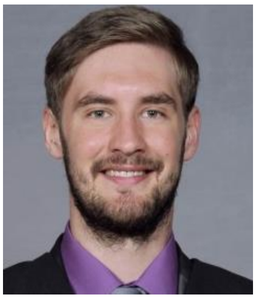
METHODOLOGY FOR ESTIMATING THE ROAD WEAR COST OF HEAVY VEHICLES ON A ROAD NETWORK



L. KEMP
CSIR Built Environment Transport Systems and Operations Graduate of the University of Pretoria Civil Engineering, 2016. Currently she is enrolled for BEng Honours Transportation Engineering at the University of Pretoria.

A.J. STEENKAMP
Mechanical Engineering graduate of the University of Johannesburg. Currently involved with the PBS project in South Africa performing road and bridge impact analyses and monitoring the PBS fleet. He is also an MSc (Eng) candidate at Wits looking at the business case for RTMS/PBS.

P NORDENGEN
Principal Researcher at the CSIR. Obtained his PhD in the area of PBS for heavy vehicles in 2013. He has been involved in the development of various infrastructure asset management systems in various countries in Africa. IFRTT Board Member and Past-President.

Abstract

Heavy vehicle traffic volumes continue to increase globally, causing the accelerated deterioration of pavement structures. This paper introduces an innovative methodology that quantifies road consumption attributed to heavy vehicles on a paved road network. This methodology combines weighbridge and traffic count data and uses Mechanistic Empirical methods for accurate estimations of road wear. Polynomial regression models were developed to reduce simulation times and to accurately predict the road wear caused by different heavy vehicle configurations. The reduction in analysis time enables parametric studies to be conducted that can provide useful insights into the interplay and relative importance of various parameters. Road wear is converted to a monetary value, giving useful insights for infrastructure management, spatial planning, funding and maintenance, and will help with decision-making in this regard. This methodology is registered as a CSIR Technology Demonstrator Tool and Namibia has incorporated this in their asset management strategy.

Keywords: Heavy vehicles, road wear, cost estimation, pavement and bridge loading, lifecycle management

1. Introduction

Transport logistics are one of the key aspects of any economy and, according to the latest Logistics Barometer, constitute 11.8% of South Africa's GDP. In South Africa, approximately 85% of freight is transported by road (Havenga, et al., 2016). The ever-expanding fleet of heavy vehicles, particularly those that are illegally overloaded, has a significant impact on the road and bridge infrastructure. The value of the paved road network in South Africa is estimated to be approximately $160 billion, and represents one of the country's most important assets. South Africa has a road maintenance backlog of R15.8 billion, which has led to a national network where currently 78% of the roads are older than their intended design life. 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 damage caused (Krygsman & Van Rensburg, 2017). In order to minimize this pavement damage, one requires a detailed understanding of the parameters that influence its life and required maintenance.

The accurate quantification of road wear is a challenging task, with many unresolved questions: How best can infrastructure deterioration caused by heavy vehicle traffic be quantified? How will different parameters from both a vehicle dynamic and pavement design perspective influence this road wear? Are current maintenance plans and infrastructure management strategies sufficient and do they aim to protect a hundred billion Dollar road network asset? Is it possible to develop fair and efficient road user charges based on actual road consumption caused by individual vehicles?

This paper introduces a newly developed methodology that aims to quantify road wear attributed to heavy vehicles on an entire road network. This methodology uses mechanistic empirical methods and allows for the accurate estimation of road wear. The methodology does not rely on generalizations such as, "an average heavy vehicle," or, "traffic growth factors," but accurately models heavy vehicle traffic with different configurations and axle masses based on weighbridge and traffic count data. The methodology takes into account climatic conditions, different pavement structure designs and various vehicle configurations.

Simulation times were impractical when simulating all of the representative vehicles recorded at the weighbridges. Polynomial regression models were developed to accurately predict the road wear caused by different heavy vehicle configurations. The reduction in analysis time allows sensitivity analyses to be performed on various vehicle dynamic and pavement structure variations, and provides a confidence interval of the calculated cost of road wear. By converting this quantified road wear to a monetary value gives insights for infrastructure management, spatial planning, funding and maintenance activities.

The methodology is still in its infancy, but with sufficient development can become a valuable tool. This will include determining fair road user fees, studying the relative impact of various vehicle parameters, quantify the effects of overloading and allowing roads authorities to design and maintain the road network based on the actual demand created by the actual operational vehicles and is adaptable to any country's road network specific conditions.

2. Background

A road pavement, like any engineering structure, is designed to withstand certain loads. In the case of a road pavement, the primary load that has to be withstood is the vehicle traffic spectrum operating on it. The traffic spectrum consists of all the individual axle loads that will travel over the road during its design life. The critical variables which affect pavement wear are tyre contact patch pressures, tyre configuration and tyre inflation pressures (J. Granlund, 2017).

Individual axle loads can vary from axles with single wheels on light motor vehicles to axles with dual wheels on heavy vehicles. For pavement design purposes, the traffic spectrum is converted to an equivalent number of standard axles. The Standard Axle (SA) in South Africa is defined as a single axle with dual wheels, with a mass of 8 200 kg, which equates to a weight of 80 kN.

A pavement is designed to have a specific bearing capacity, which is expressed in terms of the number of SA load repetitions that will result in a certain condition of deterioration (i.e. to the point where the pavement has “structurally” failed). The bearing capacity of the road, expressed as a number of SAs, must be equal to or higher than the number of Equivalent Standard Axles (ESAs) representing the traffic spectrum that the road has to carry. An ESA is commonly referred to as an E80, i.e. an Equivalent 80 kN axle.

To convert the traffic spectrum to ESAs, load equivalency factors (LEF) are calculated, which relate the number of repetitions of a given axle load (that will cause the pavement to reach a certain condition of deterioration) to the number of repetitions of SAs that will cause the pavement to reach the same condition of deterioration.

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 follows (NAS-NRC, 1962):

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

where: LEF = Load Equivalency Factor;
P = Axle load in kN;
n = relative damage exponent; and
80 = the weight of a Standard Axle in kN.

The relative damage 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, et al., 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. Also, many of the datasets developed are severely outdated and are no longer relevant to the 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 correct (J. Granlund, 2017).

In this paper, 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, et al., 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.

To precisely quantify the road damage caused by an entire fleet, one would need to know the configuration and load conditions of every vehicle, the distance travelled by each vehicle and the condition of the road at each point. With current information and technology this is not feasible. The methodology uses weighbridge and traffic count data as inputs to calculate heavy vehicle traffic volumes, heavy vehicle types, axle loads per vehicle, and total vehicle masses. This information is then used together with pavement structure data and climatic conditions to calculate LEFs. Polynomial regression models were constructed to accurately estimate LEF values for the most common heavy vehicle combinations, and the influence of different parameters were investigated. Currently only the most important parameters are considered in this regression model, namely axle loads, inflation pressures and tyre width. This addresses concerns and errors in the assumptions made in the 4th Power Law analysis, making this newly-developed methodology more reliable and realistic.

3. Input Data

A case study was conducted in Namibia, using 2015 data obtained for the Namibian paved road network and using Namibian conditions for the specific year. However, the methodology can be adjusted to model any country’s heavy vehicle traffic volumes and designs, pavement structures and climatic conditions, given the appropriate data.

3.1 Paved Road Network

A paved road network needs to be identified and data for each uniform section should be obtained from the relevant roads authority including weighbridge, traffic count and pavement structure data.

Namibia has 10 weighbridge facilities and 50 traffic count stations covering the entire paved trunk road network.

3.2 Pavement data

Different pavement structures and corresponding properties for the network are required. Assumptions in this regard can be made to simplify analyses by only using the most representative pavement structures, covering the majority of the network. For Namibia, 12 pavement structures were identified and built into the mePADS software with corresponding critical properties: layer thicknesses, Poison’s Ratios and elastic moduli. At this stage, the methodology assumes a newly-built road. In future, determining the current condition of the road by use of visual inspections will add to the accuracy of results, and could possibly be carried out autonomously. This is however considered and taken into account in the various costing models explained in Section 4.3.

3.3 Climatic conditions

Pavement structure behaviour and bearing capacity are sensitive to climatic conditions. The mePADS software allows for the analysis of pavement performance in wet and dry climatic conditions by converting dry pavement properties to wet pavement properties. Namibia is a relatively dry country, with the highest rainfall in the northern parts of the country. A ratio of 90:10 for dry and wet states was recommended to represent the Namibian climatic conditions. The condition of the road surfacing layer contributes to the wet and dry ratio. The wet and dry condition of a road is not only a function of the rainfall of a region, but also a function of the extent to which moisture infiltrates the base and subbase layers.

3.4 Heavy vehicle traffic volumes

Weighbridge data were used to identify the mass distribution of the most common heavy vehicle configurations. At the Namibian weighbridge facilities, approximately 300,000 vehicles are weighed each year, giving a representative indication of the mass distribution of heavy vehicles on the network as shown in Figure 3-1. A uniform mass distribution for each mass interval for all the weighbridge across the paved network is assumed for each of the different vehicle configurations.

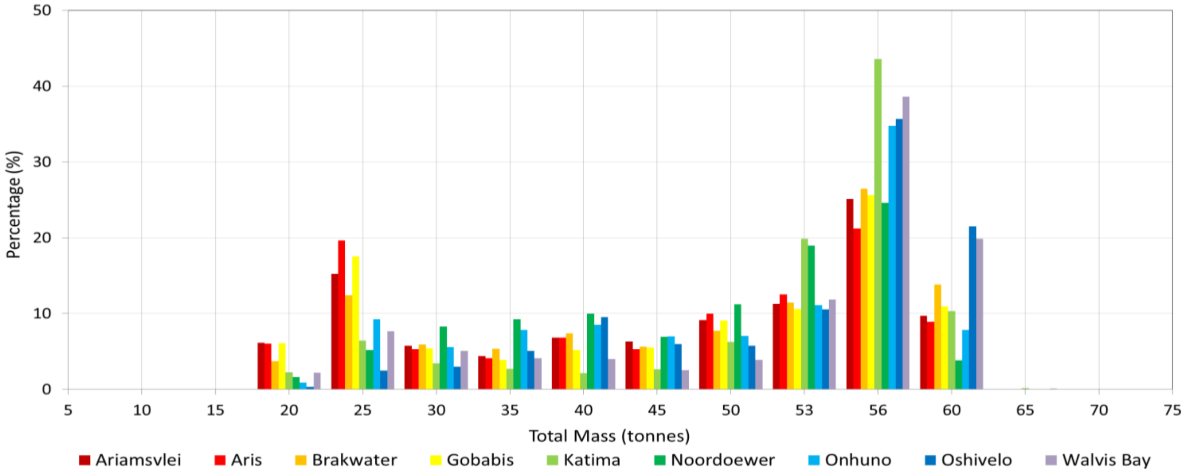


Figure 3-1: Mass distribution of 1222 vehicles at different weighbridge facilities

Namibian traffic count data classify heavy vehicles according to overall length as “Short” (4 to 10.8 m), “Medium” (10.8 to 16.8 m), and “Long” (longer than 16.8 m). The percentage distribution of these classifications were quantified for each section of the road network. In order to link traffic count and weighbridge data, the ten most common vehicle configurations, comprising 97% of all the heavy vehicles, were allocated to the three traffic count categories. In order to determine the number of vehicles per configuration per road section, the percentage split at the traffic count stations was used to distribute the heavy vehicle traffic in terms of “Short”, “Medium” and “Long” vehicles for each road section. The number of vehicles per traffic count class was then allocated to the vehicle configurations per class according to the distribution of heavy vehicle configurations derived from the weighbridge data. In future, accuracy could be improved using weigh-in-motion data, which would produce less biased results and also provide a much larger data set.

3.5 Heavy vehicle designs

The mePADS software analyses a complete vehicle at a time, requiring the longitudinal and lateral positions of all wheels on the vehicle. General arrangement drawings were obtained from trailer manufacturers in order to model the representative vehicles.

The wheelbase lengths of individual vehicles can differ from those of the representative vehicles and the sensitivity of the calculated LEFs to wheelbase lengths was therefore tested. **Error! Reference source not found.** illustrates the variation in the average LEF of a vehicle on all the pavements considered for a range of wheelbases. A variation in the wheelbase from 3 m to 10 m, representing a 333% increase in length, resulted in a change in the vehicle's LEF of only 1.2% indicating a negligible effect. From simulations using mePADS, it was evident that differences in wheelbases have a minimal effect on the road wear effect of a vehicle.

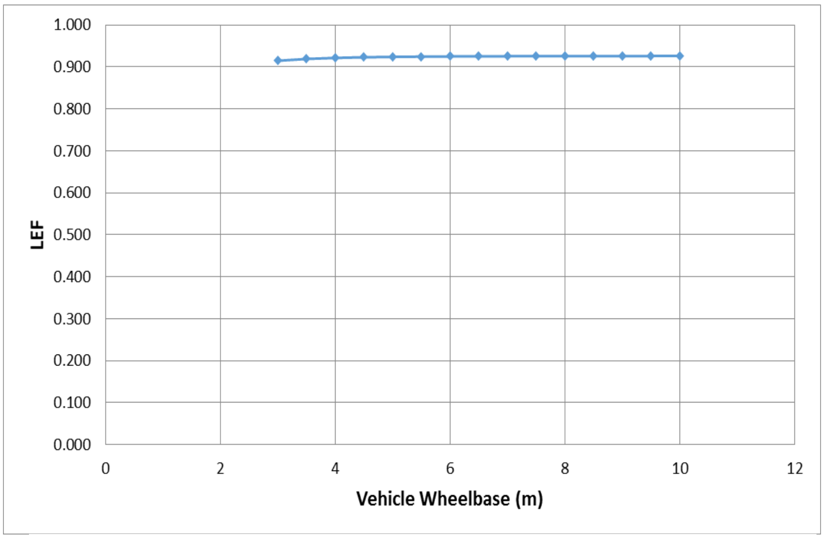


Figure 3-2: Average LEF at different wheelbase lengths

Table 3-1: Tyres used on vehicle configurations

Vehicle Class	Steer Axle(s)	Drive Axle(s)	Trailer Axle(s)
11	11R22.5	11R22.5	N/A
12	315/80R22.5	315/80R22.5	N/A
22	315/80R22.5	315/80R22.5	N/A
112	315/80R22.5	315/80R22.5	315/80R22.5
122	315/80R22.5	315/80R22.5	315/80R22.5
123	315/80R22.5	315/80R22.5	315/80R22.5
1121	315/80R22.5	315/80R22.5	11R22.5
1211	315/80R22.5	315/80R22.5	315/80R22.5
1222	315/80R22.5	315/80R22.5	315/80R22.5
12211	315/80R22.5	315/80R22.5	315/80R22.5

For simplification, tyre sizes and inflation pressures were kept constant for each configuration. This was based on surveys conducted on a sample group of operators in South Africa. Table 3-1 indicates typical tyre sizes used per vehicle class. An average tyre inflation pressure of

700 kPa was used. The influence of different tyre inflation pressures can be determined using this methodology and is included in the scope for future research.

4. Methodology

The proposed methodology for estimating the road wear costs of heavy vehicles on a road network can be summarized as follow and more details will be discussed in the subsequent sections:

1. Identify the most common vehicle classes to be analysed using weighbridge data.
2. Determine the mass distributions of these vehicle classes using weighbridge data.
3. Identify the different pavement structures present on the paved road network and select a representative sample of these.
4. For each vehicle class identified in step 1, calculate the “pavement life” under each axle of the vehicle using the mass distributions from step 2 for each of the pavement structures identified in step 3. Calculate the total “life” of each layer in the pavement under static loading conditions and by using the critical layer life (i.e. the particular layer with the shortest life) as the pavement life.
5. For each of the pavement structures identified in step 3, calculate the bearing capacity of the pavement in terms of the number of Standard Axles.
6. Calculate the LEFs for all the vehicle classes and pavement structures as the sum of the ratios (for all axles of a particular vehicle class) between the bearing capacity of the pavement as determined in step 5 and the critical layer life as determined in step 4 using the mass distributions from step 2.
7. Construct polynomial regression models to accurately estimate LEF values for all the combinations of vehicles classes, pavement structures and mass distributions.
8. Calculate the total projected cost per kilometre for each pavement structure identified in step 3, which include the construction costs and maintenance over the design life of 25 years.
9. Calculate the cost per Standard Axle-lane-km for each pavement structure by dividing the total projected cost per kilometre calculated in step 8, by the pavement’s bearing capacity in SAs, calculated in step 5.
10. Estimate the number of heavy vehicles per vehicle class on each link of paved network, using traffic count data.
11. Multiply the LEFs per vehicle class and pavement structure determined in step 7 with the number of heavy vehicles estimated in step 10 and with the total road length per link and add these all up to arrive at the cost of road wear caused by heavy vehicles on the paved road network.

4.1 Road wear quantification

The methodology involves the use of the CSIR’s Mechanistic Empirical Pavement Analysis & Design Software package mePADS (De Beer, et al., 2009). As explained in Section 2, the software calculates road wear by determining a Load Equivalency Factor (LEF) for a vehicle combination and pavement structure with a set of specified design inputs. The LEF expresses the road wear caused by a vehicle in terms of the number of Standard Axles that would cause the same quantity of road wear. The mePADS software is based on the South African pavement design manual, TRH4 (DoT, 1996).

4.2 Polynomial regression models

Using mePADS and the combined annual weighbridge and traffic data results in hundreds of thousands of different vehicle records and entries, each with a unique data set (tyres, dimensions, axle configuration, axle mass, etc.). Using mePADS, this would result in an impractically large analysis time. It was found that linear polynomial regression produced a sufficiently accurate model that can estimate the LEF value of vehicles based on their axle loads. These models significantly reduce the computation time, allowing for more accurate estimation of the LEF per vehicle actually measured at the weighbridges.

By sampling weighbridge data for different vehicle configurations, each with a variance in axle mass, and calculating the corresponding LEF, polynomial regression equations can be fit to the graph trends when plotting the combined actual mass vs LEF. Polynomial regression models were constructed for each of the different vehicle configurations and for all the different pavement structures in wet and dry climatic conditions. Using these equations, the LEF for all vehicles on the entire network can accurately be predicted.

The error for vehicles not included in the developed road wear prediction model, is small. For example, 50 random vehicles were sampled from the 1222 vehicle configuration set and it was found that the average absolute error for this vehicle configuration on a specific pavement was 0.3% as shown in Figure 4-1.

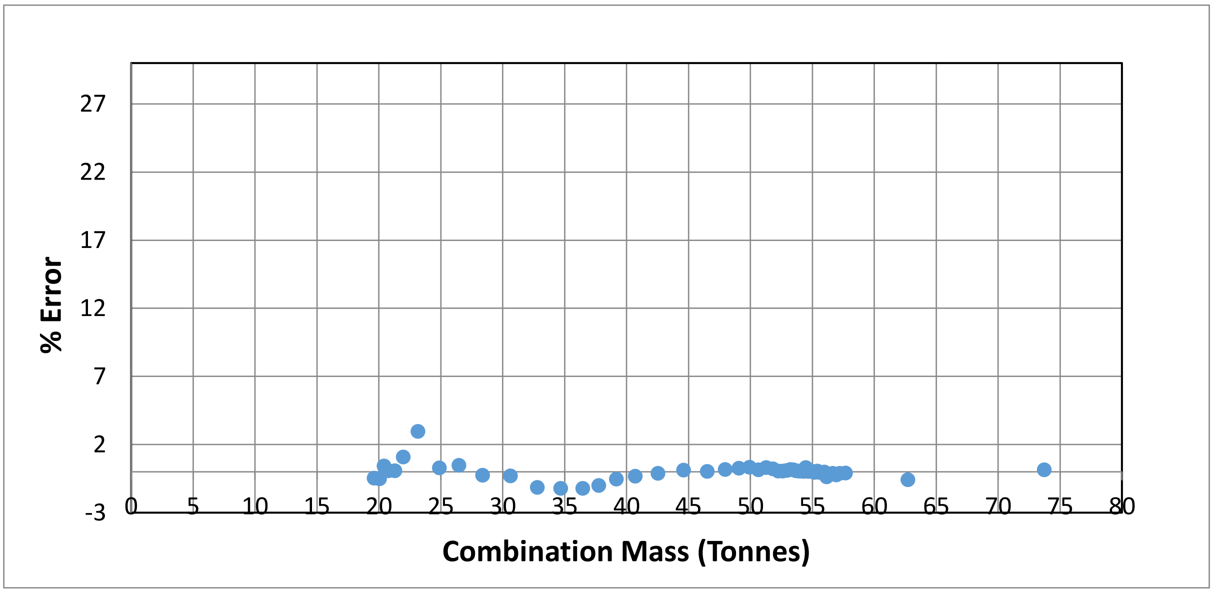


Figure 4-1: Error in calculated LEF for 50 random sampled vehicles

4.3 Unit costs estimation

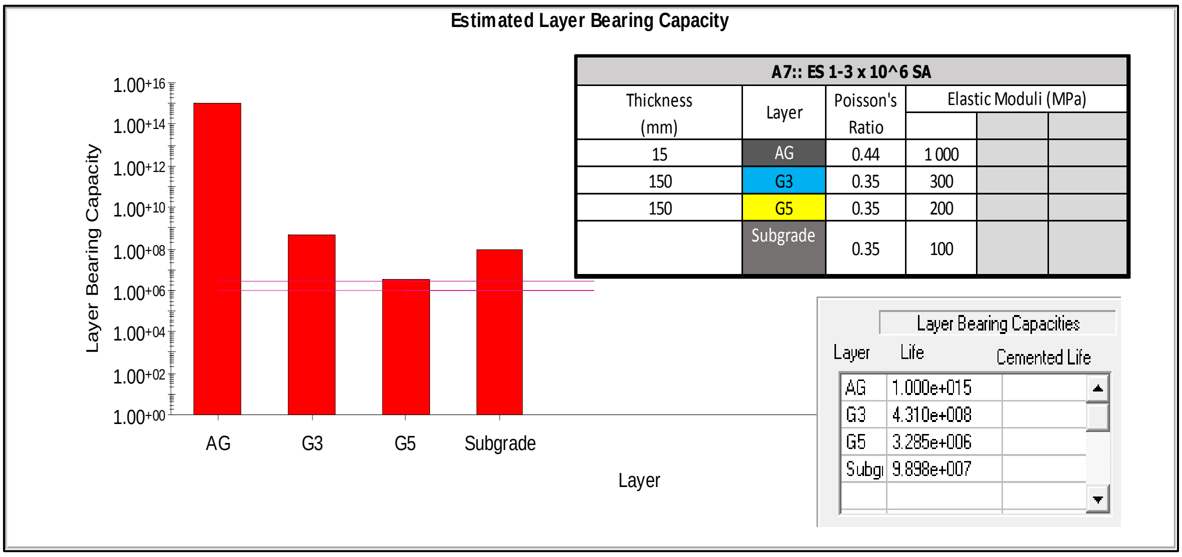
In order to convert all the heavy vehicle standard axles to a monetary value, a unit cost per standard axle per kilometre travelled is required. The cost of a pavement structure is calculated using the Present Worth of Cost (PWOC) method, as described in TRH4 and shown in Figure 4-2.

$$POWC = C + (M_1(1 + r)^{-X1} + \ldots + M_j(1 + r)^{-Xj} – S(1 + r)^{-z}$$

Where: PWOC = present worth of costs
C = present cost of initial construction
Mj = cost of the j^{th} maintenance measure expressed in terms of current costs
r = real discount rate
Xj = number fo years from the present to the j^{th} maintenance measure, with in the analysis period (where $x_1 = 1$ to z)
z = analysis period
S = salvage value of pavement at the end of the analysis period expressed in terms of present values

Figure 4-2: Present worth of cost

The mePADS software calculates the bearing capacity (the number of Standard Axle repetitions each layer of the specified pavement structure can endure before failure) and includes pavement life predictions. The estimated bearing capacity for each pavement structure is determined based on the layer with the lowest life LEF as shown in Figure 4-3.



Estimated Layer Bearing Capacity

A7:: ES 1-3 x 10^6 SA

Thickness (mm)	Layer	Poisson's Ratio	Elastic Moduli (MPa)		
15	AG	0.44	1 000		
150	G3	0.35	300		
150	G5	0.35	200		
	Subgrade	0.35	100		

Layer Bearing Capacities

Layer	Life	Cemented Life
AG	1.000e+015	
G3	4.310e+008	
G5	3.285e+006	
Subg	9.898e+007	

Figure 4-3: Pavement structure and layer bearing capacities

By dividing the PWOC by the bearing capacity, a unit cost per LEF can be determined for each of the different pavement structures. Examples of this calculation for a pavement consisting of cement stabilized and granular layers, are presented in Figure 4-5. These costs are for a single 3.7 m lane with a 1 m shoulder.

A number of cost options were developed, each option including different layers of the pavement structure as shown in Figure 4-4. This represents the total projected cost of a road, including construction and maintenance costs over the design life of the road. The construction cost assigned to the pavements, using the most conservative cost scenario (Option 1), which includes all the pavement structure layers, is shown in Figure 4-5 with the unit cost in Namibian Dollars. Option 2 with combination dry and wet ratio 90:10, was selected as the recommended costing approach by Namibia Roads Authority, which includes the construction and maintenance costs of the following pavement layers: surfacing, base, subbase and selected layers.

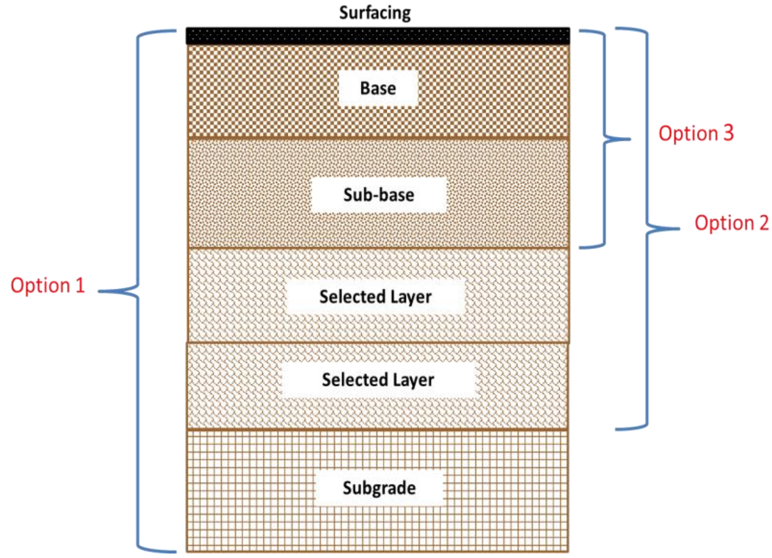
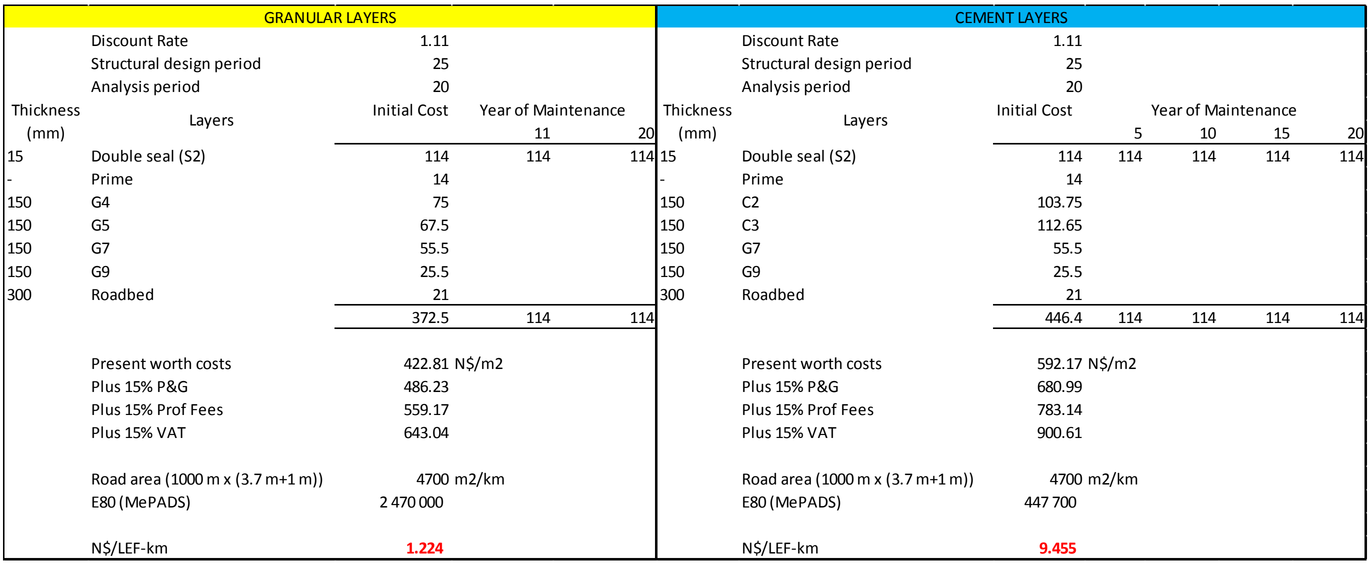


Figure 4-5: Pavement structure



GRANULAR LAYERS				
	Discount Rate	1.11		
	Structural design period	25		
	Analysis period	20		
Thickness (mm)	Layers	Initial Cost	Year of Maintenance	
			11	20
15	Double seal (S2)	114	114	114
-	Prime	14		
150	G4	75		
150	G5	67.5		
150	G7	55.5		
150	G9	25.5		
300	Roadbed	21		
		372.5	114	114
	Present worth costs	422.81	N$/m2	
	Plus 15% P&G	486.23		
	Plus 15% Prof Fees	559.17		
	Plus 15% VAT	643.04		
	Road area (1000 m x (3.7 m+1 m))	4700	m2/km	
	E80 (MePADS)	2 470 000		
	N$/LEF-km	1.224		

CEMENT LAYERS						
	Discount Rate	1.11				
	Structural design period	25				
	Analysis period	20				
Thickness (mm)	Layers	Initial Cost	Year of Maintenance			
			5	10	15	20
15	Double seal (S2)	114	114	114	114	114
-	Prime	14				
150	C2	103.75				
150	C3	112.65				
150	G7	55.5				
150	G9	25.5				
300	Roadbed	21				
		446.4	114	114	114	114
	Present worth costs	592.17	N$/m2			
	Plus 15% P&G	680.99				
	Plus 15% Prof Fees	783.14				
	Plus 15% VAT	900.61				
	Road area (1000 m x (3.7 m+1 m))	4700	m2/km			
	E80 (MePADS)	447 700				
	N$/LEF-km	9.455				

Figure 4-4: Unit cost estimaation for pavements with cement stabilized and granular layers

4.4 Road wear cost estimation

The estimated annual cost of road wear per road section, attributed to all heavy vehicles driving on the section in a year was calculated by multiplying the average number of LEFs per vehicle class with the LEF unit cost (N$/LEF-km) for each of the pavement section and the heavy vehicle kilometres travelled by each type of vehicle configuration on that section of the road. The total estimated annual cost of road wear for the entire paved road network was then calculated as the sum of the road wear cost for all the road sections.

The road wear cost of overloaded heavy vehicles can be calculated using the same methodology. Overloaded vehicles were identified based on their actual and permissible axle masses and their overall combination mass. The number of vehicles responsible for overloading can be quantified and the equivalent cost if they were to be legally loaded. The total number of overloaded vehicle kilometres travelled can then be multiplied by the same corresponding unit cost associated with the specific pavement, but multiplied by the LEF for a legal vehicle. This cost, which represents the road wear that would have been caused if these vehicles were legally loaded, is then subtracted from the actual overloaded road wear cost in order to quantify the cost of road wear due to the overloads.

5. Conclusions and Discussions

Heavy vehicle volumes have continued to increase significantly during the past decade, causing high levels of road wear. Overloading of these vehicles has been identified as one of the primacy areas that require urgent attention for the purpose of reducing the deterioration of road networks. From an infrastructure management and spatial planning, funding and maintenance perspective, it is important to quantify road wear and accurately determine the cost related to the heavy vehicles on our roads.

The mechanistic empirical methodology allows for accurate estimations of the road wear caused by heavy vehicles. Simulation times are however fairly long and it is impractical to simulate all of the vehicles recorded at the weighbridges. Preliminary polynomial models have been developed that accurately predict the road wear caused by different heavy vehicle configurations on different pavement types. The reduced analysis time, enables variance in vehicle design inputs for different heavy vehicle configurations and allows sensitivity analysis to be performed. This provides a confidence interval of the calculated cost of road wear in terms of vehicle type, tyre size and pressure, vehicle dimensions, different pavement structures, cost per LEF/km, wet and dry conditions, etc.

6. Recommendations and Way Forward

The methodology discussed in this paper delivers accurate estimates for determining the road pavement wear and associated cost caused by an entire heavy vehicle fleet on a paved road network. The methodology is however still new and there are various improvements that are being developed to improve accuracy.

The first recommendation is to include a more recent mechanistic empirical software package in this simulation suite. The CSIR is developing the meCRAMES software package that is able to use non-circular pressure distributions when performing an assessment, which will improve the modelling accuracy. This software package also contains additional updated transfers functions and test data.

Future investigations of this nature should ideally use weigh-in-motion data in order to obtain a more detailed and representative dataset of heavy vehicle axle masses. It is expected that the use of weighbridge data alone skews the analysis, thereby producing higher calculated pavement wear results. This is due to the fact that weighbridge stations often weigh the heavy vehicles that appear to be overloaded resulting in a bias in the data distribution.

It is also recommended that higher axle loads and other vehicle tyre parameters be included in the analyses such as a wider range of tyres, tyre inflation pressures and even possibly tyre tread patterns. This will however require significant additional heavy vehicle tyres testing. The CSIR is currently investigating the feasibility of such a tyre testing program. Alternatively, test data could be obtained from tyre manufacturers which would allow for even more detailed studies to be conducted. Many manufacturers are however reluctant to disclose such information

One parameter that the CSIR is currently investigating is the effect of dynamic tyre loading. The tyre loads used in almost all pavement impact studies are static and it is known that higher forces are generated during dynamic loading compared to static loading. This could also lead to interesting further investigations on the interplay between heavy vehicle dynamics and the associated road pavement damage.

The pavement condition is also a factor that needs consideration in this analysis in order to determine the rate of deterioration and current road consumption. Determining the current condition of the road by use of visual inspections can be done by autonomous systems and will add to the accuracy of results.

With the addition of new parameters it will most likely be necessary for future versions to include machine learning as it is expected that the higher order polynomial functions will be too complex to create with acceptable levels of accuracy.

This tool should also be used to conduct fair road user tax investigations to determine whether such a taxation approach would assist road authorities to more easily recover costs, especially those caused by overloading. It can also be used by roads authorities in issuing accurate fines based on individual infringements based on actual damage caused. It can also motivate and reward operators that are using road friendly combinations (especially if a guideline is available on the relative effects of various parameters).

7. References

De Beer, M., Sallie, I., Van Rensburg, Y. & Kemp, M., 2009. Load Equivalaency Factors (LEFs) for Abnormal Vehicles (AVs) and Mobile Cranes in South Africa Based on the Mechanistic -Emperical (M-E) Design Methodology. *Southern African Transport Conference (SATC).*

DoT, C. R. M., 1996. *TRH4: Structural design of flexible pavements for interurban and rural roads,* Pretoria: Department of Transport.

Havenga, J. H., Simpson, Z. P., de Bod, D. & Braun, M., 2016. *A Logistic Barometer for South Africa: Towards sustainable freight mobility,* s.l.: Stellenbosch University.

J. Granlund, J. L., 2017. *Förkortad väglivslängd - Orsaker och kostnader,* s.l.: s.n.

Krygsman, S. & Van Rensburg, J., 2017. *Funding for Roads in South Africa: Understanding the principles of fair and efficient road user charges,* Stellebosch: ResearchGate.

NAS-NRC, 1962. *The AASHO Road Test,* Washington D.C.: National Academy of Sciences.

NVF committee Vehicles and Transports, 2008. *Road Wear From Heavy Vehicle- an overview*. [Online]
Available at: http://www.nvfnorden.org/lisalib/getfile.aspx?itemid=261
[Accessed 2 May 2018].

SAICE, 2017. *SAICE 2017 Infrastructure Report Card for South Africa*, s.l.: s.n.