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Critical Geometric Design Parameters Affecting Accommodation and Haulage of Large Trucks on Selected Inter-State Roads in Southern Nigeria

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ABSTRACT
This study focused on geometric design adequacy for present truck configuration (Single Unit, Trailer and Tanker truck combinations) on frequently plied roadways in Edo State Southern Nigeria, in relation to their accommodation and safe haulage. The dimensions and operating characteristics of these trucks produce undesirable consequences such as severe off-tracking tendencies, capacity reduction, and ultimately roadway crashes on highway sections not typically designed to accommodate them. Three highways (Benin-Agbor, Benin-Ore and Benin-Sapele) with significant truck haulage ranging between 60-70% truck exposure were selected for the study. A total of 152 sections involving 679 large truck crashes over a five year period were examined. The Poisson regression model was used to analyze the truck crash data and depict the contributing significant geometric design variables by virtue of parameter estimates. Degree of curvature for horizontal alignment, vertical grade and lane width were the critical design parameters affecting truck accommodation and safety based on the model assessment. A study of this nature is intended to provide insight into key geometrics which promote safety treatments via engineering design reviews and improvements.
Keywords-Degree of Curvature, Lane Width, Poisson Regression,Truck Configuration, Vertical Grade

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I. INTRODUCTION

The proliferation of articulated large trucks i.e. Single-unit, Trailers and Tankers constitute severe traffic concerns on Nigerian roadways. Across several rural, intra and inter-state highways, they constitute significant traffic streams which reduce roadway capacity and cause traffic congestion [1]. This increase in truck traffic can be attributed to growth in socio-economic activities involving large freight haulage as well as the deposition and distribution of petroleum products across the country.

From an operational point of view, trucks generally represent vehicles with greater wheelbase turning radii than smaller buses and passenger cars [2]. According to Elefteriadou et al. [3], the dimensions that most affect the turning paths of truck vehicles are the minimum turning radius, the wheelbase, and the inner path of the rear tire. As a result of these attributes, the roadway geometric design requirements for trucks represent more critical variables than those of other design vehicles, especially for turns at intersections and horizontal curvatures on roads.

Unlike trains which travel on rail tracks, where their wheels are guided to follow a precise path along curved routes, long vehicles such as trucks ply roadways built without control tracks. Hence, their rear and front wheels veer off separate paths while negotiating curves. This phenomenon referred to as *"off-tracking"* is significant for large trucks and long combination vehicles (LCVs) especially on roads with smaller curve radii [4]. The *"swept-path width"* due to off-tracking is usually wider and consequently encroaches into opposing vehicle lanes thus reducing highway capacity at such instance for other vehicles. This in turn increases the likelihood of crash occurrence on roadways.

In developing countries particularly Sub-Saharan Africa, limited researches relating highway geometrics to significant truck exposures have been carried out in view of geometric design reviews. According to Edward [5] the safe operation and efficiency of truck haulage as a means for freight transportation in African regions remains a lingering problem due to poor pavement structure, design incompatibility for highway facilities as well as legislative restrictions in the form of regulations and laws prohibiting their smooth operation. Alex [6] highlighted inadequate designs and lack of quality control during highway infrastructure building process as a major problem that has over time resulted in high traffic volumes and traffic loads for heavy trucks and other vehicles on federal roads in Nigeria. Apart from this, there is also the lack of concise database on frequency and distribution of restrictive roadway geometric features for federal highway systems, which are required to facilitate design and maintenance improvements. It is against this backdrop that this study was carried out so as to provide an understanding of the critical geometrical elements that are restrictive to the accommodation of trucks on roadways.

II. RESEARCH METHODOLOGY

2.1 Study Area and Route Selection Criteria

Limited access roadways with relatively homogenous sections and significant truck vehicle exposure were selected for the purpose of this research. The roadways examined were:

- Benin-Agbor
- Benin-Ore
- Benin-Sapele

Each route was assessed for the distribution of typical geometric design elements (horizontal curvature, vertical grade as well as roadway cross-sectional elements). These roadways were been selected on the basis that they represent major routes which permit the movement of large volumes of vehicular traffic for trucks and connect major points of traffic generation with industrial and commercial distribution points in Southern Nigeria. Figure 1 highlights the truck haulage routes selected and investigated.

Figure 1: Map of study area and selected roadway systems [7]

2.2 Data Collection

Information relating to truck haulage activities and crash data were obtained from the Federal Road Safety Corporation [8] for a five year period (2011-2015). These data sets also comprised of Police reports and National Emergency Management Agency (NEMA) reported crashes that occurred within the entire period. For this study, exclusive truck crash records on limited access roads were extracted by making a query on the FRSC vehicle crash data-base from 2011 to 2015 for the selected routes. The types of truck vehicles included in the analysis were single unit trucks (including other converted long vehicles with less than nine seats used for commercial businesses), tanker-trucks and trailer-truck combinations with weight value greater than 4500 kilograms and number of axles greater than or equal to two.

Geometric data collection was done via Geographic Information System (GIS) and direct roadway inspections and measurements. The information gathered was based on homogeneity of roadway segment for typical road geometric design elements. While vertical curves were identified by grade change and the presence of an angle point or inflection point; horizontal curves details were identified by their curve length, radius, central angle, super-elevation and the direction of curvature. Other cross-sectional elements such as lane width, shoulder and median widths were identified and mapped out by direct inspection across roadway sections and the use of GIS and Arc maps detailing software.

2.3 Modelling of Count Data

Poisson regression modeling method was employed for count data evaluation as well as assessment of geometric design features. The model was selected on the basis of its ability to effectively assess count data of random, discrete and non-negative nature. The mathematical form is represented by the expression shown below[9]:

$$P(Y_i = y_i) = P(y_i) = \frac{(\mu_i)^{y_i} e^{-\mu_i}}{y_i!}, \quad (i = 1,2,3,\ldots n;\ y_i = 0,1,2,3,\ldots) \qquad (1)$$

where,

i = Roadway segment considered

Y_i = Number of truck crashes in a given time period for roadway segment *i*.

y_i = Actual number of truck crashes for a given time period for roadway segment *i*.

$P(y_i)$ = Probability of occurrence of truck crashes for a given time period on roadway segment *i*.

μ_i = Mean value of truck crashes occurring for a given time period, denoted as[9]:

$$\mu_i = E(y_i) = \vartheta_i \left[e^{\sum_{j=1}^{k} x_{ij}\beta_j}\right] \quad (2)$$

where,
x_{ij} = The j^{th} independent variable for roadway segment *i*.
β_j = The coefficient of the j^{th} independent variable.
ϑ_i = Traffic exposure for roadway segment *i*.

The traffic exposure for truck vehicles is denoted by the expression[9]:

$$\vartheta_i = 365 * AADT * T\%_i * l_i \quad (3)$$

where,
$AADT$ = Average annual daily traffic
$T\%_i$ = Percentage of trucks in traffic stream
l_i = Length of road section.

The variance-mean equality holds for Poisson regression and is thus fundamental.

$$Var(y_i) = E(y_i) = \mu_i \quad (4)$$

where,
$Var(y_i)$ = Variance of response variable.
$E(y_i)$ = Expected number of response variables
μ_i = Mean of the response variable

2.4 Variable Selection

The choice of variables for the model analysis was based on the following criteria:

i. Their relevance as determined from previous studies as a major influence on crash rates
ii. The feasibility of measuring such choice variables in a reliable manner
iii. Degree of correlation with other explanatory variables included.

The variables selected and subjected to statistical test using the model were: Horizontal curvature, Vertical grade, Roadway section length, lane width, AADT for trucks per lane and yearly dummy variables.

2.5 Model Validation

The Poisson regression model developed was tested for goodness of fit and equi-dispersion using Pearson Chi-square and Deviance statistics. The equations describing these parameters are as shown below[9]:

$$G^2 = 2\sum_{1}^{n} y_i In\left[\frac{y_i}{E(y_i)}\right] \quad (5)$$

where,
G^2 = Deviance
y_i = Observed number of truck crashes
$E(y_i)$ = Expected number of truck crashes
n = Number of road sections

The Chi-square equation is given by:

$$x^2 = \sum_{i=1}^{n} \frac{(y_i - \lambda_i)^2}{\lambda_i} \quad (6)$$

where,
y_i = Observed number of truck crashes
λ_i = Expected number of truck crashes
n = Number of road sections.

It is important to note that the value of Pearson Chi-square statistics divided by the associated degree of freedom must be equal to 1 to assume perfect model fitness and overall validity. However, in practicality, this is rarely obtainable. Hence, values closer to 1 are more readily acceptable as parameter estimates obtained remains valid [9]. In order to resolve problems associated with over-dispersion for the model based estimator, two fundamental steps were employed:

- Numerous zero count crash sections from the observed crash data were excluded from the model analysis as their inclusion had the tendency to invalidate the model [10,11]. Sections examined were those with significant truck crash record.
- The introduction of a scale (dispersion) parameter was also necessary to resolve the variance-mean equality principle and permit the estimation of parameters without full data using the quasi-likelihood approach method [12,13]. By so doing, the variance-mean equation was modified thus:

$$Var(y_i) = \tau\mu_i \quad (7)$$

where,
$Var(y_i)$ = Variance of response variable
τ = Dispersion parameter($\tau \geq 1$)
μ_i = Mean of the response variable y_i.

III. RESULTS AND DISCUSSION

3.1 Crash data presentation

From the FRSC data-base, the three truck vehicle configurations identified with significant haulage on the access roadways examined were: Single unit trucks (SU), Tanker trucks and Trailer trucks. The crash report for these vehicles on the plied roadways within the period of 2011 to 2015 is shown in Table 1.Figure 2 illustrates in percentages, the number of large truck crashes recorded, relative to other vehicles on plied limited access roadways in Edo State. As can also be seen in Figure 3, the chart depicts each truck crash frequency by vehicle configuration within the 5 year period investigated.

Table 1: Number of crashes involving large trucks on three limited access highways [8]

Routes	**Truck Crash Data from 2011-2015**			
	Single unit Truck (SU)	Tanker Truck	Trailer Truck	**Total**
Benin-Agbor	78	43	62	183
Benin-Ore	103	95	121	319
Benin-Sapele	95	31	51	177
Total	276	169	234	679
Percentages (By Vehicle Configuration)	40.65%	24.89%	34.46%	100%

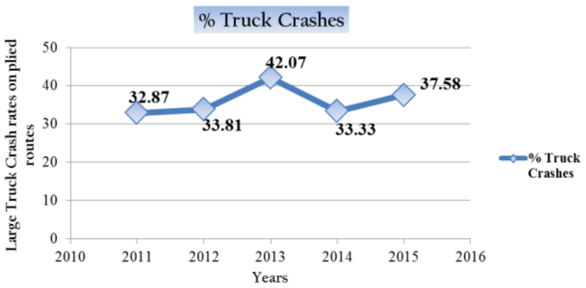

Figure 2: Percentage large truck crashes on access roadways in Edo state from 2011- 2015

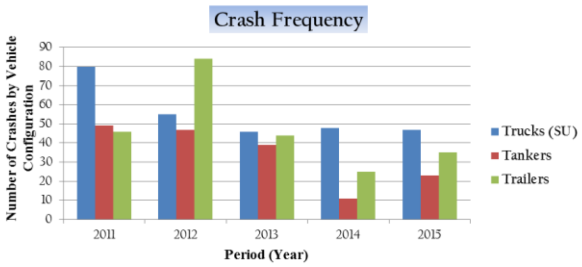

Figure 3: Crash Frequency by Truck Vehicle Configuration

3.2 Variable definition and descriptive statistics

A total of 152 road sections involving 679 large truck crashes were analyzed. The choice of variables for the truck-crash modeling was based on each roadway characteristics and attributes, previous research findings as well as engineering judgments. The variables used were those for which substantial data could be accessed and those for which measurements could be reasonably and reliably ascertained. The definitions of variables considered for each roadway selection along with their descriptive statistics is presented in Table 2.

Table 2: Variable definitions and associated statistics for Benin-Agbor, Benin-Ore and Benin-Sapele Roadways

Associated variables	**Descriptive Statistics**											
	Benin-Agbor				**Benin-Ore**				**Benin-Sapele**			
	min. value	max. value	mean (μ_i)	st.d (σ_i)	min. value	max. value	mean (μ_i)	st.d (σ_i)	min. value	max. value	mean (μ_i)	st.d (σ_i)
Truck mishap frequency (y_i)	2	17	5.33	2.40	4	21	8.35	3.16	2	15	4.93	2.42
Horizontal curvature (H_C) in degrees	0	17.79	4.33	4.08	0	13.46	3.03	2.34	0	3.65	1.50	1.04
Vertical grade (V_G) in percent	0	6.20	3.68	1.33	0	12.40	3.62	3.00	0	3.00	1.66	0.70
Section length (S_L) in kilometers	0.25	3.15	2.05	0.63	1.25	4.55	3.12	0.95	0.35	2.88	1.68	0.74
Lane width (L_W) in meters	2.95	3.65	3.55	0.15	2.95	3.65	3.20	0.18	2.75	3.65	3.25	0.41
Average Annual Daily Traffic per lane (Truck AADT/L)	609	913	752.6	114.2	367	617	486.7	81.1	466	829	645.7	134.1

Dummy variable (Y_2011)	0	1	0.69	0.47	0	1	0.77	0.43	0	1	0.68	0.47
Dummy variable (Y_2012)	0	1	0.65	0.48	0	1	0.70	0.46	0	1	0.58	0.50
Dummy variable (Y_2013)	0	1	0.64	0.49	0	1	0.70	0.46	0	1	0.52	0.50
Dummy variable (Y_2014)	0	1	0.67	0.47	0	1	0.70	0.46	0	1	0.58	0.50
Dummy variable (Y_2015)	0	1	0.62	0.49	0	1	0.60	0.50	0	1	0.60	0.49

3.3 Poisson regression model output

The relationship between the truck crashes observed and roadway geometric design features was depicted by the magnitude of the exponential effect for each variable considered at 0.05 significance level i.e. 95% confidence interval. Estimated coefficients greater than 1 indicated an increase in crash frequency with corresponding increase in variable size, while coefficients less than 1 indicated a decrease in the frequency with relative increase in variable size. On the other hand, estimates equal to 1 would mean no effect of the selected variable on crash frequency and the variable is otherwise regarded redundant.

Table 3 shows the exponential effects of each contributing variable for the roadway sections examined to observed truck crash frequency. From the table, it can be seen that the observed critical geometric design variables influencing truck haulage and safety as depicted by the model are: Horizontal curvature, Vertical grade,and Roadway lane width. Other variables such as AADT and Roadway section length were also seen to fall within the required significance level. However, they were not considered as important variables to be included in the model as for instance, AADT is a traffic phenomenon indicating volume trend and distribution for truck vehicles across road sections subject to flow rates; while the Roadway section length was marked by non-disparities in elements along portions of the roadway otherwise depicted as sections with homogenous design properties.

Table 3: Estimated coefficients from Poisson regression analysis for Benin-Agbor, Benin-Ore and Benin-Sapele roadway

Independent variables	**Description**	**Benin-Agbor Roadway**		**Benin-Ore Roadway**		**Benin-Sapele Roadway**	
		Exponential Effect (Parameter Estimate)	P-value/ significance level (0.05)	Exponential Effect (Parameter Estimate)	P-Value / significance level (0.05)	Exponential Effect (Parameter Estimate)	P-Value / significance level (0.05)
H_C	Horizontal curvature (°)	1.141 (14.1%)	0.001	1.083 (8.3%)	0.001	1.086	0.059
V_G	Vertical grade (percent)	1.040 (4.0%)	0.013	1.027 (2.7%)	0.036	0.990	0.187
S_Length	Section length (km)	1.025 (2.5%)	0.025	1.031 (3.1%)	0.031	1.046 (4.6%)	0.033
L_Width	Lane Width (m)	0.832 (-6.8%)	0.038	0.886 (-11.4%)	0.041	0.963 (-3.7%)	0.045
AADT_L	AADT per lane	1.191 (19.1%)	0.010	1.111 (11.1%)	0.019	1.061 (6.1%)	0.037
Y_2011	Dummy for 2011	0.838	0.002	0.892	0.042	0.891	0.216
Y_2012	Dummy for 2012	0.885	0.034	0.901	0.099	0.820	0.013
Y_2013	Dummy for 2013	0.900	0.063	0.868	0.030	0.635	<0.001
Y_2014	Dummy for 2014	0.913	0.105	0.825	0.010	0.728	<0.001
Y_2015	Dummy for 2015	0.882	0.051	0.989	0.862	0.999	0.992
				Goodness-of-Fit			
Criterion		Value	Value/D.F.	Value	Value/D.F.	Value	Value/D.F.
Deviance (G^2)		61.676	1.371	57.387	1.551	51.920	1.298
Chi-square (x^2)		63.716	1.416	60.606	1.638	53.561	1.339
Scaled Deviance		33.269	0.739	28.836	0.779	33.471	0.837
Scaled Chi-square		45.000	1.000	37.000	1.000	40.000	1.000
Number of observations		55		47		50	

Amongst the three geometric design variables, the Horizontal curvature was seen to be the most critical, having a significance level of 0.001 for the Benin-Agbor and Benin-Ore roadways. This implies that for these routes, the trucks were unable to complete maneuvers with ease due to short tangent lengths across some sections, thereby resulting in crashes. This inference is coherent with findings made by notable researchers [9,14]. Next was the Vertical grade, which had a significance level of 0.013 and 0.036 for the Benin-Agbor and Benin-Ore roadways respectively. For the Benin-Sapele roadway, the Horizontal curvature and Vertical grade did not have any significant effect on the truck crashes as it did for the other two roadways. The exponential effect of the lane width on the model was less than one for all the roadways, which implies that the narrower the lane width the higher the possibility of truck crash occurring.

IV. CONCLUSION

From the results obtained in the study, it was observed that the critical geometric design parameters which influenced the accommodation and safe haulage of large truck vehicles were the degree of horizontal curvature, vertical grade and lane width. Findings from the three examined routes inferred the following:

- Narrow and or reduced lane widths along plied sections resulted in the truncation of roadway capacity and congestions especially during peak travel hours.
- Poor roadway geometric alignments along some sections of the roadways contributed to truck haulage difficulties and crashes. Where sharp curves were present, trucks were unable to complete maneuvers with ease due to their length and crashes were imminent. On steep vertical grades, truck vehicles likely travelled at slower speeds increasing the tendency for smaller faster vehicles to overtake more frequently, resulting in mishaps.
- Higher Annual Average Daily Traffic (AADT) per lane indicated increased likelihood to contribute to truck crash susceptibility because of traffic build up for other vehicles and road users since the speed of travel, safety, comfort and convenience are generally affected.

Based on these findings, it is recommended that:

- Adequate consideration should be given to present truck vehicle configuration in implementing design features for roadways with significant traffic haulage condition.
- Exclusive truck lanes and alternative routes should be considered in the development of highway infrastructure to mitigate the effect of increasing truck traffic on roadways.
- Regular assessment of geometric design features on significant truck haulage routes is necessary to aid data collation in order to effectively carryout design reviews.

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