Load Equivalency Factors (LEFs) for Abnormal Vehicles (AVs) and Mobile Cranes in South Africa based on the Mechanistic-Empirical (M-E) Design Methodology

M De Beer, I M Sallie, Y van Rensburg and M Kemp
CSIR Built Environment
P O Box 395
Pretoria
0001
+2712841-2953
+2712842-7114
Corresponding Author: mbeer@csir.co.za

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ABSTRACT

This paper describes the proposed new methodology for the determination of the Permit Mass Fees for Abnormal road Vehicles (AVs) based on the estimation of road damage. The existing South African mechanistic-empirical (M-E) pavement design methodology is used to estimate the Load Equivalency Factors (LEFs), based on critical pavement layer life, under static loading conditions. The proposed methodology is not based on the traditional Equivalent Single Wheel Load (or Mass) ESWL (or ESWM), nor on the well known 4th power law for relative pavement damage but on the latest South African Mechanistic-Empirical Design Method (SAMDM) which has been used in practice for pavement design and analysis since 1996. The LEFs were calculated from estimated ratios of critical pavement layer life for each individual AV relative to the Standard Axle (80 kN, 520 kPa) bearing capacities of a range of nine (9) typical standard pavement structures found in South Africa. This was done for both relatively dry and wet pavement conditions. This paper includes examples of eleven (11) selected Mobile Cranes and eight (8) typical selected AVs. The new methodology also includes the effect of tyre inflation (or contact pressure) (TiP), including a sensitivity analysis over a range of 520 kPa to 1200 kPa for all the above vehicles and pavements. It is clear that there appears to be a wide range in the new LEFs for the different vehicles based on the new and what is considered a more rational and fully mechanistic approach (i.e. the SAMDM). Although the new LEFs (hence the associated Mass Fees) are found to be different compared to those calculated according to the existing ESWL method, they are in principle, considered to be based on a more rational (mechanistic) methodology than before and it is suggested that they be refined and applied with draft TRH 11 as soon as possible, but phased in over time.

1 INTRODUCTION AND SCOPE

This paper summarises a proposed new approach and associated principles for the revision of the determination of the “Mass Fee” (for permits), based on a more rational method for the estimation of road damage by Abnormal Vehicles (AVs) and Mobile Cranes). This was recently proposed as a review item for the updating of TRH 11 (1999-2000). The scope of this paper includes a very brief summary review of the existing methodology based on the Equivalent Single Wheel Load (ESWL), or Equivalent Single Wheel Mass (ESWM). A new and (what is considered) a more *rational* methodology is proposed, which is based on the existing South African Mechanistic-Empirical (M-E) Design Method (SAMDM).

2 EQUIVALENT PAVEMENT RESPONSE - EQUIVALENT PAVEMENT DAMAGE

The principle of *"Equivalent Pavement Response - Equivalent Pavement Damage"* (*EPR-EPD*) is used instead of reducing a single Abnormal Vehicle (or Mobile Crane) to an ESWL (or ESWM), or to an equivalent axle load of 80 kN (i.e. E80), all of which are based on the rather crude but well known so-called 4th power law of relative pavement damage.

With the new *"EPR-EPD"* approach, no "fixed equivalencies" (i.e. such as the 4th power law) are used, per se, and each vehicle is considered with its full axle/tyre configuration (i.e. tyre/axle loading and its associated tyre inflation pressure) as direct input into the SAMDM. The road damage (or "additional pavement damage") of the Abnormal Vehicle (AV) is *directly* estimated for a range of typical pavement types found in South Africa. (Nine types of pavements were used in this study for the calculation of mechanistically based Load Equivalency Factors (LEFs)). This was done for both a relatively dry pavement condition, and a relatively wet pavement condition. In addition LEFs were also determined for a range of tyre inflation pressures (TiP) ranging from 520 kPa to 1 200 kPa. With the *EPR-EPD* approach the stresses and strains (i.e. mechanistic pavement response parameters) are directly related through the associated transfer functions (TF) for pavement damage to layer life and hence "pavement life". With this approach, the pavement life is considered as being equal to the "critical layer life", i.e. the life of the structural layer with the lowest life in the pavement structure. This is fundamental to calculation of the Load Equivalency Factors (LEFs) determined in this study and is proposed for the current review of TRH 11 (2000).

2.1 PRINCIPLES OF THE NEW *"EPR-EPD"* METHOD

The *"EPR-EPD"* methodology proposed for an updated TRH 11 (2000) is based on the following driving principles:

1) Each vehicle is considered in its full static loaded configuration, i.e. all tyres/axles at their individual tyre loading and associated tyre inflation pressures (TiPs);
2) For the M-E analysis, the TiP considered to be equal to the tyre/pavement contact stress (TcS). [Note: Only vertical contact stress was used in this study for the analysis, although it is well known that the lateral contact stresses of the tyre should ideally be included as well (see De Beer *et al*., 2008];
3) Pavement damage is calculated for a range of typical pavement structures found in South Africa (SA), ranging from relatively strong to relatively light (or "weak");
4) Special provision for wet weather climates (i.e. abnormal loading during wet seasons);
5) The basic corner stone for road damage calculation proposed here is the current SAMDM, where the total "life" of each layer in the pavement is calculated under static loading conditions, and the pavement life is equal to the critical layer life (i.e. lowest life found for a particular layer in the pavement);
6) Layer life is based on the typical linear-log damage functions (or "transfer functions") obtained (and calibrated) from experience and also on the results of Heavy Vehicle Simulator (HVS) testing on the various pavement types carried out in SA since 1975 (see Theyse *et al*., 1996);

7) The "pavement life" under each axle of the vehicle is calculated, summed and compared relative to the bearing capacity of the pavement in terms of the Standard 80 kN/ 520 kPa axle with four tyres (two dual sets) at a tyre inflation pressure of 520 kPa . [It should be noted that the Standard Axle is not the well known "E80", although the configuration is exactly the same - see TRH 4 (1996) for definitions];
8) The so-called "Legal Damage" (LDv) of the vehicle is calculated as the ratio between the critical life (i.e. lowest life) obtained from the current legal 88 kN (i.e. 9 000 kg) axle with four tyres (two dual sets) at a tyre inflation pressure of 700 kPa and the critical life obtained from the Standard 80 kN/520 kPa axle with four tyres (two dual sets of tyres). [This, however, is not necessarily used for calculation of the final Load Equivalency Factor (LEF) for the vehicles considered here];
9) Total Damage (TDv) of the vehicle is calculated as the sum of the ratios (for all axles of a particular vehicle) between the critical layer life of the pavement determined from the Standard 80 kN/ 520 kPa axle with four tyres (two dual sets) at an inflation pressure of 520 kPa (i.e. the bearing capacity of the pavement), divided by the critical layer life under each individual axle load and its associated tyre pressures;
10) Strictly speaking, the Total Additional Damage (TADv) of the vehicle is simply TDv minus LDv. [Note, however, Item 8 above], and
11) The Mass Fee/km in ZAR = TADv * R, where R = ZAR average cost estimate of one "Standard Axle-lane-km" of road in SA. This cost estimate is not reviewed in this study, and it is recommended to use the existing (or current) monetary value used for issuing the permits for AVs and Mobile Cranes.

3 USE OF ESWL (or ESWM) ON CALCULATION OF THE MASS FEE

As reported by various authors, the traditional basis for the calculation of abnormal load fees in South Africa (and abroad) was strictly in accordance with the well known principle of Equivalent Single Wheel Mass (or Load), ESWM or ESWL (Report 80286, 1994, and its Supplementary Report, 1994). The basis for this calculation in South Africa was established by Van Vuuren in 1972 (Van Vuuren, 1972). This principle has been the basis of mass fee calculation for the last 36 years in SA and elsewhere (see also Ioannides and Khazanovich, 1993) and was reviewed for implementation into TRH 11 (1999/2000) in 1994 (Report 80286, 1994), incorporating some of the mechanistic-empirical (M-E) approaches for road pavement design in SA. Since 1975, full-scale pavement research with the Heavy Vehicle Simulator (HVS) in the field of Accelerated Pavement Testing (APT), as well as detailed studies on tyre-pavement interaction, have resulted in new knowledge which was incorporated into and applied to the South African Mechanistic-Empirical Design Methodology (SAMDM) (see ATC, 1984). Of particular note is the further development of the SAMDM as reported by De Beer (1992), Theyse *et al*., (1996) and Theyse and Muthen (2000). It is believed that the basis for calculation of the Mass Fee for abnormal load vehicles for road damage should be reviewed and based on a more rational (and a more fair) approach (i.e. the SAMDM), utilizing the full axle/tyre loading configuration and the associated tyre inflation pressure of the AV rather than the ESWL (or ESWM) as was done previously. The main drawback of the principle of ESWL (or ESWM) is that the response of a layered road pavement system is greatly altered by representing all the axles of an Abnormal Vehicle by a unique single wheel, especially if this is based on vertical elastic deflection alone (i.e. the "Equivalent Deflection Equivalent Damage", (ED-ED) approach). It is generally accepted that equal maximum elastic deflection of a pavement does not guarantee “similar damage”, e.g. layered pavement systems with the same maximum deflection may have different radii of curvatures (RoC), etc, as was demonstrated by various deflection and HVS APT studies. (See ATC, 1984; Horak,1986 and Lacante, 1992).

Experience with HVS testing in South Africa indicated different “behavioural states” of pavements throughout their structural life and that these should ideally be incorporated into the models for the calculation of road damage through the SAMDM (ATC, 1984). Two major studies during the 1990’s based on the SAMDM were done in South Africa (SARB, (1995a, 1995b), Prozzi and De Beer, (1997)) which adequately demonstrated their suitability for the estimation of relative damage of different axle groups on flexible pavements. For abnormal load vehicles the new approach for road damage used here (i.e. determination of the different LEFs for vehicles and pavement condition) is based on the SAMDM and is therefore proposed and discussed in this summary discussion document as an alternative to the current (or traditional) methodology based on ESWL (or ESWM).

4 PAVEMENT TYPES AND CONDITIONS EVALUATED IN THIS STUDY

For this preliminary study, nine (9) typical pavements found in South Africa, (slightly modified from a previous study (SARB, 1995)) obtained from TRH 4 (1996), were used for the mechanistic estimation of relative pavement damage (or mechanistically based Load Equivalency Factors, (LEFs)) by the eleven Mobile Cranes and eight other abnormal load vehicles. For the different flexible pavement types used here, see Figure 1. These include Pavements A to H, which is briefly described below.

4.1 Pavement A:

Pavement A is a heavy pavement with a granular base, basically representing relatively dry conditions, Road Category A and design traffic class ES100. Structure: 50 mm asphalt surfacing, 150 mm G1 granular base, and two (2) 150 mm C3 cemented subbases on the subgrade.

4.2 Pavement B:

Pavement AB is a heavy pavement with a granular base, basically representing relatively wet conditions, Road Category A and design traffic class ES100. Structure: the same as that of pavement A but with different material properties owing to the wet conditions.

4.3 Pavement C:

Pavement C is a light pavement with a granular base basically representing relatively dry conditions, Road Category D and design traffic class E0.1. Structure: 15 mm surface treatment or seal, 100 mm G4 granular base, 125 mm C4 subbase.

4.4 Pavement D:

Pavement D is a light pavement with a granular base basically representing relatively wet conditions, Road Category D and design traffic class E0.1. Structure: the same as that of Pavement C but with different material properties owing to the wet conditions.

4.5 Pavement E:

Pavement E is a heavy pavement with a bituminous base, Road Category A and design traffic class ES30. Structure: 40 mm asphalt surfacing, 120 mm asphalt base, three 150 mm layers of C3 (i.e. 450 mm of C3, built in 3 layers of 150 mm each) cemented subbase, and a 200 mm selected layer on top of the subgrade.

4.6 Pavement E1 (not shown in Figure 1, but given in Appendix C):

Pavement E1 is a heavy pavement with a bituminous base, Road Category B and design traffic class ES10. Structure: 40 mm asphalt surfacing, 120 mm asphalt base, 150 mm C3 cemented subbase and another 150 mm C4 subbase directly on top of the subgrade.

4.7 Pavement F:

Pavement F is a light pavement with a bituminous base, Road Category B and design traffic class ES1.0. Structure: 15 mm surface treatment or seal, 80 mm asphalt base, 150 m cemented subbase.

4.8 Pavement G:

Pavement G is a heavy pavement with a cemented base, Road Category B and design traffic class ES10. Structure: 30 mm asphalt surfacing, 150 mm C3 cemented base, 300 mm C4 cemented subbase.

4.9 Pavement H:

Pavement H is a light pavement with a cemented base, Road Category C and design traffic class ES0.3. Structure: 15 mm surface treatment or seal, 100 mm C4 cemented base, 100 mm C4 cemented subbase.

The pavement structures described above, which were used in this study, are illustrated in Figure 1. The material codes are in accordance with TRH 14 (CSRA, 1985). [Note that Pavement E1 is not shown in Figure 1]. The basic classification and associated definitions of the pavements according to the bearing capacity are defined in TRH 4 (1996).

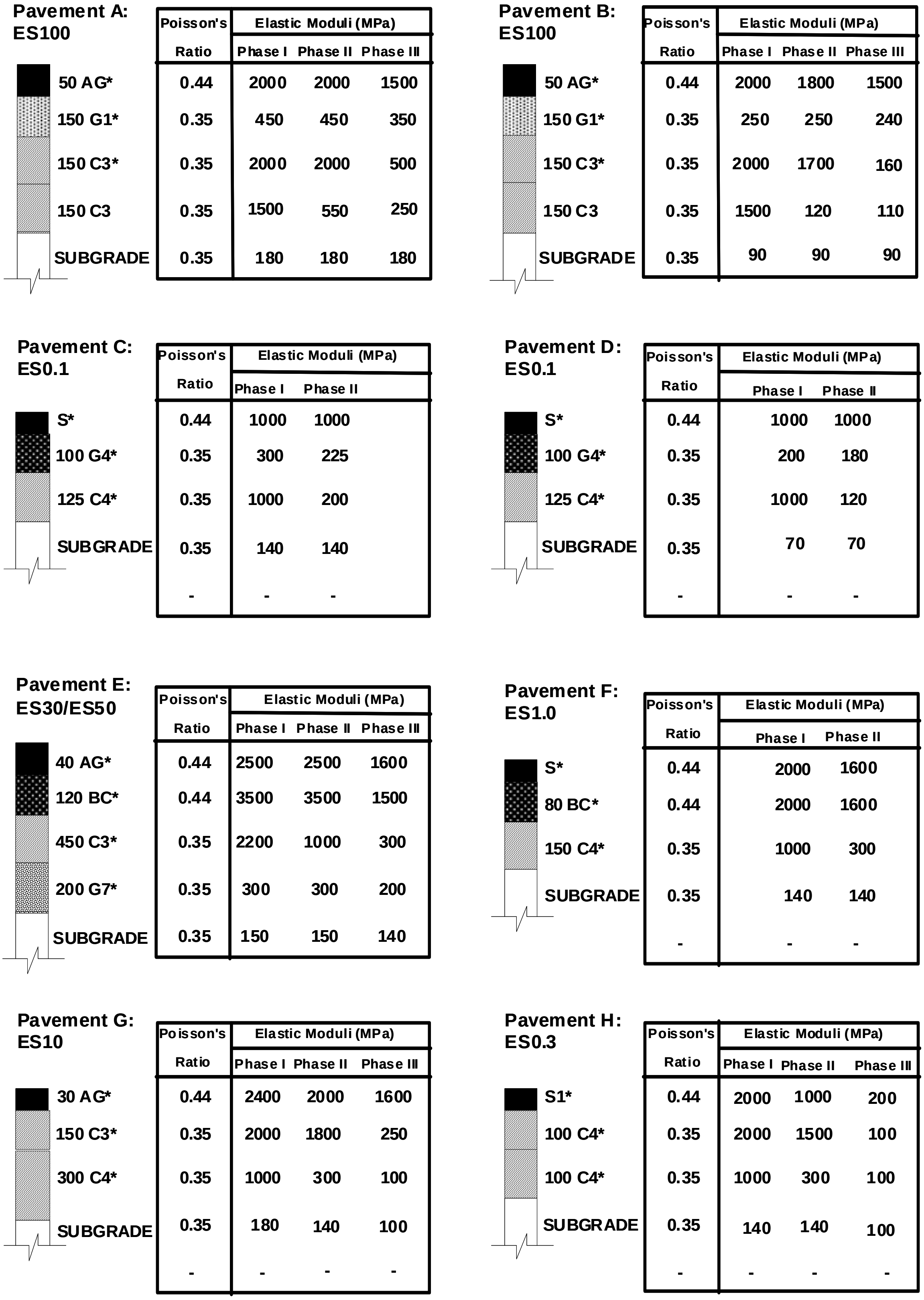
Note that all the above pavement structures are founded on selected layers or subgrade with assumed material properties according to road category and traffic class. The Road Category and design traffic class are defined in TRH 4, 1996 (CSRA, 1996). The particular pavement structures chosen are considered to be a fair representation of many of the pavements found in South Africa and should allow a pavement designer to correlate many typical cases to one of the pavements analyzed and thereafter apply the findings in terms of Load Equivalency (LEF) and hence the Mass Fees. In this study, the M-E analyses were done for both relatively dry and relatively wet pavement conditions. Material properties used in the analysis of the nine selected pavement structures were assumed according to the guidelines in document RP/19/83 (Freeme, 1983), Heavy Vehicle Simulator (HVS) (ATC, 1984) test results and TRH 14 (CSRA, 1985 and 1996). Values of elastic moduli (E – Modulus) and Poisson's ratios for each of the pavement layers as used in the mePADS software (mePADS, 2008) analysis are also defined in Figure 1.

5 MOBILE CRANES AND EXAMPLES

In this paper, the standard axle was used as reference axle. See Table 1 for details (legal axle also given in Table 1). For cranes, a selection of eleven (11) Mobile Crane axle load configurations was used. These were obtained from the current data base of abnormal load vehicles at CSIR BE (Kemp, 2008). The eleven selected Mobile Cranes evaluated in this study are listed in Table 2. The average tyre load ranges between 25.42 kN to 65.00 kN, and the total load ranging between 225.4 kN and 970.44 kN. The average TiPs for these Mobile Cranes ranging between 329 kPa and 695 kPa. The typical generic tyre load configurations of the Mobile Cranes are given in Tables 2 and an example of a 5-axle mobile crane in Table 3. The definitions and layout of the axle and load configurations of these eleven Mobile Cranes are summarised in De Beer *et al.,* (2008).

6 ABNORMAL VEHICLES (AVs) AND EXAMPLES

In this paper, a selection of various axle load configurations of eight (8) different Abnormal Vehicles (AVs) was used. These were obtained from the current data base of Abnormal Vehicles at CSIR BE (Kemp, 2008). The eight selected AVs evaluated in this study are listed in Table 3. For the AVs, the average tyre load ranges between 16.59 kN to 29.33 kN, and the total load ranging between 559.00 kN and 1 292.8 kN. The average TiPs for these AVs ranging between 463 kPa and 737 kPa. The typical generic tyre load configurations of these abnormal heavy vehicles are given in Tables 4 and 9-axle AV example in Table 5.The detailed definitions and layout of the axle and layout of the load configurations of these eight AVs are summarised in summary research report, De Beer *et al.,* (2008).



Pavement A: ES100

	Poisson's	Elastic Moduli (MPa)		
	Ratio	Phase I	Phase II	Phase III
50 AG*	0.44	2000	2000	1500
150 G1*	0.35	450	450	350
150 C3*	0.35	2000	2000	500
150 C3	0.35	1500	550	250
SUBGRADE	0.35	180	180	180

Pavement B: ES100

	Poisson's	Elastic Moduli (MPa)		
	Ratio	Phase I	Phase II	Phase III
50 AG*	0.44	2000	1800	1500
150 G1*	0.35	250	250	240
150 C3*	0.35	2000	1700	160
150 C3	0.35	1500	120	110
SUBGRADE	0.35	90	90	90

Pavement C: ES0.1

	Poisson's	Elastic Moduli (MPa)	
	Ratio	Phase I	Phase II
S*	0.44	1000	1000
100 G4*	0.35	300	225
125 C4*	0.35	1000	200
SUBGRADE	0.35	140	140
	-	-	-

Pavement D: ES0.1

	Poisson's	Elastic Moduli (MPa)	
	Ratio	Phase I	Phase II
S*	0.44	1000	1000
100 G4*	0.35	200	180
125 C4*	0.35	1000	120
SUBGRADE	0.35	70	70
	-	-	-

Pavement E: ES30/ES50

	Poisson's	Elastic Moduli (MPa)		
	Ratio	Phase I	Phase II	Phase III
40 AG*	0.44	2500	2500	1600
120 BC*	0.44	3500	3500	1500
450 C3*	0.35	2200	1000	300
200 G7*	0.35	300	300	200
SUBGRADE	0.35	150	150	140

Pavement F: ES1.0

	Poisson's	Elastic Moduli (MPa)	
	Ratio	Phase I	Phase II
S*	0.44	2000	1600
80 BC*	0.44	2000	1600
150 C4*	0.35	1000	300
SUBGRADE	0.35	140	140
	-	-	-

Pavement G: ES10

	Poisson's	Elastic Moduli (MPa)		
	Ratio	Phase I	Phase II	Phase III
30 AG*	0.44	2400	2000	1600
150 C3*	0.35	2000	1800	250
300 C4*	0.35	1000	300	100
SUBGRADE	0.35	180	140	100
	-	-	-	-

Pavement H: ES0.3

	Poisson's	Elastic Moduli (MPa)		
	Ratio	Phase I	Phase II	Phase III
S1*	0.44	2000	1000	200
100 C4*	0.35	2000	1500	100
100 C4*	0.35	1000	300	100
SUBGRADE	0.35	140	140	100
	-	-	-	-

*** Classification according to TRH 14 (CSRA, 1985)**

8 Pavement Structures-1.ppt

Figure 1. Eight of the nine road pavement structures and their material properties used for the mechanistic analysis for TRH11 (this paper).

Table 1. Summary of the Standard and Legal Axle data used in this study

STANDARD AND LEGAL AXLES:	Average Tyre Load (kN)	Standard Deviation (kN)	Total Load (kN)	Number of Tyres	Average TiP (kPa)	Standard Deviation (kPa)
Standard Axle (Std)	20.00	0.00	80.00	4	520.00	0.00
Legal Axle (Lg)	22.00	0.00	88.00	4	700.00	0.00

Table 2. Summary of the eleven Mobile Cranes used in this study (sorted on Average Tyre Load)

MOBILE CRANES (SORTED ON AVE TYRE LOAD):	Average Tyre Load (kN)	Standard Deviation (kN)	Total Load (kN)	Number of Tyres	Average TiP (kPa)	Standard Deviation (kPa)
Crane - 4 Axle Single Dual tyres	25.42	4.05	305.08	12	422.33	96.50
Crane - 3 Axle Single Dual tyres	25.72	2.83	257.24	10	434.00	65.35
Crane - 6 Axle Single Dual tyres	33.27	6.05	513.07	18	329.33	71.79
Crane - 5 Axle Single Dual tyres	36.32	1.98	508.50	14	695.00	13.00
Crane - 2 Axle Single tyres	56.26	0.74	225.04	4	664.50	12.12
Crane - 3 Axle Single tyres	56.93	1.24	341.58	6	494.67	14.46
Crane - 6 Axle Single tyres	59.38	2.22	712.60	12	523.00	17.76
Crane - 7 Axle Single tyres	60.65	0.61	849.08	14	537.71	7.03
Crane - 8 Axle Single tyres	60.65	1.86	970.44	16	537.25	21.15
Crane - 4 Axle Single tyres	64.01	5.77	512.08	8	524.50	59.33
Crane - 5 Axle Single tyres	65.00	7.05	650.02	10	586.60	79.46

Table 3. Summary of the eight Abnormal Vehicles (AVs) (sorted on Average Tyre Load)

ABNORMAL VEHICLES (SORTED ON AVE TYRE LOAD):	Average Tyre Load (kN)	Standard Deviation (kN)	Total Load (kN)	Number of Tyres	Average TiP (kPa)	Standard Deviation (kPa)
AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)	16.59	5.34	962.00	58	736.52	4.29
AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)	17.57	4.47	878.40	50	463.68	209.46
AV veh F - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305729)	19.49	5.39	1130.60	58	494.66	162.10
AV veh C - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP304803)	20.88	5.58	1211.20	58	573.52	80.22
AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)	22.29	6.62	1292.80	58	624.48	1.14
AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)	25.41	4.76	559.00	22	727.00	86.78
AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)	27.37	2.60	711.50	26	621.54	14.88
AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)	29.23	1.80	643.00	22	625.18	29.20

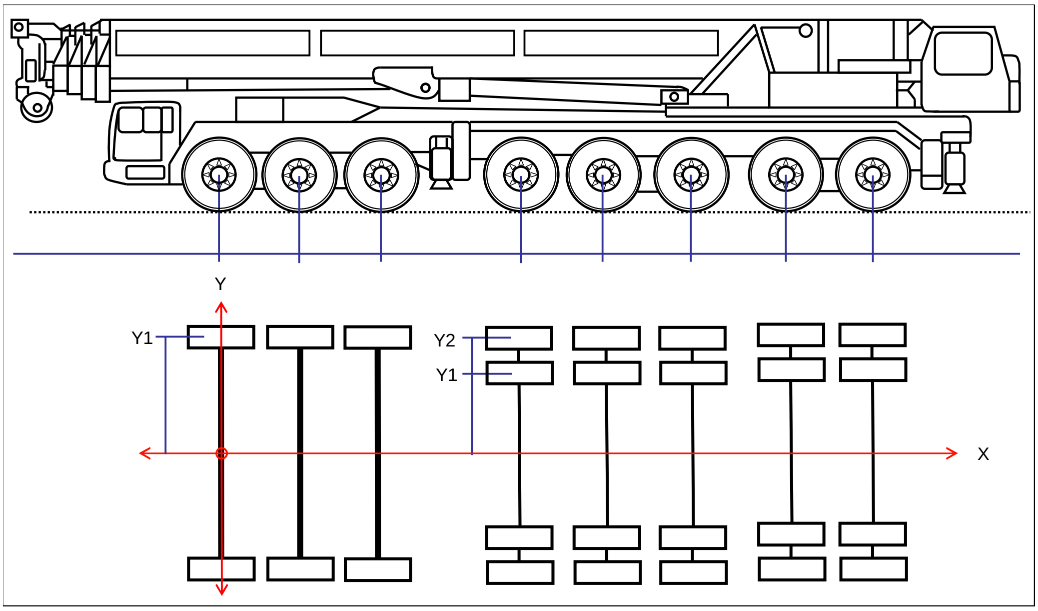
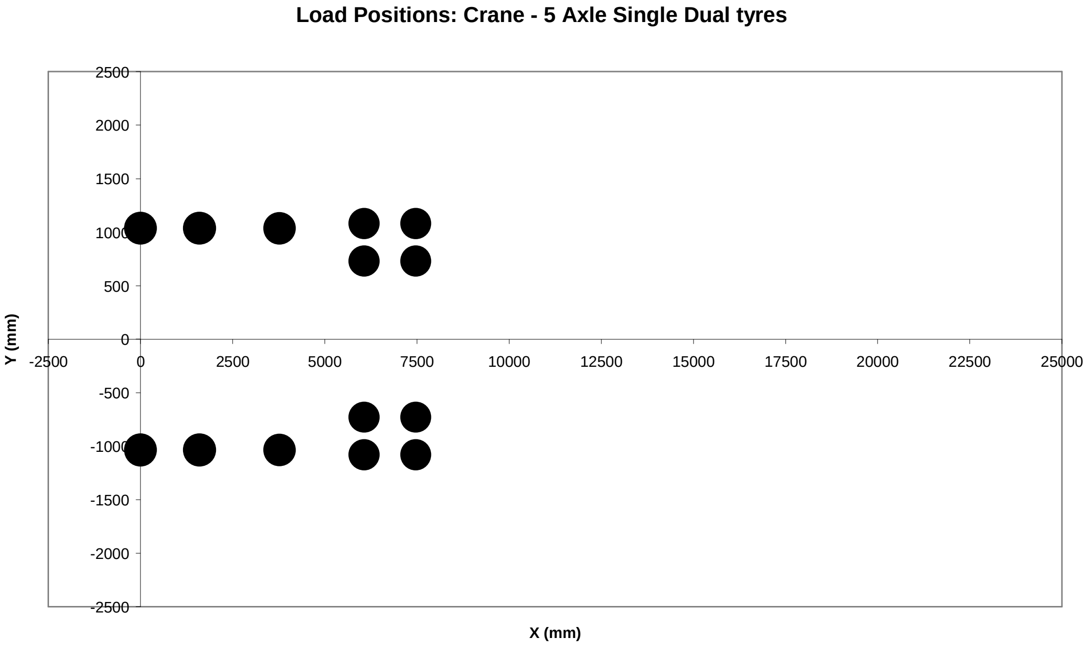


Figure 2. Generic Mobile Crane Load Configurations.



AV No.	Total Mass (kg)	Group No	Axle Type	Wheel Space A (mm)	Wheel Space B (mm)	Tyre Press	No. of Tyres	Axle No	Axle Mass	Tyre Mass	Tyre Load	Steer?	Dist. to Next Axle	Y1 (mm)	Y2 (mm)	X (mm)	Load (kN)
GP403688	51832	1	S	2070		678	2	1	7720	3860	37.9	Yes	1600	1035		0	37.87
							2	2	7720	3860		Yes	2170			1600	37.87
		2	S	2070		717	2	3	8072	4036	39.6	Yes	2300	1035		3770	39.59
		3	D	1460	350	698	4	4	14160	3540	34.7	No	1400	730	1080	6070	34.73
							4	5	14160	3540		No	0			7470	34.73
							14		**51832**								

Figure 3. Tyre layout and mass detail of the Typical Crane - 5 Axle Single and Dual tyres (read with Figure 2).

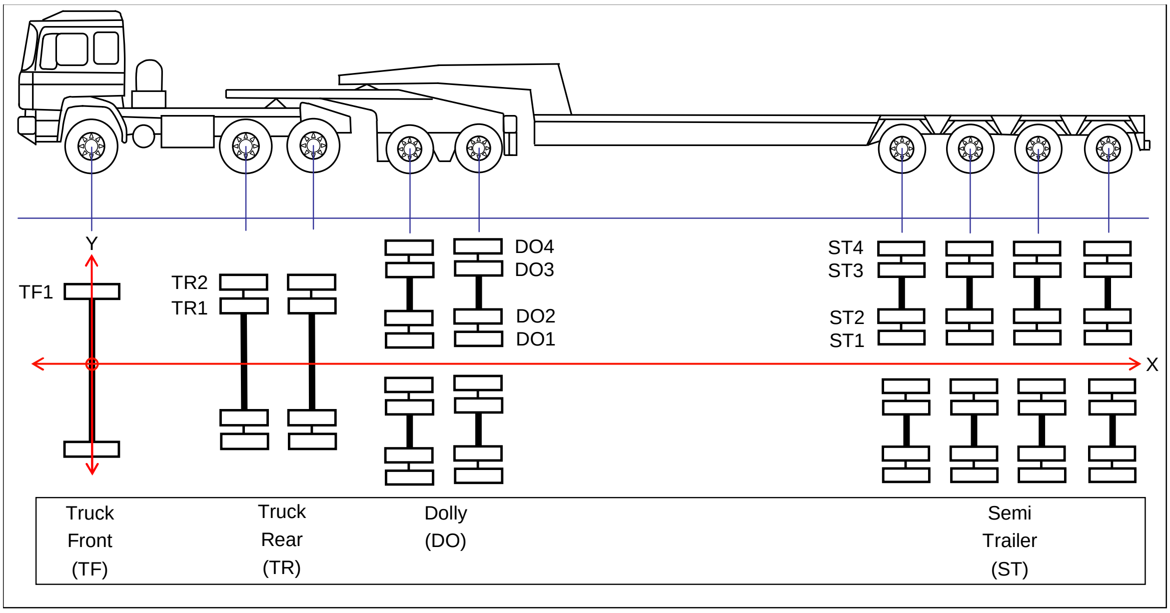
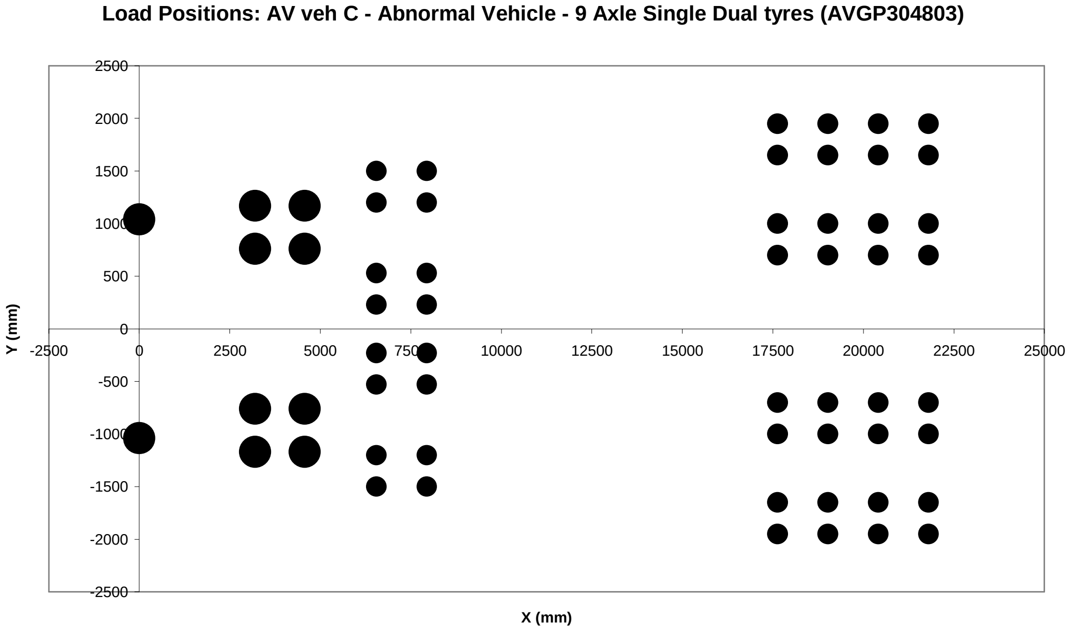


Figure 4. Generic Axle and load configurations of typical abnormal vehicle (AV) combinations.



										Y - Coordinates										
2	Axle No	Group		Group Mass	Tyre Mass	Tyre Load	Tyre Press.	Axle Type	X Coord	TF1	TR1	TR2	DO1	DO2	DO3	DO4	ST1	ST2	ST3	ST4
AVGP304803 (C)	1	TF	2	6684	3342	32.8	420	S	0	1040										
	2	TR	8	26736	3342	32.8	435	D	3200		760	1170								
	3								4570											
	4	DO	16	32584	2037	20.0	675	4D	6550				230	530	1200	1500				
	5								7940											
	6	ST	32	57496	1797	17.6	567	4D	17630								700	1000	1650	1950
	7								19020											
	8								20410											
	9								21800											
			58	123500																

Figure 5. Typical Abnormal Vehicle (AV) - Vehicle C - 9 Axle Single and Dual tyres (Read with Figure 4).

7 SOFTWARE FOR CALCULATION OF ROAD DAMAGE

The *mePADS* software of the SAMDM is discussed by Theyse and Muthen (2000). The software (albeit slightly modified for this TRH 11 study for batch analysis) is referred to here as the *"1996-mePADS-TRH 11".* The basic mechanistic-empirical (M-E) methodology is freely available within South Africa from the CSIR BE (*me*PADS, 2008) - see website: http://asphalt.csir.co.za/samdm/

8 APPROACH FOLLOWED IN THIS STUDY

The approach used in this study was to use the full vehicle tyre, axle load and tyre inflation pressure as input into the *me*PADS software (modified for TRH11 batch analysis). For each vehicle the following was done:

- Full M-E analysis with *me*PADS (1996) to calculate LEFv at a given tyre loading and Tyre Inflation Pressure) TiP;
- Calculation of LEFv using output (i.e. critical layer life) under each tyre (i.e. referred to here as "Outside" analysis);
- LEFs were determined for relatively "DRY" and relatively "WET" pavement moisture conditions for each vehicle and pavement type, and
- Repeating the analysis over a range of eight selected TiPs, ranging from 520 to 1200 kPa.

In total, 2 736 LEFvs were finally calculated (19 Vehicles * 9 Pavements * 8 TiPs * 2 moisture conditions).

9 TYRE INFLATION PRESSURES (i.e. CONTACT STRESS)

Another important research drive in SA since the 1990's was the study of the tyre – road pavement contact stresses in three dimensions (3D). Since the original work by Van Vuuren (1974), numerous publications have shown that these tyre contact stresses are neither uniform nor circular in shape and that they depend heavily on the tyre loading and tyre inflation pressure level of a particular tyre. It was also found that the *average* vertical tyre contact stress (TcS) is much lower than the maximum vertical contact stress (MVCS), which can be as much as twice the tyre inflation pressure. See references in De Beer *et al.,* (2008) and Roque *et al.,* (2000). However, for this study the tyre inflation pressure (TiP) was assumed to be *equal* to the *average* vertical contact stress (TcS). (It is also well known that the *average* vertical contact stress is normally approximately 30 per cent less than the inflation pressure.) It is, however, important to note that in 1995 the average inflation pressure of heavy vehicle tyres was approximately 733 kPa by comparison with the inflation pressure of 620 kPa found in 1974 (De Beer *et al.,* 1997). Studies that are more recent indicate that average tyre inflation pressures are in the range of 800 kPa to 900 kPa, the higher values typically being found on the tyres on steering axles of Heavy Vehicles (De Beer, 2008).

The SAMDM allows for the tyre inflation pressure, or TiP (here assumed to be *equal* to tyre contact stress) of each tyre of the vehicle to be evaluated *directly* in the calculation of the LEFs (and hence Mass and Permit Fee) related to road damage. The principle used in this study is the notion of *"EPR-EPD",* as described earlier. In addition to the foregoing, LEFs in this study were also estimated at a range of TiPs between 520 kPa and 1 200 kPa, for both the Mobile Cranes and Abnormal Vehicles (AVs). This is discussed further in Section 15.

10 PROPOSED FORMULATIONS FOR ESTIMATING ROAD DAMAGE

In this section, the potential basic formulations proposed for the quantification of the Mass Fee are defined. These include:

10.1 Legal Damage (LDv):

$$\text{Legal Damage of Vehicle} = LD_v = \sum_{i=1}^{n} \frac{(\text{Ncritical from Legal 88 kN/700 kPa Axle})}{(\text{Ncritical from Standard 80 kN/520 kPa Axle}_i)} \text{......Eq 1.0}$$

or

$$LD_V = n \text{ x } \left[\frac{(\text{Ncritical from Legal 88 kN/700 kPa Axle})}{(\text{Ncritical from Standard 80 kN/520 kPa Axle})} \right] \text{...Eq.1.1}$$

where:

- *n = number of axles on Vehicle (v).*
- *Ncritical from Legal 88 kN/700 kPa Axle = Minimum layer life of pavement under the loading of the current Legal Axle of 88 kN and 700 kPa inflation pressure on 4 tyres (i.e. 22 kN per tyre @ 700 kPa contact stress (= inflation pressure)).*
- *Ncritical from Standard 80 kN/520 kPa Axle = Minimum layer life of pavement under the loading of the Standard Axle of 80 kN and 520 kPa inflation pressure on 4 tyres (i.e. 20 kN per tyre @ 520 kPa contact stress (= inflation pressure)).*

10.2 Total Damage (TDv) (= Load Equivalency Factor (LEFv) of Vehicle):

$$LEF_v = \text{Total Damage of Vehicle} = TD_v = \sum_{i=1}^{n} \frac{(\text{Ncritical from Standard 80 kN/520 kPa Axle})}{(\text{Ncritical from Axle}_i)} \text{........Eq 2.0}$$

where:

- *n = number of axles on vehicle.*
- *Ncritical from Standard 80 kN/520 kPa Axle = Minimum layer life of pavement under the loading of the Standard Axle of 80 kN and 520 kPa inflation pressure on 4 tyres (i.e. 20 kN per tyre @ 520 kPa contact stress (= inflation pressure)).*
- *Ncritical from Axle$_i$= Minimum layer life of pavement under the loading of Axle$_i$ of vehicle in question.*

10.3 Total Additional Damage (TADv):

Total Additional Damage of Vehicle = TAD_v

$$= \left[\sum_{i=1}^{n} \left[\frac{(\text{Ncritical from Standard 80 kN/520 kPa Axle})}{(\text{Ncritical from Axle}_i)} \right] - \sum_{i=1}^{n} \left[\frac{(\text{Ncritical from Legal 88 kN/700 kPa Axle})}{(\text{Ncritical from Standard 80 kN/520 kPa Axle}_i)} \right] \right]$$

$$= \left[TD_V - LD_v \right] \text{..Eq 3.0}$$

where:

- *n = number of axles on Vehicle (v).*
- *LD_v = Legal Damage of Vehicle (v), and*
- *TD_v= Total Damage of Vehicle (v) = LEF_v*

11 MASS FEE AND PERMIT FEE FOR ROAD DAMAGE ONLY

The Mass Fee is defined as the fee in ZAR per *"Standard Axle-km (R)".* R is the average cost of one lane-km of road built to carry one Standard Axle (i.e. bearing capacity = one), where the Standard Axle is as defined above (i.e. 80 kN Axle load @ 520 kPa on 4 tyres).

Mass Fee (ZAR) per km = R x TAD_V ....*Eq 4.0*

The Permit fee (road damage only) is simply the Mass Fee x total km to be travelled:

Permit Fee (ZAR) = Mass Fee x km to be travelled...*Eq 5.0*

Note: In the results of this paper, only the TDv is determined and used for all the associated LEFs. It is debatable whether the LDv should be incorporated or not. Therefore in all examples discussed here TDv = LEFv (i.e. LDv = 0).

12 LEF RESULTS FOR THE ABNORMAL VEHICLES AND MOBILE CRANES

12.1 Mobile Cranes - Current damage LEFs - DRY pavement conditions

The new LEF results of the eleven Mobile Cranes for relatively DRY pavement moisture conditions (for all pavements) are illustrated in Figure 6 together with the current damage LEF values (determined with the existing ESWL principle, i.e. Current Damage @ given TiPs). The *current* LEFs for the eleven Mobile Cranes vary between 0.1 and 113.1, showing the "Crane – 4 Axle Single Dual tyres" to be the least aggressive, and the "Crane 5 – Axle Single tyres" to be the most aggressive in terms of pavement damage. See Figure 6. The *newly* calculated LEFs (this study) in the DRY condition show a range of LEFs between 0.5 and 382, for all 9 pavement sections considered here. Figure 2 illustrates that most (except the LEFs for Pavement D) are found to be *lower* compared to the current damage LEFs. The LEFs for Pavement D may be considered as "outliers", but it is clear that the damage to relatively weak pavements (and even in relatively DRY moisture conditions) is very high, compared with all the other pavements. In addition, Figure 6 also shows that most cranes with 4 – Axles (and higher) with *single tyres* only resulted in the most damage, compared to those incorporating dual tyres.

12.2 Mobile Cranes - Current damage LEFs - WET pavement conditions

The *current* LEFs for the eleven Mobile Cranes vary between 0.1 and 113.1, showing the "Crane – 4 Axle Single Dual tyres" to be the least aggressive, and the "Crane 5 – Axle Single tyres" to be the most aggressive in terms of pavement damage, similar as to what was found for the DRY case. *Note that the ESWL method (current) does not provide for variation of the moisture conditions of pavements.* See De Beer *et al.,* 2009. As for the DRY condition, the *newly* calculated LEFs for the WET condition (this study) show a range of LEFs between 2.5 and 382, for all 9 pavement sections considered here. The most (except the LEFs for Pavement D) were found to be *lower* compared to the *current* damage LEFs, but is in general relatively *higher* compared with those found for the DRY condition. Similar to the DRY moisture conditions, the LEFs for Pavement D may also be considered as "outliers", but it is clear that the damage to relatively weak pavements (and in relatively WET moisture conditions) is very high, compared with all the other pavements. In addition, the data also shows that most cranes with 4 – Axles (and higher) with *single tyres* only, result in the most road damage, compared to those incorporating *dual tyres*., as was found for the DRY state, Finally for the Mobile Cranes, it is interesting to observe further that Pavements D, E, E1 and H seem to be *less* sensitive to moisture conditions (i.e. DRY *vs* WET) compared to the other pavements (as was analysed in this study, see De Beer *et al.,* 2009).

12.3 AVs - Current damage LEFs - DRY pavement conditions

The LEF results of the eight AVs for relatively DRY pavement moisture conditions (for all pavements) are illustrated in Figure 7. In addition to the *newly* calculated LEFs, the *current* damage LEF values (determined with the existing ESWL principle, i.e. Current Damage @ given TiPs) is also given in Figure 7. The *current* LEFs for the eight AVs vary between 5.8 and 20.3, showing “AV veh G” (AVKN300177) to be the least aggressive, and “AV veh B” (AVNC100523) to be the most aggressive in terms of pavement damage. The *newly* calculated LEFs (this study) in DRY conditions shows a range of LEFs between 5.9 and 40.6, for all 9 pavement sections considered here. Figure 7 illustrates that most LEFs (except the LEFs for Pavement D, as for the Mobile Cranes) are found to be relatively *lower* compared to the current damage LEFs. The LEFs of the AVs for Pavement D may also be considered as “outliers”, but it is clear that the damage to relatively weak pavements (even in relatively DRY moisture condition) is very high, compared with all the other pavements, as well as compared to the current damage.

12.4 AVs - Current damage LEFs - WET pavement conditions

The *current* LEFs for the eight AVs vary between 5.8 and 20.3, showing “AV veh G” (AVKN300177) to be the least aggressive, and “AV veh B” (AVNC100523) to be the most aggressive in terms of pavement damage, similar as to what was found for the DRY case. (See De Beer *et al.,* 2009).

The newly calculated LEFs (this study) for WET conditions show a range of LEFs between 5.9 and 40.6, for all 9 pavement sections considered here. As for the DRY case most LEFs (except the LEFs for Pavement D) are found to be relatively *lower* compared to the current damage LEFs.

The LEFs for Pavement D may be considered as “outliers”, but it is clear that the damage to relatively weak pavements in the relatively WET moisture condition is very high, compared with all the other pavements, as well as compared to the current damage.

Finally, also for the AVs, it is interesting to observe further that Pavements D, E, E1 and H seem to be *less* sensitive to moisture conditions (i.e. DRY vs WET) compared to the other pavements (as was analysed in this study), similar to what was found for the Mobile Cranes above, as indicated by De Beer *et al.,* 2009.

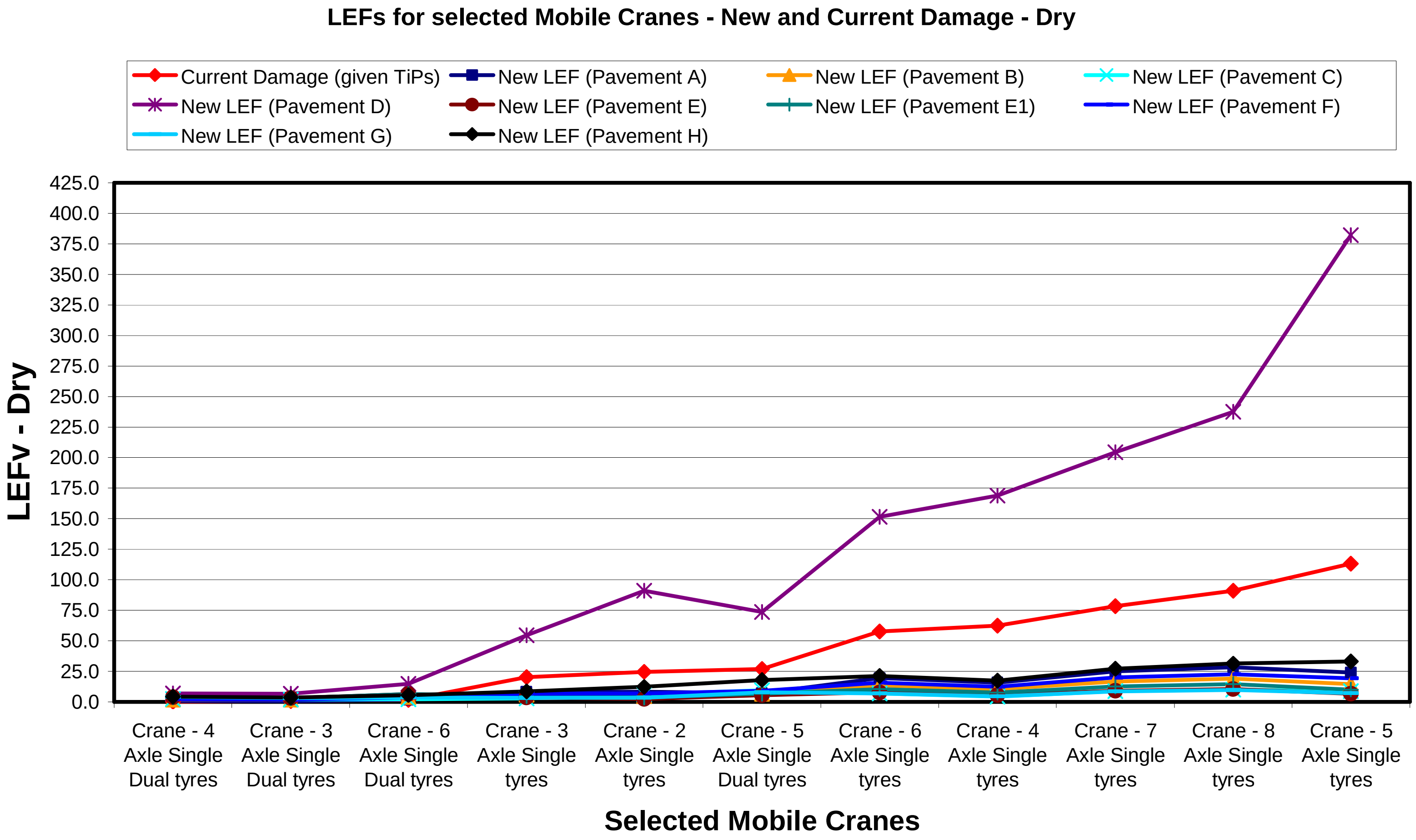


Figure 6. **Load Equivalency Factors (LEFv) of the eleven Mobile Cranes over the range of 9 Pavement Structures (A to H) analysed in the DRY condition, relative to the current damage.**

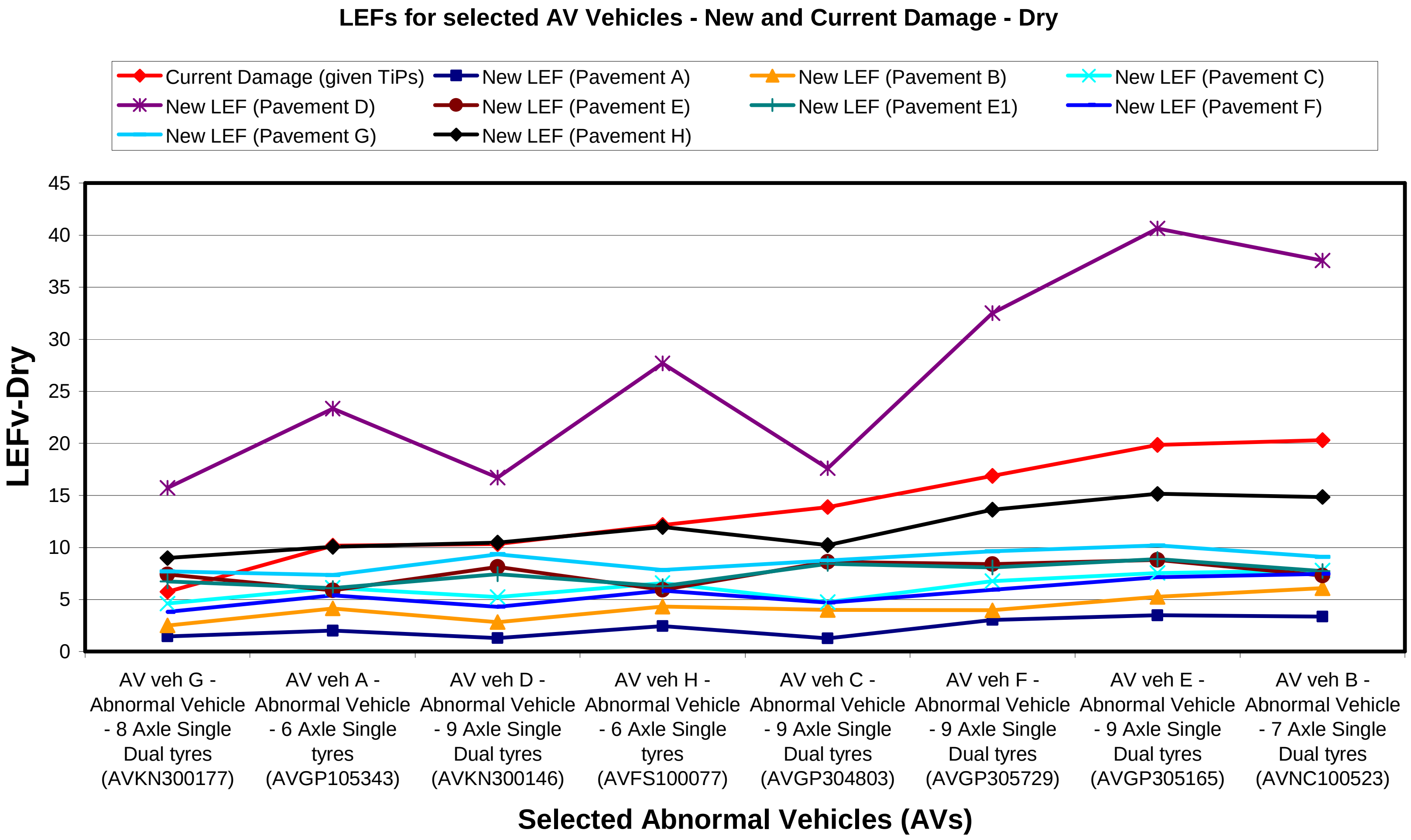


Figure 7. **Load Equivalency Factors (LEFv) of the eight Abnormal Vehicles (AVs) over the range of 9 Pavement Structures (A to H) analysed in the DRY condition, relative to the current damage.**

13 EFFECT OF TYRE INFLATION PRESSURES (TiPs) ON LEFs

13.1 Introduction

As stated before in Section 11, the LEFs of the eleven Mobile Cranes and eight Abnormal Vehicles were also estimated over a range of Tyre Inflation Pressures (TiPs). The assumption used here was to keep the TiPs for all tyres at the same level for each of the vehicles in order to study its *general* effect on the estimated LEFs. The range of tyre inflation pressures (TiPs) used was:

- 520 kPa; 650 kPa; 700 kPa; 800 kPa; 900 kPa and 1 200 kPa.

The results are discussed in the following sections, in relation to the *current* method at the given TiPs. Note that, ideally, the LEF data of the current method at different TiPs should be included. See project research report (De Beer *et al.,* 2008).

13.2 Mobile Cranes – Average damage LEFs over a range of TiPs

The *average* LEF results (for all pavements) of the eleven Mobile Cranes for relatively DRY pavement moisture conditions over the range of TiPs investigated are summarised in De Beer *et al.,* 2008.

13.2.1 *Mobile Cranes - Average damage LEFs - DRY pavement conditions*

It was found that the *current* LEFs for the eleven Mobile Cranes vary between 0.1 and 113.1, showing the “Crane – 4 Axle Single Dual tyres” to be the least aggressive, and the “Crane 5 – Axle Single tyres” to be the most aggressive in terms of pavement damage. See Figure 8. Note that these findings are similar at the given (as defined) TiPs for these vehicles. For the DRY condition, the *average* LEFs (for all pavements) over the range of TiPs investigated here for the eleven Mobile Cranes vary between 3.1 and 455.3. It is clear that an increase in TiP result in an increase in LEF, hence an increase in associated road damage. In addition, the data also shows that most Mobile Cranes with 4 – Axles (and higher) with *single tyres* only, result on average in the most damage over the range of TiPs investigated, compared to those also incorporating *dual tyres*.

Further it is interesting to note that “Crane – 5 Axle Single Dual” appears not to be so pavement sensitive for a variation in TiP compared with the other cranes. In addition, it is also interesting to note that “Crane – 5 Axle Single tyres” appears to be the most sensitive for variation in TiP compared with the other Mobile Cranes. Finally, the average results of Mobile Cranes at a TiP = 700 kPa (all tyres) compares very favourable with the current damage LEFs. The higher TiPs (i.e. TiPs $\geq$ 700 kPa) also result in relatively higher LEFs compared with the current damage LEFs for the Mobile Cranes.

13.2.2 *Mobile Cranes - Average damage LEFs - WET pavement conditions*

As before, the *current* LEFs for the eleven Mobile Cranes vary between 0.1 and 113.1, showing the “Crane – 4 Axle Single Dual tyres” to be the least aggressive, and the “Crane 5 – Axle Single tyres” to be the most aggressive in terms of pavement damage. Note that these findings are similar at the given (as defined) TiPs for these vehicles. For the WET condition the *average* LEFs (for all pavements in the WET condition) over the range of TiPs investigated here for the eleven Mobile Cranes vary between 5.2 and 461.9. It is also clear that an increase in TiP result in an increase in LEF, hence an increase in associated road damage. In addition, the data also shows that most Mobile Cranes with 4 – Axles

(and higher) with *single tyres* only, result on average in the most damage over the range of TiPs investigated, compared to those also incorporating *dual tyres*. As was found for the DRY condition, it is interesting to note that “Crane – 5 Axle Single Dual” appears not to be pavement sensitive for a variation in TiP compared with the other Mobile Cranes. In addition, it is also interesting to note that “Crane – 5 Axle Single tyres” appears to be the most sensitive for variation in TiP compared with the other Mobile Cranes. Finally, the average LEF results of Mobile Cranes at a TiP = 700 kPa (all tyres) compares very favourable with the current damage LEFs, as was found for the DRY pavement condition.
As was found for the DRY pavement conditions, the higher TiPs (i.e. TiPs ≥ 700 kPa) also result in relatively higher LEFs compared with the current damage LEFs for the Mobile Cranes.

13.3 AVs – Average damage LEFs over a range of TiPs

The *average* LEF results (for all pavements) of the eight AVs for relatively DRY pavement moisture conditions over the range of TiPs investigated are summarised in De Beer *et al.,* 2009.

13.3.3 *AVs - Average damage LEFs - DRY pavement conditions*

The *current* LEFs for the eight AVs vary between 5.8 and 20.3, showing “AV veh G” (AVKN300177) to be the least aggressive, and “AV veh B” (AVNC100523) to be the most aggressive in terms of pavement damage. Note that these findings are similar at the given (as defined) TiPs for these vehicles. It was found that for the DRY condition the *average* LEFs (for all pavements) over the range of TiPs investigated here for the eight AVs vary between 5.2 and 22.3. It is also clear here that an increase in TiP result in an increase in LEF, hence an increase in associated road damage. The higher TiPs (i.e. TiPs ≥ 1 000 kPa) also result in relatively higher LEFs compared with the current damage LEFs. Finally, the average LEF results indicate that “AV veh G” (AVKN300177) to be the least aggressive, and “AV veh E” (AVGP305165) to be the most aggressive in terms of pavement damage over the range of TiPs investigated here. De Beer *et al.,* 2009.

13.3.4 *AVs - Average damage LEFs - WET pavement conditions*

The *current* LEFs for the eight AVs vary between 5.8 and 20.3, showing “AV veh G” (AVKN300177) to be the least aggressive, and “AV veh B” (AVNC100523) to be the most aggressive in terms of pavement damage, as reported by De Beer *et al.,* 2009. Note also that these findings are similar at the given (as defined) TiPs for these vehicles. It was found that the *average* LEFs for the WET condition (for all pavements) over the range of TiPs investigated here for the eight AVs, vary between 7.4 and 26.7. It is also clear here that an increase in TiP result in an increase in LEF, hence an increase in associated road damage. The higher TiPs (i.e. TiPs ≥ 800 kPa) also result in relatively higher LEFs compared with the current damage, similar to what was found for the DRY conditions, albeit at a slightly lower TiP. Finally, as for the DRY conditions, the average LEF results indicate that “AV veh G” (AVKN300177) to be the least aggressive, and “AV veh E” (AVGP305165) to be the most aggressive in terms of pavement damage over the range of TiPs investigated here. Note that the above LEF results represent the “average LEFs” which were calculated over the range of nine pavements, separately for the DRY and WET pavement conditions, and across the range of TiPs used here.

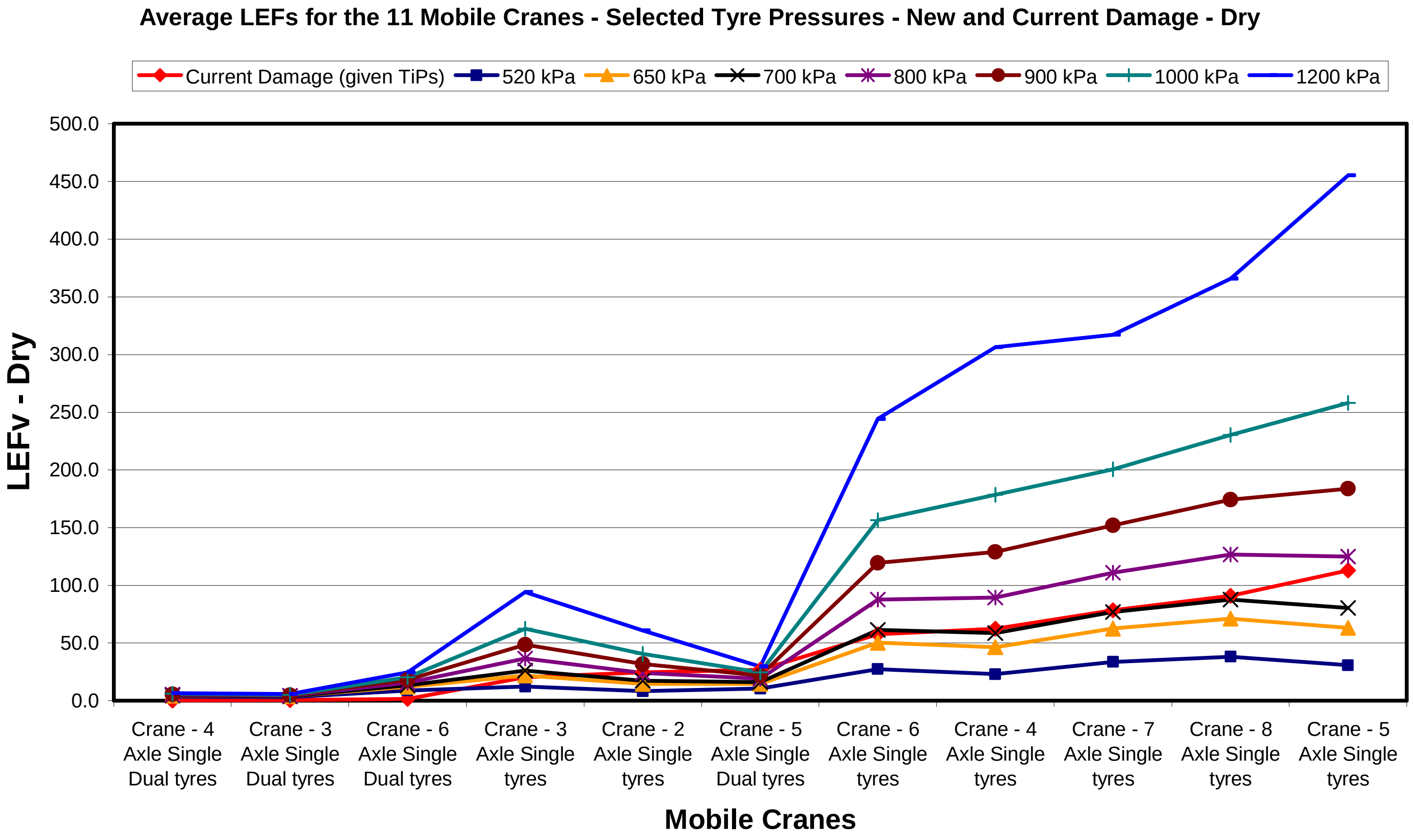


Figure 8. The effect of tyre inflation pressure (TiP) - ranging from 520 kPa to 1200 kPa - on the average LEFs for the eleven mobile cranes for all pavements studied here in the DRY state.

14 SUMMARY

In summary, this paper describes a proposed new methodology for the determination of the Permit Mass Fees for Abnormal road Vehicles (AVs) based on the estimation and quantification of road damage. The existing South African mechanistic-empirical (M-E) pavement design methodology was used here to estimate the Load Equivalency Factors (LEFs), based on critical pavement layer life, under static loading conditions. The proposed methodology is not based on the traditional Equivalent Single Wheel Load (or Mass) ESWL (or ESWM), nor on the well known 4^{th} power law for relative pavement damage but on the latest South African Mechanistic-Empirical Design Method (SAMDM) which has been used in practice for pavement design and analysis since 1996.

The *new* LEFs were calculated from estimated ratios of critical pavement layer life for each individual AV relative to the Standard Axle (80 kN, 520 kPa) bearing capacities of a range of nine (9) typical standard pavement structures found in South Africa. This was done for both relatively dry and wet pavement conditions. This paper includes examples of eleven (11) selected Mobile Cranes and eight (8) typical selected AVs. The *new* methodology also includes the effect of tyre inflation (or contact pressure) (TiP), including a sensitivity analysis over a range of 520 kPa to 1 200 kPa for all the above vehicles and pavements. It is clear that there appears to be a wide range in the new LEFs for the different vehicles based on the new and what is considered a more rational and fully mechanistic approach (i.e. the SAMDM). Although the *new* LEFs (hence the associated Mass Fees) are found to be different compared to those calculated according to the existing (i.e. *current*) ESWL method, they are in principle, considered to be based on a more rational (mechanistic) methodology than before and it is suggested that they be refined and applied with the current draft TRH 11 (2008) as soon as possible, but phased in over time.

15 CONCLUSIONS

The following conclusion can be drawn from this study:

- A new methodology based on the principle of full mechanistic road pavement analysis for each Mobile Crane and each AV considered in this study results in a variation of Load Equivalency Factors (LEFs) to be effectively quantified.
- This was demonstrated over a range of nine different pavement types, two pavement conditions and at different Tyre Inflation Pressures (TiPs);
- In general, the new LEFs compare favourably with those calculated with the existing ESWL method (i.e. current method) in terms of rating the different vehicles according to their road damage potential;
- The new method allows for different pavements and its moisture condition to be modelled effectively for the typical abnormal vehicles (including Mobile Cranes) found in South Africa;
- This study show that relatively higher LEFs were determined for the weaker pavements, and also those analysed in relatively WET pavement conditions;
- The LEFs determined for the stronger pavements were found to be lower compared with the current ESWL method for both relatively dry and relatively wet pavement moisture conditions, especially for the Mobile Cranes;

- Tyre Inflation Pressure (TiPs) plays a major role in the estimation of LEFs, and hence road pavement damage. The higher the TiP, the higher the LEF, and associated road pavement damage for all pavement analysed here.
- The new system of analysis provides for the more rational methodology for the estimation of road pavement damage, than perhaps given by the existing methodology based on ESWL. Each tyre load (hence axle load, and hence total load) is directly considered at the given TiP in the new method.
- Further, variation in the structural road pavement systems is allowed for in the new method, introducing the effect of different pavement types and conditions to be considered.

16 RECOMMENDATIONS

It is recommended that:

- The newly proposed methodology for the determination of LEFs be discussed in detail with the relevant committee members concerned with draft TRH 11, including Officials from Road Authorities;
- The newly determined methodology be incorporated/implemented into TRH 11 over time, starting as soon as practical possible;
- A simpler procedure for the determination of new LEFs for AVs and Mobile Cranes on a wider scale than is perhaps covered in this summary report should be further investigated, including appropriate software as the delivery system;
- A methodology should be developed for the implementation of the findings of this preliminary study for the future review of TRH 11 (2000), and
- The foregoing to be implemented through a Geographical Information System (GIS) of road pavement types, in order to select the applicable pavement sections for a specific route to be used by AVs and Mobile Cranes. If this can be done, appropriate road damage (and hence permit fees) could be determined for each section of road structure on that route, resulting in a fairer and more appropriate road damage cost recovery for a particular road pavement.
- Future studies to also investigate the use of “Dynamic Load Coefficients” (DLCs) or “Impact Factors” (IFs) under dynamic (or moving) loading in order to estimate road damage of moving vehicles. This to include the effect of suspension types of AVs and Mobile Cranes in relation to road roughness profiles.
- The output from this study to be used with care by industry and associated road authorities.

17 ACKNOWLEDGEMENTS

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