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Life Cycle Cost Analysis (LCCA) Delivery Model for an Urban Flexible Pavement

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Abstract

Pavement alternative evaluation is a key aspect in decision making process in transportation system planning, design and delivery. This study examined the Life-Cycle Cost Analysis (LCCA) model for flexible road pavement infrastructure delivery in a developing economy using 1.9 km urban road in Effurun Metropolis, Uvwie Local Government Area of Delta State of Nigeria as a case study. The overview of existing knowledge, the importance and evaluation of LCCA of pavement delivery is done. The Pavement delivery and design data used for this study, which were obtained from the Office of the Ministry of Works, Effurun, Delta State of Nigeria, included soil sub-grade CBR results, water content condition, soil type and grain size distribution, the reports of route investigation, vehicular traffic counts, and previous maintenance, material and market survey reports. The pavement design data previously used for the design and procurement of urban roads in the area were used for the design of three competing pavement alternatives models, viz: Hot Rolled Asphalt (HRA), Interlocking Concrete Block Pavement (ICBP) and a third; Do-nothing scenario pavement alternative. The Bill of Engineering Measurements and Evaluation (BEME) was developed for the designed alternative to compute their Life-Cycle Costs (LCCs) using present worth cost (PWC) method with varying interest rates in MS Excel software spread sheets for a design life of 20 years. Regression modeling for the three scenarios was done with computer software's (SPSS and MS Excel) packages. The model's data robustness was determined and found to be between 0.95-0.99. The model's validity and sensitivity were also carried out. The study indicates a 43.8% cost savings with the ICBP alternative over the HRA option. The Do-nothing alternative is non–aesthetical and costliest due to the maintenance cost of re-instating the road structure. The models have significance value of less than 0.001(F) respectively. The developed LCCA template and model are applicable for investment studies and decision making as well as cost effectiveness assessment of pavement and bridge delivery.

Keywords: Flexible road pavement; Transport infrastructure delivery; Life cycle cost analysis; Present worth cost

Introduction

Transportation system is the planned networks of real and abstract components that interacts and play different roles in the process of physical movement of goods and persons from an origin or source to a destination point through a motorized or non-motorized or combined means. The planning and design of flexible road pavement continue to be the core of the transportation engineering especially in areas such as operations, logistics, network analysis, road project financing and policy analysis [1,2]. Life Cycle Cost Analysis (LCCA) is the project design, delivery and asset management strategy that evaluates the total cradle to grave cost involvements or attributes to arrive at the best-value choice considering the entire life span, discount rate and specific details. In developing countries like Nigeria, this tool is inadequate. A simplified Life-Cycle Cost economic evaluation tool for determining most cost effective flexible pavement procurement [3] is lacking. The high cost of hot rolled asphalt pavement, early failures, poor pavement performance, and poor sub-structural drainage amongst others are common. These inadequacies are generally overbearing in the drive towards sustainable flexible road pavement procurement in Nigeria and especially in the Niger-Delta region with swampy terrain and poor drainages [4,5].

Most transportation infrastructure problems existing presently in developing countries are all indicative of a poor-performing transportation infrastructural system delivery [6]. Capital projects such as expressways, urban and rural roads, railways, public transportation facilities and allied systems will be most suitably delivered using an economic evaluation model [7-10]. Besides, it will guarantee an optimum project performance delivery that meets design Level of Service (LOS) and confidence of investors and all stakeholders. This study evaluates Life Cycle Cost of flexible road pavement design alternatives in a typical Niger Delta urban town to determine the most economic pavement choices and models using a case study [11]. This study is aimed at achieving a model that will aid optimum total asset value in pavement infrastructure investment, planning, design and sustained service delivery in the now-competitive road infrastructural planning, budgetary and policy formulation in developing countries. The public and private sectors will have improved confidence in decision making.

Literature Review

Road pavement design and challenges

Based on the type of construction, material used, structural design criteria or load distribution modes, pavement can be classified as Rigid or Flexible pavement or even composite. Most pavement surface alternatives fall into these three categories of pavement. Rigid pavements are specifically known to have high flexural strength and are able to distribute concentrated loads over a larger area. Cement reinforced or mass concrete pavements are classified as rigid while others are classified as flexible pavement. Flexible pavements have some intrinsic ability to adjust to effects due to traffic loading with serious deformation. Essentially, flexible pavement consists of the sub-

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base and base layers made of granular materials which distribute the load to the sub-grade mainly by inter-granular pressures. These are known to have low flexural strengths.

According to American Association of State Highway and Transportation Officials (AASHTO), Guide for Design of Pavement Structure (1993); Pavement type selection is a three-part process which includes a pavement design analysis, life cycle cost analysis and evaluation of project specific details. The pavement design should be performed first, since the results may preclude the need to continue with the remainder of the pavement type selection process which includes life cycle cost analysis and project specific details [12,13]. The alternative resulting in the lowest present worth over a given analysis period is considered the most cost effective. The pavement design analysis includes the review and analysis of sub-grade competency, geometrics, traffic analysis, materials, climate, drainage, environment, construction considerations, and any other pavement design factors. Basically, the design and selection of a sustainable road pavement or surface type is determined by these design parameters. The design criteria for flexible pavement are to have a limited sub-grade deformation under load and limited sub-grade deformation at the underside surface of the surface wearing course. Pavement design HRA overlay design can be accomplished either by use of the mechanistic-empirical based scheme used in the Everpave©1 computer program or the AASHTO Guide for Design of Pavement Structures. The Everpave© program is for use with flexible pavements. The AASHTO procedure can be applied to either flexible or rigid pavement structures.

In this study, the Hot Rolled Asphalt (HRA) pavement, flexible precast Interlocking Concrete Block Pavement (ICBP) and a do-nothing (no wearing course) depending on the construction method and strategy are considered. The flexible precast Interlocking Concrete Block Pavement (ICBP) is considered as a flexible pavement due to its advantages over HRA in terms of its behavior under flexural load due to vehicular traffic [14,15]. The Mechanistic-Empirical Pavement Design Guide (MEPDG) by the Transportation Research Board [16]; AASHTO, Guide for Design of Pavement Structure (1993) design procedures amongst others are applicable for flexible road pavement design. The mechanistic based design procedures incorporates the treatment of life-cycle costs and design reliability while the empirical design approach rely more on empirical correlations with past performance, index-value-based characterizations of material properties layer coefficient, R-value, California Bearing Ratio (CBR), etc., and adopted engineering design strategy [17,18].

The highway and transportation engineer must therefore begin to examine the various ways of improving the sector through innovations in the selection of geometrical design parameters, material research, traffic flow assessment, work method, pavement design approach, maintenance strategy and economics. Other areas include geotechnical engineering of in-situ materials, application of geo-textiles challenged terrains and local content utilization, as these design variables affect the life cycle cost of the infrastructure delivered [19-21].

Pavement life cycle cost analysis models

A considerable number of past studies on the application of Life Cycle Cost Analysis (LCCA) and Life Cycle Analysis (LCA) and Sustainability Assessments provide useful information and results to assist the pavement engineer in the pavement selection. The LCCA and LCA applications in infrastructure planning and delivery helps the stakeholders and decision makers deal with costs implication and sustainability considerations in a project life span basis using project cost evaluation methodologies and BS/ISO 15686-5 Standards [22].

Key amongst these works of these researchers is their aim at optimizing the benefits of the Life Cycle Cost Analysis (LCCA) and Life Cycle Analysis (LCA) and Sustainability objectives for buildings using various economic evaluation techniques with sets of best design alternatives, variables and assumptions [23,24]. The existing models obtainable in the United States, Europe, and Canada are complex and unsuitable for application in developing countries because of the climatic, information, technological, local systems development pattern and procurement as well as the cultural differences from that of the developed countries. Road authorities in the developed economies have adopted models for Life Cycle Cost Analysis (LCCA) with the intention to reduce the total costs for road infrastructure and maximize the socio-economic benefits with a lowered social economic cost and environmental impact. These models have been mainly used for the selection of road construction types or pavement types and other road infrastructure, such as bridges [25-28].

These models cannot be used as standard models in developing nations since they are developed according to requirements for particular road projects in some particular environment in developed countries. Moreover, the limitations of these existing models include the use of unrealistic and roughly calculated maintenance costs and user's costs, lack of regional attributes and tropical road design. Figure 1 illustrates the analysis period-pavement condition index of a

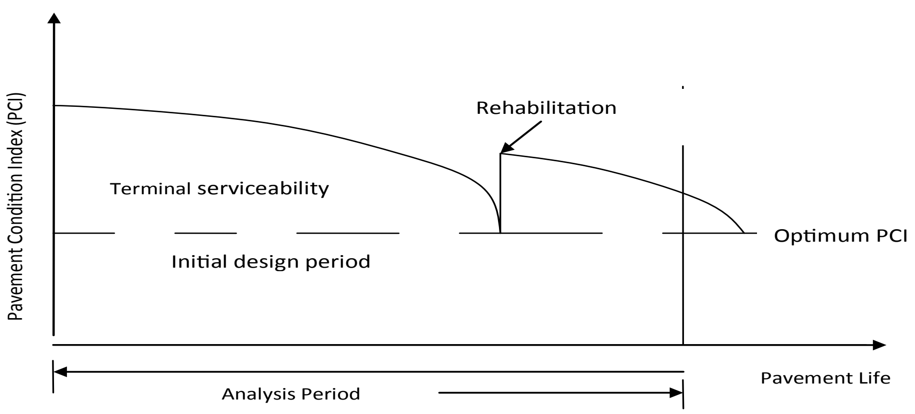

Figure 1: Analysis period for a pavement designed alternative (Adapted: FHWA-SA-98-079, Life cycle cost analysis in pavement Division interim Technical bulletin, 1998).

pavement design alternative.

Economic evaluation of transportation projects

One of the criteria in measuring any road infrastructure projects performance is the cost efficiency or life cycle cost [29]. The life cycle cost is evaluated using any of the following methods viz; Present Worth Cost (PWC); Equivalent Uniform Annual Cost (EUAC); Benefit-Cost Ratio (BCR) and Rate of Return (ROR). Using the same baseline design parameters, design life and service life, all the options mentioned above give the same results that enhance the highway engineer's decision making. In this study, the Present Worth Cost (PWC) was employed.

The present Worth Cost (PWC) method is one of the economic evaluation methods for transportation infrastructures and systems, it involves the conversion of all of the present and future estimated expenses to a base of today's costs using an appropriate discount rate. The totals of the present value costs are then compared with one another. The present worth of costs method is directly comparable to the equivalent uniform annual cost method for comparable benefits [30]. In this presentation, a limitation to the present worth cost method is made for clarity using tropical information from field practice, experience and agency costs. The general expression for the Present Worth Cost of a transportation infrastructural project, given by Kumares et al. [31]:

$$PWC = \sum_{n=0}^{N} \frac{P^n}{(1+i)^n} \quad (1)$$

Where,

P= Cost of the agency and user cost in year n

i=interest rate

n= Number of years to when the sum will be expanded or saved.

N=Service life of the facility (in years).

The factor for discounting, either costs or benefits, is:

$$Pwcf = \frac{1}{(1+i)^n} \quad (2)$$

Where,

Pwcf=Present worth cost factor for a particular i and n

Based on the preceding considerations, a possible model of present worth cost of an infrastructure (pavement) is given by:

$$P = Pi + Pwcf\,(AE) \quad (3)$$

where;

Pi=Agency's Initial Cost

Pwcf=Present worth cost factor for particular i and n.

AE=Annual Expenditure (Post-Construction maintenance costs)

This is a deterministic approach whereby all cost inputs are known or estimated; where not well documented from past experience and available data are given a single fixed value within the available pavement design output, estimates, relevant tender documents and relevant design and field data on the project is used using basically equation (3) above. Interestingly, a deterministic relationship exists between the cost elements and the infrastructure age during the life-cycle exists as contained in equation (3) above, which can be examined through the use of linear regression model in the form;

$$Y = b + mx + e \quad (4)$$

where;

Y=Dependent variable, deterministic Present worth Cost of alternative Pavement or infrastructure or scheme in Million Naira/km.

b= Independent variable, regression constant or vertical intercept on the cost axis Agency's (Pre-construction+Initial Construction) in Million Naira/km.

m=Regression coefficient or slope of trend line relating the cost and the entire project life (a function of the annual expenditure, salvage value, analysis period, discount rate)

x=Independent variable, particular period or year of interest of projection of the present worth cost in year.

e=Independent variable, other costs (such as socio-economic and political cost element and error term due to uncertainty in data analyses.

Methodology

The work specifically investigates a road structure with sub-grade and base formation common to the three competing flexible pavement alternatives in a 1.9 km urban stretch single carriageway in Effurun Metropolis in Uvwie Local Government Area of Delta State, Nigeria using the case study research approach [11]. The study area is particularly defined by Geographical coordinates 5°43' 00"N to 5° 48' 00"N and 5° 31'30"E to 5° 34'00'E. The pavement delivery and design data were obtained from the Office of the Ministry of Works, Effurun, Delta State, Nigeria.

The obtained data include soil sub-grade CBR results, water content condition, soil type and grain size distribution, the reports of route investigation, traffic vehicular traffic counts, previous maintenance, material and market survey reports. The pavement design data were processed and used for the design of three competing pavement alternatives, viz: Hot Rolled Asphalt (HRA), Interlocking Concrete Block Pavement (ICBP) and a third; Do-nothing scenario pavement surface courses. The urban road pavement thickness is on a wet sub grade. In this study, the low traffic urban road was designed to meet an average of 400 vehicles per day on both directions. Using the relevant Design Codes (such as AASHTO1993), Guides and Manuals, the Bill of Engineering Measurements (BEME) was developed for the designed alternative sectional full depth (Table 1). It was later used to compute the Life-Cycle Costs (LCCs) using Present Worth Cost (PWC) method and the varying interest rates using Microsoft (MS) Excel software, for a design life of 20 years.

The regression modeling for the three scenarios was done with computer software's packages [Statistical Package for Social Science (SPSS) and MS Excel]. The computed cost data from the various design alternatives inputs were analyzed using regression analysis with SPSS and MS Excel software packages.

The goodness of fit of the economic models or robustness were determined from the R-square values which range from 0.95 to 0.99 (See regression models statistical values in Figure 2). The model's validity was also carried out.

Results and Discussion

Results

The summary of the full depth of the flexible pavement is presented in Table 1; Figure 2 shows the combined Life Cycle Cost models for the

HRA (Alternative 1)	ICBP (Alternative 2)	Do-Nothing (Alternative 3)
2 layer HRA (90 mm) inclusive of tack and priming coats	80 mm ICPB 50 mm bedding sand	Nil Surface layer
common 150 mm thick of base course (crushed stone) on minimum 750 mm depth sub-base (sharp sand) to the 3 competing flexible pavement alternatives		

Table 1: Summary of the full depth of pavement for the three flexible pavement alternatives.

Interest Rates	Model Statistics	Hra (Alternative 1)	Interlocking Conc. Block Pavement (Alternative 2)	A Do-Nothing Scenerio (Alternative 3)	General Remarks
4.6	Model	y=6x+50	y=4x+30	y=5x-10	Initial procurement cost of Alternative 2 (ICBP) is 65.73% cheaper than the Alternative 1 (HRA), while alternative 3 is the Do-Nothing without any pavement course. N38.23 million, 43.4% cost savings made with Alternative 2 (ICBP) at 4.6% interest rate
	R square value	0.96	0.94	0.98	
	LCC (Million Naira/Km)	88.08	49.85	53.26	
4.8	Model	y=6x+50	y=4x+40	y=5x-10	
	R square value	0.96	0.95	0.98	
	LCC (Million Naira/Km)	86.79	49.03	51.92	
5.0	Model	y=6x+50	y=4x+40	y=5x-10	
	R square value	0.96	0.94	0.98	
	LCC (Million Naira/Km)	85.54	48.24	50.88	
5.20	Model	y=6x+50	y=4x+40	y=5x-10	
	R square value	0.96	0.94	0.98	
	LCC (Million Naira/Km)	84.31	47.47	49.74	
5.4	Model	y=6x+50	y=3x+40	y=5x-10	N36.4 million, 43.8% cost savings made with Alternative 2 (ICBP) at 5.4% interest rate. The Do-Nothing is even costlier due to the cost maintenance of road structure without a pavement surface.
	R square value	0.96	0.94	0.98	
	LCC (Million Naira/Km)	83.12	46.72	48.64	
5.6	Model	y=6x+50	y=3x+40	y=4x-10	
	R square value	0.96	0.95	0.99	
	LCC (Million Naira/Km)	81.96	45.99	47.56	
5.8	Model	y=6x+50	y=3x+40	y=4x-10	
	R square value	0.96	0.95	0.99	
	LCC (Million Naira/Km)	80.96	45.28	46.52	
6	Model	y=6x+50	y=3x+40	y=4x-10	
	R square value	0.96	0.95	0.99	
	LCC (Million Naira/Km)	79.74	44.59	45.51	
6.2	Model	y=6x+60	y=3x+40	y=4x-10	N34.75million, 44.2% cost savings made with Alternative 2 (ICBP) at 6.2% interest rate
	R square value	0.96	0.95	0.99	
	LCC (Million Naira/Km)	78.67	43.93	44.52	

Table 2: Life cycle cost (LCC) for the 3 pavement alternatives for the 6m-lane urban road in NAIRA/km at various interest rates.

three competing pavement design alternatives at 6.2% interest rate with their respective regression equations. The life cycle cost for the three pavement alternatives for the 6 m –lane urban road in Million-Naira/km at various interest rates is shown in Table 2.

Discussion

From the first flexible pavement alternative (2 layers 90 mm HRA surface course) shown in Table 1 and Figure 2, the Life-Cycle Costs for the HRA (alternative 1), Flexible urban road stretch using 5.4% and 6.2% interest rates (Table 2) are N83.12 million and N78.67 million per km respectively. The Life-Cycle Costs for the second pavement alternative (80 mm ICBP course) studied with a 20-year analysis period using 5.4% interest (shown in Table 2) is N46.72 million per km. This gives 43.8% savings over HRA (alternative 1), although both of the alternatives meet the design Level Of Service (LOS). The Do-Nothing alternative (alternative 3) has nil initial pavement surface construction cost but the maintenance cost of re-instating and replacing lost, eroded or weathered earthworks frequently to keep road passable is enormous. It does not meet the design Level Of Service (LOS), and it is uneconomical and non–aesthetical.

From Table 2, it was observed that the life cycle cost of the three alternatives decreases with increasing interest rates. The LCC of the alternatives at the 6.2% interest rate was found to be the most cost effective when compare with the 5.4% interest rate which was used as the baseline interest rate. The Do-nothing alternative was the costliest due to the cost of maintenance of the road structure without a pavement surface. The result also indicate that the Interlocking Concrete Pavement alternative gives better value for money apart

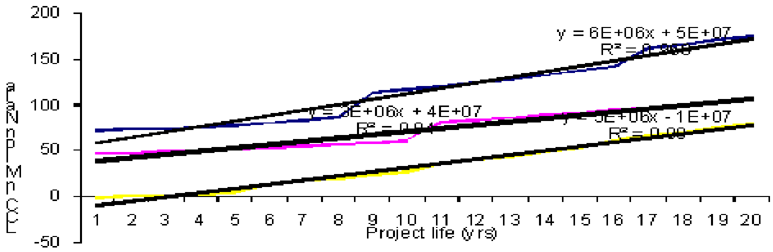

Figure 2: Combined LCC model for competing pavement design alternatives at 6.2% interest rate.

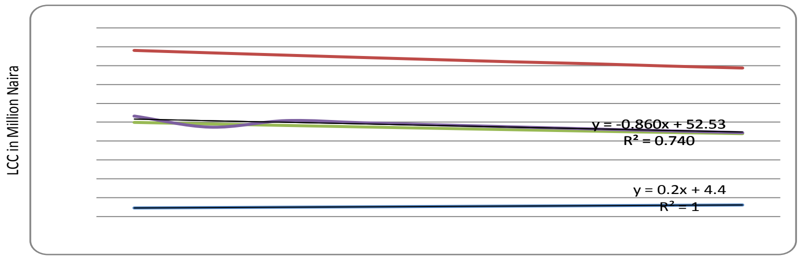

Figure 3: Interest rates-LCC plot fit plot for HRA (ALT.1), ICBP (Alt.2) and Do-nothing (Alt.3) alternatives.

from being able to offer better drainage properties [31], while the Do-Nothing has a higher LCC that does not satisfy design level of service. The Life-Cycle Cost Analysis (LCCA) template and model which are developed in this study are applicable for investment studies and decision making in bridge development and other aspects of the transport sector, telecommunication, power, and water infrastructural planning, procurement, delivery and maintenance.

Goodness of fit of the models: The goodness of fit of the developed economic models is robust as observed from the R-square values of 0.96 and 0.95 for the HRA and ICBP respectively (See regression models statistical values in Figure 2), while the SPSS analysis has a Durbin-Watson statistic coefficient of 0.95. This shows that the LCC model is highly robust in replicating the project data used in the analysis.

Model validity: Statistical parameters in Table 1, Table 2 and Figure 2 indicate that the cost models mean square value (R^2) for HRA alternative is 0.96 while that of ICBP alternative is 0.95. The models have significance value (F) of 1.5×10^{-15} and 1.3×10^{-13} respectively for the HRA and ICBP alternatives, which are less than 0.001 in both cases. Statistically, the parameters obtained in this study are in conformity with the result of study on "Cost Model for Pre-and Post-Haulage Road Freight Transport to and from the Intermodal Terminal" in Sweden [32], which had a mean square value (R^2) of 0.96 with a significance value of (F) of 0.001.

Sensitivity analysis: Sensitivity Analysis (SA) of on the Life-Cycle Costs models for the three alternatives respectively indicates a decrease with increasing interest rates. The Sensitivity Analysis (SA) carried out in this study has shown that a higher interest rate of 6.2% is most cost effective compared with the 5.4% baseline interest rate which was initially used in the study.

Conclusion

In this study, a combined Life Cycle Cost model for the delivery of three urban flexible pavement design alternatives using different interest rates was developed. This model will be of immense benefits to developing economy like Nigeria where great investment utilization, optimization and prioritization challenges are involved. The study shows that the model's independent variable (pavement age) significantly predicts the dependent variable, Life-Cycle Cost (LCC) in Million Naira per km of urban 2-lane road. The mean square value (R^2) and significance value (F) of the model for HRA and ICBP alternatives, in this study, are in conformity with the result of a similar work done in Sweden. The results of the study shows that the Interlocking Concrete Pavement alternative gives better value for money on the long term, while the Do-Nothing alternative has a higher Life-Cycle Cost (LCC) that does not satisfy the required design level of service. The results got in this study will aid transportation economists, planners and other stakeholders in budgetary, project design, finance allocation, policy making and management strategy for pavement planning delivery in developing countries.

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