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Road Cost Allocation Literature Review Findings

Project No: PRA17012

by Dr Tim Martin

for Victorian Department of Treasury and Finance

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for Victorian Department of Treasury and Finance

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ROAD COST ALLOCATION LITERATURE REVIEW FINDINGS

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SUMMARY

This review of current road cost base allocation practice and recent research has shown that there are potentially a number of changes that could be made to the current National Transport Commission (NTC) expenditure categories and their cost allocators. These changes mainly relate to the variation of the load-related (attributable to heavy vehicles) portion of the new/replacement pavement costs and the pavement maintenance and rehabilitation costs and the heavy vehicle road use parameters that allocate these costs.

The viability of these changes relies on whether the current Victorian arterial road network can be satisfactorily categorised into six arterial road categories, three urban and three rural. Each of these categories must contain adequate information on heavy and light vehicle class road use and road infrastructure expenditure, allowing the establishment of the stereo-typical pavements that represent each road category separately for both typical new/replacement pavements and typically maintained pavements.

Other minor changes to the current NTC expenditure categories and their parameters that allocate these costs are suggested.

All the above changes will reduce the amount of averaging of heavy vehicle road use and expenditure used in the current NTC cost allocation matrix allowing improved heavy vehicle charging signals and equity across all vehicle classes. Appendix C shows all the above and other minor proposed changes to the NTC cost allocation matrix.

Based on the above outcomes, further investigation is required to ensure that the recommended changes outlined below are viable and practical.

Recommendation 1 – Survey of Road Agencies

Prior to the finalisation of a revised road cost allocation matrix, a questionnaire survey directed to the road agencies is recommended as a matter of high priority to determine whether they can support a revised cost allocation matrix. The survey questions should aim to answer the following:

1. Is there adequate light and heavy vehicle class usage information, including heavy vehicle classification and weight data that is reliably and readily available on each state’s arterial road network?
2. Can the above information be assigned to the six road categories comprising three urban arterials and three rural arterials?
3. Is there adequate road infrastructure expenditure information regarding new/replacement pavements and pavement maintenance and rehabilitation that is reliably and readily available so it can be assigned to the above six road categories on each state’s arterial road network?
4. Is there sufficient information about new/replacement pavements and pavement maintenance and rehabilitation work that allows the establishment of the stereo-typical pavements that represent each road category separately for both typical new/replacement pavements and typically maintained pavements?

If satisfactory responses to the above are received, changes to the heavy vehicle % load-related costs and their cost allocator parameters can be made to the expenditure categories for new/replacement pavements and pavement maintenance and rehabilitation. This will support a revised NTC cost allocation matrix that allows improved heavy vehicle charging signals and equity across all vehicle classes.

Recommendation 2 – Additional Research

The following additional work is proposed to provide a sound basis to these expenditures:

- Using Victorian routine maintenance expenditure and road use data, confirm or otherwise, that routine maintenance (NTC cost category B1) has some % load-related cost that varies across the six proposed road categories. There is some concern that suitable expenditure and road use data may not be readily available.
- Undertake a further detailed review of cost allocation practice to determine what, if any, associated new safety and mobility facilities (traffic signals, barriers, signage, etc.) have some % load-related costs that vary across the six road categories. However, there is a possibility that a further review will not discover any new relevant information.

If the above additional research does not yield a sound estimate of the % load-related costs, it is recommended that these costs revert to 100% of non-load-related costs being allocated to all vehicle classes on the basis of either vehicle kilometres travelled (VKT) or passenger car units of kilometres travelled (PCU-km).

Recommendation 3 – Minor Changes

The following minor additions to the road cost allocation matrix expenditures are based on the approach used by the US Federal Highways Administration (FHWA):

- bridge superstructure – deck rehabilitation or replacement and other superstructure rehabilitation
- bridge substructure – new, rehabilitation and replacement.

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1 INTRODUCTION

1.1 Background to the Review

The assumptions underpinning the cost base allocators of the National Transport Commission (NTC) came under scrutiny from the Productivity Commission (2006), who noted that the NTC's assumptions were conservative compared to findings from recent literature, and therefore the current approach could allocate up to 37% more costs to heavy vehicles. These assumptions include: the highly averaged nature of the heavy vehicle road charges that do not send price signals to users and road agency providers and maintainers, and the lack of connection between charges and future investment expenditure.

The Victorian Department of Treasury and Finance (DTF) engaged the Australian Road Research Board (ARRB) to review current road cost base allocation practice and gain a thorough understanding of the data sources, requirements and the benefits of gaining appropriate accuracy for the road cost allocation methodology. This is in the context of developing evidence-based heavy vehicle road user charges to sustain adequate levels of expenditure that will support and grow the Victorian road infrastructure.

The review included identifying any knowledge gaps from examining the available resources that are required for the pavement wear cost recovery model. This means that road infrastructure performance needs to be understood under different scenarios and to make a comparative analysis of case studies where they are available.

This literature review will provide the basis for:

a. assessing any potential net benefit due to improving the accuracy of the cost base allocators by introducing the additional metric of road pavement type (rural/urban or local road/highway) as a factor of heavy vehicle wear on roads, provided adequate data is available to support this refinement

b. identifying the knowledge gaps and further research (if any) preventing the development of an accurate set of national (or state) cost base allocators

c. revealing any additional factors to be considered in the review that may arise from a thorough search of the literature

d. identifying the appropriateness of the current road expenditure categories and any changes required

e. identifying the distribution of common and allocated costs for each expenditure category

f. identifying the vehicle use metric for the distribution of common costs (or combination thereof) for the distribution of allocated costs for each expenditure category.

1.2 Net Benefits Analysis

A net benefits analysis was undertaken for the Victorian arterial road network of the potential benefits arising from increased annual maintenance funding. This was demonstrated using pavement life-cycle costing (PLCC) analyses over a 30-year period with two different real discount rates (5% and 7%) for the following cases:

- a base case of the current annual maintenance and rehabilitation budget of $378 million, increasing at an annual rate of 2.5% to match predicted traffic growth

- option (1) an additional $47.9 million of annual maintenance and rehabilitation road expenditure, made available by increasing the heavy vehicle road user charges based on updating the current road cost base allocation practice, giving a total annual budget of $425.9 million, increasing at an annual rate of 2.5% to match predicted traffic growth
- option (2) an unconstrained annual budget.

The Victorian road network of 24 093 km was represented by 34 000 road segments of varying length in the PLCC analyses. Road conditions (roughness) and the traffic on each segment were based on data used by VicRoads. Road deterioration (RD) and works effects (WE) models used to predict road conditions over the PLCC analysis period were those resulting from Austroads funded research (Austroads 2007, 2010a, 2010b).

Both options (1) and (2) were estimated to have substantial benefits, due to reductions in road user costs, arising from improved network road conditions relative to the base case. Under the base case the average network condition was predicted to be 2.97 IRI, while under options (1) and (2), network conditions were predicted to average 2.86 IRI and 2.67 IRI respectively.

Consequently, option (1) provides net benefits (PV of benefits – PV costs) ranging from $10.3 billion (7% discount rate) to $12.6 billion (5% discount rate). Option (2) provides greater net benefits than option (1). The benefits arise from reductions in the road user costs under options (1) and (2). Appendix A provides further breakdown and details of these estimates.

1.3 The Literature Review

The literature review included access to the ARRB Library's own comprehensive collection of technical land transport literature as well as access to the collections and expertise of other transport-related libraries throughout Australia and internationally. The literature search used the Australian Transport Index (ATRI) and Transportation Research Information Documentation (TRID) databases, whose content is coordinated by ARRB, and the Organisation for Economic Co-operation and Development/United States (OECD/US) Transportation Research Board respectively. Use of these databases ensured a wide coverage for quality research material within the subject area from national and international sources.

Similar to a previous study (New Zealand Institute of Economic Research (NZIER) 2008), the specific literature on road cost allocation is limited mainly to the USA, Canada, Australia and New Zealand while most of the European information is focused on the UK and Germany.

1.4 Structure of the Report

The findings of the road cost allocation review are presented in the following sequence:

- the basis for allocating road infrastructure costs to the road users
- definitions of road infrastructure costs to be allocated
- the approaches used to allocate pavement and bridge construction costs and pavement and bridge wear costs
- other road infrastructure costs that could be allocated to road users
- treatment of cost allocation parameters
- outline of a disaggregated approach to costs and the road infrastructure
- recommendations.

2 FINDINGS OF THE REVIEW

2.1 Basis for Allocating Road Infrastructure Costs to the Users

There are four basic approaches that have been used to allocate road infrastructure costs to the road users (Boile et al. 2001, Tirado et al. 2010). These are as follows:

- *A cost-occasioned approach* where the costs caused by the physical and operational characteristics of each vehicle class are related to expenditures on the road infrastructure.
- *A benefit-based approach* where the costs are allocated to each vehicle class according to the relative benefits they realise from road infrastructure investment. The greater the benefits, the greater the share of user fees a vehicle class should pay, irrespective of its contribution to road infrastructure expenditure.
- *A marginal cost approach* where vehicles are charged the marginal cost of pavement wear, pavement construction, environmental impact (pollution, greenhouse gas (GHG) emissions, etc.) and congestion associated with their road infrastructure use. The marginal cost approach aims to estimate user fees that cover the marginal cost of road use by different vehicle classes, which does not recover the full costs of road agency expenditure. However, this approach can be modified to recover all agency costs if required.
- *An incremental approach* is applied to pavement and bridge construction costs and pavement rehabilitation costs that are allocated by various methods aimed at ensuring an equitable share of the costs between the various vehicle classes (Federal Highways Administration (FHWA) 1997). The cost of the minimum possible pavement thickness to carry light vehicles is allocated to all vehicles based on kilometres of travel (VKT). The additional pavement thickness needed for heavy vehicles is allocated to them based on equivalent standard axles (ESA) weighted by VKT (ESA-km).

The cost-occasioned approach is typically used in most cost allocation practices such as the US Federal Highway Cost Allocation Study (FHWA 1997).

The benefit-based approach has the disadvantage that the benefits are more difficult to quantify than the costs.

The marginal cost approach is not appropriate in this context because it includes a number of externality costs such as congestion and environmental costs that are not part of the costs being considered by the DTF.

The incremental approach is often used as part of the cost-occasioned approaches in the UK (Ahmed et al. 2015), Germany (Bruzelius 2004) and various states in the USA (Volovski et al. 2015).

The cost-occasioned approach is extensively used as the basis for most road infrastructure cost allocation practices because it is practical and relatively transparent with respect to the costs to be allocated to the road users.

2.2 Definitions of Road Infrastructure Costs for Allocation

2.2.1 General

The following road infrastructure cost definitions are assembled on the basis that there exists either an established cost allocation for them or a cost allocation can be reasonably estimated. These definitions, in the case of pavements and bridges, will be confirmed for their usefulness by a survey of the road agencies. The load-related portions of these costs are often termed attributable (or avoidable), separable and joint costs, that are directly and uniquely attributable to a particular road user group or vehicle class (Rilett et al. 1989).

The non-load-related portion of the costs of pavements and bridges are the costs remaining after the load-related costs are allocated. The non-load-related costs are usually termed non-attributable, non-separable or common costs that cannot reasonably be assigned separately to a particular vehicle class. For example, these would be the costs associated with rubbish collection, grass cutting, drainage and other off-pavement activities.

In addition, these cost definitions should describe activities that can be quantified and recorded in physical and monetary terms at a disaggregate level in the road network so that they are accessible and available for a cost allocation process. The aim is to be able to equitably allocate costs across the whole road network so that no particular vehicle class is either over or under charged

2.2.2 Proposed Road Infrastructure Cost Categories

Table 2.1 was assembled from a review of the existing road infrastructure cost categories (FHWA 1997, Volovski et al. 2015, Agbelie et al. 2016) for construction, or provision, activities. To some extent many of the cost categories have been combined and simplified on the basis that it is unlikely that detailed cost information is easily and reliably accessible from road agency databases. In addition, some disaggregation of the road network is proposed to allow the attributable costs to vary with the levels of traffic, and location (climate and urban/rural) which also defines the pavement type as a refinement of the cost allocation process.

Table 2.1: Proposed road infrastructure cost categories: construction

Pavements – new, extra lanes and replacement	**Location**	**Road class**
	Urban	Freeways and major highways
		Main arterial
		Other arterials
	Rural	Freeways and major highways
		Main arterial
		Other arterials
Associated pavement facilities (new/replacement) – shoulders, kerbs, drains, earthworks, etc.	**Location**	**Road class**
	Urban	Freeways and major highways
		Main arterial
		Other arterials
	Rural	Freeways and major highways
		Main arterials
		Other arterials
Bridge superstructure -– new, extra lanes, and replacement	All	All
Bridge superstructure – deck rehabilitation or replacement, other superstructure rehabilitation	All	All
Bridge substructure – new, rehabilitation and replacement	All	All

Safety and mobility facilities – new, extra capacity and replacement (traffic signals, signage, barriers, etc.)	Location	Road class
	Urban	Freeways and major highways
		Main arterials
		Other arterials
	Rural	Freeways and major highways
		Main arterials
		Other arterials

Table 2.2 was assembled from a review of the existing road infrastructure cost categories (FHWA 1997, Volovski et al. 2015, Agbelie et al. 2016) for maintenance, or preservation, activities.

Table 2.2: Proposed road infrastructure cost categories: maintenance

Pavements – rehabilitation (structural)	**Location**	**Road class**
	Urban	Freeways and major highways
		Main arterials
		Other arterials
	Rural	Freeways and major highways
		Main arterials
		Other arterials
Pavements – periodic maintenance (resealing, surface correction, heavy patching, resurfacing)	**Location**	**Road class**
	Urban	Freeways and major highways
		Main arterial
		Other arterials
	Rural	Freeways and major highways
		Main arterials
		Other arterials
Pavements – routine maintenance (minor patching, drainage maintenance, pothole repairs, shoulder repairs & regrading, crack sealing, etc.)	**Location**	**Road class**
	All	All
Bridges (super and substructure) – minor repairs, repainting, etc.	**Location**	**Road class**
	All	All
Safety and mobility facilities – maintenance of traffic signals, signage, barriers, etc.	**Location**	**Road class**
	All	All

The road infrastructure cost categories in Table 2.1 and Table 2.2 are proposed because they are expected to vary with heavy vehicle road use on different road categories, thus increasing the costs that are potentially attributable to heavy vehicles. These cost categories are proposed on the basis that they can be allocated to the heavy vehicle classes by a sound scientific cost allocation process and that both the cost and road use data is available and capable of being aligned with the cost categories.

2.3 Approaches Used to Allocate Construction and Maintenance Costs

2.3.1 General

Road cost allocation can be seen as clearly distinguishing between costs that are load-related, caused by heavy vehicle use, and those that are non-load related, or common costs, that should be shared by all road users (FHWA 1997, Hong et al. 2007). There are several approaches that can be applied to make the distinction between load and non-load-related costs. These different approaches can lead to significantly different outcomes in regard to the portion of the costs that are load-related and the responsibility of the heavy vehicle classes.

Balducci and Stowers (2008) summarised these outcomes when established and well documented highway cost allocation (HCA) processes were applied across 30 states in the USA where the estimated portions of heavy vehicle costs relative to the total costs ranged from 18.9% (California in 1987) to 64.5% (Florida in 1979). Some of these differences could be accounted for by some states having a lot, or a little, cost that was load-related due to their pattern of expenditure in a particular year and the environmental impacts of either hostile or benign weather conditions. However, a significant amount of these differences is due to how the costs and heavy vehicle classes were defined and how the cost portions to them were allocated.

In Germany, for a particular charging scheme, heavy vehicles are defined as trucks with a maximum gross loaded vehicle weight of 10 tonnes or more (Link 2008), while for a European road pricing scheme for urban freight, trucks and vans with a gross loaded weight of 3.5 tonnes and less are part of the pricing scheme (Ruesh 2004).

2.3.2 Allocation of Construction Costs

Documented below is a summary of typical construction cost allocation practices that are adopted in the USA.

The non-load-related costs are typically defined as:

- For new and reconstructed pavements, the minimum pavement thickness required to either carry light vehicle traffic or for lightly trafficked roads, is usually the minimum pavement thickness that can be constructed satisfactorily. This minimum thickness pavement is nominated as the base cost of the pavement (Balducci & Stowers 2008) and is allocated to all vehicle classes as a common cost because it is a non-load-related cost.
- In the case of new and replacement bridges, the base bridge cost is based on a bridge designed to carry its own weight with the lightest vehicle class traffic loads and other non-load impacts (wind and seismic loads). The base cost is allocated as a common cost to all vehicle classes (Volovski et al. 2015), again because it is a non-load-related cost.

The load-related costs are typically defined as:

- *For new and reconstructed pavements,* the pavement thickness is designed to carry all the expected traffic load, in terms of standard axle repetitions (SARs)[1], over the design period (Austroads 2012a). The cost difference between the cost of the pavement to carry all traffic and the cost of the base pavement is the load-related cost, or attributable cost, that is allocated to the heavy vehicle classes. There are various approaches used to make this allocation (FHWA 1997, Agbelie et al. 2016, Balducci & Stowers 2008) aimed at making a fair share of these costs within the heavy vehicle classes. For flexible pavements, the FHWA (1997) estimates that the % load-related pavement cost varies between a high of 83.7 (urban interstate) to a low of 42.6 (rural local). This shows that as the pavement structural capacity is increased to carry higher traffic loads, the portion of load-related pavement costs increases.
- *In the case of new and replacement bridges*, an incremental approach is adopted in the USA for allocating the load-related costs (FHWA 1997, Volovski et al. 2015, Agbelie et al. 2016). Once the base bridge cost is estimated, as shown above, a second cost increment associated with the cost of strengthening the bridge to carry the second-lightest vehicle class with these costs is allocated to all vehicles whose gross vehicle weights (GVW) either exceed or equal the lightest vehicle class weights. Similarly, the third increment cost, the additional cost to carry the third-lightest vehicle class is allocated to all vehicle classes, except the lightest and second-lightest vehicle classes. This process is repeated until the last cost increment is allocated to the heaviest vehicle class. The actual number of passes of a particular vehicle class across the bridge is not usually relevant to bridge design, unless fatigue of critical structural bridge elements is relevant.

  The incremental approach to bridges will yield different estimates of the load-related costs depending on how the superstructure is supported, that is, either by simply supported spans or continuously supported spans (FHWA 1997). A review of current US cost allocation practice shows that there is no fixed % load-related cost for new and replacement bridges as this will vary with the type of bridge, its span length and means of support, as noted above. Past practice in New Zealand, South Africa and the UK have used a fixed % load-related construction or replacement cost (New Zealand Ministry of Works and Development (NZMWD) 1984, South African Department of Transport (SA DOT) 1991, Department of Transport (DOT) 1990). The NTC allocates 15% of bridge construction or replacement costs as load-related which was fairly typical of New Zealand, South Africa and the UK.

New and replacement pavements in Australia are mainly comprised of sprayed seal unbound granular materials and asphalt, a bound material. Features of these pavement types are discussed below with respect to their % load-related costs.

Discussion – unbound granular pavements

Appendix B.1 shows, based on some simplifying, but reasonable assumptions, the % load-related cost increases as the sprayed seal unbound granular rural pavement thickness, *t*, increases to accommodate increased traffic load. This confirms the FHWA (1997) outcomes that the % load-related pavement cost varies between a high of 83.7 (urban interstate) to a low of 42.6 (rural local).

[1] SARs for a heavy vehicle axle group are the number of equivalent standard axle (ESAs) passes that equals the wear that the whole axle group applies to the pavement. SARs are calculated by the axle group load divided by the reference axle group load all raised to a damage exponent 'n' whose value depends on the pavement material. The damage exponent varies with the pavement material: n = 4 (granular); n = 5 (asphalt); n = 12 (cement stabilised granular and concrete).

Discussion – asphalt pavements

Appendix B.2 shows, also based on some simplifying, but reasonable assumptions, that as the asphalt pavement (AC) thickness increases to accommodate higher traffic loads, the % load-related cost increases, however, at a much reduced rate than that for unbound granular pavements.

Discussion – bridges

It should be noted that, apart from the extensive computational effort involved with the incremental approach for allocating bridge costs, Australian bridge design practice (Standards Australia AS 5100) uses a conservative live loading scenario, well in excess of current group axle loadings, which results in a much higher cost for a new or replacement bridge to carry the existing heavy vehicle traffic. Consequently, if the incremental approach was used in Australia it would not allocate the difference between the full cost of the bridge conservatively designed and the base cost. The difference between the total bridge cost and the sum of the base costs and all the costs of the heavy vehicle class increments should therefore be treated as a common cost to be borne by all vehicle classes.

For pavement construction and replacement, it has been shown that as the pavement increases in thickness to accommodate more heavy vehicles, the % load-related costs also increase. The inverse is the case for pavements accommodating fewer heavy vehicles, that is, the % load-related costs decrease because the majority of the pavement thickness becomes a non-load related cost.

For bridge construction and replacement, there is no fixed % load-related cost as this will vary with the type of bridge, its span length and means of support. It is likely that, as for pavements, the % load-related bridge costs increase on the more highly trafficked road categories, however, there is no documented available evidence to support this. Due to the conservative nature of bridge design, the % load-related costs are likely to be lower than those for pavements

2.3.3 Allocation of Maintenance Costs – Pavements

As for construction costs, the main concern is to be able to determine the load-related road wear (attributable) costs of pavement maintenance. Table 2.2 shows a separation of road wear costs into rehabilitation, periodic maintenance and routine maintenance based on the expectation that these activities may have different portions of load-related road wear that may be allocated by different cost allocation parameters.

Earlier cost allocation work assumed that new pavement construction, pavement reconstruction and pavement rehabilitation were variations in scale of the same activity (Martin 1994). All these works, particularly new pavement and pavement reconstruction, could be seen as design and construction activities to accommodate heavy vehicles over a defined service life. On the other hand, rehabilitation can be seen as both a design and maintenance response to pavement wear and therefore should be seen as part of all the other pavement-related maintenance activities such as periodic and routine maintenance. Fwa et al. (1990) showed that for the FHWA (1982) cost allocation process, the % load-related portion of the rehabilitation costs was a lower amount than the % load-related portion for new and replacement pavements. Consequently, pavement rehabilitation and periodic maintenance could all be treated as part of the load-related road wear due to heavy vehicle road use.

Routine maintenance is usually treated as a non-load, or common, cost because most of this maintenance is directed at relatively minor pavement surface distress and off-pavement-related work such as drainage maintenance, grass cutting and rubbish removal.

Use of distress models

There is a strong reliance on mechanistic pavement distress models to determine the load-related portion of the road wear cost (maintenance). A National Pavement Cost Model (NAPCOM) was developed by the US Federal Highway Administration (FHWA 1997, Ahmed et al. 2015) to make these estimates of load-related wear across a range of road types in rural and urban areas. These load-related road wear estimates vary from 89.9% (urban interstate) to 85.3% (rural local) of the total road wear.

In the Canadian state of Ontario, flexible pavement deterioration models are used for cost allocation purposes (Rilett et al. 1989) resulting in load-related road wear estimates varying from 45% to 12% of the total road wear. The differences between these % load-related wear estimates could be due to the use of different distress models and the fact that non-load climatic effects in Canada are much more severe than in the USA.

Predicting pavement response to heavy vehicle traffic using a mechanistic-based finite element analysis[2] has also been used as a basis for estimating the reduction in the service life of a pavement and its associated load-related maintenance cost (Tirado et al. 2010, Dong et al. 2014).

Extensive use of observational and specific experimental studies in Australia, such as the Austroads long-term pavement performance (LTPP) study, has resulted in the development of functional and structural pavement deterioration models (Martin 2009, Austroads 2010a, 2010b). From the road roughness (ride quality) deterioration model, the percentage (%) load-related wear, IRI_l can be determined (Martin 2011) using the following algorithm for sealed flexible unbound granular pavements:

$$IRI_l = 70.533 \times (1 - EXP(-17.714 \times m \times AGE)) - 3.46 \times SNC_0 + 27.131 \times MESA \qquad 1$$

where

m	=	environmental coefficient (Paterson 1987)
	=	$0.0197 + 0.000155 \times TMI$ (Martin 1996)
TMI	=	Thornthwaite Moisture Index (Thornthwaite 1948)
AGE	=	number of years since pavement was constructed/replaced or rehabilitated, whichever is the lesser
SNC_0	=	pavement/subgrade strength value as designed and initially constructed ($AGE = 0$)
$MESA$	=	millions of equivalent standard axles (ESA), or SARs, of traffic loading per lane per year.

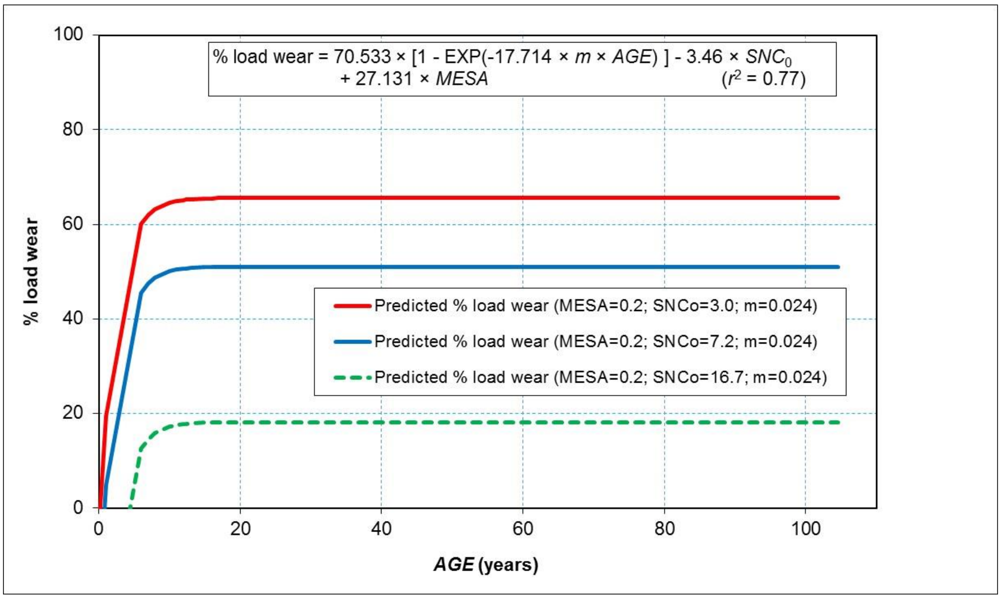
Roughness is considered to be a good general proxy for road wear and was the basis for measuring road wear under the American Association of State Highway Officials (AASHO) Road Test in the late 1950s in the USA (Highway Research Board 1961). The American Association of

[2] An analysis that represents a pavement structure as an assemblage of elements each with structural properties (stress-strain relationship, Poisson's ratio, etc.) allowing predictions of deformation due to wheel loading and other external impacts.

State Highway Transportation Officials (AASHTO) carried out the AASHO Road Test which became the basis for the fourth power law[3], or damage exponent that is used in assessing road wear in pavement design.

Figure 2.1 shows how the % load-related road wear can vary with the SNC_0 under constant climate (m) and traffic load ($MESA$). The % load-related wear relationship, Equation 1, shows that road wear can also vary with climate and traffic load. Consequently, Equation 1 could be used in a refined cost allocation process using different road types (traffic load and pavement strength) in different regions (climate).

Figure 2.1: Percentage (%) load-related road wear (attributable cost) varying with pavement strength



Source: Martin (2011).

Murillo-Hoyos et al. (2014) have noted that pavement wear costs are more reliably estimated at a specific road segment and location level lending support for a more disaggregated road network approach to cost allocation.

Henning et al. (2014) have also proposed a refinement of the New Zealand road user charge models based on their findings from New Zealand long-term pavement performance (LTPP) monitoring that were used to form load-wear relationships.

Use of maintenance cost relationships

A relationship between road maintenance expenditure (costs) of road wear and heavy vehicle road use can be used to determine the fixed (non-attributable) and variable (attributable) road wear costs (Al-Suleiman et al. 1991). This relationship has the following functional form:

$$\text{maintenance expenditure } (\$/\text{lane-km/year}) = a_1 + a_2 \times \text{road use variable}_1 + a_3 \times \text{road use variable}_2 \quad 2(a)$$

where

[3] The fourth power law estimates pavement surface wear based on the ratio of the applied wheel load to a reference wheel load with this ratio raised by an exponent of 4 (see also footnote 1 on SARs).

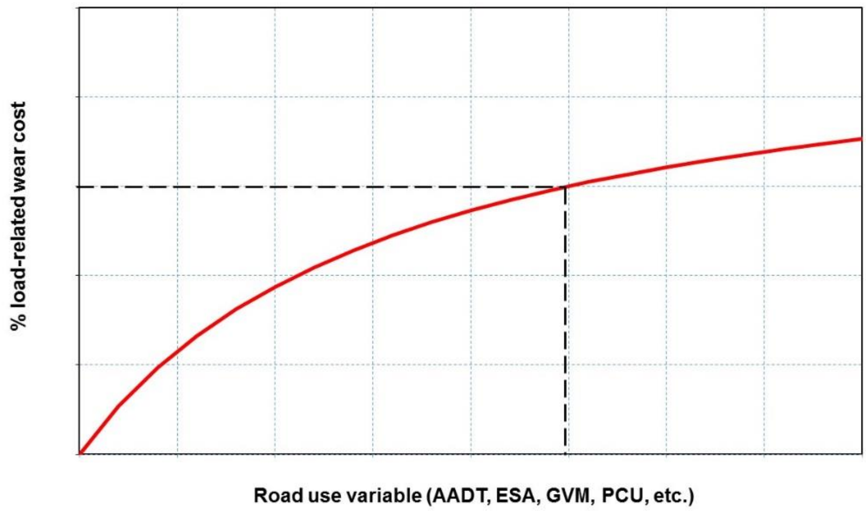
a_1	=	constant (fixed cost)
a_2, a_3	=	regression coefficients for road use variable (ESA-km, GVW-km, AADT, PCU-km, etc.)
ESA-km	=	equivalent standard axles kilometres
GVW-km	=	gross vehicle weight kilometres
AADT	=	annual average daily traffic
PCU-km	=	passenger car units kilometres.

The variable portion of Equation 2(a), when expressed as a percentage (%) of the total maintenance expenditure, represents the % attributable cost as follows:

$$\%\ \text{attributable cost} = \frac{a_2 \times \text{road use variable}_1 + a_3 \times \text{road use variable}_2}{(a_1 + a_2 \times \text{road use variable}_1 + a_3 \times \text{road use variable}_2)} \qquad 2(b)$$

Figure 2.2 shows that Equation 2(b) predicts that the % load-related (attributable) cost increases as the road use parameters increase.

Figure 2.2: Percentage attributable cost varying with road use



A pavement maintenance database for samples of Auslink, the strategically linked arterial road pavement sections of the National Highway, was established across Australia to substantially increase the number of data samples of an earlier NTC road track cost database (Austroads 2011). There were 62 580 data samples collected for the initial pilot stage of the study, which were reduced by 59% after filtering. The full data collection involving 379 639 samples covering the states of Queensland, New South Wales, South Australia and Victoria was reduced by 33% after data filtering.

The data was essentially of the same type (road condition, road use and maintenance expenditure). The data was collected over a five-year period and analysed using a state-of-the-art data mining tool called minimum message length (MML) used to establish the dependent maintenance road wear cost variable and road use independent variables relationships with each of the participating state's data. The data was the most extensive ever collected for this type of study and the data filtering ensured the data was of adequate quality.

For pavement wear, represented by rehabilitation and periodic maintenance, the % load-related cost estimates depend on the models used. Using a road roughness distress model, the % load-related road wear cost is a function of the pavement/subgrade strength, the traffic load and to a lesser extent, the climate, depending on how well the pavement is maintained. The maintenance cost and road use relationships predict that the % load-related cost increases with increased heavy vehicle road use. This approach has the limitation that it does not explicitly account for the pavement/subgrade strength and reflects the maintenance strategies road agencies use under constrained budgets.

2.3.4 Allocation of Maintenance Costs – Bridges

As for pavement and bridge construction costs and pavement maintenance costs, the determination of the % load-related bridge wear (attributable) costs is of interest to ensure fair cost allocation. Bridge wear costs that are potentially load-related include maintenance and rehabilitation costs for both the superstructure and substructure and bridge deck replacement costs.

Agbelie et al. (2016) and Volovski et al. (2015) have noted that:

1. The load-related share of a bridge deck overlay cost is 70% from the FHWA (1997) and 1999 Oregon (Stowers et al. 1999) studies.
2. Bridge deck replacement and strengthening is 50% load-related (Stowers et al. 1999), while FHWA (1997) states that 20% is load-related.
3. Bridge deck rehabilitation or replacement and other superstructure is considered to be 30% load-related by the FHWA (1997).
4. Bridge deck joint repair and replacement is 70% load-related (Stowers et al. 1999).
5. Rehabilitation of the substructure is 15% load-related (FHWA 1997).
6. The load-related share of other bridge superstructure rehabilitation is 30% (FHWA 1997).

The above Federal USA and Oregon State bridge maintenance cost allocations have significant variations in the estimates of the % load-related bridge wear as well as some internal inconsistencies in the definitions of the work. For example, the FHWA (1997) definition of bridge deck rehabilitation or replacement is 20% load-related under item (2), but a similar work definition for bridge rehabilitation or replacement under item (3) has this as 30% load-related.

Despite these variations in the % load-related bridge wear estimates, the share of these costs between the various vehicle classes for rehabilitation and replacement works was allocated on the same extensive computational basis used for bridge construction and replacement, as noted in Section 2.3.2 above (Agbelie et al. 2016).

An Austroads study examined the development of a marginal cost for heavy vehicle road use of bridges (Austroads 2012b). The development of marginal costs for bridge wear due to heavy vehicle use did not proceed using either an engineering or an econometric basis due to a lack of suitable bridge deterioration models and data. The successful completion of such a study would have aided estimation of the % load-related bridge wear.

Generally it appears that all other bridge maintenance costs, such as cleaning, painting and minor repairs, were regarded as non-load-related, or common costs (Agbelie et al. 2016). This seems to be a reasonable approach.

Estimation of the % load-related bridge wear is highly problematic due to a lack of data and suitable models and is therefore reliant on the practices of other highway cost allocation studies. The estimates of the FHWA (1997) are likely to be the more reliable due to their longstanding practice and wide adoption across the USA and can provide a useful basis for adaptation to Australia.

2.3.5 Allocation of Maintenance Costs – Other

Typically the construction and maintenance costs associated with safety, mobility and other related works are treated as non-load-related (Agbelie et al. 2016). Some of these costs may be related to vehicle size and its impact on road space so it can therefore be vehicle kilometres travelled (VKT) weighted by passenger car units (PCU) to form a PCU-km allocation. Typically the PCU has been a maximum value of 3 for a heavy vehicle, but due to the increased size of heavy vehicles (e.g. B-doubles and B-triples, etc.) and urban congestion, it is recommended by the Metropolitan Transport Research Unit (2014) in the UK that the PCU value be at least 4.

The allocation of common costs is discussed further in Section 2.4 below.

2.4 Treatment of Cost Allocation Parameters

Once the % load and non-load related costs are determined for each of the cost categories, an appropriate cost allocation parameter must be selected that adequately represents the ‘cost occasioned’ nature of the influence of road use on costs. Volovski et al. (2015) have noted that many highway cost allocation studies (HCAS) often do not adequately assess the cost allocation parameters that are capacity driven (lane width, number of lanes, etc.) and the allocation parameters that are strength driven (pavement thickness, bridge structure members, etc.).

2.4.1 Allocation of Construction Costs – Pavements

Common cost allocation

The non-load-related pavement construction costs to provide a minimum pavement thickness are usually based on the VKT parameter across all classes which can also be adjusted for pavement width effects (Agbelie et al. 2016), by reducing the pavement and shoulder width to that required by passenger cars. This is based on recent research (Martin et al. 2017) showing that heavy vehicle drivers preferred wider lanes and shoulders than passenger car drivers as part of achieving an acceptable level of service.

In the earlier Australian work on cost allocation by the Inter-State Commission, Butcher (1990) recommended the use of VKT for all non-attributable, or common, costs. Other options considered were allocation on a per vehicle basis which did not consider the level of use.

Attributable cost allocation

The FHWA (1997, 2000) allocates the attributable pavement costs based on the relative ESAs of each heavy vehicle class. Attributable new and replacement pavement costs are estimated for three pavement sections designed for each highway class in each state using selected design parameters and design methods based on state-specific and the American Association of State Highway Transportation Officials (AASHTO) manuals. The attributable pavement cost parameter is

ESA-km to account for strength and road use with some adjustments for width effects (Agbelie et al. 2016).

Other US states adopt similar attributable pavement cost allocation approaches to the FHWA (1997). Hong et al. (2007) have proposed what they regard as a more rational method to attributable pavement cost allocation based on a mechanistic-empirical design approach using real axle group load spectra to accurately reflect the actual traffic load.

In a previous review of attributable pavements costs (Martin 1991), it was found that the UK allocated 12.2% of pavement reconstruction and resurfacing costs on the basis of ESA-km (DOT 1990), South Africa allocated 15% of pavement construction and 90% of pavement rehabilitation costs on the basis of ESA-km confirmed by a letter dated 17 April 1991 from P Mainwaring for the South African Department of Transport, while New Zealand allocates 15% of pavement reconstruction and 5% of new pavement costs on the basis of ESA-km (NZMWD 1984).

Any additional lane and shoulder width cost required for heavy vehicles would therefore be allocated on a capacity basis by a parameter such as PCU-km.

The ESA-km is the usual attributable pavement cost parameter, but other allocation parameters are used such as gross vehicle weight (GVW) in the form of GVW-km, PCU-km and VKT.

> The ESA-km, or SAR-km, is the pavement cost allocator given by the usual pavement design approach and the US-based highway cost allocation studies. Other cost parameters can be used for space capacity (width and lanes) effects such as PCU-km. Some cost allocation practices use the GVW-km and VKT parameters, although there is no theoretical basis for them.

2.4.2 Allocation of Construction Costs – Bridges

Common cost allocation

The common, or non-load, costs are usually allocated across all vehicle classes by VKT (Volovski et al. 2015).

Attributable cost allocation

The load-related, or attributable, costs of bridge construction are usually allocated by the incremental process, as described in Section 2.3.2, resulting in a GVW-km allocation parameter (Agbelie et al. 2016). Sometimes the additional costs associated with vehicle width and height for special over-size heavy vehicles are also considered for cost allocation (FHWA 1982, 1997) using a PCU-km allocation parameter.

> The usual approach to allocating load-related bridge costs is the use of the GVW-km parameter. Space capacity costs are allocated by the PCU-km.

2.4.3 Allocation of Construction Costs – Other

These construction costs are listed in Table 2.1 under ‘Safety and mobility facilities’. They are not load-related, but can be considered to be capacity-related and therefore have an attributable cost.

Common cost allocation

The common, or non-attributable, costs are usually allocated across all vehicle classes by VKT (FHWA 1997).

Attributable cost allocation

Any additional space (width, height and length) due to the size of heavy vehicles is usually allocated to the heavy vehicle classes by PCU-km (FHWA 1997).

2.4.4 Allocation of Maintenance Costs – Pavements

It is essential to determine the most appropriate load-related road wear parameter for allocation of the % load-related road wear (maintenance cost).

Common cost allocation

The common non-load-related road wear costs are due to climatic effects (rainfall, temperature, humidity, etc.), intrinsic pavement material degradation and other factors that are not caused by load-related road wear. The common, or non-attributable, costs are usually allocated across all vehicle classes by VKT (FHWA 1997).

Attributable cost allocation

From Section 2.3.3, the main heavy vehicle cost allocation parameter that influences the % load-related road wear is the ESA, or SAR, in general terms for the two approaches used. These approaches were the use of distress model deterioration and the maintenance cost relationships.

Typically in most highway cost allocation studies (HCAS), load-related pavement maintenance costs are allocated by ESA-km for load effects and PCU-km for width effects (Volovski et al. 2015, Ahmed et al. 2015, Agbelie et al. 2016).

It is important to note that although two heavy vehicles may have exactly the same GVW, the actual axle configurations are the means by which loads are distributed and applied to the pavement surface. The traffic load parameter, ESA, or SAR, takes into the axle configurations so for vehicles with the same GVW, but different axle configurations, the ESA of each vehicle can be substantially different.

Doodoo and Thorpe (2002) have noted that many factors influence the load-related road wear caused by heavy vehicles. The traffic load parameter, ESA, is in fact a simplification of the complex interaction of dynamic loading, environmental conditions and the state of the pavement surface. Heavy vehicle tyre pressure, tyre width, axle configuration and suspension characteristics influence pavement wear. Dynamic wheel loads, which increase with vehicle speed and poor ride quality (roughness), can peak at up to 2 to 4 times the static measure of their loads under the phenomenon of spatial repeatability which concentrates dynamic loading at intervals of 8 to 10 metres along the pavement. As a consequence, pavement wear occurs at specific locations and is not well represented by average conditions.

Both the approaches to estimate % load-related wear costs use ESA-km, or SAR-km, to allocate these costs. Most highway cost allocation studies also use ESA-km for load-related costs and PCU-km for width-affected costs.

2.4.5 Allocation of Maintenance Costs – Bridges

Common cost allocation

The common non-load-related bridge maintenance costs are typically allocated on the basis of VKT (Volovski et al. 2015, Agbelie et al. 2016).

Attributable cost allocation

Among the states in the USA there is a wide variation in the allocation parameters used for load-related bridge maintenance costs (Volovski et al. 2015, Agbelie et al. 2016). The allocation parameters used are GVM, PCU-km ESA-km and VKT. In New Zealand, bridge repairs are allocated using VKT (NZMWD 1984), while the UK uses GVW-km as the cost allocator (Urquhart & Rhodes 1990).

It is difficult to understand the use of the ESA-km parameter for bridge maintenance when it is typically used to allocate load-related road wear costs, while the use of VKT makes no distinction between the cost impact that heavy and light vehicles have on load-related bridge wear.

The load-related bridge wear costs are allocated by a range of parameters such as GVW, GVW-km, PCU-km, ESA-km and VKT. The ESA-km parameter for bridge wear, apart from being applied to surfacing on the bridge deck, cannot be supported.

2.4.6 Allocation of Maintenance Costs – Other

The allocation of the maintenance costs for road infrastructure other than pavements and bridges is universally undertaken using VKT or PCU-km if there is a width or capacity component (FHWA 1997).

2.5 Allocation of Non-load-related, or Common, Road Infrastructure Costs

Section 2.4.1 to 2.4.5 have documented a wide range of parameters that are used for allocation of non-load-related, or common, costs. The allocation of common costs is needed if road infrastructure costs are to be recovered to meet road expenditures.

By far the most frequently used common cost allocation parameter is VKT which is used in the NTC's road cost base allocation practice as it is a simple measure of road use by all road users.

3 REVISED APPROACH TO COST ALLOCATION

3.1 General

An outline of a revised road infrastructure cost allocation approach that could potentially replace part of the NTC's cost allocation matrix is shown in Appendix B. This revised approach is aimed at using a sound engineering and practical basis for heavy vehicle charges that are less averaged and more focussed on where and how the road costs are occasioned. The current servicing and operating expenses, land acquisition, corporate services and heavy vehicle regulation, and NTC expenditure categories A, F3, G1 and G2 respectively are not included because their allocation portions and parameters do not change.

The literature review of current and past international cost allocation practice has provided the basis for the revised road infrastructure cost allocation approach. However, there are uncertainties and gaps in knowledge that need some consideration which is discussed below.

3.2 Identified Knowledge Gaps and Discussion

3.2.1 Load-related Costs – Pavement Construction and Replacement

Estimation of the % load-related pavement construction and replacement cost based on the approach in Appendix A needs to be carried out for typical representative pavements in the urban and rural road categories, a total of six stereo-typical pavements as shown in Appendix B. A set of design traffic loads and growth for these six stereo-typical pavements is also needed to make the % load-related cost estimate by designing each pavement to carry the heavy vehicle traffic load over the deign period, as noted in Section 2.3.2.

Allocation of these load-related costs between the heavy vehicle classes can be based on the proportional ESA-km contribution of each heavy vehicle class to the total cumulative ESAs that the pavement is designed to accommodate. This is a more simplified approach than that used in a traditional incremental approach where the cost contribution of each vehicle class is allocated on an incremental thickness basis (Volovski et al. 2015). The simplified approach does not address equity across the heavy vehicle classes. It is understood that the NTC uses this simplified approach.

A set of notional values of % load-related pavement construction/replacement costs are shown in Appendix B for all of the six road categories across the rural and urban areas. These notional values need to be confirmed by undertaking a study using six stereo-typical pavements that represent each road category.

3.2.2 Load-related Costs – Associated New Pavement Facilities

An estimate of 10% of the associated new pavement facility costs was notionally considered to be load-related in Appendix B, allocated to all vehicle classes on the basis of PCU-km. This is slightly lower than that currently used in the NTC cost allocation matrix.

3.2.3 Load-related Costs – Bridges New and Replacement

There is no fixed % load-related bridge new and replacement cost as it varies for each bridge. Estimation of the % load-related bridge construction and replacement cost could be carried out for typical representative bridges types in the urban and rural road categories, a total of six stereo-typical bridges. This would involve designing each bridge type, as noted in Section 2.3.2, to determine the % load-related cost where this cost will be reduced by the costs of the bridge designed to carry the design live load that is in excess of the current axle load levels.

Due to the intensity and expert resources needed for undertaking the above, it is prohibitive to proceed with a determination of the % load-related bridge costs in this context.

The % load-related bridge costs are likely to increase on the more highly trafficked road categories, although there is no documented evidence to support this. The approach adopted in Appendix B was to use a fixed estimate of 15% load-related new and replacement bridges costs, as is current NTC practice for all road categories.

Allocation of the load-related costs between the heavy vehicle classes could be based on the proportional PCU-km or GVW-km contribution of each heavy vehicle class to the total PCU-km or GVW-km of all heavy vehicle classes respectively. Again, this is a more simplified approach than the incremental approach (FHWA 1997) used. Also, it is understood that the NTC uses this simplified approach, although PCU-km is used to allocate the costs due to width effects that influence the design live loading on the bridge (Martin 1994) under Australian design standards. The use of PCU-km to allocate bridge costs, rather than GVW-km, should be retained as a consequence of how bridges are designed in Australia.

3.2.4 Load-related Costs – Pavement Maintenance and Rehabilitation

Estimation of the % load-related pavement wear (maintenance and rehabilitation) costs can be based on the approach outlined in Section 2.3.3 using the distress model Equation 1. Determination of the % load-related wear needs to be carried out for typical representative pavements in the urban and rural road categories, a total of six stereo-typical pavements as shown in Appendix C. A set of typical traffic loads, pavement/subgrade strength, climate, and pavement age is also needed for each of these six stereo-typical pavements.

Allocation of the load-related costs between the heavy vehicle classes can be based on the proportional annual ESA-km contribution of each heavy vehicle class to the total annual cumulative ESA-km that each pavement accommodates.

A set of notional values of % load-related pavement wear costs are shown in Appendix B for the all of the six road categories across the rural and urban areas. These notional values need to be confirmed by undertaking a study using six stereo-typical pavements that represent each of the six road categories.

3.2.5 Load-related Costs – Pavement Routine Maintenance

An estimate of 10% of the pavement-related routine maintenance costs was notionally considered to be load-related in Appendix C, allocated to all vehicle classes on the basis of PCU-km. This is significantly lower than that currently used in the NTC cost allocation matrix.

A relationship between routine maintenance expenditure and road use, based on Victorian data, is needed to confirm this load-related estimate and whether it varies across all road categories. If this data is not available or a definitive statistically significant relationship is unable to be derived, 100% of pavement-related routine maintenance should be regarded as common cost[4].

[4] Previous research in this area has not found a satisfactory relationship between routine maintenance expenditure and road use (ULG 2005).

3.2.6 Load-related Costs – Bridge Maintenance and Rehabilitation

Estimation of the % load-related bridge wear is highly problematic due to a lack of data and suitable models so these estimates have to be wholly reliant on the practices of other highway cost allocation studies, such as FHWA (1997).

Allocation of the load-related bridge wear costs are typically by GVW, VKT and GVW-km parameters. Appendix C shows that GVW-km is used for the load-related costs.

3.2.7 Load-related Costs – New Safety and Mobility Facilities

A notional % load-related estimate of 10% for freeways and major arterials was adopted for safety and mobility costs reducing with lower levels of traffic on the urban and rural road categories in Appendix C. Agbelie et al. (2016) note that these % load-related costs vary across the different road classes, although no definitive estimate was found for the % load-related safety and mobility costs from the review.

3.2.8 Data Support for Disaggregation

As a consequence of disaggregating the road network into six road categories, the following data is required to support a revised approach to cost allocation:

- heavy and light vehicle class information on their use on the six road categories, as notionally defined in Table 2.1 and Table 2.2
- road infrastructure expenditures in the categories proposed in Appendix B on the six road categories
- establishment of the six road category stereo-typical pavements that represent each road category separately for new pavements and maintained pavements.

Information relating to the accessibility and supply of the above data will have to be acquired from state road agencies by means of a questionnaire survey.

The following is a summary of the identified knowledge gaps found from this review that need to be undertaken and resolved:

1. Selection of three urban arterial road categories and three rural arterial road categories that contain adequate heavy and light vehicle class road use information, road infrastructure expenditure and information allowing establishment of the stereo-typical pavements that represent each road category separately for both typical new pavements and typical maintained pavements.
2. Estimation of % load-related new and replacement pavement costs based on using a total of six stereo-typical new/replacement pavement types across rural and urban areas.
3. Estimation of % load-related pavement maintenance and rehabilitation costs based on using a total of six stereo-typical maintained pavement types across rural and urban areas.
4. Confirmation that routine maintenance has some % load-related costs that varies across the six road categories using Victorian routine maintenance expenditure and road use data.
5. Confirmation that associated new safety and mobility facilities have some % load-related costs that vary across six road categories and are acceptable from a further review using Victorian routine maintenance expenditure and road use data.

If items (4) and (5) in the above list of knowledge gaps cannot be adequately confirmed, it is recommended that these costs revert to 100% non-load-related costs allocated to all vehicles on the basis of either VKT or PCU-km.

4 SUMMARY AND RECOMMENDATIONS

4.1 Summary

This review of current road cost base allocation practice and recent research has shown that there are potentially a number of changes that could be made to the current NTC expenditure categories and their cost allocators. These changes mainly relate to the variation of the load-related (attributable to heavy vehicles) portion of the new/replacement pavement costs and the pavement maintenance and rehabilitation costs and the heavy vehicle road use parameters that allocate these costs.

The viability of these changes relies on whether the current Victorian arterial road network can be satisfactorily categorised into six arterial road categories, three urban and three rural. These road categories must contain adequate information on heavy and light vehicle class road use and road infrastructure expenditure, allowing the establishment of the stereo-typical pavements that represent each road category separately for both typical new/replacement pavements and typically maintained pavements.

Other minor changes to the current NTC expenditure categories and their parameters that allocate these costs are suggested.

All the above changes will reduce the amount of averaging of heavy vehicle road use and expenditure used in the current NTC cost allocation matrix allowing improved heavy vehicle charging signals and equity across all vehicle classes. Appendix C shows all the above and other minor proposed changes to the NTC cost allocation matrix.

Further investigation is recommended to ensure that the changes recommended are viable and practical.

4.2 Recommendations

4.2.1 Survey of Road Agencies

Prior to the finalisation of a revised road cost allocation matrix, a questionnaire survey directed to the road agencies is recommended as a matter of high priority to determine whether the state road agencies can support a revised cost allocation matrix. The survey questions should aim to answer the following:

1. Is there adequate light and heavy vehicle class usage information, including heavy vehicle classification and weight data that is reliably and readily available on each state's arterial road network?
2. Can the above information be assigned to the six road categories comprising three urban arterials and three rural arterials?
3. Is there adequate road infrastructure expenditure information regarding new/replacement pavements and pavement maintenance and rehabilitation work that is reliably and readily available so it can be assigned to the above six road categories on each state's arterial road network?
4. Is there sufficient information about new/replacement pavements and pavement maintenance and rehabilitation work that allows the establishment of the stereo-typical pavements that represent each road category separately for both typical new/replacement pavements and typically maintained pavements?

If satisfactory responses to the above are received, changes to the heavy vehicle % load-related costs and their cost allocator parameters can be made to the expenditure categories for new/replacement pavements and pavement maintenance and rehabilitation. This will support a revised NTC cost allocation matrix that allows improved heavy vehicle charging signals and equity across all vehicle classes.

4.2.2 Additional Research

The following additional work is proposed to provide a sound basis to these expenditures:

- Using Victorian routine maintenance expenditure and road use data, confirm or otherwise, that routine maintenance (NTC cost category B1) has some % load-related cost that varies across the six proposed road categories. There is some concern that suitable expenditure and use data may not be readily available.
- Undertake a further detailed review of cost allocation practice to determine what, if any, associated new safety and mobility facilities have some % load-related costs that vary across the six road categories. There is a possibility that a further review will not uncover any relevant information.

If the above additional research does not yield a sound estimate of the % load-related costs, it is recommended that these costs revert to 100% of non-load-related costs being allocated to all vehicles on the basis of either VKT or PCU-km.

4.2.3 Other Recommendations

The following minor additions to the road cost allocation matrix expenditures are based on the approach used by the FHWA (1997):

- bridge superstructure – deck rehabilitation or replacement and other superstructure rehabilitation
- bridge substructure – new, rehabilitation and replacement.

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Standards

AS 5100.5:2017, *Bridge design: concrete.*

AS 5100.6:2017, *Bridge design: steel and composite construction.*

AS 5100.7:2017, *Bridge design: bridge assessment.*

APPENDIX A NET BENEFIT ANALYSIS

A.1 PLCC Analysis of Options

A 30-year pavement life-cycle costing (PLCC) analyses of the following three maintenance and rehabilitation funding options was undertaken using real discount rates of 5% and 7%:

- a base case of the current annual maintenance and rehabilitation budget of $378 million, increasing at an annual rate of 2.5% to match predicted traffic growth
- option (1) an additional $47.9 million of annual maintenance and rehabilitation road expenditure, made available by increasing the heavy vehicle road user charges by updating the current road cost base allocation practice, giving a total annual budget of $425.9 million, increasing at an annual rate of 2.5% to match predicted traffic growth
- option (2) an unconstrained annual budget, increasing at an annual rate of 2.5% to match predicted traffic growth.

Table A 1 shows the present values (PV) of the road agency costs (RAC), road user costs (RUC) and resulting average network roughness values (IRI) for the base-case funding and two other funding options for the 5% and 7% discount rates for the 30-year analysis period.

Table A 2shows the net benefits which are the difference between the PV of the base-case road user costs, RUC_{base}, and the option road user costs, RUC_{option}. In addition, the benefits of the options can also be expressed as the total transport cost in net present value (NPV) terms which is the sum of the RAC and RUC. The NPV was calculated for the base-case funding and two funding options using the 5% and 7% discount rates.

Table A 1: Summary of PLCC analysis outcomes (30-year period)

Annual funding option	RAC ($PV 5% discount)	RUC ($PV 5% discount)	RAC ($PV 7% discount)	RUC ($PV 7% discount)	Average network IRI
Base ($376 m)	7 369 588 769	4 165 548 009 798	5 843 611 957	3 235 458 452 860	2.97
Option 1 ($425.9 m)	7 729 083 655	4 152 999 154 992	6 212 226 622	3 225 168 638 599	2.86
Option 2 (Unlimited)	8 637 118 473	4 131 419 561 907	7 277 893 228	3 205 798 410 091	2.67

Table A 2: Summary of PLCC analysis net benefits

Annual funding option	Net benefits RUC_{base} - RUC_{option} ($PV 5% discount)	Net benefits RUC_{base} - RUC_{option} ($PV 7% discount)	$transport NPV RAC + RUC (5% discount)	$NPV RAC + RUC (7% discount)	Average network IRI
Base ($376 m)			4 172 917 598 566	3 241 302 064 816	2.97
Option 1 ($425.9 m)	12 548 854 805	10 289 814 261	4 160 728 238 647	3 231 380 865 220	2.86
Option 2 (Unlimited)	34 128 447 891	29 660 042 769	4 140 056 680 380	3 213 076 303 319	2.67

Table A 2shows that both funding options (1) and (2) have significant net benefits compared to the base case. Options (1) and (2) also have lower total transport costs compared to the base case. Figure A 1 plots all the PLCC analysis results and shows that the RUC are an order of magnitude greater than the RAC on the y-axes.

Figure A 1: Summary of PLCC analysis results

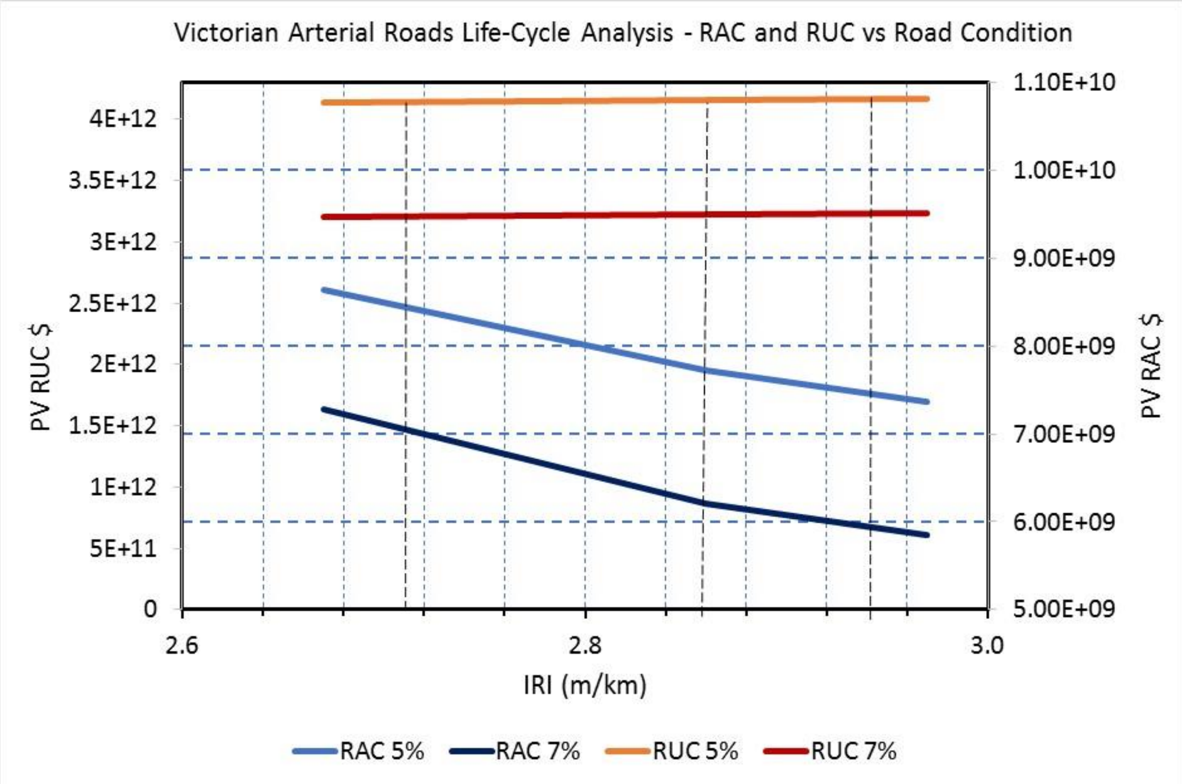


Figure A 1 shows clearly that with a reduction in RAC, the RUC increase.

APPENDIX B VARIATION OF LOAD-RELATED PAVEMENTS COSTS WITH INCREASED TRAFFIC

B.1 Sprayed Seal Unbound Granular Pavements

For Australia's sealed arterial road network, some 95% are sprayed bituminous seal unbound granular pavements (Oliver 1999, Austroads 2005, Bureau of Infrastructure, Transport and Regional Economics (BITRE) 2016). In the past, these pavements were designed (Equation A1) for a granular pavement thickness, t, that was a function of the cumulative design traffic load, DESA, which ranges from 10^5 to 10^8, and a design Californian Bearing Ratio (CBR) for the pavement subgrade, which ranges from about 3 to 7 with a typical value of 5.

Equation A1 does not consider the properties of the unbound granular pavement, but was based on empirical evidence (Austroads 2004); however, the most recent pavement design guide (Austroads 2012a) does consider material properties.

$$t = [\ 219 - 211 \times (\log \mathrm{CBR}) + 58 \times (\log \mathrm{CBR})^2\ ] \times \log (\mathrm{DESA}/120) \qquad \text{A1}$$

where

t	=	total pavement thickness (mm)
DESA	=	design traffic load in equivalent standard axles
CBR	=	Californian Bearing Ratio

The minimum pavement thicknesses for the base pavement cost can be related to the thickness that would apply to the hypothetical case of no usage by heavy vehicles. This pavement would need sufficient strength to carry construction and maintenance traffic. A lower-bound DESA of 10^3 ESA from the light-duty pavement design guide would be representative of such pavements (Austroads 1998). These pavements have design thicknesses (mm) of about 270 200 and 160 for design CBR values of 3, 5 and 7 respectively. Taking these as the minimum thickness, t_{min}, the % load-related cost portion for a pavement is the portion of the total pavement thickness, t, that exceeds the minimum pavement thickness as shown in Equation A2:

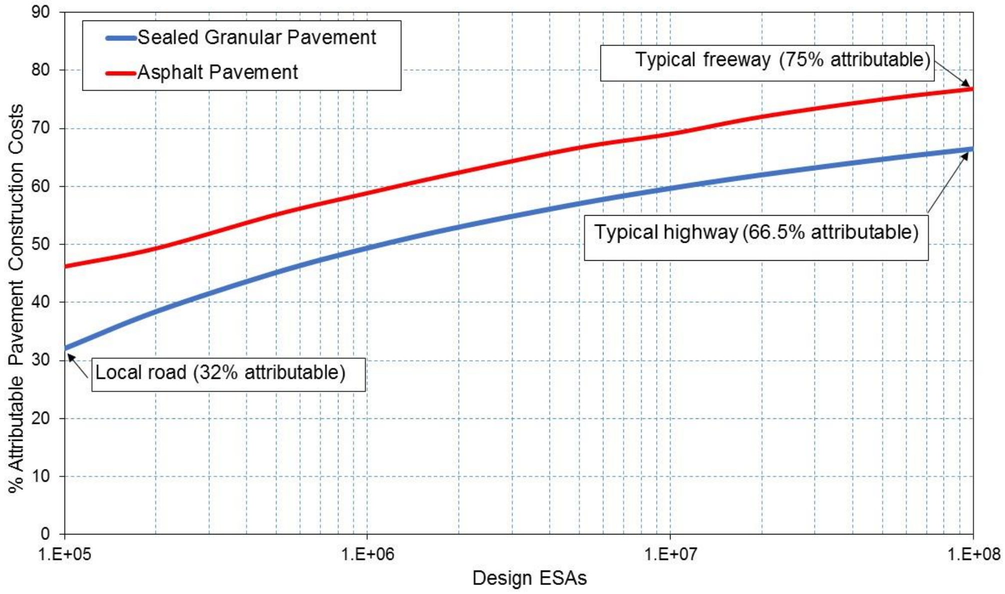
$$\%\ \text{load-related cost} = 100 - \frac{t_{\min}}{t} \times 100 \qquad \text{A2}$$

Equation A2 assumes that the pavement cost is directly proportional to pavement thickness which is a reasonable approximation of reality. Practices such as constructing the more heavily trafficked pavements with a base and sub-base, using lower quality/cost material in the sub-base will serve to reduce costs relative to thickness. However, this may be offset to a greater or lesser extent by the practice of specifying higher-quality/higher-cost materials in the base than would be used in less heavily trafficked pavements.

Equation A2 shows, for sprayed seal unbound granular rural pavements, that as the pavement thickness, t, gets bigger with increased traffic load, the % load-related cost increases. This confirms the FHWA (1997) outcomes that the % load-related pavement cost varies between a high of 83.7 (urban interstate) to a low of 42.6 (rural local).

Using Equation A2 with a CBR value of 5, Figure B 1 shows the variation of % load-related construction costs for a sprayed seal unbound granular pavement with increasing traffic load (ESAs).

Figure B 1: Variation of % load-related construction costs with traffic load (ESAs)



B.2 Asphalt Pavements

Asphalt pavements (AC) are usually found in urban areas and are often used for heavily trafficked rural roads (AADT[5] > 15 000 vehicles/day). Typically these pavements comprise a surface layer of asphalt over an unbound granular base. A 30 mm non-structural asphalt layer over the same minimum base thicknesses for granular pavements can be used for the base pavement cost case and regarded as the equivalent case for asphalt pavements.

Austroads (2004) recommends a mechanistic design procedure for pavements with a structural AC layer. However, design charts are given for subgrade conditions corresponding to CBR values of 3, 5 and 7 (Austroads 2004, Figures EC01, EC02 and EC03). These give the thickness of the AC layer as a function of the thickness of the granular sub-base and the DESAs. For the purpose of estimating % load-related pavement costs, the thickness of the granular sub-base was assumed to remain the same as for the minimum pavement and that the thickness of the asphalt layer would change in response to DESAs.

Because of the different costs for asphalt and granular materials, it cannot be assumed that the pavement cost is directly proportional to total pavement thickness. However, a relative cost, *RC*, for the pavement can be defined as:

$$RC = t_g + CF \times t_a \qquad \text{A3}$$

[5] AADT = Annual average daily traffic.

where t_g is the thickness of granular material, and t_a is the thickness of asphalt and CF is the cost of asphalt per unit of volume divided by the cost of granular material per unit of volume. The % load-related pavement cost is then given by:

$$\% \text{ load-related cost} = 100 - \frac{(t_{g\,\min} + CF \times t_{a\,\min})}{(t_g + CF \times t_a)} \times 100 \qquad \text{A4}$$

where

CF	=	cost of asphalt per unit of volume divided by the cost of granular material per unit of volume
$t_{g\ min}$	=	granular thickness for minimum pavement (mm)
$t_{a\ min}$	=	asphalt thickness for minimum pavement (mm)

Within the practical range, changes in subgrade CBR will have a similar relative effect on both the numerator and denominator for the ratio term in Equation A4, so the % load-related cost does not vary greatly with design CBR. The volume cost of asphalt is typically three to four times that of granular material (i.e. CF = 3 to 4).

The assumption used in the analysis of increased traffic loading being accommodated by increasing the asphalt thickness only is an over-simplification. In practice, designers seek to optimise the pavement configuration at the project level. Hence, the analysis tends to overestimate both pavement cost and therefore the % load-related cost. The % load-related cost using Equation A4 considers only the cost of the pavement above the subgrade allocated by the ESA-km parameter. Any other pavement cost items are excluded from the pavement costs being allocated as these costs are non-load related. Refinement of the load-related costs considering width effects may be possible, as noted in Section 2.4.1.

Equation A4 shows that the % load-related pavement cost will increase with the increased thickness of asphalt, t_a, needed to accommodate increased traffic, although at a much lower rate than for sealed granular pavements. Using Equation A4 with assumed values for CF (= 3.5), $t_{g\ min}$ (= 200 mm) and $t_{a\ min}$ (= 30 mm), Figure B 1 shows the variation of the % load-related construction costs for an asphalt pavement with increasing traffic load (ESAs).

The difference in the % load-related construction costs for granular and asphalt pavements in Figure B 1 is due to the assumed values used in Equation A2 and A4.

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APPENDIX C OUTLINE OF REVISED COST ALLOCATION MATRIX

Expenditure category	Location	Road class	Attributable cost		Non-attributable cost	
			%[1]	Parameter[(2)]	%[(1)]	Parameter[(2)]
Pavements – new, extra lanes and replacement	Urban	Freeways and major highways	65–75	ESA-km	35–25	VKT
		Main arterial	55–65	ESA-km	45–35	VKT
		Other arterials	45–55	ESA-km	55–45	VKT
	Rural	Freeways and major highways	55–65	ESA-km	45–35	VKT
		Main arterial	45–55	ESA-km	55–45	VKT
		Other arterials	35–45	ESA-km	65–55	VKT
Associated pavement facilities (new/replacement) – shoulders, kerbs, drains, earthworks, etc.	Urban	Freeways and major highways	5	PCU-km	95	VKT
		Main arterial	0		100	VKT
		Other arterials	0		100	VKT
	Rural	Freeways and major highways	10	PCU-km	90	VKT
		Main arterials	5	PCU-km	95	VKT
		Other arterials	5	PCU-km	100	VKT
Bridge superstructure – new, extra lanes and replacement	All	All	15	PCU-km	85	VKT
Bridge superstructure – deck rehabilitation or replacement, other superstructure rehabilitation	All	All	30	PCU-km	70	VKT
Bridge substructure – new, rehabilitation and replacement	All	All	15	GVW-km	85	VKT

Expenditure category	Location	Road class	Attributable cost		Non-attributable cost	
			%[1]	Parameter[(2)]	%[(1)]	Parameter[(2)]
Safety and mobility facilities – new, extra capacity and replacement (traffic signals, signage, barriers, etc.)	Urban	Freeways and major highways	10	PCU-km	90	VKT
		Main arterials	5	PCU-km	95	VKT
		Other arterials	5	PCU-km	95	VKT
	Rural	Freeways and major highways	5	PCU-km	95	VKT
		Main arterials	5	PCU-km	95	VKT
		Other arterials	0	PCU-km	100	VKT
Pavements – rehabilitation (structural)	Urban	Freeways and major highways	35–45	ESA-km	65–55	VKT
		Main arterials	45–50	ESA-km	55–50	VKT
		Other arterials	50–60	ESA-km	50–40	VKT
	Rural	Freeways and major highways	40–50	ESA-km	60–50	VKT
		Main arterials	45–55	ESA-km	55–45	VKT
		Other arterials	50–60	ESA-km	50–40	VKT
Pavements – periodic maintenance (resealing, surface correction, heavy patching, resurfacing)	Urban	Freeways and major highways	35–45	ESA-km	65–55	VKT
		Main arterial	45–50	ESA-km	55–50	VKT
		Other arterials	50–60	ESA-km	50–40	VKT
	Rural	Freeways and major highways	40–50	ESA-km	60–50	VKT
		Main arterials	45–55	ESA-km	55–45	VKT
		Other arterials	50–60	ESA-km	50–40	VKT

Expenditure category	Location	Road class	Attributable cost		Non-attributable cost	
			%[1]	Parameter[(2)]	%[(1)]	Parameter[(2)]
Pavements – routine maintenance (minor patching, drainage maintenance, pothole repairs, shoulder repairs & regrading, crack sealing, etc.)	All	All	10	PCU-km	90	VKT
Bridges (super and substructure) – minor repairs, repainting, etc.	All	All	0		100	VKT
Safety and mobility facilities – maintenance of traffic signals, signage, barriers, etc.	All	All	0		100	VKT

1 % is a nominal value (to be confirmed).
2 Parameter is nominal (TBC).