THE EFFECT OF ROAD CROSSFALL ON ROAD WEAR CAUSED BY HEAVY VEHICLES

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ABSTRACT

The paved road network is a critical asset to any economy. South Africa has a paved road network that has an estimated value in excess of R2 trillion. This asset is however under threat as there was a backlog in maintenance of more than R197 billion in 2014. Heavy vehicles are primarily responsible for road wear, and overloaded vehicles can cause more than 60% of road wear. Most road wear assessments use static axle loads that are assumed to be symmetrical on either side in order to calculate the road wear caused by a heavy vehicle. This paper investigates the effect of road crossfall on the road wear caused by heavy vehicles, and compares it to the wear calculated using the static loading scenario. This was done by simulating four Performance Based Standards (PBS) vehicles and four conventional baseline vehicles. A representative road profile was used and the crossfall was varied from 0% to 5%. The average road wear from eight South African pavements was used to assess overall road wear impact. TruckSim® software was used to perform the heavy vehicle simulations, and the mePADS mechanistic empirical simulation software was used to perform the road wear simulations using the RMS axle loads from TruckSim®. It was found that crossfall values as low as 3% can produce a difference in road wear of more than 26.1% between the left and right sides. When comparing the road wear from a static analysis to the dynamic analyses, it was found that there is a substantial difference in the calculated road wear, even at low values of 2 to 3% crossfall, with a maximum difference of 59.3% recorded at 3% crossfall. It is therefore recommended that future road wear assessments incorporate the effect of vehicle roll motion and crossfall into road wear assessments.

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, Simpson, King, De Bod, & Braun, 2016). Road freight transport, in particular, is essential to logistics, 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. This asset is however under threat as there was an estimated road maintenance backlog of R197 billion in 2014.

It is therefore crucial to minimize the road wear caused by heavy vehicles which, if overloaded, can account for more than 60% of all road wear caused (Krygsman & Van Rensburg, 2017).

Load equivalency factors (LEFs) are the most commonly used method of representing 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.

The most common formula used to calculate the LEF is the AASHO Load Equivalency Factor (the so-called "4th 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):

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

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.

The relative wear exponent n is dependent on the type of pavement, its failure mechanism and its state. Based on the AASHO test, the average recommended n-value is 4.2. Research using heavy vehicle simulators in South Africa has shown that n can vary from 2 to 6, depending on the pavement type, and in South Africa n has traditionally been taken as 4 (De Beer, Sallie, Van Rensburg, & Kemp, 2009). Assessments based on this AASHO methodology therefore require substantial 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). Another widely used assumption is that the stresses and strains under the standard axle on duel mounted tyres is equivalent to the same axle load on wide base tires, which is not necessarily the case (J. Granlund, 2017).

In this study, the LEFs were not calculated using the 4th Power Law, but were calculated using the mechanistic empirical pavement design method. This method is the basis of the South African pavement design method as described in the TRH4 document (DoT, 1996). The South African Mechanistic Empirical Design Method 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, Sallie, Van Rensburg, & Kemp, 2009). The CSIR and several consultants developed the mePADS software package using this data in order to perform road wear impact studies based on individualized vehicle input parameters and a specified pavement structure. This software package is however 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. The software package was also developed using quasi-static vehicle testing and therefore its usefulness at high speeds is limited, but still provides very useful insights in road wear caused by heavy vehicles.

Many road wear assessments are conducted using the static axle loads of the vehicle, usually as obtained in the general arrangement (GA) drawing of the vehicle combination provided by the trailer manufacturer. It is however known that dynamic axle loading produces higher road wear compared to the static scenario. Dynamic loads are mostly expressed in terms of the Dynamic Load Coefficient (DLC) which is defined by the OECD 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).

Numerous methods and techniques have been proposed on how to accurately calculate the road wear caused by heavy vehicles during dynamic loading scenarios. Many of these methods are complex and require detailed information that is not readily available. Many of the techniques attempt to calculate the cumulative wear caused by heavy vehicles by studying the loads produced at every point of interest. This requires detailed information on the road surface and wheel loads at every single point as a function of time (Cebon, 1992). The road wear calculated using the mePADS software is not able to perform these types of time-dependent road wear calculations. Instead, it calculates the equivalent number of standard axle repetitions that would cause the same wear as the vehicle combination over an entire road section. mePADS therefore calculates an average wear over a road section, rather than the wear produced at every single point.

Various road wear studies developed models in which the rolling effect of vehicles can be ignored. Single- or two-degree-of-freedom vehicle models are typically used, for example quarter-car or half-car models. This assumption implies that the loads on the left and right sides of each axle are identical. This assumption greatly simplifies the mathematics involved, but as this study will demonstrate, results in significant inaccuracies in the calculated road wear due to lateral load transfer.

Road crossfall represents the lateral decrease in height of the road section from the road centre to the edge of the road. Road crossfall is necessary in road pavement design to ensure adequate removal of surface water from the road. Excess water on the road surface can lead to potential problems such as hydroplaning of vehicles and accelerated road wear. Typical values for road crossfall in South Africa are in the range of 2 to 3% but can be as high as 10% when using super-elevation as is needed during steep cornering manoeuvres (CSIR, 2000).

Static rollover threshold (SRT) refers to a measure used to describe the potential of a vehicle to roll over sideways when it experiences lateral acceleration (New Zealand Transport Agency, 2019). This measure therefore is related to a vehicles ability to resist lateral load transfer and as such has been included in this study. The values used were obtained from the PBS assessments conducted on each combination.

The CSIR, with support from other 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 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 safety through innovative and optimised vehicle design. PBS vehicles are designed to perform their tasks as productively and sustainably as possible, but at the same time ensuring acceptable 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 road wear impact analysis through the use of computer modelling. All PBS vehicles are required to perform less road wear per tonne of payload when considering the static assessment. As such it was decided to include both PBS and legal baseline vehicles in this study.

1.2 Aim

This paper is primarily aimed at investigating the influence that road crossfall has on the road wear caused by a heavy vehicle, as compared with static road wear assessments. A simplified method was selected to provide an easy to understand overview of general observations. The method selected uses computer software to simulate the dynamic axle loads of a select set of heavy vehicles on a given road profile. The RMS value of axle loads are used as representative quasi-static loads to be used in the road wear calculations. The road wear is then calculated using mePADS.

1.3 Scope

A total of eight vehicles were studied - four PBS and four baseline vehicles from the timber, fuel, mineral side tipper and general freight tautliner transport sectors. A single, road profile for a straight road was considered (the National Transport Commission of Australia road profile as used to determine tracking ability on a straight path) and a constant operating speed of 80km/h. The road wear was calculated using the mechanistic empirical method as packaged in the mePADS software. The RMS values of the axle loads were used to perform the road wear assessments. The vehicle simulations were performed using the TruckSim® 2019 multibody dynamics software package. Eight common road pavements, as used for PBS road infrastructure assessments, were used in this study and an unweighted average of these pavements was determined. Uniform circular road-tyre contact patch stresses were assumed.

2. METHOD

Eight heavy vehicles as described in the scope were considered. A PBS and a representative standard baseline vehicle from each were selected in order to compare the trends of PBS and baseline vehicles during this study. The eight vehicle configurations are shown in Figure 1. The vehicles were simulated using the TruckSim 2019 multibody vehicle dynamics software package. All essential parameters of the heavy vehicles were included as obtained from the trailer manufacturers and truck-tractor manufacturers. This includes the positions of tyres, sprung and unsprung masses and their centre of gravity (CoG) locations, and the stiffness and damping values of the springs and dampers. All simulations were done with a sampling rate of 2 000 Hz in order to ensure a high degree of accuracy of the calculated dynamic axle loads.

All PBS road wear comparison studies use eight typical pavements encountered in South Africa. These eight pavements have been used in this study and an average value was taken over all the pavements. The average LEF value between wet and dry conditions was used.

Suitable tyre models were needed to calculate the uniform stress produced by heavy vehicle tyres at various loads. Constant tyre inflation pressures were assumed, namely 800 kPa for 385 and 425 tyres, and 700 kPa for all other tyres in line with the recommended tyre inflation pressures from tyre manufacturers. The equivalent circular uniform tyre-road contact stresses at the various loads were estimated using the stress-in-motion data captured from the stress-in-motion system (SIM) as developed by the CSIR (Maina, De Beer, & Van Rensburg, 2013). Polynomial regression models were developed to estimate the equivalent circular uniform contact stress at various loads. The polynomial equations produced average absolute errors less than 1% compared to the SIM measurements.

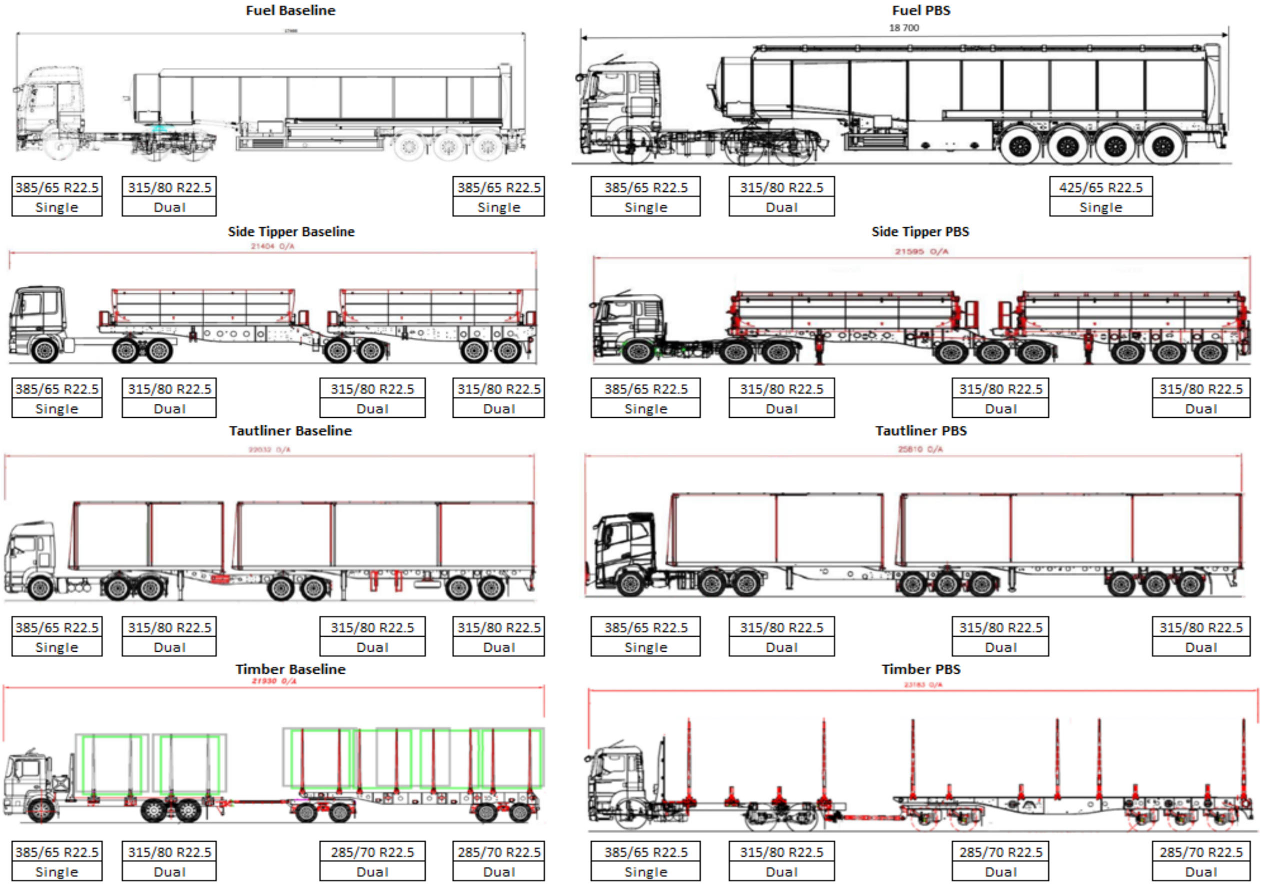

Figure 1: Vehicles used during the road crossfall study

The Australian National Transport Commission (NTC) road used is shown in Figure 2, with the profiles for both left and right wheel tracks indicated. All dynamic assessments were done at a constant speed of 80 km/h. No other speeds or road profiles were considered. The road section is defined over a 1km road section.

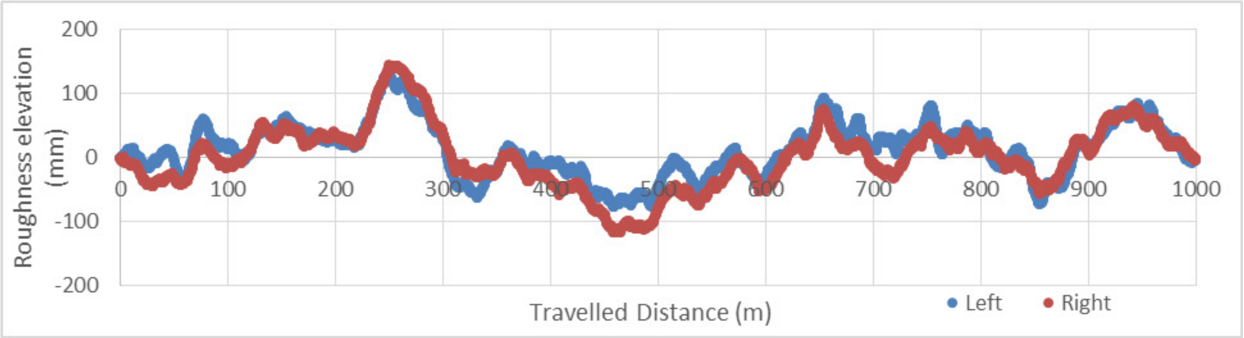

Figure 2: NTC road profile elevation

The average crossfall values were varied from 0% to 5%. The static axle loads were obtained from GA drawings provided by the trailer manufacturers, and dynamic axle loads were obtained from TruckSim®.

For all dynamic manoeuvres, the RMS (root-mean squared) values of the axle loads were calculated for the left and right wheel tracks of each axle. The RMS value was selected as it provides a slightly more weighted value to account for the higher peak loads that cause more road wear. The RMS values are also to be compared to the average values.

In the case of dual tyres, the assumption was made that the axle load on each side of the vehicle is shared equally in order to simplify the first iteration of this analysis.

The mePADS software (De Beer, Sallie, Van Rensburg, & Kemp, 2009) assumes that a vehicle is symmetrically loaded on the left and right side and therefore only uses the loads on the left side of the vehicle during the assessment. As such mePADS assessments had to be done separately for each side of the axles.

3. RESULTS AND DISCUSSION

3.1 Heavy vehicle loads

In order to understand the road wear caused by a heavy vehicle, one first needs to investigate the axle loads and their variation with travelling distance. Figure 3 provides an example of the variation of the left steer axle load of the timber baseline vehicle over the first 100m of the travel distance. As seen, the highest and lowest measured values can differ by more than 50%. As indicated in the method section, the RMS value for all axle loads on the left and right sides were calculated to provide a slightly weighted average value to account for the higher damaging effect of the higher peak loads. It was however found that the average and RMS values were typically within 2% of one another, with the RMS values always being higher.

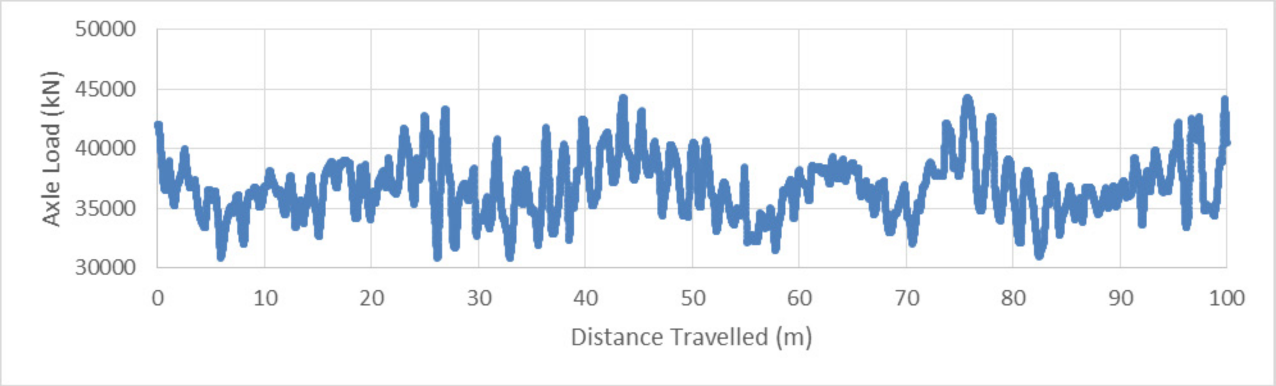

Figure 3: Fuel Baseline left steer axle load at 0% crossfall

When considering the RMS values of the axle loads on either side of the vehicles, it was observed that a near perfect linear correlation exists between the change in the total RMS load and the crossfall as shown in Figure 4. As indicated, as the crossfall increases, the load on the left side increases whilst the load on the right side decreases. This trend was observed for all vehicles and also holds true when considering individual axles.

It was observed that at a crossfall value of 0%, the left side wheel loads were always lower than the right side loads. This variation is due to the location of the driver and heavy vehicle fuel tanks, which are both placed on the right side of the vehicles and cause a rolling effect to be introduced. The variation of the left and right side loads at 0% crossfall was typically around 3-5%. With all vehicle combinations and individual axles, it was found that at 1% crossfall, the loads on either side of the vehicle or individual axles were almost equal.

When plotting the static roll over threshold (SRT) of each combination (as obtained from the PBS reports of each vehicle combination) against the percentage load transfer per percentage change in the crossfall, it was found that a strong negative correlation exists. This is shown in Figure 5. This trend is logical as vehicles with higher SRT values are more stable and less likely to roll over and hence will have a lower transfer of load during rolling manoeuvres. SRT can therefore be used as an indicator of a vehicles load transfer resistance with increases in road crossfall.

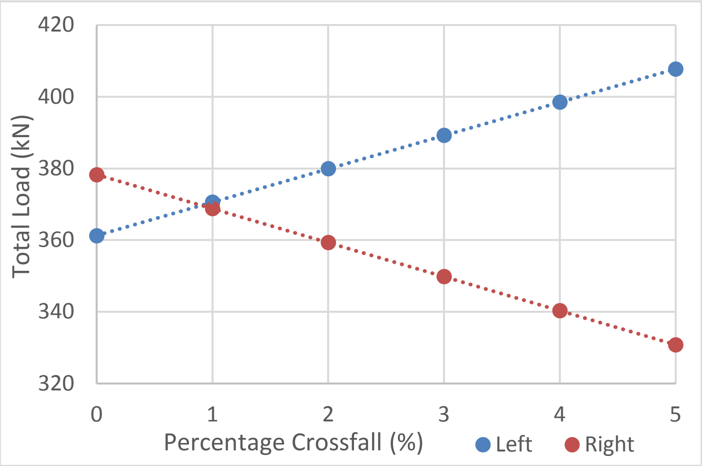

Figure 4: Total load on both sides of timber PBS vehicle at various crossfall values

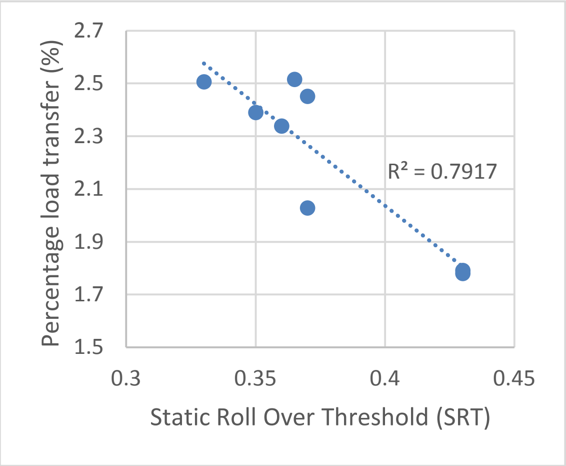

Figure 5: Percentage load transfer at 1% crossfall vs vehicle SRT

All of the LEFs of the studied vehicles are summarised in Table 1. From this data, a few general trends can be observed. The first is that as the crossfall value increases, the left side LEF values increase whilst the right side decrease. In reality, both of these trends follow a near perfect linear relationship as illustrated in Figure 6. This linear relationship holds true for all combinations and individual axles studied.

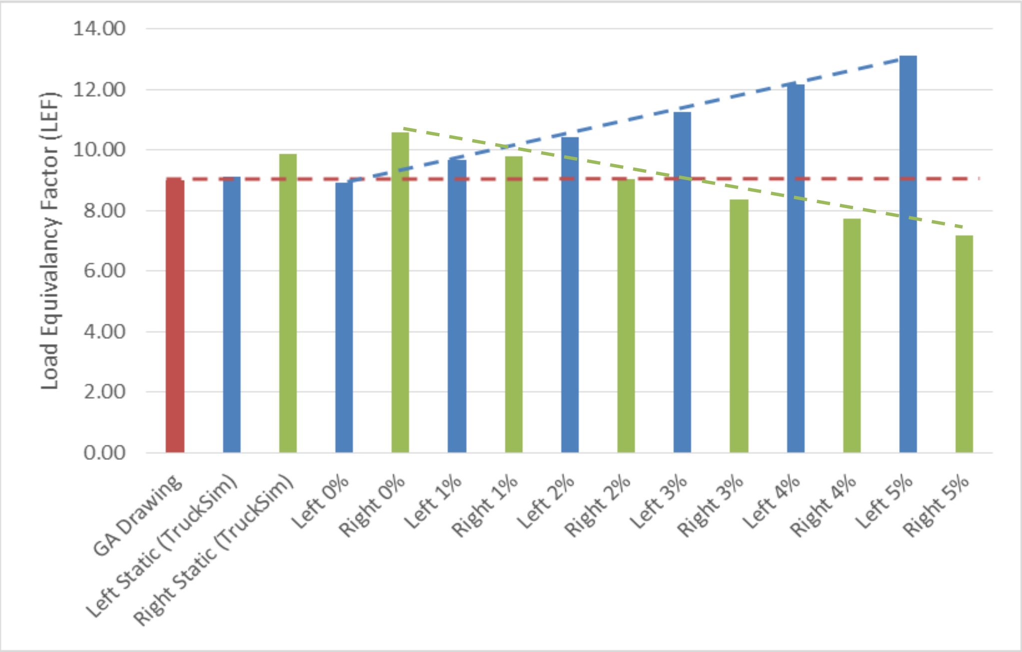

Figure 6: All LEF values for the PBS timber combination

Table 1: LEFs for all assessed vehicles

Tautliner Baseline LEFs						Tautliner PBS LEFs				
	Average LEF Left	Percentage Difference relative to GA Drawing	Average LEF Right	Percentage Difference relative to GA Drawing	Percentage difference between sides	Average LEF Left	Percentage Difference relative to GA Drawing	Average LEF Right	Percentage Difference relative to GA Drawing	Percentage difference between sides
GA Drawing	6.31		6.31		**0.0%**	7.73		7.73		**0%**
Static (TruckSim)	6.06	**-3.8%**	6.42	**1.8%**	**5.9%**	8.11	**5.0%**	8.33	**7.8%**	**2.7%**
0% Crossfall	5.91	**-6.2%**	6.78	**7.5%**	**14.7%**	7.91	**2.4%**	8.78	**13.6%**	**10.9%**
1% Crossfall	6.33	**0.3%**	6.33	**0.4%**	**0.1%**	8.44	**9.2%**	8.23	**6.5%**	**-2.5%**
2% Crossfall	6.77	**7.4%**	5.92	**-6.2%**	**-12.6%**	9.00	**16.5%**	7.71	**-0.2%**	**-14.3%**
3% Crossfall	7.24	**14.9%**	5.53	**-12.4%**	**-23.7%**	9.59	**24.2%**	7.23	**-6.4%**	**-24.6%**
4% Crossfall	7.75	**22.9%**	5.16	**-18.1%**	**-33.3%**	10.22	**32.3%**	6.78	**-12.2%**	**-33.7%**
5% Crossfall	8.28	**31.3%**	4.83	**-23.4%**	**-41.7%**	10.89	**40.9%**	6.36	**-17.7%**	**-41.6%**
Fuel Baseline LEFs						**Fuel PBS LEFs**				
GA Drawing	12.72		12.72		**0%**	15.73		15.73		**0%**
Static (TruckSim)	16.85	**32.4%**	18.30	**43.8%**	**8.6%**	19.63	**24.8%**	20.52	**30.5%**	**4.5%**
0% Crossfall	16.19	**27.2%**	19.30	**51.7%**	**19.2%**	18.92	**20.3%**	21.52	**36.9%**	**13.8%**
1% Crossfall	17.45	**37.2%**	17.89	**40.6%**	**2.5%**	20.34	**29.4%**	20.03	**27.4%**	**-1.5%**
2% Crossfall	18.81	**47.9%**	16.58	**30.3%**	**-11.9%**	21.83	**38.8%**	18.61	**18.4%**	**-14.7%**
3% Crossfall	20.27	**59.3%**	15.36	**20.8%**	**-24.2%**	23.38	**48.7%**	17.28	**9.9%**	**-26.1%**
4% Crossfall	21.83	**71.6%**	13.20	**3.8%**	**-39.5%**	24.97	**58.8%**	16.03	**1.9%**	**-35.8%**
5% Crossfall	23.48	**84.5%**	13.20	**3.8%**	**-43.8%**	26.58	**69.1%**	14.87	**-5.4%**	**-44.1%**
Side Tipper Baseline LEFs						**Side Tipper PBS LEFs**				
GA Drawing	6.58		6.58		**0%**	8.66		8.66		**0%**
Static (TruckSim)	5.91	**-10.2%**	6.26	**-4.8%**	**5.9%**	7.19	**-17.0%**	8.13	**-6.2%**	**13.0%**
0% Crossfall	5.82	**-11.6%**	6.59	**0.1%**	**13.2%**	7.58	**-12.4%**	8.63	**-0.4%**	**13.7%**
1% Crossfall	6.08	**-7.6%**	6.24	**-5.2%**	**2.6%**	8.09	**-6.6%**	8.09	**-6.6%**	**0.1%**
2% Crossfall	6.49	**-1.3%**	5.90	**-10.3%**	**-9.1%**	8.62	**-0.5%**	7.59	**-12.4%**	**-12.0%**
3% Crossfall	6.86	**4.2%**	5.58	**-15.2%**	**-18.6%**	9.19	**6.1%**	7.12	**-17.8%**	**-22.5%**
4% Crossfall	7.24	**10.0%**	5.28	**-19.7%**	**-27.1%**	9.79	**13.0%**	6.67	**-22.9%**	**-31.8%**
5% Crossfall	7.64	**16.1%**	5.00	**-24.1%**	**-34.6%**	10.42	**20.4%**	6.26	**-27.7%**	**-39.9%**
Timber Baseline LEFs						**Timber PBS LEFs**				
GA Drawing	7.16		7.16		**0%**	9.00		9.00		**0%**
Static (TruckSim)	7.50	**4.6%**	8.18	**14.2%**	**9.2%**	9.12	**1.3%**	9.86	**9.6%**	**8.2%**
0% Crossfall	7.38	**3.0%**	8.85	**23.5%**	**19.9%**	8.94	**-0.6%**	10.60	**17.8%**	**18.5%**
1% Crossfall	7.97	**11.3%**	8.18	**14.2%**	**2.6%**	9.66	**7.3%**	9.80	**8.9%**	**1.5%**
2% Crossfall	8.62	**20.3%**	7.56	**5.5%**	**-12.3%**	10.43	**15.9%**	9.06	**0.7%**	**-13.1%**
3% Crossfall	9.31	**30.0%**	6.99	**-2.4%**	**-24.9%**	11.26	**25.1%**	8.38	**-6.9%**	**-25.6%**
4% Crossfall	10.06	**40.4%**	6.46	**-9.8%**	**-35.8%**	12.16	**35.1%**	7.75	**-13.9%**	**-36.3%**
5% Crossfall	10.87	**51.7%**	5.97	**-16.6%**	**-45.0%**	13.12	**45.8%**	7.17	**-20.3%**	**-45.4%**

The magnitude of the variation between the road wear caused by the left side and right side exceeded initial expectations. The maximum calculated difference in road wear caused by the left and right side of a vehicle was 45.4% in the case of the PBS timber vehicle at a crossfall of 5%. In South Africa the majority of crossfall values are within the 2 to 3% range (CSIR, 2000). The minimum and maximum difference in road wear between the sides of a vehicle for 2% crossfall were calculated as 9.1% and 14.3% respectively. In the case of 3% crossfall these values increased to 18.6% and 26.1%. This illustrates that for general road operating conditions, crossfall has a significant influence on the amount of road wear caused by a heavy vehicle.

When comparing the road wear caused at various crossfall values to the static assessment of the vehicle combinations, it is clear that the dynamic road wear is considerably more than the static road wear. The maximum calculated difference between the static symmetrical analysis and dynamic analysis was 84.5% with the fuel baseline vehicle on the left side for a crossfall of 5%. The static analysis indicated the road wear was 12.72 LEFs, whilst at 5% crossfall the LEF on the left side was calculated as 23.48 LEFs. Once again, considering the typical 2% and 3% crossfall values, the maximum recorded difference in road wear from the static assessments was 47.9% and 59.3% respectively.

It was also observed that the road wear calculated using the GA drawing and the TruckSim® data on 0% crossfall was different. This is primarily due to the assumption made in the trailer manufacturer drawings that the axle loads are symmetrical. It was also expected that the trailer manufacturers may not be simulating the CoG heights of the payloads and components as accurately as is required during a PBS assessment. This implies that the loads will be distributed differently than when using a simple static equilibrium analysis.

Both the fuel baseline and PBS vehicles had the highest values of increased road wear, even though the load transfer values were lower due to the increased SRT values. The main reason for this is the use of single tyres on the fuel trailers which produce higher road-tyre contact stresses. Due to the 4th power nature of road wear, small increases in the contact stresses can have a large increase in road wear. It is therefore important that the correct tyre sizes and tyre inflation pressures be used on all combinations.

4. CONCLUSION

From the results, it is clear that road crossfall and the resultant lateral load transfer of heavy vehicles cannot be ignored when conducting road wear calculations. Small variations in road crossfall will result in a notable change in the load transferred to the left side of the vehicle (in the case of South African roads). Due to the exponential nature of road wear, these increases in loads on the leftside wheel will produce substantially higher road wear factors. This is especially true in the case of vehicles that have single tyres configurations instead of duals.

It is also clear that even with zero crossfall, there are variations between the left side and right side road wear factors calculated. Therefore, the assumption of symmetrical loading during road wear calculations severely limits the accuracy of this type of assessment.

5. RECOMMENDATIONS

Although this study has provided insights into the effect that road crossfall has on road wear caused by heavy vehicles, several simplifying assumptions have been made that should be tested in future work.

Firstly, the difference in the loading of inner and outer tyres in a dual tyre configuration should be considered. Results from simulations indicated that these values can differ by more than 50% and would therefore have an effect on the calculated road wear.

Future work can also include varying vehicle speeds and road roughness in order to create more realistic operating conditions and will produce more accurate results.

Varying tyre inflation pressures (i.e. vertical contact stress) can also be included, especially when considering the difference in inner and outer tyre loads with dual tyre configurations. Equally important is developing more complex road-tyre contact stress distributions and incorporating these non-uniform contact stresses into road wear simulations. This is of particular interest at higher tyre loads as would be experienced during dynamic manoeuvres.

A more detailed study could also investigate the cumulative wear caused at each point on a specific road section. This will however be significantly more computationally intensive, but would provide an invaluable understanding of the peak loads and subsequent road wear caused by heavy vehicles under various operating conditions. It is expected that this assessment method would provide valuable insights into the peak loads produced by vehicles and illustrate that air suspension and well damped vehicles produce less wear than steel suspension and poorly damped vehicles.

Physical field-testing and validation of the simulations would also be desirable. A first iteration of testing could be done using the HVS and building road sections with various average crossfall values. Another possibility is to rig strain gauges or load cells to heavy vehicles and measure the wheel loads over various road sections with varying average crossfall values. Of especial interest would be to determine if road wear and failure does occur more on the left side of the road as is predicted with the simulation used in this study.

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