STUDY ON PAVEMENT DAMAGE CAUSED BY AXLE OVERLOADING AND ASSOCIATED COSTS IN KENYA

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ABSTRACT

Road transport remains the predominant mode of transportation in most developing countries for both freight and passenger traffic. To this end, most developing countries have invested heavily in improving the condition of their road network since the turn of the millennia. However, it is emerging that these gains are coming under increasing threat as a result of overloading vehicle axles. This study focuses on vehicle loading trends in Kenya.

The study involved performing pavement life-cycle cost analysis using the Highway Development & Management (HDM-4) tool based on the concept of Equivalent Standard Axle Load Factor (ESALF). HDM-4 was used to determine annual road condition trends, road user costs, and yearly road works costs for two-axle loading scenarios; (i) using ESALF determined from the legal axle load limits, and (ii) those determined from independent field axle load surveys.

The study revealed that axle overloading is still prevalent in Kenya, and that Kenya is losing about US$ 43 million per year to pavement damage as a result of overloading while collecting less than 10% of that amount in axle overloading fines. The study further quantified the average increase in road user cost per vehicle-km and additional maintenance costs due to axle overloading.

1. INTRODUCTION

Road transport currently accounts for over 90% of all freight and passenger traffic in Kenya, making it the predominant mode of transportation (KRB, 2019). It is against this background that improvement in the road network condition has become a priority for most countries, with the current emphasis being on asset preservation of the capital investments made in condition improvement since the turn of the millennia (Gwilliam, 2011). In Kenya, for instance, increased expenditure by the government over the last two decades has made road assets to be a significant component of public investments that must be preserved.

One of the threats to the preservation of road assets has been identified to be axle overloading. An Axle Load Control Monitoring Study carried out in 2014 by the Kenya Roads Board (KRB) revealed that axle overloading threatened the life of road assets with premature pavement failure (KRB, 2014). This confirmed prior findings by the Sub-Saharan Africa Transport Policy Program (SSATPP), which identified axle overloading as one of the biggest threats to road assets within the Sub-Saharan Africa region (SSATPP, 2007). More worrying still, a 2007 World Bank report revealed that most African countries could not enforce axle load control initiatives (World Bank, 2007).

One of the main challenges facing those tasked with enforcing axle load control initiatives has been quantifying the cost of the damage caused by axle overloading to road assets. In Kenya, initial efforts to quantify the damage caused by axle overloading were carried out in 2006 under a study funded by the European Union known as the Axle Load Control Best Options Study for Kenya. The study, however, only focused on the 926 km Northern Corridor (i.e., the road corridor linking the port of Mombasa to the landlocked countries of Uganda, Rwanda, Burundi, South Sudan and DR Congo). It estimated the damage caused by axle overloading in terms of the cost of the extra depth of pavement that would be required to support the additional equivalent standard axles due to axle overloading. The study estimated the total damage cost per annum of US$ 7.2 million for the entire Northern Corridor, which translated to about US$ 7,770 per km per year (SSI, 2006). Across the region, SSATPP has been at the forefront in quantifying the cost of axle overloading with a 2010 report estimating the cost of axle overloading in East and Southern Africa to be about US$ 4 billion per annum against a total network of about 90 000 km (Pinard, 2010). Pinard (2010), however, noted that data challenges are hindering the assessment of axle overloading problems across the continent.

Unlike these past studies, which relied on estimates, this paper presents a detailed approach for quantifying the cost of axle overloading on Kenya's roads by undertaking a pavement life-cycle cost analysis using the HDM-4 model concept of Equivalent Standard Axle Load Factor. Additionally, the paper also presents vehicle loading trends in Kenya, the impacts of axle overloading on pavement deterioration, and road user costs.

2. BACKGROUND

2.1 Overview of Kenya's Roads Sub-Sector

The management of Kenya's road network is split into a two-tier system made up of the National Government, which is in charge of the national roads, and the County Governments, which are in charge of the county roads (KRB, 2019). The national roads are managed by four institutions, namely, Kenya National Highways Authority (KeNHA), Kenya Urban Roads Authority (KURA), Kenya Rural Roads Authorities (KeRRA), and Kenya Wildlife Services (KWS). The county roads, on the other hand, are managed by the devolved 47 County Governments. In terms of road classification, Kenya's road network is segregated into various classes ranging from road class A to road class P, depending on functionality. This study focuses on the paved arterial roads (classes S, A, and B), collector roads (class C) and urban roads (classes H and J).

As of 2018, Kenya's total classified road network stood at about 161 821 km, with national roads constituting about 40 000 km and the remaining 121 821 km forming the county road network. Table 1 provides a detailed breakdown of the classified road network by road class and the surfacing type, revealing that only about 10% of the classified road network is paved.

Table 1: Road network by class and surfacing type as at 2018 (in km)

Road Class	Paved	Gravel	Earth	Others	Total
National Roads	12,740	17,202	9,766	137	40,000
County Roads	4,245	49,116	66,366	2,094	121,821
Total	16,985	66,318	76,132	2,231	161,821

Source: KRB (2019)

In terms of network condition, Kenya's road network has improved significantly over the last decade, with about 62% of the network in fair/ good condition as of 2018.

2.2 Axle Load Control (ALC) in Kenya

The Axle Load Control Monitoring Study carried out in 2014 revealed that axle overloading was still a major challenge in Kenya, with about 40% of the trucks overloaded in terms of individual axles and 15% overloaded in terms of gross vehicle weight (KRB, 2014). To this end, there have been concerted efforts to improve ALC practices in Kenya. Table 2 below summarises the current ALC regime in Kenya.

Table 2: Axle load control in Kenya as at the year 2020

No.	Feature	KeNHA	KURA	KeRRA
1	ALC department established?	Yes	Yes	Yes
2	Is the management of ALC operations outsourced?	Yes	No	No
3	No. of static weighbridges	11	0	0
4	No. of virtual weighbridges	10 installed & 13 being installed	0	0
5	No. of mobile weighbridges	6	2	2
6	Frequency of ALC operations?	All year round	Annual	Annual

2.3 Load Factor and the Rationale for Axle Load Control

Passage of heavy vehicles over a road often causes deflection, stresses, and strain to the road pavement, resulting in pavement failure in terms of cracking, rutting, potholing, ravelling, and edge break.

The impact of repetitive and cumulative loading is aptly captured using the equivalent standard axle (ESA), which is determined using an expression that was developed in the 1950s following the AASHO Road Tests as shown in equation (1).

$$ESA = \left\{\frac{AL}{SAL}\right\}^{LE} \tag{1}$$

In this expression, AL is the actual axle load in kN, SAL is the standard axle load (80kN), and LE is the exponent representing the relative damage - taken to be 4.5 in Kenya. The ESA of an axle is its pavement damaging effect in relation to a standard axle load of 80 kN. This equation depicts an exponential relationship between the pavement damaging effect and increasing axle load, as shown in Figure 1. For instance, it shows an increase in axle load from 8 tonnes to 10 tonnes, nearly triple the pavement damaging effect.

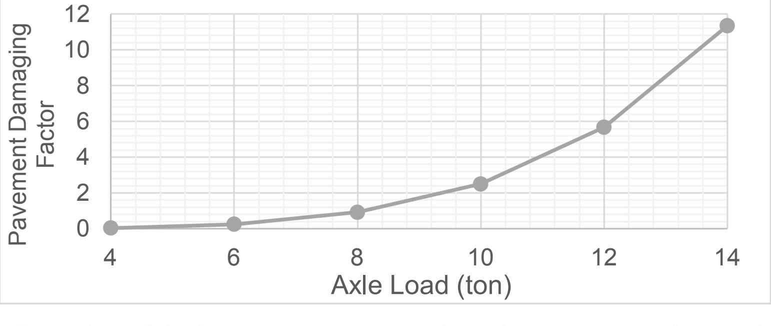

Figure 1: Relationship between axle load and pavement damaging factor

From the same ESA expression, the impact of axle overloading on pavement life can also be derived. Figure 2 shows this relationship and reveals that axle overloading by, say 20%, translates to nearly halving the pavement life.

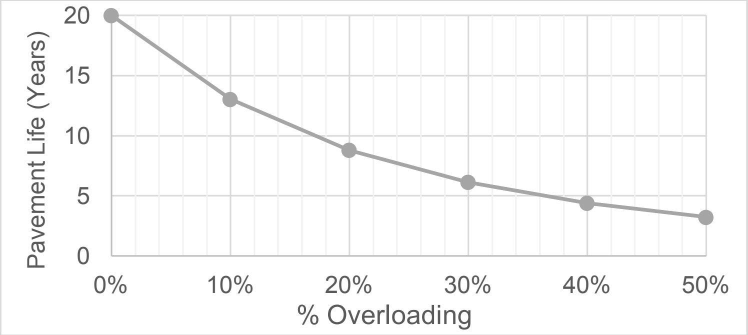

Figure 2: Impact of overloading on pavement life

As shown by the computation of ESA, axle loading trends significantly impact pavement damage. Axle overloading control serves to prevent premature pavement failure, ensure fair competition amongst transporters due to standardized payloads, reduces hazards posed by axle overloading, reduces vehicle operating costs, and reduces the amount of road maintenance required.

3. STUDY METHODOLOGY

3.1 Overall Approach

The first step involved developing a sampling criterion for selecting the 54 sample roads for carrying out independent axle load surveys. This was followed by assessing the level of network compliance to axle load limits by comparing data from the independent axle load surveys vis-à-vis the legal axle load limits. The next step involved determining ESALF using data from independent surveys and the legal axle load limits before undertaking a 20-year life-cycle analysis using HDM-4. The outputs from HDM-4 yielded annual road condition trends, road user costs per vehicle km, and total annual road work cost for the two analysis scenarios that were then compared to quantify the impacts of axle overloading.

3.2 Data Collection and Analysis

The independent ad hoc axle load and traffic counts data were collected every 3 months for a period of 36 hours on each road using the guidelines of Overseas Road Note 40 (ORN40). During these field surveys, a total of 8 525 trucks were weighed against a total traffic count of 27 786 trucks across the 54 road sections. This represented an average sampling rate over the weighing period of about 31%. Of the 54 locations, 18 sites were situated along Class A roads, 16 sites were located along Class B roads, 12 sites were located along Class C roads, and 8 sites were situated along urban road Classes H and J.

The various input data were collated in multiple formats, which required processing into acceptable formats for use in the analysis. Data sets provided in Microsoft Excel files were processed to Microsoft Access format before imported into HDM-4 software. In contrast, those supplied in the HDM-4 objective file formats (*i.e., objects.dat and objects.idx*) required no further processing. The data details are as provided in Table 3 below.

Table 3: Data category, data type sources, and formats

Category	Data Type	Source	Format
Road network data	Inventory, pavement type, pavement strength, road condition, length, climate, works history, drainage condition, etc.	KRB	Microsoft Excel
Traffic data	Traffic composition, traffic volumes, speed-flow types, traffic flow pattern, etc.	Field surveys	Microsoft Excel
Vehicle fleet data	Vehicle physical characteristics, vehicle utilization, loading, and performance, etc.	KRB/ Field surveys	HDM-4 object files
Road works data	Construction maintenance standards and unit costs.	KRB	HDM-4 object files

The road inventory and condition data used for developing the road sections were for the year 2020 and, therefore, relatively up to date. The rest of the network data that was not readily available was estimated using the concept of Information Quality Level and HDM-4 default data sets.

Traffic volume counts were carried out simultaneously as the weighing of heavy goods vehicles was also being carried out. The traffic volume counts data was used to determine the 2019 Annual Average Daily Truck Traffic (AADTT). The trucks were classified based on the axle configuration.

For predicting future traffic impacts on the road sections, annual traffic growth rates of 5.6% were used for Class A and B roads, 3.5% for Class C roads, and 5.7% for urban roads. The growth rates were the long-term planning rates proposed by KRB (KRB, 2018).

The basic vehicle fleet characteristics shown in the Table 4 were used to estimate physical quantities of vehicle resource consumption. To determine road user costs, HDM-4 multiplies the predicted physical quantities of vehicle resource consumption with the specified unit cost of resource consumption (Table 5). These basic and economic vehicle fleet characteristics were derived from the configured Kenyan HDM-4 workspace and updated where necessary to reflect the then market prices. The unit costs of vehicle resource consumption were expressed in economic prices rather than financial prices. This involved adjusting the financial prices to take cognizance of taxes, duties, and subsidies by multiplying them using a Standard Conversion Factor (SCF) of 0.85.

Table 4: Basic vehicle fleet characteristics

Truck Type	Base Type	Passenger Car Space Equivalent (PCSE)	No. of Wheels	No. of Axles	Tire Base Recaps	Tyre Re-tread Cost (%)	Annual Km	Annual Work Hours	Average Life (years)
2 - Axle	Medium Truck	1.5	6	2	0.60	12.00	75 000	2 000	10
3 - Axle	Heavy Truck	1.8	10	3	0.60	12.00	75 000	2 000	10
4 - Axle		1.8	12	4	0.60	12.00	75 000	2 000	10
5 - Axle	Articulated Truck	2.2	18	5	0.60	12.00	75 000	2 000	10
6 - Axle		2.2	22	6	0.60	12.00	75 000	2 000	10
7 - Axle		2.2	26	7	0.60	12.00	75 000	2 000	10

Source: KRB (2018). HDM-4 Calibration Report

Table 5: Economic vehicle fleet characteristics (US$)

Truck Type	Base Type	New Vehicle	Replace Tyre	Fuel (per litre)	Lubricating Oil (per litre)	Maintenance Labour (per hr)	Crew Wages (per hr)	Annual Overhead	Annual Interest (%)	Cargo Holding (per hr)
2 - Axle	Medium Truck	49 500	430	0.6	2.0	2.7	3.2	12 404	18	4.9
3 - Axle	Heavy Truck	99 000	563	0.6	2.0	2.7	3.2	12 404	18	4.9
4 - Axle		104 000	563	0.6	2.0	2.7	3.2	13 000	18	4.9
5 - Axle	Articulated Truck	107 000	563	0.6	2.0	2.7	3.7	17 080	18	4.9
6 - Axle		112 000	563	0.6	2.0	2.7	3.7	17 900	18	4.9
7 - Axle		118 000	563	0.6	2.0	2.7	3.7	18 800	18	4.9

Source: KRB (2018). HDM-4 Calibration Report

Road works data is another critical input in modelling pavement deterioration. A work standard comprises one or more work items (e.g., overlay, patching, reconstruction, etc.); defined intervention criteria to determine the timing; design characteristics; unit costs; and the after-works effects. Table 6 summarizes the adopted road work standards.

Table 6: Work standards and unit financial costs (US$)

Treatment Type	Intervention Criteria	Financial Cost
Rehabilitation/reconstruction: Asphalt Mix on Granular Base (AMGB) – Class A & B roads	IRI ≥ 9.0 AADTT ≥ 351 veh/day Year ≤ 2037	US$ 60 per m^2
Rehabilitation/reconstruction: Double Bituminous Surface Treatment on Granular Base (STGB) – Class C roads	IRI ≥ 9.0 AADTT ≥ 351 veh/day Year ≤ 2037	US$ 53 per m^2
75mm Asphalt Concrete Overlay	4 ≤ IRI ≤ 8.0 AADTT ≥ 351 veh/day Year ≤ 2037	US$ 24 per m^2
50mm Asphalt Concrete Overlay	4 ≤ IRI ≤ 8.0 Mean rut depth ≤ 20mm AADTT ≤ 350 veh/day Year ≤ 2037	US$ 15 per m^2
Reseal (20mm Double Seal Surface Treatment)	4 ≤ IRI ≤ 8.0 AADTT ≤ 350 veh/day	US$ 8 per m^2
Light Reseal (6mm Single Seal Surface Treatment)	Wide cracking ≥ 3% AADTT ≤ 350 veh/day	US$ 3.2 per m^2
Pothole Patching	Potholes ≥ 5 no. /km	US$ 30 per m^2
Edge Repair	Edge breaks ≥ 5m^2/km	US$ 32 per m^2

Source: Adapted from KRB (2018); AADTT is the annual average daily truck traffic and considers truck volumes only; IRI – International Roughness Index

3.3 Determination ESALF

The main input parameter for assessing the impact of axle overloading in the HDM-4 road deterioration models is the Equivalent Standard Axle Load Factor (ESALF), also known as the Equivalent Factor (EF). The ESALF was calculated for each vehicle class using the Kenya Road Design Manual Part III (1981) guidelines using the formula in equation (2).

$$ESALF = \left\{\frac{Ls}{8{,}160}\right\}^{4.5} \qquad (2)$$

where *ESALF = Equivalency Standard Axle Load Factor per vehicle*
Ls = Axle Load in kg on the single axle weighed
8,160 = Standard Axle Load in kg

The ESALF value was computed for each axle. It was then summed up for each vehicle type and forecasted along with the average daily truck traffic to calculate the Cumulative Standard Axle (CSA) loading along the sampled project roads.

To assess the impacts of axle overloading, ESALF were computed while assuming adherence to the legal axle load limits and also using the field independent axle load survey data. The provisions of the 2nd Schedule of the East African Community Vehicle Load Control Act 2013 were used for determining the legal axle load limits (Table 7).

Table 7: Legal axle load limits for conventional tires

Axle Type	No. of Tires on Axle	Permissible Limit (tons)
Single	2	8
Single	4	10
Tandem	8	18
Tridem	12	24
Liftable single	4	10

Source: EAC (2013)

From the preceding, two analysis scenarios were, therefore, developed:

1. Analysis using ESALF determined from the independent surveys carried out by the Consultant; and
2. Analysis using ESALF determined from the legal axle load limits.

3.4 The Highway Development & Management (HDM-4) Analysis

The HDM-4 is a model for assessing road management investment decisions (Odoki and Kerali, 2009). Its analytical framework is premised on the concept of pavement life cycle analysis which applies, amongst others climatic information, road geometry, pavement characteristics, traffic data, road works data, vehicle fleet characteristics, etc., to predict road deterioration, road works effects, road user effects, and, socio-economic and environmental effects (Odoki and Kerali, 2009). The applications of HDM-4 in road management include strategy analysis, programme analysis, project analysis, and operational analysis (Odoki and Kerali, 2009). This study involved undertaking project analysis for the sampled roads.

The decision to use HDM-4 stemmed from the fact that it is the most-acclaimed international standard tool for road sector planning and management with models developed from large-scale field experiments worldwide (Kerali, 2001). Moreover, the HDM-4 workspace used in this study was calibrated and configured to suit the local Kenyan conditions.

For the use of HDM-4 in this study, the processed representative road section data were imported into the HDM-4 model and runs undertaken for the two scenarios over 20 years discounted to present value at a 12% discount rate. A comparison of the maintenance cost between these two scenarios over a 20 year analysis period yielded the additional maintenance cost due to axle overloading. The additional maintenance cost was then converted into cost per km per year, which was then applied across the entire network spectrum of roads with similar characteristics to obtain the total additional maintenance cost over the whole network.

3.5 Study Assumptions and Limitations

The following are the main study assumptions and limitations:

1. In calculating Equivalent Standard Axle Load Factor, it was assumed that most trucks use conventional tires although a small proportion of trucks now use super-single tires.
2. Independent axle loads surveys excluded large buses and light goods vehicles. This is despite past studies showing axle overloading is rampant in these vehicle categories.
3. Since sampling was only focused on loaded trucks, the estimated damage costs may be slightly higher as it assumes that all the counted trucks are loaded.

4. RESULTS AND DISCUSSIONS

4.1 Vehicle Loading Trends in Kenya

In terms of network traffic, the truck traffic composition is as presented in Table 8 below. It shows that 2-axle trucks are the predominant truck type across the entire network.

Table 8: Average traffic composition network across the network

Road Class	2-Axle	3-Axle	4-Axle	5-Axle	6-Axle	7-Axle
Class A Roads	57%	13%	1%	0.5%	28%	0.1%
Class B Roads	74%	19%	1%	0.1%	7%	0%
Class C Roads	72%	17%	1%	0%	10%	0%
Urban Roads	45%	35%	2%	1%	18%	0%
Network Average	62%	21%	1%	0.3%	16%	0%

For all the vehicles weighed during the independent axle load surveys, compliance with the Gross Vehicle Weight (GVW) limits, grouped axle weight limits, and single axle weight limits stood at 79%, 51%, and 58%, respectively (See Figure 3).

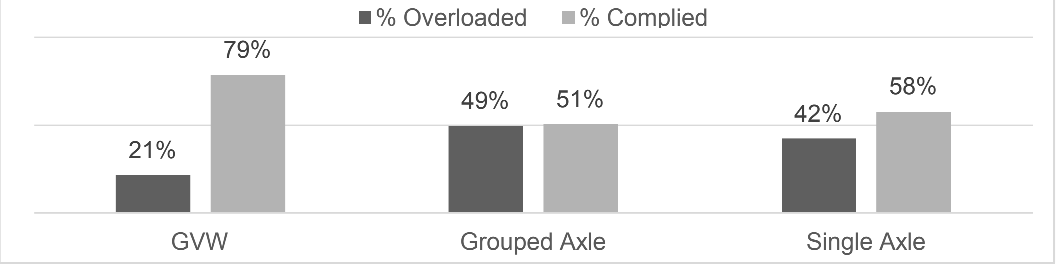

Figure 3: Overall loading compliance rates from independent weighing findings

In terms of axle configuration, 2-Axle trucks and 3-Axle trucks were the most overloaded, comprising about 75% and 18%, respectively, of the total proportion of overloaded trucks (See Figure 4).

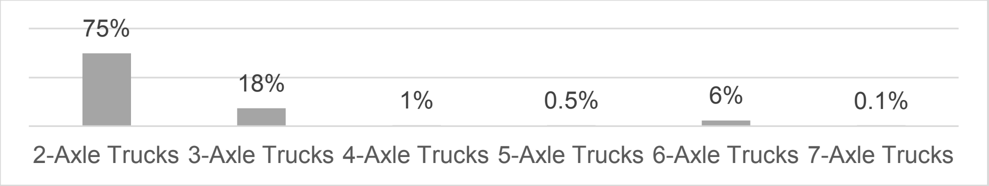

Figure 4: Overall grouped axle overloading rates from independent weighing findings

The average percentage overloading beyond the legal GVW axle load limits is as summarised in Table 9 below.

Table 9: Network overloading extent by truck type

Truck Type	Network Average	Standard Deviation
2-Axle Trucks	5%	7.9%
3-Axle Trucks	5%	6.3%
4-Axle Trucks	1%	0.8%
6-Axle Trucks	10%	0.4%
7-Axle Trucks	3%	-

To assess the contribution to pavement damage by each truck type over the analysis period, plots of cumulative standard axle per lane per truck type were plotted for each of the 54 sample roads. The findings revealed that 5-axle and 6-axle trucks contributed the most to pavement damage with 2-axle trucks contributing the least to pavement damage (Figure 5).

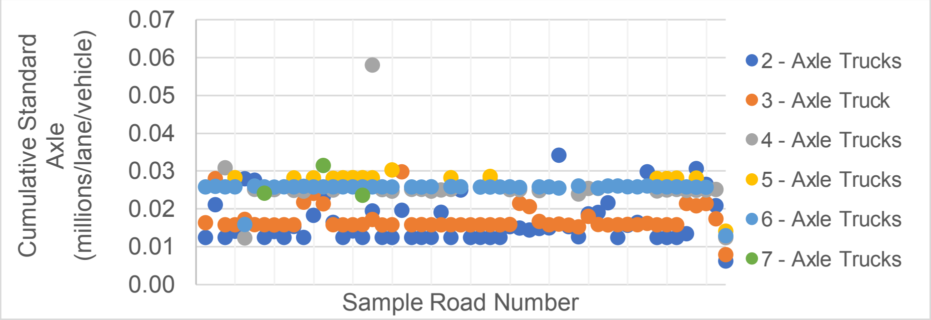

Figure 5: Cumulative standard axle by truck type over the analysis period

4.2 Impacts of Overloading on Pavement Deterioration

One of the significant impacts of axle overloading is that it causes premature pavement failure, which is often characterized by rapid deterioration of the road into poor condition. In HDM-4, the condition of the road is captured in terms of surface roughness. This roughness is typically expressed in terms of the International Roughness Index (IRI), which measures the quality of the riding surface in m/km. IRI depends on the road type and increases as the condition of the riding surface worsen. For this study, an IRI of less than 3.0 IRI implies that a road in good condition, an IRI between 3.0 to 4.0 means that a road is in fair condition, while an IRI exceeding 4.0 means that a road is in poor condition.

Figure 6 shows the typical average roughness progression trend for a sample road (A7), assuming no periodic works are undertaken during the 20-year analysis period. A7 road had an AADTT of 2 014 trucks made up of 1 395 (2-axle), 329 (3-axle), 38 (4-axle),10 (5-axle) and 242 (6-axle) trucks. The measured ESALF from independent field surveys results in premature pavement failure by about a year than if the axle load limits were observed. To allow for comparison of the two analysis scenarios, all the other factors that influence pavement deterioration (e.g., climate, pavement type, construction quality, etc.) were similar with only the ESALF being varied.

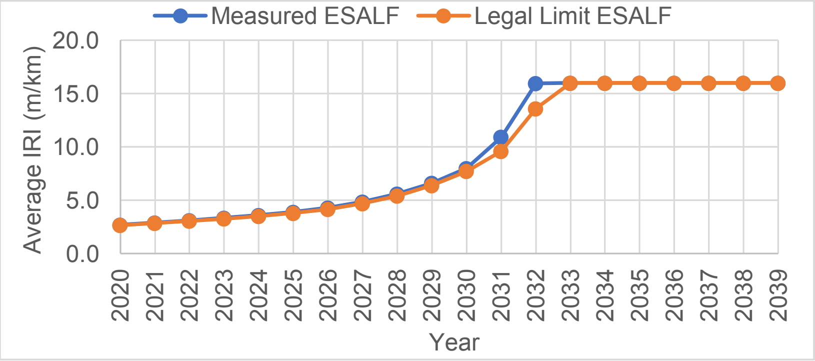

Figure 6: Roughness progression without periodic maintenance for A7 road

The above findings are in tandem with plots of cumulative standard axle loading as shown in Figure 7 below.

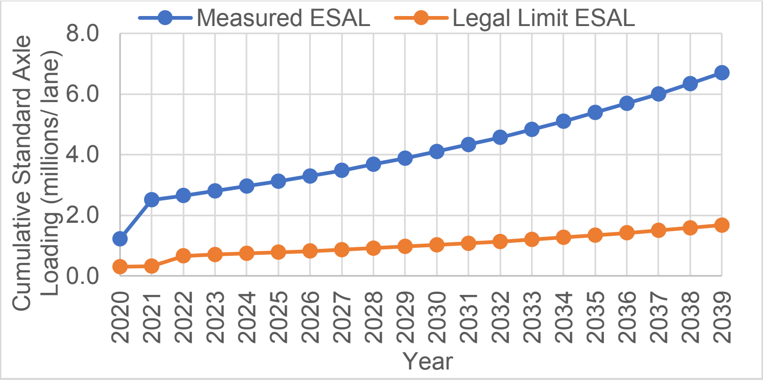

Figure 7: Cumulative standard axle loading per lane for A7 road

Axle overloading also has a significant bearing on the timing when the major works are triggered and the frequency at which these works are triggered during a pavement's life cycle. For instance, Figure 8 below show the average roughness (IRI) progression trends for A7 Road. The measured ESALF triggers major works not only earlier but also twice during the 20-year analysis period, while the other case triggers major capital works only once over the same analysis period adopting an intervention trigger level of 4.0 IRI.

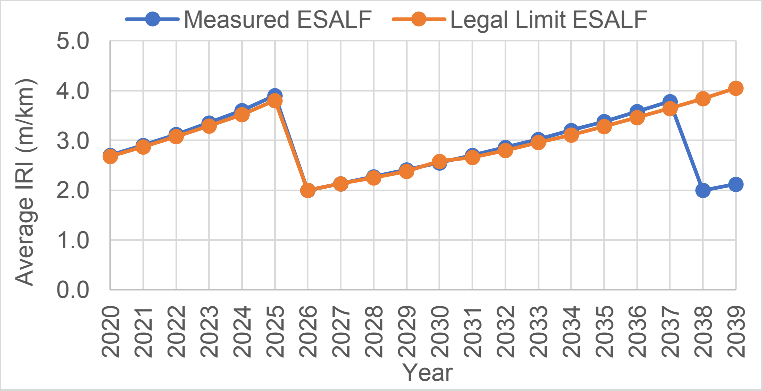

Figure 8: Comparison of average roughness progression (A7 road)

4.3 Additional Maintenance Cost Due to Axle Overloading

Using the concept of pavement life-cycle analysis over a 20 year analysis period, the average additional maintenance costs due to the extra work triggered by axle overloading were determined from HDM-4 analyses. Table 10 gives the average additional cost per km per year due to pavement damage. The additional annual costs are mainly due to the extra capital works triggered during the analysis period.

Table 10: Additional maintenance cost due to axle overloading

Road Class	Costs (US$ per km per year)
Class A Roads	8 400
Class B Roads	7 800
Class C Roads	7 210
Urban Roads	7 200

The additional road maintenance cost per km per year was then applied across the entire network of roads of similar classes to obtain additional maintenance costs over the whole network. Table 11 presents the additional road maintenance costs due to axle overloading.

Table 11: Additional road network maintenance cost due to axle overloading

Road Network	Paved Network (km)	% Network Overloaded	Average Unit Costs (US$ per km per year)	Total Costs (US$ per year)
Classes A & B	8 338.89	41%	8 100	27 693 454
Class C	3 446.03	48%	7 210	11 926 021
Urban Roads	957.32	45%	7 200	3 101 717
				42 721 191

Table 10 shows that, on average, about US$ 43 million is being lost per year due to pavement damage as a result of axle overloading on the four road classes. This pales in comparison to the US$ 2.5 million and US$ 4.3 million overload penalties collected by the Kenya National Highways Authority in 2018 and 2019, respectively.

4.4 Impact of Axle Overloading on Road User Costs (RUCs)

RUCs are primarily made up of vehicle operating costs, travel time costs, and accident costs. These costs are mainly influenced by the condition of the road, which in turn affects vehicle speeds, cost of vehicle operation, and accident rates. The RUCs presented here exclude accident costs majority of which have often been linked to non-engineering factors. The additional annual average RUC per vehicle-kilometre (veh-km) for each vehicle type and each road class is presented in Figure 9 below.

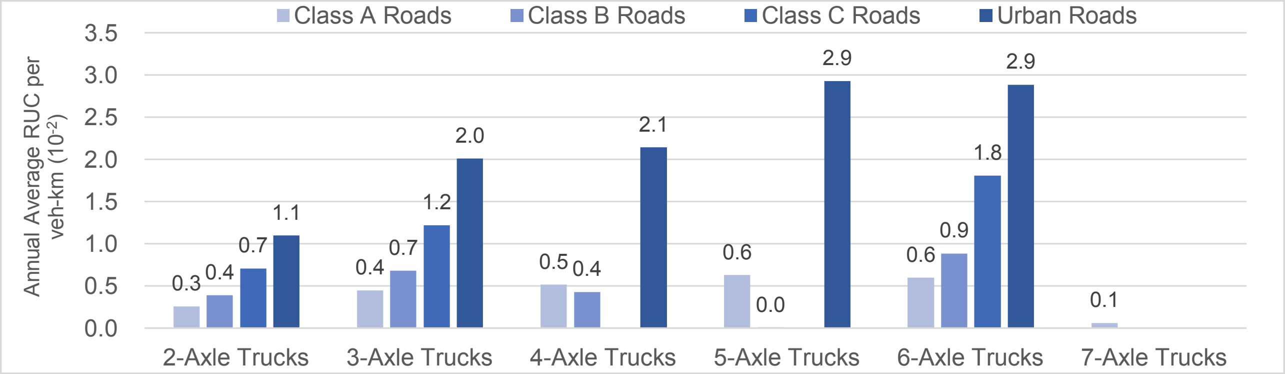

Figure 9: Impact of axle overloading on annual average RUC per veh-km

5. CONCLUSION

This study has demonstrated clearly that axle overloading is a real problem being experienced on the Kenyan road network and that the impacts of axle overloading include premature pavement failure leading to increased road maintenance costs and increased road user costs. The study revealed the following:

1. Axle overloading is generally more prevalent in 2-Axle and 3-Axle trucks categories.
2. The average additional road maintenance cost due to pavement damage is about US$ 7 652.5 per km per year.
3. The average increase in road user cost per veh-km due to axle overloading is about US$ 0.004, US$ 0.006, US$ 0.012, and US$ 0.022 for road classes A, B, C, and urban roads, respectively.
4. About US$ 43 million is being lost per year due to pavement damage as a result of axle overloading on the assessed road classes. This is way beyond the overload penalties, which stood at US$ 2.5 million in 2018 and US$ 4.3 million in 2019.

6. ACKNOWLEDGMENTS

The authors profoundly thank the Kenya Roads Board (KRB) for granting permission to use their data in preparing this paper. In particular, the authors are grateful to Eng. Margaret Ogai and Eng. Victor Odula, both of KRB. Furthermore, the authors would also like to acknowledge KIRI Consult Ltd., who were contracted by KRB to conduct the study and, therefore, collected the data used in this study.

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