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REVISION OF TRH 11 (1999-2000): RECOVERY OF ROAD DAMAGE - DISCUSSION DOCUMENT ON A PROVISIONAL BASIS FOR POSSIBLE NEW ESTIMATION OF MASS FEES -

-- UNDER REVIEW FOR TRH 11 (2000) --

--- FINAL SUMMARY REPORT V1.0 ---

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Abstract: This summary report 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 South African mechanistic-empirical 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 practise 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 typical standard pavement structures found in South Africa. This was done for both relatively dry and wet pavement conditions. This study includes examples of eleven selected Mobile Cranes and eight other 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.

Keywords: Abnormal Vehicles, Mobile Cranes, Permit Fee, Mass Fee, Load Equivalency Factor (LEF), South African Mechanistic-Empirical Design Method (SAMDM), critical layer life, TRH 11.

Proposals for implementation: Through the Abnormal Loads Technical Committee. [Note that the associated SATC 2009 paper on SATC 2009 CD was subsequently updated with the new results as reported in this updated summary report].

Related documents: Project Research Report: CSIR/BE/IE/ER/2008/0006/B

Signatures:				
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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

APPENDICES and its PAGE NUMBERS:

Executive Summary

In this summary report a new methodology for the determination of the associated road damage for Permit Mass Fees of Abnormal road Vehicles (AVs) based on the South African Mechanistic-Empirical Design Method (SAMDM) is proposed and demonstrated. 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. The current SAMDM methodology is used instead to estimate the Load Equivalency Factors (LEFs) of each vehicle, based on the critical pavement layer life approach. The SAMDM used in this study is the latest procedure which has been used in practise 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 typical standard pavement structures found in South Africa. This was done for both relatively dry and wet pavement conditions under each of the most outside tyres and then summed for each vehicle. This study includes examples of eleven selected Mobile Cranes and eight other selected Abnormal Vehicles (AVs). The new methodology for the determination of LEFs discussed here also includes the effect of tyre inflation (or contact pressure) (TiP), and a sensitivity analysis over a range of 520 kPa to 1200 kPa for all the above vehicles and pavements was done. Each of the above vehicles was analysed at different tyre pressures, and for the nine different pavement types and tyre inflation pressures. The newly estimated LEFs were compared with the current ESWL method. It is clear that the new methodology results in different road damage values, i.e. LEFs (which is dependent on pavement type, moisture condition and tyre inflation pressure), compared with those determined with the current ESWL method.

The following conclusions 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.

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.

This study indicates that there appears to be a wide range in the new LEFs for the different vehicles based on the new and (it is hoped) 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 perhaps 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.

- *NOTE: There are 49 Appendices associated with this report, containing all the detailed data computed and analysed for this project.*

1. INTRODUCTION

This discussion document 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 sole purpose of this summary document is to act as a catalyst for further discussion on this topic.

2. SCOPE AND CONTENT

The scope of this document 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). The philosophy of *“Equivalent Pavement Response - Equivalent Pavement Damage” (EPR-EPD)* is used instead of reducing a single Abnormal Vehicle 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 4^{th} power law of relative pavement damage.

With the new *EPR-EPD* approach, no “fixed equivalencies” 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 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 1200 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 review of TRH 11 (2000).

3. 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[1] 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) (See Section 9 later). [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.,* 1997, 1999, 2002, 2004a, 2004b, 2006 and 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[2]. [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" (LD_v) 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

[1] In this study the mechanistic analysis was done under static (or stationary) loading conditions. The "dynamic" loading (or "moving" or "cyclic" loading) of the various abnormal vehicles (including Mobile Cranes) is not considered here, as this involve road roughness profile as well as suspension type to be known in advance. From this information, the "Dynamic Load Coefficient" (DLC) can be calculated and used in the mechanistic analysis for the prediction of "dynamic" LEFs. This however was outside the scope of this study.
[2] Note that for this study it is proposed that the Tyre Contact Stress (TcS) be considered as equal to the Tyre Inflation Pressure (TiP). See Section 9 later.

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 (TD_v) of the vehicle is calculated as the sum of the ratios (for all axles of a particular vehicle)[3] 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 (TAD_v) of the vehicle is simply TD_v *minus* LD_v. [Note, however, Item 8 above], and

11) The Mass Fee/km in ZAR = TAD_v * 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.

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

As reported by various authors, the 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) (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,

[3] Cumulative damage determined according to the well known Miners Law, summing the damage from each axle. See Section 12.

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[4] 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).

5. BACKGROUND TO THE SAMDM

The SA Mechanistic Design procedure (SAMDM) was developed over the past three decades and includes both flexible and semi-rigid pavement types. An overview of the method is given by Theyse *et al.,* (1996). This procedure takes into account factors relating to design strategy, including road category, traffic volumes and structural design period, and considers material types, environment, drainage, compaction and cost analysis. A simpler approach is based on a catalogue of designs, which is typically used as a preliminary assessment of the pavement type required. Appropriate descriptions of some of the developments of the SA mechanistic approach is given by Walker *et al.,* (1977) and Paterson and Maree (1978). The basic approach of the method has not altered to any great extent since the publication of the above-mentioned documents but better quantification of existing failure criteria and recognition of new ones have taken place (De Beer, 1992). For the detailed background on the SAMDM the reader is referred to De Beer (1992), SARB (1995), Theyse *et al.,* (1996) and Theyse and Muthen (2000). A summary of the different pavement response parameters used for this study and their associated failure (incorporated in the software "*me*PADS" (*me*PADS, 2008)) is given in Table 1.

[4] During 1995/6 the TRH 4 (1996) document was reviewed, with the SAMDM being used as a basis for the determination of pavement bearing capacities (TRH 4 Revision (1995a, 1995b)) and (Theyse *et al.,* 1996).

Table 1. Pavement response parameters used in the mechanistic analysis (*me*PADS, 2008). Material Codes in accordance with CSRA, (1985). [For detail on the content of the table, see SARB, (1995b).]

Material Type and layer	Failure Criteria	Pavement Response Parameters used in the Analyses	Critical Position in Pavement Layer
Granular Base/Subbase/ Selected layer(G)	Shear Failure (Factor of Safety)	σ_1, σ_3	Middle
Cemented Base and Cemented Subbases (C3, C4)	Crushing (N_c)	σ_Z	Top
	Effective Fatigue (N_{ef})	ε_h	Bottom
	Shear Failure (in equivalent Granular (EG) phase)	σ_1, σ_3	Middle
Asphalt Surfacing (20-75 mm thick) (AC/AG)	Flexural Fatigue Cracking	ε_h	Bottom
Asphalt Base (> 75 mm) (BC)	Flexural Fatigue Cracking	ε_h	Bottom
Subgrade (Soil)	Rutting	ε_z	Top

Where:

σ_Z = Vertical Stress (used for estimation of crushing failure on the top of lightly cementitious (i.e. stabilised) layers);

ε_h = Horizontal Tensile Strain (used for estimation of fatigue failure of bound layers);

ε_z = Vertical Compressive Strain (used for estimation of rutting (i.e. plastic deformation) of unbound layers);

σ_1, σ_3 = Major Principal Stresses (used for estimation of shear failure of granular layers, leading to rutting).

6. 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.

6.1. Pavement A:

This 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.

6.2. Pavement B:

This 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.

6.3. Pavement C:

This 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.

6.4. Pavement D:

This 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.

6.5. Pavement E:

This 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.

6.6. Pavement E1 (not shown in Figure 1, but given in Appendix 3):

This 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.

6.7. Pavement F:

This 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.

6.8. Pavement G:

This 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.

6.9. Pavement H:

This 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 given in TRH 4 (1996) are given in Table 2.

Table 2. **Classification of Pavements and Traffic for Structural Design purposes (*from* TRH 4, 1996).**

Pavement class*	Pavement design bearing capacity (million 80 kN axles/lane- (MISA))	Volume and type of traffic **	
		Approximate v.p.d. per lane	**Description**
ES0.003	< 0,003	< 3	Very lightly trafficked roads; very few heavy vehicles. These roads could include the transition from gravel to paved roads and may incorporate semi-permanent and/or all weather surfacings.
ES0.01	0,003 - 0,01	3 – 10	
ES0.03	0,01 - 0,03	10 – 20	
ES0.1	0,03 - 0,10	20 – 75	
ES0.3	0,10 - 0,30	75 – 220	
ES1	0,3 - 1	220 - 700	Lightly trafficked roads, mainly cars, light delivery and agriculture vehicles; very few heavy vehicles.
ES3	1 - 3	> 700	Medium volume of traffic; few heavy vehicles.
ES10	3 - 10	> 700	High volume of traffic and/or many heavy vehicles.
ES30	10 - 30	> 2200	Very high volume of traffic and/or a high proportion of fully laden heavy vehicles.
ES100	30 - 100	> 6500	

* ES = Equivalent Standard Axle (80 kN) Class. The numerical value indicates the top range of million standard 80 kN axles/lane (MISA);

** Traffic demand in this document converted to *Equivalent* 80 kN axles (Million Equivalent Standard Axles, (MESA)).

Pavement A: ES100

Layer	Poisson's Ratio	Elastic Moduli (MPa) 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

Layer	Poisson's Ratio	Elastic Moduli (MPa) 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

Layer	Poisson's Ratio	Elastic Moduli (MPa) 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

Layer	Poisson's Ratio	Elastic Moduli (MPa) 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

Layer	Poisson's Ratio	Elastic Moduli (MPa) 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

Layer	Poisson's Ratio	Elastic Moduli (MPa) 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

Layer	Poisson's Ratio	Elastic Moduli (MPa) 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

Layer	Poisson's Ratio	Elastic Moduli (MPa) 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 study).

Note that all the 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). Note: 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[5]. 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 *me*PADS software (*me*PADS, 2008) analysis are also defined in Figure 1. See also summary table in Appendix 3.

7. MOBILE CRANES AND EXAMPLES

In this study, the standard axle was used as reference axle. See Table 3 for details (legal axle also given in Table 3). 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 below. [Note: The notation used for the Mobile Cranes in the tables and figures that follow after this section is given in square brackets below]:

1). 2 Axles, Single Tyres [Crane - 2 Axle Single tyres];
2). 3 Axles, Single Tyres [Crane - 3 Axle Single tyres];
3). 3 Axles, Single and Dual Tyres [Crane - 3 Axle Single Dual tyres];
4). 4 Axles, Single Tyres [Crane - 4 Axle Single tyres];
5). 4 Axles, Single and Dual Tyres [Crane - 4 Axle Single Dual tyres];
6). 5 Axles, Single Tyres [Crane - 5 Axle Single tyres];

[5] The relatively "dry" and "wet" analyses options were selected in the *me*PADS Software as described by Theyse and Muthen (2000), based on the SAMDM as given by Theyse *et al.,* (1996). Note that this selection is strictly related to the life prediction of granular layers (i.e. safety factors against shear failure), and may not be sensitive for stabilised (or cementitious) layers. Therefore one may find that when the cementitious layers are found to be the "critical layers", the LEFs for "dry" and "wet" may be equal, as was indeed found for Pavements D, E, E1 and H (See Tables 10 to 13) of this study.

7). 5 Axles, Single and Dual Tyres [Crane - 5 Axle Single Dual tyres];
8). 6 Axles, Single Tyres [Crane - 6 Axle Single tyres];
9). 6 Axles, Single and Dual Tyres [Crane - 6 Axle Single Dual tyres];
10). 7 Axles, Single Tyres [Crane - 7 Axle Single tyres];
11). 8 Axles, Single Tyres [Crane - 8 Axle Single tyres];

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. For tyre load configurations of these Mobile Cranes, see Tables 4, 6 and 8. The definitions and layout of the axle and load configurations of these eleven Mobile Cranes are summarised in Appendix 1.

8. ABNORMAL VEHICLES (AVs) AND EXAMPLES

In this study, 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 below. [Note: The notation used for the AVs in the tables and figures that follow after this section is given in square brackets below]:

1). AVGP 105343 [AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)];
2). AVNC 100523 [AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)];
3). AVGP 304803 [AV veh C - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP304803)];
4). AVKN 300146 [AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)];
5). AVGP 305165 [AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)];
6). AVGP 305729 [AV veh F - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305729)];
7). AVKN 300177 [AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)];
8). AVFS 100077 [AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)];

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 1292.8 kN. The average TiPs for these AVs ranging between 463 kPa and 737 kPa. The tyre load configurations of these abnormal heavy vehicles are given in Tables 5, 7 and 9.

The definitions and layout of the axle and layout of the load configurations of these eight AVs are summarised in Appendix 2.

Table 3. 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 4. 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 5. 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

Table 6. **Summary of the eleven Mobile Cranes used in this study (sorted on Total Load)**

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

Table 7. Summary of the eight Abnormal Vehicles (AVs) (sorted on Total Load)

ABNORMAL VEHICLES (SORTED ON TOTAL LOAD):	Average Tyre Load (kN)	Standard Deviation (kN)	Total Load (kN)	Number of Tyres	Average TiP (kPa)	Standard Deviation (kPa)
AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)	25.41	4.76	559.00	22	727.00	86.78
AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)	29.23	1.80	643.00	22	625.18	29.20
AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)	27.37	2.60	711.50	26	621.54	14.88
AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)	17.57	4.47	878.40	50	463.68	209.46
AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)	16.59	5.34	962.00	58	736.52	4.29
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

Table 8. Summary of the eleven Mobile Cranes used in this study (sorted on Tyre Inflation Pressure (TiP))

MOBILE CRANES (SORTED ON AVE TYRE INFLATION PRESSURE, TiP):	Average Tyre Load (kN)	Standard Deviation (kN)	Total Load (kN)	Number of Tyres	Average TiP (kPa)	Standard Deviation (kPa)
Crane - 6 Axle Single Dual tyres	33.27	6.05	513.07	18	329.33	71.79
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 - 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 - 4 Axle Single tyres	64.01	5.77	512.08	8	524.50	59.33
Crane - 8 Axle Single tyres	60.65	1.86	970.44	16	537.25	21.15
Crane - 7 Axle Single tyres	60.65	0.61	849.08	14	537.71	7.03
Crane - 5 Axle Single tyres	65.00	7.05	650.02	10	586.60	79.46
Crane - 2 Axle Single tyres	56.26	0.74	225.04	4	664.50	12.12
Crane - 5 Axle Single Dual tyres	36.32	1.98	508.50	14	695.00	13.00

Table 9. Summary of the eight Abnormal Vehicles (AVs) used in this study (sorted on Tyre Inflation Pressure (TiP))

ABNORMAL VEHICLES (SORTED ON AVE TYRE INFLATION PRESSURE, TiP):	Average Tyre Load (kN)	Standard Deviation (kN)	Total Load (kN)	Number of Tyres	Average TiP (kPa)	Standard Deviation (kPa)
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 B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)	27.37	2.60	711.50	26	621.54	14.88
AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)	22.29	6.62	1292.80	58	624.48	1.14
AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)	29.23	1.80	643.00	22	625.18	29.20
AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)	25.41	4.76	559.00	22	727.00	86.78
AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)	16.59	5.34	962.00	58	736.52	4.29

9. SOFTWARE FOR CALCULATION OF ROAD DAMAGE

The *mePADS* software of the SAMDM is discussed by Theyse and Muthen (2000). Its methodology is based on earlier work reported by Theyse *et al.,* (1996). 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 methodology is freely available within South Africa from the CSIR BE (*me*PADS, 2008) - see website: http://asphalt.csir.co.za/samdm/

Engineering features: The Pavement Analysis & Design Software package (*me*PADS) is based on the SA Mechanistic Pavement Design Method (SAMDM). The software combines a stress-strain computational engine with pavement materials models developed at CSIR (Theyse and Muthen, 2000). The Windows Graphical User Interface enables any pavement system and vehicle load configuration to be defined and analysed for bearing capacity and design reliability. Amongst others, the design outputs include pavement layer lives and contour plots of stresses and strains. In this study, the critical pavement layers were used for calculating the LEFs in each vehicle/pavement combination for both relatively "DRY" and relatively "WET" pavement conditions. The results are discussed in more detail later in Section 14 of this summary report.

10. 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).

11. 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 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 also De Beer and Fisher (2000), De Beer *et al.,* (1997, 1999, 2002, 2004a, 2004b and 2006) 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, as was shown by Van Vuuren (1974).) 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 1200 kPa, for both the Mobile Cranes and Abnormal Vehicles (AVs). This is discussed further in Section 15.

12. 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:

12.1. Legal Damage (LDv):

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

or

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

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)).*

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

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

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.*

12.3. Total Additional Damage (TADv):

Total Additional Damage of Vehicle $= TAD_v$

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

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

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

13. 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).

$$\text{Mass Fee (ZAR) per km} = R \times TAD_V \qquad \text{Eq 4.0}$$

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

$$\text{Permit Fee (ZAR)} = \text{Mass Fee} \times \text{km to be travelled} \qquad \text{Eq 5.0}$$

Note: In the results of this summary report, 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).

14. LEF RESULTS FOR THE ABNORMAL VEHICLES AND MOBILE CRANES

14.1. Mobile Cranes - LEFs

The LEF results of the eleven Mobile Cranes for relatively DRY pavement moisture conditions (for all pavements) are summarised in Table 10. It is also illustrated in Figure 2. In addition to the newly calculated LEFs, the current damage LEF values (determined with the existing ESWL principle, i.e. Current Damage @ given TiPs) are also given in the table and Figure 2. For the relatively WET pavement conditions the results are given in Table 11, and are illustrated in Figure 3.

14.1.1. *Mobile Cranes - Current damage LEFs - DRY 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. See Table 10 and also Figure 2.

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 (even in relatively DRY moisture conditions) is very high, compared with all the other pavements. See Figure 2.

In addition, Figure 2 also shows that most cranes with 4 – Axles (and higher) with *single tyres* only, result in the most damage, compared to those incorporating dual tyres.

14.1.2. *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. *Note that the ESWL method (current) does <u>not</u> provide for variation of the moisture conditions of pavements.* See Table 11 and also Figure 3.

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. Figure 3 also illustrates that most (except the LEFs for Pavement D) are 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, Figure 3 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*.

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).

14.2. Abnormal Vehicles (AVs) - LEFs

The LEF results of the eight AVs for relatively DRY pavement moisture conditions (for all pavements) are summarised in Table 12. It is also illustrated in Figure 4. 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 the table and Figure 4. For the relatively WET pavement conditions the results are given in Table 13, and illustrated in Figure 5.

14.2.3. *AVs - Current 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. See Table 12 and also Figure 4.

The newly calculated LEFs (this study) in DRY conditions shows a range of LEFs between 1.3 and 40.6, for all 9 pavement sections considered here. Figure 4 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. See Figure 4.

14.2.4. *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. See Table 13 and also Figure 5.

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. Figure 5 illustrates that most (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. See Figure 5.

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.

Table 10. Summary of the Load Equivalencies (LEFs) for the eleven Mobile Cranes in the DRY state (sorted on Current Damage at the given TiPs).

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	New LEF (Pavement A)	New LEF (Pavement B)	New LEF (Pavement C)	New LEF (Pavement D)	New LEF (Pavement E)	New LEF (Pavement E1)	New LEF (Pavement F)	New LEF (Pavement G)	New LEF (Pavement H)
Outside	DRY	Crane - 4 Axle Single Dual tyres	0.1	0.5	1.9	2.3	6.9	3.8	3.7	2.1	3.9	4.0
Outside	DRY	Crane - 3 Axle Single Dual tyres	0.7	0.5	1.7	1.8	6.5	2.9	3.0	1.8	3.0	3.4
Outside	DRY	Crane - 6 Axle Single Dual tyres	1.6	1.7	3.9	2.1	14.8	6.2	6.3	3.6	3.6	5.6
Outside	DRY	Crane - 3 Axle Single tyres	20.3	8.0	5.8	2.8	54.5	3.6	4.7	6.7	3.2	8.4
Outside	DRY	Crane - 2 Axle Single tyres	24.6	8.2	4.7	6.2	91.1	2.5	3.5	6.8	3.4	12.1
Outside	DRY	Crane - 5 Axle Single Dual tyres	26.8	7.1	6.8	9.5	73.6	5.4	6.5	9.1	7.9	17.9
Outside	DRY	Crane - 6 Axle Single tyres	57.6	19.4	13.7	6.8	151.4	7.7	10.5	15.7	6.9	21.0
Outside	DRY	Crane - 4 Axle Single tyres	62.4	15.8	10.4	4.2	168.9	5.3	7.5	12.4	4.5	17.2
Outside	DRY	Crane - 7 Axle Single tyres	78.3	24.9	16.8	8.7	204.4	9.1	12.6	19.8	8.5	27.2
Outside	DRY	Crane - 8 Axle Single tyres	91.0	28.3	19.1	9.9	237.5	10.4	14.3	22.6	9.7	31.3
Outside	DRY	Crane - 5 Axle Single tyres	113.1	24.1	14.4	8.6	382.1	6.7	10.0	19.3	7.1	33.0

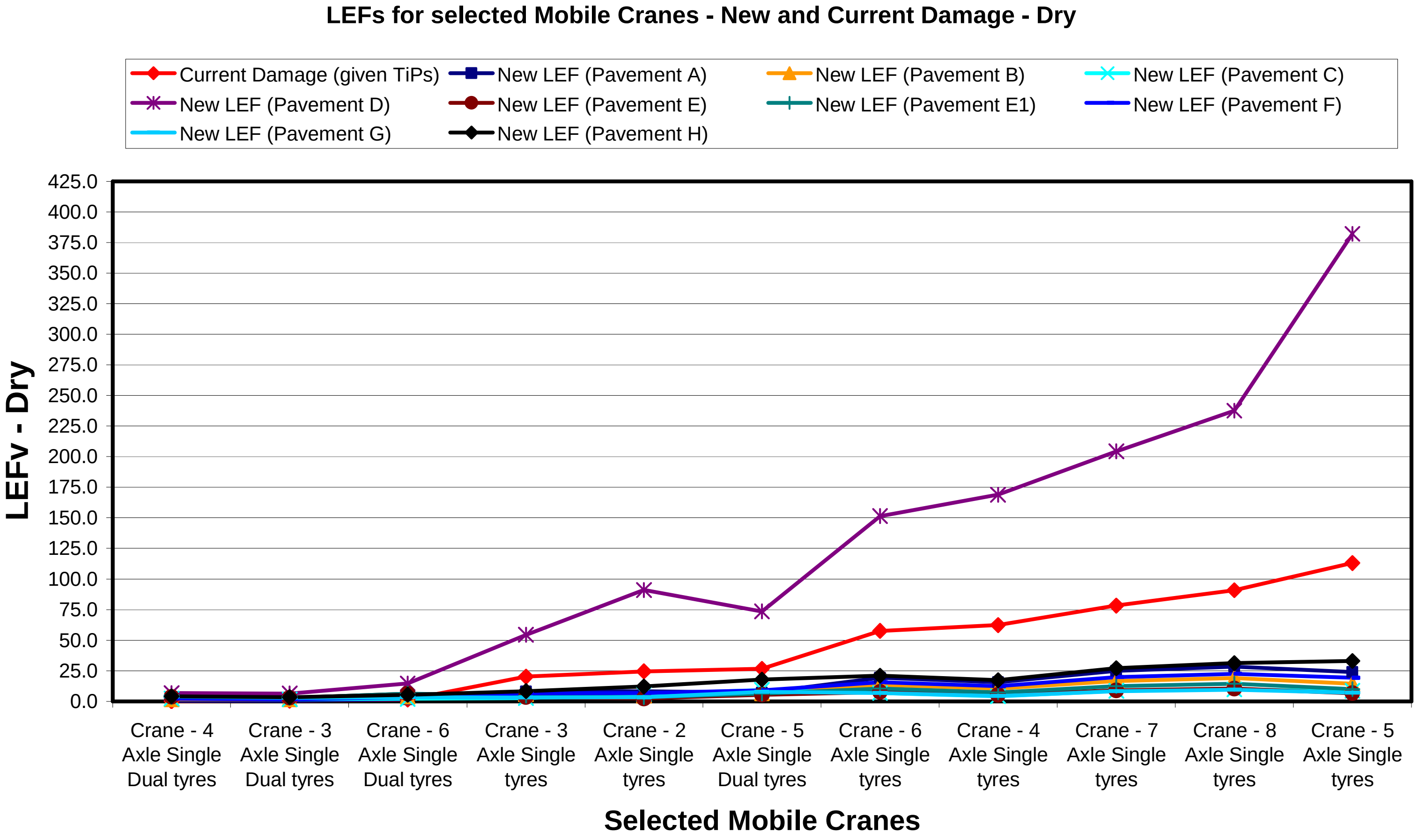

Figure 2. Load Equivalency Factors (LEFv) of the eleven Mobile Cranes over the range of 9 Pavement Structures (A to H) analysed in the DRY condition, relative to the current damage.

Table 11. Summary of the Load Equivalencies (LEFs) for the eleven Mobile Cranes in the WET state (sorted on Current Damage at the given TiPs).

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	New LEF (Pavement A)	New LEF (Pavement B)	New LEF (Pavement C)	New LEF (Pavement D)	New LEF (Pavement E)	New LEF (Pavement E1)	New LEF (Pavement F)	New LEF (Pavement G)	New LEF (Pavement H)
Outside	WET	Crane - 4 Axle Single Dual tyres	0.1	7.0	4.1	4.8	6.9	3.8	3.7	4.5	4.1	4.0
Outside	WET	Crane - 3 Axle Single Dual tyres	0.7	6.2	3.5	3.9	6.5	2.9	3.0	3.8	3.2	3.4
Outside	WET	Crane - 6 Axle Single Dual tyres	1.6	13.3	7.5	5.6	14.8	6.2	6.3	7.6	5.1	5.6
Outside	WET	Crane - 3 Axle Single tyres	20.3	18.4	7.2	7.3	54.5	3.6	4.7	11.0	3.8	8.4
Outside	WET	Crane - 2 Axle Single tyres	24.6	14.5	5.5	11.1	91.1	2.5	3.5	10.7	3.6	12.1
Outside	WET	Crane - 5 Axle Single Dual tyres	26.8	23.8	9.0	17.1	73.6	5.4	6.5	14.9	8.0	17.9
Outside	WET	Crane - 6 Axle Single tyres	57.6	40.5	16.6	16.9	151.4	7.7	10.5	25.7	8.2	21.0
Outside	WET	Crane - 4 Axle Single tyres	62.4	29.5	12.4	11.1	168.9	5.3	7.5	20.4	5.6	17.2
Outside	WET	Crane - 7 Axle Single tyres	78.3	49.0	20.2	21.4	204.4	9.1	12.6	32.3	10.0	27.2
Outside	WET	Crane - 8 Axle Single tyres	91.0	55.8	23.1	24.3	237.5	10.4	14.3	36.9	11.4	31.3
Outside	WET	Crane - 5 Axle Single tyres	113.1	40.2	16.9	19.9	382.1	6.7	10.0	31.3	8.2	33.0

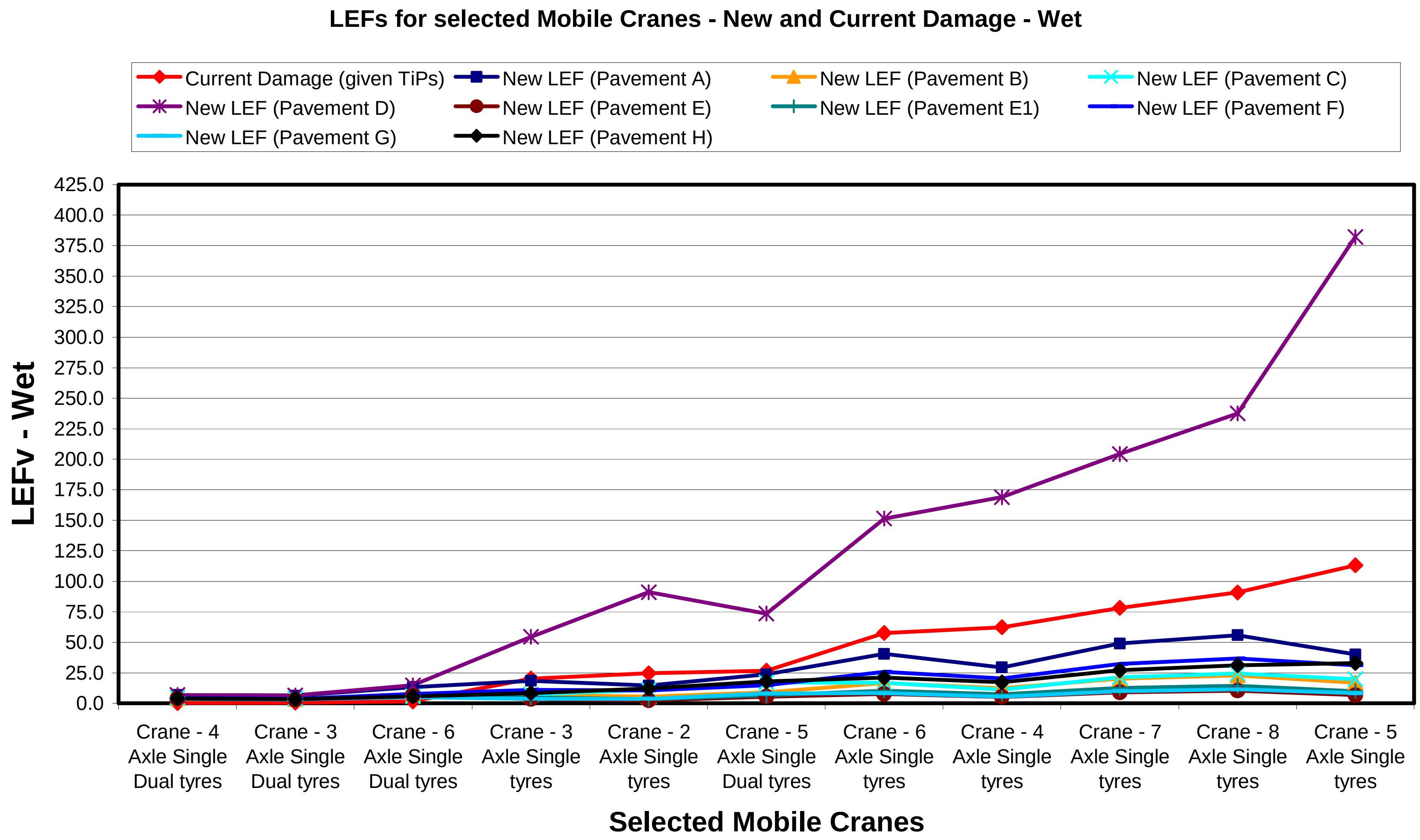

Figure 3. **Load Equivalency Factors (LEFv) of the eleven Mobile Cranes over the range of 9 Pavement Structures (A to H) analysed in the WET condition, relative to the current damage.**

Table 12. Summary of the Load Equivalencies (LEFs) for the eight AVs in the DRY state (sorted on Current Damage at the given TiPs).

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	New LEF (Pavement A)	New LEF (Pavement B)	New LEF (Pavement C)	New LEF (Pavement D)	New LEF (Pavement E)	New LEF (Pavement E1)	New LEF (Pavement F)	New LEF (Pavement G)	New LEF (Pavement H)
Outside	DRY	AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)	5.8	1.5	2.5	4.6	15.7	7.4	6.7	3.8	7.7	9.0
Outside	DRY	AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)	10.2	2.0	4.1	6.1	23.3	5.9	6.1	5.4	7.3	10.1
Outside	DRY	AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)	10.3	1.3	2.8	5.2	16.7	8.1	7.4	4.3	9.4	10.5
Outside	DRY	AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)	12.2	2.4	4.3	6.6	27.7	5.9	6.3	5.8	7.8	12.0
Outside	DRY	AV veh C - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP304803)	13.9	1.3	4.0	4.7	17.6	8.6	8.4	4.7	8.8	10.2
Outside	DRY	AV veh F - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305729)	16.9	3.0	4.0	6.8	32.5	8.4	8.1	5.9	9.6	13.6
Outside	DRY	AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)	19.8	3.5	5.2	7.6	40.6	8.8	8.9	7.1	10.2	15.1
Outside	DRY	AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)	20.3	3.4	6.1	7.8	37.6	7.3	7.7	7.5	9.1	14.8

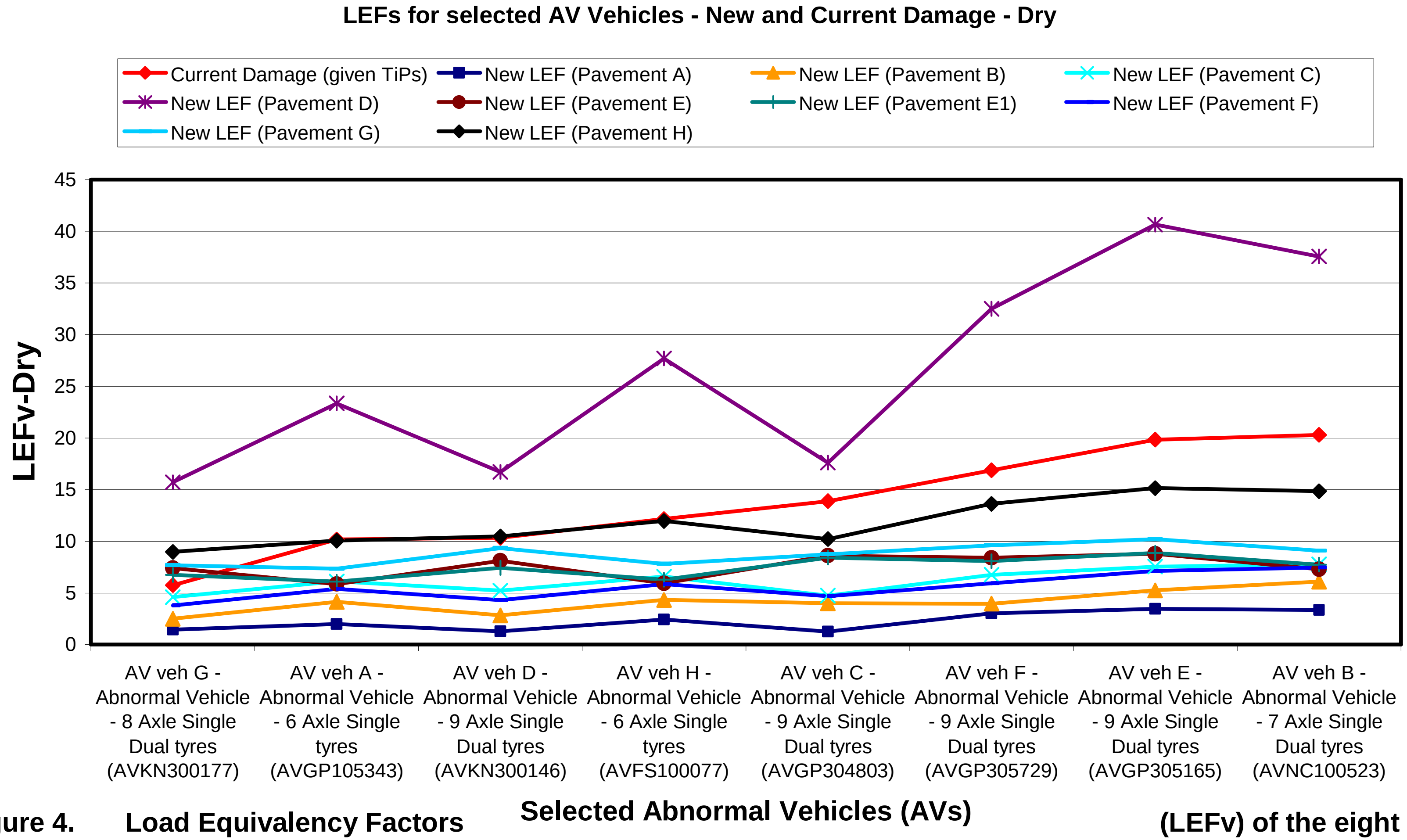

Figure 4. Load Equivalency Factors (LEFv) of the eight Abnormal Vehicles (AVs) over the range of 9 Pavement Structures (A to H) analysed in the DRY condition, relative to the current damage.

Table 13. Summary of the Load Equivalencies (LEFs) for the eight AVs in the WET state (sorted on Current Damage at the given TiPs).

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	New LEF (Pavement A)	New LEF (Pavement B)	New LEF (Pavement C)	New LEF (Pavement D)	New LEF (Pavement E)	New LEF (Pavement E1)	New LEF (Pavement F)	New LEF (Pavement G)	New LEF (Pavement H)
Outside	WET	AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)	5.8	9.4	6.4	9.3	15.7	7.4	6.7	7.9	8.2	9.0
Outside	WET	AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)	10.2	16.0	7.2	11.3	23.3	5.9	6.1	9.5	7.5	10.1
Outside	WET	AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)	10.3	10.7	6.8	10.7	16.7	8.1	7.4	9.0	9.6	10.5
Outside	WET	AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)	12.2	16.2	7.5	12.5	27.7	5.9	6.3	10.5	8.0	12.0
Outside	WET	AV veh C - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP304803)	13.9	13.9	9.1	10.8	17.6	8.6	8.4	10.5	9.3	10.2
Outside	WET	AV veh F - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305729)	16.9	14.5	8.4	13.6	32.5	8.4	8.1	11.6	10.1	13.6
Outside	WET	AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)	19.8	18.6	10.0	15.3	40.6	8.8	8.9	13.9	10.5	15.1
Outside	WET	AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)	20.3	22.4	9.7	15.4	37.6	7.3	7.7	13.5	9.3	14.8

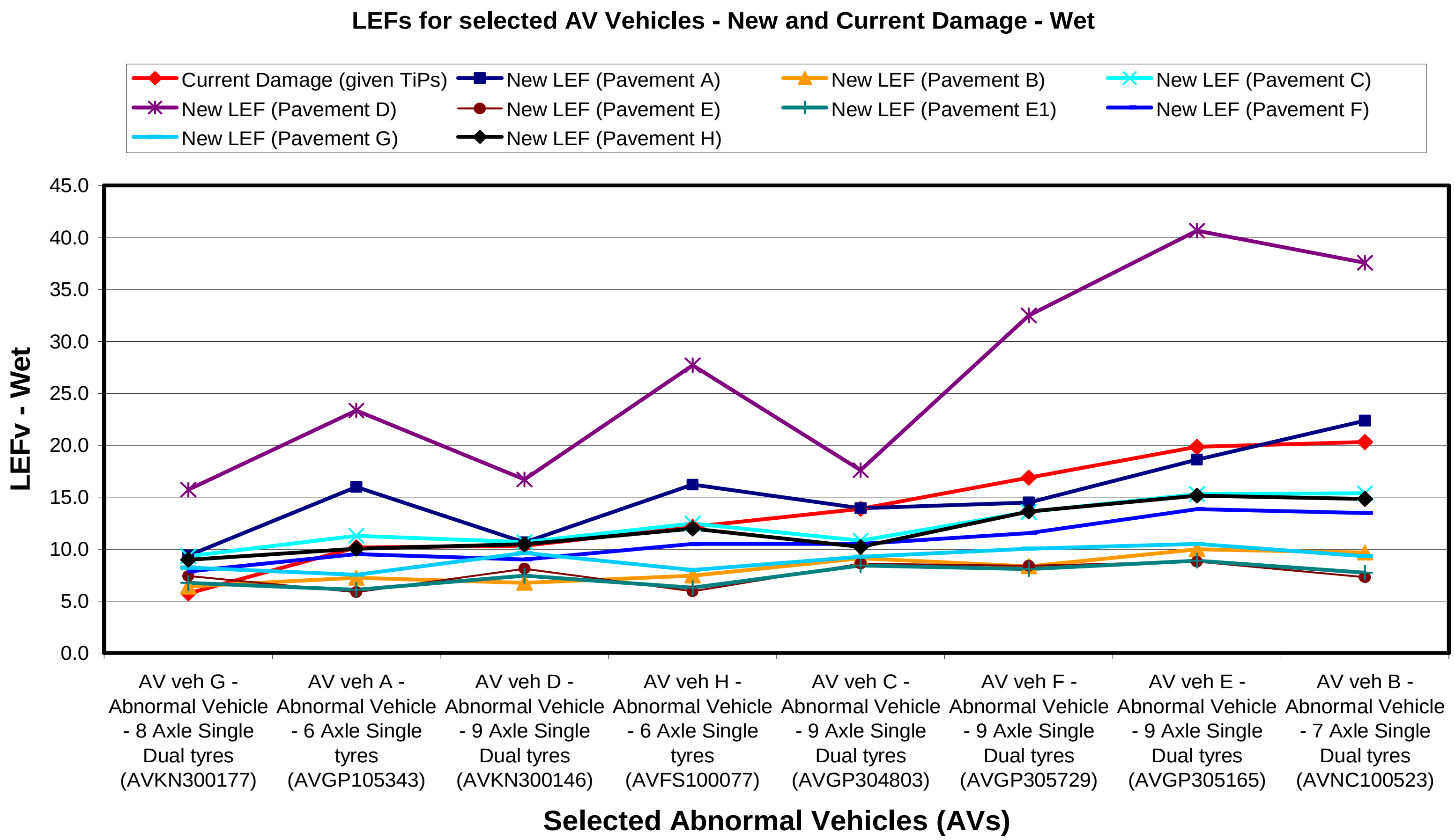

Figure 5. Load Equivalency Factors (LEFv) of the eight Abnormal Vehicles (AVs) over the range of 9 Pavement Structures (A to H) analysed in the WET condition, relative to the current damage.

15. EFFECT OF TYRE INFLATION PRESSURES (TiPs) ON LEFs

15.1. 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 also be investigated but this was outside the scope of this study.

15.2. 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 Table 14, and standard deviations in Table 15. It is also illustrated in Figure 6. In addition to the newly calculated LEFs, the current damage LEF values (determined with the existing ESWL principle) is also given in the table and Figure 6. For the relatively WET pavement conditions the results are given in Table 16 (standard deviations in Table 17), and are illustrated in Figure 7.

15.2.1. *Mobile Cranes - Average damage LEFs - DRY 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. See Table 14 and also Figure 6. 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. See Table 14 and also Figure 6. It should be noted that as these former results represent *average* values over the range of relatively strong pavements to relatively weak pavements, that a measure of standard deviation is needed, which is given in Table 15. The standard deviations vary between 2.1 to 1222.5, which is indicative of the relative effect of pavement type on the LEFs in this analysis. It is also clear that an increase in TiP result in an increase in LEF, hence an increase in associated road damage.

In addition, Figure 6 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 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.

The average results of Mobile Cranes at a TiP = 700 kPa (all tyres) compares very favourable with the current damage LEFs. See Figure 6. Finally, 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.

15.2.2. *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. See Table 16 (Table 17 for standard deviation) and also Figure 7. 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. See Table 16 and also Figure 7. As before, it should be noted that as these former results represent *average* values over the range of relatively strong pavements to relatively weak pavements, that a measure of standard deviation is needed, which is given in Table 17. The standard deviations vary from 1.6 to 1220, which is indicative of the effect of pavement type in this analysis. It is also clear that an increase in TiP result in an increase in LEF, hence an increase in associated road damage.

In addition, Figure 7 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 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.

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 in Figure 6. Finally, as was also found for the DRY pavement conditions, 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.

15.3. 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 Table 18 (Standard deviation in Table 19). It is also illustrated in Figure 8. In addition to the newly calculated LEFs, the current damage LEF values (determined with the existing ESWL principle) is also given in the table and Figure 8. For the relatively WET pavement conditions the results are given in Table 20 (Standard deviation in Table 21), and are illustrated in Figure 9.

15.3.3. *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. See Table 18 and also 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 eight AVs vary between 5.2 and 22.3. See Table 18 and also Figure 8. (It is, however, much lower compared with the standard deviation results obtained for the Mobile Cranes, probably because of the more road friendly tyre configuration). As before, it should be noted that as these former results represent *average* values over the range of relatively strong pavements to relatively weak pavements, that a measure of standard deviation is needed, which is given in Table 19. The standard deviations vary between 2.9 to 30.1, which is indicative of the effect of pavement type in this analysis (Also here the results are much lower compared with the standard deviation results obtained for the Mobile Cranes, probably because of the more road friendly tyre configuration). 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 higher LEFs compared with the current damage LEFs.

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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. See Figure 8.

15.3.4. *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. See Table 20 (Standard deviation in Table 21) and also Figure 9. Note that these findings are similar at the given (as defined) TiPs for these vehicles.

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. See Table 20 and also Figure 9. (It is, however, much lower compared with the standard deviation results obtained for the Mobile Cranes, probably because of the more road friendly tyre configuration). As before, it should be noted that as these former results represent *average* values over the range of relatively strong pavements to relatively weak pavements, that a measure of standard deviation is needed, which is given in Table 21. The standard deviations vary between 0.7 to 28.6, which is indicative of the effect of pavement type in this analysis (Also here the results are much lower compared with the standard deviation results obtained for the Mobile Cranes, probably because of the more road friendly tyre configuration). It is also clear here that an increase in TiP result in an increase in LEF, hence an increase in associated road damage. In general, the higher TiPs (i.e. TiPs $\geq$ 800 kPa, which is lower compared with the DRY case) also result in higher LEFs compared with the current damage, similar to what was found for the DRY conditions, albeit slightly higher. See Figure 9.

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. The results of the Standard Deviations of the average LEFs are given in Table 21, and it is seen that these values are relatively high compared with the *average* LEFs because it represents the nine road pavements together, as discussed before.

Table 14. **Summary of the average Load Equivalencies (LEFs) for the eleven Mobile Cranes at different TiPs in the DRY state for all pavements (sorted on Current Damage).**

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	520 kPa	650 kPa	700 kPa	800 kPa	900 kPa	1000 kPa	1200 kPa
Outside	DRY	Crane - 4 Axle Single Dual tyres	0.1	3.6	4.3	4.6	5.1	5.5	5.9	6.6
Outside	DRY	Crane - 3 Axle Single Dual tyres	0.7	3.1	3.8	4.0	4.4	4.8	5.1	5.7
Outside	DRY	Crane - 6 Axle Single Dual tyres	1.6	8.9	12.0	13.3	15.7	18.0	20.3	24.6
Outside	DRY	Crane - 3 Axle Single tyres	20.3	12.3	21.8	26.3	36.5	48.6	62.3	94.0
Outside	DRY	Crane - 2 Axle Single tyres	24.6	8.3	14.5	17.4	24.1	31.9	40.7	60.8
Outside	DRY	Crane - 5 Axle Single Dual tyres	26.8	10.7	14.6	16.1	19.0	21.9	24.6	29.7
Outside	DRY	Crane - 6 Axle Single tyres	57.6	27.4	50.2	61.5	87.7	119.4	156.3	244.4
Outside	DRY	Crane - 4 Axle Single tyres	62.4	23.1	46.3	58.6	89.3	129.1	178.4	306.3
Outside	DRY	Crane - 7 Axle Single tyres	78.3	33.6	62.5	76.9	110.8	152.1	200.6	317.2
Outside	DRY	Crane - 8 Axle Single tyres	91.0	38.2	71.2	87.8	126.7	174.3	230.3	365.8
Outside	DRY	Crane - 5 Axle Single tyres	113.1	30.8	63.0	80.5	125.0	183.8	258.0	455.3

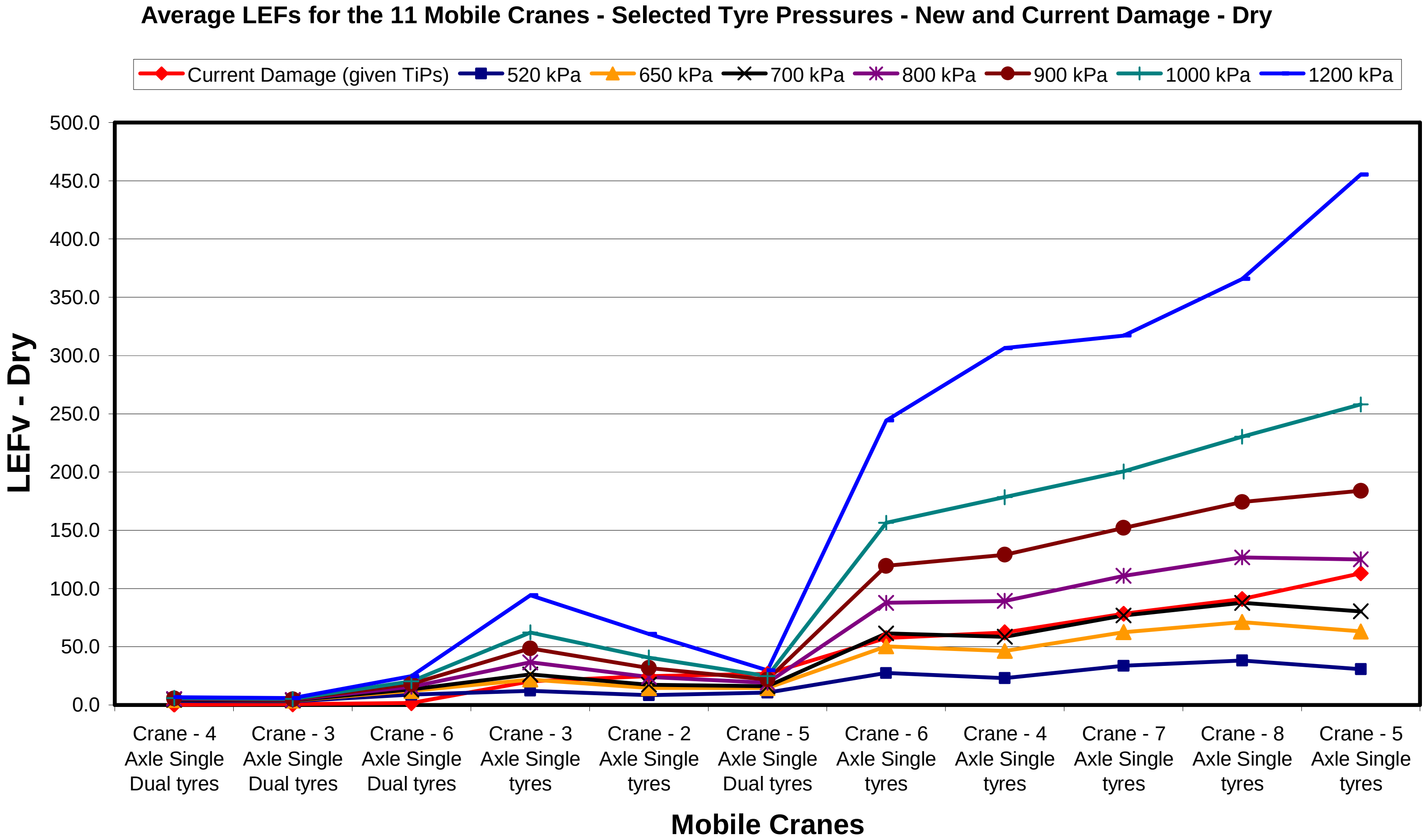

Figure 6. The effect of tyre inflation pressure (TiP) - ranging from 520 kPa to 1200 kPa - on the average LEFs for the eleven mobile cranes for all pavements studied here in the DRY state.

Table 15. **Summary of the standard deviations of the average Load Equivalencies (LEFs) for the eleven Mobile Cranes at different TiPs in the DRY state for all pavements (sorted on Current Damage).**

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	520 kPa	650 kPa	700 kPa	800 kPa	900 kPa	1000 kPa	1200 kPa
Outside	DRY	Crane - 4 Axle Single Dual tyres	0.11	2.1	2.8	3.1	3.7	4.2	4.7	5.5
Outside	DRY	Crane - 3 Axle Single Dual tyres	0.65	2.1	2.8	3.1	3.6	4.1	4.6	5.4
Outside	DRY	Crane - 6 Axle Single Dual tyres	1.64	7.9	12.7	14.7	18.9	23.2	27.6	36.2
Outside	DRY	Crane - 3 Axle Single tyres	20.34	19.3	40.0	50.5	75.7	106.3	141.9	226.3
Outside	DRY	Crane - 2 Axle Single tyres	24.64	12.9	26.5	33.4	49.7	69.3	92.1	145.5
Outside	DRY	Crane - 5 Axle Single Dual tyres	26.76	12.5	19.4	22.1	27.8	33.4	39.0	49.6
Outside	DRY	Crane - 6 Axle Single tyres	57.57	44.8	96.3	123.0	188.7	270.7	368.3	606.6
Outside	DRY	Crane - 4 Axle Single tyres	62.42	42.0	98.4	129.5	210.1	317.4	453.0	811.3
Outside	DRY	Crane - 7 Axle Single tyres	78.31	55.9	121.9	156.5	242.0	349.4	478.4	795.7
Outside	DRY	Crane - 8 Axle Single tyres	90.95	63.5	139.0	178.6	277.0	401.0	550.2	919.3
Outside	DRY	Crane - 5 Axle Single tyres	113.08	57.1	136.9	181.9	300.0	460.1	665.9	1222.5

Table 16. **Summary of the average Load Equivalencies (LEFs) for the eleven Mobile Cranes at different TiPs in the WET state for all pavements (sorted on Current Damage).**

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	520 kPa	650 kPa	700 kPa	800 kPa	900 kPa	1000 kPa	1200 kPa
Outside	WET	Crane - 4 Axle Single Dual tyres	0.1	5.2	6.2	6.5	7.0	7.5	8.0	8.7
Outside	WET	Crane - 3 Axle Single Dual tyres	0.7	4.5	5.3	5.6	6.1	6.5	6.9	7.5
Outside	WET	Crane - 6 Axle Single Dual tyres	1.6	12.2	15.7	16.9	19.5	21.9	24.3	28.8
Outside	WET	Crane - 3 Axle Single tyres	20.3	14.7	24.4	28.9	39.3	51.5	65.3	97.2
Outside	WET	Crane - 2 Axle Single tyres	24.6	9.9	16.3	19.2	26.0	33.8	42.7	62.9
Outside	WET	Crane - 5 Axle Single Dual tyres	26.8	14.0	18.1	19.7	22.8	25.7	28.5	33.7
Outside	WET	Crane - 6 Axle Single tyres	57.6	32.4	55.7	67.1	93.7	125.6	162.8	251.3
Outside	WET	Crane - 4 Axle Single tyres	62.4	26.6	50.2	62.6	93.7	133.6	183.1	311.4
Outside	WET	Crane - 7 Axle Single tyres	78.3	39.5	69.0	83.6	117.9	159.5	208.3	325.5
Outside	WET	Crane - 8 Axle Single tyres	91.0	45.0	78.7	95.4	134.8	182.8	239.1	375.2
Outside	WET	Crane - 5 Axle Single tyres	113.1	35.1	68.0	85.6	130.5	189.6	264.1	461.9

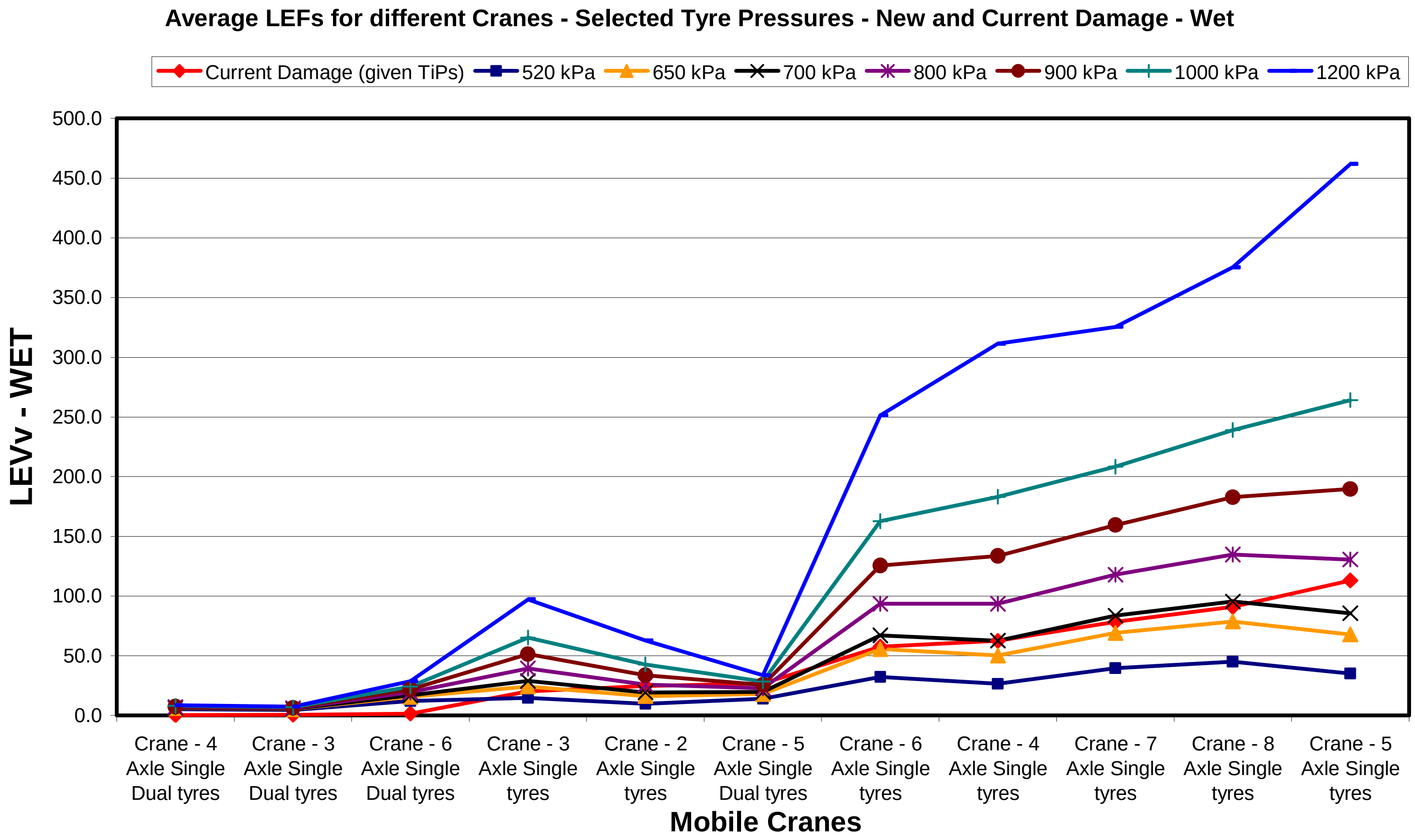

Figure 7. **The effect of tyre inflation pressure (TiP) - ranging from 520 kPa to 1200 kPa - on the *average* LEFs for the eleven mobile cranes for all pavements studied here in the WET state.**

Table 17. **Summary of the standard deviations of the average Load Equivalencies (LEFs) for the eleven Mobile Cranes at different TiPs in the WET state for all pavements (sorted on Current Damage).**

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	520 kPa	650 kPa	700 kPa	800 kPa	900 kPa	1000 kPa	1200 kPa
Outside	WET	Crane - 4 Axle Single Dual tyres	0.1	1.6	2.4	2.7	3.3	3.8	4.3	5.1
Outside	WET	Crane - 3 Axle Single Dual tyres	0.7	1.7	2.5	2.8	3.3	3.8	4.2	5.0
Outside	WET	Crane - 6 Axle Single Dual tyres	1.6	7.6	12.2	14.1	18.1	22.3	26.6	35.2
Outside	WET	Crane - 3 Axle Single tyres	20.3	18.9	39.4	49.8	74.8	105.3	140.9	225.1
Outside	WET	Crane - 2 Axle Single tyres	24.6	12.7	26.1	32.9	49.1	68.7	91.4	144.8
Outside	WET	Crane - 5 Axle Single Dual tyres	26.8	12.1	18.7	21.4	26.9	32.4	37.9	48.5
Outside	WET	Crane - 6 Axle Single tyres	57.6	43.8	94.7	121.3	186.8	268.5	366.0	604.1
Outside	WET	Crane - 4 Axle Single tyres	62.4	41.2	97.1	128.2	208.6	315.8	451.2	809.4
Outside	WET	Crane - 7 Axle Single tyres	78.3	54.7	120.0	154.4	239.6	346.9	475.6	792.7
Outside	WET	Crane - 8 Axle Single tyres	91.0	62.1	136.9	176.3	274.3	398.0	547.1	915.8
Outside	WET	Crane - 5 Axle Single tyres	113.1	56.1	135.3	180.2	298.1	458.0	663.6	1220.0

Table 18. Summary of the average Load Equivalencies (LEFs) for the eight AVs at different TiPs in the DRY state for all pavements (sorted on Current Damage).

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	520 kPa	650 kPa	700 kPa	800 kPa	900 kPa	1000 kPa	1200 kPa
Outside	DRY	AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)	5.8	5.2	6.1	6.4	7.0	7.5	8.0	8.8
Outside	DRY	AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)	10.2	6.4	8.0	8.5	9.5	10.5	11.4	12.8
Outside	DRY	AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)	10.3	5.7	6.7	7.0	7.7	8.2	8.7	9.5
Outside	DRY	AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)	12.2	6.6	8.1	8.6	9.6	10.5	11.3	12.8
Outside	DRY	AV veh C - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP304803)	13.9	8.3	10.2	10.9	12.2	13.4	14.5	16.4
Outside	DRY	AV veh F - Abnormal Vehicle 9 Axle Single Dual tyres (AVGP305729)	16.9	7.5	9.2	9.8	10.9	12.0	13.0	14.7
Outside	DRY	AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)	19.8	9.7	12.5	13.5	15.4	17.3	19.1	22.3
Outside	DRY	AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)	20.3	9.4	11.6	12.4	13.9	15.3	16.5	18.6

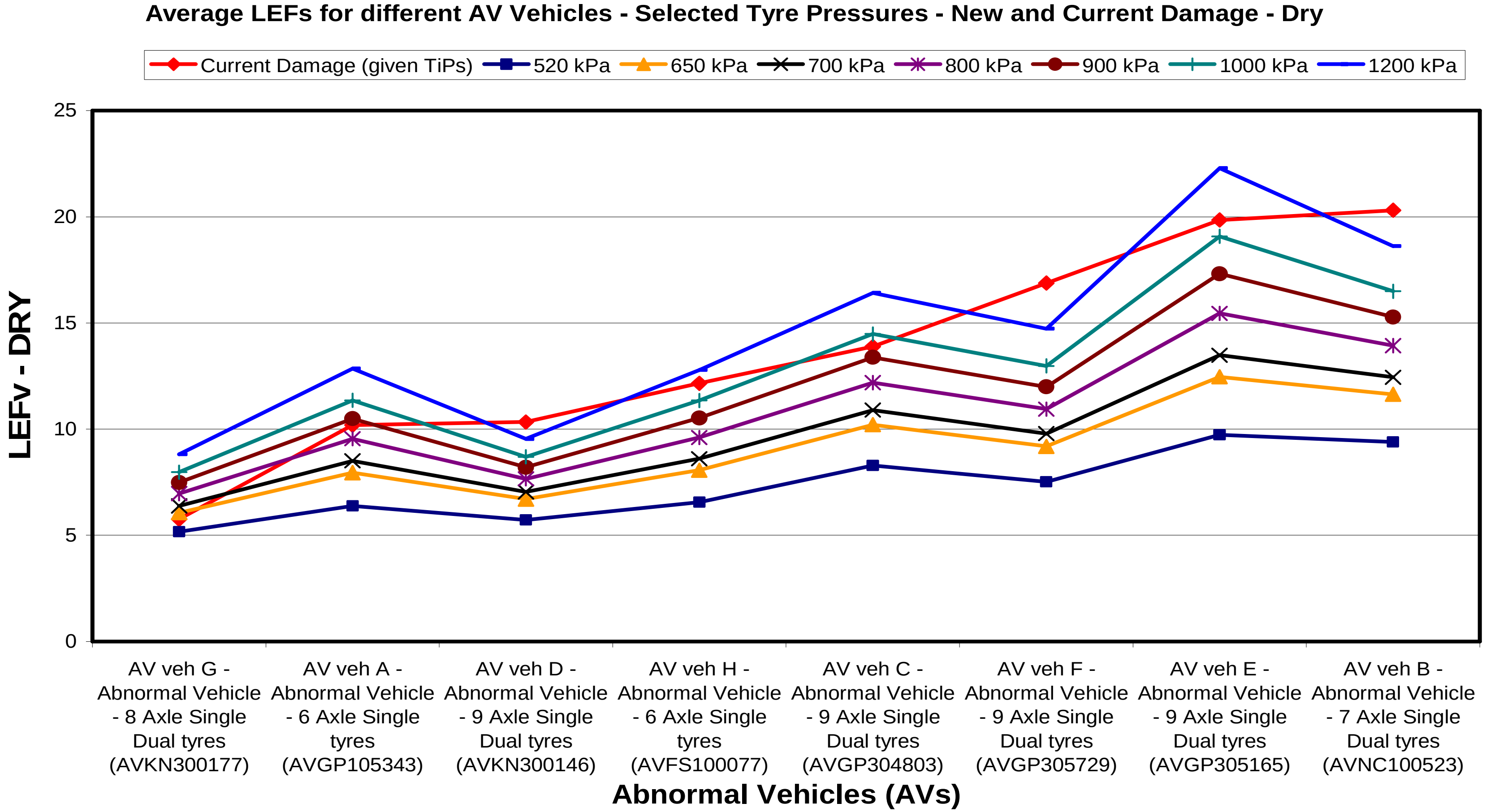

Figure 8. The effect of tyre inflation pressure (TiP) - ranging from 520 kPa to 1200 kPa - on the *average* LEFs for the eight AVs for all pavements studied here in the DRY state.

Table 19. Summary of the standard deviations of the average Load Equivalencies (LEFs) for the eight AVs at different TiPs in the DRY state for all pavements (sorted on Current Damage).

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	520 kPa	650 kPa	700 kPa	800 kPa	900 kPa	1000 kPa	1200 kPa
Outside	DRY	AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)	5.8	2.9	3.4	3.7	4.2	4.8	5.4	6.5
Outside	DRY	AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)	10.2	4.5	6.3	7.0	8.4	9.7	11.0	13.2
Outside	DRY	AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)	10.3	3.4	4.1	4.4	5.0	5.6	6.2	7.2
Outside	DRY	AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)	12.2	4.8	6.7	7.4	8.8	10.2	11.4	13.7
Outside	DRY	AV veh C - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP304803)	13.9	5.7	8.1	9.1	11.0	12.9	14.6	17.9
Outside	DRY	AV veh F - Abnormal Vehicle 9 Axle Single Dual tyres (AVGP305729)	16.9	4.8	6.8	7.6	9.2	10.8	12.3	15.3
Outside	DRY	AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)	19.8	8.0	12.2	13.9	17.2	20.6	23.9	30.1
Outside	DRY	AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)	20.3	7.8	10.9	12.1	14.3	16.4	18.3	21.9

Table 20. Summary of the average Load Equivalencies (LEFs) for the eight AVs at different TiPs in the WET state for all pavements (sorted on Current Damage).

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	520 kPa	650 kPa	700 kPa	800 kPa	900 kPa	1000 kPa	1200 kPa
Outside	WET	AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)	5.8	7.4	8.5	8.9	9.5	10.1	10.6	11.6
Outside	WET	AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)	10.2	9.1	10.9	11.6	12.7	13.8	14.7	16.3
Outside	WET	AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)	10.3	8.1	9.3	9.6	10.3	11.0	11.5	12.4
Outside	WET	AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)	12.2	9.3	11.1	11.7	12.8	13.8	14.6	16.2
Outside	WET	AV veh C - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP304803)	13.9	11.7	13.9	14.6	16.1	17.4	18.5	20.6
Outside	WET	AV veh F - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305729)	16.9	10.6	12.5	13.1	14.4	15.5	16.6	18.4
Outside	WET	AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)	19.8	13.4	16.4	17.5	19.6	21.5	23.4	26.7
Outside	WET	AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)	20.3	13.2	15.7	16.6	18.2	19.7	21.0	23.2

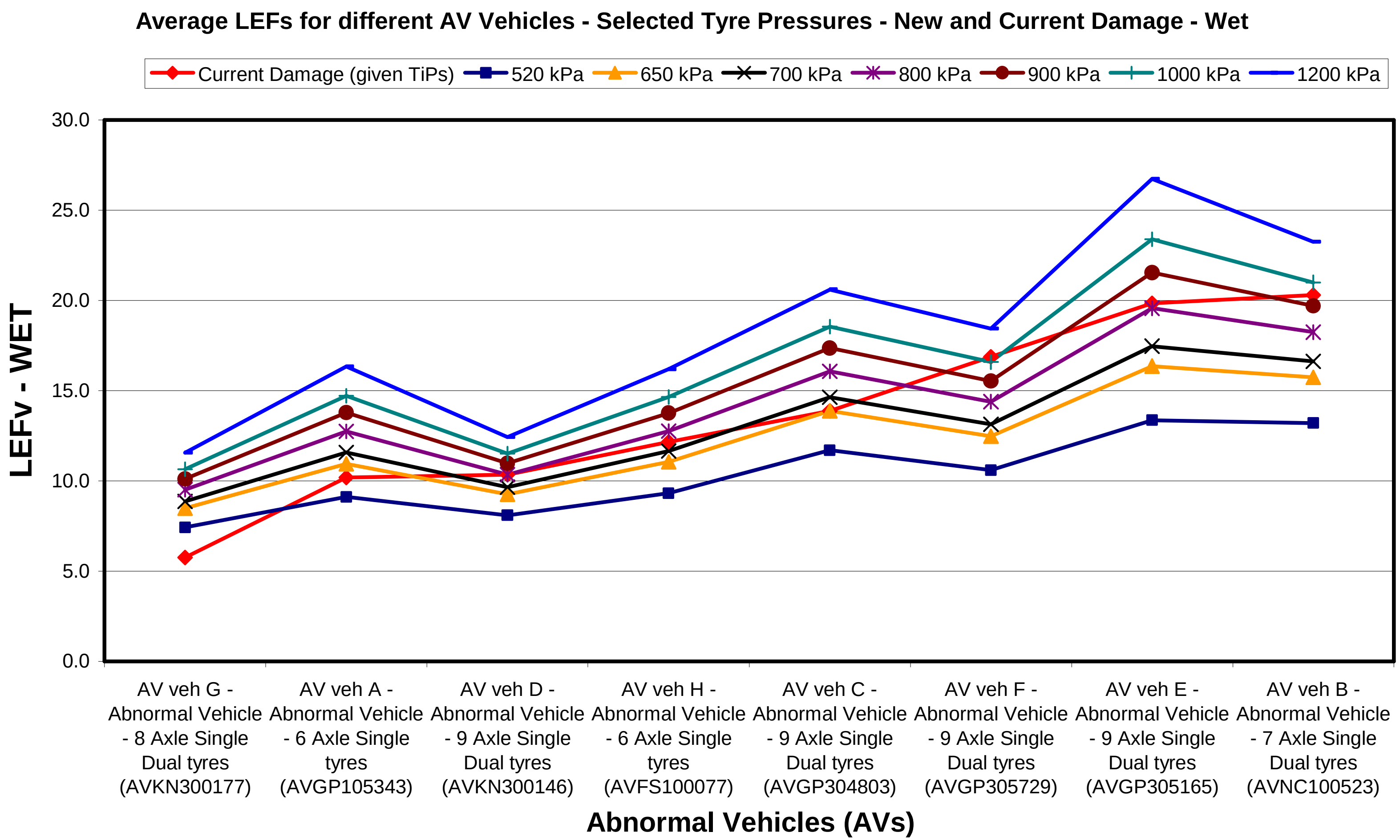

Figure 9. The effect of tyre inflation pressure (TiP) - ranging from 520 kPa to 1200 kPa - on the *average* LEFs for the eight AVs for all pavements studied here in the WET state.

Table 21. **Summary of the standard deviations of the average Load Equivalencies (LEFs) for the eight AVs at different TiPs in the WET state for all pavements (sorted on Current Damage).**

DESIGN LOCATION	Moisture Condition	VEHICLE ID	Current Damage (given TiPs)	520 kPa	650 kPa	700 kPa	800 kPa	900 kPa	1000 kPa	1200 kPa
Outside	WET	AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)	5.8	0.7	1.6	1.9	2.6	3.3	3.9	5.1
Outside	WET	AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)	10.2	3.9	5.8	6.5	7.8	9.1	10.3	12.5
Outside	WET	AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)	10.3	1.2	2.2	2.6	3.3	4.0	4.7	5.8
Outside	WET	AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)	12.2	4.0	5.9	6.7	8.0	9.3	10.6	12.8
Outside	WET	AV veh C - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP304803)	13.9	4.1	6.7	7.7	9.6	11.5	13.2	16.5
Outside	WET	AV veh F - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305729)	16.9	3.1	5.3	6.1	7.8	9.4	11.0	14.0
Outside	WET	AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)	19.8	6.7	10.8	12.5	15.9	19.2	22.4	28.6
Outside	WET	AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)	20.3	7.1	10.1	11.3	13.4	15.4	17.3	20.8

16. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

16.1. Summary

In this *preliminary* study a new fully mechanistically based methodology is proposed for the calculation of Load Equivalency Factors (LEFs) for a given sample of 11 (Eleven) different Mobile Cranes and eight Abnormal Vehicle (AV) combinations. The LEF calculations were based on nine typical types of road pavement found in South Africa. These were estimated at different positions under each of the outermost tyres, (per axle) and then summed for cumulative damage, which is represented by the LEFv of the particular AV or Mobile Crane. The analyses were expanded to include both relatively dry and relatively wet pavement conditions. In addition to the above basic analysis, a sensitivity analysis was also done for each case over a range of tyre inflation pressures (TiPs), ranging from 520 kPa to 1 200 kPa at the given vehicle loading, which showed a general increase in LEFs (i.e. pavement damage) for all the vehicles considered in this study owing to increased tyre inflation pressures (TiPs).

16.2. Conclusions

The following conclusions 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.
- Above 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 in terms of their road damage potential;
- The new method allows for different pavements and its condition to be modelled effectively for the typical abnormal vehicles (including Mobile Cranes) found in South Africa <u>under static loading conditions only</u>;
- The study show that relatively higher LEFs were determined for the weaker pavements, and also those analysed in the relatively WET pavement condition;
- 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 a more rational methodology for the estimation of road pavement damage, than perhaps given by the existing methodology based on ESWL, as each tyre load (hence axle load, and hence total load) is directly considered at the given TiP. 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.
- Note: In this study the mechanistic analysis was done under static (or stationary) loading conditions. The “dynamic” loading (or “moving” or “cyclic” loading) of the various abnormal vehicles (including Mobile Cranes) is not considered here, as this involve road roughness profiles as well as suspension types to be known in advance. From this information, the “Dynamic Load Coefficient” (DLC) can be calculated and used in the mechanistic analysis for the prediction of “dynamic” LEFs. This however was outside the scope of the study presented in this report.

16.3. 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 more wider definition of the Mobile Cranes and AVs be drawn up in terms of tyre load, tyre inflation pressures and axle configuration for further analysis;
- 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.

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Date: August 2009

APPENDICIES:

REVISION OF TRH 11 (1999-2000): RECOVERY OF ROAD DAMAGE - DISCUSSION DOCUMENT ON A PROVISIONAL BASIS FOR POSSIBLE NEW ESTIMATION OF MASS FEES -
-- UNDER REVIEW FOR TRH 11 (2000) --
--- FINAL APPENDICES for SUMMARY REPORT V2.2 ---

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TABLE OF CONTENTS: APPENDICIES

LIST OF FIGURES: APPENDICIES

Appendix 1: LAYOUT OF THE LOAD CONFIGURATIONS FOR THE ELEVEN MOBILE CRANES USED IN THIS STUDY

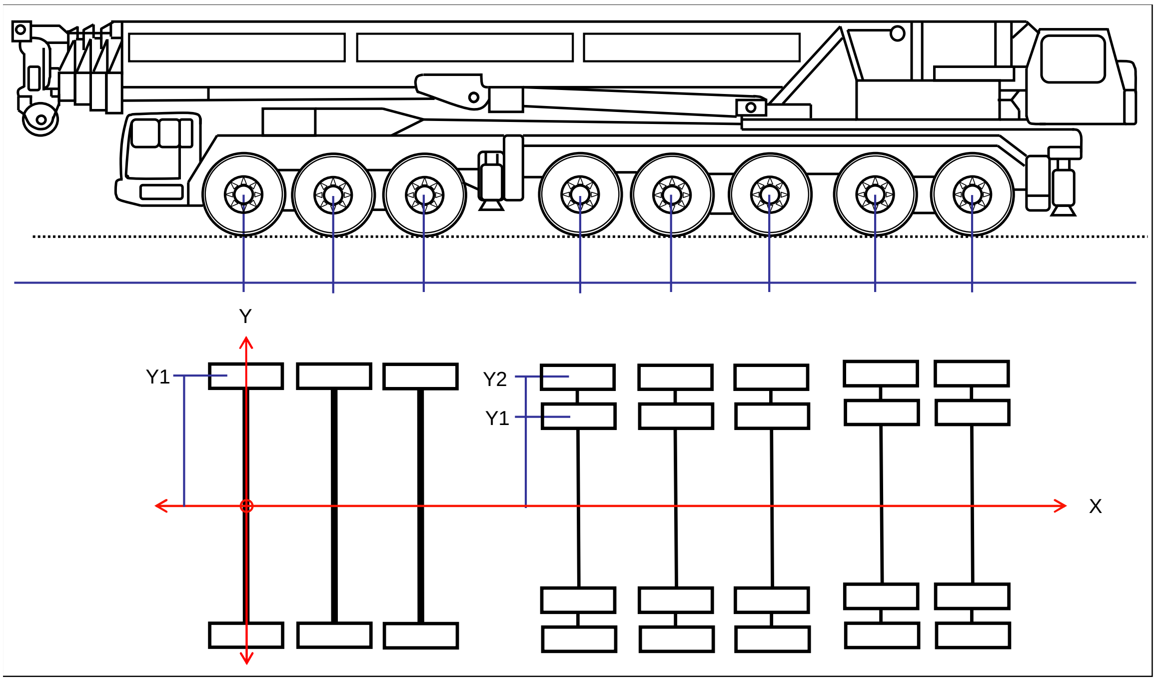
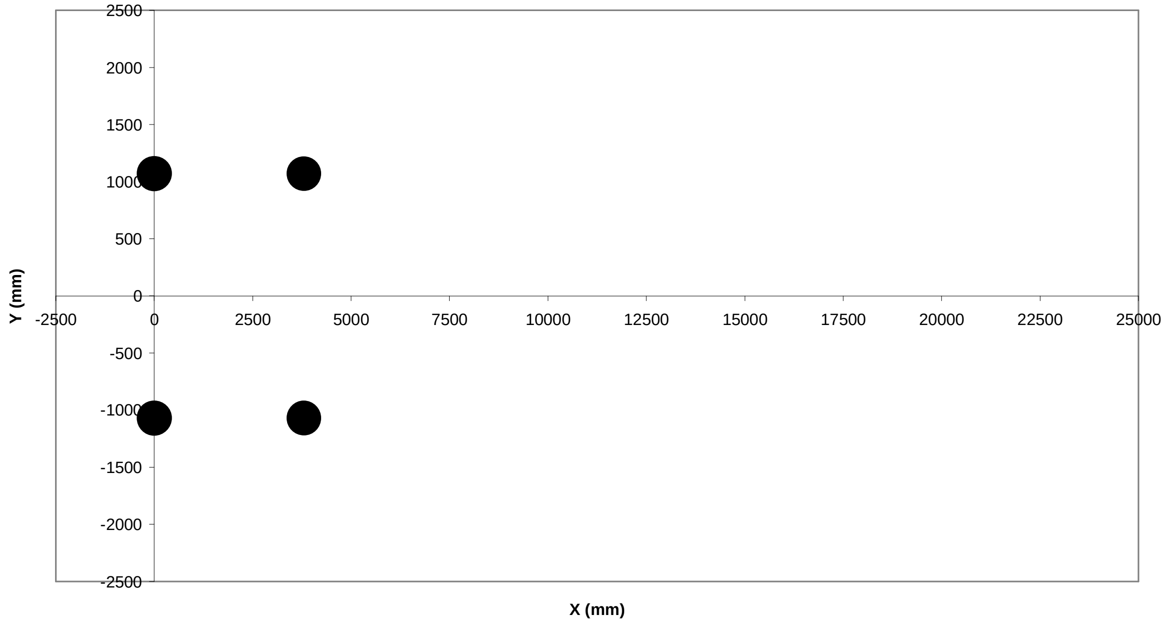


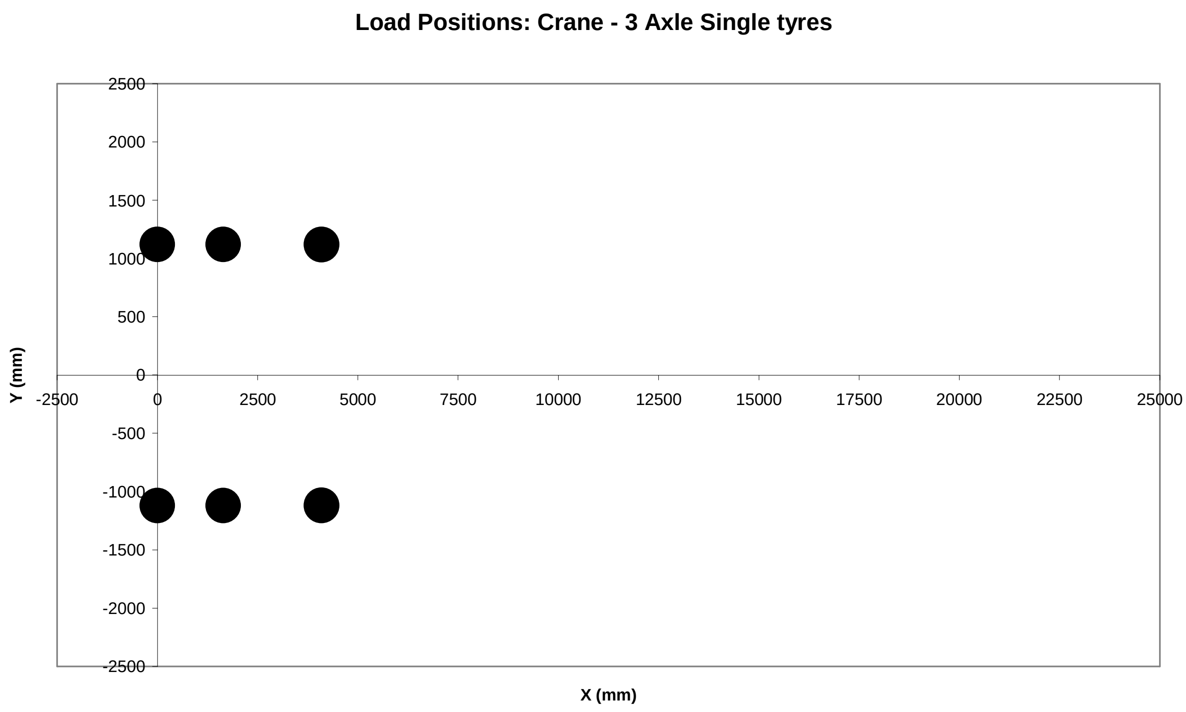
Figure App 1.1: **Mobile Crane Load Configurations**

Load Positions: Crane - 2 Axle Single tyres



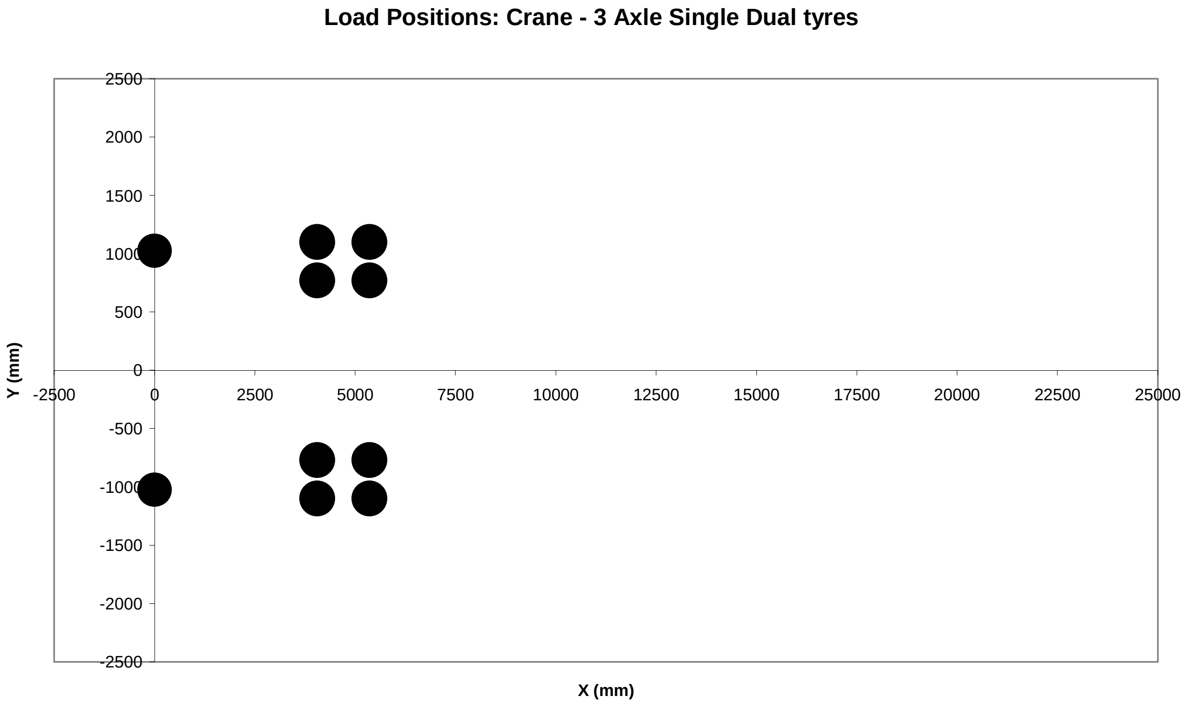
AV No.	Total Mass (kg)	Group No	Axle Type	Wheel Space A (mm)	Wheel Space B (mm)	Tyre Press	No. of Tyres	Axle No	Axle Mass	Tyre Mass	Tyre Load	Steer?	Dist. to Next Axle	Y1 (mm)	Y2 (mm)	X (mm)	Load (kN)
GP403756	22940	1	S	2140		654	2	1	11340	5670	55.6	Yes	3800	1070		0	55.62
		2	S	2140		675	2	2	11600	5800		No	0	1070		3800	56.90
							4		**22940**								

Figure App 1.2: Crane - 2 Axle Single tyres



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)
GP403614	34820	1	S	2240		504	2	1	11770	5885	57.7	Yes	1640	1120		0	57.73
							2	2	11770	5885		Yes	2450			1640	57.73
		2	S	2240		476	2	3	11280	5640	55.3	No	0	1120		4090	55.33
							6		**34820**								

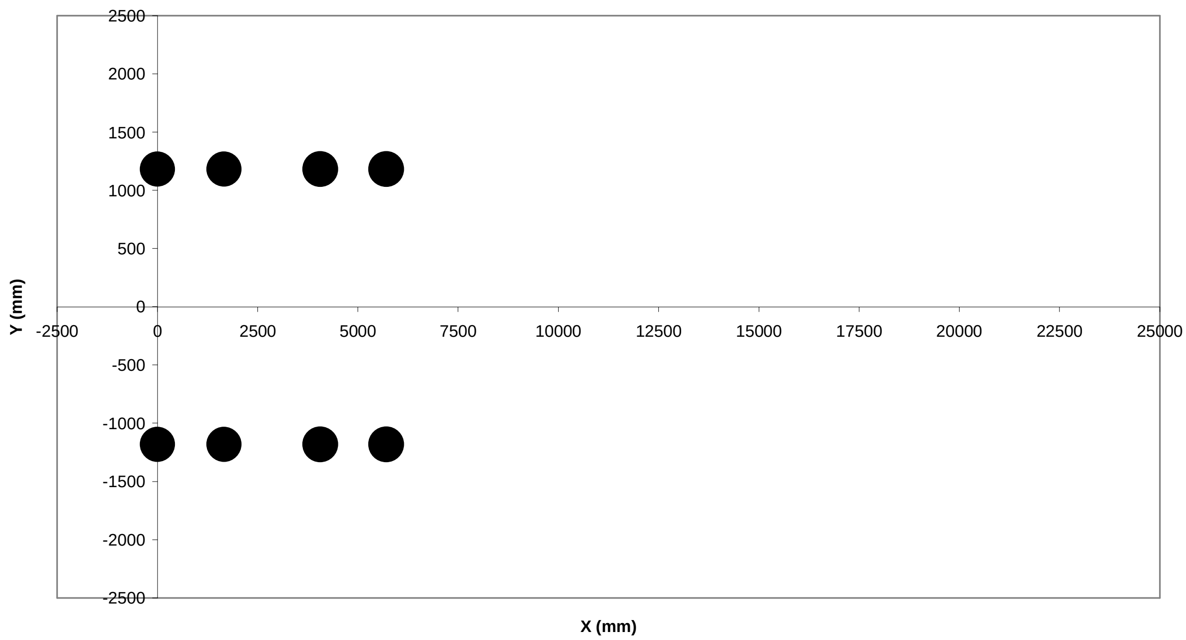
Figure App 1.3: Crane - 3 Axle Single tyres



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)
GP403560	26220	1	S	2050		558	2	1	6340	3170	31.1	Yes	4050	1025		0	31.10
		2	D	1540	330	403	4	2	9940	2485	24.4	No	1310	770	1100	4050	24.38
							4	3	9940	2485		No	0			5360	24.38
							10		**26220**								

Figure App 1.4: Crane - 3 Axle Single Dual tyres

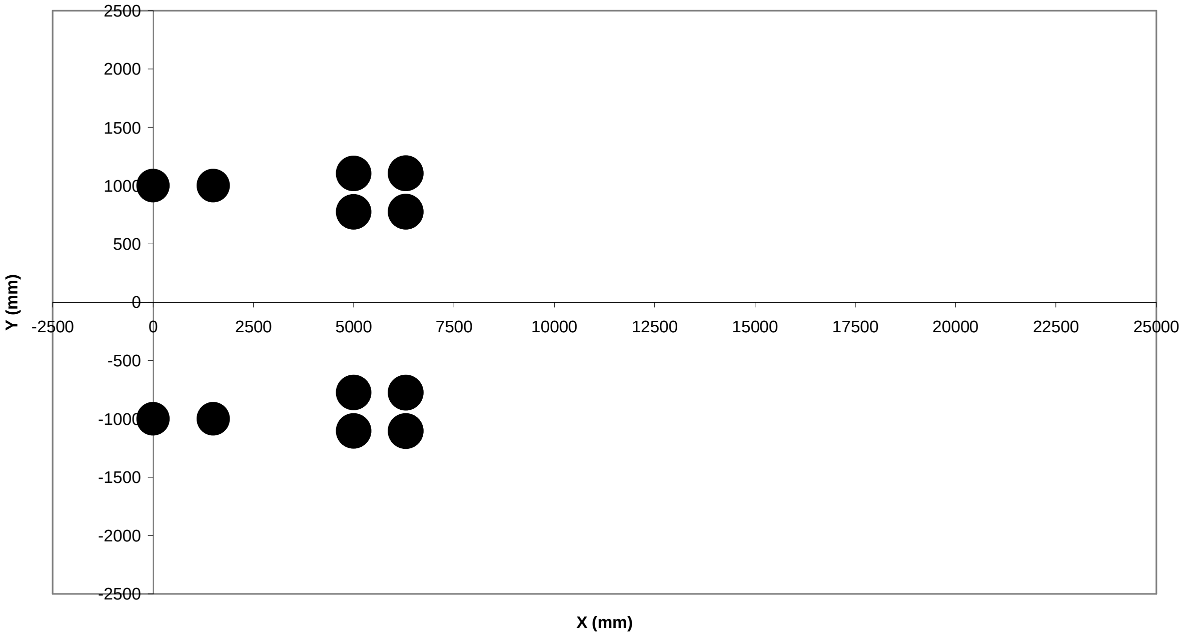
Load Positions: Crane - 4 Axle Single tyres



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)
GP403520	52200	1	S	2365		580	2	1	14150	7075	69.4	Yes	1660	1183		0	69.41
							2	2	14150	7075		Yes	2400			1660	69.41
		2	S	2365		469	2	3	11950	5975	58.6	No	1650	1183		4060	58.61
							2	4	11950	5975		Yes	0			5710	58.61
							8		**52200**								

Figure App 1.5: **Crane - 4 Axle Single tyres**

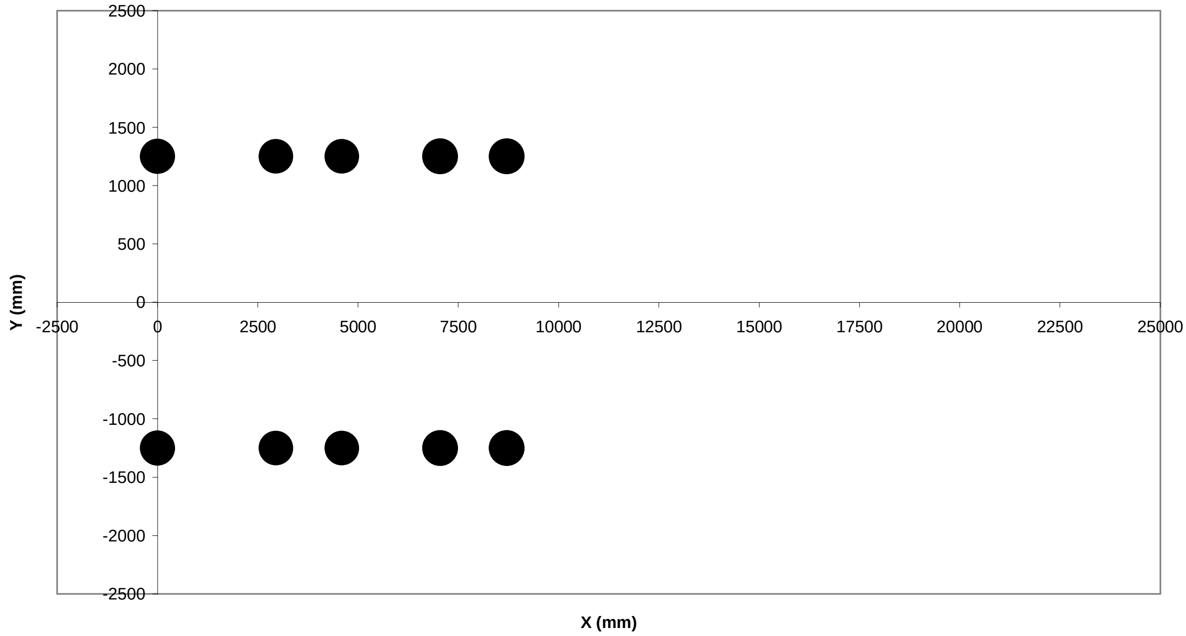
Load Positions: Crane - 4 Axle Single Dual tyres



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)
GP403489	31100	1	S	2000		553	2	1	6300	3150	30.9	Yes	1500	1000		0	30.90
							2	2	6300	3150		Yes	3500			1500	30.90
		2	D	1550	330	357	4	3	9200	2300	22.6	No	1300	775	1105	5000	22.56
							4	4	9300	2325		No	0			6300	22.81
							12		**31100**								

Figure App 1.6: Crane - 4 Axle Single Dual tyres

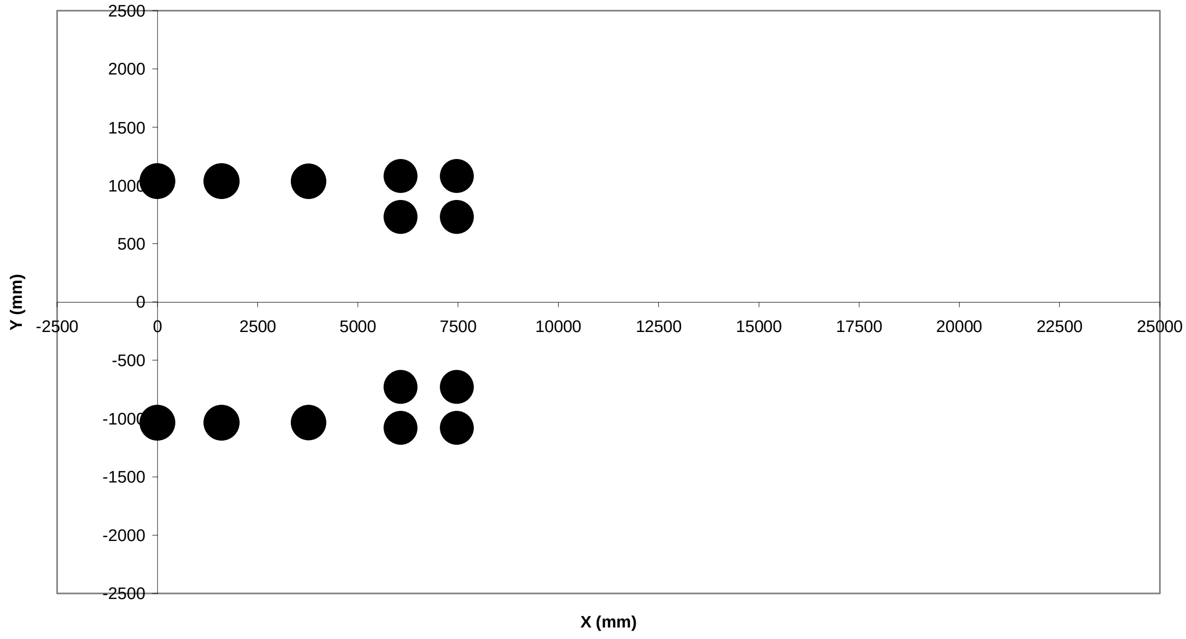
Load Positions: Crane - 5 Axle Single tyres



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)
GP403760	66260	1	S	2500		607	2	1	13620	6810	66.8	Yes	2950	1250		0	66.81
		2	S	2500		665	2	2	14670	7335	71.9	Yes	1650	1250		2950	71.96
							2	3	14670	7335		Yes	2450			4600	71.96
		3	S	2500		498	2	4	11650	5825	57.1	Yes	1660	1250		7050	57.14
							2	5	11650	5825		Yes	0			8710	57.14
							10		**66260**								

Figure App 1.7: Crane - 5 Axle Single tyres

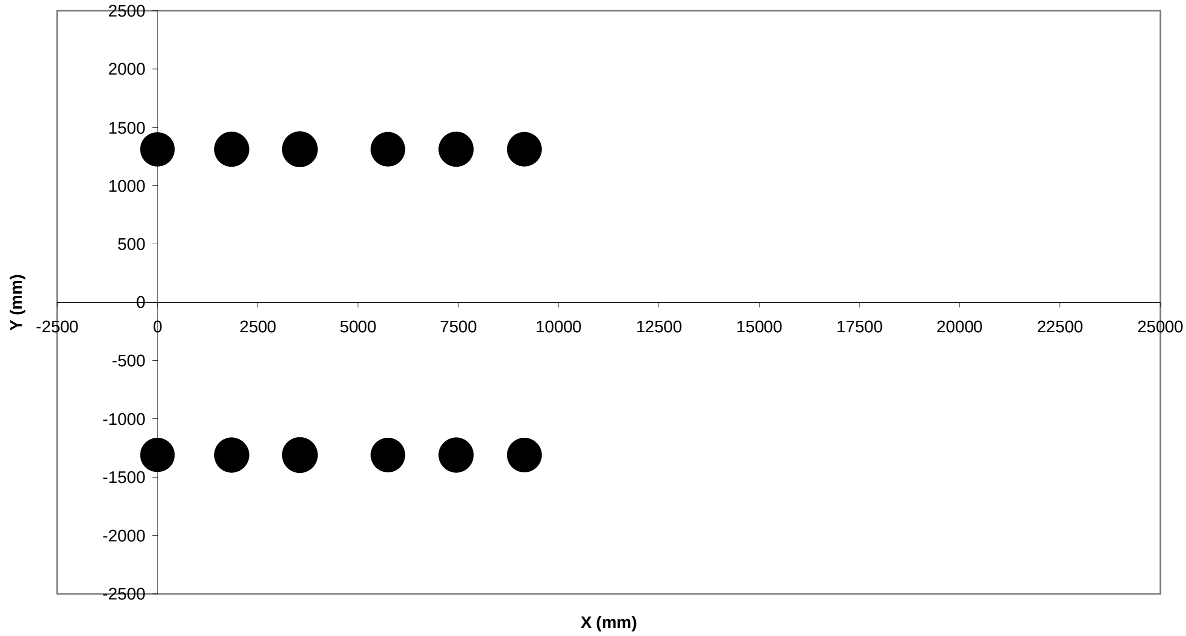
Load Positions: Crane - 5 Axle Single Dual tyres



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 App 1.8: Crane - 5 Axle Single Dual tyres

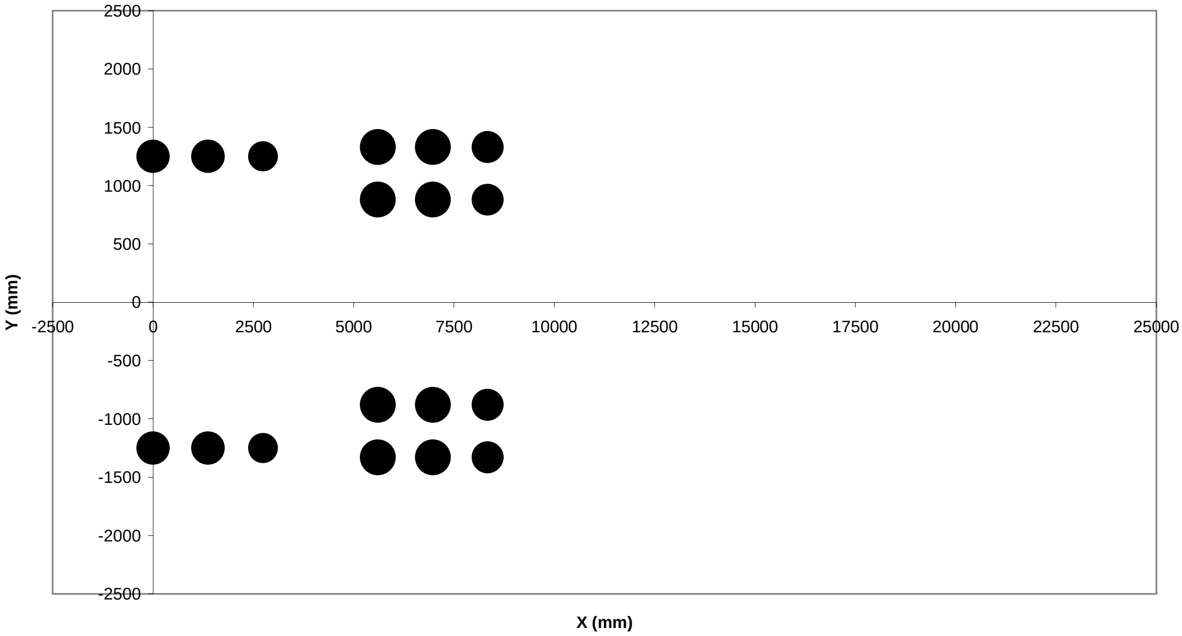
Load Positions: Crane - 6 Axle Single tyres



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)
GP403698	72640	1	S	2620		506	2	1	11280	5640	55.3	Yes	1850	1310		0	55.33
							2	2	11800	5900		Yes	1700			1850	57.88
							2	3	12320	6160		Yes	2200			3550	60.43
		2	S	2620		540	2	4	12380	6190	60.7	No	1700	1310		5750	60.72
							2	5	12520	6260		No	1700			7450	61.41
							2	6	12340	6170		Yes	0			9150	60.53
							12		**72640**								

Figure App 1.9: Crane - 6 Axle Single tyres

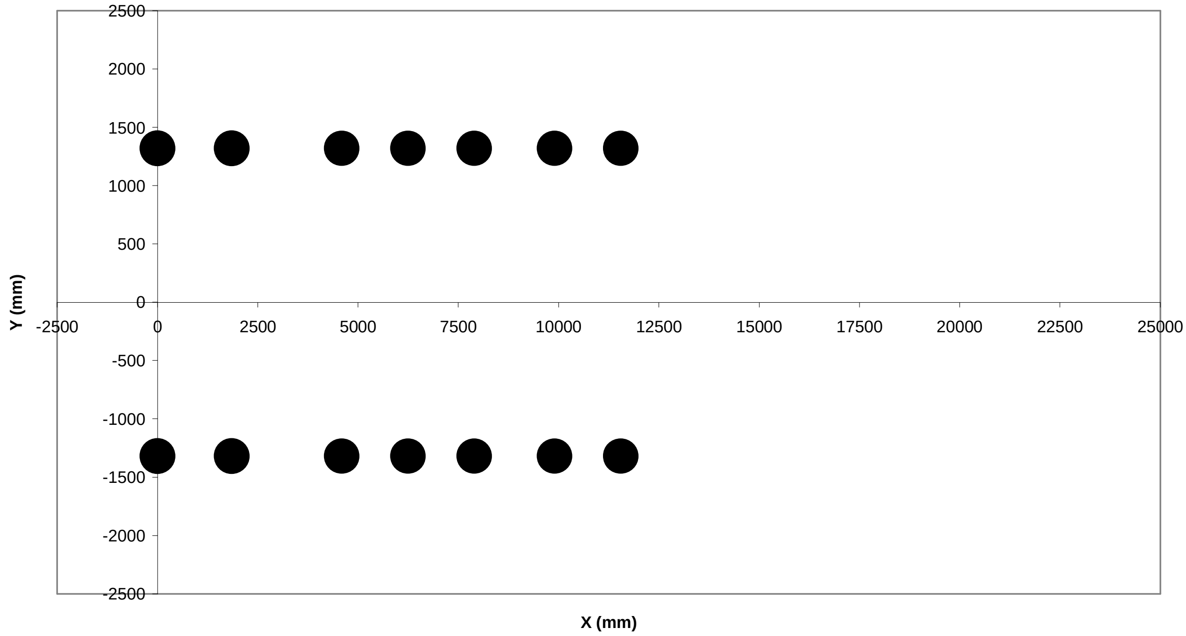
Load Positions: Crane - 6 Axle Single Dual tyres



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)
GP403576	61050	1	S	2500		428	2	1	8700	4350	42.7	Yes	1371	1250		0	42.67
							2	2	8800	4400		Yes	1370			1371	43.16
							2	3	6900	3450		Yes	2860			2741	33.84
		2	D	1760	450	280	4	4	13100	3275	32.1	No	1370	880	1330	5601	32.13
							4	5	13150	3288		No	1370			6971	32.25
							4	6	10400	2600		No	0			8341	25.51
							18		**61050**								

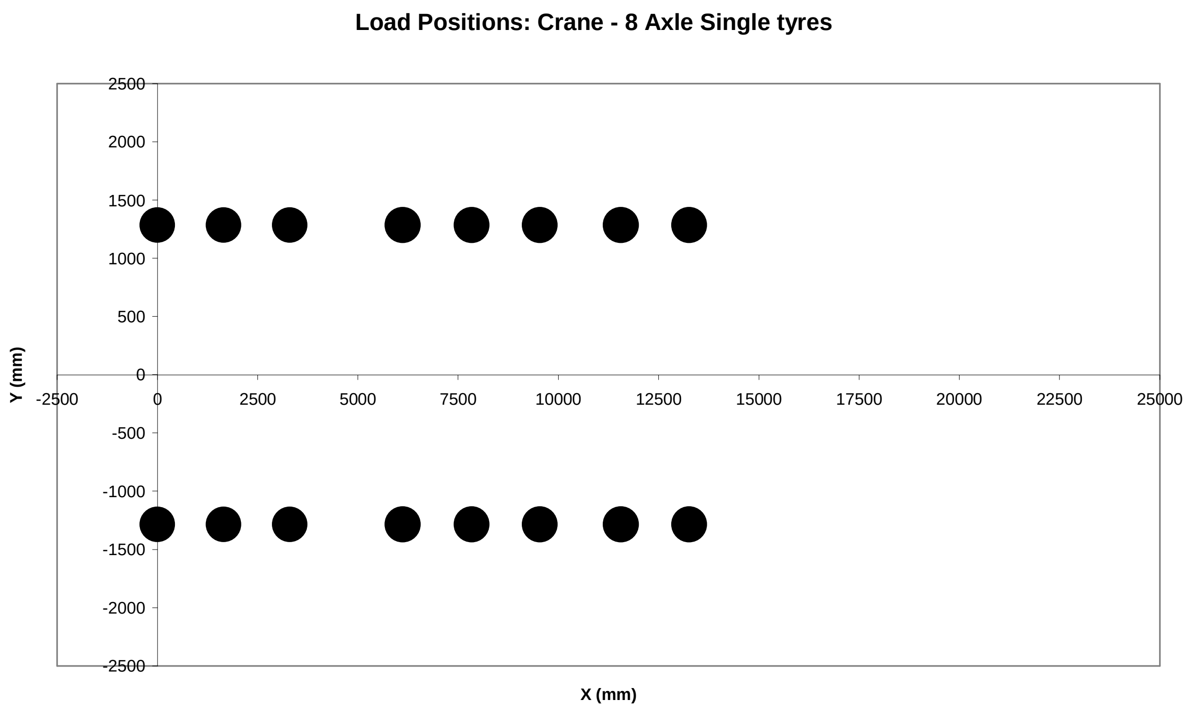
Figure App 1.10: Crane - 6 Axle Single Dual tyres

Load Positions: Crane - 7 Axle Single tyres



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)
GP403468	86550	1	S	2640		527	2	1	12175	6088	59.7	Yes	1850	1320		0	59.72
							2	2	12175	6088		Yes	2750			1850	59.72
		2	S	2640		542	2	3	12440	6220	61.0	Yes	1650	1320		4600	61.02
		3	S	2640		542	2	4	12440	6220	61.0	Yes	1650	1320		6250	61.02
		4	S	2640		542	2	5	12440	6220	61.0	No	2000	1320		7900	61.02
		5	S	2640		542	2	6	12440	6220	61.0	Yes	1650	1320		9900	61.02
							2	7	12440	6220		Yes	0			11550	61.02
							14		**86550**								

Figure App 1.11: Crane - 7 Axle Single tyres



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)
GP403525	98921	1	S	2570		563	2	1	12827	6414	62.9	Yes	1650	1285		0	62.92
							2	2	12827	6414	62.9	Yes	1650			1650	62.92
							2	3	12827	6414		Yes	2820			3300	62.92
		2	S	2570		517	2	4	12000	6000	58.8	Yes	1720	1285		6120	58.86
							2	5	12000	6000		No	1700			7840	58.86
							2	6	12000	6000		No	2020			9540	58.86
		3	S	2570		529	2	7	12220	6110	59.9	No	1700	1285		11560	59.94
							2	8	12220	6110		No	0			13260	59.94
							16		**98921**								

Figure App 1.12: **Crane - 8 Axle Single tyres**

Appendix 2: LAYOUT OF THE LOAD CONFIGURATIONS OF THE EIGHT ABNORMAL VEHICLES (AVs) USED IN THIS STUDY

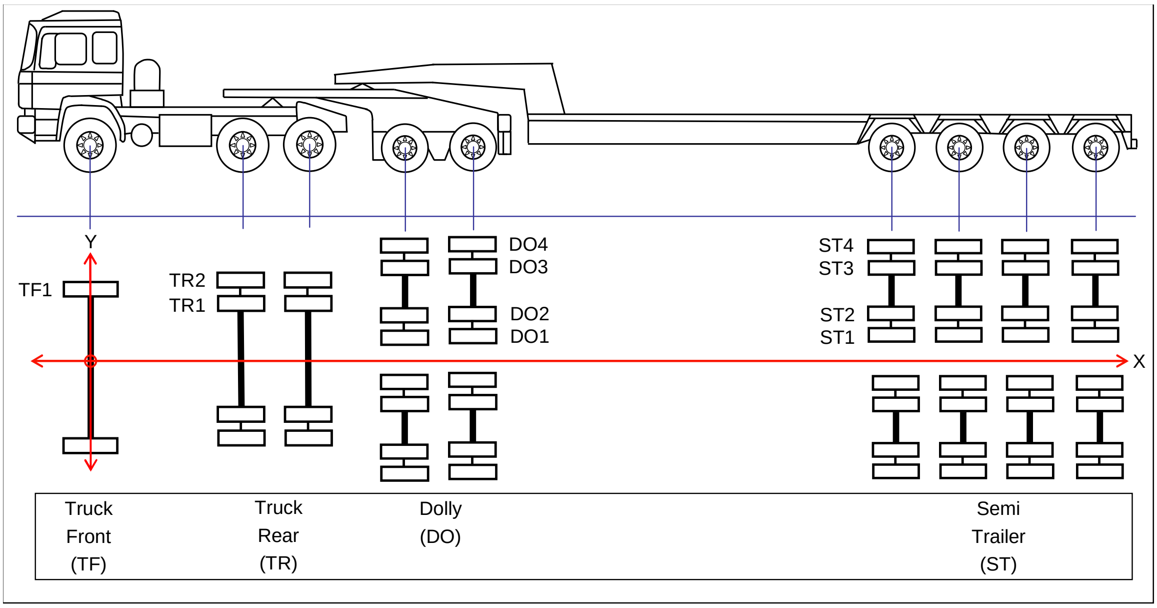
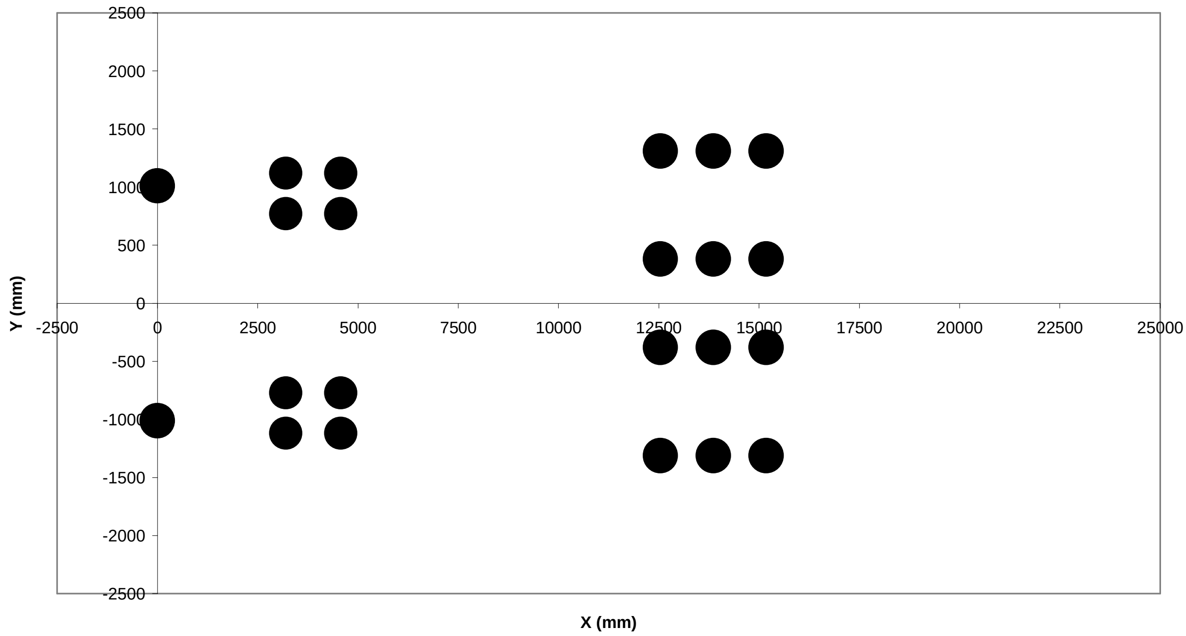


Figure App 2.1: Axle Configurations of typical abnormal load combinations

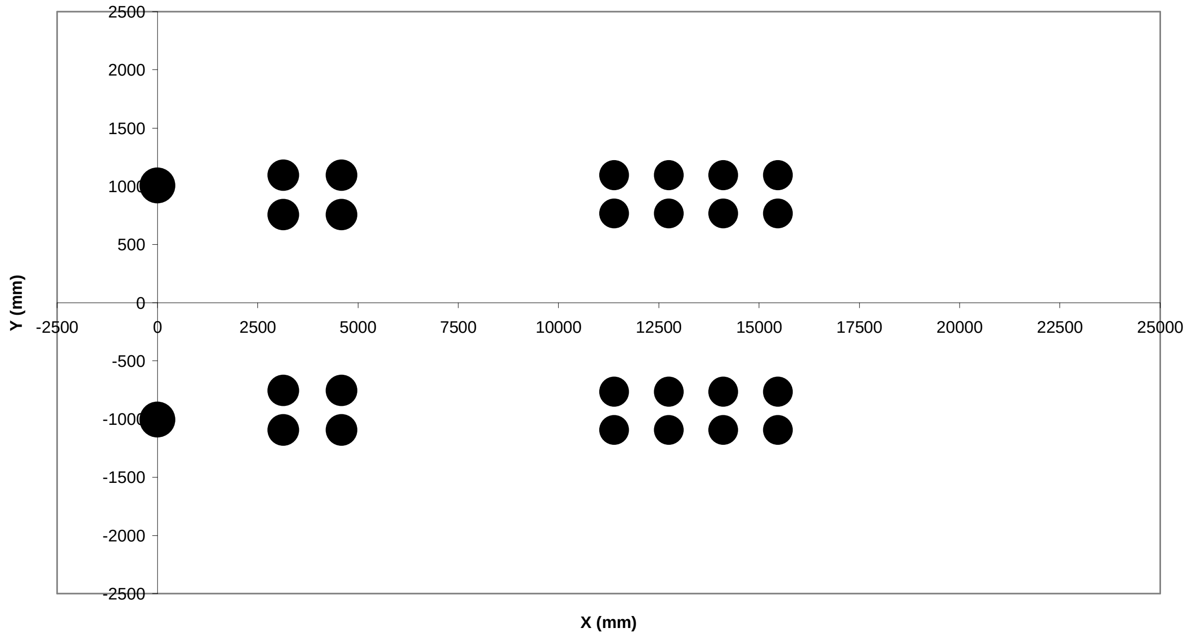
Load Positions: AV veh A - Abnormal Vehicle - 6 Axle Single tyres (AVGP105343)



7	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
AVGP105343 (A)	1	TF	2	6899	3450	33.8	677	S	0	1010										
	2	TR	8	22423	2803	27.5	650	D	3200		770	1120								
	3								4570											
		DO																		
	4	ST	12	36223	3019	29.6	600	4S	12541								380	1310		
	5								13861											
	6								15181											
	7																			
			22	65545																

Figure App 2.2: AV vehicle A - 6 Axle Single Dual tyres

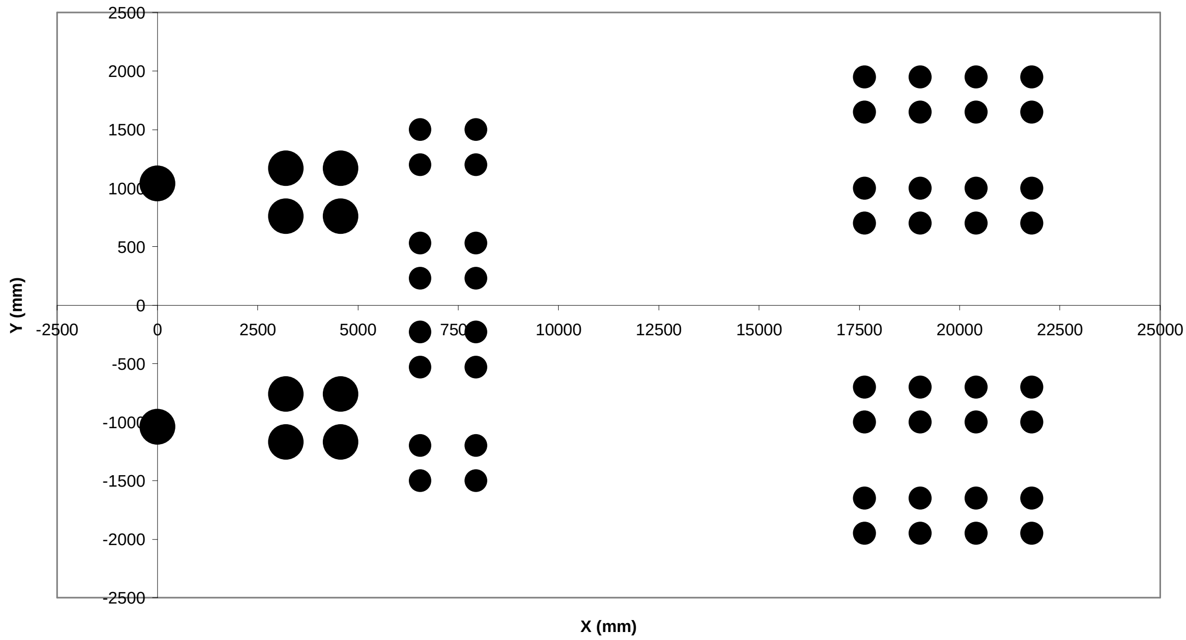
Load Positions: AV veh B - Abnormal Vehicle - 7 Axle Single Dual tyres (AVNC100523)



6	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
AVNC100523 (B)	1	TF	2	6962	3481	34.1	640	S	0	1005										
	2	TR	8	19890	2486	24.4	600	D	3140		755	1095								
	3								4590											
		DO																		
	4	ST	16	45748	2859	28.0	630	D	11390								765	1095		
	5								12750											
	6								14110											
	7								15470											
			26	72600																

Figure App 2.3: AV vehicle B - 7 Axle Single Dual tyres

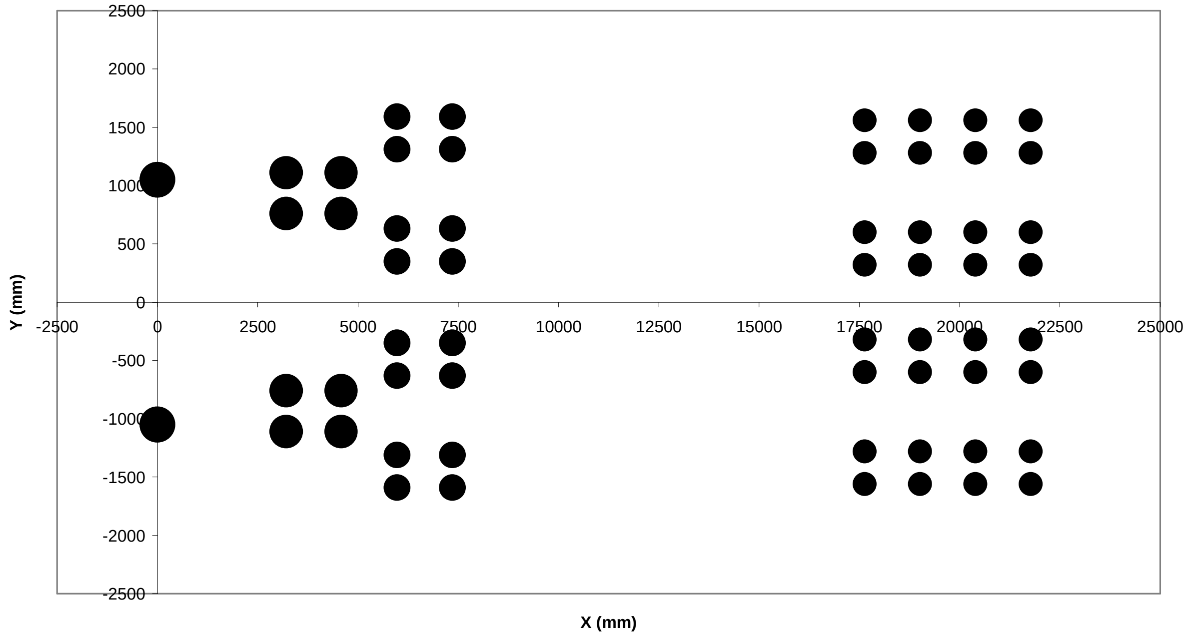
Load Positions: AV veh C - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP304803)



2	Axle No	Group		Group Mass	Tyre Mass	Tyre Load	Tyre Press.	Axle Type	X Coord	Y - Coordinates 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 App 2.4: AV vehicle C - 9 Axle Single Dual tyres

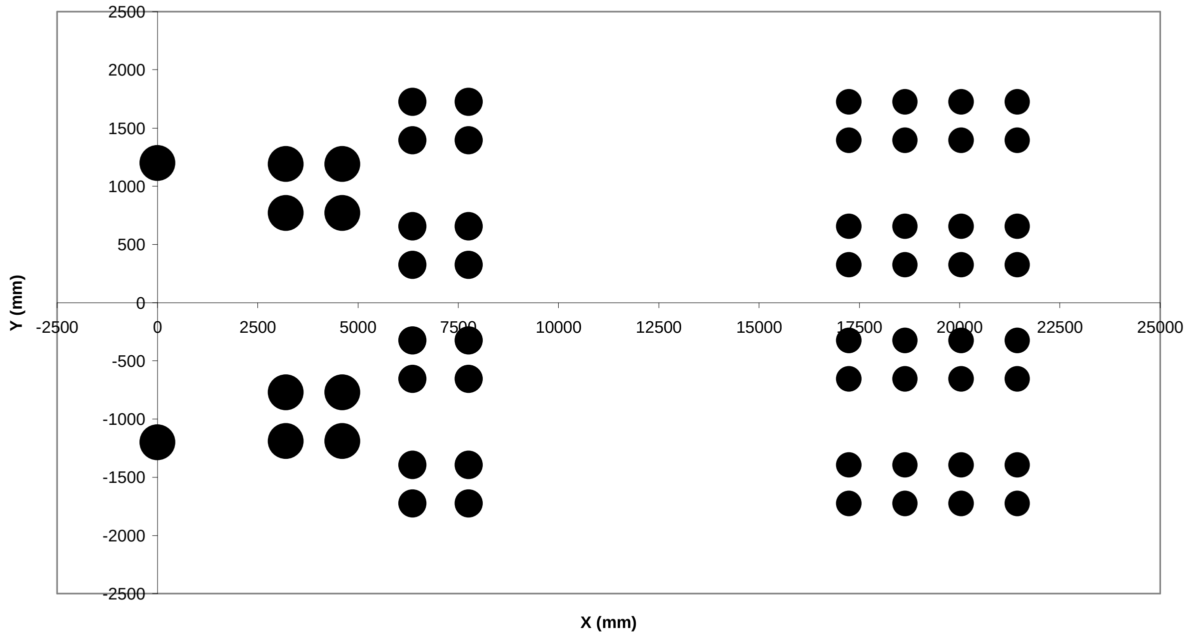
Load Positions: AV veh D - Abnormal Vehicle - 9 Axle Single Dual tyres (AVKN300146)



										Y - Coordinates										
4	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
AVKN300146 (D)	1	TF	2	6244	3122	30.6	731	S	0	1050										
	2	TR	8	22036	2755	27.0	747	D	3210		760	1110								
	3								4580											
	4	DO	16	26710	1669	16.4	735	4D	5976				350	630	1310	1590				
	5								7356											
	6	ST	32	43060	1346	13.2	735	4D	17636								320	600	1280	1560
	7								19016											
	8								20396											
	9								21776											
			58	98050																

Figure App 2.5: **AV vehicle D - 9 Axle Single Dual tyres**

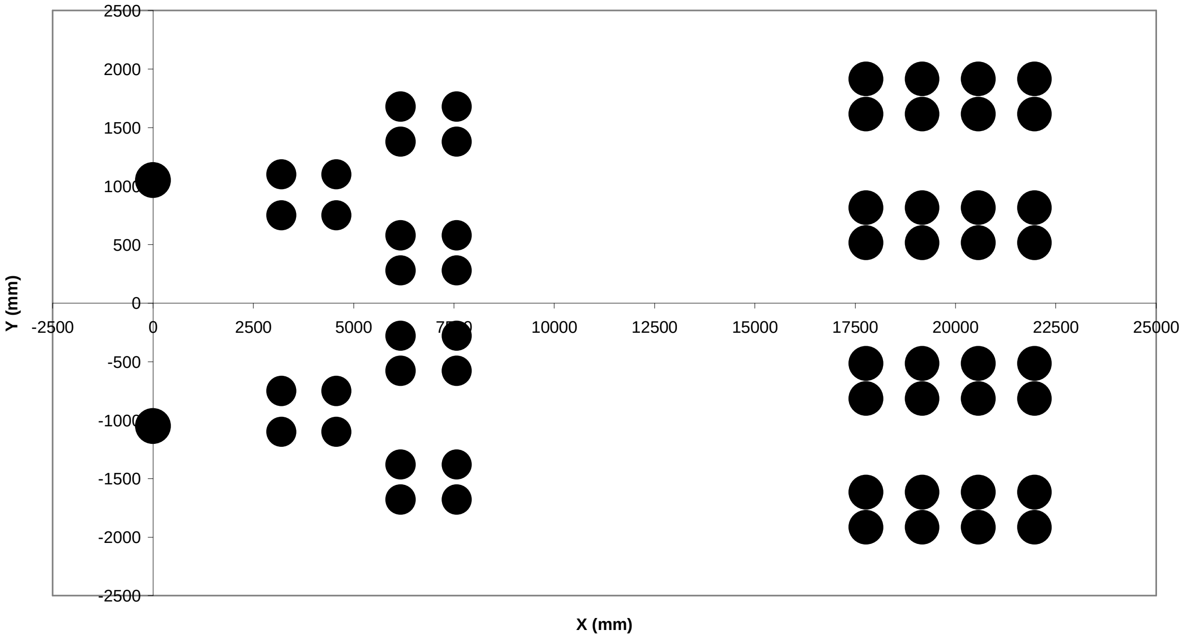
Load Positions: AV veh E - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305165)



1	Axle No	Group	No. of Tyres	Group Mass	Tyre Mass	Tyre Load	Tyre Press.	Axle Type	X Coord	TF1	TR1	TR2	DO1	DO2	DO3	DO4	ST1	ST2	ST3	ST4
										Y - Coordinates										
AVGP305165 (E)	1	TF	2	7333	3667	36.0	622	S	0	1200										
	2	TR	8	29333	3667	36.0	622	D	3200		770	1190								
	3								4610											
	4	DO	16	36666	2292	22.5	625	4D	6360				325	655	1395	1725				
	5								7760											
	6	ST	32	58418	1826	17.9	625	4D	17240								325	655	1395	1725
	7								18640											
	8								20040											
	9								21440											
			58	131750																

Figure App 2.6: AV vehicle E - 9 Axle Single Dual tyres

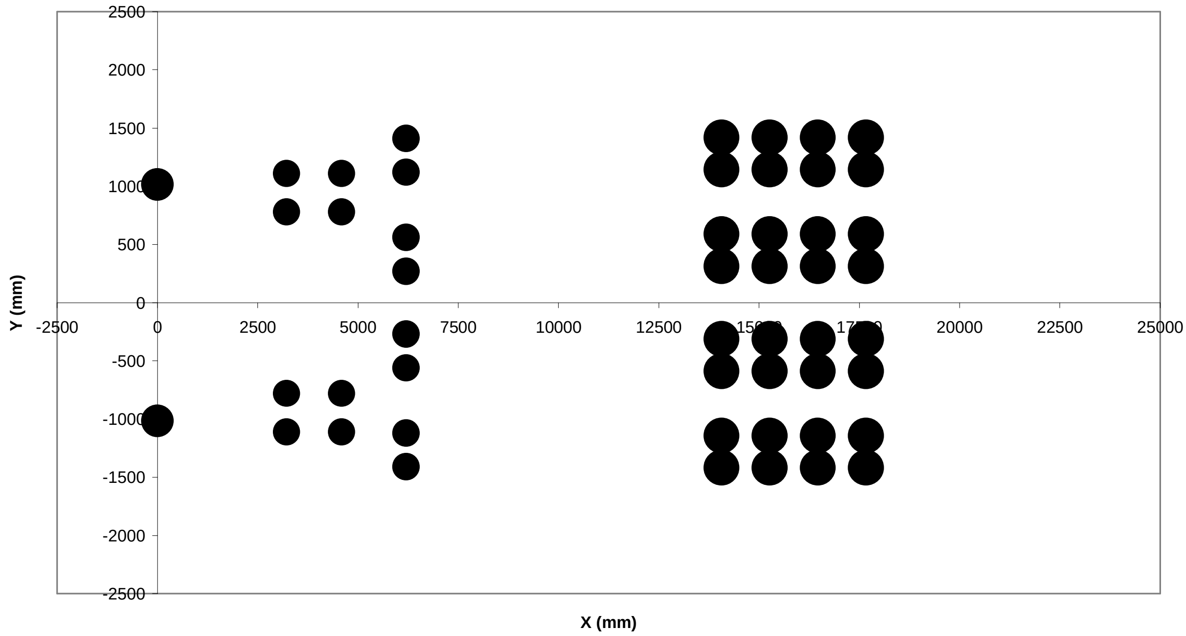
Load Positions: AV veh F - Abnormal Vehicle - 9 Axle Single Dual tyres (AVGP305729)



3	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
										Y - Coordinates										
AVGP305729 (F)	1	TF	2	8015	4008	39.3	809	S	0	1005										
	2	TR	8	23072	2884	28.3	834	D	3200		750	1100								
	3								4570											
	4	DO	16	27670	1729	17.0	503	4D	6170				280	580	1380	1680				
	5								7570											
	6	ST	32	56603	1769	17.3	386	4D	17770								515	815	1615	1915
	7								19170											
	8								20570											
	9								21970											
			58	115360																

Figure App 2.7: AV vehicle F - 9 Axle Single Dual tyres

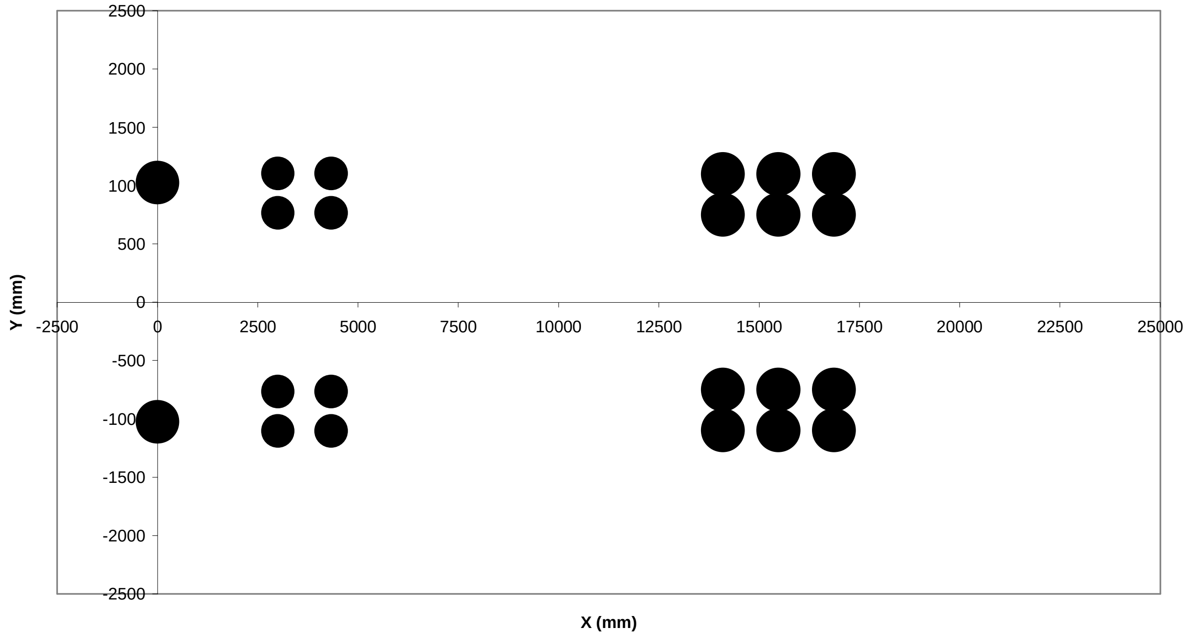
Load Positions: AV veh G - Abnormal Vehicle - 8 Axle Single Dual tyres (AVKN300177)



5	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
AVKN300177 (G)	1	TF	2	7344	3672	36.0	892	S	0	1015										
	2	TR	8	17912	2239	22.0	813	D	3220		780	1110								
	3								4590											
	4	DO	8	13667	1708	16.8	590	4D	6200				270	560	1120	1410				
	5	ST	32	50637	1582	15.5	318	4D	14065								313	588	1143	1418
	6								15265											
	7								16465											
	8								17665											
			50	89560																

Figure App 2.8: AV vehicle G - 8 Axle Single Dual tyres

AV veh H - Abnormal Vehicle - 6 Axle Single tyres (AVFS100077)



8	Axle No	Group		Group Mass	Tyre Mass	Tyre Load	Tyre Press.	Axle Type	X Coord	Y - Coordinates TF1	TR1	TR2	DO1	DO2	DO3	DO4	ST1	ST2	ST3	ST4
AVFS100077 (H)	1	TF	2	7125	3563	34.9	845	S	0	1025										
	2	TR	8	16229	2029	19.9	813	D	3000		765	1105								
	3								4330											
		DO																		
	4	ST	12	33646	2804	27.5	650	D	14095								750	1100		
	5								15480											
	6								16865											
			22	57000																

Figure App 2.9: AV vehicle H - 6 Axle Single Dual tyres

Appendix 3: MECHANISTIC INPUTS FOR THE NINE PAVEMENT STRUCTURES AS DEFINED FOR THE MECHANISTIC-EMPIRICAL (M-E) ANALYSES (mePADS) USED IN THIS STUDY.

Materials and Pavements		Pavement Phases used in mePADS analysis								
Pavement A ES100		**Phase I**			**Phase II**			**Phase III**		
Material Code used in mePads-TRH11 (1996)	**Thickness (mm)**	**Slip Rate**	**Poisson Ratio**	**E-Modulus (MPa)**	**Material Code used in mePads-TRH11 (1996)**	**Poisson Ratio**	**E-Modulus (MPa)**	**Material Code used in mePads-TRH11 (1996)**	**Poisson Ratio**	**E-Modulus (MPa)**
1	50	0	0.44	2000	1	0.44	2000	1	0.44	1500
6	150	0	0.35	450	6	0.35	450	6	0.35	350
4	150	0	0.35	2000	4	0.35	2000	9	0.35	500
4	150	0	0.35	1500	13	0.35	550	14	0.35	250
16	0	0	0.35	180	16	0.35	180	16	0.35	180
Pavement B ES100										
1	50	0	0.44	2000	1	0.44	1800	1	0.44	1500
6	150	0	0.35	250	6	0.35	250	6	0.35	240
4	150	0	0.35	2000	4	0.35	1700	14	0.35	160
4	150	0	0.35	1500	13	0.35	120	14	0.35	110
16	0	0	0.35	90	16	0.35	90	16	0.35	90
Pavement C ES0.1										
1	15	0	0.44	1000	1	0.44	1000			
9	100	0	0.35	300	9	0.35	225			
5	125	0	0.35	1000	13	0.35	200			
16	0	0	0.35	140	16	0.35	140			
Pavement D ES0.1										
1	15	0	0.44	1000	1	0.44	1000			
9	100	0	0.35	200	9	0.35	180			
5	125	0	0.35	1000	13	0.35	120			
16	0	0	0.35	70	16	0.35	70			
Pavement E ES30										
4	450	0	0.35	2200	5	0.35	1000	13	0.35	300
12	200	0	0.35	300	12	0.35	300	14	0.35	200
16	0	0	0.35	150	16	0.35	150	16	0.35	140
Pavement E1 ES10										
1	40	0	0.44	2400	1	0.44	2000	1	0.44	1600
17	120	0	0.44	2000	17	0.44	1800	17	0.44	1500
4	150	0	0.35	2000	4	0.35	1000	13	0.35	300
5	150	0	0.35	1000	13	0.35	300	14	0.35	200
16	0	0	0.35	140	16	0.35	140	16	0.35	140
Pavement F ES1.0										
1	15	0	0.44	2000	1	0.44	1600			
17	80	0	0.44	2000	17	0.44	1600			
5	150	0	0.35	1000	13	0.35	300			
16	0	0	0.35	140	16	0.35	140			
Pavement G ES10										
1	30	0	0.44	2400	1	0.44	2000	1	0.44	1600
4	150	0	0.35	2000	4	0.35	1800	13	0.35	250
5	300	0	0.35	1000	14	0.35	300	14	0.35	100
16	0	0	0.35	180	16	0.35	140	16	0.35	100
Pavement H ES0.3										
1	15	0	0.44	2000	1	0.44	1000	1	0.44	200
5	100	0	0.35	2000	5	0.35	1500	13	0.35	100
5	100	0	0.35	1000	14	0.35	300	14	0.35	100
16	0	0	0.35	140	16	0.35	140	16	0.35	100
									Pav & VehSummary-MDB.xls	

Note: Slip Rate = 0 refers to full friction between pavement layers.

Figure App 3.1: Mechanistic Inputs of the nine pavement structures used for mePADS analysis

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. These include Pavements A to H, which is briefly described below.

Pavement A:
This 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.

Pavement B:
This 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.

Pavement C:
This 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.

Pavement D:
This 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.

Pavement E:
This 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.

Pavement E1:
This 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.

Pavement F:
This 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.

Pavement G:
This 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.

Pavement H:

This 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.