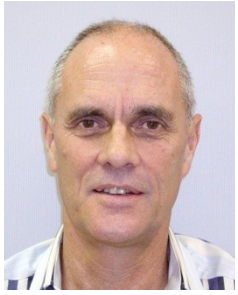
ESTIMATING THE MARGINAL COST OF ROAD WEAR ON AUSTRALIA'S SEALED ROAD NETWORK

Obtained B.E.(Hons) and PhD from Monash University and M.Eng.Sc. from the University of Melbourne, Australia. Currently Chief Scientist, Sustainable Infrastructure Management, ARRB Group.



T.C. MARTIN
ARRB Group
Australia

Obtained B.Ec.(Hons) from Monash University and M.App.Sc. from Swinburne University, Australia. Currently Principal Research Economist, Sustainable Infrastructure Management, ARRB Group.

T.R. THORESEN
ARRB Group
Australia

Obtained B.Comm (Hons) and M. App. Fin. from the University of Melbourne, Australia.
Currently Senior Manager Economics, National Transport Commission.

M.G. CLARKE
National Transport Commission
Australia

Obtained B.E. (Civil) from the University of Melbourne, Australia. Currently Graduate Consulting Engineer, ARRB Group.

W. C. HORE-LACEY
ARRB Group
Australia

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Abstract

In Australia improvements to road freight productivity have arisen mainly by increasing freight vehicle payloads. The higher axle group loads associated with increased payloads can, in some cases, significantly increase the marginal cost of road wear. Plans to permit operation of larger heavier freight vehicles in Australia make this an important issue. ARRB, through Austroads and the National Transport Commission (NTC) funding, have undertaken estimates of the marginal cost of road wear covering six axle group types with loads ranging from axle group tare weight to well in excess of the current general mass limits (GML) regulatory framework for a range of road types representing Australia's sealed road network. Through the use of a well informed pricing system, based on these marginal road wear cost estimates, road freight operators should improve their freight productivity while road agencies would be appropriately compensated for the road wear costs. Prices, costs and revenues based on marginal road wear costs would also provide signals for effective management of their road networks in regard to the availability of targeted funds for maintaining road freight routes.

Keywords: Marginal road wear costs, Heavy vehicles, Improved freight transport productivity

1. Introduction

Historically, improvements to Australia's road freight productivity has been on increasing freight vehicle payloads and allowing access to vehicles with longer, wider and taller configurations in a way that ensures safety. However, the road infrastructure service providers (that is, state government road agencies and local governments) are, generally speaking, close to the limit beyond which they are comfortable providing greater access. There are a variety of reasons for this, including the perception that road wear is quite significant at the higher end of the mass scale. Therefore, two significant challenges exist. Firstly, can the current road network be used more efficiently and productively and, secondly, can the road network access be expanded in a way that enables the additional cost of this improved access to be recovered.

In this context, following the Productivity Commission's (2006) inquiry into road and rail infrastructure pricing, Australian governments have been engaged in a process of exploring alternative road infrastructure pricing models for heavy vehicles through the Council of Australian Governments (COAG)'s road reform plan. This plan has a number of components to it, however, one common theme is the belief that more efficient price signals to heavy vehicle road users about use of road infrastructure taking into account the actual nature of the usage of the vehicle, in terms of weight (or mass), distance travelled and the location of the road usage, has the capacity to improve the utilisation of the road network by encouraging the right vehicle onto the right road. In addition, this plan included investigation of pricing schemes that would enable access to be opened up for vehicles to carry loads greater than the current mass limits provided that they were associated with a charge to reflect the additional road wear cost.

This paper presents some initial findings of a research study that has investigated the marginal costs associated with higher loads on a vehicle, taking into consideration that the Australian road network has many different road types. The research was funded by Austroads (Australian and New Zealand association of state, federal and local government road agencies) and the National Transport Commission (NTC) and undertaken by ARRB (formerly the Australian Road Research Board). The expectation is that these marginal costs can provide input into the evaluation of road infrastructure pricing reform.

2. General Approach and Assumptions

2.1 Definition of Marginal Cost

Economic efficiency requires that prices are set equal to marginal costs. The marginal costs of road usage[1] take into account two factors:

- the impact on road users in terms of vehicle operating costs
- the impact of heavy vehicles on the road infrastructure

In this light, the focus of this paper is on estimating the marginal road infrastructure cost resulting from additional units of road usage, focusing on higher loads on a vehicle. The marginal cost impact on road users has not been estimated. However, the analysis has been structured to test and ensure that the level of service, in terms of the roughness of the road pavement, stays within defined bounds[2]. Since the focus is on the impact that additional mass

[1] Congestion, safety and emission costs are not considered here.

[2] This should mean that the marginal cost impact on road users is close to zero which was illustrated in Newbery (1988).

(higher loads) has on road costs, this paper is focused on estimating the marginal cost of road wear[3]. There are two types of marginal costs that will be considered[4]:

- Short-run marginal costs (SRMC) will take into account the cost of maintaining a road within its defined roughness level but with the constraint that no pavement strengthening will be allowed beyond its initial design strength.
- The long-run marginal costs (LRMC) will also take into account the cost of maintaining a road within its defined roughness level with an allowance for pavement strengthening of any nature (including reconstructions) to occur at any time during its life-cycle as part of the cost minimisation function.

2.2 Model Construction

Road wear costs were estimated using the Freight Axle Mass Limits Investigation Tool (FAMLIT), a pavement life-cycle costing analysis model (Michel and Toole 2006), which was applied to six axle groups on a range of road types, representing Australia's sealed road network, over a 50 year analysis period. Road wear costs were based on the present value (PV) of the routine and periodic maintenance and rehabilitation costs incurred by managing each road type within agreed condition (roughness) limits over the analysis period. The PVs of these aggregated costs were converted (Hudson et al. 1997) to their equivalent annual uniform costs (EAUC, Australian dollars, AUD/lane-km) to simplify the analysis.

The impacts of increasing axle load increments on road wear were quantified by developing separate load-wear-cost (LWC) relationships for each of six axle groups for each of the designated road types in the Australian sealed road network (Thoresen et al. 2009). Load-wear costs, in terms of EAUC, were estimated using FAMLIT for 1 tonne increment increases in each group axle load over a range of axle load increases ranging from the tare weight to well in excess of those allowed under the 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.

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

- Some 17 road types were used to represent the road network, which were further categorised in terms of design traffic levels, in urban and rural locations under typical climates (three zones). They formed the basis of an initial network matrix of new and in-service pavements.
- The new pavements (N) were designed to suit assumed existing traffic loads (Austroads 2004) using an assumed Californian Bearing Ratio (CBR) of 5%.
- The existing in-service pavements (S) of 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 (10, 20, 30 and 40 years, including new pavements).

[3] Road wear is defined to include all of the relevant road costs that are impacted by road usage. Note that bridges have been excluded from the analysis and would most likely have very different marginal cost curves.

[4] SRMC and LRMC are alternative views of marginal costs and not different measures which are to be added. The distinction between SRMC and LRMC has been made because it has been assumed that the decision to strengthen a road beyond its original design is a different type of expenditure decision than a decision to repair a road back to its original design standard.

The condition (roughness) of these sections was predicted by applying a road deterioration (RD) model to a newly constructed or rehabilitated pavement.

- Each section was assumed to be one lane wide, with typical width, and one kilometre long so road wear costs could be calculated in terms of AUD/lane-km.

The following assumptions were used in determining 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 budget, that is, the road wear costs of all loading scenarios assumed that adequate funds were available to perform maintenance and rehabilitation works when needed.
- Routine and periodic maintenance costs were increased with increasing axle loads. This was to simulate increases in these costs due to either the increased frequency of resealing/resurfacing or the use of higher quality reseals/resurfacing along with additional routine maintenance work to cope with the increased axle loads[5].

2.3 FAMLIT lifecycle costing analysis

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

- Rehabilitation works were triggered as a result of meeting the intervention criteria. Following rehabilitation works, the surface conditions were reset to new condition values (Austroads 2007) and the pavement age was reset to zero. Road deterioration prediction then recommenced from this point in the same manner as before.
- The road costs for the maintenance works (*me*, see equation (1) in footnote 3) were applied annually and at a specific point in time for pavement rehabilitation.
- The weighted average EAUC for each pavement and road type and each climatic region was then determined using the nominated pavement age distribution for each axle group load increment to develop the LWC relationships with axle group load (tonne-km) and with standard axle repetitions (SAR-km).

2.4 Pavement deterioration and interventions

One of the key aspects of the modeling is the way in which the road deteriorates over time and interventions are triggered. Two different models were applied:

- Strength/roughness deterioration model (SRD): This model assumes that roughness deterioration is a function of cumulative standard axle repetitions, climate and the annual strength estimate. This roughness deterioration model was derived from an HDM[6] aggregate roughness model. Therefore, under the SRD model an intervention through rehabilitation occurs once cumulative standard axle repetitions results in roughness reaching a predefined trigger point.

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[5] The annual pavement maintenance cost (AUD/lane-km), *me*, was previously found to be related to road use (Byrne and Martin 2008) as follows:

$me = \alpha + 0.00309 \times ESA/lane/year$(1)where

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

Equation (1) quantified the impact of increased axle group loads on the pavement maintenance expenditure.

[6] Patterson, WDO and Attoh-Okine, B (1992)

- Rutting/roughness deterioration model (RRD): Similar to the first model, the RRD model (Martin 2009) assumes that roughness deterioration is a function of cumulative SAR, climate and initial strength. However, the RRD model has three additions:

    1. The amount of routine and periodic maintenance undertaken affects the need for an intervention by rehabilitation.
    2. Rutting as well as roughness is taken into consideration in establishing whether an intervention by rehabilitation is required.
    3. Roughness deterioration is a function of the initial design strength (or new value after intervention) instead of the annual strength value.

Therefore, under the RRD model a similar method of intervention occurs except there is an allowance for two other key factors to play a role in the timing of intervention (that is, routine maintenance and rutting).[7]

2.5 Loading Scenarios

The loading scenarios considered covered six axle groups as follows: single axle single tyre (SAST), single axle dual tyre (SADT), tandem axle single tyre (TAST), tandem axle dual tyre (TADT), triaxle dual tyre (TRDT) and quad axle dual tyre (QADT). The loading scenarios used 1 tonne axle group load increments starting at the tare weight and increasing well beyond GML. Table 1 summarises the loading scenarios used.

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 had assumed the distribution of load on the different axles groups 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.

2.6 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 2004) recommend the following damage exponents in estimating SAR to assess the road wear impacts of different axle group loads on the different pavement types:

- granular pavements with a sprayed seal, GN, used SAR4, i.e., a damage exponent of 4
- asphalt pavements, AC, used SAR5, i.e., a damage exponent of 5

[7] Note that the change from a variable strength to initial strength does not have a significant impact on the results.

- cement stabilised pavements, CS, used SAR12, i.e., a damage exponent of 12.

2.7 Incorporating SRMC and LRMC

Initially, marginal costs were estimated using the standard SRMC approach with both SRD and RRD models in FAMLIT. At each intervention, rehabilitation by either an AC overlay or a GN resheet was undertaken at a thickness that ensured that the pavement strength was returned to no greater than the initial design strength. However, the weakness of this approach was that the thickness was likely in many cases to be substantially less than what was required to return roughness back to a satisfactory achievable reset value of roughness. This first approach was defined as SRMC1.

In order to address the weakness of the SRMC1 approach, FAMLIT was altered to allow for a realistic minimum overlay/resheet thickness to be applied at each rehabilitation intervention in order ensure that roughness was returned back to a satisfactory achievable reset value of roughness. The minimum thickness that was applied was different for an AC overlay and GN resheet. This altered approach was defined as SRMC2. The unintended result of applying a minimum overlay thickness was that if the strength did not deteriorate to a certain point by the time roughness reached its intervention trigger point, the minimum overlay thickness would increase strength beyond its initial design value. This somewhat contradicts the definition of SRMC and is verging on our 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.

In terms of LRMCs, the constraint that strength cannot be varied beyond its initial design strength has already been breached with SRMC2. However, this was only done to ensure service levels. A standard LRMC would allow strength to be varied at any point in the pavement life-cycle. In this context LRMC1 has been developed in FAMLIT such that strength is improved at the first intervention point if this is considered optimal in the sense that higher loads necessitate a higher design strength. Clearly, there are some imperfections in this approach since strength is only altered at the first intervention point and reconstruction at the start of the life-cycle has not been considered as an option. However, it was considered that reconstruction would not be optimal given current pavement engineering practices except for very high loads on low strength pavements.

2.8 Representation of Analysis

To simplify the representation of the results, the EAUC values were regressed against the tonne-kms and SAR-kms values for each 1 tonne load increment on the axle group. This resulted in a series of regression equations for each axle group and road type combination[8].

[8] The marginal cost (MC) of road usage was determined for each climate/axle group/pavement type/road type combination. The MC was based on the LWC relationship, in terms of EAUC as a function of axle group load, as follows:

$EAUC = a0 + (TMI + TMIOFFSET)^{a1} + a2 \times (Axle\ Load - Offset)^{a3}$ (2)The annual marginal cost (c/tonne-km/year), MC_{ann}, is the first derivative of equation (2):

The marginal cost was based on the first derivative of the appropriate LWC relationship with respect to load (tonne) and SAR. These regression equations [9]will be illustrated throughout the results section. Marginal axle load costs per axle pass were calculated by dividing marginal axle load costs per annum by the number of axle group passes per year. This approach is equivalent to marginal cost per tonne-km, as the analysis sections were one kilometre in length.

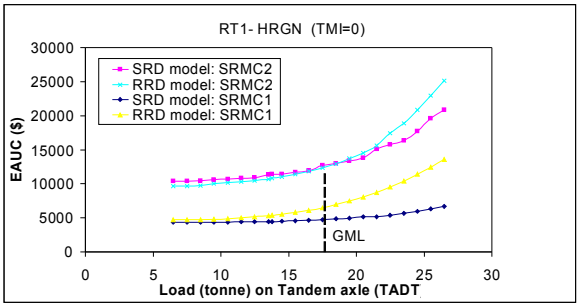
3. Results

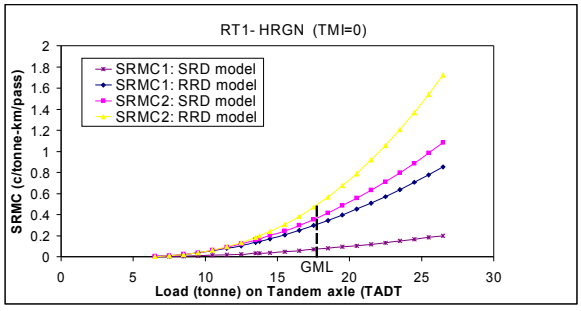
In order to illustrate some of the analysis three different sealed road types were selected, which represent approximately 63% of the total Australian sealed road kilometres, to provide a representative perspective on the results of the analysis. These road types[10] were:

1. High daily traffic rural granular pavement (RT1 – HRGN)
2. High daily traffic urban asphalt pavement (RT2 – HUAC)
3. Low daily traffic rural granular pavement (RT3 – LRGN)

3.1 SRMC and Deterioration Models

Figure 1 shows the LWC relationship, in terms of EAUC and tonne-km, for the TADT axle group on road type RT1 based on the SRMC1 and SRMC2 approaches using the SRD and RRD models to predict roughness during the life-cycle. Figure 2 shows the SRMC1 and SRMC2 estimates derived from the LWC relationships, using the SRD and RRD models, shown in Figure 1.





EAUC = 3786 + (TMI + TMIOFFSET)$^{1.602}$ + 0.288 (Axle Load – 5.5)$^{2.912}$ (SRMC1 approach, SRD model)

EAUC = 4131 + (TMI + TMIOFFSET)$^{1.61}$ + 1.264 (Axle Load – 5.5)$^{2.904}$ (SRMC1 approach, RRD model)

EAUC = 7356 + (TMI + TMIOFFSET)$^{1.936}$ + 1.193 (Axle Load –

SRMC1 = 0.288 × 2.912 (Axle Load – 5.5)$^{1.912}$ (SRD model)

SRMC1 = 1.264 × 2.904 (Axle Load – 5.5)$^{1.904}$ (RRD model)

SRMC2 = 1.193 × 2.991 (Axle Load – 5.5)$^{1.991}$ (SRD model)

SRMC2 = 0.618 × 3.325 (Axle Load – 5.5)$^{2.325}$ (RRD model)

MC_{ann} =a2 × a3 × (Axle Mass – Offset)$^{(a3 - 1)}$ (3)The marginal cost per axle group pass (c/tonne-km), MC_{axle}, is as follows: MC_{axle} =MC_{ann} /Number of axle group passes per year (4)where: a0, a1, a2 and a3 = regression coefficients; Axle Load = total load on axle group (tonne); TMI = Thornthwaite Moisture Index (Thornthwaite 1948) measure of climate; TMIOFFSET = the minimum TMI value used for each road type plus one; Offset = approximates axle group reference base tonnes before incremental axle loads were varied.

The MC was also based on the LWC relationship, in terms of EAUC as a function of standard axle repetitions (SAR):

EAUC =$a0^{l}$ + (TMI + TMIOFFSET)^{a11} + $a2^{l}$ × (SAR-km – Offset) (5)The annual marginal cost (c/SAR-km), MC_{ann}, is the first derivative of equation (5):
MC_{ann} =$a2^{l}$ (6)where: $a0^{l}$, a11, and $a2^{l}$ = regression coefficients; SAR-km = annual pavement wear, SAR, per lane-km; Offset = approximates reference base SAR-km before incremental axle loads increased.

[9] The regression analysis was non-linear least squares.

[10] Daily traffic in the context of these pavements is a reflection of the number of vehicles per day, not the loading on the vehicle.

$5.5)^{2.991}$ (SRMC2 approach, SRD model)
EAUC = 6770 + (TMI + TMIOFFSET)$^{1.995}$ + 0.618 (Axle Load – $5.5)^{3.325}$ (SRMC2 approach, RRD model)

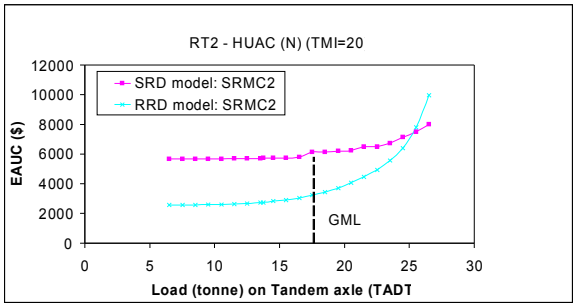
Figure 1 – EAUC vs tonne-km for TADT axle group (road type RT1)

Figure 2 – SRMC vs tonne-km for TADT axle group (road type RT1)

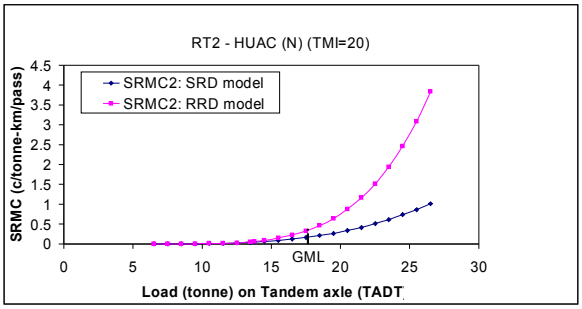
The LWC relationships based on the SRMC1 approach in Figure 1 are lower than those of the SRMC2 approach. This is because of the rehabilitation thickness needed to return the strength to its original value was thinner for the SRMC1 approach than that of the minimum thickness used for the SRMC2 approach. This was consistent for the LWC relationships across the three road types. SRMC2 was judged to be more appropriate in reflecting the intent of the SRMC definition since it results in achieving a roughness level that is within the bounds that were initially anticipated by the design of the road and therefore providing a consistent service to road users. In addition, although SRMC2 results in potentially a higher level of strength, and therefore lower marginal costs, this strengthening was not being undertaken to provide directly for more capacity to withstand loading, rather its focus was on maintaining a consistent level of roughness (with defined bounds).

Figure 3 shows the LWC relationship, in terms of EAUC and tonne-km, for the TADT axle group on road type RT2 based on the SRMC2 approach using the SRD and RRD models. Figure 4 shows the SRMC2 estimates derived from the LWC relationships, using the SRD and RRD models, shown in Figure 3. As shown in Figures 1, 2 3 and 4, the LWC relationships are different for the different road deterioration models, SRD and RRD. Interestingly, EAUC increased at a greater rate based on the RRD model after GML was exceeded compared with the EAUC estimates based on the SRD model.

The basis of the RRD model, as noted earlier, reflects the reality of pavement maintenance practice more closely than the SRD model and it includes more of the variables that impact on deterioration. For this reason the RRD model was used to estimate the relationships for the LWC and the SRMC and LRMC analysed further in this paper.



EAUC = 4747 + (TMI + TMIOFFSET)$^{1.715}$ + 0.00478 (Axle Load – $5.5)^{4.305}$ (SRMC2 approach, SRD model)
EAUC = 2049 + (TMI + TMIOFFSET)$^{1.654}$ + 0.0005 (Axle Load – $5.5)^{5.407}$ (SRMC2 approach, RRD model)



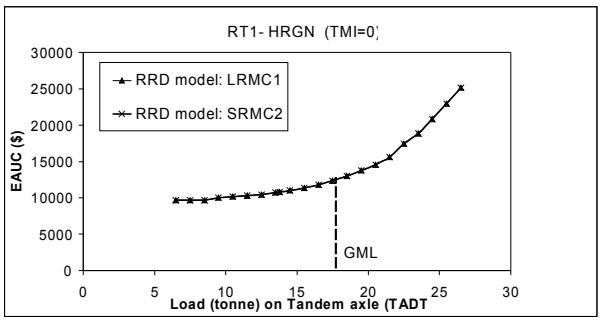
SRMC2 = 0.00478 × 4.305 (Axle Load – $5.5)^{3.305}$ (SRD model)
SRMC2 = 0.0005 × 5.407 (Axle Load – $5.5)^{4.407}$ (RRD model)

Figure 3 – EAUC vs tonne-km for TADT axle group (road type RT2)

Figure 4 – SRMC vs tonne-km for TADT axle group (road type RT2)

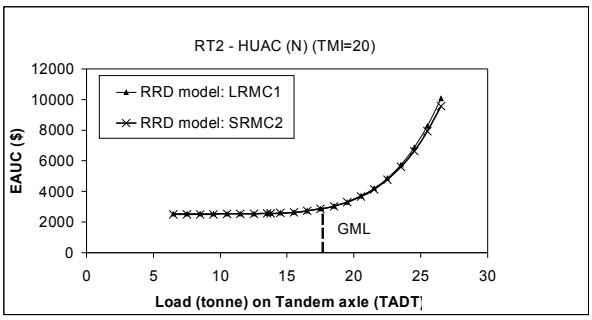
3.2 SRMC and LRMC

Figures 5, 6 and 7 show the LWC relationships, in terms of EAUC and tonne-km, for the TADT axle group on road types RTI, RT2 and RT3 based on the SRMC2 and LRMC1 approaches using only the RRD model. This allowed comparison of the estimates based on the SRMC2 and LRMC1 approaches.



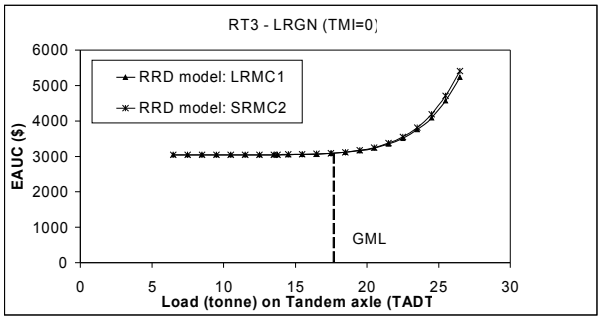
EAUC = 6770 + (TMI + TMIOFFSET)$^{1.995}$ + 0.618 (Axle Load – 5.5)$^{3.325}$ (SRMC2, RRD model)
EAUC = 6770 + (TMI + TMIOFFSET)$^{1.995}$ + 0.618 (Axle Load – 5.5)$^{3.325}$ (LRMC1 RRD model)

Figure 5 – EAUC vs tonne-km for TADT axle group (road type RT1)



EAUC = 2049 + (TMI + TMIOFFSET)$^{1.654}$ + 0.0005 (Axle Load – 5.5)$^{5.407}$ (SRMC2, RRD model)
EAUC = 2064 + (TMI + TMIOFFSET)$^{1.654}$ + 0.000335 (Axle Load – 5.5)$^{5.561}$ (LRMC1 RRD model)

Figure 6 – EAUC vs tonne-km for TADT axle group (road type RT2)



EAUC = 1162 + (TMI + TMIOFFSET)$^{1.918}$ + 0.0000006 (Axle Load – 5.5)$^{7.257}$ (SRMC2, RRD model)
EAUC = 1163 + (TMI + TMIOFFSET)$^{1.918}$ + 0.0000004 (Axle Load – 5.5)$^{7.364}$ (LRMC1, RRD model)

Figure 7 – EAUC vs tonne-km for TADT axle group (road type RT3)

For road type RT1, the SMRC2 is the same as the LRMC1 at all increments of mass as their LWC relationships were estimated to be exactly the same for both the SRMC2 and LRMC1 approaches. For this road no additional strengthening occurred under the LRMC1 approach so it matches the SRMC2 approach. However, for road type RT2, the LWC relationships show that the LRMC1 increases slightly more than the SRMC2 after a certain axle load above GML. This reflects the additional strengthening being undertaken under the LRMC1 approach when future strength requirements exceed the initial design strength.

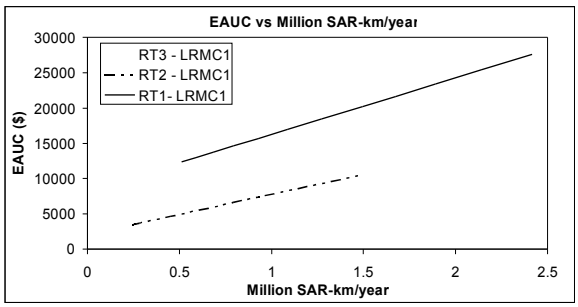
For road type RT3, the LWC relationships found show that the SRMC2 increases slightly more than the LRMC1 after a certain axle load above GML[11]. However, generally, the

[11] This result may be explained by the fact that more frequent rehabilitation occurs with the SRMC2 approach, while additional strengthening under the LRMC1 approach extends the period between rehabilitations at the relatively low traffic load on this road.

difference in LWC relationships under the SRMC2 and LRMC1 approaches is small and only appears to occur at the higher axle loads above GML for RT1, RT2 and RT3.

3.3 Marginal cost representation

As shown by equation (5), the LWC relationships can be expressed in terms of EUAC and SAR-km. These relationships can be converted to a marginal cost per SAR-km as shown by equation (6). Figures 8 and 9 for road types RT1, RT2 and RT3, using the RRD model for the TADT axle group with the LRMC1 approach show the LWC relationship as a function of SAR-km and the estimated LRMC1 ($/SAR-km), respectively.

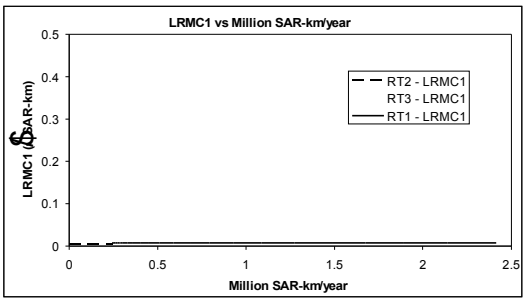


EAUC = 6444 + (TMI + TMIOFFSET)$^{1.995}$ + 0.00801 (SAR-km – 480000) (RT1, LRMC1, RRD model)

EAUC = 1718 + (TMI + TMIOFFSET)$^{1.651}$ + 0.00569 (SAR-km – 240000) (RT2, LRMC1, RRD model)

EAUC = 847 + (TMI + TMIOFFSET)$^{1.918}$ + 0.419 (SAR-km – 1200) (RT3, LRMC1, RRD model

Figure 8 – EAUC vs SAR-km for road type RT1, RT2, RT3 (LRMC1 approach)



LRMC = 0.00801 (RT1, LRMC1, RRD model)

LRMC = 0.00569 (RT2, LRMC1, RRD model)

LRMC = 0.419 (RT3, LRMC1, RRD model)

Figure 9 – LRMC vs SAR-km for road type RT1, RT2, RT3 (LRMC1 approach)

The LRMC1 estimated for the lightly loaded RT3 road type (41.9c/SAR-km) is significantly higher than that found for the more heavily loaded RT1 and RT2 road types (0.801 to 0.569c/SAR-km). This appears to be the general trend with estimates of LRMC1, that is, the marginal cost of road wear (c/SAR-km) increases when moving down the road type hierarchy. One of the key reasons for the variation in marginal costs is that RT3 has much lower pavement strength values than RT1 and RT2, which means that RT3 deteriorates relatively quicker and is therefore more sensitive to higher loads.

3.4 Some interesting findings

Road Types

The LRMC1 estimates vary for different road types, as noted previously. This can be indicated in Table 2, which illustrates the scale of marginal costs, in terms of c/SAR-km, for the three road types analysed in this paper using the LRMC1 approach with the RRD model. The significance of each road type, based on its portion of the Australian sealed road network, is also shown.

Table 2: Marginal cost (LRMC1) estimates (c/SAR-km) by road type

Road type	LRMC1 (c/SAR-km)	% Sealed road network
RT1	0.801	24
RT2	0.569	2

RT3	41.9	37

Climate
Although different climatic conditions, represented by the variable TMI, were tested for each road type and do have an impact on EAUC (and total road costs) they did not have an impact on marginal costs.

Axle groups
For any given road type, the individual axle groups have quite different LWC relationships when expressed as a function of tonne-km. The resulting LRMC1 and SRMC2, in terms of cost-tonne-km are also different for each axle group. Figure 10 shows the LWC relationship in terms of EAUC and tonne-km for the SADT, TADT and TRDT axle groups on road type RT2, using the RRD model.

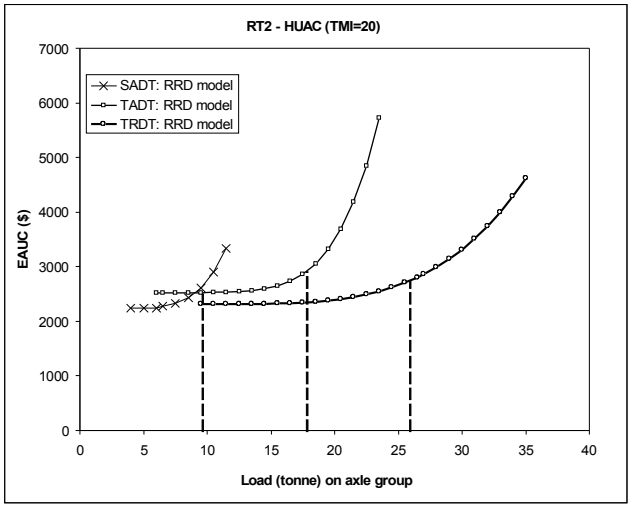


Figure 10 – LWC relationships for different axle groups on RT2 - HUAC

As Figure 10 shows, the marginal costs increase at varying rates as load increases across the different axle groups. However, when marginal costs are expressed in terms of SAR-km there is no need to present the results by different axle group because of the axle load equivalency nature of the specific reference load for each axle group that aims to give equal wear for each axle group relative to the standard single axle. This outcome is also driven by the fact that rehabilitation interventions are largely a function of SAR-km. This result is illustrated in Figure 11, which shows the LWC relationship, in terms of EAUC against SARs, for all six axle groups (as defined in Table 1) using the LRMC1 approach with the RRD model. As noted above, despite the different axle groups, the relationship between EAUC and SAR-km is a linear one for each road type.

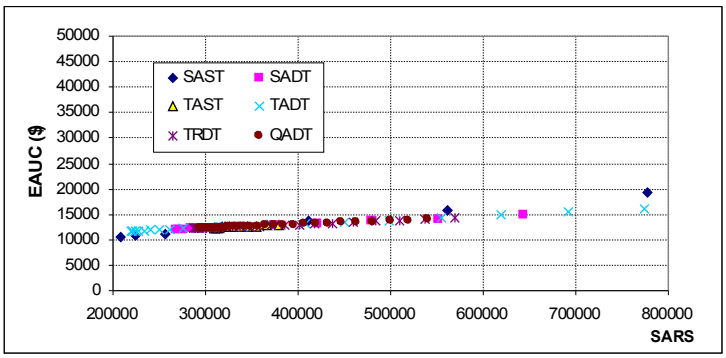


Figure 11 – LWC relationships for different axle groups on RT2 – HUAC

4. Conclusions

The initial findings from this research study have illustrated some important conclusions about the marginal costs of road wear. Firstly, some adjustments have had to be made to measurement of the SRMC definition to achieve a realistic assessment of this measure in this context. Secondly, LRMC (as defined in this paper) and SRMC are the same for most points on the cost curves up until the loads on axle are well above the GML. Thirdly, marginal costs can be simplified to a cost per SAR-km measure, which can be applied to all axle groups. The result of this is that the point of differentiation then becomes road types, which have a reasonable amount of variation.

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