COMPARING DYNAMIC ROAD WEAR OF A PERFORMANCE-BASED STANDARDS AND BASELINE VEHICLE

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ABSTRACT

The paved road network is a critical asset to any country and its economy. South Africa's paved road network has an estimated value in excess of R2 trillion. This asset is threatened by a backlog in maintenance of more than R416.6 billion, estimated in 2018. Overloaded heavy vehicles can cause more than 60% of the road wear on a road network. Most road wear analysis methods use static axle loads that are assumed to be symmetrical on either side of the road. Generally, Performance-based standards (PBS) vehicles have been shown to cause less road wear per tonne of payload compared to baseline vehicles when an assessment based on static axle loads is conducted. In this study, the dynamic road wear effects and the effects of road crossfall are studied in a road wear comparison of a PBS side tipper with a baseline vehicle. The results show that the PBS side tipper vehicle produces less road wear per tonne of payload when considering the first and fourth order aggregate tyre damage criteria for 0% and 3% crossfall. The road wear saving for fourth order aggregate tyre damage criteria for the left and right side was 10% and 11.5% at 0% crossfall and 5.7% and 11.3% at 3% crossfall. The results from the aggregate fourth order tyre damage and that from the mechanistic-empirical methodology produced similar results and indicate that the aggregate tyre damage criteria could be used for assessing PBS and baseline vehicle dynamic road damage. The study supports previous research that crossfall has a substantial influence on road damage of the left and right side of a vehicle. The maximum difference in the left and right side dynamic fourth order aggregate tyre damage was 32% for the baseline vehicle and 38% for the PBS vehicle.

1 INTRODUCTION

1.1 Background

Transport logistics in South Africa is the backbone of the economy, representing 11.8% of Gross Domestic Product (GDP) in 2016 or approximately R499 billion (Havenga, 2016). Road freight transport in particular is an essential component of logistics in South Africa, as approximately 85% of general freight is transported via road (Havenga, Simpson, King, De Bod, & Braun, 2016). The paved road network in South Africa is therefore a key national asset which has an estimated value in excess of R2 trillion (Ross & Townshend, 2019). This asset is threatened due to an estimated road maintenance backlog of R416.6 billion for provincial and municipal roads, estimated in 2018 (Ross & Townshend, 2019). It is therefore crucial to minimise the road wear caused by heavy vehicles which, if overloaded, can account for more than 60% of all road wear on the network (Krygsman & Van Rensburg, 2017).

1.2 PBS in South Africa

The CSIR, with support from partners including Wits University, University of KwaZulu-Natal, SANRAL, the national Department of Transport (DoT) and the KZN Department of Transport (KZN DoT), have developed and initiated the Smart Truck pilot project, also referred to as the "Performance-Based Standards" (PBS) pilot project. The Smart Truck pilot project has been operational since 2007. PBS is an alternative to traditional prescriptive heavy vehicle legislation, where the vehicle design limitations are more flexible. PBS offers the heavy vehicle industry the potential to achieve higher productivity and improved safety through innovative and optimised vehicle design. PBS vehicles are designed to perform their tasks as productively and sustainably as possible, while at the same time ensuring high levels of vehicle safety performance. The PBS project also ensures that vehicles operate on road networks that are appropriate for their level of performance. PBS, therefore, ensures a better match between vehicles and the roads, as well as the freight task (National Heavy Vehicle Regulator, 2017).

Each PBS vehicle is required to undergo a thorough vehicle dynamics safety assessment, and a bridge and road wear impact analysis using computer simulation. All PBS vehicles are required to perform less road wear per tonne of payload when considering static loads. There is no evidence of previous research on quantifying the dynamic-loading damage caused by PBS vehicles, in comparison with baseline vehicles. A baseline vehicle is a vehicle that complies with the National Road Traffic Regulations e.g., with an overall length not greater than 22 m and a combination mass not more than 56 tonnes (Department of Transport, 2009). The aim of this study is to take these effects into account.

1.3 Road damage criteria

The Load Equivalency Factor (LEF) is the most used metric to measure the relative road wear caused by a heavy vehicle. It represents the equivalent number of standard axle repetitions that would cause the same road wear as the full vehicle combination under assessment. A standard axle in South Africa is defined as a single axle with dual wheels which has a mass of 8 200 kg or 80 kN (De Beer M. , Sallie, Van Rensburg, & Kemp, 2009).

The most common formula used to calculate the LEF was inferred from the AASHO Load Equivalency Factor (the so-called "4^{th} Power Law") that has its origin in the AASHO road test in the USA. This is calculated as shown in equation 1 (NAS-NRC, 1962):

$$LEF = \left(\frac{P}{80}\right)^n \quad (1)$$

where the LEF is the load equivalency factor, P is the axle load in kN, n is the relative wear exponent and 80 is the load of a standard axle in kN (so-called "80 kN" axle). The relative wear exponent n is dependent on the type of pavement layered structure, its failure mechanism and its state. Based on the AASHO test, the average recommended n-value is 4.2. Research using Heavy Vehicle Simulators (HVSs) in South Africa has shown that n can vary from 2 to 6, depending on the pavement layer type, and for permanent deformation (rutting) in South Africa n has traditionally been taken as 4 (De Beer M. , Sallie, Van Rensburg, & Kemp, 2009). Assessments based on this AASHO methodology therefore require technical expertise to determine the correct values of n and are prone to being inaccurate if the incorrect exponent is selected. In addition, many of the datasets developed are severely outdated and are no longer relevant to modern pavement designs. This is demonstrated by statements made by experts such as "the validity of the 'fourth power law' is questionable, particularly for current axle loads and axle group configurations; tyre sizes and pressures; road construction; and traffic volumes: all of which are significantly different from the conditions of the AASHO road test" (NVF committee Vehicles and Transports, 2008). A widely-used assumption is that the stresses and strains under the standard axle on dual mounted tyres is equivalent to the same axle load on wide base tires, which is not necessarily the case and is not currently considered in road wear studies (J. Granlund, 2017).

Another popular method used to calculate LEF is the mechanistic-empirical (ME) pavement design method. This method is the basis of the classical South African pavement design method used to develop a road catalogue of designs as described in the TRH 4 document (DoT, 1996). The classic South African Mechanistic Empirical Design Method (SAMPDM) is based on empirical data obtained from Heavy Vehicle Simulator (HVS) and Stress-In-Motion (SIM) tests and has been the preferred method for pavement design and analysis since 1996 (De Beer M. , Sallie, Van Rensburg, & Kemp, 2009). The CSIR and several consultants developed the mePADS software package using this data to perform static road wear impact studies based on individualised vehicle input parameters and a specified pavement structure.

The mePADS software is only able to analyse one vehicle at a time and can have simulation times of several minutes depending on the complexity of the vehicle design and pavement structure. Furthermore, the software package was developed using quasi-static vehicle testing and therefore its usefulness at high speeds is limited. Nevertheless, it still provides useful insights in road wear caused by heavy vehicles. The mePADS software is currently the only recognised method for calculating the relative road wear of PBS vehicle designs as part of the Smart Truck Pilot Project approval process in South Africa.

Many road wear assessments are conducted using the static axle loads of the vehicle, usually as obtained from the general arrangement (GA) drawing of the vehicle combination provided by the trailer manufacturer, and assuming symmetrical loading on the left and right tyres of the vehicle. It is however known that dynamic axle loads produce greater road wear compared to the static scenario (Hjort, Haraldsson, & Jansen, 2008). Furthermore, a recent study has shown that the assumption of symmetrical loading can lead to large errors in the calculated road damage (or wear) with differences as high as 59% being recorded between the static symmetrical analysis and dynamic road wear analysis for a crossfall value of 3% (Steenkamp, Berman, Kemp, & De Saxe, 2019). Road crossfall values typically range between 2% and 3% in South Africa (CSIR, 2000).

Both the AASHO method and the mechanistic empirical method are limited to pavement types and do not account for dynamic loading road wear effects. The mePADS and related software are furthermore currently proprietary and not freely available. Therefore, an alternative methodology was required to calculate the dynamic road damage in this study.

A common method is to express dynamic loads in terms of the Dynamic Load Coefficient (DLC) which is defined in an OECD (Hjort, Haraldsson, & Jansen, 2008) as the ratio of the root mean square (RMS) dynamic wheel load to the mean wheel load. DLC values can vary from 5-10% for heavy vehicles with well-damped air suspension, to 20 to 40% for less road-friendly suspensions (Hjort, Haraldsson, & Jansen, 2008). The DLC however calculates the road damage caused over an entire road section and does not look at the dynamic damage caused at a specific location (Cebon, 1992) (Cebon, 2000). A useful method for calculating dynamic road damage at specific locations is the aggregate tyre force method shown in equation 2 (Cebon, 2000).

$$A_k^n = \sum_{j=1}^{N_a} P_{jk}^n \quad \mathrm{k} = 1,2,3, \dots , N_s \tag{2}$$

Where A_k^n is the n-th power aggregate tyre force, P_{jk} is the force applied by tyre j to location k on the road, N_a is the number of axles on the vehicle and N_s is the number of points along the road. This means that the forces produced by each tyre on a specific side of a vehicle are added as they pass specific locations on a road. The power of n is selected according to the type of road damage that is being considered. For flexible pavements n = 4 is usually suitable for fatigue damage. Permanent deformation (rutting) is usually better represented by n = 1 (Cebon, 2000) (Cebon, 1992). These are generalized values and can be optimised for specific pavement types if sufficient data is available. The purpose of this study is however comparative and not absolute.

Equation 2 can be used to compare the road-damaging potential of different vehicles, if all of the tyres are assumed to have the same vertical contact area. The method can be enhanced by dividing each individual wheel force by an appropriate nominal tyre contact area. The damage prediction is then based on the nominal contact stress. The resulting "damage" is then given as shown in equation 3 (Cebon, 2000).

$$D_k^n = \sum_{j=1}^{N_a} \left(\frac{P_{jk}}{a_j} \right)^n \quad \mathrm{k} = 1,2,3, \ldots, N_s \qquad (3)$$

Where a_j is the nominal contact area of tyre j (Cebon, 2000).

Equation 3 does not account for the dynamic variation of the contact area with varying dynamic tyre loads. This is a second order effect. Equation 3 can be further refined by including an appropriate material constant and can then be used to consider the fatigue and rutting damage caused by the vehicle (Cebon, 2000).

Determining the nominal contact area (and associated tyre-road stresses) is not simple as measurements show that tyre contact areas are neither uniformly rectangular nor circular in shape (CSIR, 2014). The Stress-In-Motion (SIM) system has been used in South Africa since the 1990s to research the interaction forces between slow moving tyres and textured road surfaces (De Beer & Sallie, 2012). Currently the results from SIM analyses of 33 tyres have been logged in the "TyreStress-Internal" application (CSIR, 2014). These 33 tyres span a wide range in widths of 275 to 445 mm including bias and radial tyres. This database is used in this study to calculate the nominal contact area.

1.4 Aim

The aim of this paper is to investigate the road damage effects of dynamic loading when including different levels of road crossfall, in a comparative study between common PBS and baseline vehicle combinations operating in South Africa (a side tipper B-double/interlink). The aggregate tyre force and damage criteria are also investigated as possible methodologies for comparing PBS and baseline dynamic road damage in the Smart Truck Pilot Project.

1.5 Scope

The scope of this paper only includes a single PBS and baseline combination which was considered on one road profile using a single operating speed. Furthermore, only two crossfall values were considered. The road damage criteria are limited to first and fourth order aggregate tyre forces and damage.

2 METHOD

In this proposed methodology a single PBS and a single corresponding baseline vehicle were considered. For the South African PBS pilot project, the side-tipper B-double is a common vehicle combination in the mining sector. The PBS and baseline side tipper vehicles are very similar in dimensions and suspension, the maximum combination mass being the major differentiator. The National Transport Commission of Australia road profile was used to determine tracking ability on a straight path and a constant operating speed of 80km/h was assumed. The vehicle simulations were performed using the TruckSim® 2019 multibody dynamics software package. Uniform circular road-tyre contact patch areas were assumed as obtained from the "TyreStress-Internal" software package at the CSIR. Two road crossfall values of 0% and 3% were considered.

The PBS and baseline vehicles studied are shown in Figure 1. The technical specifications of the vehicles were obtained from the trailer manufacturers and truck-tractor manufacturers. These include the tyre locations, the sprung and unsprung masses and associated centre of gravity (CoG) locations, and the stiffness and damping values of the suspension spring and damper assemblies. All simulations were conducted using a sampling rate of every 10 mm (2 222 Hz at 80 km/h) to ensure a high degree of accuracy of the calculated dynamic axle loads.

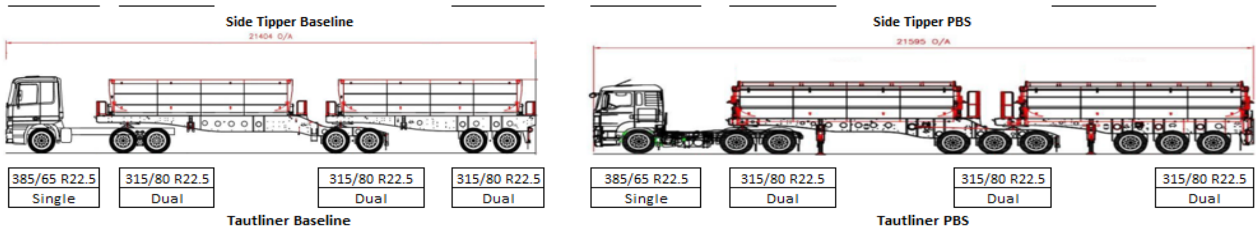

Figure 1: Vehicles and Tyres used for the road crossfall study

The Australian National Transport Commission (NTC) road section (1 km section) used in this study is shown in Figure 2, with the profiles for both left and right wheel tracks indicated.

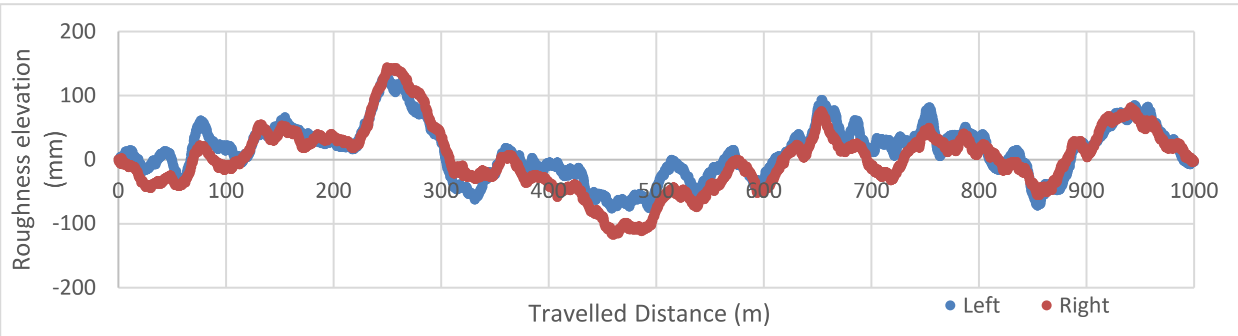

Figure 2: NTC road profile elevation (National Transport Commission of Australia, 2008)

The tyre loads were obtained for the PBS and baseline vehicles under four different conditions namely:

- The static tyre loads as obtained from the general arrangement (GA) drawing
- The static tyre loads as obtained from TruckSim® 2019
- The dynamic tyre loads obtained using 0% crossfall
- The dynamic tyre loads obtained using 3% crossfall

The aggregate tyre forces and damage as defined by equation 2 and equation 3 were calculated for n = 1 and n = 4 to account for rutting and fatigue failure modes.

To calculate the road damage using equation 3, the equivalent circular uniform contact area was calculated at the static tyre loads as obtained from TruckSim® 2019. To simplify the analysis, the dual tyre forces were assumed to be equal. The uniform areas at each load location were estimated using the “TyreStress-Internal” application (CSIR, 2014). This application was developed from the data captured from the stress-in-motion system (SIM) as developed by the CSIR (Maina, De Beer, & Van Rensburg, 2013). The tyre inflation pressure on the steer axles was assumed to be 800 kPa and 700 kPa on all other axles. All contact patch areas were assumed to be circular and no variation in the contact patch shape was considered with different loading levels.

The road damage calculated previously from mePADS during a 2019 study were also included to provide a comparison of the results (Steenkamp, Berman, Kemp, & De Saxe, 2019)

3 RESULTS AND DISCUSSION

The results are divided into two sections, the first focussing on the aggregate tyre forces and damage and the second on a comparison with the results from mePADS from the 2019 study (Steenkamp, Berman, Kemp, & De Saxe, 2019).

3.1 <u>Aggregate tyre forces and damage</u>

The aggregate tyre forces and damage as defined by equation 2 and 3 were calculated for n = 1 and n = 4 to account for rutting and fatigue failure modes. It was decided to calculate both the aggregate tyre forces and damage (wear) in order to determine the impact of including vs excluding the nominal tyre contact area. In the case of dual tyres, the force and area were assumed to be equal. The steer axle was assumed to have 385/65 R22.5 tyres fitted with an inflation pressure of 800 kPa (Cold). The other tyres are all dual tyres (315/80 R22.5) and a tyre inflation pressure of 700 kPa (Cold) was assumed. The nominal area used for each tyre is provided in Table 1.

Table 1: The tyre footprint area used for each tyre

	Axle 1 (cm2)	Axle 2 (cm2)	Axle 3 (cm2)	Axle 4 (cm2)	Axle 5 (cm2)	Axle 6 (cm2)	Axle 7 (cm2)	Axle 8 (cm2)	Axle 9 (cm2)
Left Baseline	417.7	363.6	360.7	385.1	377.1	341.1	334.5		
Right Baseline	421.8	368.5	366.7	389.6	389.8	336.3	336.1		
Left PBS	432.5	389.5	389.1	346.1	345.8	345.5	372.7	372.9	373.0
Right PBS	438.3	396.9	397.0	347.6	347.9	348.0	374.1	374.0	373.8

Due to space constraints, only the figures for the first and fourth order aggregate tyre damage are presented. The results for the rutting damage (n = 1) at 0% and 3% crossfall are shown in Figure 3 and Figure 4 and the results for fatigue failure (n = 4) are shown in Figure 5 and Figure 6 respectively.

Figure 3 and Figure 5 show that the right side of the vehicle produces the highest dynamic aggregate tyre damage for 0% crossfall for both PBS and baseline vehicles for fatigue and rutting failure. This is due to non-symmetric loading of the combinations resulting from the driver and fuel tanks being located on the right side of the vehicles. The PBS vehicles produce higher aggregate tyre damage as expected due to the increased mass of the combination. The right-side average first order damage is 3.3% higher than the left side. The PBS vehicle recorded a 3.5% higher average damage on the right side for the first order damage. The right side fourth order damage for 0% crossfall is however 11.6% higher for the case of the baseline vehicle and 12.6% for the PBS vehicle.

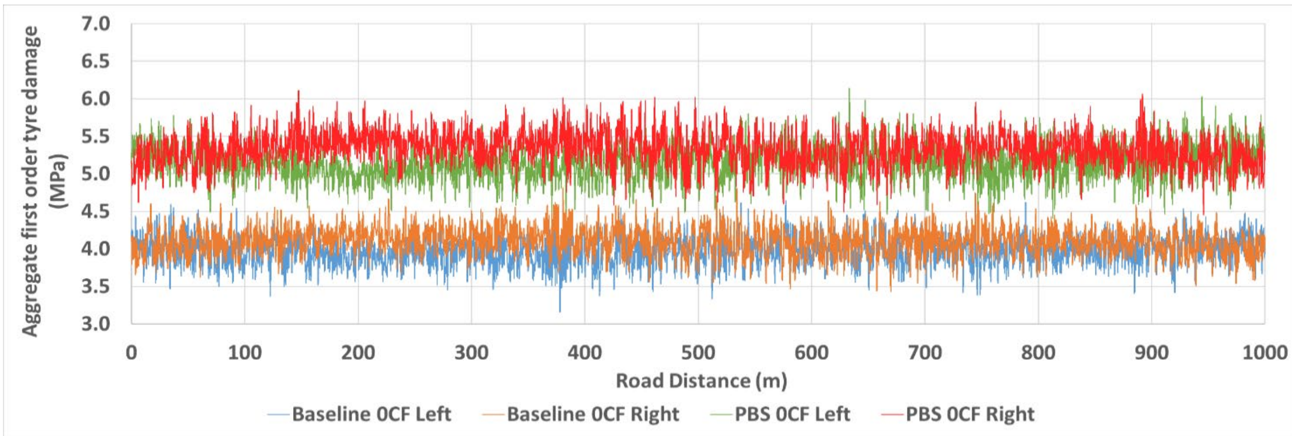

Figure 3: Aggregate first order tyre damage (in MPa) of the PBS and baseline vehicles with 0% crossfall

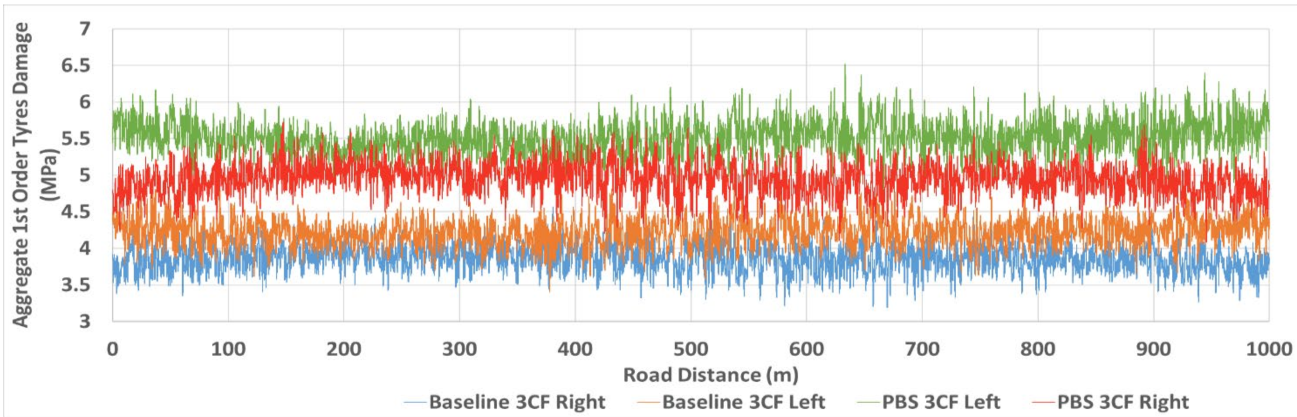

Figure 4: Aggregate first order tyre damage of the PBS and baseline vehicles with 3% crossfall

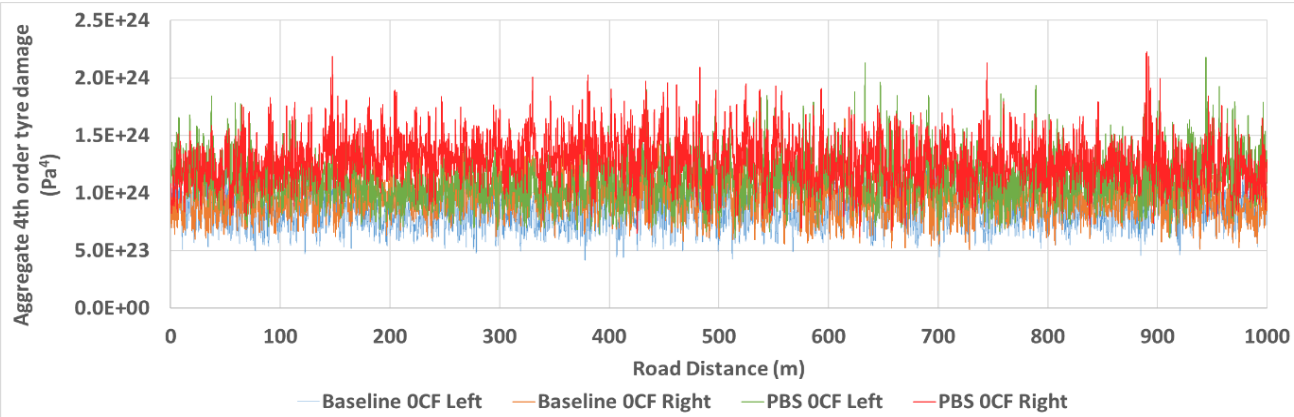

Figure 5: Aggregate fourth order tyre damage of the PBS and baseline vehicles with 0% crossfall

The results show that loading of a vehicle can play a significant role as there can be a substantial difference in the left and right-side road damage from even a slight variation in symmetrical loading.

The results change considerably when considering the aggregate damage at 3% crossfall as shown in Figure 4 and Figure 6. When 3% crossfall is included, the first and fourth order road damage is highest on the *left side* of the vehicle. The left side average first order damage is 9.1% higher than the right side for the baseline vehicle. The PBS vehicle recorded a 10.8% higher average damage on the right side for the first order damage. The right side

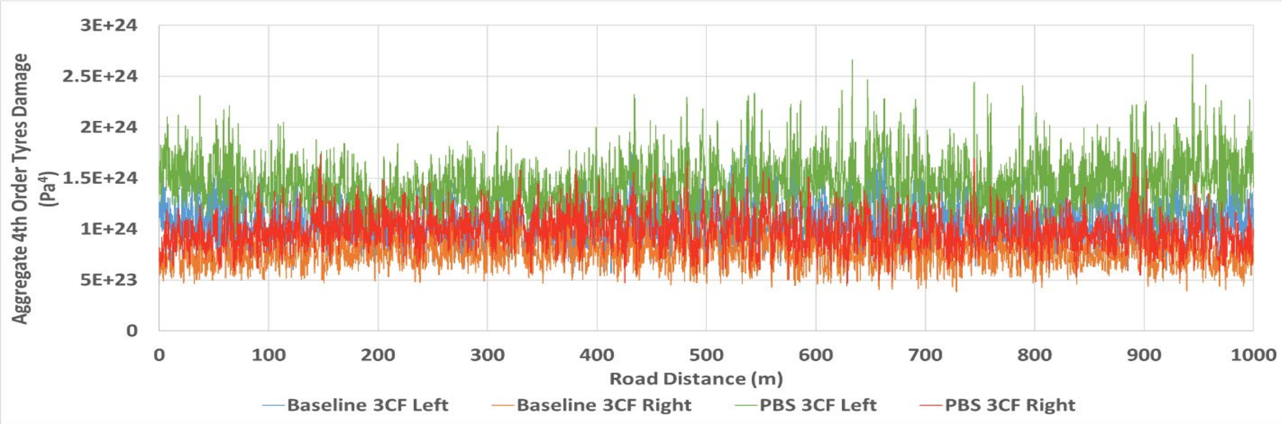

Figure 6: Aggregate fourth order tyre damage of the PBS and baseline vehicles with 3% crossfall

fourth order damage for 3% crossfall is however 32.2% higher for the case of the baseline vehicle and 38.1% for the PBS vehicle.

These results show that crossfall has a significant effect on the road damage on either side of the vehicle for both first and fourth order tyre forces. Fatigue failure is usually the most important and problematic failure criteria as fatigue failure leads to potholes (Cebon, 2000). Crossfall can therefore not be ignored when considering the fatigue failure of roads.

The results show that the PBS vehicle causes more road damage *per vehicle* than the baseline vehicle for all scenarios tested. However, to provide a fair comparison, it is necessary to normalise the results with respect to the payload carried. A truck carrying more payload will require fewer trips (and hence fewer axle passes) to transport the same amount of freight. The PBS vehicle carries a higher payload compared to the baseline vehicle (50 550 kg compared to 34 830 kg for the baseline vehicle).

When the first and fourth order aggregate tyre damage criteria were normalized with respect to the payload, the PBS vehicles caused less road wear than the baseline vehicle in all instances. Specifically, the PBS vehicle showed a reduction of 10.8% for the first order damage on the left side and 10.6% on the right side for 0% crossfall. Considering the fourth order damage at 0% crossfall, the reduction was 10% and 11.5% on the left and right sides, respectively. When considering 3% crossfall the PBS vehicles showed a reduction of 8.9% for the first order damage on the left side and 8% on the right side whilst showing a reduction of 5.7% and 11.3% for the left and right side, respectively, for the fourth order damage.

The results for all the simulations conducted during this study are summarised in Table 2 to Table 5. It should be noted that this includes the aggregate tyre forces as well as the aggregate tyre damage (pavement wear) criteria. This was done to show that the two criteria have similar trends. The inclusion of the nominal contact area is however important in comparing the PBS and baseline vehicles due to the difference in contact area resulting from differences in tyre loads. This is supported by the result showing that the PBS vehicle does more “damage” per tonne payload for the aggregate fourth order tyre force criteria but not the damage criteria when the area is included. Therefore, simply using the aggregate tyre force criteria is not suitable for comparing PBS and baseline vehicles and only the first and fourth order damage criteria are advised.

Table 2: Baseline aggregate tyre forces and damages

	1st Order Forces			1st Order Damage			4th Order Forces			4th Order Damage		
	Left	Right	% Difference left and right	Left	Right	% Difference left and right	Left	Right	% Difference left and right	Left	Right	% Difference left and right
Units	(N)	(N)	(%)	(Pa)	(Pa)	(%)	(N^4)	(N^4)	(%)	(Pa^4)	(Pa^4)	(%)
GA drawing	2.75E+05	2.75E+05	**0.0**	4.05E+06	4.05E+06	**0.0**	1.74E+19	1.74E+19	**0.0**	8.51E+23	8.51E+23	**0.0**
Static	2.69E+05	2.75E+05	**2.2**	4.02E+06	4.06E+06	**1.0**	1.71E+19	1.88E+19	**9.3**	8.27E+23	8.58E+23	**3.7**
0CF RMS	2.66E+05	2.79E+05	**4.6**	3.98E+06	4.11E+06	**3.3**	1.83E+19	2.18E+19	**17.5**	8.62E+23	9.69E+23	**11.6**
3CF RMS	2.83E+05	2.61E+05	**8.2**	4.23E+06	3.86E+06	**9.1**	2.33E+19	1.71E+19	**30.8**	1.07E+24	7.75E+23	**32.2**

Table 3: PBS aggregate tyre forces and damages

	1st Order Forces			1st Order Damage			4th Order Forces			4th Order Damage		
	Left	Right	% Difference left and right	Left	Right	% Difference left and right	Left	Right	% Difference left and right	Left	Right	% Difference left and right
Units	(N)	(N)	(%)	(Pa)	(Pa)	(%)	(N^4)	(N^4)	(%)	(Pa^4)	(Pa^4)	(%)
GA drawing	3.61E+05	3.61E+05	**0.0**	5.24E+06	5.24E+06	**0.0**	2.39E+19	2.39E+19	**0.0**	1.16E+24	1.16E+24	**0.0**
Static	3.62E+05	3.68E+05	**1.7**	5.22E+06	5.26E+06	**0.8**	2.54E+19	2.74E+19	**7.6**	1.09E+24	1.12E+24	**3.2**
0% Crossfall	3.57E+05	3.73E+05	**4.5**	5.15E+06	5.33E+06	**3.5**	2.74E+19	3.26E+19	**17.3**	1.14E+24	1.29E+24	**12.6**
3% Crossfall	3.84E+05	3.47E+05	**10.1**	5.52E+06	4.96E+06	**10.8**	3.60E+19	2.47E+19	**37.4**	1.47E+24	9.98E+23	**38.1**

Table 4: Increase in PBS aggregate tyre forces and damages compared to the baseline

	1st Order Forces			1st Order Damage			4th Order Forces			4th Order Damage		
	Left	Right	% Difference left and right	Left	Right	% Difference left and right	Left	Right	% Difference left and right	Left	Right	% Difference left and right
Units	%	%	%	%	%	%	%	%	%	%	%	%
GA drawing	31.6	31.6	**0.0**	29.5	29.5	**0.0**	37.4	37.4	**0.0**	35.9	35.9	**0.0**
Static	34.4	33.8	**0.6**	29.8	29.5	**0.3**	48.3	45.8	**2.5**	31.6	30.9	**0.7**
0% Crossfall	34.1	34.0	**0.1**	29.5	29.7	**0.2**	49.8	49.5	**0.3**	32.2	33.5	**1.3**
3% Crossfall	35.3	32.7	**2.6**	30.7	28.4	**2.2**	54.6	44.6	**10.0**	36.9	28.7	**8.2**

Table 5: Percentage difference in PBS and Baseline aggregate forces and damage when normalised by payload

	1st Order Forces			1st Order Damage			4th Order Forces			4th Order Damage		
	Left	Right	% Difference left and right	Left	Right	% Difference left and right	Left	Right	% Difference left and right	Left	Right	% Difference left and right
	%	%	%	%	%	%	%	%	%	%	%	%
GA drawing	-9.3	-9.3	**0.0**	-10.8	-10.8	**0.0**	-5.3	-5.3	**0.0**	-6.4	-6.4	**0.0**
Static	-7.4	-7.8	**0.4**	-10.6	-10.8	**0.2**	2.2	0.4	**1.7**	-9.3	-9.8	**0.5**
0% Crossfall	-7.6	-7.6	**0.1**	-10.8	-10.6	**0.2**	3.2	3.0	**0.2**	-8.9	-8.0	**0.9**
3% Crossfall	-6.7	-8.5	**1.8**	-10.0	-11.5	**1.5**	6.5	-0.4	**6.9**	-5.7	-11.3	**5.7**

3.2 Results Comparison of the Aggregate Tyre Damage and mePADS Methods

Table 6 shows the results from the 2019 study that used the average tyre loads and the mePADS software to calculate the LEF for the PBS and baseline vehicles. When comparing the results from Table 2 Table 3 to that of Table 6, one can see that similar trends exist between the mePADS and aggregate tyre force and damage criteria. Specifically, the difference between the left and right tyre damage increases as the crossfall increases. There are however differences in the absolute values recorded for the different criteria.

Table 6: Road damage for PBS and baseline vehicle using mePADS

	Baseline			PBS		
	Left	**Right**	**% Difference left and right**	**Left**	**Right**	**% Difference left and right**
Units	**LEF**	**LEF**	**(%)**	**LEF**	**LEF**	**(%)**
GA drawing	6.6	6.6	**0.0**	8.7	8.7	**0.0**
Static	5.9	6.3	**5.8**	7.2	8.1	**12.3**
0% Crossfall	5.8	6.6	**12.4**	7.6	8.6	**13.0**
3% Crossfall	6.9	5.6	**20.6**	9.2	7.1	**25.4**

As mentioned, fatigue failure is considered the most important road damage mechanism as it leads to potholes and determines the road life. Table 7 compares the road damage savings of the PBS vehicle versus the baseline vehicle on a per tonne payload basis for the mePADS and fourth power aggregate tyre damage criteria. Similar trends exist between the two methodologies. The results show that the road wear savings increase from the general arrangement (GA) drawing scenario to the static crossfall scenario for both methodologies. The road damage then decreases for the 0% crossfall scenario for both methodologies. For the 3% crossfall, the lowest savings are recorded on the left side and the highest savings on the right side for both methodologies.

Table 7: Comparison of road damage caused by the PBS vehicle vs the baseline vehicle when using mePADS and 4th order damage criteria per tonne payload

	mePADS			4th Order Damage		
	Left	**Right**	**% Difference left and right**	**Left**	**Right**	**% Difference left and right**
Units	**LEF**	**LEF**	**(%)**	**%**	**%**	**%**
GA drawing	-9.3	-9.3	**0.0**	-6.4	-6.4	**0.0**
Static	-16.2	-10.5	**5.7**	-9.3	-9.8	**0.5**
0% Crossfall	-10.3	-9.8	**0.5**	-8.9	-8.0	**0.9**
3% Crossfall	-7.7	-12.1	**4.4**	-5.7	-11.3	**5.7**

In many instances the absolute values of the road wear savings do not differ substantially between the mePADS and 4th order damage methodologies. This indicates that the fourth order road damage criteria could be a viable alternative to mePADS in calculating the relative road wear caused by PBS and baseline vehicles. This methodology could therefore be considered by the Smart Truck Review Panel for calculating road wear savings of PBS vehicles.

4 CONCLUSIONS

This research investigated the dynamic road wear caused by PBS and baseline vehicles using aggregate tyre force and damage criteria. The impact of road crossfall was also included to highlight the variation in damage between the left and right side of the road.

The results show that the PBS vehicle produces more road damage than the baseline vehicle for any criteria considered. The results also showed that crossfall plays a significant role in dynamic road damage, especially for crossfall values of 3% or more. The maximum difference between the left and right fourth order damage was 32.2% for the baseline vehicle and 38.1% for the PBS vehicle. Therefore, crossfall should be included in future road wear assessments, whether static or dynamic. Loading conditions should also be taken into consideration as unsymmetrical loading will cause significant variations in left and right tyre damage even with 0% crossfall.

When calculating the road damage caused by the PBS vehicle and the baseline vehicle per tonne of payload, it was shown that the PBS vehicle causes less road damage than the baseline vehicle for all criteria except the fourth order tyre force. The four-order tyre force on its own however does not objectively compare different vehicle configurations as it assumes the contact area of each tyre is the same which is not the case. *Importantly, the side tipper PBS vehicle was found to cause less road wear than the baseline for all crossfall values when considering fourth order aggregate road damage normalised by the payload of each combination.*

It is important to note that an increase in crossfall values will change the relative PBS road wear savings per tonne of payload between the left and right side. The left side will show a decrease and the right side an increase in road wear savings. This once again highlights the importance of crossfall, and vehicle loading being included in road wear assessments when quantifying the absolute road wear. The effect of crossfall could however be ignored when performing a study investigating the relative road wear produced by a PBS and baseline vehicle as done in the Smart Truck Pilot Project.

Although the aggregate force and damage criteria showed similar trends, the inclusion of the nominal contact area played a substantial role in the road wear savings calculated. This means that tyre inflation pressure and nominal tyre contact area are important inputs in these assessments and should be carefully considered. This study has also only considered uniformly distributed circular contact patch areas and should ideally be updated to take into account different tyre contact patch areas and load distributions at different loading levels.

The road damage savings per tonne of payload calculated using mePADS and the fourth order aggregate damage criteria showed similar results and trends. It is therefore plausible that the fourth order damage criteria could also be considered as an acceptable methodology by the Smart Truck Review Panel for calculating and comparing the dynamic road wear caused by PBS and baseline vehicles.

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