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Improving Roadway Operations and Safety for Large Truck Vehicles by Optimizing some Critical Geometric Design Parameters

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ABSTRACT

Large truck vehicles are constrained by their physical and operational attributes such as length, width, height and axle loading, which affect their performance on highway infrastructure. In recent times, car-truck and truck only crashes have increased due to the complex interactions of such vehicles on geometrically deficient roadway systems. By adjusting geometric design parameters in accordance with stipulated requirements across deficient roadway sections it is possible to estimate using crash rate index the degree of improvements observed. A total of 189.4 kilometers of three roadway lengths (Benin-Ore, Benin-Agbor and Benin-Sapele) were investigated for geometric design deficiencies across crash sections. Adjustments were made using AAHSTO design specifications based on speed limit, terrain type and roadway functional class for three critical geometric design parameters namely: degree of horizontal curvature, vertical grade and roadway lane width. Comparison of parameter estimates before and after adjustments showed corresponding cumulative percentage improvements of 6.5%, 13% and 4.7% for Benin-Ore, Benin-Agbor and Benin-Sapele roadways respectively. This implies that adjustments to critical design parameters at deficient roadway sections can help in mitigating large truck crash rates and allow for better accommodation and operation of such truck vehicles on plied roadways.

Keywords: highway infrastructure, highway improvement, geometric design parameters, Nigerian highways, truck crash rates.

1.0. Introduction

The necessity of highway geometric design is to cater for the safe operation of vehicles of known configuration. When plied road sections are geometrically deficient, there is an increased likelihood that the safety of road users will be jeopardized. The AASHTO highway design manual (AASHTO, 2011) recognizes four (4) different classes of vehicles for which roadways may be designed for. These include: passenger cars, buses, trucks, and recreational vehicles. Large trucks otherwise referred to as long combination vehicles (LCVs) represent the most complex design vehicles due to their overall physical dimensions and operational attributes (Elefteriadou et al., 1997). Sections of existing roadway systems with small curb return radii at intersections and interchanges, steep vertical grades as well as narrow or reduced lane widths pose haulage difficulty and high crash susceptibility for large truck vehicles especially among traffic mix on significantly plied routes (Galadima et al., 2017).

Harkey et al. (1996) documented several operational characteristics of long combination vehicles, including their off-tracking tendency, stability, speed, acceleration, braking and stopping distance, believed to have impact on transportation safety as well as close relationship to geometric design.

The study was geared towards understanding how such large truck vehicles operate in order to better accommodate them through geometric design or regulate them through more stringent laws and better enforcement. The operational characteristics of these vehicles have an impact on transportation safety and relationship with geometric design features. The authors suggested the need for additional study in the following areas:

i. The operation of large truck vehicles on road sections with poor horizontal and vertical grades.
ii. The operation of LVCs on congested freeways and
iii. The operation of such vehicles on rural and urban roadway intersections.

These were suggested in order to foster geometric design improvements to critical parameters on freeway road systems facilitating significant traffic movement.

Miaou and Lum, (1993) developed a Poisson regression based model to evaluate the effects of highway geometric design on truck accident involvement rates on rural interstate highways in Utah and to quantify the uncertainties of the expected reductions in truck accident involvement from the improvements in highway geometric design. The analyses gave predictions for the number of truck accident reductions due to improvements in geometric design elements such as: horizontal curvature, vertical grade and paved inside shoulder width for roadway sections.

On many interstate roadway systems in Nigeria, these design elements are often deficient or inadequately designed for in accordance with standard design practices stipulated by AASHTO. Roadway shoulder widths for instance may be unavailable or inconsistent across road sections with average width sometimes spanning from 1.0 to 1.5m which falls short of the minimum truck design vehicle (WB-15) width of 2.6m. By investigating selected roadway systems it is intended to check via estimates the degree of improvements recorded in order to foster truck safety through adjustments to some geometrically deficient elements (degree of horizontal curvature, vertical grade and lane width) across sections. Due to lack of data availability and consistency, roadway shoulder width was not included as a critical parameter.

2.0. Methodology

2.1. Data Collection and Route Selection

The Federal Road Safety Commission (FRSC), Ikpoba Hill zonal division in Benin City, Edo State, furnished the primary crash data for the routes investigated. The focal point of this study was constrained to two and three lane (divided) access roadways with flow rates across sections averaging 3000 or above vehicles per day per lane relative to average daily traffic (ADT). From the data source, Benin-Agbor (2-lane), Benin-Ore (3-lane) and Benin-Sapele (2-lane) were the most significant truck haulage routes recording a total of 679 large truck crashes observed between years 2011 to 2015. With the aid of roadway navigational softwares such as Google maps, Google earth and Geographic Information System (GIS), these roadway layouts indicating geometrically deficient sections were identified. Also, the observed crash areas for each roadway were identified.

2.2. Method

The three (3) critical geometric design elements identified from the route layouts investigated were: degree of horizontal curvature, vertical grade and roadway lane width. The degree of horizontal curvature was obtained from the radius of curvature via curve lengths, central angles and super-elevations associated with each horizontal alignment across roadway chainages. This parameter was defined by the central angle subtended by an arc, mathematically expressed as (Ficker and Whitford, 2005):

$$\frac{D}{360} = \frac{100}{2\pi R} \; ; \; D = \frac{36000}{2\pi R} = \frac{5729.6}{R} \qquad (1)$$

where:

D = Degree of horizontal curvature,

R = Radius of curvature.

The vertical grades across road sections were identified by slope change and presence of an angle or inflection point across sections. On the other hand, the roadway lane width was obtained via GIS navigational software and direct observation and measurement upon inspections across sections.

Throughout each roadway layout across chainages, these geometric design elements were investigated for design deficiencies on the basis of each roadway functional class, design speed as well as terrain condition in accordance with AASHTO's geometric design policy (AASHTO, 2001). The calibration of design variables was carried out for statistically significant parameters. The descriptive statistics for the data-base employed through the calibration process is given in Table 1 below.

Table 1: Descriptive Statistics for significant Roadway Variables

Variables	Benin-Ore Roadway			
	Average (μ_i)	**Std. Dev. (σ_i)**	**Minimum**	**Maximum**
Crash frequency (yi)	8.35	3.16	4	21
Vehicular Average daily Traffic per lane (ADT/L)	3351.13	2109.17	1,850	11,972
Section length (km)	3.12	0.95	1.25	4.55
Horizontal Curvature (°)	3.03	2.34	0	13.46
Vertical Grade (%)	3.62	3.00	0	12.40
Lane Width (m)	3.20	0.20	2.95	3.65
Variables	**Benin-Agbor Roadway**			
	Average (μ_i)	**Std. Dev. (σ_i)**	**Minimum**	**Maximum**
Crash frequency (yi)	5.33	2.40	2	17
Vehicular Average daily Traffic per lane (ADT/L)	3027.14	1178.05	1,826	14,912
Section length (km)	2.05	0.63	0.25	3.15
Horizontal Curvature (°)	4.33	4.08	0	17.79
Vertical Grade (%)	3.68	1.33	0	6.20
Lane Width (m)	3.55	0.15	2.95	3.65
Variables	**Benin-Sapele Roadway**			
	Average (μ_i)	**Std. Dev. (σ_i)**	**Minimum**	**Maximum**
Crash frequency (yi)	4.93	2.42	2	15
Vehicular Average daily Traffic per lane (ADT/L)	3987.67	2104.66	3,730	17,760
Section length (km)	1.68	0.74	0.35	2.88
Horizontal Curvature (°)	1.50	1.04	0	3.65
Vertical Grade (%)	1.66	0.70	0	3.00
Lane Width (m)	3.25	0.41	2.75	3.65

3.0. Results and Discussions

3.1. Critical Geometric Parameters of Routes Examined

Three (3) significant truck haulage routes were investigated over a combined length of 189.4 km. Records obtained from the FRSC crash data base indicate that 679 large truck crashes were recorded within a five (5) year period, from 2011 to 2015 (FRSC, 2016). The critical geometric design parameters observed to be deficient across each roadway crash section were: degree of horizontal curvature, vertical grade and roadway lane width.

Table 2 shows the roadway lane width for sections of the road where large truck crashes were observed to be prevalent. From the table, it can be seen that the roadway lane widths measured for all the affected sections fall below the minimum lane width of 3.65m for urban roads, as prescribed by AASHTO. Of the three roadways studied, the Benin-Agbor road was observed to contain the highest number of sections with large truck crash prevalence, followed by the Benin-Ore road. However, comparing the lane widths of both roads, as seen in Table 1, it can be seen that the average lane width of the Benin-Ore road is lesser than that of the Benin-Agbor road. This would explain why the crash frequency was higher for the Benin-Ore road as compared with the Benin-Agbor road.

Table 2: Chainages indicating roadway lane width on sections with large truck crash prevalence

Benin-Ore (94 km)			Benin-Agbor (50.8 km)			Benin-Sapele (44.6 km)		
Chainages		**Roadway lane width (m)**	**Chainages**		**Roadway lane width (m)**	**Chainages**		**Roadway lane width (m)**
From	To		From	To		From	To	
11.5	13	3.27	4.5	5.4	3.25	13.5	15	2.75
13.7	14.6	3.15	5.5	6.5	3.25	17	19	2.95
35	46	2.95	7	7.5	3.25	20	21	2.77
59.5	62.3	2.97	9	9.4	3.27	24	27	3.25
72.8	73.8	3.25	10	10.6	3.25	30	33	3.10
74	76.6	3.25	15	15.7	3.05	38	40	3.15
78	81	3.11	16.4	16.8	3.10	42	43	3.00
84	85	3.45	19	20	2.95			
86	87	3.33	29	29.4	3.25			
90	90.5	2.98	30	30.7	3.15			
			32	33	3.55			
			40	40.9	3.27			

Table 3 shows the degree of horizontal curvature for the sections of the roadway where large truck crash was prevalent. As observed in Table 2, the Benin-Agbor road also contained the highest number of affected sections, followed by the Benin-Ore road. The maximum degree of horizontal curvature as recommended by AASHTO (2001) is 6°. Of the three roads studied, only the Benin-Sapele road met with this requirement. This explains why it had the lowest crash frequency, as seen in Table 1.

Table 3: Chainages indicating degree of horizontal curvature on sections with large truck crash prevalence

Benin-Ore (94 km)			Benin-Agbor (50.8 km)			Benin-Sapele (44.6 km)		
Chainages		**Degree of horizontal curvature (°)**	**Chainages**		**Degree of horizontal curvature (°)**	**Chainages**		**Degree of horizontal curvature (°)**
From	To		From	To		From	To	
11.5	13	2.34	4.5	5.4	5.97	13.5	15	2.01
13.7	14.6	13.46	5.5	6.5	6.72	17	19	1.99
59.5	62.3	1.57	7	7.5	17.79	24	27	1.11
72.8	73.8	2.74	9	9.4	14.33	30	33	1.88
74	76.6	1.74	10	10.6	9.81	38	40	3.65
78	81	1.00	15	15.7	6.73	42	43	2.92
84	85	5.60	16.4	16.8	13.33			
86	87	1.12	29	29.4	13.68			
90	90.5	6.33	30	30.7	11.78			
			32	33	2.50			
			40	40.9	3.01			

The vertical grade of sections where large truck crashes were observed is shown in Table 4. Again, the Benin-Agbor road was seen to have the highest number of affected sections. A value of 12.4% was recorded in the Benin-Ore road. This is far higher than the value recommended by AASHTO, which is 3.0%, and will thus explain why this road recorded the highest truck crash rate.

3.2. Parameter Estimation

The Poisson's regressions modeling method was employed to ascertain parameter estimates for the investigated variables at 95% confidence interval (Galadima et al., 2017), before experimental adjustments were made to critical design parameters across observed deficient crash sections in order to meet optimum design specifications outlined by AASHTO's geometric design policy (AASHTO, 2001).

The identified critical geometric design parameters (horizontal curvature, vertical grades and lane width) were adjusted along roadway sections that were observed to be deficient so as to follow required standards that would facilitate enhanced accommodation and safety of such large trucks vehicles on roadways. The criterion for the adjustments was in accordance with AASHTO's geometric design policy (AASHTO, 2001) based on design speed limits (80 - 110 km/h), terrain condition (plain/level) and roadway functional class (free-ways). The maximum degree of horizontal curvature and vertical grade was set at 6° and 3% respectively, while minimum lane width was set at 3.65 m. Estimates at significance level beyond 0.05 benchmark were regarded redundant with no improvements recorded.

Table 4: Chainages indicating vertical grade on sections with large truck crash prevalence

Benin-Ore (94 km)			Benin-Agbor (50.8 km)			Benin-Sapele (44.6 km)		
Chainages		Vertical curvature (%)	Chainages		Vertical curvature (%)	Chainages		Vertical curvature (%)
From	To		From	To		From	To	
10.8	15.2	12.4	5.4	6.7	5.0	18.2	20.2	3.0
24.7	39.3	8.7	6.7	7.6	6.2	43	44.6	3.0
42.6	44.8	4.3	8.8	9.6	3.4			
49	51.3	3.7	9.6	10.5	3.0			
58.6	62	2.6	15.2	15.9	5.8			
79.6	82.7	1.3	15.9	16.6	5.5			
			17.4	18.6	2.8			
			18.6	19.5	4.4			
			28.5	29.6	4.9			
			29.6	30.8	4.5			

Table 5 shows the degree of improvement obtained when the identified critical geometric design parameters were adjusted in line with AASHTO's geometric design policy. Cumulatively, the total estimated truck crash reduction rate from geometric design variable improvement was 6.5% for Benin-Ore roadway, 13% for Benin-Agbor roadway and 4.7% for Benin-Sapele roadway. As shown by these estimates, it can be deduced that adjustments to critical design parameters at roadway sections found to be deficient can yield positive effects in mitigating large truck crash frequency and allow for better accommodation and operation of such truck vehicles on plied roadways thereby improving safety and convenience.

Table 5: Estimated Degree of Improvement for Critical design parameters

Benin-Ore				
Critical variables	**Significance level (0.05)**	**Initial parameter estimate**	**Adjusted parameter estimate**	**Degree of improvement**
H_C (adjusted max. = 6°)	<0.0001	1.083	1.047	3.6%
V_C (adjusted max.= 3%)	0.036	1.027	1.011	1.6%
L_W (adjusted min.) =3.65m	0.041	0.886	0.873	1.3%
Benin-Agbor				
Critical variables	**Significance level (0.05)**	**Initial parameter estimate**	**Adjusted parameter estimate**	**Degree of improvement**
H_C (adjusted max.= 6°)	<0.0001	1.141	1.076	6.5%
V_C (adjusted max.= 3%)	0.013	1.040	1.018	2.2%
L_W (adjusted min.) =3.65m	0.038	0.832	0.789	4.3%
Benin-Sapele				
Critical variables	**Significance level (0.05)**	**Initial parameter estimate**	**Adjusted parameter estimate**	**Degree of improvement**
H_C (adjusted max.= 6°)	0.59	1.086	N/A	N/A
V_C (adjusted max.= 3%)	0.187	0.990	N/A	N/A
L_W (adjusted min.) =3.65m	0.045	0.963	0.916	4.7%

In Table 5, H_C = Horizontal curvature in degrees, V_C = Vertical grade in percent, L_W = Lane width in meters.

The estimated degree of improvement with respect to truck crash reduction rate on the plied roadways was carried out for tested critical variables only. However, other variables identified by previous researches (Dissanayake and Niranga, 2012; Schneider et al., 2009; Milton et al., 1996), that were of significant effect to large truck haulage such as roadway shoulder widths (left and right), median width, super-elevation on horizontal curves, and posted speed limits were omitted due to data unavailability or inconsistency with measured roadway sections. Overall, the improvement of these geometric design features proffers reasonable measures to highway designers and policy makers in alleviating safety concerns and boosting operational requirements for existing and future truck vehicle configurations.

4.0. Conclusion

The safety of highway infrastructure is of paramount importance to vehicle operators and other road users hence highway designers often engage measures, practices and reviews to promote improvements in this regard. Large truck vehicles can pose problematic consequences particularly on geometrically deficient roadway segments due to their unique physical and operational attributes. Though legislations may be put in place to restrict the operation of these vehicles on significant traffic routes especially during peak travel hours, this measure appears seemingly inadequate to curb undesirable roadway effects resulting from their haulage. Hence geometric design improvements to better accommodate these truck vehicles represents a dynamic and efficient approach to mitigating roadway mishaps thereby enhancing safety.

From this study, three key elements were crucial to large truck haulage improvement for the roadways examined (Benin-Ore, Benin-Agbor and Benin-Sapele). Optimizing them across deficient roadway sections in accordance with AASHTO geometric design specifications yielded positive results (6.5%, 13% and 4.7% respectively) associated to crash rate reduction.

To improve vehicular operations and safety by mitigating traffic effects on roadway systems, alternative freight haulage means should be adopted. Waterways and rail transportation represent viable options if efficiently harnessed.

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