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Evaluating the Geometric Design Consistency and Road Safety on Two-lane Single Carriageways Using Operating Speed Criteria

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Abstract

This work focuses on two-lane single carriageways that contain sections, which make transition from one geometric feature to another unsafe, and thereby resulting in driving errors that may eventually lead to driving off course and accidents. The two-lane single carriageway selected for the study was the Ekiadolor-Olumoye-Uhen road, a rural highway in Edo State, Nigeria. Alignment data such as curve radius, length of curve, beginning and end point of curve, as well as vertical slope, were obtained from satellite imageries using Geographic Information System (GIS); while the operating speed reduction (ΔV_{85}) between tangents and curves was estimated at various sections of the selected route. These data were used as input parameters in generating an Accident Prediction Model. The model was generated using the Generalized Linear Regression Modelling (GzLM) approach. The results obtained from the study showed that the curves between sections 11.4 – 11.9km, 21.5 – 22.0km and 24.0 – 24.5km, fell slightly short of the criteria of a good design and therefore required warning signs to be placed before the transitions; whereas the curves between sections 16.8 – 17.4km and 26.6 – 27.8km, fell very short of the criteria of a good design, and were classed as poorly designed.

1.Introduction

According to [1], the goal of transportation is to ensure the safe and efficient movement of people and goods. To achieve this goal, designers use many tools and techniques, one of which is to improve the safety on roadways by examining the consistency of the design.

Design consistency refers to the conformance of highway geometry with driver expectancy. It is generally known that drivers make fewer errors at geometric features that conform to their expectations than at features that violate their a priori and/or ad hoc expectancies. In the study by [2], it was stated that the most important single rule in highway design is consistency. Only by making every element conform to driver's expectation and by avoiding abrupt changes in standards can a smooth-flowing, collision-free facility be produced. Even the [3] maintains that sudden reductions in standards should be avoided as these introduce the element of surprise to the driver.

A consistent design avoids abrupt changes in operating speed over a short period of time and in geometric feature of adjacent highway elements. Its successive elements act in coordinated way to produce harmonized driver performance. It ensures that the expectancy or ability of the motorist to guide and control a vehicle in a safe manner is not violated [4, 5, 6]. On the other hand, an "*inconsistency in design"* according to [6] and [7] can be described as a geometric feature or combination of features with unusual or extreme characteristics that drivers may drive in an unsafe manner. This situation could lead to speed errors, inappropriate driving manoeuvres, and/or an undesirable level of accidents. Lamm et al. [8] reported that half of all the collisions on two-lane rural highways may be indirectly attributed to inadequate speed adaptation, indicating that design consistency is related to safety.

Yet, despite the importance of geometric design consistency to road safety, it is not always ensured in current design practice. One of the main sources of inconsistency in design is inherent in geometric design standards, which are developed based on the design speed concept. This concept has been in use since the 1930s and is still in use today. The major problem with the design speed concept is that the design speed is not the maximum permissible safe speed; hence, adherence to it may not be guaranteed. The design speed can only be applied to horizontal curves and has no practical meaning to tangents, except when physical highway characteristics limit the speed of travel. Consequently, on low speed roads, drivers can reach an operating speed on a tangent that is much higher than the design speeds of the horizontal curves at its either ends. Therefore, driver's expectation may be violated due to geometric design inconsistency at such transitions. Unfortunately, current design standards do not consider proper coordination among individual geometric features along a highway to ensure design consistency. For example, in the Nigerian, the American and even the Canadian design standards [3, 9, 10], there is no provision of maximum tangent lengths to control the maximum operating speeds attainable.

With a relatively high number of sources of design inconsistency in current geometric design practice, it is necessary to carry out evaluation of inconsistencies of existing alignments to determine their safety [11]. Several researchers have pointed out that treating inconsistencies in highway alignments can significantly improve their safety performance [12]. However, in the aspect of developing countries like Nigeria, very few studies have been done in this regard. This paper evaluated the geometric design consistency on the alignment of Ekiadolor-Olumoye-Uhen road (a rural highway in Edo State, Nigeria), with a view of identifying inconsistent sections on the alignment that can be targeted for improvement and redesign where necessary.

2. Methodology

2.1 The Study Area

The selected route for the study was the Ekiadolor-Olumoye-Uhen road, which is a rural highway located in Ovia North-East Local Government Area (LGA) of Edo State, Nigeria (see Figure 1). It starts off the Benin–Lagos Expressway and runs through twelve (12) communities. It has a total length of 36.2 km and an average daily traffic of about 730 vehicles per day. It has a very peculiar alignment (see Figure 2) – comprising of numerous curves – hence, it was selected for this study.

Figure 1: Location of study area (Google Earth)

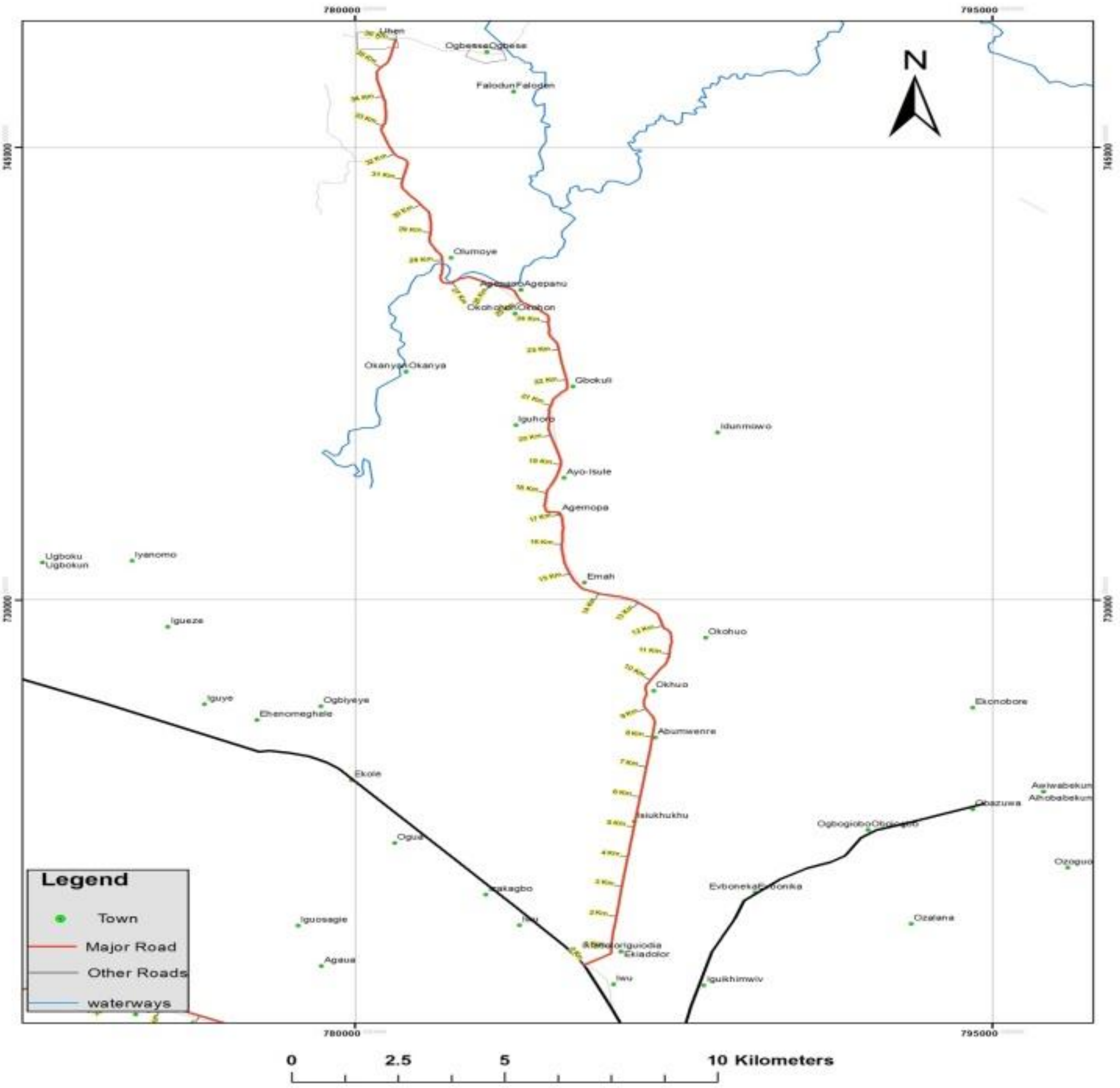

Figure 2: Layout of selected route as obtained from ARCGIS

2.2 Data Collection

Satellite imageries were obtained and digitized to determine the alignment data such as radius of curvature (R), vertical slope (%), beginning of curve (PC), end of curve (PT), length of curve (L_c), the approach and departure tangent lengths associated with each curve.

2.3 Measures of Quantifying Design Consistencies

There are four main measures of quantifying design consistency. These are: Operating speed; Vehicle stability; Alignment indices; and Driver workload.

For this study, the operating speed criterion was used. Operating speed is defined as the speed selected by highway users when not restricted by other road users. Lamm et al. [13] argued that speed errors may be related to inconsistencies in highway alignment that cause the driver to be surprised by sudden changes in the road's characteristic, to exceed the critical speed of a curve and to lose control of the vehicle. These inconsistencies can and should be controlled by the engineer, when a roadway section is designed or improved. Therefore, the primary interest of the engineer is

to develop methodologies suitable for estimating the speed behavior of drivers. The traditional approach to evaluating design consistency is based on calculating the operating speed of the drivers separately on the curved and the tangent sections. Speed differential between curve and tangent is used to evaluate the consistency in the transition between two successive geometric elements [14]. The consistency in the transition between two successive geometric elements is evaluated by the speed differential between curve and tangent, which is usually expressed as the absolute difference in the 85th percentile operating speeds (ΔV_{85}) between successive highway geometric elements.
The speed reduction between two successive elements (ΔV_{85}) was estimated using the model proposed by [15].

$$\Delta V_{85} = 0.9433DC + 0.0847DF; \qquad R^2 = 0.92 \qquad (1)$$

where:
ΔV_{85} = speed reduction between tangent and of curve (km/h);
DC = degree of curvature (degrees) expressed in degree per 30 m;
DF = deflection angle (degree).

2.4 Accident Prediction Model Development

An Accident Prediction Model was developed in this study incorporating the design consistency measure (speed reduction, ΔV_{85}). Accident data were collected from The Nigerian Police Force (Ekiadolor Division). Twenty-one (21) sections, which include eleven (11) curves and ten (10) non-independent tangents, were considered for the model development. The generalized linear regression modelling (GzLM) approach was adopted for the model development.
GzLM has the advantage of overcoming the limitations associated with the use of conventional linear regression in modeling accident occurrence; and is random, discrete, and non-negative in nature.
The approach adopted for this study was based on the work of [16,17,18].
Let *Y* be a random variable that represents the number of accidents at a location in a specific time period, and assume it follows the Poisson distribution with parameter *X*. Let Λ be the variable that represents the mean of the Poisson distribution, such that Λ = λ.
Hauer et al. [16] showed that for an imaginary group of locations of similar characteristics, Λ can be regarded as a random variable, which follows the gamma distribution with parameters κ and κ/μ. The mean and variance can be obtained from the expressions given below:

$$E(\Lambda) = \mu \qquad (2)$$

$$Var(\Lambda) = \frac{\mu^2}{\kappa} \qquad (3)$$

The variance obtained from the above expressions is equal to the expected value only when κ approaches infinity.
The Pearson χ^2 statistic and the scaled deviance (SD) were used to assess the goodness of fit of the developed accident prediction model. The scaled deviance is computed depending on the error structure. If the error structure follows the Poisson distribution, the scaled deviance (SD) is obtained using Equation (4) and if the error structure follows the negative binomial distribution, Equation (5) is used to obtain the scaled deviance (SD) as follows:

$$SD = 2\sum_{i=1}^{n}[y_i \ln\left\{\frac{y_i}{E(\Lambda)_i}\right\}] \qquad (4)$$

$$SD = 2\sum_{i=1}^{n}[y_i \ln(\frac{y_i}{E(\Lambda)_i}) - (y_i + \kappa)\ln(\frac{y_i+\kappa}{E(\Lambda)_i+\kappa})] \qquad (5)$$

where:
SD = scaled deviance,
y_i = observed number of collisions on section i,

E(Λ) = predicted number of collisions on section i, and
κ = shape parameter of the gamma distribution which the imaginary group follows.

3. Results and Discussion

3.1 Results from reconnaissance survey

The results presented in Table 1 were obtained from reconnaissance survey coupled with remote sensing and use of GIS software.

Table 1: Alignment data obtained for the selected route

Chainage (km)		Linear Radius (m)	Slope (%)
From	To		
8.2	8.9	593.92	1.2
9.0	9.5	534.94	0.9
11.4	11.9	368.79	1
14.0	15.0	840.58	3.6
16.8	17.4	236.77	0.5
18.5	19.5	1063.29	0.9
21.5	22.0	368.27	1.7
23.1	24.0	868.46	3
24.0	24.5	340.19	2.6
25.0	26.0	676.96	2.4
26.6	27.8	226.34	1.2

From Table 1, the minimum curve radius (226.34m) occurs between km 26.6 and km 27.8 whereas the maximum radius of 1063.29m occurs between km 18.5 and km 19.5. The table also shows that the slope has a minimum value of 0.5% (between km 16.8 and km 17.4), and a maximum value of 3.6% occurring between km 14.0 and km 15.0.

3.2 Alignment Indices

Table 2 shows the summary of the alignment indices for the sections from km 8.2 to km 27.8 of the Ekiadolor-Olumoye-Uhen road.

Table 2: Alignment indices for section 8.2 – 27.8km of the selected route

Minimum Radius (m)	226.34
Maximum Radius (m)	1063.29
Average Radius (m)	556.23
Ratio of Maximum Radius to Minimum Radius	4.70
Average Tangent Length (m)	1063.29
Average Curve Change Rate CCR (gon/km)	98.64
Average Degree of Curvature (DC)=5729.58/R	10.30
Average Workload (WL) = 0.193+0.016*DC	0.36

3.3 Geometric Design Consistency Evaluation Based on Speed Reduction Criterion

The speed reduction between successive geometric elements (ΔV_{85}) was calculated using the expression in Equation 6.

$$\Delta V_{85} = 0.9433DC + 0.0847DF \quad (6)$$

DC and DF represent Degree of Curvature and Deflection Angle respectively, both of which are given in Tables 3 and 4 respectively, for the Ekiadolor-Olumoye-Uhen road.
According to this evaluation, a geometric design can be classed as good, fair or poor, as follows:

- *Good design:* ΔV_{85} < 10 km/h (Consistency)
- *Fair design:* 10 km/h < ΔV_{85} < 20 km/h (Minor Inconsistency; traffic warning devices required)
- *Poor design:* ΔV_{85} > 20 km/h (Strong Inconsistency; redesign recommended)

Table 3: Degree of Curvature (DC) for section 8.2 – 27.8km of the selected route

Chainage (km)		Linear Radius (m)	Degree of Curvature (DC) = $\frac{5729.58}{R}$
From	To		
8.2	8.9	593.92	9.65
9.0	9.5	534.94	10.71
11.4	11.9	368.79	15.54
14.0	15.0	840.58	6.82
16.8	17.4	236.77	24.20
18.5	19.5	1063.29	5.39
21.5	22.0	368.27	15.56
23.1	24.0	868.46	6.60
24.0	24.5	340.19	16.84
25.0	26.0	676.96	8.46
26.6	27.8	226.34	25.31

Table 4: Deflection Angle (DF) for section 8.2 – 27.8km of the selected route

Chainage (km)		Linear Radius (m)	Deflection Angle (DF) = $\frac{L^2}{6xRxLs}$
From	To		
8.2	8.9	593.92	0.2
9.0	9.5	534.94	0.2
11.4	11.9	368.79	0.2
14.0	15.0	840.58	0.2
16.8	17.4	236.77	0.4
18.5	19.5	1063.29	0.2
21.5	22.0	368.27	0.2
23.1	24.0	868.46	0.2
24.0	24.5	340.19	0.2
25.0	26.0	676.96	0.2
26.6	27.8	226.34	0.9

The geometric design consistency evaluation using the Speed Reduction criterion, between geometric elements (ΔV_{85}), is presented in Table 5. From the evaluation of the geometric design consistency of Ekiadolor-Olumoye-Uhen road using Speed Reduction criterion (as shown in Table 5), it can be seen that speed reduction at km 11.4-11.9, km 21.5-22.0 and km 24.0-24.5 exceed 10km/h but is less than 20km/h and are therefore categorized as fair design. These, therefore require warning signs. However, speed reduction at km 16.8-17.4 and km 26.6-27.8 exceed 20km/h. These on the other hand, are categorized as poor design, and should be redesigned.

Table 5: Geometric design consistency evaluation for the selected route using the speed reduction criterion

Chainage (km)		Linear Radius (m)	ΔV_{85}=(0.9433*DC)+(0.0847*DF)	Criterion
From	To			
8.2	8.9	593.92	9	*Good design*
9.0	9.5	534.94	10	*Good design*
11.4	11.9	368.79	15	*Fair design*
14.0	15.0	840.58	6	*Good design*
16.8	17.4	236.77	23	*Poor design*
18.5	19.5	1063.29	5	*Good design*
21.5	22.0	368.27	15	*Fair design*
23.1	24.0	868.46	6	*Good design*
24.0	24.5	340.19	16	*Fair design*
25.0	26.0	676.96	8	*Good design*
26.6	27.8	226.34	24	*Poor design*

3.3 Model Relating Speed Reduction (ΔV_{85}) to Safety

Accident occurrence per five (5) year period (Acc/5yrs) was selected as the dependent variable while section length (L), degree of curvature (DC) and Speed Reduction between design elements (ΔV_{85}) were selected as the independent variables. Table 6 shows the summary statistics of data used for model development.

Table 6: Summary statistics of data used for model development

Continuous Variable Information						
		N	Minimum	Maximum	Mean	Std. Deviation
Dependent Variable	Accident per 5years period	21	0	4	0.81	1.21
Covariate	Section Length (km)	21	0	2.1	0.93	0.60
	Degree of curvature (°)	21	0	25	6.95	8.35
	Change in Speed (km/hr)	21	0	24	9.76	6.29

A model which relates Speed Reduction between design elements (ΔV_{85}) to safety is presented in Table 7.

Table 7: Model Showing the Relationship between Speed Reduction ΔV85 and Safety

Parameter Estimates										
			90% Wald Confidence Interval		Hypothesis Test				90% Wald Confidence Interval for Exp(B)	
Parameter	B	Std. Error	Lower	Upper	Wald Chi-Square	df	Sig.	Exp(B)	Lower	Upper
(Intercept)	-4.94	1.13	-6.79	-3.09	19.23	1	0.00	0.007	0	0.05
L	2.78	0.59	1.81	3.75	22.15	1	0.00	16.13	6.1	42.62
DC	-0.01	0.06	-0.1	0.09	0.018	1	0.89	0.99	0.91	1.09
ΔV_{85}	0.13	0.07	0.01	0.24	3.042	1	0.08	1.13	1.01	1.28
(Scale)	.428									
(Negative binomial)	1									
Dependent Variable: Accident per 5years period (Acc/5yrs)										
Model: (Intercept), Section length (L), Degree of Curvature (DC) and Speed Reduction (ΔV_{85})										

Goodness of Fit			
	Value	df	Value/df
Deviance	6.502	17	0.382
Scaled Deviance	15.188	17	
Pearson Chi-Square	7.277	17	0.428
Scaled Pearson Chi-Square	17	17	
Log Likelihood	-19.093		
Adjusted Log Likelihood	-44.6		
Akaike's Information Criterion (AIC)	46.185		
Finite Sample Corrected AIC (AICC)	48.685		
Bayesian Information Criterion (BIC)	50.363		
Consistent AIC (CAIC)	54.363		

It can be seen from Table 7 that section length (L) and Speed Reduction (ΔV_{85}) are statistically significant at 90% confidence interval. Results from the model developed showed that accident frequency per five (5) year period is positively correlated to ΔV_{85}. That is, the larger the speed reduction required when moving from one section to the next (ΔV_{85}), the more the accidents that are expected to occur.

4. Conclusion

It is well known that inconsistencies in geometric design of highways results in the disruption of drivers' expectations, which can lead to inappropriate maneuvering, and ultimately in accidents. Yet, in most highway designs, geometric design consistency is not always ensured at the design stage. This is primarily because research on design consistency is still in the early stages, and very few works have been done to see how it impacts on road safety, especially for two-lane single carriageways. This work evaluated the consistency of the geometric design of a two-way single carriageway (rural highway) in Edo State, Nigeria, using the operating speed criterion. From the results obtained, it was observed that some sections of the selected route did not satisfy the operating speed criterion for a good design. An accident prediction model, which was also developed to relate speed reduction (ΔV_{85}) to safety, showed a strong positive correlation between speed reduction and accident occurrence.

Two-lane rural highways designed solely on the concept of design speed have proved inadequate in several cases. From the results of this study, it is recommended that the operating speed of vehicles (which is more realistic) be used as much as possible for the design of these roads.

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