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ESTIMATION OF THE MARGINAL COST OF ROAD WEAR AS A BASIS FOR CHARGING FREIGHT VEHICLES

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ABSTRACT

In Australia one option for improved freight vehicle productivity, as part of major road reform, is increasing the allowable freight vehicle axle loads above current load limits and reduce the transport cost per tonne-km. This can also potentially reduce greenhouse gas (GHG) emissions by reducing the number of freight vehicle movements for a given freight task. Decisions regarding increased axle loads on the existing road infrastructure can be founded on the marginal cost of road wear as the basis of a price for increasing axle loads. These prices can provide a clear signal for targeting maintenance and rehabilitation funding and works provided the revenue raised by the price is directly linked to the funding.

The Freight Axle Limits Investigation Tool (FAMLIT) is a pavement life-cycle costing model that can be used to estimate load-wear-cost (LWC) relationships for a range of typical roads and pavement types for six heavy vehicle axle groups. Loads were incrementally increased above current load limits to estimate the LWC relationships. Life-cycle road wear costs were based on the present value (PV) of the routine and periodic maintenance and rehabilitation costs associated with managing each road type within agreed functional and structural conditions. The PVs of these costs were subsequently converted into equivalent annual uniform costs (EAUC) which were used to form LWC relationships with axle load (tonne-km) and standard axle repetitions (SAR-km), providing alternative independent variables. The marginal cost of road wear was determined by the first derivative of the LWC relationships.

The estimated marginal road wear costs, in both short-run marginal cost (SRMC) form and long-run marginal cost (LRMC) form were found to vary across a range of road types and were highly dependent on the pavement/subgrade strength and traffic load. The marginal costs based on the LWC relationship using SAR-km as the independent variable were a constant value until axle group loads were increased significantly above current limits.

Keywords: heavy vehicle charging, load wear costs, marginal wear cost, life-cycle costs, freight productivity

INTRODUCTION

Historically, improvements to Australia's road freight productivity have been brought about by increasing freight vehicle payloads and allowing road access for vehicles with longer, wider and taller configurations that still comply with safety standards. Most state and local government road agencies are concerned about allowing greater heavy vehicle access to the road infrastructure because of the cost consequences of increased pavement wear. Agencies expect that increased road wear will be appreciable once the current legal axle limits are exceeded. Consequently, the following significant questions need to be resolved: (i) can the current road network be used more productively; and, (ii) can road network access be managed in a way that enables the additional cost of this improved access to be fully recovered to allow preservation of road network capabilities.

Following an inquiry (Productivity Commission 2006) into road and rail infrastructure pricing, Australian governments have engaged in a process of exploring improved road infrastructure pricing models for heavy vehicles. The main thrust of this that more efficient price signals to heavy vehicles using the road infrastructure has the capacity to improve the use of the road network by encouraging use of the right vehicle on the right road. Further investigation was also undertaken into pricing schemes that enable access by vehicles carrying loads greater than the current mass limits provided charges to reflect additional road wear cost.

This paper presents the research findings of Austroads (Australian and New Zealand association of state, federal and local government road agencies) and the National Transport Commission (NTC) and other agency research work in this area directed at estimation of the marginal costs (MC) associated with higher axle loads for heavy vehicles. A range of different road and pavement types and climatic zones typical of the Australian road network were considered. MCs could provide key inputs into the proposed road infrastructure pricing reform.

APPROACH AND DEFINITIONS

Marginal road wear cost definition

Economic efficiency requires that prices are set equal to MC. The total and marginal costs of road usage, excluding congestion and other external costs, typically take into account two sets of factors: (i) the impact on road users in terms of vehicle operating costs; and, (ii) the impact of heavy vehicles on the road infrastructure.

This paper explains an approach used to estimate the marginal road wear cost resulting from increased axle loading on heavy vehicle axle groups beyond current legal or agreed axle load limits. MC estimates have been computed to measure the additional whole of life road agency wear cost associated with either an additional axle group load (tonne) pass, or a

Standard Axle Repetition[1] (SAR) unit. The marginal road wear cost impact on road users was not considered. The approach used in estimating the MC was a pavement life-cycle costing analysis based on engineering principles. This ensured that the level of service (LOS), in terms of the road roughness (functional condition) and strength (traffic load capacity) of the road pavement, was maintained to fall within defined bounds which meant that the MC impact on road users was close to zero as illustrated in Newbery (1988). Since the focus was on the impact that additional axle loading had on road wear costs, this paper estimates of the MC of road wear which is defined as including all the relevant road agency costs that are impacted by road usage. Two types of MC in the context of road infrastructure are considered:

1. The short-run marginal costs (SRMC) of road wear take into account the cost of maintaining a road within its defined roughness and strength level (LOS) and within its original design capacity. No pavement strengthening was allowed beyond its initial design strength.

2. The long-run marginal costs (LRMC) of road wear take into account the cost of maintaining a road within its defined roughness and strength level and allow pavement strengthening of any nature (including reconstructions) to occur at any time during its life-cycle.

It should be noted that pavement strengthening under LRMC conditions was timed so that the road agency life-cycle costs were reduced as much as possible. Optimisation was not possible as road user costs were not directly considered. The LOS, as noted above, was used as an alternative indirect measure.

SCOPE OF ANALYSIS

Initially the SRMC and LRMC were derived from the estimated increased road wear costs on various road and pavement types in three climatic zones, representing the Australian sealed road network, including local access roads. Increased road wear costs were caused by incremental axle load increases across six common axle groups used by the bulk of Australia's heavy vehicles.

Road wear cost estimates were made for each different axle group for each road and pavement type, including local roads, over a 50 year analysis period using the Freight Axle Mass Limits Investigation Tool (FAMLIT), a pavement life-cycle costing analysis model developed by Michel and Toole (2006). Road wear costs comprised the present value (PV) of the routine, periodic maintenance and rehabilitation costs incurred by maintaining each road type within set LOS conditions for roughness and strength over the analysis period. The PVs of these aggregated costs were converted (Hudson et al. 1997) into equivalent

[1] SARs represent the traffic load impact (wear) on the pavement. SARs are based on a standard axle equivalency estimated by the ratio of the actual axle group load to the axle group reference load, this ratio is raised by a damage exponent 'n' whose value depends on the pavement type. For granular (GN) pavements, n = 4; for asphalt (AC) pavements, n = 5; and for cement stabilised (CS) pavements, n = 12 (Austroads 2010c).

annual uniform costs (EAUC, Australian dollars, AUD/lane-km/year) to simplify the subsequent marginal cost analysis.

The impacts of increasing axle group load increments on road wear were quantified by developing separate load-wear-cost (LWC) relationships for each of the six axle groups for each of the designated road and pavement types representative of the Australian sealed road network. Load-wear costs, in terms of EAUC, were estimated using FAMLIT for one tonne increments for each group axle load over a range of axle group load increases ranging from their tare weight to well in excess of those allowed under the existing general mass limits (GML) regulatory framework. For each axle group pass, apart from the target axle group, the axle loads of the other axle groups were held constant at GML.

A simulated generic road network, using representative traffic and traffic load data, was developed as follows to represent three sealed pavement types (sprayed seal unbound granular (GN); asphalt (AC); and, cement stabilised(CS)) categorised in terms of traffic load capacity across a range of different locations and climates in Australia:

- 17 road types defined by pavement type and road hierarchy represented the road network, which were further categorised in terms of design traffic levels, urban and rural locations and three typical regional climates zones. This formed the basis of an initial road network matrix of both new (N) and in-service (S) pavements.

- New pavements (N) were designed to suit assumed existing traffic loads (Austroads 2010c) using an assumed Californian Bearing Ratio (CBR) of 5%.

- Existing in-service pavements (S) for each road type were examined at different points of their life-cycle, so each road type was assumed to include sections covering a typical range of pavement ages (distributed over 10, 20, 30 and 40 years, including new pavements). The conditions (roughness and strength) of these sections were predicted by applying roughness and strength road deterioration (RD) models to a newly constructed or rehabilitated pavement.

- Each road section was assumed to be one lane wide (typical width) and one kilometre long so the road wear costs could be calculated in terms of AUD/lane-km/year. Potential biases associated with initial pavement age and condition were controlled by using a range of ages and conditions for each road/pavement type.

The above assumptions regarding pavement conditions and ages were necessary because the relevant detailed Australian wide network level pavement condition information was not available for the study. These condition and age assumptions, although reasonable for a network simulation, did not represent any actual part of the Australian road network. However, the simulation did cover the usual expected range of the variables impacting on the MC of road wear associated with higher axle loads, taking into account the range of road and pavement types currently in service.

The following additional assumptions were used when determining the road wear costs:

- No traffic growth of heavy vehicles was considered during the life-cycle costing analyses of road wear.

- The life-cycle costing analyses of road wear were conducted under an unconstrained road budget, that is, all loading scenarios assumed that adequate funds were available to perform maintenance and rehabilitation works when needed.

- The annual routine and periodic pavement maintenance costs, '*me*', increased with increasing axle loads (see Equation 1). These costs increase due to the increased frequency, or higher quality, of resealing/resurfacing along with additional routine maintenance work in response to increased axle loads.

Quantification of the impact of increasing axle loads on annual pavement maintenance costs, *me* (AUD/lane-km/year), was based on a previous analysis of heavy vehicle road use (Martin et al. 2010) as follows:

$$me = \alpha + 0.00309 \times \text{SAR/lane/year} \quad (1)$$

where

α = routine maintenance cost (increased with traffic load range)

SAR/lane/year = equivalent standard axles based on a damage exponent of 4 per lane per year.

FAMLIT LIFE-CYCLE COSTING ANALYSIS

The life-cycle costing analysis in FAMLIT involved the following:

- Rehabilitation works were triggered to meet specified intervention criteria for roughness and strength. Post rehabilitation, surface conditions were reset to new condition values (Austroads 2007) with the pavement age reset to zero. Road deterioration prediction then recommenced from zero age in the same manner as before.

- The road costs for the maintenance works (*me*, see Equation 1) were applied annually and at a specific point in time for pavement rehabilitation.

- The weighted average EAUC for each pavement and road type and climatic zone was then determined using the nominated pavement age distribution for each axle group load increment to develop the LWC.

Pavement deterioration and interventions

Roughness and structural RD models were used (Austroads 2010a, 2010b) to predict functional and structural deterioration over time due to the increased axle loads and conditions under which the interventions were triggered. Roughness deterioration was modelled as a function of cumulative SAR, climate, initial pavement strength (post construction or reset value after rehabilitation) and the following variables:

1. The amount of annual pavement maintenance cost, '*me*', influences the rate of roughness deterioration. Increasing the amount of '*me*' reduces the rate of deterioration while reducing the amount of '*me*' increases the rate of deterioration which influences the early need for an intervention by rehabilitation.

2. The amount of rutting present influences the rate of roughness deterioration and is considered in establishing whether an intervention by rehabilitation is required to avoid rapid roughness deterioration (Austroads 2010a).

The roughness RD model was calibrated to match the typical observed roughness deterioration on the road types in the network.

Loading scenarios

Table 1 summarises the loading scenarios used. The loading scenarios covered loading of the six main axle groups as follows: single axle single tyre (SAST), single axle dual tyre (SADT), tandem axle single tyre (TAST), tandem axle dual tyre (TADT), tri-axle dual tyre (TRDT) and quad axle dual tyre (QADT). The loading scenarios used one tonne axle group load increments starting at the mass associated with vehicle tare weight and were increased well beyond the current GML.

Table 1 - Axle group loading combinations used in the analysis

Loading scenario	SAST (tonne)	SADT (tonne)	TAST (tonne)	TADT (tonne)	TRDT (tonne)	QADT (tonne)
Reference load	5.4	8.15	9.17	13.76	18.45	22.53
Load increment	1	1	1	1	1	1
Axle load offset	2	3	5	5.5	9	9.75
Tare weight	3	4	6	6.5	10	10.75
Base GML	6	9	11	16.5	20	24
Maximum load	12	15	20	26.5	35	45
Load increment range	3 - 12	4 - 15	6 – 20	6.5 - 26.5	10 - 35	10.75 - 45

As the analysis assumed an invariant distribution of load on axle groups other than the target group for each pavement and road type, it was therefore possible to make the above separate assessment of the road wear cost of each axle group with incremental load increases.

Traffic Loading

The annual traffic loading (base case) for each road type was based on annual weigh-in-motion (WIM) data, which allowed assessment of the various heavy vehicle types and axle group load distributions (Austroads 2008) together with typical annual average daily traffic (AADT) volumes. Studies on the load equivalency and damage exponents for different pavement types (Austroads 2010c) recommend the following damage exponents in estimating SAR to assess the road wear impacts of different axle group loads on the different pavement types: (i) granular pavements (GN) with a sprayed seal, used SAR4, i.e., a damage exponent of 4; (ii) asphalt pavements (AC) used SAR5, i.e., a damage exponent of 5; and, (ii) cement stabilised pavements, CS, used SAR12, i.e., a damage exponent of 12.

ESTIMATION OF SRMC AND LRMC

The SRMC was based on FAMLIT estimates using a realistic minimum overlay/re-sheet thickness applied at each rehabilitation intervention to ensure that the roughness was returned to a satisfactory achievable reset value. The minimum thickness was different for an AC overlay and GN re-sheet. The unintended result of applying a minimum overlay thickness was that if the strength did not deteriorate to defined points by the time roughness reached its intervention trigger point, the minimum overlay thickness increased strength beyond its initial design value. This somewhat contradicts the definition of SRMC and is close to the definition of LRMC. However, it does deliver a reasonably consistent level of service for road users, in terms of roughness within defined bounds and reflects the reality of maintaining pavements.

A standard LRMC estimation allows strength to be varied at any point in the pavement life-cycle. Pavements were allowed to strengthen in response to higher loads. The LRMC estimation was developed in FAMLIT such that strength was improved at the first intervention point if this was considered optimal in the sense that higher loads necessitate higher design strength. Clearly, there are some imperfections in this approach since strength can only be altered at the first intervention point and reconstruction at the start of the life-cycle was not considered as an option. It was also considered that reconstruction would not be optimal given current pavement engineering practices except for the non-typical case of very high loads on low strength pavements.

The analyses conducted using FAMLIT in this context were estimated under the condition of SRMC because under most conditions SRMC is approximately equal to LRMC as found previously (Martin et al. 2010).

PRESENTATION OF RESULTS

To simplify presentation of the results, the EAUC values resulting from the FAMLIT analyses were regressed against tonne-km and SAR-km values separately for each one tonne load increment on the axle group to form the LWC relationships. The two complementary sets of equations allow MC to be appreciated from both the vehicle operator and pavement provider perspectives. This resulted in a series of regression equations (LWC) for each axle group and road and pavement type combination. The MC of road usage was determined for each climate/axle group/pavement type/road type combination. The MC was based on the LWC relationship, a non-linear relationship in terms of EAUC as a function of axle group load (tonne-km), as shown in Equation 2:

$$EAUC = a0 + (TMI + TMIOFFSET)^{a1} + a2 \times (\text{Axle load} - \text{Offset})^{a3} \qquad 2$$

The environmental impacts are modelled as independent of load impacts. The annual marginal cost (c/tonne-km/lane/year), MC_{ann}, is the first derivative of Equation 2 with respect to load as shown by Equation 3:

$$MC_{ann} = a2 \times a3 \times (\text{Axle load} - \text{Offset})^{(a3 - 1)} \qquad 3$$

where

TMI = Thornthwaite Moisture Index (Thornthwaite 1948)
TMIOFFSET = minimum TMI value used for each road type plus one
Offset = approximate group axle reference load base tonnes before incremental load were varied
Axle load = total load on axle group (tonne) per lane-km
a0, a1, a2, a3 = non-linear regression coefficients.

The MC was also based on the LWC relationship, a non-linear relationship expressed in terms of EAUC as a function of standard axle repetitions (SAR-km) as shown in Equation 4:

$$EAUC = a0^{/} + (TMI + TMIOFFSET)^{a1/} + a2^{/} \times (\text{SAR-km} - \text{Offset}) \qquad 4$$

The annual marginal cost (c/SAR-km/lane/year), MC_{ann}, is the first derivative of Equation 4 with respect to SAR-km as shown by Equation 5:

$$MC_{ann} = a2^{/} \qquad 5$$

where

SAR-km = annual pavement wear, SAR per lane-km
Offset = approximately reference base SAR-km before incremental loads increased
$a0^{/}$, $a1^{/}$, $a2^{/}$ = non-linear regression coefficients

all other variables are as defined previously.

The MC determined from Equation 5 has the convenience of being a constant value with increased SARs. This is in contrast to the MC determined from the non-linear Equation 3 which gives an increasing MC with increased axle load.

Marginal axle load costs per lane per axle pass can be calculated by dividing marginal axle load (tonne-km) costs per lane per annum by the number of axle group passes per year. Similarly, the marginal costs per SAR can be calculated by dividing the marginal SAR-km costs per lane per annum by the number of SAR-km per year.

LWC RELATIONSHIP ANALYSES AND RESULTS

Road and pavement types considered

Six road and pavements types (Austroads 2005) were analysed as part of the determination of the LWC relationships (Equations 2 and 4) and the MC estimation (Equations 3 and 5):

- rural freeways with GN pavements; this road type represented less than 0.2% of the sealed road network
- rural arterials with GN, AC and CS pavements in-service (S); this road type represented nearly 26% of the sealed road network with the GN pavement representing 96% of this road type
- rural arterials with GN pavements new (N); this road type represented less than 2% of the sealed road network
- urban arterials with GN pavements; this road type represents 3.9% of the sealed road network and the GN pavement represents 39% of this road type
- rural collectors with GN pavements; this road type represents 10% of the sealed road network
- rural access roads with GN pavements; this road type represents 19% of the sealed road network.

Climates considered

The TMI extreme values considered were from -50 to +80. Table 2 shows the climate zones for TMI variations that were applied to the various road types.

Table 2 - TMI climate classification

Climate zones	TMI
Alpine/wet coastal	+80 to + 40
Wet temperate	+ 10 to + 40
Temperate	+ 10 to - 5
Dry temperate	- 5 to - 25
Semi-arid	- 25 to -50

The location of the climate zones in Table 2 were based on estimates of the Thornthwaite Moisture Index, TMI, for all locations across Australia using a climate tool developed by Byrne and Aguiar (2009). This tool estimates TMI values for any site based on its GPS coordinates and on annual rainfall and temperature data published by the Australian Bureau of Meteorology.

Table 3 summarises the 17 road types analysed, based on their road hierarchy and pavement types, together with the TMI values used to represent their locations across Australia and to broadly represent the Australian sealed road network.

Table 3 - Details of TMI values and dummy variable used for modelling

Road number	Road name	TMI and TMI dummy variable values		
		Low	Mid	High
1	Rural Freeway GN	50	0	-50
2	Rural Arterial GN (S)	50	0	-50
3	Urban Freeway CS	80	20	-20
4	Urban Arterial CS	80	20	-20
5	Rural Arterial AC (S)	50	0	-50
6	Urban Arterial AC (S)	80	20	-20
7	Urban Arterial GN	1	1	0
8	Urban Collector GN	80	20	-20
9	Urban Access GN	80	20	-20
10	Rural Arterial AC (N)	1	1	0
11	Urban Freeway AC	80	20	-20
12	Urban Arterial AC (N)	80	20	-20
13	Urban Collector AC	80	20	-20
14	Rural Arterial CS	50	0	-50
15	Rural Arterial GN (N)	1	1	0
16	Rural Collector GN	50	0	-50
17	Rural Access GN	50	0	-50

Notes: GN = granular, AC = asphaltic concrete, CS = cement stabilised, (S) = in service, (N) = new.

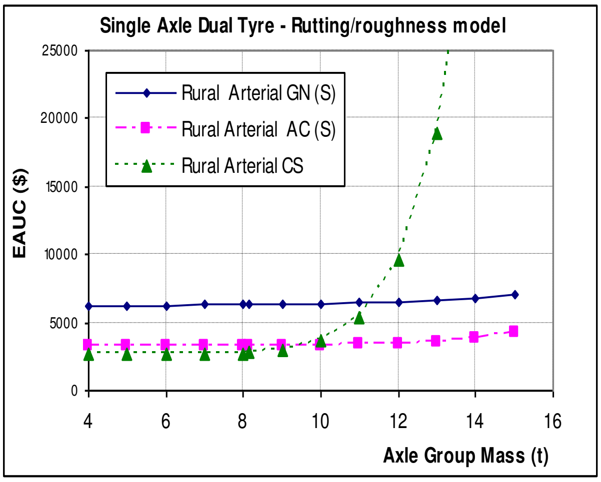
LWC RELATIONSHIPS AS A FUNCTION OF AXLE LOAD

Impact of pavement type and axle group on a given road type

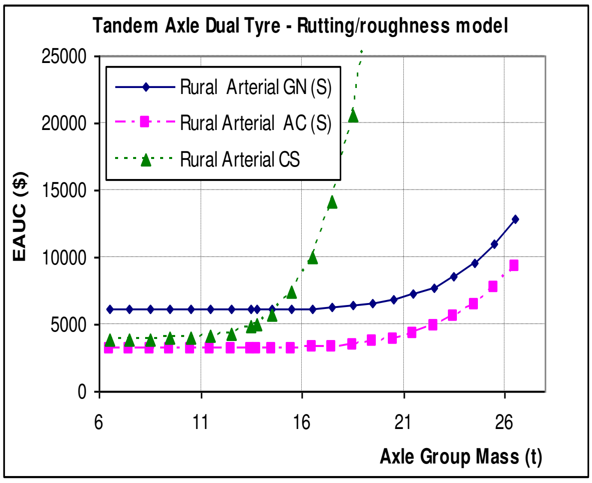
For the three most common heavy vehicle axle groups, SADT, TADT and TRDT, the LWC relationships using EAUC as a function of tonne-km (Equation 2) were determined for an in-service (S) rural arterial whose pavement types were: GN, AC and CS under mid-range TMI values (temperate climate).

Figures 1(a) to 1(c) show the distinctly different LWC relationships for the different pavement types, while the variations in LWC relationships due to the different axle groups are relatively minor. From these figures it is apparent that the CS pavements, which have a load damage exponent of 12, are the most cost sensitive to increases in axle load and therefore will have the highest MC. The next most cost sensitive to axle load increases are the AC pavements with a load damage exponent of 5, followed by the GN pavements with a load damage exponent of 4.

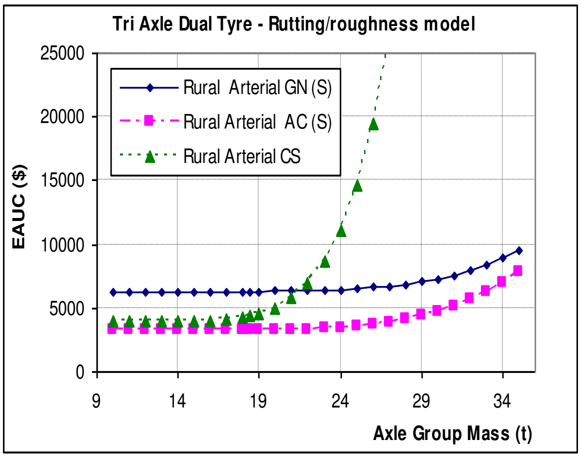
Figure (1b) for the TADT axle group appears to have the highest LWC relationships for all pavement types. This means that this axle group is most likely to produce the highest MC.



1(a) - SADT axle group



1(b) - TADT axle group



1(c) - TRDT axle group

Figure 1 - EAUC axle group load variations with load for pavement types on a rural arterial (mid-range TMI values)

Impact by road hierarchy type

For the most common heavy vehicle axle group, SADT, the LWC relationships using EAUC as a function of tonne-km (Equation 2) were determined for various representative road types with a GN pavement under mid-range TMI values.

Figure 2 shows that although the rural collectors and rural access roads have relatively low magnitudes of EAUC (road wear cost), they are the most cost sensitive to axle load increases. This means that these road types are likely to have a high MC. On the other hand, while the rural freeway has the highest magnitude of EAUC, it is the least cost sensitive to axle load increases and therefore is likely to have a low MC.

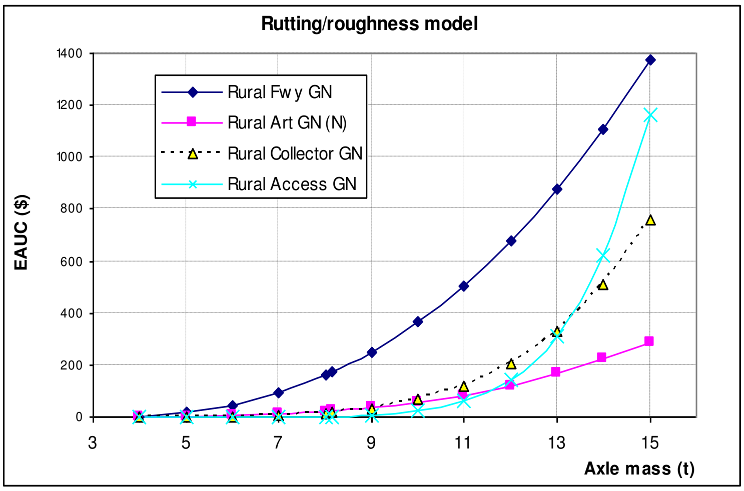
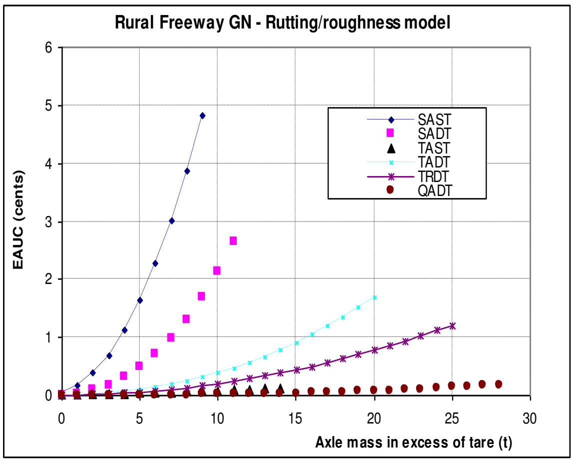


Figure 2 - EAUC road types variations with load on GN pavements (mid-range TMI values, SADT axle group)

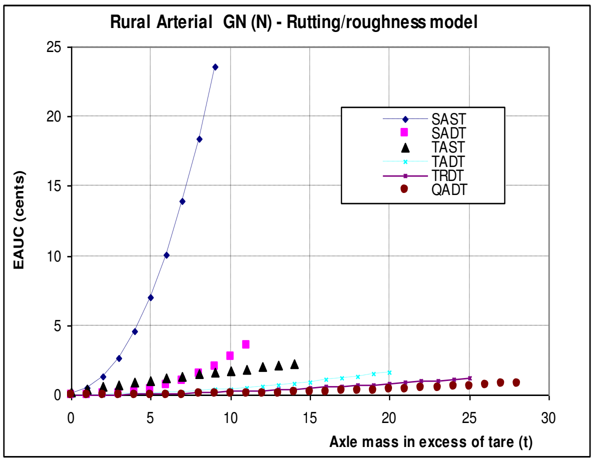
Impact of axle groups on various road types

For the six common heavy vehicle axle groups, SAST, SADT, TADT, TAST, TRDT and QADT, the LWC relationships using EAUC as a function of tonne-km (Equation 2) were determined for various typical road types with a GN pavement under mid-range TMI values.

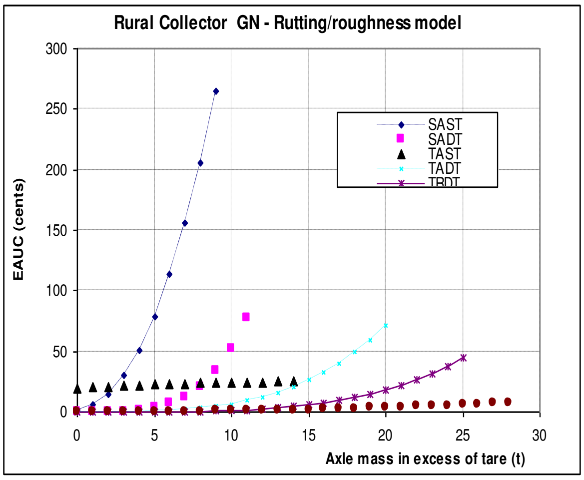
Figures 3(a) and 3(b) show that the rural freeways and rural arterials were much less cost sensitive. Figures 3(a) to 3(d) all show that the SAST axle group was the most cost sensitive on the road types examined, followed by the SADT axle group. Figures 3(c) and 3(d) show that the rural collectors and rural access roads were the most cost sensitive to axle load increases. The least cost sensitive to axle load increases were the TRDT and QADT axle groups.



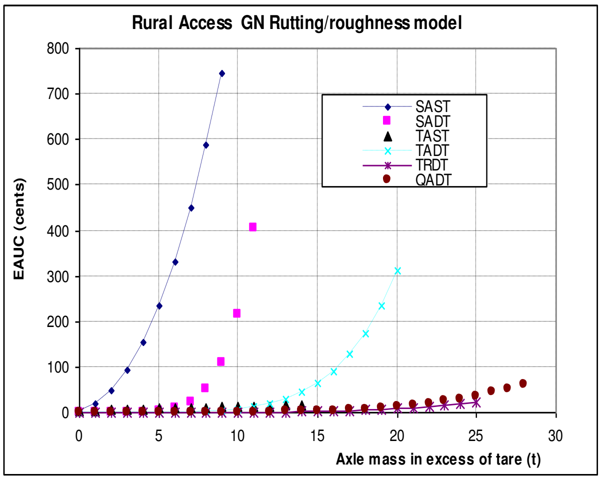
3(a) - Rural freeway



3(b) - Rural arterial



3(c) - Rural collector



3(d) - Rural access

Figure 3 - EAUC variation with load by axle group and road type (rural GN road types, mid-range TMI values)

Sensitivity analyses

For a given in-service (S) rural arterial with a GN pavement and TRDT axle group, three main parameters influencing sensitivity of EAUC to increased axle load were varied as follows under a constant climate, TMI (= 0):

1. the pavement/subgrade strength was varied ± 30% from the original value used in the FAMLIT analysis

2. the roughness progression for the pavement was reduced by lowering the calibration factor in the RD model

3. the traffic level on the road type was varied ± 15% from the original value used in the FAMLIT analysis.

Figure 4 shows the resulting impact on the EAUC estimates with increasing axle load due to changes in the above variables. Figure 4 shows the most significant influence on EAUC with increased axle load was the reduction in pavement strength. Under these conditions EAUC increased exponentially with increased axle load, consistent with increasing MC. Strength change impacts were asymmetric. An increase in strength reduced EAUC to a lesser extent than the decrease in strength increased EAUC. Figure 4 also shows under these conditions only minor increases in MC would occur with increased axle load. Changes in traffic had much less influence on EAUC, while the reduction in roughness progression uniformly reduced EAUC with increased axle load. These results show that the most pronounced influence on MC was a reduction in strength.

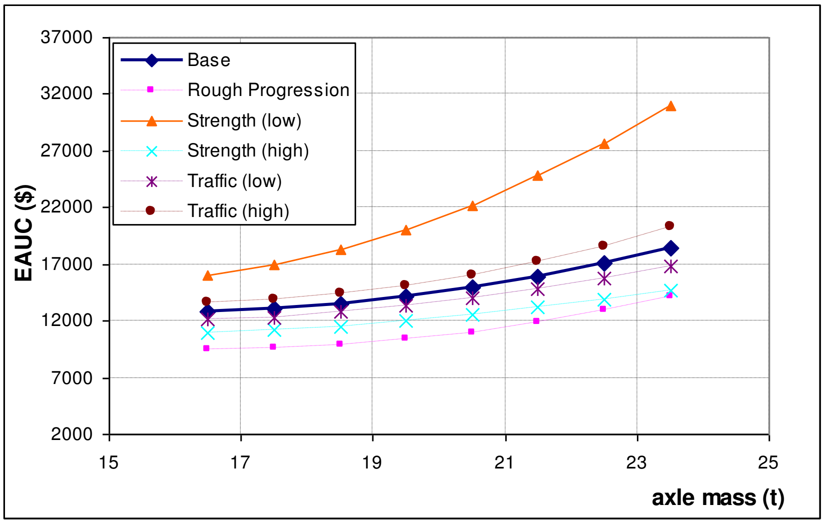


Figure 4 - Effect of varying pavement and traffic characteristics on EAUC for TRDT axle group load on in-service rural arterial GN pavements (TMI = 0)

LWC RELATIONSHIPS AS A FUNCTION OF SARS

Impact of axle group on a given road type

For all the axle groups, the LWC relationships using EAUC as a function of SAR-km (Equation 4) were determined on an urban arterial with pavement types GN under a given TMI.

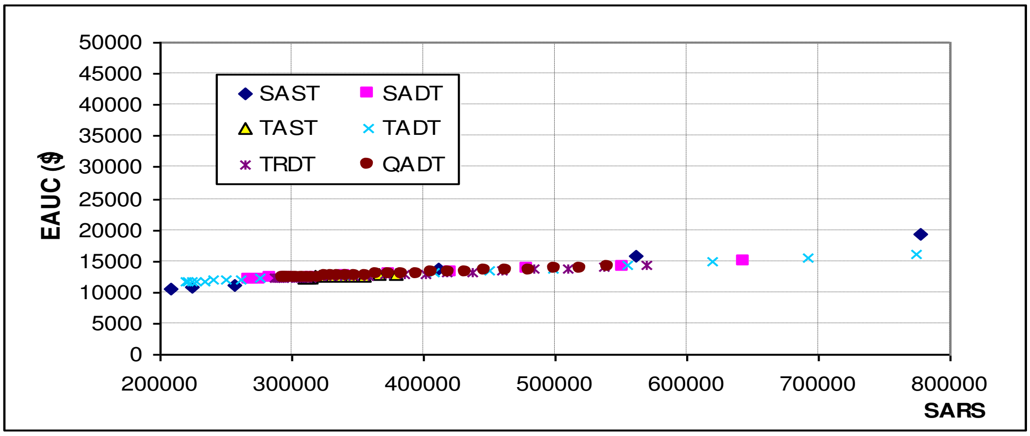


Figure 5 - EAUC vs. SAR for all axle groups, urban arterial GN pavement

As Figure 5 shows, approximately the same linear EAUC relationship with SAR-km occurs for all the axle groups on a given road type. When the axle loads (tonne-km) are expressed as SAR-km there is no need to present the results by different axle groups because the axle load equivalency nature of the specific reference load for each axle group (in converting axle load to SARs) gives equal wear for each axle group relative to the standard single axle.

Impact of road type on SAR relationships

For the TADT axle group, the LWC relationships using EAUC as a function of SAR-km (Equation 4) were determined for five typical road types with a GN pavement and constant TMI value. Figure 6 shows the five distinct LWC relationships with EAUC as a function of SAR-km for the five road types. The first derivative of these relationships (see Equation 5) gives the MC. The lowest MC occurs on the rural freeway and rural arterial (N), while the highest MC occur on the rural collector and rural access roads. This is the same outcome found when using the LWC relationship with EAUC as a function of tonne-km for the SADT axle group.

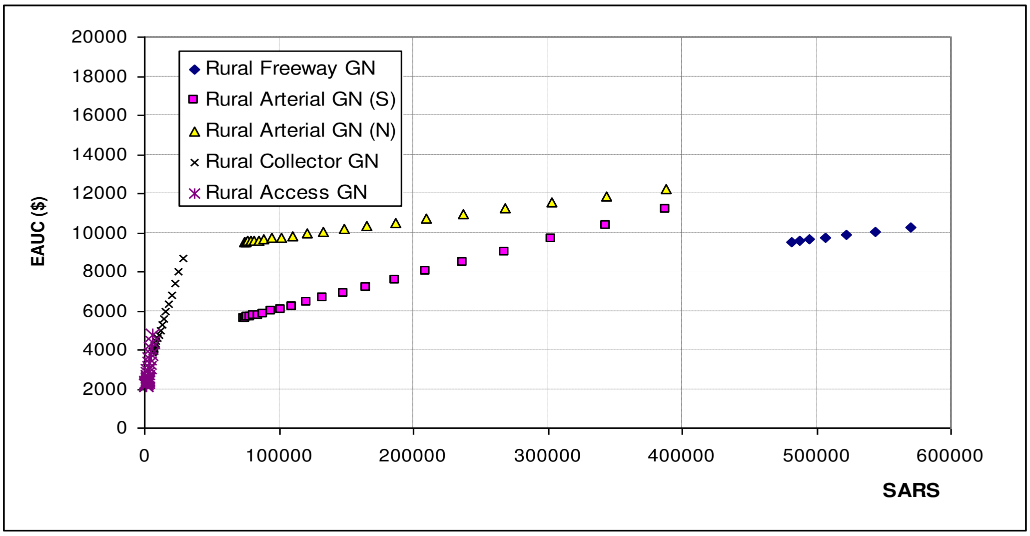


Figure 6 - EAUC vs. SAR relationships for GN pavements (TADT axle group)

Climate

Although different climatic conditions, represented by the variable TMI, were tested for each road type, and while they influenced the magnitude of EAUC, they did not have an impact on MC as no statistical evidence of interaction was detected. This is confirmed by Equation 5 where the coefficient, $a2^{/}$, in the original LWC relationship as a function of SAR-km (see Equation 4), is the coefficient for load, in terms of SAR only.

SUMMARY OF MARGINAL COST ESTIMATES

Table 4 summarises the MC estimates for the road types considered by this paper using the LWC relationships based on EAUC as a function of SAR-km.

Table 4 shows and confirms the earlier observations that the rural collectors and rural access roads have the highest MC while the rural freeways and rural arterials have the lowest MC. Table 4 also shows the impact of a new pavement (N) compared to an in-service pavement

(S) for rural arterials on the MC, with the rural arterial (S) having a much larger MC than the rural arterial (N) as expected.

Table 4 - Summary of marginal cost estimates

Road type	Marginal cost (cents/SAR-km) 2005 values	LWC relationship (r^2)	t-test significance (*p*) for SAR-km	No. observations
Rural freeway GN	0.8	0.97	$p < 0.005$	1380
Rural arterial GN (S)	1.8	0.95	$p < 0.005$	1380
Rural arterial GN (N)	0.9	0.98	$p < 0.005$	1380
Rural collector GN	21.6	0.97	$p < 0.005$	1380
Rural access GN	55.7	0.94	$p < 0.005$	1380
Urban arterial GN	0.8	0.94	$p < 0.005$	1380

MARGINAL COST ESTIMATES FOR A STATE ROAD NETWORK

Scope of Work

The Queensland Department of Transport and Main Roads (QTMR) requested an investigation of the potential MC of road wear arising from increased axle group loads on Queensland's sealed road network. The investigation was intended to assist QTMR in its participation in Australia's road reform discussions and enable it to prepare for any possible changes to regulations and legislation relating to heavy vehicle axle group load limits.

Data and sensitivity analysis

The QTMR data used to represent the network wide range of QTMR sealed road types was adapted into a format suitable for the development of the pavement LWC relationships. This involved acquiring and reconciling large quantities of pavement, sub-grade, traffic, road inventory and WIM traffic data (see Table 5) with the support of QTMR. The resulting database was more representative of Queensland conditions than the generic database previously developed for the development of the LWC relationships discussed earlier. Additional engineering and pavement performance data also led to improvement of the underlying FAMLIT pavement life-cycle costing model.

The MC of road wear was estimated under the condition of SRMC as undertaken earlier in this paper.

A sensitivity analysis was conducted for the QTMR roads which again confirmed that the pavement/sub-grade strength was the most sensitive input to the FAMLIT analysis when estimating the MC of road wear from the LWC relationships. Where lower pavement/subgrade strength values were used for four of the road types examined, the estimated MC increased by factors ranging from 1.3 to 8.9, depending on road and pavement type.

Increases in unit cost rate of maintenance/rehabilitation works and the RD model calibration factors produced increases in the overall annual maintenance or road wear costs. However, neither of these inputs caused significant change in the estimated MC of road wear because neither of these factors increased as the axle load increased. This outcome occurred when pavement conditions were constrained to an acceptable LOS.

Table 5 - Characteristics of road types defined by cross tabulation of route length (km) of road segments

Road type (function)	Pavement type	Traffic group AADT range								Total (km)
		<= 1500 (1)[1]		1501 – 5000 (2)[1]		5001 – 10000 (3)[1]		10001+ (4)[1]		
		Sub-grade reactivity								
		Non-reactive (km) (0)[2]	Reactive (km) (1)[3]	Non-reactive (km) (0)[2]	Reactive (km) (1)[3]	Non-reactive (km) (0)[2]	Reactive (km) (1)[3]	Non-reactive (km) (0)[2]	Reactive (km) (1)[3]	
Inter-regional	AC									
	CS	160	170							330
	GN	1,341	1,474	1,500	325	325		207		5172
Major-through	AC									
	CS	192								192
	GN	2,549	1,138	548	192					4427
Regional distributor & connector	AC									
	CS	557								557
	GN	8,201	4,056	1,356						13613
Rural land access	AC									
	CS									
	GN	643	97	22						762
Urban arterial	AC							841	63	904
	CS							43		43
	GN							269		269
Urban sub-arterial	AC					32		202		234
	CS									
	GN	25		37		44		126		232
Total		13668	6935	3463	517	401		1688	63	26,734

Note: 1. Denotes traffic range; 2. denotes non-reactive sub-grade (0); 3. denotes reactive sub-grade (1). This nomenclature was used in defining the road types.

Queensland Network Analysis

The QTMR road network, represented by 30 road types, provided a framework for assigning traffic and representative pavement characteristics, climatic variables, and other characteristics. The 30 road types were defined by the attributes of road functional class, three pavement types, traffic group, and sub-grade reactivity (sensitivity to moisture) as shown in Table 5.

In subsequent analyses each road type was assigned a pavement age distribution (five different initial ages), and three different climate zones. As a consequence, some 450 (= 30 x 5 x 3) road segments were analysed by FAMLIT for the full network analysis to develop LWC relationships under increased axle group load for the six main axle groups. The axle loading ranged from the tare weight (tonne) of each axle group to five tonnes in excess of the current GML of each axle group to fully develop the LWC relationships over the relevant range of expected load increases.

LWC relationships, in the form of EAUC versus tonne-km and EAUC versus SAR-km, respectively were estimated for each of the 30 road types and six axle groups, as well as additional LWC relationships for combinations of the 1 – 3 axle groups and the 1 – 6 axle groups. These relationships allowed estimation of the annual MC for axle group load increase on either a tonne-km or SAR-km basis. MC estimates were expressed in terms of annual cents/SAR-km because, as shown earlier, this was a convenient form for practical application.

The estimates of the annual MC from the combined axle groups for each road type were reasonably similar and did not provide MC estimates that were as high and as low as those MC estimates found for individual axle groups. The MC estimates based on sensitivity analysis, assuming the pavement/sub-grade strengths were the same as those used for the road types discussed earlier in the paper, were significantly increased for all road types.

Outcomes

The following outcomes arose from the MC estimation of road wear on the QTMR network:

- The impact of the various climatic zones in Queensland affected the aggregate annual road wear costs, EAUC, but did not appreciably impact on the MC estimates as found earlier. This outcome suggests that road wear charges need not be influenced by environmental factors associated with regional locations.

- The sensitivity analysis again confirmed that the pavement/sub-grade strength was the most sensitive input to the FAMLIT analysis when estimating the MC.

- A relativity analysis of the MC between the different QTMR road types showed that there are not very distinct differences in the relativities of MC between the different road types, except for the inter-regional roads (pavement type, CS) which have the greatest range of MC estimates.

- The above outcome was likely due to the relatively high QTMR pavement/sub-grade strengths which altered the relativities between the road types that were found earlier in the paper using assumed pavement/subgrade strength values.

- In the long term a review of QTMR road strength data could be undertaken to more reliably account for the differences in MC estimates across the different road types. This work could be deferred until reliable network level strength measurements are available with new technology that allows network level strength assessment at traffic speed.

These outcomes could form an initial basis for heavy vehicle charging in Queensland which is unlikely to be particularly sensitive to road type, with the possible exception of the inter-regionals (pavement, CS). However, further work needs to be done to reliably assess network pavement strength that forms the much of the basis for relative differences in MC estimates between road types.

SUMMARY AND CONCLUSIONS

The findings from the national research study and the Queensland road network example have illustrated some important outcomes regarding the estimation of the MC of road wear as follows:

1. An investigation into the definition and measurement of the SRMC and LRMC was needed to achieve a realistic assessment of these measures in this context. The SRMC was defined by its aim to restore pavement strength to its original design value when intervention is needed to maintain set levels of service, using a minimum rehabilitation treatment thickness. This definition could result in the restored pavement having a slightly higher strength than the original design strength because of the magnitude of the minimum thickness of the rehabilitation treatment. A previous study found that the SRMC and LRMC were approximately equal under commonly encountered conditions.

2. The MC of road wear can be simplified by using a cost per SAR-km measure, which can be applied to all axle groups on a given road type. This has the advantage of being a constant cost per road type while the MC, using tonne-km, varies as the axle load varies.

3. Variation in climatic conditions, as represented by TMI, while they can influence the magnitude of the annual road wear costs, EAUC, do not influence the MCs based on LWC relationships using Equations 2 and 4. This outcome suggests that road wear charges associated with load increases need not be influenced by regional locations.

4. Both sensitivity analyses confirmed that the pavement/subgrade strength has the greatest impact on the estimated MC. This is because the RD models used in FAMLIT were sensitive to increased axle load where the pavement strength is inadequate for the load.

5. From the earlier work in the paper, the LWC relationships of EAUC as a function of tonne-km and SAR-km both confirmed that the rural collectors and rural access roads have the highest MC while the rural freeways and rural arterials have the lowest MC, although these relativities were reduced when roads in Queensland were examined. Results confirm that load increases have more impact on a minor road.

6. The impact of the age of the pavement, either a new (N) or an in-service (S) pavement, has a significant impact on the MC.

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