LOCALISED BRIDGE LOADING FOR SOUTH AFRICA USING WIM DATA

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ABSTRACT

Bridges in South Africa are designed in accordance with TMH7, which was first published in 1981 and revised in 1989. Since the publication of the code, there have been revisions to traffic legislation and the nature of the vehicles that currently occupy our roads has changed over the past forty years with respect to gross vehicle weight, axle weight, number of axles, axle spacing and dynamic amplification. There is enough reason to believe that bridge loading may not be the same across our provinces as it is highly dependent on localised economic activity. This study investigates bridge loading across South Africa using weigh-in-motion data from six provinces. The number of vehicle records captured by WIM stations are approaching one hundred million and in-house software, together with extreme value statistics are used to compare load effects from the available data. The aim is to identify province specific bridge loading to prevent unnecessary conservatism in some locations.

1. INTRODUCTION AND MOTIVATION

Weigh in Motion (WIM) data is in abundance in South Africa (SA), mainly due to toll concessions operating in the Northern parts of the country. WIM data reflects economic activity, and it is reasonable to believe that characteristic bridge loading could be different across provinces. This study uses WIM data from six provinces and draws a comparison between the characteristic load effects for different span lengths. The study considers span lengths up to 30 m as these span lengths typically experience single-vehicle crossings for critical load effects and are governed by free-flowing traffic. For span lengths longer than 30 m it is often found that congested traffic governs.

2. WEIGH-IN-MOTION DATA IN SOUTH AFRICA

WIM stations from different provinces were selected based on economic activity, international freight movement and the location of the highways in SA. Figure 1 shows the geographical location of the chosen WIM sites.

The Roosboom WIM station, situated on the N3 highway in KwaZulu-Natal (KZN), is known to transport heavy freight between Durban ports to inland industrial locations such as Johannesburg. Previous studies (Lenner, de Wet & Viljoen, 2017; Van der Spuy, 2020) which investigated bridge loading in SA have confirmed that Roosboom is potentially the WIM station that experiences the heaviest traffic loading in SA. Roosboom is therefore used as a reference station in this study. In the Eastern Cape (EC) province, the Kinkelbos

WIM station was selected as it is situated on the N2 highway, which carries freight on the East coast of the country, between Cape Town and Durban, and therefore represents this province well. Bethal WIM station is frequently used to transport freight between Gauteng and neighbouring countries, such as Eswatini and Mozambique, as it is located on the R35 in Mpumalanga (MP). In the Gauteng province (GP), the Kilner Park WIM station is used and is located on the N1. The WIM station in the North West (NW) province is located on the N4 highway while the Northern Cape (NC) WIM station is located on the R31.

All of the stations were chosen strategically to represent traffic movement from industrial areas, mines and areas with high economic activity, transporting heavy freight to and from neighbouring countries and ports along the coast of SA.

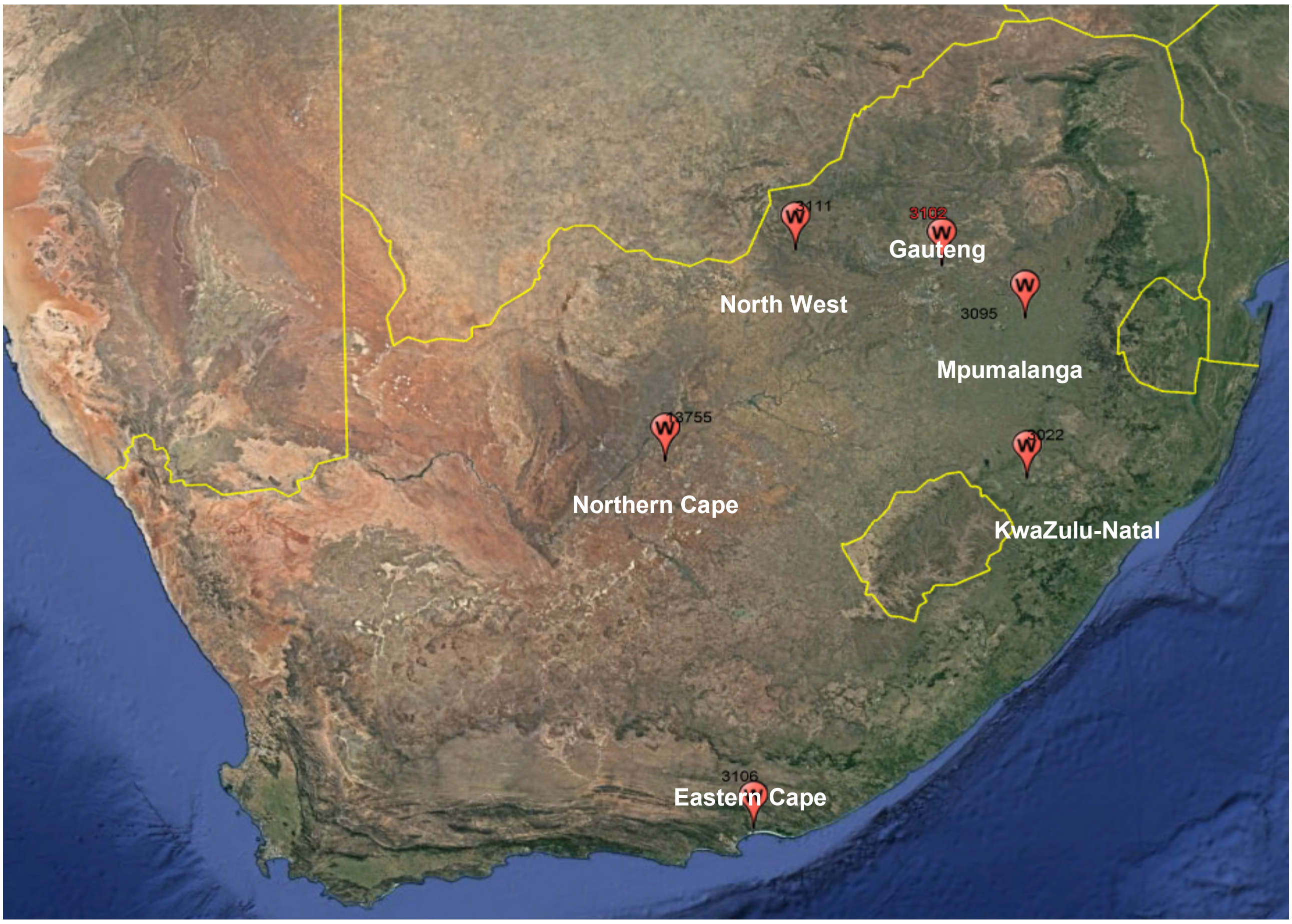

Figure 1: WIM stations for this study

2.1 WIM Data Collection Regulation and Formats

The collection of WIM data in South Africa is governed by three specifications. TMH3 specifies the provision of WIM services (COTO, 2016) whereas TMH8 sets procedures for how traffic and axle load monitoring should be conducted (COTO, 2014). TMH14 specifies the data collection format and output. The format is known as the South African Standard Data Collection Format (COTO, 2013).

Although there are some stations where more than one lane is measured in each direction, the majority of WIMs have a single sensor in the outer lane. This sensor is also only half a lane wide and only collects data from the outer row of wheels of vehicles (Slavik, 2007). Wheel loads are typically multiplied by a factor of 2.0 to determine the axle weights. This is known as Data Record 13 in the South African system and presents some inaccuracies due to the cross fall of roads.

Table 1 shows a typical record and the information required to create a convoy for the calculation of various forces, which obtained from a WIM sensor in South Africa. The record type in the first column provides information on an individual vehicle logged on a particular lane with axle weights and axle spacing. There are a number of different record types, however “type 13” includes the information required for the purpose of this study and are the only record types utilised. The second and third columns contain the date and time stamps of the vehicle travelling across the WIM sensor. Column 4 provides the number of axles, followed by the weight of each axle group (100xkg) and the distance between the axles (centimetres) in the arrangement vehicles are recorded by the WIM sensor. The abovementioned information which includes the date and time stamps, vehicle travelling speed, axle weights and axle spacing’s are used in the analysis when calculating distances between vehicles and assembling a convoy to calculate load effects, which is elaborated on in Section 3.

Table 1: Example of Record Type 13

Record Type	Data	Time	No of axles	Weight 1	Space 1	Weight 2	Space 2	Weight 3	Space 3	Weight 4	Space 4	Weight 5	Space 5	Weight 6	Space 7	Weight 7
13	150101	00011680	7	59	305	66	139	64	566	80	137	83	672	68	137	56

2.2 Cleaning of WIM data in South Africa

During WIM measurements, gross errors occur that must be addressed. This is done by correcting values through calibration and by removing false recordings from the records (Enright & OBrien, 2011). Although the derivation of the method is undocumented, Slavik developed a technique named Golem to specifically address sources of false recordings for South African data and according to the South African Standard Data Collection Format discussed in the previous section. Golem’s rejection criteria are as follows:

- Any vehicle travelling at less than 5 km/h or more than 150 km/h.
- Any truck length less than 4 m or greater than 26 m.
- Any vehicle with fewer than two axles.
- Vehicles with gross vehicle weight (GVW) less than 3.5 t.
- Any vehicle with an individual axle weighing more than 16 t.
- Any vehicle with an axle spacing less than 0.53 m or more than 10 m.

2.3 Calibrating WIM Data in South Africa

To remove the dynamic component, WIM systems are calibrated to remove possible bias due to dynamic effects (OBrien & Enright, 2013). In South Africa, De Wet and Slavik (de Wet, 2010a) developed the Truck Tractor (TT) method which provides corrections for the systematic errors in WIM data (de Wet, 2010a,b). Systematic errors refer to the calibration of the WIM data. The application of this method results in a k-factor by which all axle weights are multiplied to suppress the systematic WIM error.

The systematic error causes a shift in the distribution of measured axle loads and the random error enlarges the dispersion of the distribution (Slavik, 1998). It is vital that the errors are addressed before using the data to determine a bridge load model. The TT method uses a sub population of six and seven axle trucks with a single steering axle and a double driving axle, called “eligible trucks.” It was found that the monthly average of TT loads is 21.8 t with a COV of 1.7 %. Measured “eligible trucks” are compared to the 21.8 t weight to calibrate the WIM data. The TT method is used in this study to correct the systematic WIM error. The method has been accepted by the South African National Roads Agency Limited (SANRAL) and is included in Technical Methods for Highways 3 (TMH3) (Committee of Transport Officials South Africa, 2016).

3. CONVOYS AND LOAD EFFECTS

3.1 Assembling Convoys from WIM Data

By using the time stamps and speeds, it is possible to calculate the distance between vehicles and to assemble a convoy of axles for each day by using the date stamps. The distance between the rear axle of the front vehicle and the front axle on the following vehicle is calculated by using time difference and speed.

Table 2 and Figure 2 illustrates the arrangement of vehicles in a convoy using WIM data. The difference in time between the recordings and the speed of the front vehicle is used to calculate inter-vehicle spacing between the front wheels of following vehicles.

Table 2: Example of two following vehicles from a WIM file

	Vehicle 1	Vehicle 2	Units
Date	170101	170101	yymmdd
Time	00:06:38.60	00:12:20.70	hhmmss.ss
Speed	93	68	km/h
No of axles	2	7	[]
Axle 1 Weight	27	48	Tonnes x10
Spacing 1	608	298	cm
Axle 2 Weight	33	52	Tonnes x10
Spacing 2	N/A	137	cm
Axle 3 Weight	N/A	51	Tonnes x10
Spacing 3	N/A	706	cm
Axle 4 Weight	N/A	41	Tonnes x10

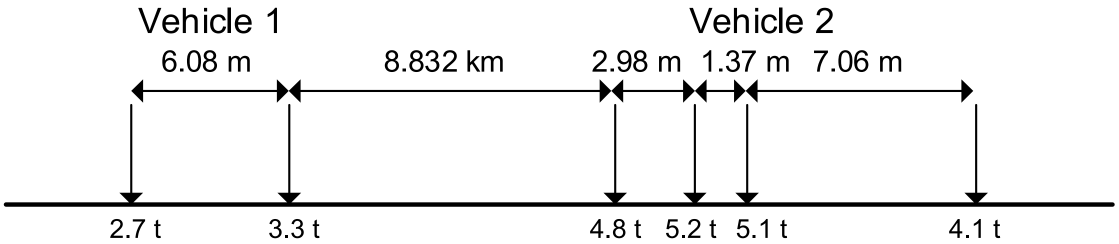

Figure 2: Spatial arrangement of example WIM vehicles

3.2 Calculating Load Effects

Simplified studies utilise a single-vehicle analysis (Nowak & Hong, 1991; Nowak, 1994; Anderson, 2006), but South African data has satisfactory accuracy for continuous convoys of vehicles to be passed over varying span lengths for the different load effects (LEs) while recording the daily maximum values for each load effect and span length. These load effects are calculated using simple principles of statics and influence.

The convoys contain all observed vehicles after which were not removed during the raw data cleaning process as described in Section 2.2. Moving convoys over various spans as opposed to single-vehicle crossings enables capturing load effects resulting from multiple presence of heavy trucks in the same lane travelling at close distances, which occupy a bridge simultaneously. This improves the accuracy of the results at longer span lengths where multiple vehicle events govern the loads experienced by the structure. Axle loads and axle spacing, as opposed to the GVW of single or multiple vehicles, which governs the loads on longer spans due to an entire truck being able to occupy longer spans, induce governing LEs on shorter spans.

When deriving traffic load models for bridges it is common to investigate hogging moments for two span structures as well as sagging moments and shear forces for single span structures (Caprani, 2005; Enright & OBrien, 2012; Lenner, 2014; Lenner, Keuser & Sykora, 2014). Nowak & Hong (1991) considered shear on two span structures, which was deemed less onerous than for single span structures.

4. CHARACTERISTIC LOAD EFFECTS

4.1 Return Period

The characteristic LEs are determined by extrapolating to a return period of 975 years, which is calculated to correspond to a 5% exceedance probability (p =0.05 fractile) in a 50-year reference period, and is in accordance with the Eurocodes (CEN, 2003; Enright, 2010). The return period is essential to obtain characteristic LE values, but not at ULS or SLS which are functions of partial factors and therefore of target reliability.

4.2 Distribution Fitting

Extreme Value Theory (EVT) is implemented with the block maxima method, using the smallest block size to avoid discarding excessive data (Van der Spuy, 2020). As only the upper tail of the parent distribution contributes significantly to the extrapolated LEs for a given return period, a censored Generalised Extreme Value (GEV) distribution is fitted to the daily maxima LEs (Bailey, 1996; Zhou, Schmidt & Jacob, 2012; Zhou, 2013). It is critical to choose a tail length of the censored distribution such that the data is considered identically distributed, which is a requirement to use EVT. A tail length of $2\sqrt{n}$ is used, where n is the total number of data points in the population. This tail length has been shown to isolate the tail of traffic load effects (Van der Spuy & Lenner, 2018, 2019; Van der Spuy, 2020).

4.3 Extrapolation

The selected censored GEV distribution is fitted to the tail of the traffic load effect data and extrapolated to characteristic load effects corresponding to a return period of 975 years.

5. RESULTS

The studies by Lenner, de Wet & Viljoen (2017) and Van der Spuy (2020) suggested that the Roosboom WIM station experiences the heaviest traffic in SA. To verify the findings and to assess bridge LEs in different regions in SA, this study compares the characteristic

LEs using WIM stations from different provinces in SA. The results of this study forms part of a greater project in which a newly developed load model for bridge loading in SA is potentially calibrated regionally. The results are depicted in Figures 3 through 6 and discussed in this section.

The characteristic sagging moments are depicted in Figure 3. By visual inspection it is clear that an overall trend exists with no clear dominant region. For span lengths between 5 m and 10 m, the Northern Cape produces the highest LEs, followed by the Eastern Cape for span lengths between 15 m and 20 m. At a span length of 15 m, it is found that the Eastern Cape, North West and Northern Cape provinces produce a similar magnitude LEs. Between span lengths 5m and 15m, KwaZulu-Natal experiences lower sagging moments, which linearly increases and dominates at span lengths between 25m and 30 m. The Gauteng province experiences the lowest sagging moments.

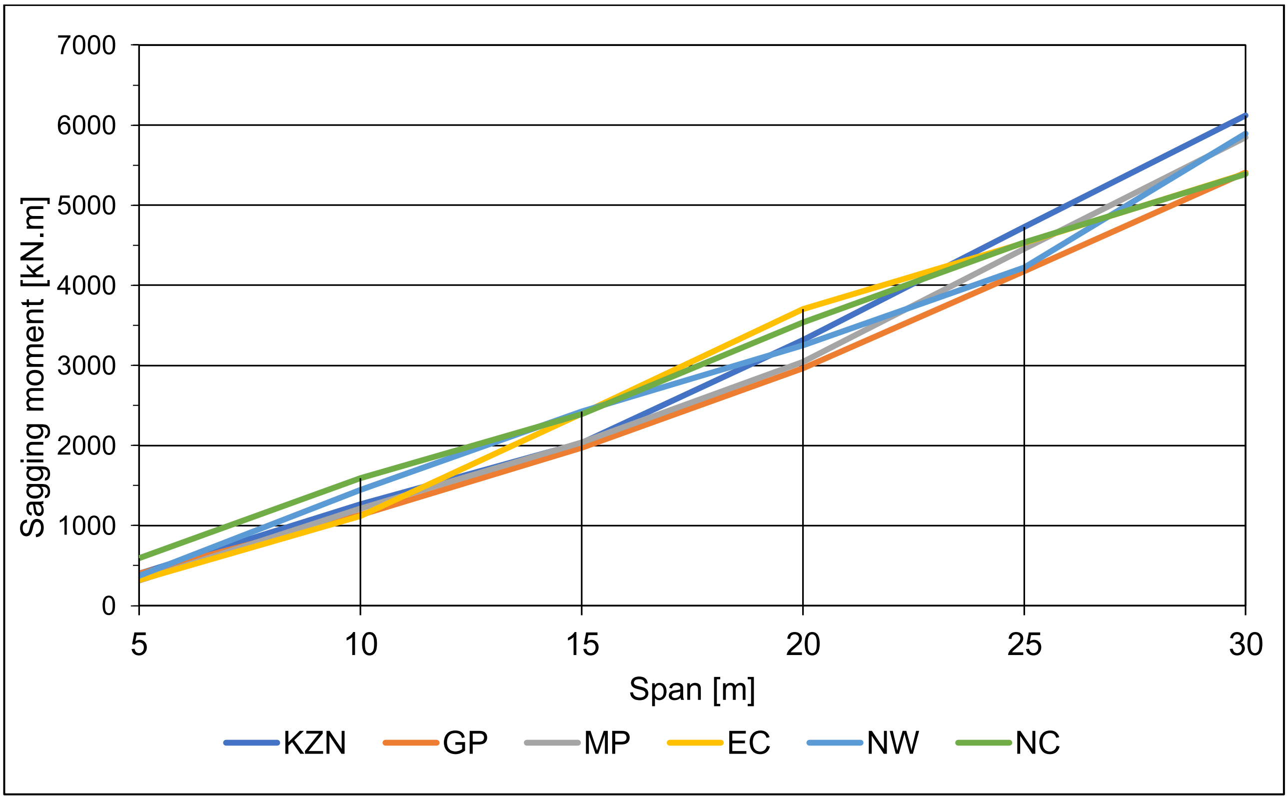

Figure 3: Characteristic sagging moments in the different provinces throughout SA

Contrary to sagging moments, the hogging moments in Figure 4 shows greater variability in the relative magnitudes of the LEs between the different provinces, i.e. considerable differences exist in the magnitude of LEs experienced in different provinces. The inter-provincial variability in LE magnitude confirms the existence of dominant provinces, which experiences higher LEs as opposed to other provinces. From inspection, it is clear that for span lengths between 5 m and 15 m, a trend can be found with less variation in the magnitude of the LEs with minimal rapid trend changes, which suggests that inter-provincial LEs have a similar order in magnitude for the particular span lengths. The variation gradually increases for span lengths greater than 15 m, with a less pronounced trend up to span lengths between 20 m and 30 m. For span lengths greater than 20 m there exists significantly higher variability in the order by which the magnitudes of the lowest LEs (Eastern Cape) differs from the highest LEs (KwaZulu-Natal). A possible explanation holds that entire vehicles occupying the span may justifiably be the governing cause of LEs on longer span lengths (typically greater than 20 m); hence, the GVW dominates the maximum LEs as opposed to individual axle weights and configurations dominating the maximum LEs, which is typically the case for shorter span lengths.

For span lengths between 5 m and 10 m, Gauteng province produces the most severe hogging moments with the Eastern Cape; Northern Cape and North West provinces experiences significantly lower LEs. The LEs experienced by bridges in KwaZulu-Natal and Mpumalanga provinces experiences similar LEs for span lengths between 5 m and 15 m, whereas KwaZulu-Natal experiences the highest magnitude LEs from 15 m to 30 m. The greatest variability in hogging moments occurs at span lengths between 20 m and 30 m. At a 20 m span length, the hogging moments experienced by bridges in KwaZulu-Natal is approximately 1.5 times higher in magnitude as compared to the LEs experienced in the Northern Cape and Eastern Cape provinces. This variability increases at a span length of 25 m, with the magnitude of hogging moments in KwaZulu-Natal is in the order of 1.8 and 1.6 times higher compared to the LEs in the Eastern Cape and Northern Cape provinces, respectively.

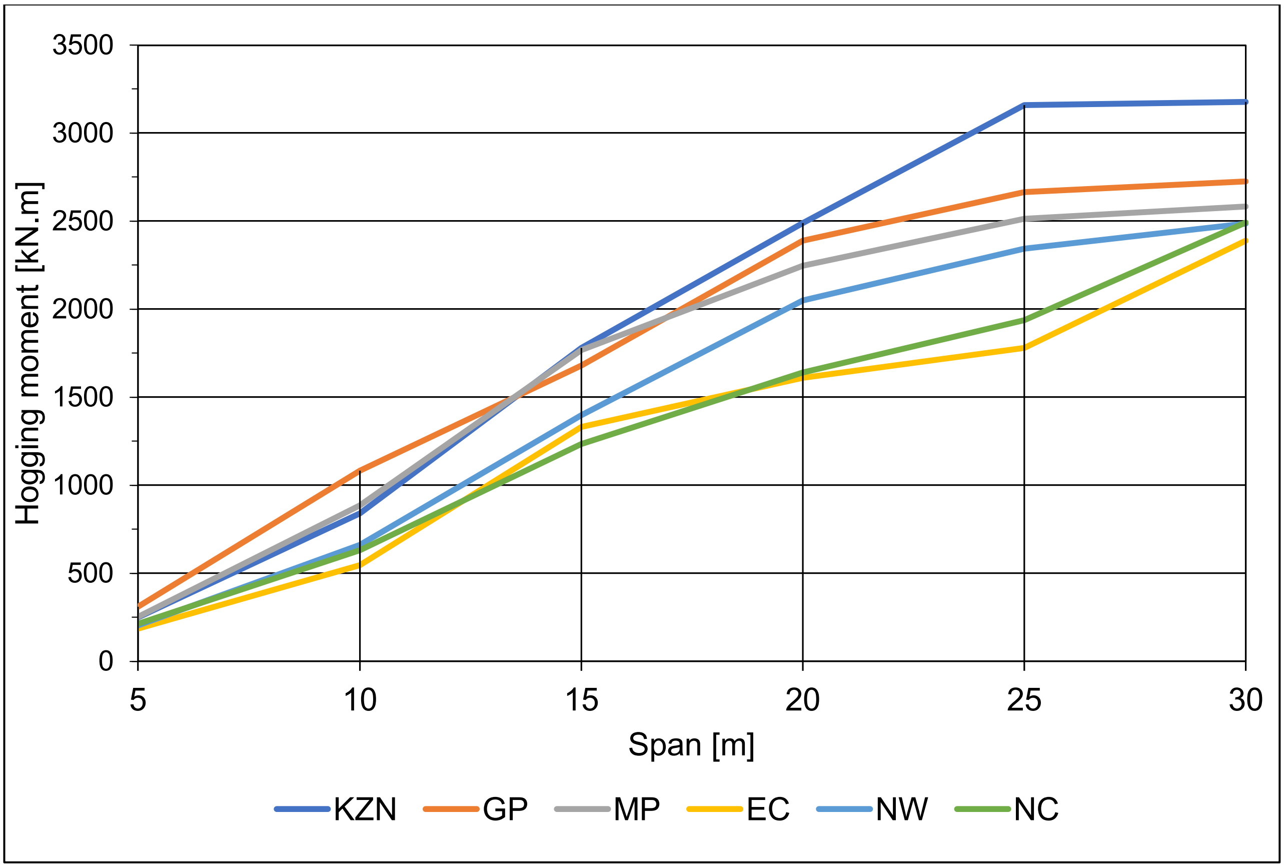

Figure 4: Characteristic hogging moments in the different provinces throughout SA

Furthermore, this variation is proportional to the traffic composition, expressed in terms of the average daily truck traffic (ADTT) and average daily traffic (ADT) in this study. As depicted in Figure 5, KwaZulu-Natal, the ADTT is 5734 is considerably more compared to Eastern Cape. The Northern Cape experiences significantly lower traffic. The considerably higher truck traffic experienced in KwaZulu-Natal gives rise to an increased probability of extremely heavy vehicles and abnormal trucks occupying bridges in this province, along with a higher probability of multiple heavy trucks occupying longer span lengths, resulting in significantly higher LEs.

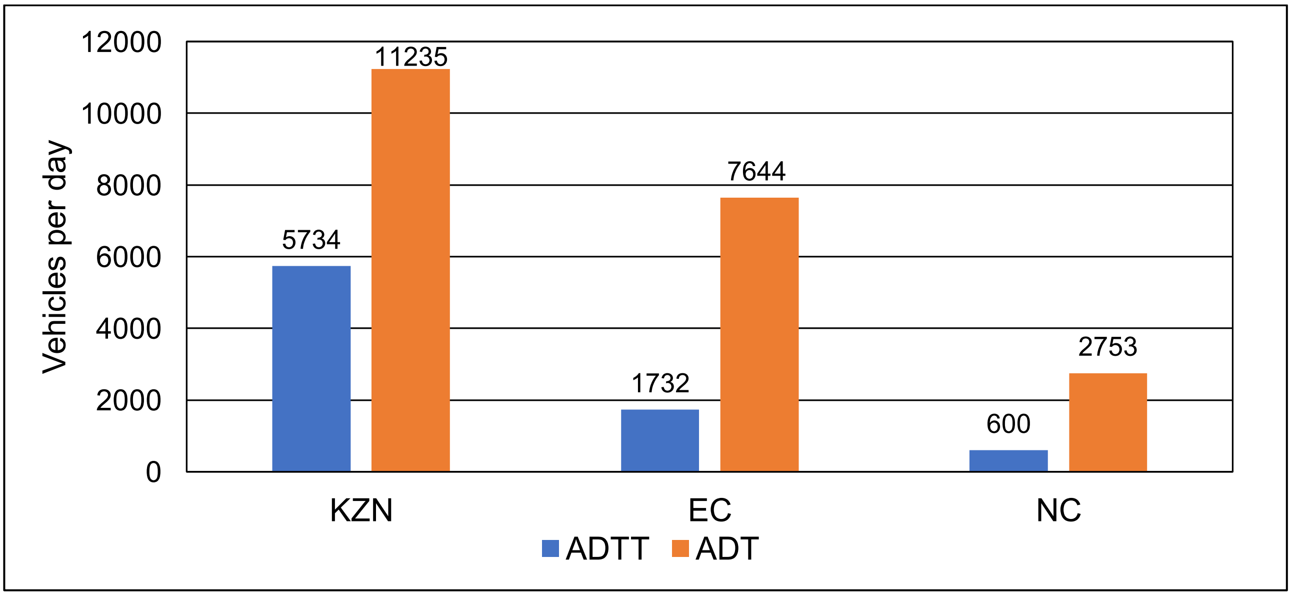

Figure 5: Comparison between traffic and truck volumes

Figure 6 depicts a similar trend for shear forces experienced by span lengths between 5 m and 10 m exhibiting a lower degree of interprovincial LE variability, i.e. the order of LE magnitudes are similar, with no clear dominant province with the different provinces experiencing similar shear force magnitudes for the particular span lengths. Practically this is attributed to the relatively short span lengths that are unable to occupy entire trucks, resulting in individual axle weights and axle configurations inducing the dominating LEs. Standard vehicles with standard axle configurations and axle loads within legal limits that pass over short span lengths are less likely to cause LEs that are extremely high, as compared to traffic compositions with a high percentage of abnormal vehicles. This is due to abnormal vehicles typically having non-standard axle configurations, which results to point loads located in sequences that induce critical LEs. The shear forces dominate on span lengths greater than 10 m in Gauteng province, and at a span length of 20 m, Gauteng province experiences LEs that are in the order of 1.9 times higher compared to the LEs in the Northern Cape for the same span length.

KwaZulu-Natal experiences aggregate shear force magnitudes relative to the other provinces, i.e. the magnitudes of the LEs is approximately located in the centre between the highest and lowest magnitudes experienced in other provinces. This trend is opposite to the magnitudes for hogging moments where KwaZulu-Natal experienced the most severe LEs. This can once again be attributed to the span lengths considered where hogging moments are calculated with double the total length, enabling entire vehicles to occupy a bridge. This is an indication that KwaZulu-Natal experiences extremely heavy vehicles with high GVW, having standard axle configurations, whereas Gauteng province is more likely to experience truck types of which the axle weights and configurations with point loads on a bridge span induces the most severe LEs.

Such significant regional variation in traffic LEs, with reference to hogging moments and shear forces, can cause unnecessary conservatism when calibrating traffic load models throughout the entire country based on traffic data from a single WIM station. This leads to certain bridges designed uneconomically with a higher level of reliability and others with lower reliability.

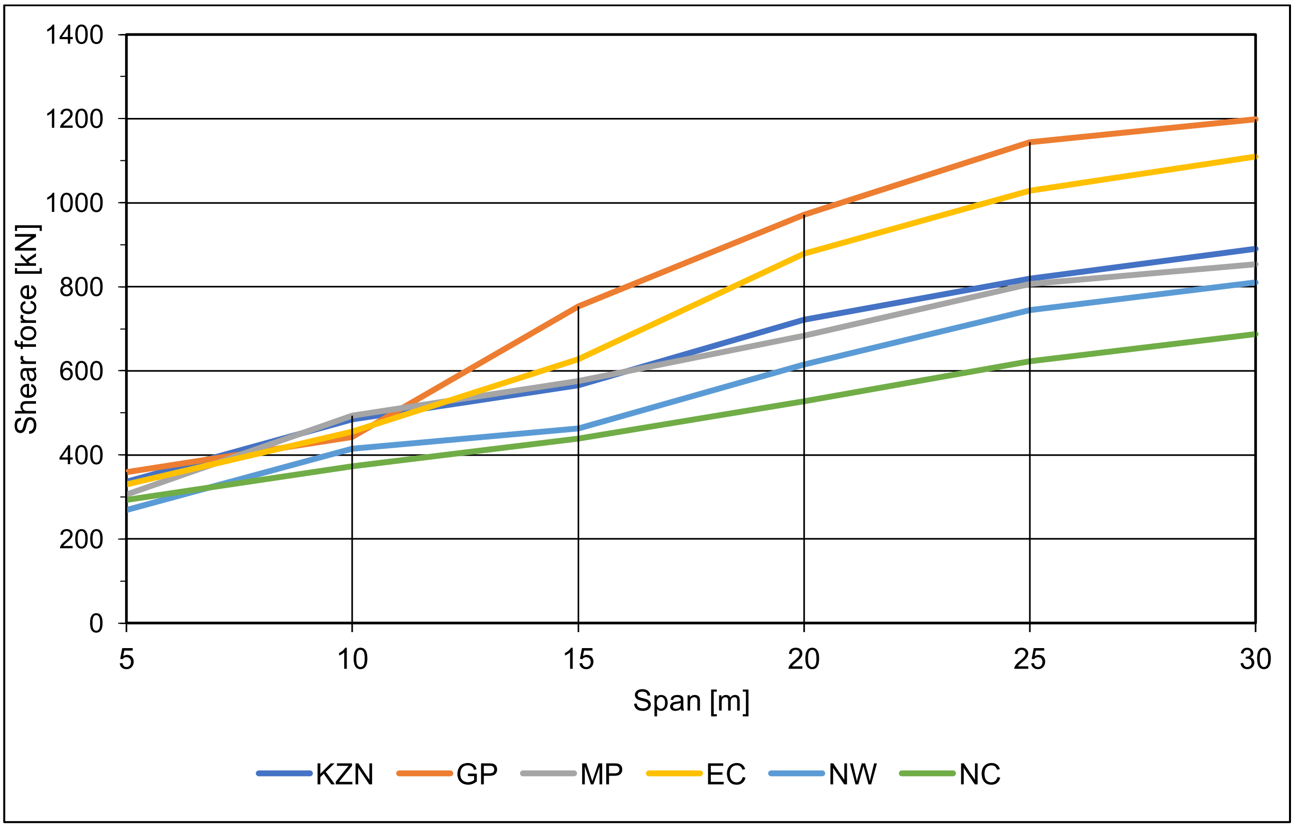

Figure 6: Characteristic shear forces in the different provinces throughout SA

6. CONCLUSION

The results from this study confirm that characteristic load effects caused by truck traffic varies in magnitude throughout the different provinces that are geographically different within the borders of South Africa. The significance in the variation differs in the nature of LEs, where the least variation occurs for sagging moments, whereas significant variation was found in different provinces for hogging moments and shear forces, where LE magnitudes differ by factors up to 1.9 inter-provincially. This can be due to different vehicle configurations and the dominant occurrence of particular truck types in the different provinces, which is directly related to the nature of freight being transported which depends on specific routes connecting the locations of different economic activities. Currently in SA, the design of the entirety of highway bridges is done in accordance with the TMH-7 bridge design code, resulting in all the bridge stock designed for the same magnitude of traffic loads. This has considerable disadvantages, primarily economical, if a significant portion of the bridge stock is designed to withstand traffic loads that is likely to be in the order of 1.9 times higher than the traffic loads in experienced in reality. A plausible solution is to scale design loads for different provinces according to the actual traffic experienced by the particular province, to achieve a desired level of reliability without being overly conservative. A potential solution is to incorporate this into the new bridge design codes that are in the process of being formulated to supersede the outdated TMH-7 design code.

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