A MODEL RELATING VEHICLE STABILITY TO SAFETY ON RURAL TWO-LANE SINGLE CARRIAGEWAYS

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ABSTRACT

This research work develops a model relating accident occurrence per five (5) year period to vehicle stability on rural two-lane single carriageways which are characterized by extreme alignments and determines the direction of correlation.

Alignment data such as curve radius (R) and degree of curvature (DC) were evaluated to determine the vehicle stability at different curves present on Ekiadolor-Uhen road. Also, an Accident Prediction Model was developed in this research work which incorporates vehicle stability (ΔF), section length (L) and degree of curvature (DC) using the Generalized Linear Regression Modelling (GzLM) approach.

Results showed a strong negative correlation between accidents per five (5) year period to vehicle stability (ΔF),which means that an increase in the difference between side friction supplied and side friction demanded, (ΔF),results in a decrease in accident occurrence.

Keywords: *Vehicle Stability, Geometric Design, Model, Regression.*

INTRODUCTION

When designing the alignment of a roadway, skid resistance is considered the most important characteristic of the road surface. Super elevation is a geometric feature used to reduce side friction demand by counterbalancing a portion of the centripetal acceleration encountered by drivers. Excessive centrifugal forces acting on vehicles traveling on a curve may lead to skidding, vehicle rollover, and head on collision. Therefore, to ensure alignment consistency, vehicle stability and driver comfort, sufficient side friction should be provided to balance centrifugal forces. McLean (1976) maintained that side friction is fundamental to curve design but the "design values must be based on a realistic assessment of driver behavior and comfort tolerance of modern drivers". An evaluation of the design consistency can be done based on a margin of safety of the difference between side friction supply and side friction demand on a curve (ΔF). If friction demand exceeds supply, this may prohibit safe vehicle operation and would imply inconsistency and vehicle instability. Locations that do not provide vehicle stability can be considered geometrically inconsistent (Gibreel et al, 1999).

Vehicle Stability Prediction Models on Curves

Different approaches have been adopted worldwide, for measuring side friction factors. Several models have been developed to predict side friction supplied and side friction demanded separately.

SIDE FRICTION SUPPLIED

Side friction supplied is calculated using the point mass formula by simply inserting the operating speed in place of the design speed. When a vehicle moves in a circular path, it is forced radially outward by centrifugal force. To counterbalance the force and stay moving in the circular path, the friction force that is developed by vehicle weight and friction factor between tires and pavement must be greater than the centrifugal force. In the design of highway curves, there exists the relation between design speed and curvature and also the joint relations with super elevation and side friction. This relationship is expressed as follows (AASHTO, 2011).

$$f + e = \frac{V^2}{127R} \quad (1)$$

Where:
f = Coefficient of side friction,
e = Super elevation rate (%),
V = Design speed (km/h), and
R = Radius of horizontal curve (m).

Available friction, which is the friction provided by the pavement depends on the vehicle speed. Studies have shown that skid resistance diminishes as speed increases, at a nonlinear rate defined by the macro texture of the pavement. This has been theoretically established in the model developed by Pennsylvania State University (Kulakowski, 1991), and it has also been empirically verified through series of experiments(Wambold and Henry 1995). Likewise, it has been verified by Lamm et al. (1999) that there is a decreasing tendency of friction as speed increases. They proposed relationship for finding relevant side friction factors in highway curve design. Side friction is directly related to the tangential friction factor as shown in Equation (2)

$$fTP = 0.59 - 4.85 \times 10^{-3} \times VD + 1.51 \times 10^{-5} \times VD^2 \quad (2)$$

where:
fTP = maximum permissible tangential friction factor, and
VD = design speed (km/hr).:

Lamm (1984) noted that after establishing the relationship between the maximum permissible tangential friction factor and the design speed, the range from which the utilization ratio "n" of the maximum permissible side friction factor shall be selected. And based on international experiences, this value varies between n = 40% and n = 50% for rural roads. Therefore, the equation for the maximum permissible side friction factor is given in equation (3) as:

$$fRPerm. = n \times 0.925 \times fTP \quad (3)$$

where:
fRPerm. = maximum permissible side friction factor,
n = utilization ratio, and
0.925 = reduction factor corresponds to tire-specific influences.

Based on Lamm et al. (1994) different utilization ratios were considered as reasonable for side friction factors for specific topographic conditions (flat, hilly and mountainous). The recommended equations (4) and (5) for maximum

permissible side friction factors (fRPerm.) with respect to topography are given:
a) Flat Topography (n = 45 %)

$$fRPerm. = 0.25 - 2.04 \times 10^{-3} \times VD + 0.63 \times 10^{-5} \times VD^2 \quad (4)$$

b) Hilly and Mountainous Topography (n = 40 %)

$$fRPerm. = 0.22 - 1.79 \times 10^{-5} \times VD + 0.56 \times 10^{-5} \times VD^2 \quad (5)$$

where:
fRPerm. = maximum permissible side friction factor.

Lamm et al. (1996) developed several models for evaluating the side friction assumed for various topographic conditions on rural highways. These models are presented in Table 1.

S/N	Model	R^2
1	$FA = 0.25 - 2.04 \times 10^{-3}V_D - 0.63 \times 10^{-5}V_D^2$ (Rural) for flat topography and implementing e_{max}; $e_{max} = 0.08$ assumed.	N/A
2	$FA = 0.22 - 1.79 \times 10^{-3}V_D - 0.56 \times 10^{-5}V_D^2$ (Rural) for hilly and mountainous topography and implementing e_{max}; $e_{max} = 0.07$ assumed.	N/A
3	$FA = 0.05 - 0.45 \times 10^{-3}V_D + 0.14 \times 10^{-5}V_D^2$ (Rural) for all topography and implementing e_{min}; e = 0.025 assumed	N/A
F_A = side friction assumed; V_D = design speed of the roadway (km/h); e = super elevation rate (percent);		

SIDE FRICTION DEMANDED

Bonneson (2001) developed a side friction prediction model based on the hypothesis that drivers will modify their side friction demand to achieve a combination of safe and efficient travel. Bonneson's model was mainly based on the approach speed and operating speed reduction of a curve. The form of the model is shown in equations (6), (7), (8) and (9):

$$FD = 0.256 - 0.0022\,Va + B(Va - Vc),\ R^2 = 0.88 \quad (6)$$

$$Vc = 63.5 \times \left[-B\left(\frac{B^2 + 4c}{(127R)^{0.5}}\right)\right] \leq Va \quad (7)$$

with

$$c = \frac{e}{100 + 0.256 + (B - 0.0022) \times Va} \quad (8)$$

$$B = 0.0133 - 0.00741 \times I_{TR} \quad (9)$$

where:
FD = side friction demanded,
VA = 85th percentile approach speed (km/hr),
VC = 85th percentile curve speed (km/hr),
e = super elevation rate (%), and
ITR = indicator variable (=1.0 for turning roadways; 0.0 otherwise).

ACCIDENT PREDICTION MODELS

According to Sayed et al. (1999), accident prediction models are statistical regression models which relate accident occurrence to traffic and geometric characteristics of a location, and are developed based on a group of locations of similar geometric make-up. The models can be used to predict future accident occurrence at other locations of similar characteristics. They can also be used to identify accident-prone locations, to set up critical accident frequency curves, to rank accident-prone locations, and to perform before-and-after studies to show the effectiveness of an implemented treatment.

THE GENERALIZED LINEAR REGRESSION METHOD (GzLM)

The generalized linear regression method (GzLM) is used to estimate the parameters of accident prediction models. GzLM has the advantage of overcoming the limitations associated with the use of conventional linear regression in modeling accident occurrence, which is random, discrete, and non-negative in nature. Since the conventional linear regression requires that the model must be a linear combination of the explanatory variables, the error terms of which must be normally distributed, uncorrelated, and have equal variance, it is not suitable for modeling accident occurrence (Jovanis et al., 1986; Hauer et al., 1988 and Saccomanno et al., 1988).

Based on the work of Hauer et al. (1988), Kulmala (1995) and Sayed et al. (1999), Let Y be a random variable that represents the number of accident at a location in a specific time period, and assume it follows the Poisson distribution with parameter X. Let Λbe the variable that represents the mean of the Poisson distribution, such that Λ = λ. Hauer et al. (1988) showed that for an imaginary group of locations of similar characteristics, Λcan be regarded as a random variable which follows the gamma distribution with parameters κ and κ/μ, the mean and the variance of which are presented in equations (10) and (11):

$$E(\Lambda) = \mu \tag{10}$$

$$\mathrm{Var}(\Lambda) = \frac{\mu^2}{\kappa} \tag{11}$$

Consequently, considering the accident occurrence characteristics of a specific location and the imaginary group to which the location belongs, Hauer et al. (1988)and Kulmala (1995)have shown that Y follows the negative binomial distribution instead, with the mean and variance being equal to (equations 12 and 13):

$$E(Y) = \mu \tag{12}$$

$$\mathrm{Var}(Y) = \mu + \frac{\mu^2}{\kappa} \tag{13}$$

The author argued that the variance is equal to the expected value only when κapproaches infinity; assuming a Poisson error structure is computationally simple because the mean and variance are equal and that the negative binomial error structure can more realistically depict the over dispersion of the data, as the variance of this distribution is greater than the mean.

MODEL STRUCTURE

The model structure shown in equations (14) and (15) relates accidents to exposure and other explanatory variables such as geometric design features or design consistency measures. The following two model forms can be adopted when studying highway sections, the merits of which are discussed in detail in (Sawalha and Sayed, 2001).

$$E(\Lambda) = a_0 \times MKV^{a_1} \times e^{\Sigma b_j x_j} \tag{14}$$

$$E(\Lambda) = a_0 \times L^{a_1} \times V^{a_2} \times e^{\Sigma b_j x_j} \tag{15}$$

where:
E(Λ) = expected collision frequency,
MVK = exposure in million-vehicle-kilometer = LxV,
L = length of section,
V = average annual traffic volume,
xj= any additional variable,
a0, a1, a2= model parameters, and
bj= model parameters of additional variables.

To estimate the model parameters, the error structure is first assumed to follow the Poisson distribution. The dispersion parameter (σd) is calculated as shown in equation (16) to determine whether this assumption is valid:

$$\sigma_d = \frac{Pearson\chi^2}{n-p} \tag{16}$$

where:
n = number of observations,
p = number of model parameters, and

$$\text{Pearson } \chi^2 = \sum_{i=1}^{n} \frac{[y_i - E(\Lambda)_i]^2}{Var(y_i)} \tag{17}$$

where:
yi = observed number of collisions on section i,
E(Λ) = predicted number of collisions on section i, and
Var (yi) = variance of the observed collisions on section i.

It should be noted that Pearson χ^2 follows the χ^2 distribution with n-p-l degrees of freedom.

McCullagh and Nelder (1983) argued that the dispersion parameter is a useful statistic for assessing the variability in the observed data. In their submission, if is σ_d greater than 1.0, it signifies that the data have greater dispersion than the Poisson distribution can accurately model, thus the negative binomial error structure is required. And according to Hauer et al., (1988), the parameters of the negative binomial distribution are estimated by an iterative process based on the maximum-likelihood estimates.

Goodness of Fit

The Pearson χ^2 statistic and the scaled deviance (SD) are the two statistical measures that can be used to assess the goodness of fit of accident prediction models developed using GLM (McCullagh et al., 1983).

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 (18) and if the error structure follows the negative binomial distribution, equation (19) is used to obtain the scaled deviance (SD) as follow:

$$SD = 2\sum_{i=1}^{n} [y_i \ln\left\{\frac{y_i}{E(\Lambda)_i}\right\}] \tag{18}$$

$$SD = 2\sum_{i=1}^{n} [y_i \ln(\frac{y_i}{E(\Lambda)_i}) - (y_i + \kappa)\ln(\frac{y_i + \kappa}{E(\Lambda)_i + \kappa})] \tag{19}$$

where:
SD = scaled deviance,
yi = observed number of collisions on section i,
E = predicted number of collisions on section i, and
κ = shape parameter of the gamma distribution which the imaginary group follows.

METHODOLOGY

THE STUDY AREA

The study area is Ekiadolor-Uhen road which is located in Ovia North East of Edo State Nigeria. The state is made up of 18 local government areas (LGAs) and a total population of 3,233,366 (National Population census, 2006). Ovia North East lies between latitude 6° 38' 41" N and longitude 5° 34' 48" E. Figure 1 shows the study area and the road profile obtained from ARCGIS.

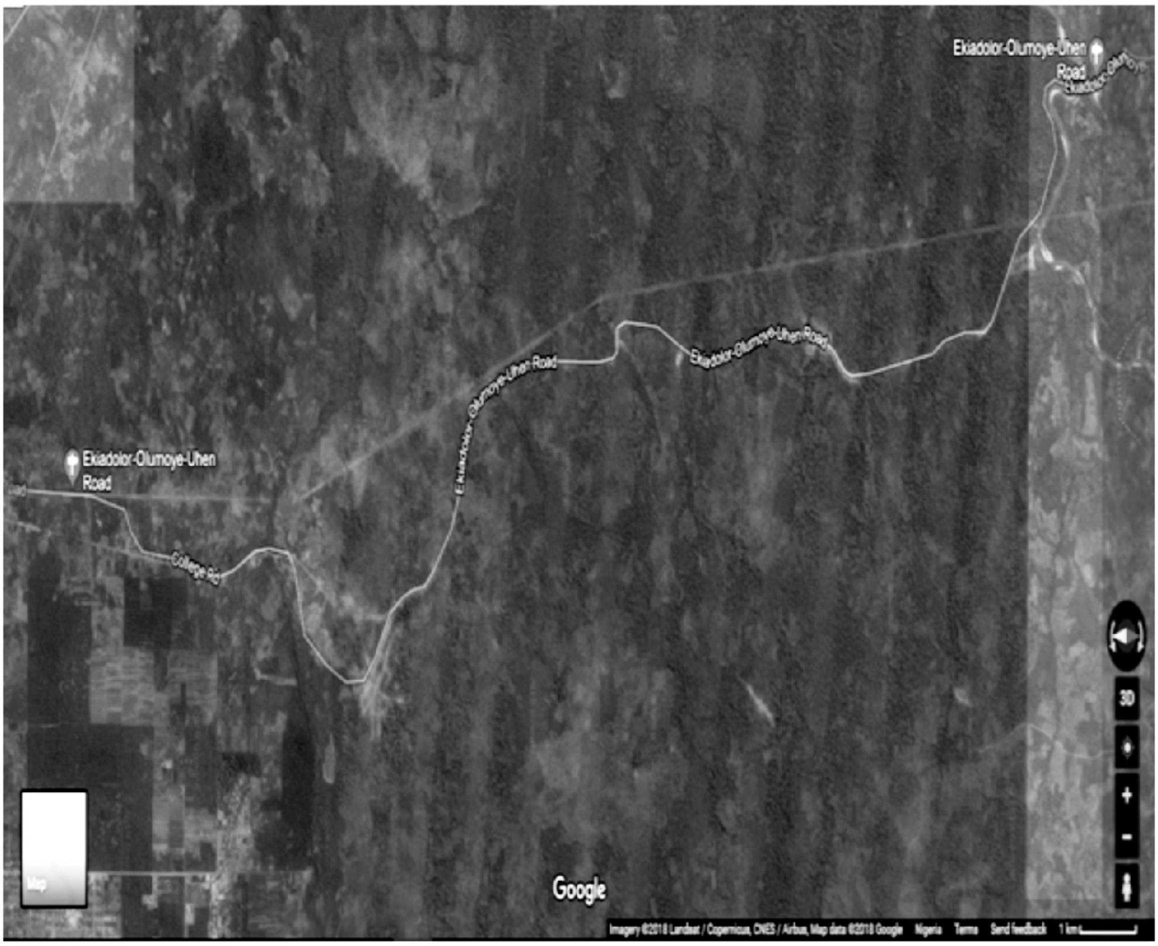

Figure 1: *Location of study area (Google Earth)*

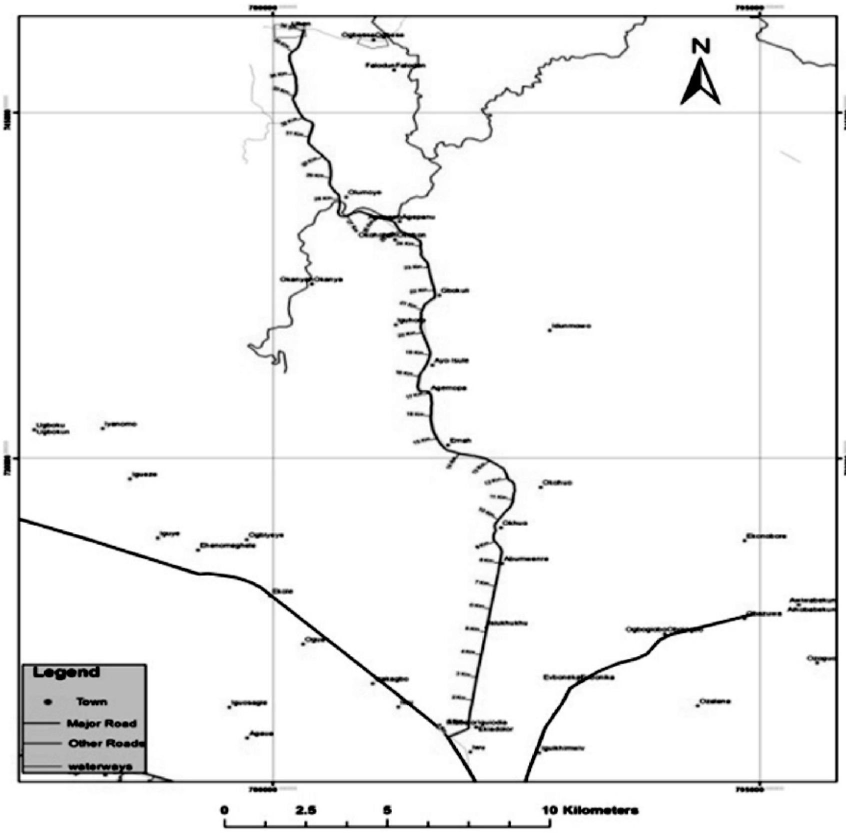

Figure 1: *Location of the study region and the selected route (Google Earth, ARCGIS)*

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 (Lc); the approach and departure tangent lengths associated with each curve.

EVALUATING VEHICLE STABILITY CRITERIA

Side friction supplied was determined using equation (#2) presented in Table (1) while applying the appropriate design speed of 80km/h. Whereas, side friction demanded was estimated using equation (6) of this work.

DEVELOPMENT OF ACCIDENT PREDICTION MODEL

An Accident Prediction Model was developed in this study incorporating vehicle stability (? F), section length (L) and degree of curvature (DC). 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 model development. As many design consistency variables as are statistically significant are incorporated to improve the prediction accuracy of the models.

RESULTS AND DISCUSSION

The results presented in Table 2 were obtained from reconnaissance survey coupled with remote sensing and use of GIS software.

Table 2: *Summary of alignment data for Ekiadolor – Uhen road (26.6km)*

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

ALIGNMENT INDICES

Table 3 shows the summary of the alignment indices for the sections (from km 8.2 to km 27.8) of Ekiado-lor-Uhen road.

Table 3 *Summary of Alignment indices for Ekiadolor – Uhen road (km 8.2-km 27.8)*

Minimum Radius	226.34
Maximum Radius	1063.29
Average Radius	556.23
Ratio of Maximum Radius to Minimum Radius	4.70
Average Tangent Length	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

EVALUATION OF VEHICLE STABILITY

$FS = 0.22 - 1.79x10^{-3}VD + 0.56x10^{-5}VD^2$ and it depends on the design speed of the road (that is, 80km/hr for rural highways). Also, $FD = 0.256 - 0.0022xVA$+ B(VA-VC), it depends of the approach speed (VA) and speed at curve (VC). Table (4) shows the summary of approach speeds (VA) and speed at curves (VC) for Ekiadolor-Uhen Road (km 8.2-km 27.8).

? F= FS - FD= difference between side friction assumed and demand; FS = side friction supplied; FD = side friction demanded.

Table 4: *Summary of estimated Approach Speed (VA) and Curve Speed (VC) for Ekiadolor-Uhen Road (km 8.2-km 27.8)*

Chainage (km)		Linear Radius (m)	$VA = 108.3 - \frac{3498}{LT} - 0.71\frac{(DF1 * DF2)}{(DF1 + DF2)}$	B = 0.0133-0.00 741x IR	C = 0.2567+0.003 69xVA	$VC = 63.5Rx(-B + \sqrt{B^2 \frac{4C}{127R}})$
From	To					
8.2	8.9	593.92	108	0.00589	0.654808619	92
9.0	9.5	534.94	102	0.00589	0.63156094	88
11.4	11.9	368.79	101	0.00589	0.628944315	82
14.0	15.0	840.58	102	0.00589	0.632739778	94
16.8	17.4	236.77	104	0.00589	0.641829113	76
18.5	19.5	1063.29	101	0.00589	0.630269154	96
21.5	22.0	368.27	104	0.00589	0.64187199	84
23.1	24.0	868.46	108	0.00589	0.656061613	97
24.0	24.5	340.19	106	0.00589	0.649551495	83
25.0	26.0	676.96	106	0.00589	0.648077967	93
26.6	27.8	226.34	205	0.00589	1.013353572	76

Evaluation of Vehicle Stability for Ekiadolor-Uhen Road (km 8.2-km 27.8) is presented in Table (5).

Table 5: *Evaluation of Vehicle Stability for Ekiadolor-Uhen Road (km 8.2-km 27.8)*

Chainage (km)		Linear Radius (m)	$FS = 0.22 - 1.79x10^{-3}VD + 0.56x10^{-5}VD^2$	$FD = 0.256 - 0.0022xVA + B(VA-VC)$	$\Delta F = FS - FD$
From	To				
8.2	8.9	593.92	0.11	0.11	0.00
9.0	9.5	534.94	0.11	0.11	0.00
11.4	11.9	368.79	0.11	0.15	-0.03
14.0	15.0	840.58	0.11	0.08	0.03
16.8	17.4	236.77	0.11	0.19	-0.08
18.5	19.5	1063.29	0.11	0.06	0.05
21.5	22.0	368.27	0.11	0.15	-0.03
23.1	24.0	868.46	0.11	0.08	0.03
24.0	24.5	340.19	0.11	0.16	-0.05
25.0	26.0	676.96	0.11	0.10	0.01
26.6	27.8	226.34	0.11	0.57	-0.45

The vehicle stability evaluated for Ekiadolor-Uhen road (km8.2-27.8) is presented graphically in Figure 2.

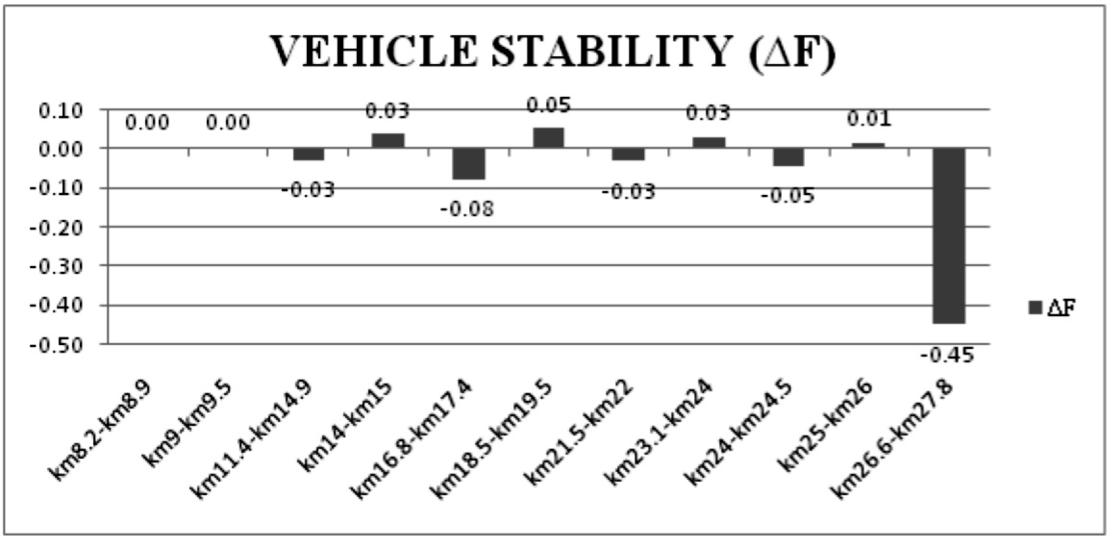

Figure 2: *Vehicle Stability for Ekiadolor-Uhen Road (km 8.2-km 27.8)*

MODEL RELATING VEHICLE STABILITY 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 Vehicle Stability (? F) 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 (^{0})	21	0	25	6.95	8.35
	Change in Friction Factor (? F)	21	-0.45	0.05	-0.02	0.10

A model which relates Vehicle Stability (? F) to safety is presented in Table (7).

Table 7: Model Showing the Relationship between Vehicle Stability (ΔF) 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)	-2.95	1.107	-4.771	-1.13	7.092	1	0.01	0.052	0.008	0.324
L	1.96	0.653	0.889	3.036	9.048	1	0.00	7.119	2.434	20.83
DC	-0.01	0.071	-0.126	0.107	0.018	1	0.89	0.99	0.881	1.113
? F	-5.05	3.827	-11.35	1.242	1.743	1	0.19	0.006	1E-05	3.464
(Scale)	.484									
(Negative binomial)	1									

Dependent Variable: Accident per 5years period (Acc/5yrs) Model: (Intercept), Section length (L), Degree of Curvature (DC) and Change in Friction Factor (? F)			
Goodness of Fit			
	Value	df	Value/df
Deviance	6.924	17	0.407
Scaled Deviance	14.299	17	
Pearson Chi-Square	8.231	17	0.484
Scaled Pearson Chi-Square	17	17	
Log Likelihooda	-19.303		
Adjusted Log Likelihoodc	-39.868		
Akaike's Information Criterion (AIC)	46.607		
Finite Sample Corrected AIC (AICC)	49.107		
Bayesian Information Criterion (BIC)	50.785		
Consistent AIC (CAIC)	54.785		

DISCUSSION OF RESULTS

As seen from Table (7), only section length (L) is statistically significant at 90% confidence interval, but as expected vehicle stability (? F) has a strong negative correlation to accident occurrence per five (5) year period as indicated by the negative parameter estimate. That is, an increase in the difference between the side friction supplied and side friction demanded (? F) results in a decrease in accident occurrence.

CONCLUSION AND RECOMMENDATIONS

CONCLUSION

From the data available for accident occurrence for the five year period under consideration, model results have shown that the likelihood of accident occurrence has a negative correlation to vehicle stability. That means, the less the stability assured at curves (as represented by ? F),the more the rate of accident.

RECOMMENDATIONS

The accuracy of an accident prediction model is limited by the quality of their independent variables. Therefore, future research effort should be devoted to improving the prediction of these variables. For example, vehicle stability models should be developed which reflect local conditions.

The model developed in this study is limited to horizontal curves and tangents of two-lane rural highways only. More work is needed to expand the applicability to sections which are combined with vertical curves, as well as to those of other types of highways.

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