Calibration of Sigmoid Function for Performance Prediction of Flexible Road Pavement in Nigeria

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Abstract- The performance prediction of road pavement for optimum maintenance decision to attain sustainable infrastructural development in Nigeria has been a challenge to highway engineers over time. This study attempted to calibrate a sigmoid function using historic dataset on performance variables of flexible road pavement for efficient and reliable pavement management decision in Nigeria. The curve fitting of three sigmoid functions I, II and III using OriginPro software based on historic dataset obtained from the Federal Ministry of Power, Works and Housing Nigeria showed a better fit for Sigmoid Function I with coefficient of determination value of 0.54. Though there were somewhat high margin of Root Mean Square Error (RMSE) of 51.49 for the estimated statistical parameters of the relatively best fit model, the poor performance of the fitted function was attributed to poor dataset characterized by missing and outlier or noisy elements. The relatively best fit sigmoid function was therefore recommended for use by highway management agencies with further calibrations using more recent, accurate and sufficient dataset that defines the present pavement condition in Nigeria.

Keywords- Flexible Pavement, Nigeria, Pavement Management System, Road Transport, Sigmoid Function

1 INTRODUCTION

The economy of most developing countries like Nigeria majorly depends on the efficiency of the road transport system for haulage of goods and services across the states. The over 34,000 km of federal highway in Nigeria is made of flexible pavement which requires periodic maintenance and rehabilitation strategies for sustainable development (Olowosulu *et al.*, 2021). Generally, the life cycle of road infrastructure is usually threatened by several deteriorating factors which affect its performance index over time; such factors include traffic load, environmental conditions, material properties, age of pavement, original design of pavement structure, quality of construction and maintenance policy (Elhadidy *et al.*, 2020). Consequently, the effects of bad roads include intensive traffic noise and air pollution, massive wear and tear of vehicles, high cost of travel due to congestions, accidents and fuel consumption (Xiao and Wu, 2016). Since huge funds are required for highway projects, periodic and timely maintenance strategies are essential for effective management system (Huang, 2017; Olowosulu *et al.*, 2021).

Following the peculiarities of countries in the world, it is required that transportation agencies of different locations develop pavement performance prediction models to suit the uniqueness of their location for sustainable development (Mohammadi *et al.*, 2019). A set of tools or methods that assist decision makers in finding the optimum strategies for providing, evaluation and maintaining pavements in a serviceable condition over a period of time is known as pavement management system (PMS) (AASHTO, 1993).

Components of PMS include pavement performance prediction models (Elhadidy *et al.*, 2020); the applications of such models could be at network-level or project-level (Ayed, 2016; Abaza, 2016; Mohammadi *et al.*, 2019; Pérez-Acebo *et al.*, 2020). Previous studies identified deterministic, probabilistic and subjective models for pavement management (AASHTO, 2012; Salpiso, 2014). In recent times, Artificial Intelligence (AI) techniques have been employed in the development of pavement performance prediction models (Olowosulu *et al.*, 2021).

Like every other asset management system, the modelling of pavement performance requires sufficient well-spread time series dataset that gives a complete explanation of the system behaviour. The lack of sufficient, accurate and reliable dataset on road pavement performance in most developed and developing countries necessitate the use of historic dataset for developing pavement performance prediction models that could serve the current basic needs and for future improvement (Rahman *et al.*, 2017; Olowosulu *et al.*, 2020; Elhadidy *et al.*, 2020).

The standard indices used for measuring pavement performance include; Pavement Condition Index (PCI) (ASTM D6433, 2007), Pavement Condition Rating (PCR) (Chen and Mastin, 2015), International Roughness Index (IRI), Present Serviceability Index (PSI), Pavement Distress Index (PDI), Pavement Quality Index (PQI) (Rahman *et al.*, 2017), Present Serviceability Rating (PSR), Urban Distress Index (UDI) (Mubarak and Sallam, 2020), Condition Survey Rating Scores (CSRS) (Claros *et al.*, 1987), etc. According to ASTM D6433 (2007) and Mubarak and Sallam (2020), the performance index is classified on a scale of good to worse. These classifications are a function of the severity, quantity and frequency of surface defects caused by deterioration of the pavement structure.

1.1 PAVEMENT PERFORMANCE FUNCTION

The analysis of most system behaviour can be presented using the life cycle concept presented using linear or

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nonlinear regression equations (Chen and Mastin, 2015). In this context, it involves a performance function which defines rate of deterioration over time due to the impact of damaging factors expressed as a mathematical function. Previous studies have established that pavement performance is best defined using a sigmoid function, a curve which could be concave, convex or S – shape (Riggins *et al.* 1984; Sotil and Kaloush, 2004; Chen and Mastin, 2015; Ayed, 2016; Elhadidy *et al.*, 2020). The commonest sigmoid function is the normal logistics function which is generally expressed in the form of Equation 1;

$$f(x) = \frac{1}{1 + e^{-x}}$$

(1)

where, x is the independent variable and e is the Euler’s number.

The development of a logistic function requires some statistical operations which may be complicated to some extents, therefore adoption of existing function with some calibrations to suit the peculiarities of the concerned system is acceptable (El-Khawaga *et al.*, 2019). Previous studies have used sigmoid functions for performance prediction of pavement as stated in Sotil and Kaloush (2004), Nassiri *et al.* (2013), Chen and Mastin (2015) and Ayed (2016). The functions present variables for minimum (initial) and maximum (final) index values the performance curve can reach against age of pavement and the coefficient values that define the slope with which the curve reaches the peak point.

Other essential values may include the mid-point of the curve measured along the horizontal axis and the shape of the curve. The common characteristic among mathematical functions is the calibration process that suit or qualifies its application at location other than where the model was originally built to serve (Ayed, 2016). Therefore, the aim of this study is to calibrate a sigmoid function that can be used for performance prediction of flexible road pavement in Nigeria by curve-fitting a suitable sigmoid function using historic dataset.

2 METHODOLOGY

2.1 STUDY AREA

The map of study area is as shown in Figure 1.

Fig. 1: The Map of Nigeria

Figure 1 shows the map of Nigeria indicating her six (6) geopolitical zones. The distribution of federal road network across Nigeria is as shown in Table 1.

Table 1. Federal Road Network in Nigeria

Geopolitical Zones	States	Road Network (km)
South-East	Anambra, Enugu, Imo, Ebonyi and Abia	3,121.70
South-West	Lagos, Oyo, Osun, Ondo, Ekiti and Ogun	4,161.06
South-South	Akwa Ibom, Delta, Cross River, Bayelsa, Rivers and Edo	4,150.89
North-East	Adamawa, Bauchi, Borno, Gombe, Taraba and Yobe	6,787.90
North-West	Kaduna, Jigawa, Kano, Katsina, Kebbi, Sokoto and Zamfara	6,363.40
North-Central	Niger, Kwara, Plateau, Benue, Nasarawa, Kogi, FCT Abuja	9,756.00
Total		34,340.95

(Source: Federal Government of Nigeria, 2012)

2.2 DATA COLLECTION AND DESCRIPTION

This study considered secondary dataset obtained from the database of pavement condition evaluation unit of the Federal Ministry of Power, Works and Housing Nigeria. The dataset presented attributes of flexible road pavement condition of 102 highway segments in six (6) suitable zones across Nigeria. The dependent variable used for calibration of the function was the Condition Survey Rating Scores (CSRS) which depends on the average rut depth (cm), percentage area of alligator or fatigue cracks and the drainage condition per road segment, while the pavement age from when it was commissioned for traffic was the independent variable. It was assumed that, the effect of all performance attributes of the pavement such as traffic load, material properties, weather and pavement surface condition were influenced by time measured as the age of the pavement in years (Sotil and Kaloush, 2004; Nassiri *et al.*, 2013; Chen and Mastin, 2015).

2.3 DATA ANALYSIS

Calibration of the function involved simulation of three (3) sigmoid functions using curve-fitting approach on historic dataset implemented used OriginPro software. The aim was to check for best fit model for the study area based on statistical parameters of the dataset used. Plate 1 shows an extract of pavement condition survey data processing sheet used for computing average CSRS.

Processing Date: 02/13/87						LINK No. : 89
Date of Survey : 01/31/87						TEST SECTION : 6.12
LINK # : 093						STATE : ANAMBRA
Prefix Node : 259						
SECTION	PERCENT ALLIGATOR Class 1	PERCENT ALLIGATOR Class 2	PERCENT ALLIGATOR Class 3	AVE. RUT DEPTH (CM)	DRAINAGE CONDITION	CSRS
0.40	99.5	99.5	9.7	0.5	A	70
0.80	99.5	99.5	0.0	0.0	A	81
1.20	99.5	99.5	0.0	0.0	A	81
1.60	99.5	99.5	0.0	0.0	G	81
2.00	99.5	99.5	0.0	0.0	G	81
2.40	99.5	99.5	0.0	0.0	G	83
2.80	51.5	24.2	0.0	0.0	A	85
3.20	24.2	24.2	0.0	0.0	A	86
3.60	24.2	24.2	0.0	0.0	A	86
4.00	9.7	9.7	0.0	0.0	G	89
4.40	9.7	9.7	0.0	0.0	A	89
4.80	9.7	9.7	0.0	0.0	A	94
5.20	9.7	0.0	0.0	0.0	A	91
5.60	9.7	0.0	0.0	0.2	A	97
6.00	0.0	0.0	0.0	0.0	A	97
6.40	9.7	0.0	0.0	0.0	G	94
6.80	0.0	0.0	0.0	0.0	G	96

Plate 1: Extract of Pavement Condition Survey Data Processing Sheet (Claros *et al.*, 1987)

Table 2. Nigeria Road Pavement Condition

Zones	States	Link Code	Length (km)	Age (Years)	Average CSRS
Zone 1	Kaduna	130	46.8	5	92
	Kaduna	252	60.9	8	86
	Kano	291	18.9	6	89
	Kano	472	74.4	8	86.4
	...	...	...	...	...
Zone 2	Bauchi	98	32.4	9	88
	Bauchi	285	50.3	8	92
	Borno	42	108	9	86
	Borno	716	50.7	9	60
	...	...	...	...	...
Zone 3	Lagos	8	8.10	6	74
	Lagos	333	5.2	10	92
	Kwara	5	22.8	10	91
	Bendel	50	12.6	9	92
	Bendel	51	40.2	8	85
	Ondo	224	1.8	7	92
	Oyo	22	23.4	10	81
	Ogun	179	2.8	NA	88
Zone 4	...	...	...	...	...
	Niger	247	93.3	10	NA
	Niger	455	13.2	9	89
	Sokoto	27	133.2	9	92
	Sokoto	254	144.9	9	93
Zone 5	...	...	...	...	...
	Benue	111	50.0	6	NA
	Benue	112	53.6	6	NA
	Gongola	317	30.3	6	74
	Plateau	136	10.0	9	75
Zone 6	...	...	...	...	...
	C/River	322	33.6	9	86
	C/River	298	21.2	3	72
	Rivers	144	18.0	8	76
	Imo	115	32.4	8	74
	Anambra	89	43.7	7	88
Zone 6	Anambra	90	17.6	NA	77
	...	...	...	...	...

NA = Not Available

(Source: Claros *et al.*, 1987)

Table 2 presents an extract of the summary of processed dataset of highway segments across Nigeria as considered by the study.

3 RESULTS AND DISCUSSION

The calibrated sigmoid functions and respective statistical parameters were as follows;

Sigmoid Function I: The first simulated and calibrated sigmoid function was as shown in Equation 2;

$$f(x) = A_2 + \frac{A_1 - A_2}{1 + \left(\frac{x}{x_0}\right)^p} \quad (2)$$

where, A_1 is the maximum CSRS value, A_2 is the minimum CSRS value, x_0 and x represent the average age of pavement (centre point on x-axis) and the age at minimum CSRS value respectively. p is a coefficient defined as the power of the function.

Figures 2 (a) and (b) present the actual distribution curve of pavement performance and the fitted function for Sigmoid Function I respectively.

Fig. 2: (a)Actual and (b)Fitted Sigmoid Functions I

Figure 2 (a) revealed that the actual function had gentle slope while the fitted sigmoid function shown in Figure 2 (b) showed a sharp slop which conforms to curve properties established as coefficients defined in Sotil and Kaloush (2004), Nassiri *et al.* (2013) and Chen and Mastin (2015). The statistical properties of Sigmoid Function I were as shown in Table 3.

Table 3 revealed that the simulation process completed successfully, though with non-satisfactory statistical properties. Also, estimation of the major variables recorded somewhat high standard errors and the Root Mean Square Error (RMSE) had relatively high estimations compared to those of Chen and Mastin (2015) which shows poor performance.

Table 3. Statistical Properties of Sigmoid Function I

Parameters	Values
Number of points	93
Degree of freedom	89
Reduced Chi-square	51.490
Residual sum of squares	4582.597
R ²	0.5400
Adjusted R ²	0.522
Root Mean Square Error	51.4898
Number of Iterations	13
Fit status	Succeeded
Fitted Values:	Standard Error
A1 = 86.000	1.1296
A2 = 49.267	3.6397
x ₀ = 12.455	0.9705
p = 8.551	3.6754

Sigmoid Function II: The second simulated and calibrated sigmoid function was as shown in Equation 3;

$$f(x) = A_{min} + \frac{A_{max} - A_{min}}{\left(1 + \left(\frac{x}{x_0}\right)^{-h}\right)^s} \quad (3)$$

where A_{min} is the minimum value of CSRS, A_{max} is the maximum value of CSRS, x is the age at minimum CSRS value, x_0 , s and h are coefficients of the function which assumed values of 5, 0.5 and 10 respectively for a dataset of range 0 – 100 for A_{min} and A_{max} respectively.

Figures 3 (a) and (b) present the actual distribution curve of pavement performance and the fitted sigmoid function for Sigmoid Function II respectively.

Fig. 3: (a)Actual and (b)Fitted Sigmoid Functions II

Figure 3 (a) revealed that the actual function assumed a concave shape with gentle slope while the fitted function attempted to assume a sigmoid shape of pavement performance as established by previous studies (Sotil and Kaloush, 2004; Nassiri *et al.*, 2013; Chen and Mastin, 2015).

The statistical properties of Sigmoid Function II were as shown in Table 4.

Table 4. Statistical Properties of Sigmoid Function II

Parameters	Values
Number of points	93
Degree of freedom	88
Reduced Chi-square	51.470
Residual sum of squares	4529.281
R ²	0.540
Adjusted R ²	0.52213
RMSE	51.4691
Number of Iterations	400
Fit status	Failed
Fitted Values:	Standard Error
$A_{min} = -6110.3506$	3.6×10^6
$A_{max} = 86.2805$	1.5327
$x_0 = 8.8818$	4.9979
$h = -8.9706$	16.8874
$s = 6.44 \times 10^{-4}$	0.3768

Table 4 revealed somewhat high level of standard errors for all estimated variables which justified the failed status of the function as presented in the fitting analysis by OriginPro software. Also, its statistical parameters showed a failed status after 400 iterations. This indicates that the function does not fit the distribution. The negative value of A_{min} disqualified the function for use in pavement performance predictions since only pavement age ≥ 0 exists. Therefore, the sigmoid function was rejected for the intended purpose.

Sigmoid Function III: The third simulated and calibrated sigmoid function was as shown in Equation 4;

$$f(x) = \frac{a}{1 + e^{-k(x-x_c)}} \quad (4)$$

where a is the maximum value of CSRS, x_c and x are the centre (mid-point) of curve on the horizontal axis and its highest values respectively. k is the coefficient which defines the shape of the curve.

Figures 4 (a) and (b) present the actual distribution and the fitted sigmoid function for Sigmoid Function III respectively. Figures 4 (a) shows a convex curve with gentle slope. The fitted curve does not assume the ideal shape of performance curve of pavement deterioration. Table 5 presents the statistical parameters of the fitted function after successful completion of the iterations process.

Table 4 revealed a successful iteration of the fitting process. Although, there were somewhat high margin of errors, the magnitude of deviation was relatively low compared to that of Sigmoid Function II. The Sigmoid Function III was disqualified for use in pavement performance predication since the shape of the curve does not conform to the normal sigmoid or logistic function used for performance prediction of pavement in the past studies (Sotil and Kaloush, 2004; Nassiri *et al.*, 2013; Chen and Mastin, 2015). Performance comparison of the sampled sigmoid functions showed a more promising performance for the Sigmoid Function I when used on a sufficient and well-spread dataset.

Fig. 4: (a)Actual and (b)Fitted Sigmoid Functions III

Table 5. Statistical Properties of Sigmoid Function III

Parameters	Values
Number of points	93
Degree of freedom	90
Reduced Chi-square	51.7299
Residual sum of squares	4655.689
R ²	0.530
Adjusted R ²	0.5197
RMSE	51.7299
Number of Iterations	4
Fit status	Succeeded
Fitted Values:	Standard Error
$a = 90.1163$	4.50809
$x_c = 26.6160$	1.2537
$k = -0.14276$	0.04089

4 CONCLUSION

Though there was no recent and sufficient dataset for performance prediction of flexible road pavement in Nigeria, this study attempted to calibrate a sigmoid function for performance prediction of flexible road pavement in Nigeria using historic dataset. The classification of pavement surface condition was based on percentage of crakes, rut depth and drainage condition to estimate the Surface Condition Rating Scores (SCRS) index which yielded a promising result. The Sigmoid Function I was selected as the best fit among the three functions tested, and was selected for the purpose due to its relatively better performance. It was therefore recommended for use and further calibrations using more recent and sufficient dataset for efficient and reliable pavement performance prediction in Nigeria.

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