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Estimation of the Impact of the Overloaded Truck on the Service Life of Pavement Structures in Nigeria

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Abstract Overloading by commercial trucks in Nigeria is a serious problem. The overloaded trucks stress the road structure beyond safe bearing capacity. Traffic load is a dominant function on pavement design because the main feature of pavement is to resist traffic load. In Nigeria, the percentage of overloaded trucks can reach more than 94% in the total number of vehicles and maybe one of the substantial factors that reduce the service life of the road pavements. This paper presents the analysis results of the weigh-in-motion survey data at Lokoja-Abuja in Nigeria and the impact of overloaded trucks on the pavement. For the analysis the simplified approach was used, the axle loads were converted into representative single-axle loads based on 4th power formula by AASHTO 1993 equation. The vehicle damage factor of vehicles is presented and was compared with the Highways National Standard to estimate the remaining service life of the pavement. The analysis showed that the vehicle damage factor determined from weigh-in-motion data is hugely higher than vehicle damage factor of the national standard in Nigeria which may lead to accelerated deterioration, reducing the service life of the pavement structures. From this result, we can conclude that there is a reduction in the service life of approximately about 10.48 years from the design life of the pavement. Which means the service life of the Lokoja-Abuja pavement designed for 15 years will start deterioration just after four years and six months of commissioning.

Keywords Overloading, Weigh-in-motion, Service life, Axle-load and VDF

1. Introduction

In an age of deteriorating road infrastructure and declining budgets for road upgrades and repairs, the sensible thing to do to boost the lifespan of our highway would be to move more cargo transport from truck to rail and the enforcement of weight and Axle load controls on the existing road infrastructure. The US Department of Transportation-District Seven released a Report of Early Distress for a 6.5-mile stretch of US 8 and an 8-mile stretch of US 51 near Rhinelander, WI [9]. A cursory look at the causes of premature failures shows that overloaded trucks were a key factor leading to the early failure of jointed plain concrete pavements (JPCP). Based on the recommendations from this report, [9] developed design guidelines for heavy truck loading on concrete pavements in Wisconsin.

Over the period, the number of larger farms has increased, and farming techniques continuously improved. [10] did a research to identify the impact of heavy farming vehicles on Minnesota road pavements and bridges. The researchers filtered the technical literature on heavy-vehicle pavement impact provided by the Minnesota Department of Transportation (Mn/DOT) Research Services Section. The report, as mentioned above, showed pavement deterioration information and quantitative data from Minnesota and other Midwestern states. Based on the literature review, the researchers found that the performance characteristics of both rigid and flexible pavements were negatively affected by overloading. The lengthy wheel spacing and slow movement of heavy farming vehicles further increased the damage on the roadway. The researchers also found that two performance measures—bending and punching-were used in the literature for evaluating the impact of farming vehicles on bridges. A comparison between the quantified fundamental metrics of a variety of farming vehicles and those of the bridge design vehicle yielded two crucial conclusions. (1) The majority of the farm vehicles investigated created more extreme structural performance conditions on bridges as it pertains to bending behaviour. (2) Several of the farming vehicles surpassed design vehicle performance conditions based on punching.

Many studies show the relationship between high-grade vehicles and pavement deterioration. [8] carried out a

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literature review on these studies as a part of the FHWA's Truck Pavement Interaction research program on truck size and weight. This study focused on spatial repeatability of dynamic wheel loads produced by heavy vehicles and its effect on pavement damage. The analysis included several studies identifying the impact of the environment, vehicle design, vehicle characteristics and operating conditions on pavement damage. According to the review, suspension type and components, as well as tire type and configuration, were significant contributors to pavement damage. The literature review also revealed the relationship among consistency of vibrant forces on the wheel, kind of suspension, and road deterioration.

Various types of vehicles cause different types of damage to the roadway. Vehicle loading on highway pavement is related to the weight of the axle and its configuration. [14] surveyed the impact of agricultural equipment on the response of low-volume roads in the field. In this study, a gravel pavement and a blotter pavement in South Dakota were tested with farms equipment. Each sample had pressure cells in the base and subgrade, and deflection gauges to estimate surface displacement. Field tests were conducted in different conditions in 2001. Data were studied for repeatability, and then the average of the most repeatable set of measurements was synthesized. Results showed that agricultural equipment could be more destructive to low-volume roads than an 18,000-lb single-axle vehicle. It was discovered that the impacts depended on factors such as season, load level, the thickness of the aggregate base of roads, and soil type. The researchers suggested that a highway agency could effectively reduce this impact by increasing the width of the thickness of the base layer and maintaining the load to the approved limit.

Over the years, single tires have gradually replaced dual tires due to their efficiency and economic characteristics. Previous studies on a wide range of single wide-base tires have shown that super-single tires would result in a significant increase in pavement deterioration compared to dual tires. [13] examined the effects of super-single tires on pavements using plane-strain, static and dynamic finite-element calculations. The study focused on sand and clay subgrades rather than on asphalt and base layers. The subgrades were modelled as saturated to investigate the effects of pore water pressures under the most severe conditions. By comparing the difference of strains in the subgrade induced by super-single tires with those influenced by dual tires for the same load, the effects of overlay and sub-soil improvements were significant. Besides, the researchers recommended enhancing the road design method that would decrease the adverse effects of super-single tires on the subgrades.

[5] measured pavement responses to a new generation of single wide-base tire compared with dual tires. The current single wide-base tires have a full tread and a higher load-carrying capacity than conventional wide-base tires; therefore, this design has been supported by the trucking industry. Their study aimed to quantify pavement damage caused by traditional dual tires and two new models of wide-base tires by using FE analysis. Fatigue cracking, primary rutting, secondary rutting, and top-down cracking were four main failure mechanisms considered in the pavement performance analysis. In the FE models developed for this research, geometry and dimensions were selected to simulate the axle configurations typically used in North America. The models also considered actual tire tread sizes and applicable contact pressure for each tread and incorporated laboratory-measured pavement material properties. The researchers calibrated and validated the models based on stress and strain measurements obtained from the experimental program. Pavement damage was calculated at a reference temperature of 77 ℉ and two-vehicle speeds- 5 and 65 mph. Results showed that the new generations of wide-base tires would cause the same or more considerable pavement deterioration than conventional dual tires.

Because heavy trucks cause more damage to highways, it is of interest to federal and state legislatures whether the current permitted weight limit reflects the best tradeoff between trucking productivity and highway maintenance cost. A study [5] was mandated by Virginia's General Assembly to determine if pavements in the southwest region of the state under higher allowable weight limit provisions had more significant repair than pavements bound by lower weight limits elsewhere. This study included traffic classification, weight surveys, an investigation of subsurface conditions, and comprehensive structural evaluations, which were conducted at 18 in-service pavement sites. Visible surface distress, ride quality, wheel path rutting, and structural capacity were measured during 1999 and 2000. A subsurface investigation was conducted at each site in October 1999 to document pavement construction history and subgrade support conditions. Also, a study consisting of vehicle counts, classifications, and approximate measurements of weights was administered to collect site-specific information about traffic volume and composition. The results were used to estimate the cost of the roadway deterioration attributed only to the net increase in allowable weight limits. The study concluded that pavement damage increased drastically with relatively small increases in truck weight. The cost of damage to roadway pavements in those counties with a higher allowable weight limit was estimated to be $28 million over 12 years. Among other factors, this value did not include costs associated with damage to bridges and motorist delays through work zones.

In Louisiana, [12] completed a study to assess the economic impact of overweight vehicles hauling timber, lignite coal, and coke fuel on highways and bridges. First, researchers identified 1,400 key control sections on Louisiana highways that carried timber, four sections that carried lignite coal, and approximately 2,800 bridges that were involved in the transport of both of these commodities. Second, a calculation methodology was developed to estimate the overlays required to support the transportation of these commodities under the various gross vehicle weight

(GVW) scenarios. Three different GVW scenarios were selected for this study, including (1) 80,000 lbs., (2) 86,600 lbs. or 88,000 lbs., and (3) 100,000 lbs. Finally, a methodology for analyzing the effect of these loads on pavements was developed, and it involved determining the overlay thickness required to carry traffic from each GVW scenario for the overlay design period. Using the following two steps: (1) determining the shear, moment and deflection induced on each bridge type and span, and (2) developing a cost of repairing fatigue damage for each vehicle passage with a maximum tandem load of 48,000 lbs. This analysis showed that 48-kilo pound axles produced more pavement damage than the current permitted GVW for timber trucks and caused significant bridge damage at all GVW scenarios included in the study. The researchers recommended that the legislature eliminate the 48-kip maximum individual axle load and keep GVWs at the current level, but increase the permit fees to sufficiently cover the additional pavement costs produced by overweight vehicles.

Accelerated pavement damage due to vehicle overloads has historically been quantified according to two general approaches. The first, based upon research conducted at the AASHO Road Test [1] quantifies damage in terms of equivalent single axle loads (ESALs) from the overloaded trucks. The second approach utilizes mechanistic-empirical (M-E) pavement analysis concepts to predict accelerated pavement damage due to the overloads. Though both methods have their inherent advantages and disadvantages, the ESAL approach is currently the most popular among states. According to [4] "TxDOT and almost all other countries are still basing predictions of overload damage on the 'fourth power rule' that was developed based on conditions that prevailed in the 1960s". The following subsections will detail both approaches, with examples provided from a variety of states. Equivalent Single Axle Approach The so-called "fourth-power rule" resulted from the AASHO Road Test that was conducted from 1958-1960 in Illinois [1]. This full-scale pavement test set the standard for flexible and rigid pavement design and is currently used by most U.S. states and has been adapted to other parts of the world. The fourth-power rule refers to the equivalent single axle load equations that were derived from converting axles of various configurations and load magnitudes into an equal number of passes of a standard axle. The standard axle was selected as an 18,000 lb single axle with dual tires.

The ESAL approach was used by [7] in their cost-benefit study to estimate infrastructure damage. They calculated ESALs/truck and then multiplied by the miles driven and a cost-coefficient ($/mile) to arrive at an infrastructure cost. Only loaded trips were counted since the empty trips resulted in very low ESALs [7]. While [7] examined ESALs from both per vehicle and per axle basis, they concluded that per axle better represented actual pavement damage. A study conducted in New Jersey [3] also utilized the ESAL approach to quantify the damaging effects of overloaded vehicles, developed a "model" truck fleet based upon violation data. Barros applied this truck fleet to "typical" New Jersey flexible and rigid pavements. It was assumed that the flexible pavements had a structural number of 5, and the rigid pavements had a 9-inch slab. They were able to estimate 38,146 ESALs of pavement damage per year based upon 9,060 overweight violations per year. This corresponded to 7.63% loss in pavement life due to the overloads when considering a design traffic level of 500,000 ESAL per year. This analysis assumed that the same number of trucks were carrying a more substantial amount of freight. They conducted a second analysis where he concluded that additional vehicles were used such that overloads were not needed. The increased traffic volume also resulted in accelerated pavement damage resulting in a 6.17% loss of pavement life per year which was slightly less than the case where overloads were used. Barros highlights an essential concept in pavement damage analysis. That is, given a total weight of cargo to carry within a local economy it can either be sent by fewer, more heavily loaded trucks, or more, legally loaded trucks. Either case may result in reduced pavement life. Roberts and Djakfar's study of particular, commodity-specific, permitting in Louisiana utilized the ESAL concept [11] and computed the shortened time to overlay of flexible pavements due to overloads. They computed reduced life as a function of increasing the vehicle weights, increasing the number of trips and a combination of the two to carry the total freight.

A study from Ontario in 1985 [3] examined the increased pavement damage due to increasing the single axle load limits from 18,000 lb to 20,000 lb. Using actual load distributions measured in 1967 (18,000 lb limit) and 1981 (20,000 lb limit), [3] applied load equivalency factors to determine the relative damaging effect of the increased weight limit with an assumed structural number equal to 6. They stated the importance of a long time horizon in their analysis so that changes in trucking technology due to the increased limit would be reflected in the loading data. Using too short a time interval after the increase would not accurately capture the change in axle weights.

This paper aims to examine the effect of the overloaded truck on pavement structure. This paper presents the effects of overloaded vehicles on pavement structure by considering the service life based on WIM survey.

2. Methodology

The primary data was collected from traffic surveys on the Lokoja-Abuja road. Axle Load Survey is used to examine the axle load of vehicles. In this survey, the axle loads are checked and surveyed with the help of a portable axle weigh pad. Figure 1 is the picture of the Axle weigh pad used for the study and the axle load survey. The secondary data required for the work is the traffic growth rate, pavement life and existing pavement layer, maintenance cost of the roads. These data are collected for determining the deterioration of pavement life.

Figure 1. A portable Axle Weigh pad

In this study, traffic data was collected within a week using weigh-in-motion facilities operated by Exosphere Nig. Ltd. Traffic and vehicular data, including the gross vehicle weight of all vehicle categories, was obtained from a weigh-in-motion system customized and installed on site. To ensure the accuracy of weight data collected from the WIM system, proper calibration of the WIM system and validation of the WIM data were conducted. A thorough analysis of the vehicle weight data, namely the GVW, was performed to determine the vehicle overloading characteristics at the study location.

The gross vehicle weight permit is categorized based on vehicle class, and the summary will be shown in a table. For this study, the focus will be given to the 1-axle, 2-axle, 3-axle, 4-axle trucks, 5-axle and 6-axle. The number of overloaded trucks was shown in the study location.

This study will make conservative assumptions to model the incremental load damage effects of overweight trucks to selected federal highway pavement structures. The scope of this paper included assumptions to assure the analysis was conservative. This study will assume pavement deterioration due to commercial vehicle loading can be related to pavement deflections.

3. Results and Discussion

In this study, the data from Lokoja - Abuja road were collected within a week in April 2019 using weigh-in-motion facilities and automatic traffic counter (ATC) operated by Exosphere Nig. Ltd. The segment considered more the most congested than other section since these segment heading to Abuja. A total of more than 43,514 commercial vehicle data obtained during a week (2nd April 2019 to 8th April 2019). The detail of the survey location presented in Table 1. Table 2 gives a piece of information about the type of truck, class and VDF standard that evaluated. Five types of trucks considered in the analysis of this study. This VDF standard will be compared with the VDF value generated from the WIM data survey.

Table 1 is a data of WIM survey report. Truck type of 6-axle is the most type of truck that recorded in these WIM survey report, followed by a truck type of 4-axle.

3.1. Overloaded Trucks

The percentages of the overloaded truck are estimated by identifying truck axle load that greater than the ECOWAS standard legal limit (10 tons). Each of type truck has a different percentage number of overloaded. In Table 2, the percentage of overloaded trucks varies for each type of vehicle in the study location. The values vary between 20% - 96%.

The result indicates that the majority of the truck is overloaded and the traffic control in that area is abysmal. Compared to other countries, this number is exceptionally high. Additional study is developed, the percentage of overloaded vehicles vary from 6% to 16.5%, which is quite low when compared to these results [6].

Table 1. Summary of Automatic Traffic Count showing axle load distribution for Lokoja-Abuja

	2 Axle rigid vehicle	3 Axle rigid vehicle	4 Axle rigid vehicle	3 Axle Articulated	4 Axle Articulated	5 Axle Articulated	6 Axle Articulated
Tues. 2nd April 2019	705	148	134	3	303	165	357
Wed. 3rd April 2019	634	113	133	0	392	186	419
Thurs. 4th April 2019	751	122	173	3	390	186	505
Fri. 5th April 2019	746	124	161	3	382	216	449
Sat. 6th April 2019	723	112	173	3	396	156	365
Sun. 7th April 2019	692	112	161	2	325	193	382
Mon. 8th April 2019	502	93	149	0	330	166	328
Total counted k	4753	824	1084	14	2518	1268	2805
% overloaded from the sample survey	20%	50%	86%	50%	86%	73%	94%
Number of HGV's overloaded	951	412	932	7	2165	926	2637
Number of HGV's weighed on 4th April	177						
Number of HGV's counted on 4th April	2130						
Sample size weighed	8%						

Table 2. Class of vehicle and their standard VDF and overloaded VDF

Lass of Vehicle	Vehicle Damaging Factor (Standard)	Vehicle Damaging Factor (Overloaded)
2-axle	3.898	1.926
3-axle	3.679	4.464
4-axle	5.934	9.009
5-axle	6.222	8.210
6-axle	6.003	19.557

Table 3. Summary of axle load survey indicating axle load distribution

Vehicle Type	Total No. of Vehicles	ECOWAS Standard Weight (Tonnes)	No. of Vehicles Within Standard Limit	No. of Vehicles Above Tolerance limit	% of Overloaded Vehicles
Two axle	10	21	8	2	20%
Three axle	6	26	3	3	50%
Four axle	74	38	10	64	86%
Five axle	15	46	4	11	73%
Six axle	69	51	4	65	94%
Total	174		29	145	

Table 4. Summary of Daily Automatic Traffic Count showing axle load distribution for Lokoja-Abuja

	2 Axle rigid vehicle	3 Axle rigid vehicle	4 Axle rigid vehicle	3 Axle Articulated	4 Axle Articulated	5 Axle Articulated	6 Axle Articulated
Day 1	705	148	134	3	303	165	357
Day 2	634	113	133	0	392	186	419
Day 3	751	122	173	3	390	186	505
Day 4	746	124	161	3	382	216	449
Day 5	723	112	173	3	396	156	365
Day 6	692	112	161	2	325	193	382
Day 7	502	93	149	0	330	166	328
Total counted k	4753	824	1084	14	2518	1268	2805
% overloaded from the sample survey	**20%**	**50%**	**86%**	**50%**	**86%**	**73%**	**94%**
Number of HGV's overloaded	951	412	932	7	2165	926	2637

Table 5. Calculated VDF for various classes of trucks along Lokoja-Abuja route

Class of Vehicle	**ECOWAS Standard Limit**	**Total Gross Weight**	**Allowable Gross Weight**	**VDF**	**The ratio of Overloaded VDF and Standard VDF**
2-axle	16000	158,490	160000	1.93	0.49
3-axle	26000	172,300	156000	4.46	1.21
4-axle	38000	3,444,860	2812000	9.01	1.52
5-axle	48000	815,040	720000	8.21	1.32
6-axle	51000	4,728,340	3519000	19.56	3.26

Vehicle Damage Factor used as a representation of the trucks that encountered on the pavement structure that defined as the equivalent number of standard axles per truck. The VDF estimated by using the empirical approach through the 4th power formulas derived by Liddle [1].

$$DF = k\,(Qj\,/Qs)^{4}$$

DF: Damage Factor,

Qi: Actual Load,

Qs: standard single axle load 80 kN,

k: 1 for single, 0.086 for tandem and 0.053 for tridem axle load

In this study, the vehicle damage factor will be estimated from WIM survey. Since the WIM survey will be conducted on different days of the week, the VDF value calculated by analyzing for a day. This was done to analyze the traffic condition and the tendency of the overloaded truck.

Table 5 presents the calculation of VDF value. The result shows that the VDF value tends to decrease mainly in all other types of trucks; the VDF values is ups and downs. The VDF result (overloaded VDF) then compared with the national standard VDF for each truck that stated in Table 2. From the analysis, the VDF result was higher than standards vehicle damage factor except for single axle vehicles which are rarely overloaded. The range comparison between overloaded VDF and standard VDF about 1.2 to 3.3 times. This is the reason why the pavement structures in Lokoja-Abuja tend to rapidly deteriorates during its service life.

3.2. Estimation of Overloaded Truck Impact on the Service Life of Pavement Structure

Cumulative Single Axle Loads [1] gives the formula to estimates the total number of traffic during the service life by using the following Cumulative Equivalent Single-Axle Loads (CESAL) formula:

$$W_{18} = \sum_{j=1}^{n} \mathrm{Nj} \times \mathrm{VDF}_j \times D_D \times D_L \times 365$$

W_{18} is design traffic in the design life of the pavement,

N_j denotes the number of vehicles while

D_D and D_L are the distribution factor for direction and lanes.

To analyze the impact of the overloaded truck on design life, VDF value and the percentage of the overloaded truck from WIM survey analysis will be used to estimate the CESAL (Cumulative Equivalent Single Axle Loads**)** and the number of design traffic. The daily traffic data collected from automatic traffic counter (traffic census). The CESAL result (Overloaded CESAL) will be compared with CESAL estimation using standard load (Standard CESAL) to calculate the impact caused by overloaded trucks. Then the reduction value of service life of pavement structures can be measured. CESAL value comparison is to compare the Overloaded and Standard CESAL.

To calculate the impact of overloaded vehicles on pavement structure, we can calculate the remaining service life of the pavement. Remaining service life (RSL) has been defined as the estimation of total years that a pavement will be functionally and structurally in a normal condition by with only routine preservation. The RSL was calculated using the formula:

$$RSL = (\text{CESAL standard}/\text{CESAL overloaded}) \text{ X } D_L$$

Where: RSL is remaining service of pavement (years), and D_L is design life (15 years).

RSL = (434682/1441923)*15 = 4.52 years (4 years and 6 months)

By using the equation, the RSL of pavement in this study is 4.52 years. From this result, we can conclude there is a reduction in the service life of approximately about 10.48 years from the design life of the pavement. Which means the service life of the roadway that is designed for 15 years will start deterioration just after four years and six months. Considering the date of completion of the projection (which is 2014), it, therefore, means that the road starts deteriorating from 2019.

Table 6. Estimated traffic in the design life of pavement (standard)

Vehicle Type	N_J	VDFj	D_D	D_L	Number of days	Design Traffic
Two axle	110	3.898	0.5	0.5	365	241515
Three axle	79	3.679	0.5	0.5	365	40189
Four axle	407	5.934	0.5	0.5	365	278629
Five axle	120	6.222	0.5	0.5	365	102845
Six axle	147	6.003	0.5	0.5	365	219501
Total						434682

Table 7. Estimated design traffic in the design life of pavement (overloaded)

Vehicle Type	N_J	VDFj	D_D	D_L	Number of days	Design Traffic
Two axle	679	1.925562	0.5	0.5	365	119305
Three axle	120	4.464409	0.5	0.5	365	48769
Four axle	515	9.009175	0.5	0.5	365	423023
Five axle	181	8.210237	0.5	0.5	365	135709
Six axle	401	19.5573	0.5	0.5	365	715116
Total						1441923

4. Conclusions

This study outlines weigh in motion survey data consideration in traffic data analysis at Lokoja-Abuja in Abuja to estimate the impact of overloaded trucks on the pavement structures. Nearly more than 43,514 total number of the vehicle that recorded and from the analysis found that the total of the overloaded truck is varying between 20% - 94% for a different type of truck. The specific result of this study shows that the VDF values form the WIM survey report is hugely more significant than the standard VDF. The overloaded trucks contributed significantly to reducing the service life of the pavement. From the above analyses, we can conclude that the overloaded truck has severe damage to the pavement, especially on service life. The government needs to enforce a restriction regarding axle-load control to achieve the economic life of the road.

5. Data Availability Statement

Some or all data, models, or code used during the study were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the Acknowledgements.

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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