SIMULATION OF DAMAGE EVOLUTION IN A SPRAY SEALED ROAD

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ABSTRACT

In Australia, heavy vehicles with 'road-friendly' suspensions are allowed higher static axle loads ('Higher Mass Limits' – HML), based on a type-approval test, performed on new vehicles. The 'Road Friendliness' regulation does not have any requirement for suspensions to retain their road-friendliness in-service. To pass the road-friendliness test, an air suspension needs to have fully-functioning hydraulic shock absorbers. These components wear with time, which reduces the damping level of the suspensions and can result in a substantial increase in the dynamic tyre forces. The question addressed in this paper is whether this poor suspension performance, when taken over the entire heavy vehicle fleet, will cause a significant increase in the maintenance costs of Australian roads.

The approach of the study is: (i) to develop a mathematical model of the interaction between a fleet of heavy vehicles and the road surface; (ii) to validate the model using road performance data; (iii) to predict long-term road maintenance intervention costs; (iv) to compare the predicted road maintenance costs for various vehicle fleet scenarios.

Key features of the model include: (i) modelling the dynamic performance of the vehicle fleet using a set of 'quarter car' vehicle models; (ii) careful accounting for the 'spatial repeatability' of tyre forces; (iii) use of accelerated pavement performance test data to model the evolution of the road surface profile; (iv) surface maintenance intervention based on permanent deformation (rutting), pot-holing and excessive surface roughness.

The simulation results indicate that conversion of a fleet with 'Current Mass Limits' (CML) from conventional leaf spring suspensions to 'road-friendly' suspensions would results in a reduction in road maintenance costs per tonne-km of 14%. Increasing the freight load to HML would reduce this benefit to approximately 1%. If the fleet was to have 100% poorly maintained shock absorbers, the simulations show an increase in road maintenance expenditures per tonn-km: about 29% higher than conventional suspensions at CML and 46% higher at HML. At CML, road maintenance costs for 'road-friendly' fleets are less than for conventional suspensions, provided no more than 40% of the fleet has disabled shock absorbers. However no such break-even point exists for HML, which is predicted to increase road maintenance costs whatever the suspension mix.

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1 INTRODUCTION

Road damage due to heavy vehicles depends on both the static tyre forces and the dynamic tyre forces caused by vehicle vibration, excited by road surface roughness, [1], [2]. Typically, suspensions with a combination of air springs and hydraulic shock absorbers are considered to be 'road friendly', while suspensions with steel leaf spring are not [3]. Hence the use of road–friendly vehicles is encouraged by some road authorities because they can have a higher static loads, but lower dynamic tyre forces, consequently reducing road damage, [4] [5].

The Australian Federal Office of Road Safety has issued a procedure, [6] [7] to certify the road - friendliness of vehicles using type-approval tests on new vehicles. Those suspensions passing the test are allowed to carry higher static axle loads, [8][1], [9]. Currently this is not supplemented by any legislation to maintain the in–service dynamic performance of heavy vehicles.

A theoretical study by Sweatman et al., [10] drew the conclusion that vehicles with air springs and non-functioning shock absorbers would not generate dynamic forces greater than vehicles with steel leaf springs suspensions. A subsequent economic study by Starrs et al., [11] based on Sweatman's data, reached the predictable conclusion that the costs of in–service assessment of the road–friendliness of heavy vehicles would not be justified by the reduction in road maintenance costs. Sweatman [10] also measured the effectiveness of a number of shock absorbers sampled from vehicles in-service, and found that 23% were ineffective.

Sweatman and Starr's results were questioned by Cebon, [12] who highlighted that air spring suspensions with poorly maintained shock absorbers may have significantly lower damping than leaf spring suspensions (e.g. as quantified by Woodroffe et al. [4]). Therefore the dynamic forces generated by poorly maintained air spring suspensions could be significantly higher than predicted by Sweatman. If Sweatman's conclusions [10] are flawed, then so is Starr's analysis [11].

Cebon [12] performed a simplified analysis, based on the 'road stress factor' (RSF) approach used by Sweatman, to evaluate the relative change in road maintenance expenditures due to various fleet scenarios (see Table 1). He concluded that a fleet of heavy vehicles fitted with partially non-functioning shock absorbers and Higher Mass Limits (HML) may be expected to increase road maintenance costs by 6% - 12 % compared with conventional steel leaf spring suspensions at Current Mass Limits (CML).

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[1] Higher Mass Limits (HML) allow a 6-axle tractor semi-trailer to have a GVW of 45.5t, consisting of 6.0t steering axle, 17.0t tandem drive and 22.5t triaxle trailer. This is increased from 42.5t at CML, (6.0t, 16.5t, 20.0t).

Table 1 - Preliminary calculation of the change in road maintenance costs for fleets of vehicles with different types of suspensions and loading - based on the ‘road stress factor’ approach (excerpt from [12]).

	Fleet Composition Scenarios					
Suspensions	1	2	3	4	5	6
Conventional steel leaf springs	100%	0%	0%	0%	0%	0%
Air springs + well-maintained shock absorbers	0%	100%	0%	75%	50%	25%
Air spring + poorly maintained shock absorbers	0%	0%	100%	25%	50%	75%
Pavement Maintenance Cost Change						
Current Mass Limits (CML)	**0%**	**-14%**	**7%**	**-9%**	**-3%**	**2%**
Higher Mass Limits (HML)	**10%**	**-6%**	**19%**	**0%**	**6%**	**12%**

In this paper, a more accurate analysis of road performance and maintenance costs is performed on a sample of sprayed sealed road. Sprayed seal is a light-duty construction that is widely used in Australia, New Zealand and South Africa for country roads (see [13] for details). The road simulation is validated using data obtained from a 122km section of State Highway No.17 (‘Newell Highway’), between Moree and Boggabilla, in North-Western New South Wales. This road was built around 1970 and the construction is mainly a sprayed seal (96% of the total length).

The NSW RTA, supplied the authors with the following information about the road: [14]

(i) Surface deflections recorded every 5m along both wheel – paths using a Deflectograph [15] in the years 2001-2004;

(ii) Surface elevation (longitudinal profile) recorded every 50 mm in both wheel tracks in the prescribed direction (Moree → Boggabilla) in the years 2001-2004;

(iii) Transverse profile every 50 mm along the road in the prescribed direction in the years 2001-2004;

(iv) Photographic survey with one photo approximately every 10 m in both directions, taken on January 12th 2004 (before some rehabilitation works).

(v) Results of a vehicle survey, performed in September 1999 [16] (see Table 2).

2 DESCRIPTION OF THE MODEL AND ITS VALIDATION

The performance of a section of the Newell Highway under heavy vehicle loading was simulated using a whole-life modelling methodology. See discussion of this modelling approach in [1] and a flow chart in Figure 1. A road profile is fed into the vehicle simulation module, which calculates the dynamic forces applied to the surface. The surface deformation is calculated and the road profile is updated. The process is repeated, using a number of different vehicle models, to simulate the passage of a fleet of vehicles over the progressively deforming road profile. When the road surface reaches various possible intervention conditions, the surface profile is ‘repaired’ and the maintenance costs are calculated.

The best available index of the surface condition for the Newell Highway is the International Roughness Index (IRI, see, [17], [18]) [19]). The IRI was calculated for each road subsection using ‘RoadRuf’ [20] in each year of data collection (2001-2004). The road was divided into lengths of approximately 1500 m and a regression line fitted to the IRI values collected over the four years of data. Two representative lengths of road were chosen for study: (i) a length exhibiting a slow evolution of the IRI, considered representative of a ‘strong’ road; (ii) a length exhibiting a faster evolution of the IRI, considered representative of a ‘weak’ road.

Each road profile was 'back–dated' to an initial IRI of 2.0 m/km by suitably decreasing the magnitude of its short wavelength roughness components. This made the profile representative of a typical newly–constructed sprayed seal road.

In modelling the dynamic tyre forces generated by mixed traffic it was assumed that all axles could be classified into three categories: steer axles, axles in tandem units and axles in triaxle units. In the simulation, the axles in tandem and triaxle units could have steel leaf spring suspensions, without shock absorbers, or air spring suspensions with hydraulic shock absorbers. They could be loaded to the static load limits defined by either the CML or HML regulations. A traffic survey taken on the road in September 1999, (first column of Table 2) was used to reconstruct the percentages of each type of axle present in the traffic using the road. Each axle type was simulated with an appropriate 'Quarter Car Model' (QCM), see Figure 2.

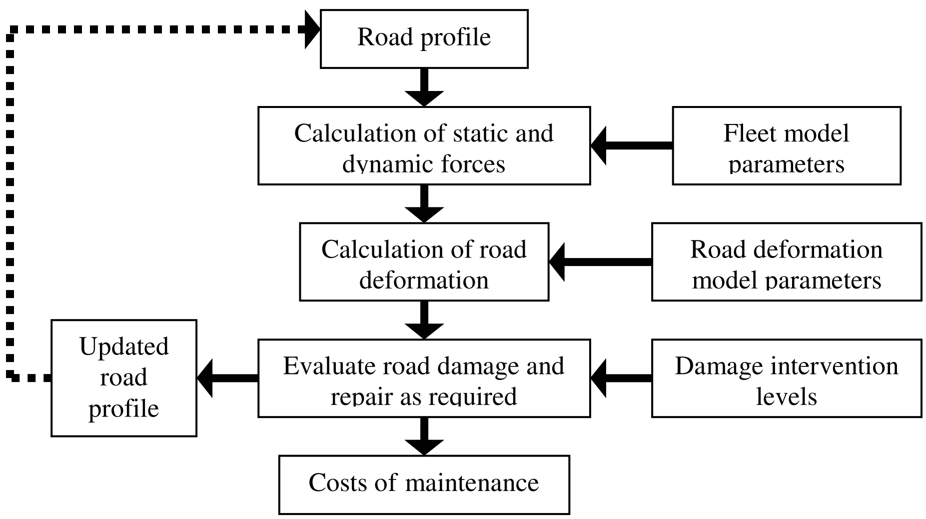


Figure 1 – Flow chart of the vehicle–road interaction calculation.

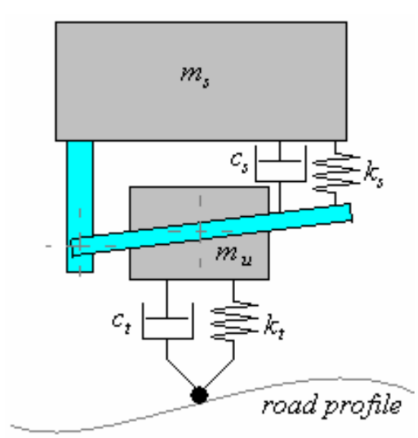


Figure 2 - Quarter Car Model used to simulate "averaged" commercial vehicle axles. The unsprung m_u and the sprung m_s mass are connected through a trailing arm and a system of springs k_s and dampers c_s, while the contact with the road through the tyre is simulated by a tyre spring k_t and a damper c_t. Leaf springs and residual friction levels in air springs are modelled using the leaf spring model by Fancher et al [21]. Lever geometry depends on the suspension.

Four baseline vehicles, representing four fleets of vehicles, were simulated (numbering as per Cebon's report [12], Table 1). The dynamic characteristics of these four fleets are shown in Table 3. Previous research has shown that the majority of vehicles in mixed traffic apply their loading in a repeatable pattern, [22], [23] and that this 'spatial repeatability' has a strong effect on the mechanisms of degradation of road surfaces, particularly when the road wear mechanisms are sensitive to load level [24]. Therefore, a key feature of the simulation is modelling the statistical variation of the dynamic tyre forces for the Newell Highway. The level of spatial repeatability was set to be the same as that measured previously on a highway in the UK [22]. It was simulated by the phase shifting method described in [24] (See [13] for more details).

Table 2 - Distribution of the axle types in the fleets used for simulations, from [16].

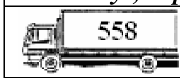
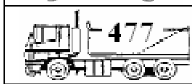
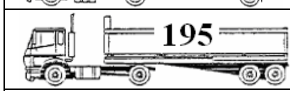
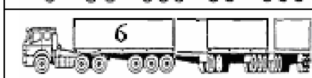
Number of commercial vehicles of each class in the fleet (manual counting in 21 days, Sept. 1999)	***Axles per vehicle in each class***				***Axles in the fleet in each class***			
	Steer type	**Tandem unit type**	**Triaxle unit type**	**Total**	**Total**	**Steer type**	**Tandem unit type**	**Triaxle unit type**
	1	1	0	2	1116	558	558	0
	1	2	0	3	1431	477	954	0
	2	2	0	4	232	116	116	0
	1	2	0	3	168	56	112	0
	1	3	0	4	780	195	585	0
	1	4	0	5	1260	252	1008	0
	1	2	3	6	29556	4926	9852	14778
	1	4	3	8	20128	2516	10064	7548
	1	4	6	11	4818	438	1752	2628
	1	6	9	16	96	6	36	54
TOTAL: 9482			**TOTAL:**		**59585**	**9540 (16%)**	**25037 (42%)**	**25008 (42%)**

Table 3 – Summary of vehicle models used in simulations. The suspensions characteristics are those 'measured' on the corresponding QCMs in a drop test as per [6]. Black numbers: working shock absorbers; red numbers: not-working shock absorbers. * In fleet #5, 50% of the suspensions have disabled shock absorbers (assumed that all tractors have working shock absorbers and all trailers have disabled shock absorbers).

Fleet	Steer- axles		Tandem unit axles		Triaxle unit axles	
No.	Frequence [Hz]	Damping coeff. [%]	Frequence [Hz]	Damping coeff. [%]	Frequence [Hz]	Damping coeff. [%]
1 (CML)	1.66	20.5	2.15	10.3	2.28	10.1
2 (CML)	1.66	20.5	1.60	21.2	1.52	20.1
3 (CML)	1.66	20.5	1.63	7.0	1.56	9.2
5 (CML)	1.66	20.5	1.60/1.63*	21.2/7.0	1.52/1.56	20.1/9.2
2 (HML)	1.66	20.5	1.62	21.0	1.60	22.0
3 (HML)	1.66	20.5	1.64	9.2	1.60	5.0
5 (HML)	1.66	20.5	1.62/1.64*	21.0/9.2	1.60/1.60	22.0/5.0

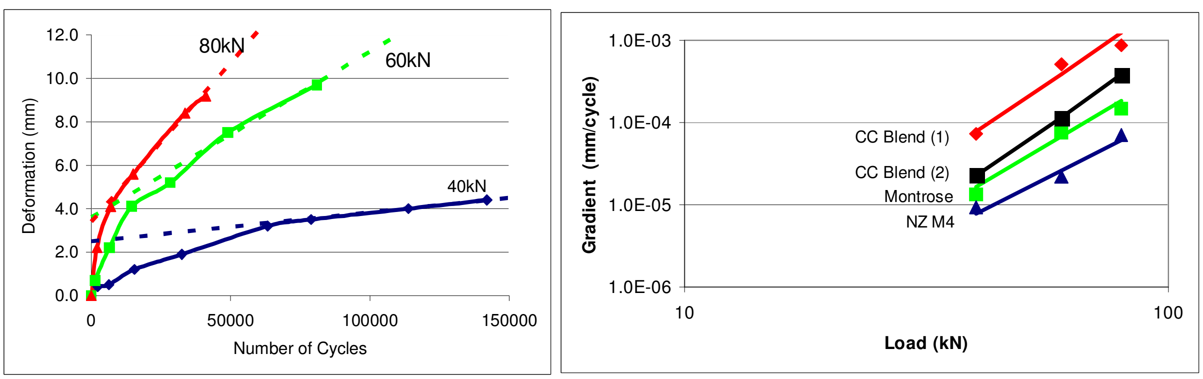
The road surface deformation calculation was based on empirical data collected from accelerated tests on full–scale spray sealed granular pavements by Yeo et al [25] at various wheel loads. (Specifications of the materials used in the three test sections can be found in [26].) Repeated loads of 40 to 80 kN were applied using the Accelerated Load Facility (ALF) until significant rutting was observed. Figure 3(a) gives an example of permanent deformation data for one of the test sections. The graphs generally show a steady-state deformation region in which the deformation rate increases linearly with load cycles (like steady-state creep). Figure 3(b), summarizes the steady-state deformation rates from the three experiments. It can be seen that a suitable model relating the steady-state deformation rate $d\delta/dN|_{ss}$ and the applied load F is:

$$d\delta/dN|_{ss} = A \cdot F^n \qquad \text{(m/cycle)} \tag{1}$$

Therefore for ΔN applications of a wheel load of magnitude F, the increment in permanent deformation is given by:

$$\Delta\delta = A \cdot \Delta N \cdot F^n \qquad \text{(m).} \tag{2}$$

This equation was used directly to calculate road surface deformation at regularly spaced points along the road surface due to the simulated dynamic tyre forces. The values used for A and n in the simulations were those given in Table 4. The parameter A was varied randomly along the road around its average value, using the spectral density of the measured deflectograph data as a template. This accounted for the expected variability in load bearing properties along the road. See [13] for details.



(a) (b)

Figure 3 – Surface deformation from ALF tests, from. [12] (a) Tests on 'Montrose CR' pavements showing lines of best fit for steady state deformation. (b) Summary of steady-state deformation gradients from all experiments.

At each step in the simulation the road surface deformation was calculated from the simulated dynamic tyre forces using equation 2, the new road profile was calculated and various measures of road performance were compared with the intervention criteria listed in Table 5. (These criteria are typical of the maintenance practice used on the Newell Highway). When an intervention threshold was reached, potholes were patched or the road was resurfaced as needed and the road profile was updated to account for the intervention. (See examples of profile interventions in last column of Table 5.) Table 6 lists the unit rehabilitation costs used to calculate maintenance expenditure in the simulation.

To validate the model, the simulation was used to predict the evolution of IRI and average rut depth for the 'weak' and 'strong' road sections. The surface profiles of the selected road lengths in 2001 were used as the initial profiles and the simulation was run until 2004, using fleet #2 with CML (see Table 3), at a nominal speed of 80 km/h. This enabled comparison with the four years of test data available. Agreement between the experimental data and the simulated values was found to be good for both ‘weak’ and ‘strong’ roads - see Figure 4).

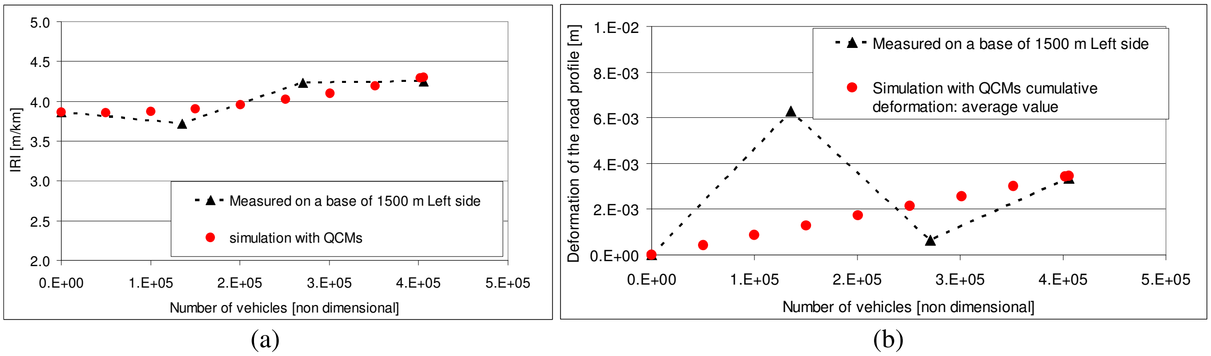
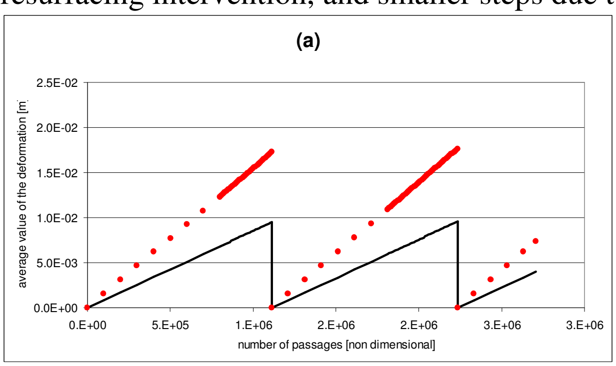
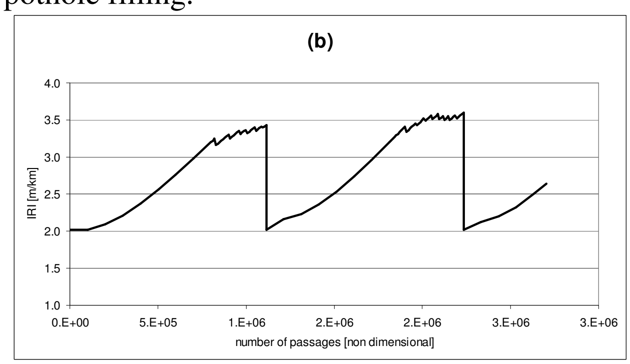


Figure 4 - Comparison between the simulation and road performance data collected between 2001 and 2004 (years converted into number of vehicles according the assumed traffic load) for the ‘weak’ road. (a) Roughness (IRI); (b) Average rut depth. (Note that the scatter in the measured rut depths is due to experimental variability.)

3 EFFECT OF SUSPENSION MAINTENANCE ON WHOLE – LIFE ROAD COSTS

The simulation was run for 2.7×10^6 commercial vehicle passes over the road, which corresponded to 20 years of traffic, at the rate recorded in the 1999 survey, Table 2. Figure 5 shows typical results for the ‘weak’ road. In Figure 5(a) the rut depth displays a regular saw – tooth profile, with resurfacing occurring approximately every 1.2×10^6 vehicle passes. In Figure 5(b), pothole filling is seen to become a frequent activity after about 0.8×10^6 vehicle passes. After 1.2×10^6 vehicle passes, patching becomes excessive and it is necessary to resurface. The maintenance costs vs. time plot in Figure 5(c) shows almost regular large ‘steps’, due to resurfacing intervention, and smaller steps due to pothole filling.





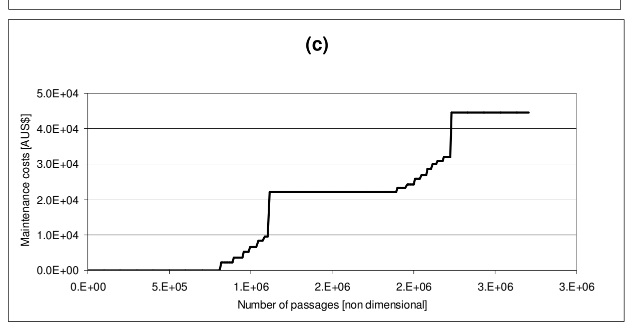
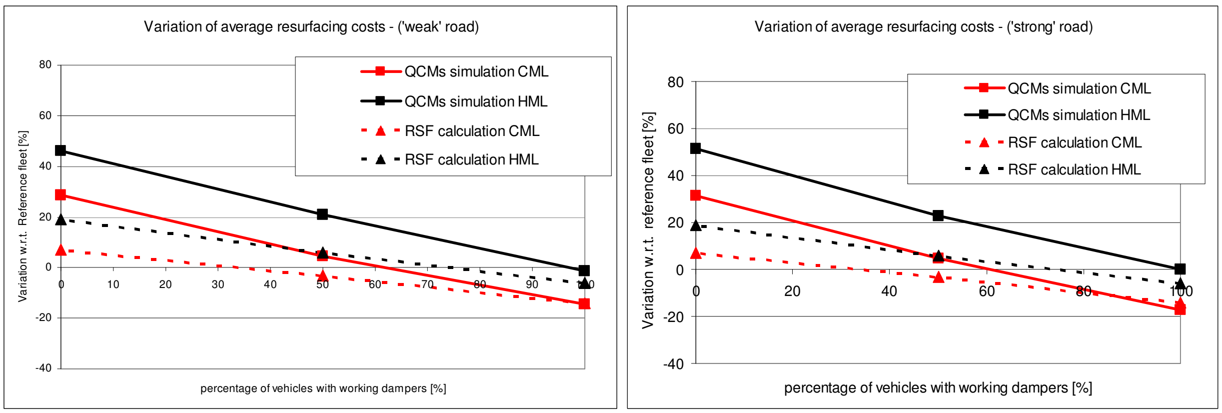


Figure 5 - Evolution of the road profile vs. passages of vehicles of fleet #1 (steel leaf spring suspensions, with CML) on the ‘weak’ road.
(a) —— average rut depth, ‘+’: 95% percentile deform’n
(b) evolution of roughness (IRI)
(c) cumulative rehabilitation costs.

For the maintenance intervention criteria used in this study, two main types of road performance were observed. (i) For fleets with *steel leaf spring* suspensions, potholing generally triggered maintenance intervention by patching. Resurfacing occurred either when the number of patches became excessive or when the surface roughness exceeded the allowable limit. (ii) For fleets with *air spring* suspensions potholing and rutting generally were not sufficient to trigger maintenance. The main intervention was generally complete resurfacing due to excessive roughness (IRI). Consequently, the mode of failure and the type of maintenance interventions required may be expected to change somewhat if the dynamic characteristics of the fleet change significantly.



(a) (b)

Figure 6 - Resurfacing costs vs. percentage of vehicles with well maintained shock absorbers in fleets with air spring suspensions running on a 'weak' road (a); and on a 'strong' road (b). The costs are avualuated in AUS$/km/1000 tonnes payload. The simulation results are compared with the previous calculations based on the 'Road Stress Factor' approach [12].

The results of all simulations on the 'weak' road are summarized in Table 7. Two performance parameters are considered: (i) the average rehabilitation cost per km *for 10^5 commercial vehicles*; (ii) the average rehabilitation cost per km *for 10^3 tonnes payload*. This latter figure assumes that the higher axle load limits will enable the same amount of freight to be carried using fewer vehicles. The results for each fleet are displayed in the table in absolute terms as well as the percentage variation relative to the reference fleet #1 (conventional leaf spring suspensions at CML). Figure 6 compares the results from the RSF calculation (see Table 1) with the simulation results, for both the weak road, Figure 6(a) and the strong roads, Figure 6(b). Several important points can be noted:

(i) Comparing Figure 6(a) and (b), it can be seen that the *relative* effects of the various suspension configurations on road maintenance costs is largely *independent of road strength* for the spray-seal roads investigated here [12].

(ii) Comparing the numbers in Table 7 with the previous estimates in Table 1 it can be seen that the effects of suspension performance on pavement maintenance costs are considerably greater than previously estimated. This is because the previous estimates [12] used the 'road stress factor' calculation (as employed by Starrs) [11] which is based on average level of road damage. It underestimates the effects of dynamic tyre forces because it does not account correctly for the effects of spatial repeatability [12].

Table 4 - Parameters describing road damage evolution in the simulations.

	A [m] (Average)	*n* [-]
'strong' road	0.283×10^{-14}	3.5
'weak' road	0.472×10^{-14}	3.5

Table 5 - Intervention conditions for road surface maintenance.
In far right column: ——— original profile; ——— profile prior to intervention; ——— profile after repair.

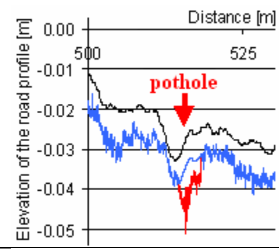
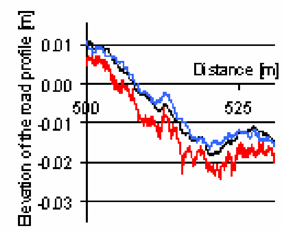
Type of road damage	Parameter Value	Rehabilitation	Sample Rehabilitation
POTHOLING			
Depth of depression considered to be a pothole	25 mm	Patching potholes	
Max. No. of potholes	6 potholes per km	Patching potholes	
Max. depth of a single pothole	40 mm	Repair single pothole	
Max amount of patching tolerated	20% of the length of the road	Resurfacing	
ROUGHENING			
Max. value of IRI	3.67 m/km	Resurfacing	
RUTTING			
Maximum rut depth	20mm	Resurfacing	

Table 6 – Unit rehabilitation costs in the simulation (from RTA records of rehabilitation costs of Newell Highway).

Type of intervention	**Unit Cost**
Resealing with a 14 mm nominal aggregate size	3.11 A$/m²
Resealing as above on 1 km of a 2.7 m wide lane	8400 A$/km
Total resurfacing consisting of pothole patching with 200 mm in-situ modification/ stabilisation, top-up and primer seal	35 A$/m²

Table 7 - Comparison of road maintenance costs for various fleet scenarios on 'weak' roads. Fleet #1 is considered as the reference scenario. Figures in green show lower maintenance costs than the reference fleet. Figures in red show higher maintenance costs than the reference fleet.

COMPOSITION OF THE FLEET				
Type of suspensions	Fleet #1	Fleet #2	Fleet #3	Fleet #5
Leaf springs on the trailer	100%	0%	0%	0
Air springs – well maintained shock absorbers	0%	100%	0%	50%
Air springs – poorly maintained shock absorbers on the trailer	0%	0%	100%	50%
AVERAGE RESURFACING COST [AUS$/km/$10^5$ commercial vehicles] for each lane				
Current Mass Limits	1334 (ref.)	1143 (-14.3%)	1717 (+28.7%)	1394 (+4.5%)
Higher Mass Limits		1398 (+4.8%)	2069 (+55.1%)	1710 (+28.2%)
AVERAGE RESURFACING COST [AUS$/km/1000 tonnes payload] for each lane				
Current Mass Limits	0.53 (ref.)	0.45 (-14.3%)	0.68 (+28.7%)	0.56 (+4.5%)
Higher Mass Limits		0.52 (-1.2%)	0.77 (+46.2%)	0.63 (+20.8%)

(iii) From Table 7, converting all leaf spring suspensions to well-maintained air suspensions at CML is predicted to give a 14% reduction in road maintenance costs per tonne-km. If this same fleet is allowed HML the benefit in maintenance costs per tonne-km is essentially lost… just 1% lower maintenance costs than the conventionally-sprung fleet at CML.

(iv) The road-friendliness of air suspensions is significantly compromised if shock absorbers are not maintained in working condition. If the air suspended HML fleet has 50% poorly maintained air suspensions, road maintenance costs per tonne-km are predicted to be 21% more than for the reference CML fleet. This compares to 6% increase predicted by the previous simplified analysis based on the road stress factor (Table 1).

(v) At CML, road maintenance costs for ‘road-friendly’ fleets are less than for conventional suspensions, provided no more than 40% of the fleet has disabled shock absorbers. However no such break-even point exists for HML, which is predicted to increase road maintenance costs whatever the suspension mix.

4 CONCLUSIONS

(i) The whole-life pavement modelling approach is more sensitive to dynamic tyre forces than simplified approach based on the Road Stress Factor, because it takes accurate account of the spatial repeatability of dynamic tyre forces. Consequently the effects of poor suspension condition on road maintenance costs in Australia are expected to be significantly greater than previously calculated.

(ii) The calculations indicate that the relative effects of the various suspension scenarios is largely independent of road strength for the spray-sealed roads considered in this study.

(iii) Converting all leaf spring suspensions to well-maintained air suspensions at CML is predicted to give a 14% reduction in road maintenance costs per tonne-km. If this same fleet is allowed HML the reduction in maintenance costs per tonne-km falls to 1% compared to the conventionally-sprung fleet at CML.

(iv) If the air suspended HML fleet has 50% poorly maintained air suspensions, road maintenance costs per tonne-km are predicted to be 21% more than for the reference CML fleet. This compares to 6% increase in the previous simplified analysis based on the road stress factor.

(v) The simulation predicts that changing to a fleet of air suspensions may change the type of maintenance intervention required on Australian roads. It is likely that less potholes would form but infrequent complete resurfacing would be needed to repair rutting and excessive surface roughness. This may change maintenance expenditure profiles.

5 ACKNOWLEDGEMENTS

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