAL

The questionnaire was completed sufficiently comprehensively by 26 out of 28 respondents, with the information providing the required detailed on maintenance practice, material constraints, traffic, treatment costs, etc. The responses were divided as follows:

- Cost zone 2 (GS/WB/MW) – 6 responses
- Cost zone 3 (SW) - 14 responses
- Cost zone 4 (GAS/PB/KIM/GF) – 8 responses

The key conclusions drawn were as follows:

- Only 3 responses on earth roads comprised a significant length of their network. The SP all sample, and the absence of valid earth roads models meant that gravel roads would remain the focus of the study.
- The most common traffic loading scenario was 2 years or less and a task of 100,000 tonnes per annum, although examples of up to 1 million tonnes per annum and longer durations were quoted.
- Both scheduled and condition response maintenance is done regularly.
- Few organisations undertake thickness designs, the exception being where surface upgrading is required.
- The majority of responses indicated low plasticity materials were commonplace, whilst acknowledging that high plasticity materials were important though less so. From prior knowledge and the investigation of models under this study, applying appropriate calibration factors was seen as a means to addressing model deficiencies at this stage.

B.2 Summary responses and choices

A summary of the responses to the questions and their implications, and the recommendations for each is presented in Table B 1.

Table B 1 Summary of responses and implications

Question	Summary	Implications/Recommendation
A.3 Vehicle type(s)	Wide range	Need to consolidate to equivalent LVU and test changes in assumption, i.e. 1 HV = 1, 3 or 5 LVU.
A.4 Annual loading and duration	50% at 100k payload tonnes, and rest spread up to 500k Less than 2 years most common, 5% > 10 years	Test a minimum of 100k and < 500k for 2 years, 2 – 5 years, and 5 – 10 years
A.5.1 Costs - Treatments	Average gravelling cost significantly different by zone with zone 4 up to 2.5 times higher. Routine costs > 10 times higher (per year) in Zone 3, and reasonably close in 2 and 4	Account for regravelling and RM costs by cost zone
A.5.2 Costs – Variation by location	60% up to 50% more expensive	Test 0%, 20% and 50% increase
A.5.3 Costs – Grading frequency	Schedule by road category or reactive most common in zones 2 and 3, zone 4 variable	Apply 1, 3 and 6 per year
A.6.1 Roads – Surface type and loading	Mix of road surface types, with gravel dominant in regional roads in Zone 2	Can we confidently model unformed earth, or earth? No – gravel only (in/out spec).

Question	Summary	Implications/Recommendation
A.6.2 Roads – Deterioration	Significant dry deterioration (50%), and greater in dry areas (70%)	Vary wet season duration, 3 and 6 months or address through climate zone and annual rainfall.
A.6.3 Roads – Single lane	60% of responses suggest effectively 1-lane operation, with some responses stating 100% applies to all roads	Assume all 100% single lane, or as per model basis (two-way ADT)
A.6.4 Roads – Plasticity	Significant % low (> 30%), with more in dry areas (> 40%)	Test for low, compliant, high, but also apply a calibration factor of 1.5 and 2 if low to address increase deterioration rate
A.6.5 Roads– Aggregate grading	Significant level of non-compliance or oversize (> 45%)	Test for compliant, but also apply calibration factor if high to ensure estimates are responsive
A.6.6 Roads – Gravel thickness	Access roads show significant % of minimum thicknesses or no gravel, others close to 150 mm or above	Test with and without immediate treatment
A.6.7 Roads – Condition	Generally reasonable conditions with 80% in good and fair (but some exceptions)	Start with good and fair only, noting no likely effect as maintenance based on gravel loss and a schedule of grading

B.3   Quantitative data

A summary of a selection of responses covering treatment costs (Table B 2), basis for grading (Table B 3) and thickness design (Table B 4) are provided below. The full data is held in project files.

Table B 2   *Average cost of maintenance treatments*

Cost zone	Cost of pothole repairs/spot regravelling ($ per km/year)	Cost of light grading ($ per cycle)	Cost of heavy grading ($ per cycle)	Cost of Regravelling/Resheeting ($ per km)
2	1,105	426	1,886	43,747
3	1,900	1,980	3,644	35,656
4	924	950	3,405	78,133
Overall Average	1,615	1,399	3,339	52,596

Table B 3   *Basis for grading strategy (number of responses)*

Cost zone	Scheduled by road category	Scheduled by AADT	Scheduled by road category & AADT	Condition responsive (or reactive)	Based on historical deterioration
2	3	0	2	5	2
3	5	2	2	7	1
4	1	-	2	2	3
Total	9	2	6	14	6

Table B 4   *Application of formal thickness design (number of responses)*

Cost zone	Always	Never	Significant change in use	Significant change in use, Surface upgrade	Surface upgrades
2	1	1	1	2	1
3	3	3	4	3	-

Cost zone	Always	Never	Significant change in use	Significant change in use, Surface upgrade	Surface upgrades
4	-	5	-	2	1
Total	4	9	5	7	2

Appendix C CALIBRATION AND REVIEW OF GRAVEL LOSS ESTIMATES AND LRDS DATA

C.1 BACKGROUND

In collaboration with LG road agencies, ARRB developed the first national Australian local road deterioration models (Giummarra et al 2007). The models were derived from analysing the findings of a long-term monitoring program covering approximately 500 sealed and 100 unsealed local road sites in various traffic and climatic environments across Australia. For the first time, asset managers were provided with access to a range of evidence-based deterioration models to assist in making decisions about maintenance programs for local roads. Models were also developed for each State, and results provided to each participating road agency.

Whereas the basis for the models was presented to the client agencies in state-specific reports soon after the respective studies were completed, the full details of the national models which drew on all studies was reported at a later stage (Martin et al 2013). Studies of unsealed roads have also been widened and have drawn on studies in Moorabool Shire and Gannawarra Shire Council in Victoria, and Cassowary Coast Regional Council (CCRC) in Queensland and Blayney Shire Council (BSC) in New South Wales (NSW). These have investigated the performance of different surface materials and the effects of maintenance (Dias et al 2014 and Martin et al 2016).

The national models have been chosen for application in this study because of the wide coverage of climatic and other operating conditions, and the range of materials and maintenance regimes examined, a selection of which are illustrated in Table C 1 and Table C 2.

Table C 1   Coverage of a selection of climate by state/territory in the national unsealed LRDS (no. of sections)

State	Climate classification			
	Arid/Semi-arid	Sub-humid	Humid	Per-humid
NSW	8	8	4	-
QLD	9	5	7	1
SA	12	6	2	-
VIC	6	2	9	8
WA	2	6	5	-

Table C 2   Coverage of a selection of grading frequency and climate in the national unsealed LRDS (no. of sections)

Grading frequency (no. of cycles per year)	Climate classification			
	Arid/Semi-arid	Sub-humid	Humid	Per-humid
1 - 2	18	9	9	-
2 - 4	12	12	12	5
> 4	7	6	6	4

Of note is, whereas WA is dominated on a real basis by arid and semi-arid climates, only two of the WA LRDS sections from a total of 13 sections were located in predominantly dry climatic areas, whereas 37 sections were represented in the full national study.

The structure of the LRDS based gravel loss model is shown below (Equation 3), and the coefficients applied in the national model are shown in Table C 3.

$$GL = D \times (F_1 \times ADT + F_2 \times mmp + F_3 \times PF)$$
3

where

GL	=	Gravel loss (mm)
D	=	Days since grading/100
ADT	=	Annual daily traffic
mmp	=	Mean monthly precipitation (mm)
PF	=	"plasticity factor "("PI x p075")
F1, F2, F3	=	Gravel Loss factors.

Table C 3   Model coefficients for gravel loss[1]

Factor	Variable	Coefficient
F1	ADT	-0.00985
F2	mmp	-0.02991
F3	PF	-0.00583

Notes:

In the national model for gravel loss, the selected coefficients were chosen from the New South Wales model. This is understood to be because of the assessed quality of the relationship and data. The data as a whole is shown later (Appendix C.2) to display considerable scatter, not all of which is explained by the model. It is also for this reason that further investigation has been warranted.

Whereas the effect of materials properties (represented by the plasticity factor (PF)) on gravel loss was shown to be statistically significant, the effect of the resulting coefficient is weak. Also, the effect of both PF and rainfall is to increase gravel loss. This contradicts observed performance in low rainfall areas where experience shows that reduced plasticity and low rainfall combines to increase material loss, and to increase the prevalence of corrugations with this aggravated by the net loss of fine materials as airborne dust.

Furthermore, the LRDS models do not incorporate a variable which responds to the different levels of maintenance applied. As illustrated earlier in Section 2.3, the frequency of grading can impact gravel loss particularly in predominantly dry climates, with the possibility that a reduction in the loss of material may occur due to the cushioning effect of loose materials spread across the surface and its re-compaction in wet periods. This can lead to a net reduction in the annual rate of gravel loss.

C.2   Investigations

In order to examine the possible effects of maintenance, materials properties and climatic conditions, the original gravel loss data from the LRDS was reviewed, with the relationship between annual gravel loss (AGL) (normalised to the metric mm per km per year per 100 ADT).

The results are illustrated in Figure C 1, Figure C 2, and Figure C 3. From these, the following observations have been made:

a) The AGL is highest for materials with low PM[5] and PF and is highly variable
b) Figure C 1.
c) The AGL is higher and more variable for low PF and low PM, and at low grading frequencies for semi-arid climates (Figure C 2).
d) Whereas high values may exist in wetter climates, the variability and incidence of extreme values is lower (Figure C 2 (sub-humid) and Figure C 3 (humid and per-humid). This is considered typical of such conditions, where a reduction in the net gravel loss may result after successive periods of operation due to compaction by traffic in the presence of moisture.

Figure C 1   Relationship between annual gravel loss and materials properties for all climatic conditions

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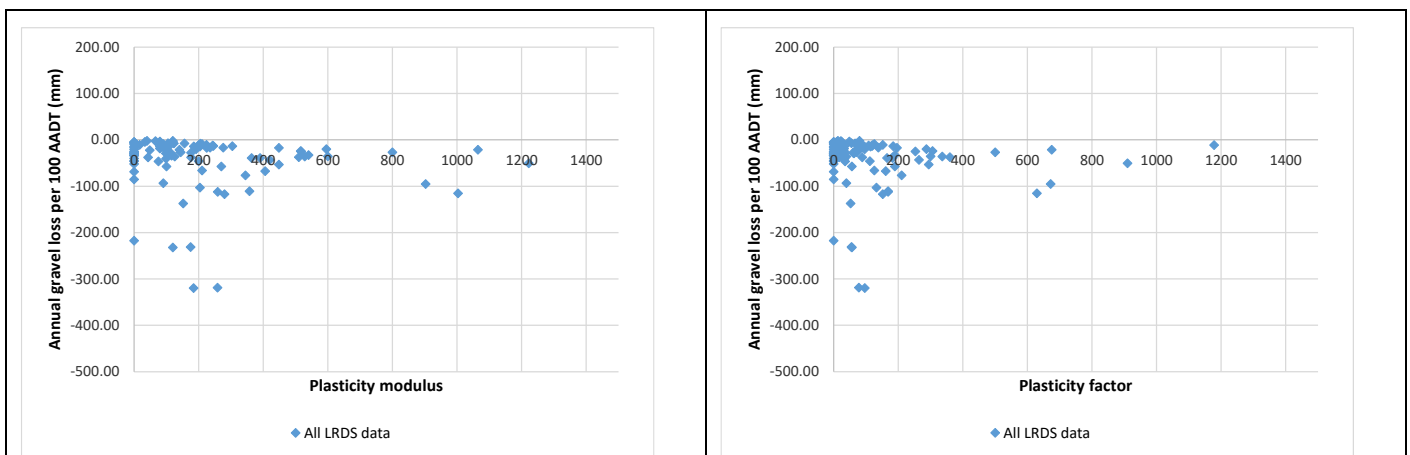
[5] The variable Plasticity Modulus (PM) has been included because it is also used in road deterioration models and specifications. However, the attribute shrinkage product (SP) is also used as an alternative and is approximately half the value of PM based on a two-to-one relationship between linear shrinkage (LS) and plasticity index (PI). Both the PM and SP play a similar role to PF by capturing a measure of the plasticity and quantity of the soil fines.

Figure C 2   Relationship between annual gravel loss, materials properties and grading frequency for semi-arid and sub-humid sections
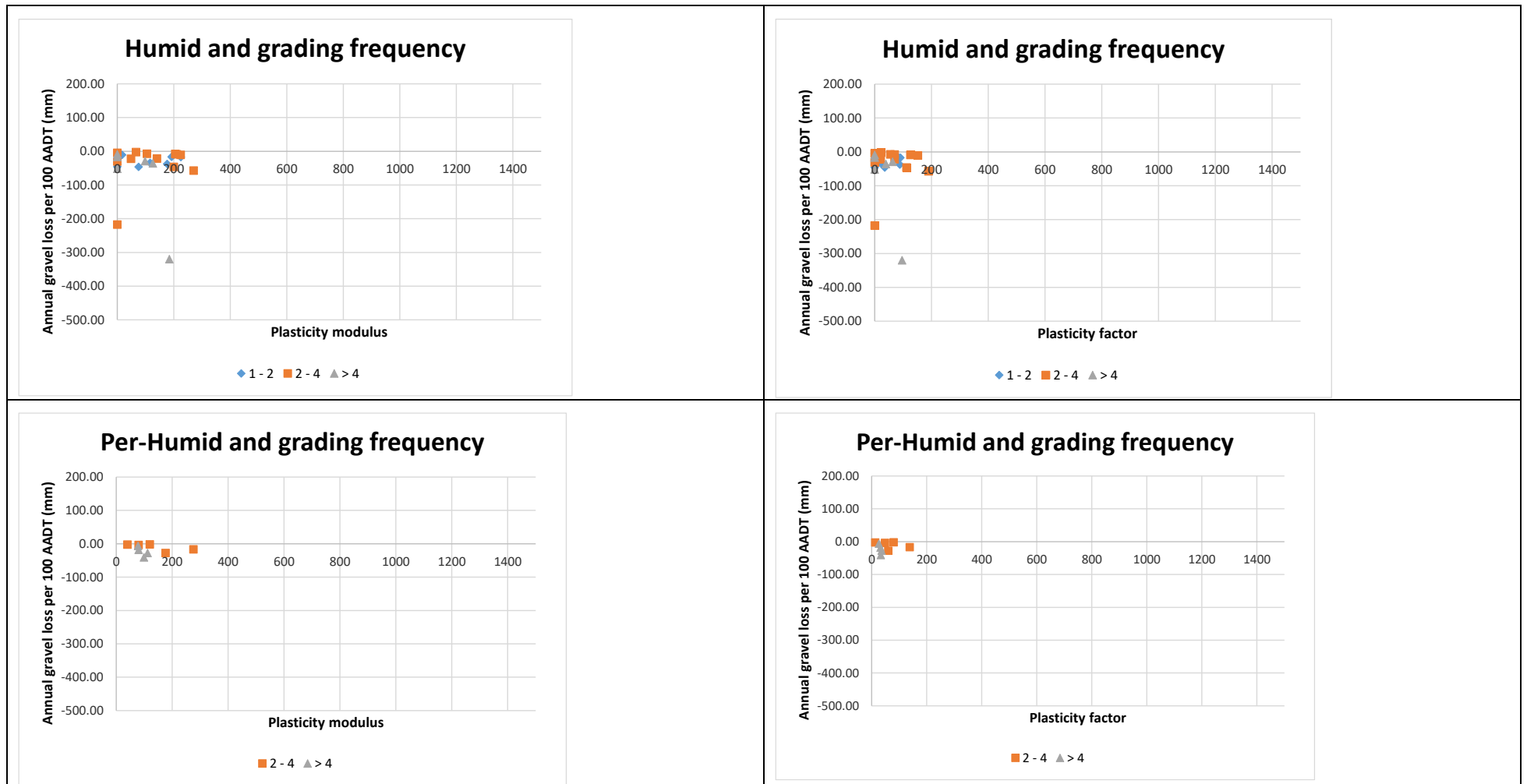
C.3   CALIBRATION

As illustrated above, an increasing PF or PM may not lead to a significant change in the AGL, based on observations using the original LRDS data (as supplied). The rate of AGL, however, appears to be affected by grading frequency, particularly in semi-arid conditions.

To address this, calibration factors, denoted K_{gl}, were determined as the ratio between the actual, or observed, AGL and the model prediction, with a factor greater than unity meaning the model prediction underestimates AGL and a factor below unity meaning the model overestimates the AGL. Depending on the result, the possibility is the multi-linear regression form may not offer the best fit to the observed results for all conditions.

The actual and predicted AGL values for semi-arid conditions are shown in Figure C 4, and the estimated K_{gl} factors are presented in Table C 4. On the basis of these results, a K_{gl} of 3 has been adopted for NCB in semi-arid areas as the basis for this preliminary (Phase 1) analysis. This has been justified because those sites with a higher K_{gl} should also have a higher grading frequency based on the traffic levels they carry, with the estimated optimum frequency based on the relationship by TRL Overseas Centre (1987). Where this occurs consistently in practice it is also possible that grading frequency will not be identified as a separate variable, being also a function of traffic. However, in this example, the highest K_{gl} (of 11.9) is associated with a low grading frequency, the likelihood being that this has affected the results.

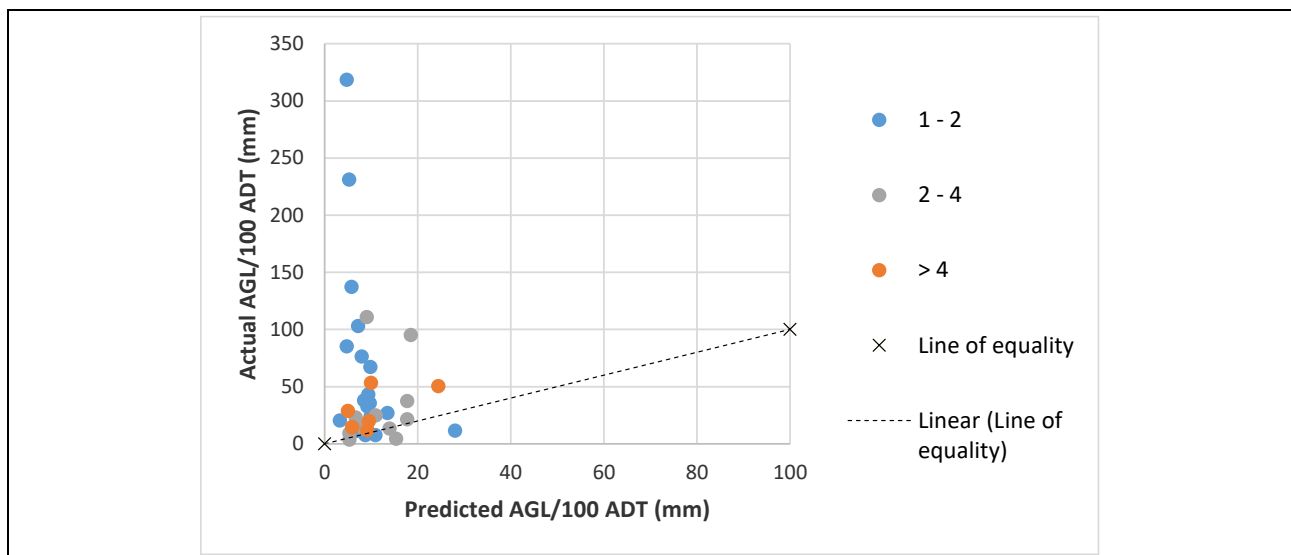*Figure C 4   Comparison of actual and predicted AGL values for semi-arid sections*

Table C 4   Estimated calibration factors for annual gravel loss for semi-arid climates

| Actual grading frequency (no./yr)	Optimum average frequency for the selected sites (no./yr)	Average K_{gl} for the selected sites
1 - 2	2.6	11.9
2 - 4	3.8	2.8
> 4	3.1	3.1

Source: This study

Appendix D   RESULTS OF REGRESSION ANALYSIS

The regression coefficients for the adopted model are presented in Table D 1, with the model producing a good fit (r^2 approximately 0.8, and a residual standard error of 1.3 to 5 cents per loading unit. A visual check for these regression equations show that they are a good fit for the data (Figure D 1).

Table D 1   Regression model coefficients

Compliancy	RemoteCost	CostZone	Intercept	Gradient
NCB	no	2	36.2	-3.996162
SB	no	2	34	-3.996162
C	no	2	31.8	-3.996162
SA	no	2	31.8	-3.996162
NCA	no	2	31.8	-3.996162
NCB	yes	2	54.2	-5.994243
SB	yes	2	51	-5.994243
C	yes	2	47.8	-5.994243
SA	yes	2	47.8	-5.994243
NCA	yes	2	47.8	-5.994243
NCB	no	3	72.2	-9.720768
SB	no	3	71.4	-9.720768
C	no	3	70.5	-9.720768
SA	no	3	70.5	-9.720768
NCA	no	3	70.5	-9.720768
NCB	yes	3	108.4	-14.581151
SB	yes	3	107	-14.581151
C	yes	3	105.7	-14.581152
SA	yes	3	105.7	-14.581152
NCA	yes	3	105.7	-14.581151
NCB	no	4	74.9	-7.527373
SB	no	4	67.3	-7.527373
C	no	4	59.6	-7.527373
SA	no	4	59.6	-7.527373
NCA	no	4	59.6	-7.527373
NCB	yes	4	112.4	-11.291059
SB	yes	4	100.9	-11.291059
C	yes	4	89.3	-11.291059
SA	yes	4	89.3	-11.291059
NCA	yes	4	89.3	-11.291059

Marginal cost by cost zone and compliancy

Appendix E   CHARTS FOR USER GUIDE
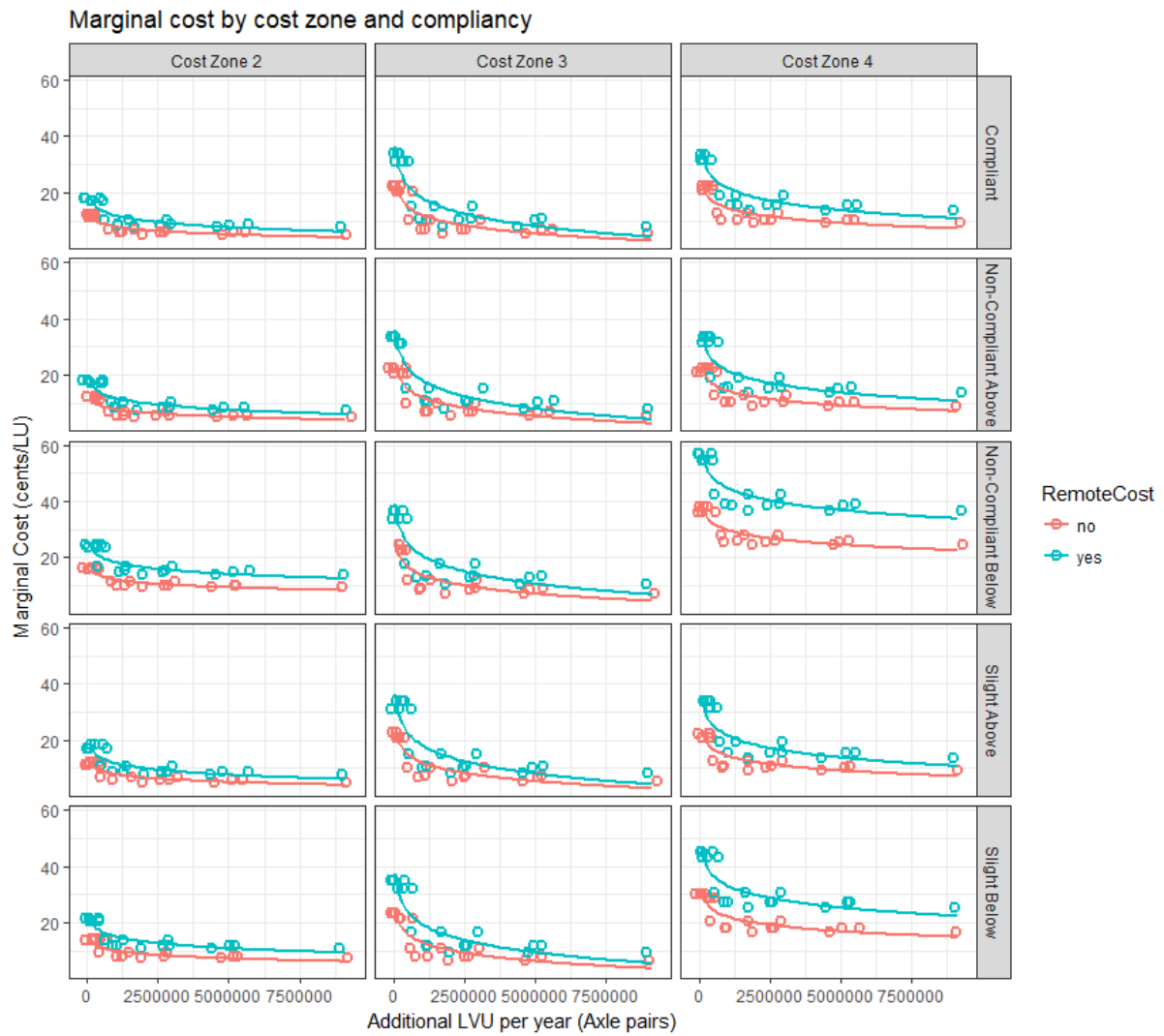
E.1   GENERAL

Example charts for the unsealed road user guide are presented below.

E.2   HISTOGRAMS

The following figures present pre-calculated solutions as histograms.

Figure E 1   Marginal cost per additional loading unit (cents per km) for Zone 2 and 5,000 LU per annum
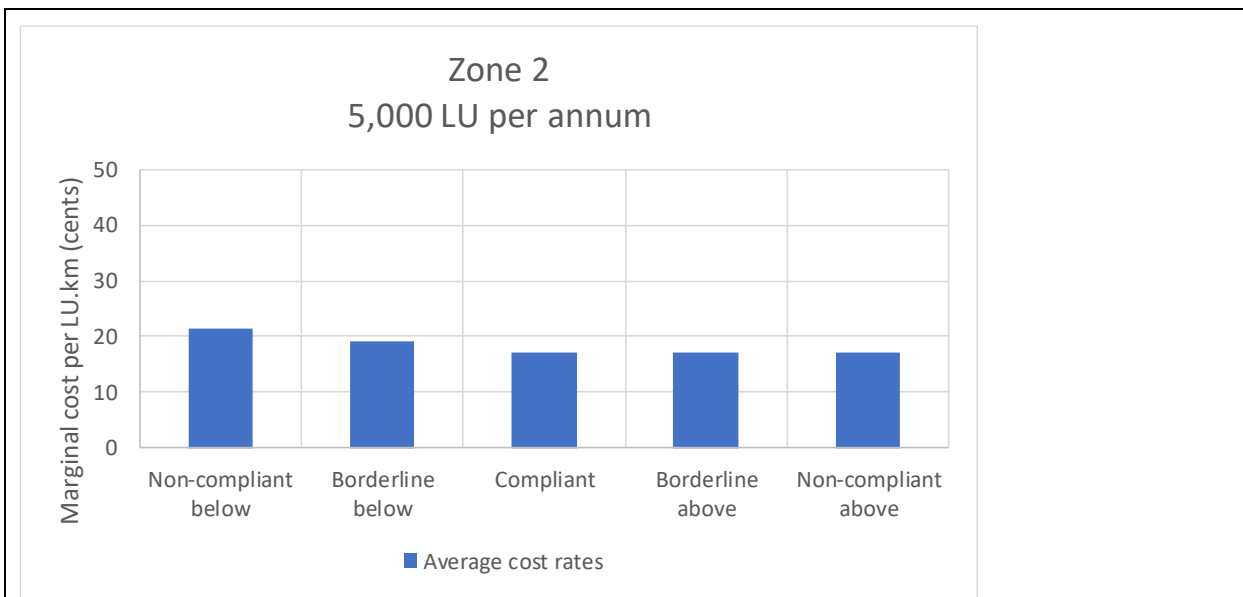
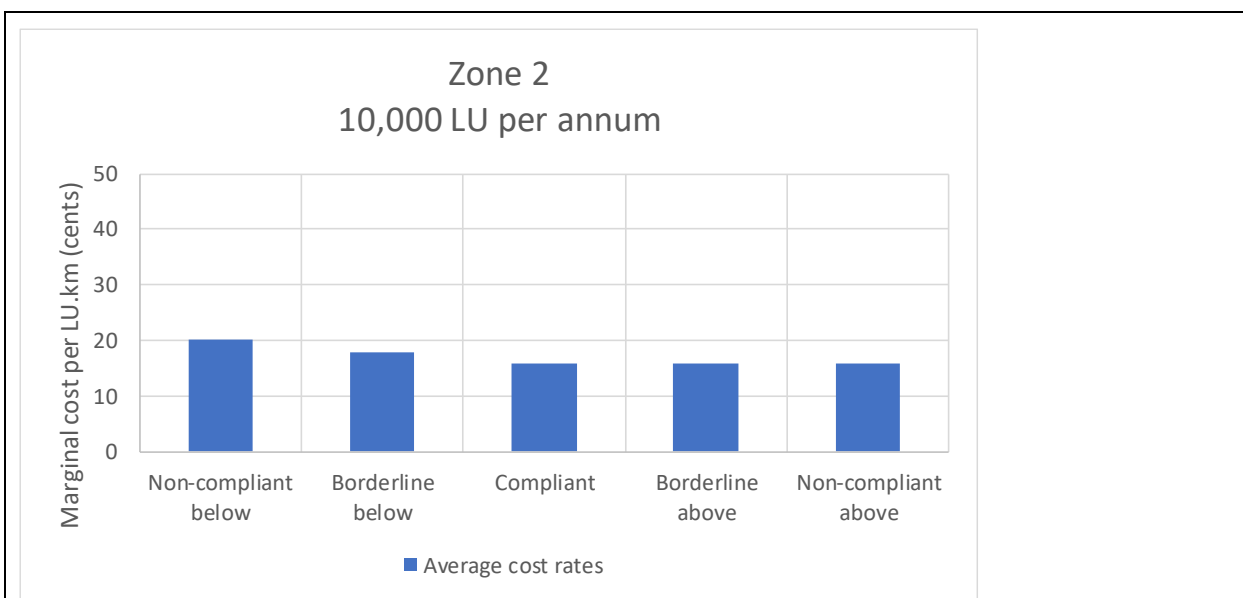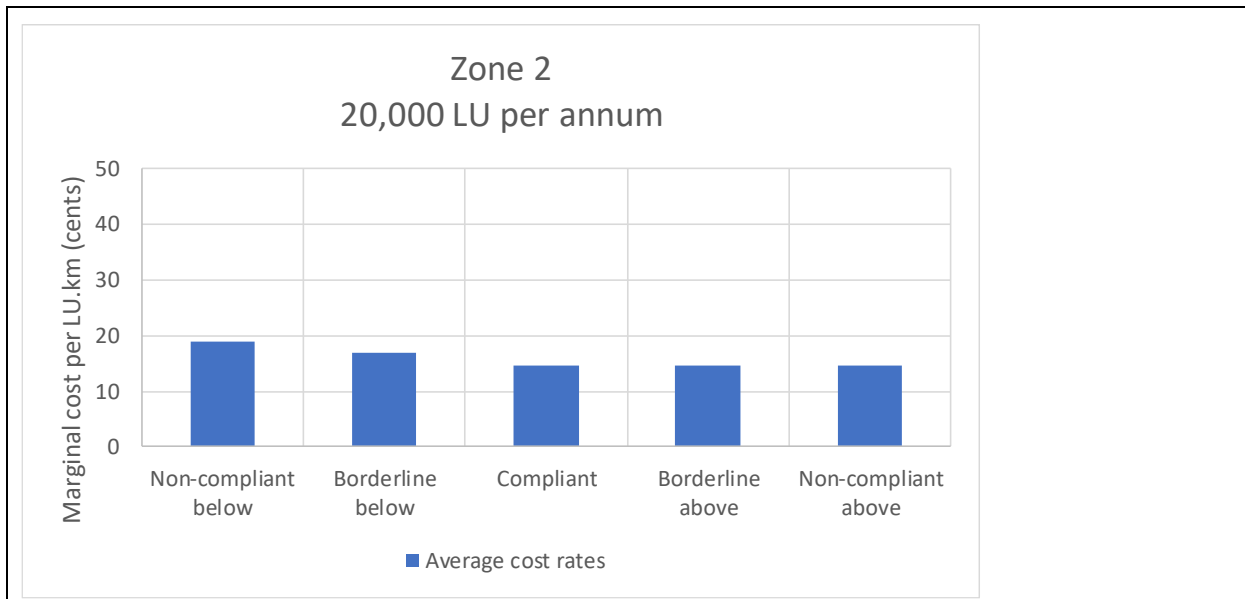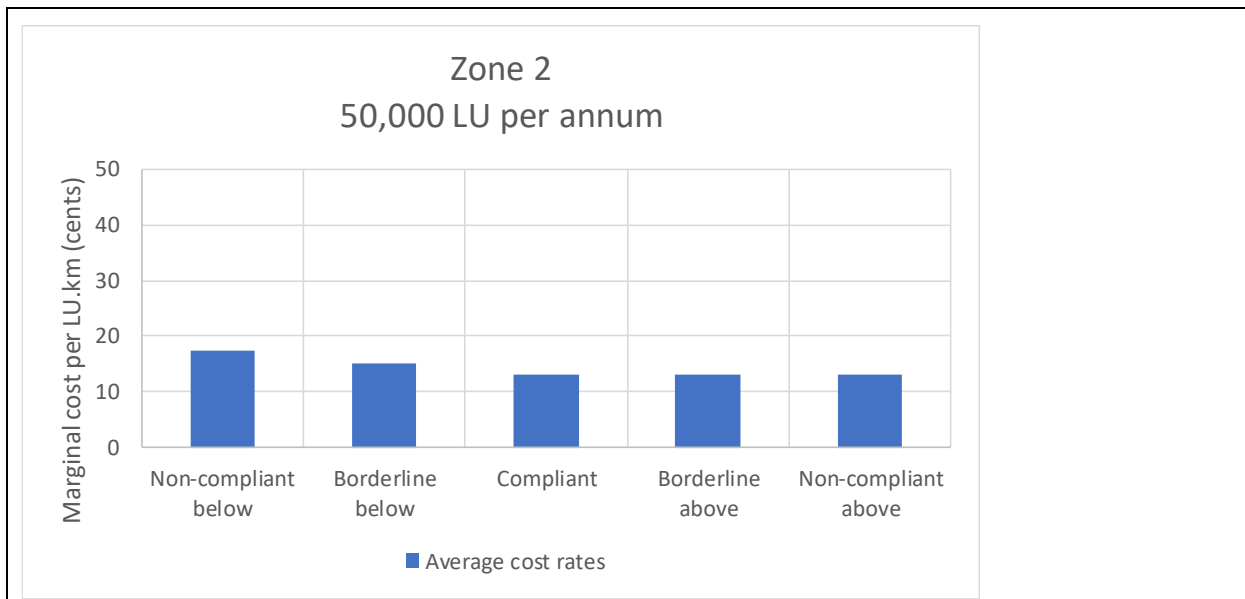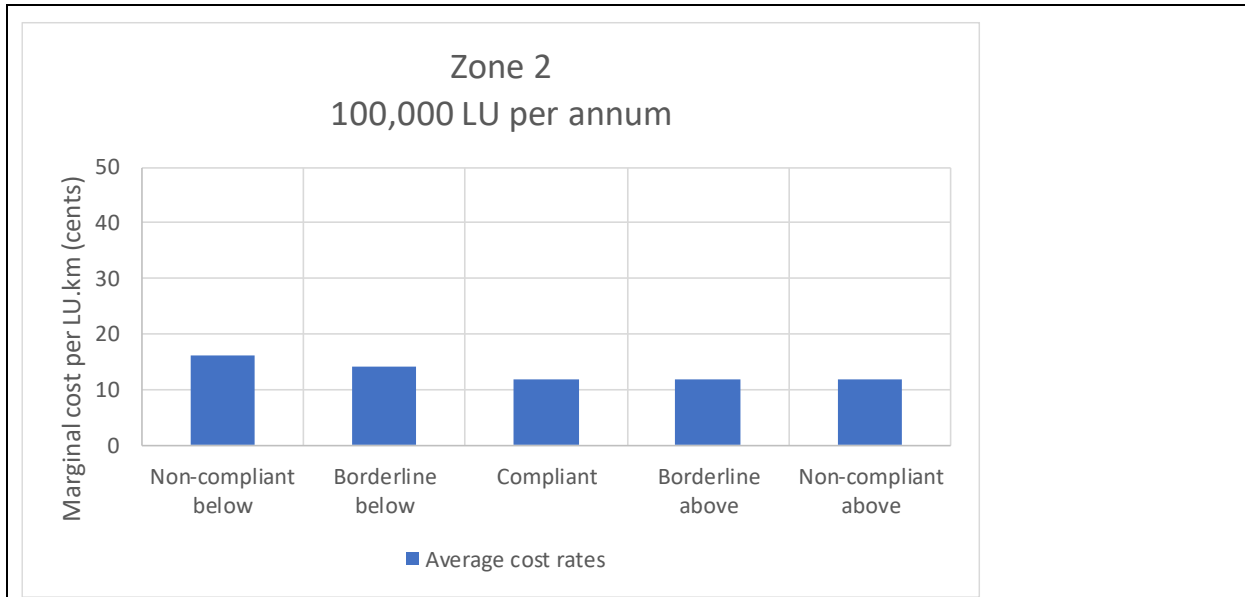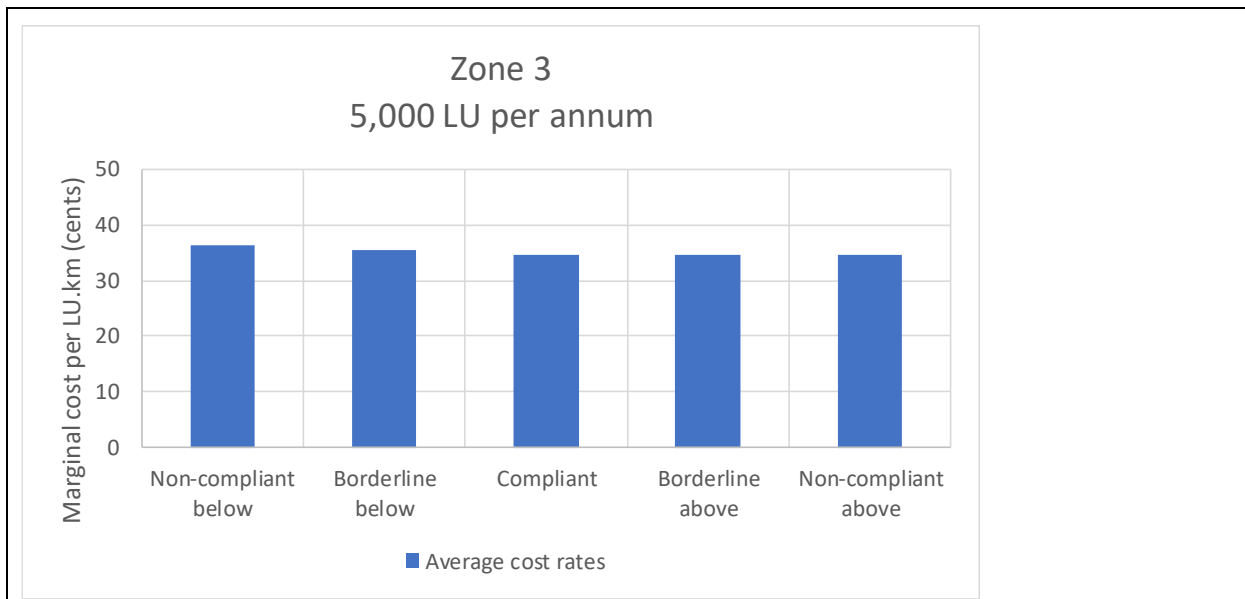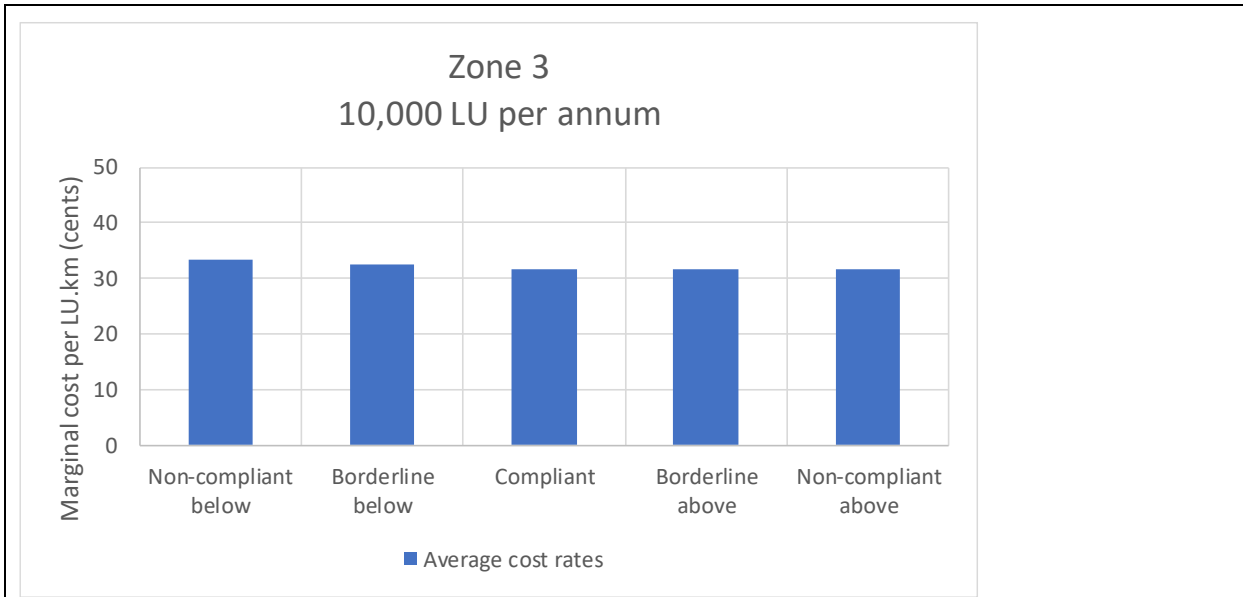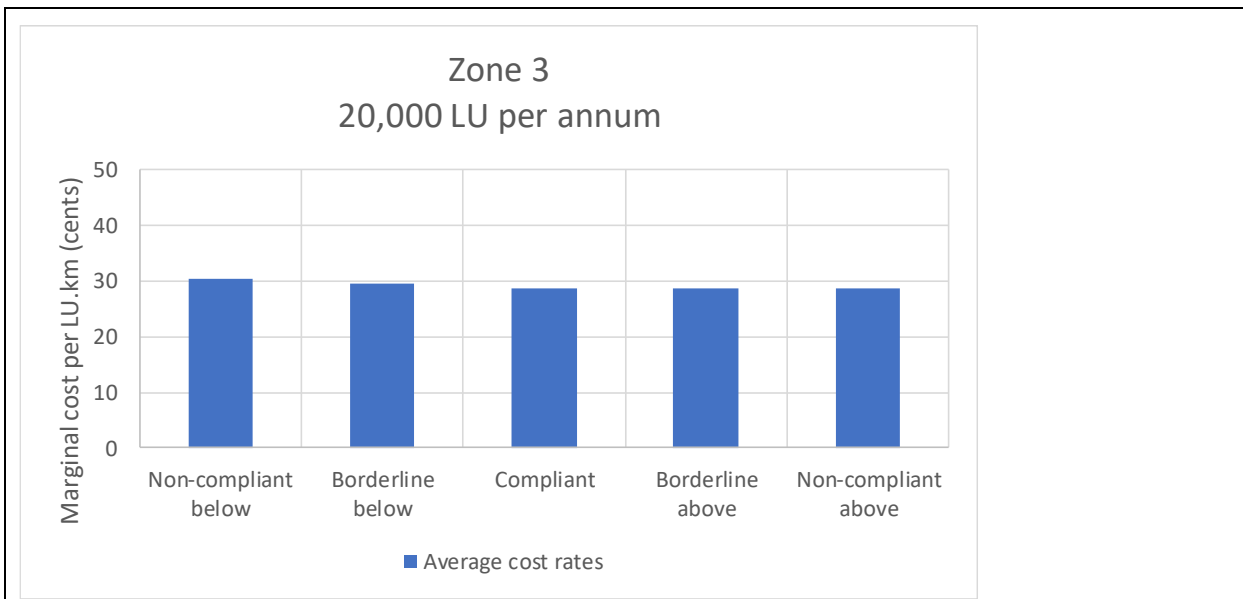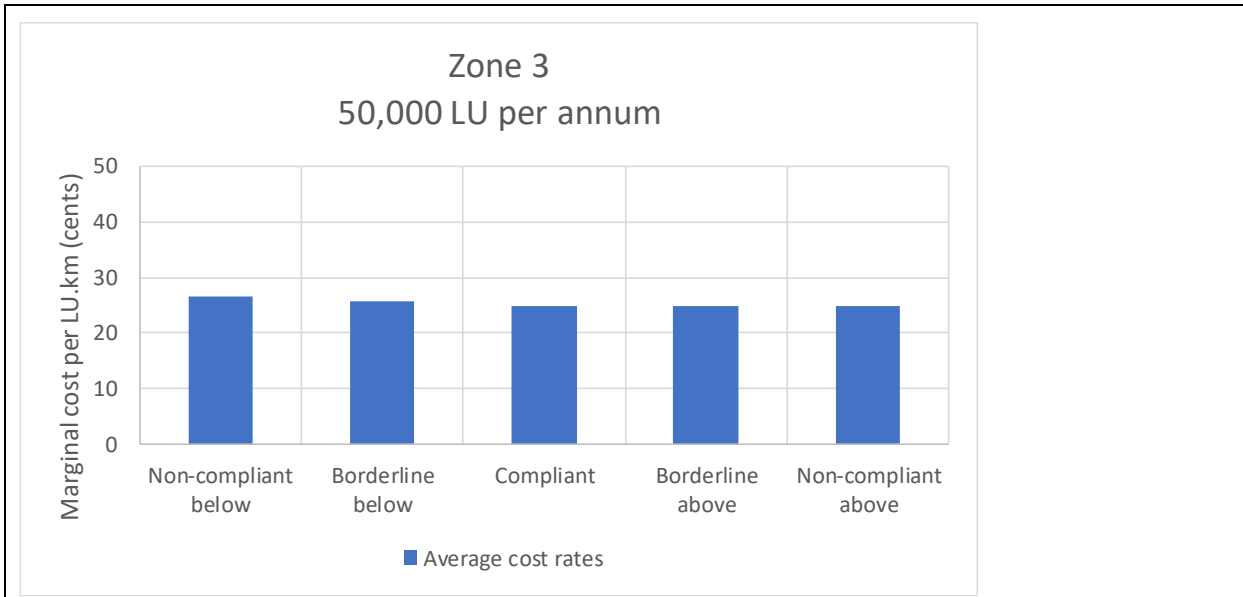*Figure E 2   Marginal cost per additional loading unit (cents per km) for Zone 2 and 10,000 LU per annum*

Zone 2
20,000 LU per annum

Zone 2
50,000 LU per annum

Figure E 7   Marginal cost per additional loading unit (cents per km) for Zone 3 and 10,000 LU per annum

Figure E 8   Marginal cost per additional loading unit (cents per km) for Zone 3 and 20,000 LU per annum
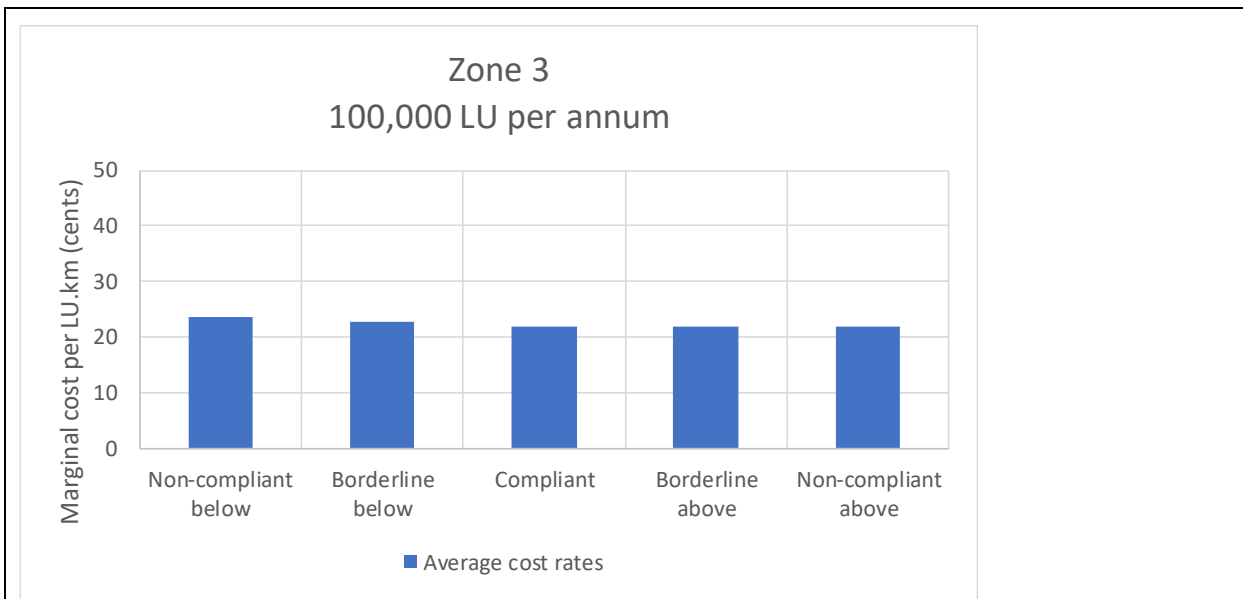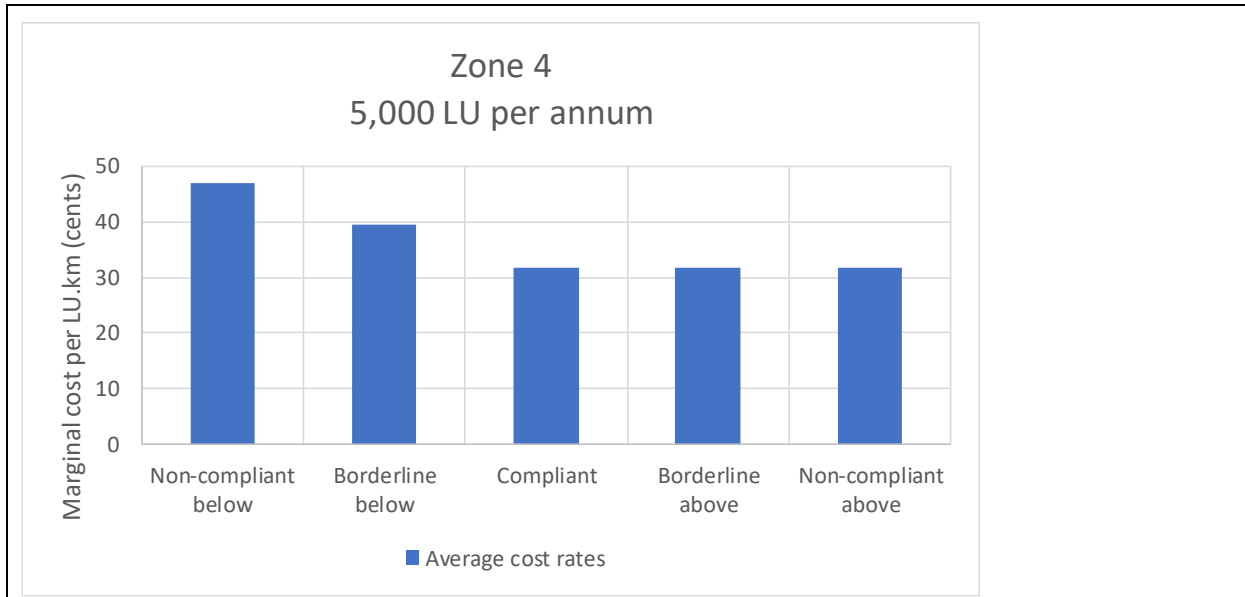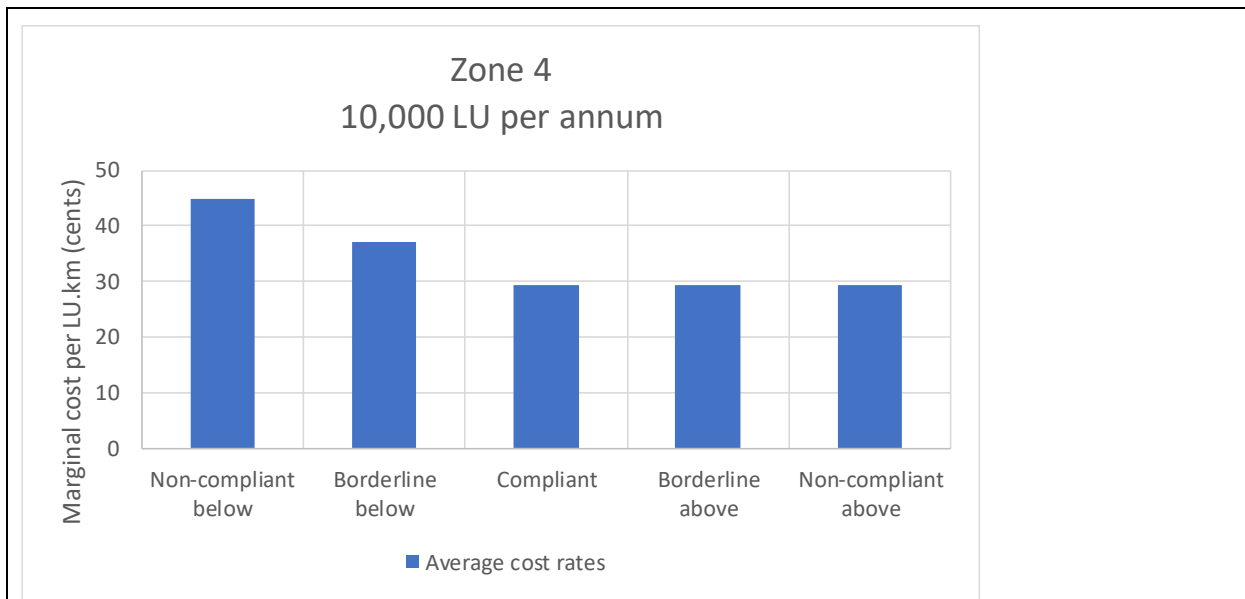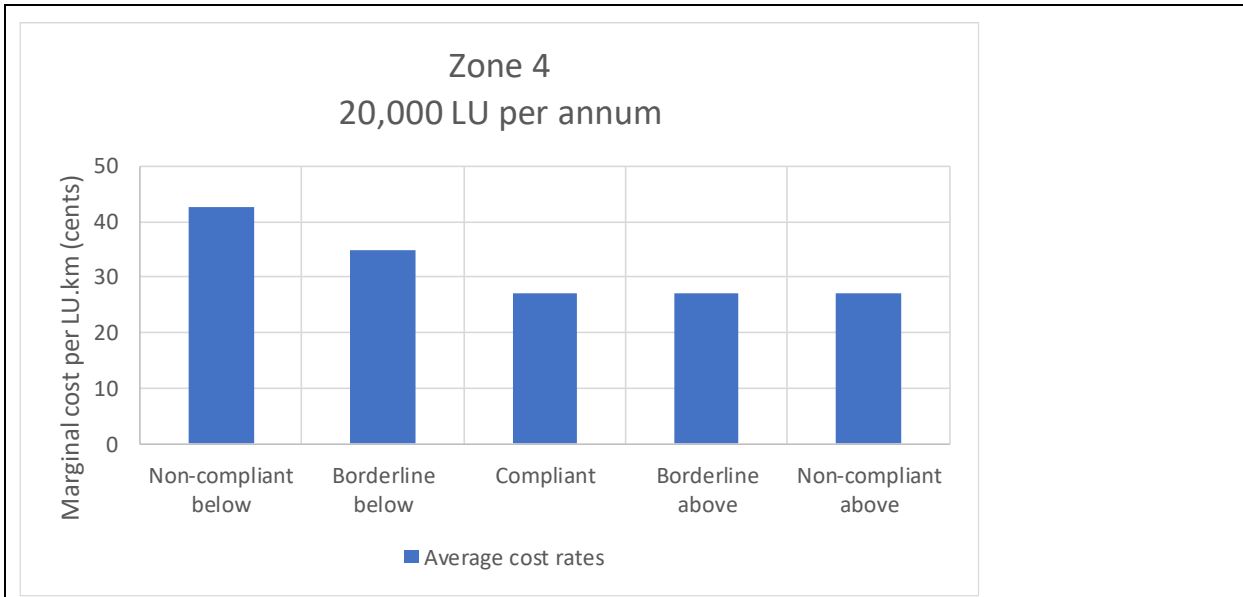
Figure E 9   *Marginal cost per additional loading unit (cents per km) for Zone 3 and 50,000 LU per annum*
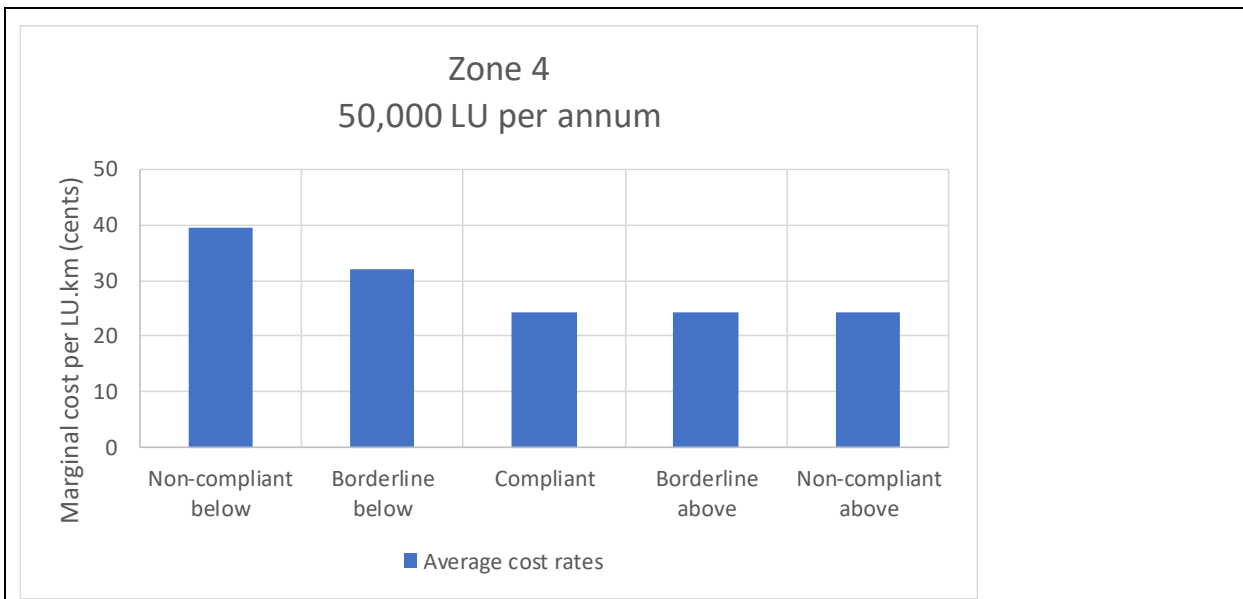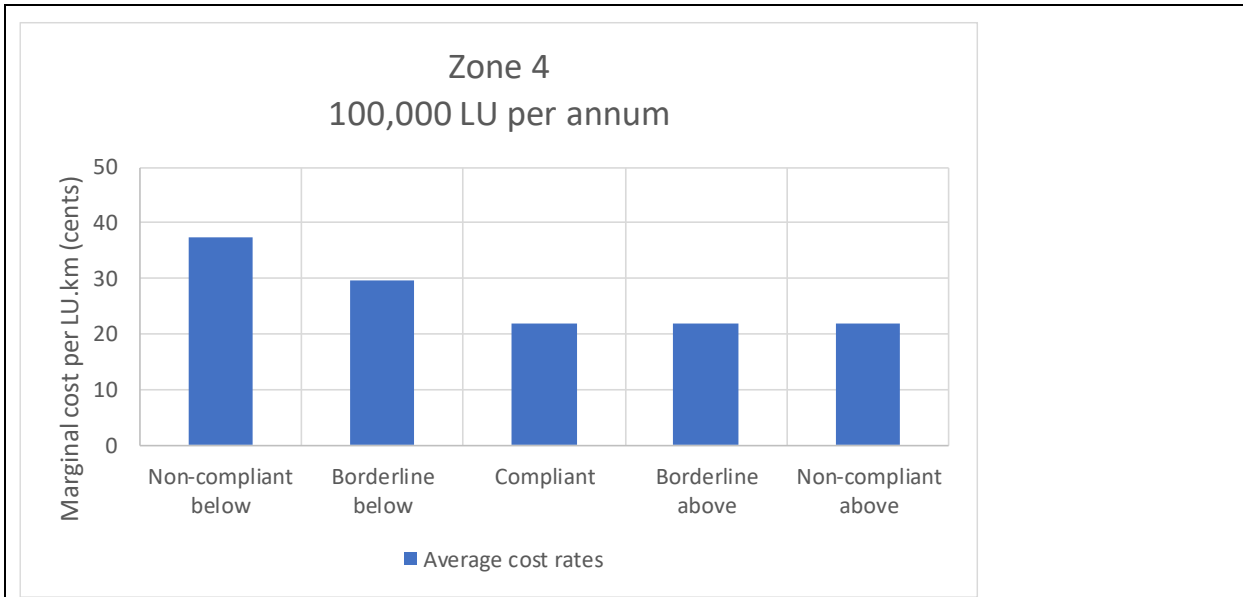

Figure E 10   *Marginal cost per additional loading unit (cents per km) for Zone 3 and 100,000 LU per annum*

E.3   Line graphs

The following figures present pre-calculated solutions as line graphs.

Appendix F TEXT FOR USER GUIDE

F.1 CONTENTS

F.2 MAIN TEXT

F.2.1 Introduction

Western Australian Local Governments face significant costs from road wear as a consequence of unforeseen heavy vehicle traffic triggered by projects, typically in the resources industry. The impacts of additional heavy vehicle traffic on shortening road life and increasing maintenance requirements are greater for roads that were not designed and constructed for this purpose, which is the case for most Local Government roads.

This guide provides Local Governments with a tool to quantify the cost of additional wear and damage to affected roads for a defined freight task on unsealed roads. It can be used as the basis for negotiation of cost recovery from industry, to ensure that the local community does not bear the costs imposed by private businesses, and to adjust long term financial plans.

Methods previously used to estimate the cost impact often required detailed input data, specialised engineering evaluation and modelling skills which are not readily available to Local Government. This user guide presents a method for estimating the cost of road wear using simple input parameters. The technical basis is provided in a separate report, 'Estimating the Cost of Road Wear on Unsealed Local Government Roads in Western Australia' (Toole & Hore-Lacy 2018).

Users of this guide will require a basic understanding of the Western Australian road classification system and will be assisted to select appropriate parameters based on the situation and freight task. The guide is designed to be applied to unsealed roads only. Estimating the cost of additional heavy vehicle traffic on sealed roads is covered by a separate guide (WALGA & ARRB 2015).

F.2.2 Development background

The guide has been developed around the concept of a marginal cost of road wear. The marginal cost of road wear in this context for unsealed roads, is defined as the difference in cost of maintaining a road in a serviceable condition, between an increased level of traffic and a base traffic level. Analysis has shown that the marginal cost is mostly dependent on the surfacing materials properties, climate or cost zone and the

magnitude and duration of the additional load, and the cost of road maintenance activities. Within a zone higher costs may also apply, termed a premium cost.

Using these critical variables, a catalogue of charts has been developed to represent the spectrum of scenarios that are likely to be encountered on Local Government roads across the state. The marginal cost for each scenario was modelled by using a custom-built spreadsheet tool developed by ARRB and incorporating an analysis framework and models based on Australian conditions. The model undertakes a LCC analysis of the road based on deterioration curves that were developed by monitoring numerous different types of roads over many years. As the defined road deteriorates under specific loading conditions, the model triggers maintenance interventions that are required to keep the road serviceable. The marginal costs are then derived by accounting for the difference in costs incurred between the additional load and the normal load.

The scenarios are presented by graphs showing the marginal cost based on the cost zone, the additional loading units per annum and materials compliance. The user needs therefore to define their scenario in these terms and select and interpret the applicable graph. Detailed information on how to use the guide is provided below.

F.2.3   What are the limitations of the guide?

Practitioners need to be aware that the marginal costs presented in the guide have been developed by modelling a synthetic road network designed to represent the majority of scenarios likely to be encountered in Western Australia. There are a multitude of variables that will influence the cost of road wear and the calculated values are only an estimate of the actual cost. Users need to be aware that their scenario may include factors that render the estimate inaccurate.

Some of the limitations are listed below:

1. The marginal cost graphs are based on a synthetic network and the user should select the scenario that best fits their circumstances. There may be aspects at a project level that require a review of the calculated cost. Possible examples are:

    a) The existing road is unable to carry the additional traffic, and therefore needs an initial treatment, the choice and cost of which is outside the scope of this manual.
    b) Sections of the road are subject to unusual conditions, e.g. flooding or very weak subgrades.

2. The method does not calculate the costs for associated infrastructure, e.g. bridges, culverts and guardrails.
3. The actual loading values and durations may lie between or outside of the given values. The user will need to interpolate or extrapolate accordingly. The guide may not be valid for scenarios that lie well beyond the modelled limits.
4. The guide has been developed for unsealed local roads only with heavy vehicles consistent with typical configurations and loading schemes relevant to public roads, e.g. the RML and AMMS as operated in Western Australia. It assumes the road is passable and represents an engineered or partly engineered gravel road and does not cater for unformed or formed earth roads. A separate guide applies to sealed roads.
5. The unit rates are current for 2017. Escalation factors should be applied to the marginal costs for future years.

F.3   HOW TO USE THE GUIDE

The guide is structured around a simple stepped process, and details for completing each step.

This is followed by a series of typical worked examples.

F.3.1   What information is required?

The user will need the following information:

1. The type of vehicles to be used for the task
2. The annual freight tonnage for the task
3. The duration of the task
4. The task routing and distance
5. Further detail on the quality of road surfacing materials on the route, and the availability of materials for regravelling purposes.

The following sections outline the sequential steps to determine a marginal cost for a particular additional loading task.

STEP 1: Determine the vehicle type undertaking the task

The first step is to determine the type of vehicle or vehicles that will be used to undertake the task. The vehicle type will typically be supplied by the freight operator. The vehicle type must then be converted to a MRWA RAV designation. The user must select the appropriate RAV designation from Appendix A of the User Guide as per Table 5.2, Figure A 1 and Figure A 2 of this report.

STEP 2: Determine the annual freight loading, distance and duration

To determine the annual freight loading, a good appreciation of the total freight task needs to be gained.

This will usually involve discussions with the freight operator to determine the duration of the additional loading and the total loading to be applied. Typically, such requests are well structured, with the proponent possibly having a lease on a mine or similar to extract a certain amount of product over a defined period of time.

An example of a typical total load and duration is shown below:

*   Iron ore extraction – 600,000 tonnes over 3 years.

In this case, the annual tonnage is determined by dividing the total freight tonnage by the duration:

*   600,000/3 = 200,000 tonnes per year.

The distance is defined as the road distance (in both directions) to be traversed by the vehicles undertaking the task.

STEP 3: Determine the allowable payload per trip for the selected vehicle

This information should be supplied by the operator. A cross-check can be obtained by comparing the value(s) with those in Table 5.2.

STEP 4: Calculate the number of one-way trips required to complete the annual freight task

This is calculated as:

No. of trips = Annual task (from STEP 2)/allowable payload per trip (STEP 3).

STEP 5: Calculate the number of Additional Loading Units

The road wear caused by the movement of a quantity of freight will differ depending on the types of heavy vehicles that are used for the task. That is why the load equivalencies of all heavy vehicles need to be expressed in a common measure that is related to the amount of road wear.

The road wear caused by the passage of a heavy vehicle is proportional to the number and type of axle groupings (e.g. single, double or tri-axle) and the load carried by each of the axle groups. The allowable load on an axle group is strictly controlled in Western Australia and is termed the Regulation Mass Limit (RML). Some vehicles may operate under the Accredited Mass Management Scheme (AMMS) which allows for up to an additional 3.5 tonnes per tri-axle combination and 1.0 tonne per tandem axle combination. The damage

caused per payload tonne will therefore differ depending on the type of vehicle that is used and the loading scheme that is applied.

For consistency, all heavy vehicles are therefore converted to a common standard termed 'Loading Units' (LU), represented as pairs of axles. This approach does not distinguish between loading schemes, nor does it employ the sealed road concept of pavement damage factors.

A full list of RAV descriptions is given in Table 5.2, Figure A 1 and Figure A 2.

STEP 6: Determine the Materials Compliance

This involves classifying the materials available in accordance with Table F 1. For this, basic materials test properties are required including the Shrinkage Product (SP) and the Grading Coefficient (GC). The aim should be to provide compliant materials, particularly with respect to Shrinkage Product and to ensure the material is sufficiently well graded to provide adequate mechanical interlock under all conditions and resistance to rutting in the wet with this assessed in terms of Grading Coefficient. Where possible the selected material should possess a SP and GC represented by the 'Good' zone in Figure F 1. However, materials with higher SP are likely to be suitable except under wet conditions.

Table F 1   Indicative compliance level and performance of unsealed road granular surfacing materials in predominantly dry climatic conditions
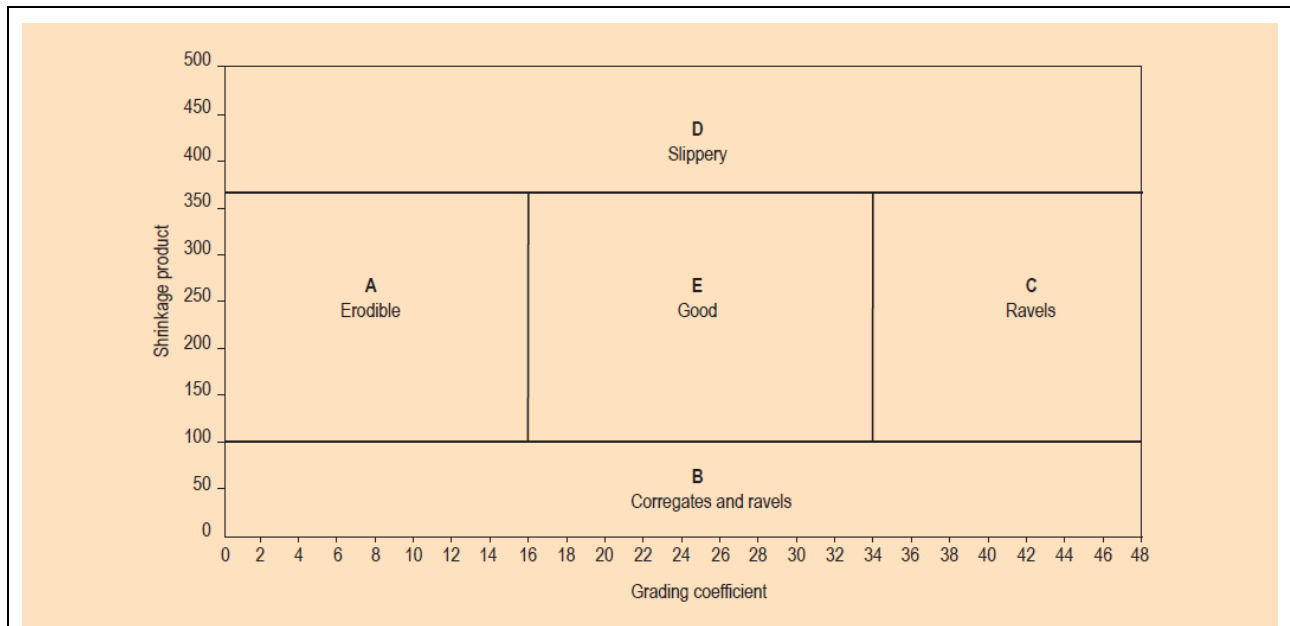
Indicative compliance level	Materials and performance attributes
Non-compliant below	High rate of material loss (> 20 – 40 mm per year per 100 AADT) with the surface ravelling and corrugations under traffic. Shrinkage Product (SP) below 100, whereas the Grading Coefficient (GC) may vary widely. Uniformly graded fine materials with a low GC display low resistance to erosion and coarsely graded higher GC materials tend to ravel badly and are generally unsuitable.
Borderline below	Moderate rate of material loss (10 – 20 mm per year per 100 AADT), with the surface tending to loosen and corrugate under the action of traffic but may remain tolerable to heavy traffic at low to moderate speeds. SP below 200, whereas GC may vary widely. Performance can improve with regular grading/cushioning operations.
Compliant	Low rate of material loss, typically less than 5 – 10 mm per year per 100 AADT, with a well-knit surface resulting from a mechanically stable particle size distribution with few weak particles and containing a sufficient quantity of plastic fines. Ideal materials typically have a SP greater than 200 with an upper limit of 600 depending on the proportion of heavy traffic and tolerance of dust and a GC of between 20 and 30. Arm-chair type (or gap) gradings are acceptable with concretionary materials, such as calcretes and laterites.
Borderline above	Moderate rate of material loss (10 – 20 mm per year per 100 AADT), with the surface tending to rut and become slippery in the wet but may remain tolerable to heavy traffic under wet conditions. SP above 600, whereas GC may vary widely. Performance can improve with regular grading/cushioning operations.
Non-compliant above	Moderate to high rate of material loss (> 20 mm per year per 100 AADT) with a risk of severe rutting and slipperiness in the wet. SP above 700, whereas GC may vary widely. Uniformly graded fine materials with lower GC display low resistance to erosion and are generally unsuitable, whereas high GC materials tend to be ravel badly leading to extensive potholes.

Notes:

3 The range of SP used, particularly the lower and upper limits to 'good' performance are based on observations from the Local Roads Deterioration Study (see Appendix C.2 drawing and Figure 2.6), but these should be adjusted based on local experience with reference to the actual rates of material loss and performance characteristics.

Source: Toole & Hore-Lacy (2018).

Notes:

1. Shrinkage product = linear shrinkage x %passing the 0.425 mm sieve
2. Grading coefficient = (%passing the 26,5 mm sieve - % passing the 2mm sieve) x per cent passing the 4.75 mm sieve/100
3. Reference should be made to Figure F 1 and accompanying notes when interpreting the above chart.

Source: Jones and Paige-Green 1996

STEP 7: Select the applicable MC per one-way trip

This should be selected considering the following (in order):

- Cost zone, with this selected based on Figure 3.3
- Additional loading (from Step 5)
- Materials compliance (from Step 6)

The specific marginal cost graph should then be chosen from the examples in Appendix E.2 which include 15 charts representing three cost zones and five loading scenarios.

Users must select the chart or charts that are relevant to the scenario that is being assessed.

The charts are structured in order of cost zone, then by the modelled loading scenarios. Table F 2 facilitates easy access to the generated charts with a series of links to each of the relevant figures. The user must select the loading scenario that is closest to their actual scenario.

Table F 2   List of marginal cost charts (histogram format)

Cost Zone	Additional LU/per (two-way)	Chart
2	5,000	Figure E 1
	10.000	Figure E 2
	20,000	Figure E 3
	50,000	Figure E 4
	100,000	Figure E 5
3	5,000	Figure E 6
	10.000	Figure E 7
	20,000	Figure E 8
	50,000	Figure E 9
	100,000	Figure E 10
4	5,000	Figure E 11
	10.000	Figure E 12
	20,000	Figure E 13
	50,000	Figure E 14
	100,000	Figure E 15

It is likely that the estimated additional loading calculated in Step 5 will not match one of the five loading scenarios presented in this guide. The user must select the (next highest) loading scenario that is closest to their calculated value. For instance, a calculated value of 15,000 LU/year would result in the selection of a loading scenario of 20,000 LU/year from Table F 2 as this is the closest matching available scenario.

STEP 8: Calculate the applicable actual marginal cost

Using the chart selected in STEP 7, the marginal cost of the additional loading can be determined considering:

- The quality of road surface materials (termed compliance)
- The actual cost of materials supply, where for general application, the MC determined in STEP 7 should be adjusted by applying a simple equation (see below) by using the actual cost of supply for each case. For all examples tested in the development of this guide, the marginal cost was found to be directly proportional to the cost increase (or decrease) relative to the average cost rate per zone.

$$AMC = MC \times a/b \qquad\qquad A1$$

where

AMC = Actual Marginal Cost for specific case study

MC = Marginal Cost based on average (supply) cost rates (cents/LU)

a = Actual cost of supply ($/km)

b = Average cost rate per Cost Zone ($/km) (see Table F 3)

Table F 3   *Unit cost rate used in the development of the user guide*

Cost Zone	Average cost rate per Cost Zone ($/km 2017)
2	43,747
3	35,656
4	78,133

STEP 9: Calculate an annual cost

The annual total cost is calculated using the annual marginal cost. The relevant equations are as follows:

- Annual Cost = Actual Marginal Cost x LU per year x Distance

Where,

- Average Marginal Cost in cents/ ESA.km is determined from Step 8
- LU per year is the actual LU per year from Step 5.
- Distance is the road distance in kilometres (round trip).

This can be converted back to a cost per payload tonne as follows:

Cost per payload tonne = Annual Cost / (Annual Tonnage x Distance)

The calculated costs are only valid for 2017 as ongoing years will need to have an escalation factor applied to accommodate for the increases in costs. Relevant factors will need to be obtained by users of the guide from appropriate sources to suit their particular study.

F.3.2   EXAMPLE CALCULATIONS (Based on Worked Example #4 from sealed road user guide)

A new mining company has decided to open up a mine site in the Gascoyne region. In this case however they are constrained by the number of vehicles they have at their disposal and have calculated that within a year they can deliver 5,000 trips to the site while using only prime movers with a semi-trailer towing two six axle dog trailers. The company is operating their vehicles under the Accredited Mass Management Scheme Level 3.

The life of the mine is forecast as 6 years. The company would like access to a 30 km long regional distributor that is managed by the Local Government.

The available materials possess a Shrinkage Product of approximately 250 and a Grading Coefficient of approximately 20, are available at a cost of approximately $48,000 (2018 prices) or roughly 10% higher than average cost rates.

Task:

Calculate the annual cost (first year only) of road wear resulting from this additional freight task.

Solution:

1.   Determine the vehicle type undertaking the task:

Refer to Appendix A for an outline of all defined vehicles in WA.

A prime mover and semi-trailer towing two six axle dog trailers is a RAV 10(A).

2.   Determine the annual freight loading, distance and duration:

As outlined above, the annual freight loading is unknown but the number of trips with a RAV 10(A) is estimated to be 5,000 per year.

- The distance is 30 km.
- The duration is 6 years.

3.   Determine the allowable payload per trip for the selected vehicle:

Go to Table 5.2 and select the allowable pay load, which for RAV 10(A) is 83.5 tonnes.

4.   Calculate the number of trips (both directions) required to complete the annual freight task:

The no. of trips equals 10,000 per year.

5.   Determine the number of additional LU per year:

The LU per vehicle for a RAV 10(A) with concessional mass limit is approximately 9, calculated as the number of axles/2.

The total LU per year is therefore 9 x 10,000 trips = 90,000 LU/year.

6.   Determine the Materials Compliance

The materials are compliant in relation to Table F 1 and rated 'Good' with respect to Figure F 1.

7.   Select the estimated MC per one-way trip:

For Cost Zone 4 (which includes Gascoyne), and the nearest additional LU as 100,000 and compliant materials, the estimated MC from Figure E 5 is 22 cents/LU.km.

8.   Calculate the applicable actual marginal cost

The applicable actual marginal cost (AMC) needs to account for the actual cost of supply, therefore:

AMC = MC x 48000/43747 = 24.14 cents/LU.km

Accounting for a nominal 2% increase in costs per year (price escalation), the resulting AMC for 2018 is 24.62 cents/LU.km.

9.   Calculate an annual cost and total revenue:

The annual cost can now be calculated from all of the above information.

The total loading task was 90,000 LU/year being applied over a route length of 30 km, so the total marginal cost can be determined by multiplying these together:

0.2462 x 90,000 x 30 = $664,740 per year

The total estimated revenue (unadjusted for CPI for future years) is $3,988,4

REVIEWED		
Project Leader	Tyrone Toole	
Quality Manager	Dr Tim Martin	

CONTACT US

Name Surname
Tyrone Toole
Department
E: TYRONET@ARRB.COM.AU

Name Surname
Dr Tim Martin
Department
E: tim.martin@arrb.com.au

ARRB.COM.AU