Estimating Australia's Heavy Vehicle Road Wear Cost Responsibilities (Load Related Road Wear)

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ABSTRACT

The Australian Road Research Board (ARRB) has recently completed estimating the attributable (or separable) road track costs (state road agency costs) for Australia's arterial roads. The attributable road track maintenance costs (load related road wear costs) were estimated by a specifically developed load related road wear measuring technique using the ARRB road roughness profilometer and Falling Weight Deflectometer. This technique was adopted in conjunction with the conventional method of developing a statistical relationship between road agency maintenance expenditure (assumed equal to cost) and heavy vehicle road use.

The basis of the load related road wear measuring technique and its limitations are outlined. The technique appears reliable from measurements of load related wear taken on the same arterial road sites in 1991 and 1993. The relative importance and influence of variables, such as pavement strength, heavy vehicle road use and the environment, on the estimated levels of load related road wear have also been assessed by this measuring technique. The work indicates that for Australia's arterial roads, heavy vehicle road use and the environment are the significant factors influencing load related road wear.

The outcome of this research can be applied to heavy vehicle road user charging and life-cycle costing analyses for road asset management.

INTRODUCTION

The Australian Road Research Board (ARRB) has undertaken research since 1990 into the attribution of road track costs (road agency expenditures) to the users that give rise to them. This cost attribution research has been based on a pay-as-you-go (PAYGO) approach to road user charging.

ARRB has produced three reports on the attribution of road track costs to road users (Martin 1991, 1992, 1994). The attributable road wear costs, considered equivalent to attributable maintenance cost due to heavy vehicles, form one of the components that make up road user charges. The attributable road wear costs were estimated by the following approaches:

(i) Field measurement of load related road wear on 45 arterial road samples in all states except Queensland, Tasmania and South Australia. Load related wear measurements from 14 local roads in Victoria were included in a final review of this technique for assessing the relationship between load related wear and the variables influencing it; and

(ii) The variable portion of the annual average maintenance expenditure relationship. The maintenance expenditure relationship was developed by relating the annual average maintenance expenditure relationship with heavy vehicle road use and pavement age.

The basis of approach (i), the measurement of load related road wear, its limitations and the measurement results are presented in this paper.

DEFINITION OF LOAD RELATED ROAD WEAR

Road wear is considered to be the wear that is addressed by road maintenance activities. Road maintenance is aimed at preserving and restoring the road to a level of performance that does not exceed that of the original design. Load related road wear is the portion of road wear that is caused by, or attributable to, heavy vehicles.

Road roughness is used to represent pavement surface condition because previous studies have found a high degree of correlation between pavement surface condition and roughness (Lay 1985). Other measures of pavement surface condition, such as cracking and rutting, also reflect pavement surface condition and in many cases are responsible for initiating maintenance, but road roughness data has the advantage that it is inexpensive and easy to collect.

Road roughness is postulated (Potter 1991) as a simple addition of non-load related roughness changes (environmental) and load related roughness changes (heavy vehicle axle loads). In equation form this postulation is as follows:

$$R(t) = R_o + f_1\,(E,S,t) + f_2\,(E,S,L,t) \qquad (1)$$

where,

$R(t)$ = total road roughness measured at time t
R_0 = initial road roughness at time $t = 0$
$f_1\ (E,S,t)$ = change in non-load related road roughness = $\Delta R(t)_{n/l}$
$f_2\ (E,S,L,t)$ = change in load related road roughness = $\Delta R(t)_l$
E = environmental effects
S = pavement and subgrade strength assessment
L = load applied to pavement from heavy vehicles

EQ (1) does not have the separate load/non-load interaction terms used by some other models (eg. Fwa and Sinha 1985, 1987). This implies that EQ (1) may over estimate the load related road wear. However, load related wear would not occur without the presence of loads from heavy vehicle axles irrespective of the possible adverse combinations of load and the environment.

If a separate interaction term was used it implies that there is 'pure' load related road roughness. In reality loads are always applied in some form of environment and cannot be separated from it unless a reference environment is assumed and defined. EQ (1) theoretically avoids this problem as the interaction between the load imposed L and the environment E in the function f_2 term recognises that loads are always applied in some form of environment.

EQ (1) is an additive roughness model similar to that used in the World Bank's HDM-III roughness progression model (Paterson 1987). Other model configurations are possible such as a multiplicative model involving the terms R_0, f_1, and f_2, but were not used as they do not easily lend themselves to the direct measurement of road wear adopted by this study.

For any change in road roughness $\Delta R(t)$ with time t EQ (1) reduces to the following:

$$\Delta R(t) = \Delta R(t)_{n/l} + \Delta R(t)_l \qquad (2)$$

where,

$$\Delta R(t)_{n/l} = R(t)_{n/l} - R_0$$
$$\Delta R(t)_l = R(t) - R(t)_{n/l}$$

The load related road wear portion of total road wear in terms of EQs (1) and (2) is defined as follows:

$$\text{load related portion of total road wear} = \frac{\Delta R(t)_l}{\Delta R(t)} = \frac{R(t) - R(t)_{n/l}}{R(t) - R_0} \qquad (3)$$

EQ (3) assumes that all road wear is reflected by some form of structural deformation, regardless of whether it is caused by load or non-load factors. In reality some surface road wear, such as polishing, flushing and ravelling, does not involve structural deformation, although this surface wear leads to major structural deformation with time. The surface road wear is probably a small component initially of all road wear in terms of its initial repair cost, but it becomes an increasingly large component of road wear with time if not repaired. Consequently, EQ (3) may under estimate all road wear because it is based on a structural approach to road wear.

FIELD MEASUREMENT OF LOAD RELATED ROAD WEAR

TWO LANE ARTERIALS

The total roughness along the inner and outer truck wheel paths 2 metres apart, $R(t)_{iwp}$ and $R(t)_{owp}$ respectively, was measured by the ARRB profilometer vehicle concurrently with the roughness between truck wheel paths, $R(t)_{bwp}$. This wheel path roughness measurement assumes that trucks travel centrally within lanes (Shankar and Lee 1985). The ARRB profilometer also measured the roughness along the road centre line, $R(t)_{cl}$, in a separate pass. Figure 1 shows the location of these roughness measurements relative to the pavement.

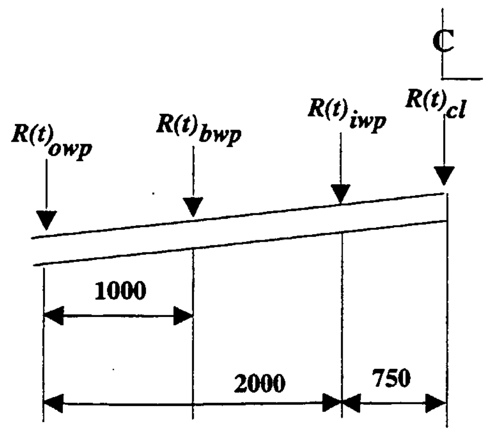

Figure 1 - Load Related Road Wear Measurement (Two Lane Road)

The total roughness measurements, $R(t)_{iwp}$ and $R(t)_{owp}$, comprise both the load related and non-load related roughness in the truck wheel paths, according to EQ (1), while the measurements, $R(t)_{bwp}$ and $R(t)_{cl}$, comprise non-load related roughness and the 'induced' load related roughness due to the adjacent truck wheel loads. The amount of 'induced' load related roughness depends on the capacity of the pavement to transfer deformation from truck wheel loads. Where the pavement is highly rigid there is considerable 'induced' load related roughness at the $R(t)_{bwp}$ and $R(t)_{cl}$ locations, while with an extremely soft pavement little 'induced' load related roughness occurs at the $R(t)_{bwp}$ and $R(t)_{cl}$ locations.

In order to account for the capacity of the pavement to 'induce' adjacent truck wheel loads, the Falling Weight Deflectometer (FWD) measured pavement deformation under a simulated truck wheel load. The FWD testing and its associated treatments are detailed elsewhere (Martin 1994, Appendix D). The FWD measurements of the pavement's vertical surface deformation (deflection bowl), were used in determining the correction factors, F_{cbwp} and F_{ccl} (Martin 1994, Appendix C.2). The correction factors, F_{cbwp} and F_{ccl}, were applied to the measured roughness changes at the $R(t)_{bwp}$ and $R(t)_{cl}$ locations respectively to give quantitative estimates of the 'induced' load related roughness.

The factors F_{cbwp} and F_{ccl} are defined as follows:

$$F_{cbwp} = \frac{D_{bwp}}{D_0} \quad (4a)$$

$$F_{ccl} = \frac{D_{ccl}}{D_0} \quad (4b)$$

where,

D_{bwp} = estimated total vertical deflection of the pavement surface between outer and inner wheel paths due to FWD test loads applied in truck wheel paths ('induced' load deformation)

D_{ccl} = estimated total vertical deflection of the pavement surface along the centre line due to FWD test loads applied in truck wheel paths ('induced' load deformation)

D_0 = estimated average vertical deflection of the pavement surface in wheel paths due to FWD test loads applied in truck wheel paths

EQs (4a) and (4b) assume a simple linear ratio of 'induced' load deformation (D_{bwp}, D_{ccl}) to the load deformation directly beneath the wheel path. This linearity may not occur on real pavements, but it is a useful first approximation until further refinement of the approach is undertaken.

EQ (3) is the 'reference' used in this study for load related road wear. Estimates of $\Delta R(t)$ and $\Delta R(t)_{n/l}$ were made as follows:

$$\Delta R(t) = 1/2 \times (\Delta R(t)_{iwp} + \Delta R(t)_{owp}) \quad (5a)$$

$$\Delta R(t)_{n/l} = 1/2 \times (\Delta R(t)_{n/lbwp} + \Delta R(t)_{n/lcl}) \quad (5b)$$

where,

$\Delta R(t)_{n/lbwp}$ = non-load related roughness between wheel path

$\Delta R(t)_{n/lcl}$ = non-load related roughness along road centre line

It is evident from the variation in transverse roughness measurements that load related road wear varies across a pavement's width, apart from the expected longitudinal variations. This outcome makes the assessment of $\Delta R(t)$ and $\Delta R(t)_{n/l}$ critical as alternative assessments could lead to different estimates of load related wear.

The following expression was derived (Martin 1994, Appendix C.1) for estimating load related road wear based on EQ (3), using the roughness measurements, $R(t)_{iwp}$, $R(t)_{owp}$, $R(t)_{bwp}$ and $R(t)_{cl}$, and the correction factors, F_{cbwp} and F_{ccl}:

$$\frac{\Delta R(t)_l}{\Delta R(t)} = \frac{\{R(t)_{iwp} + R(t)_{owp} - 2R_0 - [\{1 - F_{cbwp}\} \times (R(t)_{bwp} - R_0) + \{1 - F_{ccl}\} \times (R(t)_{cl} - R_0)]\}}{\{R(t)_{iwp} + R(t)_{owp} - 2R_0\}} \quad (6)$$

Inherent in this approach are a number of assumptions. The application of the correction factors F_{cbwp} and F_{ccl} to roughness measurement changes at $R(t)_{bwp}$ and $R(t)_{cl}$ implies that the 'induced' load related roughness changes are proportional to the sum of the 'induced' load deformations. This in turn assumes that the pavement is perfectly elastic and homogenous which is not the case in reality, but this assumption forms the basis of pavement design (Yoder and Witzcak 1975, AUSTROADS 1992).

A critical element in EQ (6), the initial roughness R_0, of each sample was not measured by this technique, but was assessed on the basis of historical roughness measurements (Martin 1994, Appendix C.3).

MULTI-LANE ARTERIALS

The approach outlined above for two lane roads was adapted to multi-lane roads. For four and six lane arterials, the total wheel path roughness was measured on the most heavily loaded lane, while the between wheel path roughness was measured along the least loaded lane. Estimates of the 'induced' load related roughness were made using correction factors specifically developed for the four and six lane configurations encountered during the study (Martin 1994, Appendix C.2).

LOAD RELATED ROAD WEAR RELATIONSHIPS WITH ROAD USE AND OTHER VARIABLES

FORMULATION OF RELATIONSHIPS

The measured load related road wear on the roads sampled was investigated for possible relationships with variables such as, road use, pavement strength and climatic effects. A multi-variable linear regression analysis was applied to these samples using the percentage load-related road wear as the dependent variable and the independent variables as follows:

$$\%\text{ load road wear} = a + b_1 \times \text{road use variable} + b_2 \times \text{SNC} + b_3 \times I \quad (7a)$$

where,

a = constant from regression analysis

b_1, b_2, b_3, = independent variable coefficients from regression analysis

SNC = modified structural number (Paterson 1987), representing pavement/subgrade strength

I = Thornthwaite Index (Thornthwaite 1948)

The road use variable is one of the following:

CESA/lane/year = cumulative equivalent standard axles/lane/year (heavy vehicles)

CGVM/lane/year = cumulative gross vehicle mass/lane/year (heavy vehicles)

CPCU/lane/year = cumulative passenger car units/lane/year (all vehicles)
AADT/lane = annual average daily traffic/lane (all vehicles/lane/day)

In addition to the simple linear relationship for percentage load related road wear of EQ (7a), two non-linear relationships for load related road wear were used. One of these relationships, EQ (7b), postulates that the percentage load related wear asymptotes ultimately to 100% as the independent variables increase in magnitude. The other relationship, EQ (7c), is a function of only one independent variable, *I*, the Thornthwaite Index. These relationships are defined as follows:

$$\%\text{ load related wear} = 100 \times \{1 - e^{[-c \times (d_1 \times \{\text{road use variable}\}^e + d_2 \times \{\text{SNC}\}^f + d_3 \times \{I + 50\}^g)]}\} \qquad (7b)$$

and,

$$\%\text{ load related wear} = x + y_1 \times (I) + y_2 \times (I)^2 \qquad (7c)$$

where,

x = constant from regression analysis
e, f, g = power coefficients from calibration
$y_1, y_2, d_1, d_2, d_3, c$ = independent variable coefficients from calibration or regression analysis
I, SNC, and road use variables are as defined previously.

EQ (7b) was calibrated by iteration with coefficients that gave the best statistical fit by the method of least squares (ie. highest R^2). EQ (7c) was solved by linear regression analysis.

The basis for selecting one of the road use variables in EQ (7a) was according to its statistical significance, from '*t*' and '*F*' testing, relative to other road use variables. Selection of the road use variable for EQ (7b) was based on using the road use variable that gave the best fit to the load related wear measurements. Only one road use variable appears in EQs (7a) and (7b) (Mendenhall and Sincich 1986) as these variables are not independent due to the method used in deriving them (Martin 1994, Appendix B.2).

Road Use The heavy vehicle road use variables in EQs (7a) and (7b) are an average of heavy vehicle road use accumulation per lane per year over the years of recorded road use. This measure was used rather than the usual heavy vehicle road use accumulation per lane, measured from the time when pavements are of zero age (commencing from construction/reconstruction or major rehabilitation), as pavements are subject to fatigue loading. The heavy vehicle road use data extended from 7 to 10 years and the average pavement age of the sample groups ranged from 8 to 23 years. Therefore the accumulative heavy vehicle road use measure was not used as it would involve making assumptions about heavy vehicle road use well beyond the years of record for most samples.

Other Variables The variable, SNC, was estimated from a statistical correlation between it and representative surface deflection bowls determined from FWD testing on each of the road samples (Jameson 1994). This correlation between SNC and surface deflection was estimated to be accurate to within one unit of SNC. The SNC estimation also assumed a constant pavement temperature of 25^0C during testing and the life of all the asphalt surfaced samples, which would not occur in practice. The effect of this assumption on SNC estimation is unknown as the asphalt thickness of each sample pavement was not measured.

Pavement age may account for variation in load related road wear. However, the pavement strength variable, SNC, acts as a proxy for pavement age effects as SNC decreases with time due to the influence of load and climate.

The Thornthwaite Index *I* is a measure of climate based on the soil suction properties of the subgrade beneath the pavement. A representative value of the variable *I* for each sample was based on previous broad estimates made in Australia (Aitchinson and Richards 1965, Figure 2).

Field Measurement Samples Table 1 summarises features of the sample roads measured for load related road wear. Some 45 arterial road sites in three states and the Northern Territory were measured for load related road wear. The urban arterial road sites were limited to Melbourne and Perth. Load related wear measurements made on a total of 14 local rural and urban roads were also included for comparison purposes from another study (Martin 1993).

Nearly 1% of Australia's sealed arterials (by length) were measured for load related wear.

REPEAT MEASUREMENTS ON RURAL AND URBAN ARTERIAL SAMPLES

A sample of 35 arterial road sites (18 in rural Victoria, 8 in rural New South Wales and 9 in urban Victoria) were measured for load related road wear in 1991. These measurements were repeated on these sites in 1993 to assess the reliability of the measuring technique. The load related wear estimates, based on EQ (6), from the 1991 and 1993 measurements were then compared. The maximum difference in these consecutive load related wear measurements at any one site was 9.8%. Most of this difference can be accounted for by the following effects:

(i) the profilometer has an estimated tracking error of 3%, that is, the roughness measurements can differ by up to 3% in the same lane due to the profilometer not always passing along exactly the same wheel paths within the lane; and
(ii) the FWD measurements from the 1991 survey were used in 1993 in calculating the correction factors F_{cbwp} and F_{ccl}, causing errors in estimating load related wear if pavement strength changes occurred after the 1991 FWD measurements.

Table 1

Load Related Road Wear Samples

Arterial Road Type	Location	No. of Samples	Sample Length Range (Av)* (km)	Total Sample Length (km) (% of Total)	Sample Pavement Age (yrs) (Av)	AADT / lane Range (Av)	CESA/l/yr (x 10^6) Range (Av)	Thornthwaite Index (*I*) Range (Av)	SNC Range (Av)
RURAL									
2–4 lanes	VIC	18	11 – 40 (25)	489 (0.5)	(23)	270 – 11,600 (2450)	0.03 – 1.27 (0.24)	– 22.5 to 70 (17)	2.3 – 4.7 (3.7)
2 lanes	NSW	8	14 – 20 (19)	154 (0.15)	(12)	1,650 – 6,500 (3700)	0.18 – 0.59 (0.36)	– 22.5 to 70 (30)	2.4 – 3.8 (2.9)
2 lanes	WA	3	15 – 23 (19)	56 (0.06)	(18)	160 – 820 (600)	0.03 – 0.1 (0.06)	– 40 to 80 (20)	2.6 – 5.2 (3.5)
2 lanes	NT	6	15 – 41 (29)	184 (0.18)	(13)	40 – 210 (100)	0.01 – 0.05 (0.03)	– 50 to 60 (-13)	2.7 – 5.0 (4.0)
URBAN									
4 - 6 lanes	VIC	9	0.8 – 2 (1.4)	13 (0.01)	-	5,100 – 11,100 (9400)	0.11 – 0.46 (0.23)	25 (25)	2.8 – 6.6 (4.0)
4 lanes	WA	1	6 (6)	6 (0.01)	(8)	4,400 (4400)	0.15 (0.15)	25 (25)	4.1 (4.1)
LOCAL									
Rural 2 lanes	VIC	7	4 – 15 (9)	58 (0.06)	-	25 – 1,000 (330)	0.003 – 0.14 (0.025)	5 to 25 (13)	1.6 – 3.4 (2.3)
Urban 2 lanes	VIC	7	0.9 – 8 (2.2)	16 (0.02)	-	160 – 5,100 (2900)	0.04 – 0.29 (0.16)	25 (25)	2.6 – 7.0 (3.4)
	TOTAL	**59**		**(1.0)**					

* Average (arithmetic mean)

The magnitude of effect (ii) is not known as it depends on the magnitude of the pavement strength change between surveys. Pavement strength between surveys may increase significantly due to major surface improvements and favourable climatic conditions. However, significant decreases in pavement strength are not expected from normal pavement deterioration alone, unless combined with adverse climatic conditions.

The urban arterial samples had a mean difference of a 0.4% (+ve) increase in measured load-related wear between the 1991 and 1993 surveys (difference range; -6.2% to +5.9%). Over the survey period the samples experienced a net average increase in total roughness of 0.28 IRI, due to roughness increases from pavement deterioration outweighing roughness decreases from surface improvements.

The New South Wales rural arterial samples had on average no difference in measured load related wear between the 1991 and 1993 surveys (difference range; -4.5% to +9.0%). During the survey period the samples underwent a net average decrease in total roughness of 0.2 IRI. This roughness decrease was due to the surface improvements reducing roughness being slightly greater than the roughness increases from pavement deterioration.

The Victorian rural arterial samples had a mean difference of a 1.6% (-ve) decrease in measured load related wear between the 1991 and 1993 surveys (difference range; -9.8% to +6.9%). Over the survey period the samples experienced a minor net average increase in total roughness of 0.03 IRI, due to the roughness increases from pavement deterioration being marginally greater than the roughness reductions from surface improvements.

In summary, the above results indicate that the load related wear measurement technique is reasonably robust when measurement errors are accounted for. However, the demonstrated robustness of the technique does not necessarily imply that the various assumptions used in its development have been validated.

LOAD RELATED WEAR RELATIONSHIPS

The results of the load related wear measurements on all samples are plotted in Figure 2 against the road use variable, CGVM/lane/year. These samples were stratified into several groups (A to I), based on state of origin, region and arterial road type, for further analysis using the formulations defined by equations (7a), (7b) and (7c).

Group (A) combined all samples. Group (B) combined and re-proportioned the arterial road samples so that samples from each state were represented in proportion to their heavy vehicle road use relative to that of Australia's total heavy vehicle road use. The group (B) re-proportioning could also have included other factors such as state/regional variations in climate I and pavement strength SNC along arterial roads, but data on these parameters was insufficient.

The results of these analyses are summarised in Table 2. The load related wear relationship for groups (A) and (B) significantly depend on the road use variable, CGVM/lane/year, and the Thornthwaite Index I ($p \leq 0.05$ and $p \leq 0.01$, respectively from 't' tests), but the coefficients of determination are low ($R^2 = 0.18$ to 0.19), demonstrating that the relationships do not fit the data very well. Improved R^2 values were gained with the stratification process for other sample groups. However, the improved R^2 values with sample stratification were at the general expense of the statistical significance of the independent variables ('t' tests) and the overall relationships ('F tests).

In summary, a general relationship with a reasonable goodness of fit to the measured load related wear of Australia's arterials was not obtained. However, the relationships found for sample groups (A) and (B) are similar even with the re-proportioning of samples in group (B). Improved relationships for the load related wear of the stratified sample groups were obtained, but these are not representative of Australia's arterials. On the other hand, while sample groups (A) and (B) have relationships of relatively poor fit, they are statistically significant (in terms of 't' and 'F' tests) and superior on this basis to the predictive relationships for the stratified sample groups.

ESTIMATES OF AUSTRALIA'S LOAD RELATED ROAD WEAR COST

The following summarises the estimates of load related road wear obtained for Australia's arterial roads:

(i) The 45 rural and urban arterial road samples gave a weighted arithmetic average estimate for load related wear of 47% (±9%). The weighting process was based on heavy vehicle road use;

(ii) Using the relationship (see Table 2) for group (A), and Australian wide representative values of its independent variables, CGVM/lane/year (Martin 1994, Appendix B.3) and I (= 19), gave an unweighted load related road wear estimate of 45% (±3%); and,

(iii) Using the relationship (see Table 2) for group (B), and the above representative values of the independent variables, gave a load related road wear estimate of 44% (±3%).

Approach (i) assumes that the sample results from each state group are representative of that state, while approach (ii) assumes that the relationship for group (A) is representative of Australia. Neither approach (i) nor approach (ii) is correct considering the sample size, although approach (i) is superior to approach (ii) as it accounts for some of the differences in sample sizes between state groups. Approach (iii) also attempts, by the re-proportioning of the sample groups, to be representative of Australia. Approach (iii) is superior to that of approach (i) because it relies on the regression analysis to provide the overall relationship rather than using a weighted average of sample group relationships. In addition, the estimated 95% confidence limits (±3%) associated with the approach (iii) estimate are narrower than those of approach (i).

Table 2
Load Related Road Wear Relationships

Sample Group	% Load related road wear relationship	No. Samples	R^2	F_{value}	t_{value}
(A) Rural & urban arts & local roads	$= 40.2 + 0.0.14 \times I + 0.75 \times$ CGVM/l/yr(10^6)	59	0.19	6.7 *($p < 0.05$)*	CGVM/l/yr 1.9 *($p < 0.05$)* *I* 2.5 *($p < 0.01$)*
(B) Australian rural & urban arterials (re-proportioned)	$= 38.7 + 0.0928 \times I + 0.985 \times$ CGVM/l/yr(10^6)	322*	0.18	7.3† *($p < 0.01$)*	CGVM/l/yr 2.3† *($p < 0.01$)* *I* 2.3† *($p < 0.01$)*

NOTE:

* Sample size increased from 45 to 322 by re-proportioning (multiplying) samples from States to achieve appropriate Australia wide representation of groups.

† F_{value} and t_{value} based on original sample numbers.

The above estimates of load related wear are relatively similar as they are based on the same arterial road samples, except for the group (A) samples which included 14 local roads. These estimates of load related wear, despite the generally poor goodness of fit for the relationships, are marginally lower than the attributable total maintenance expenditure estimate based on the statistical relationship between total maintenance expenditure and road use (Martin 1994).

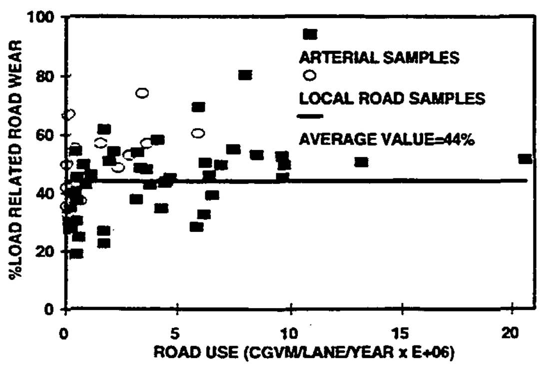

Figure 2. Load Related Road Wear vs Road Use (CGVM/Lane/Year).

ATTRIBUTION VARIABLE FOR THE LOAD RELATED ROAD WEAR COST

The independent road use variables in EQs (7a) and (7b) for load related road wear attribute load related road wear. For most sample groups the attribution variable for load related wear was CGVM/lane/year.

The road use variables that attribute load related wear were examined further by relating the load related wear measured on four samples, where road use was more precisely measured by CULWAY (weigh-in-motion), to the road use variables of these samples. This analysis yielded CESA/lane/year as having the highest statistical significance relative to the other road use variables, although the statistical significance of all these results was low ($R^2 \leq 0.25$ and $p \geq 0.1$ for the 't' and 'F' tests) and the number of samples was small.

In summary all the above results indicate that the load related wear attribution variable ranges from CGVM/lane/year to CESA/lane/year, despite the varying statistical significance of the relationships.

CONCLUSIONS

A method of measuring load related road wear was developed by ARRB in estimating Australia's heavy vehicle road wear cost responsibilities. Using this approach the following findings were made:

- The load related road wear measurement technique is robust and repeatable when measurement errors are accounted for;

- The load related road wear measurements varied from a minimum of 19% (rural arterial) to a maximum of 80% (urban arterial) on the 45 arterial road samples examined (see Figure 2);
- A general predictive relationship for the measured load related road wear of Australian arterial roads with reasonable goodness of fit to the data was not obtained (see Table 2, group (B)), although the group (B) relationship is statistically significant;
- The estimated load related road wear on Australia's arterial roads is lower than the statistical approach estimate of attributable total maintenance expenditure (Martin 1994, Table 5.1);
- The above result is consistent with the structural assumptions behind the load related road wear measurement approach providing an under estimate of load related road wear;
- As a consequence of the above, it follows that the load related road wear on Australia's arterial roads is a lower bound estimate of attributable total maintenance expenditure; and
- The load related road wear attribution variable ranges from CGVM/lane/year (GVM.km) to CESA/lane/year (ESA.km), consistent with the statistical approach estimates of attributable total maintenance expenditure (Martin 1994, Table 5.1).

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