"MATHEMATICAL MODELLING FOR EVALUATING ROAD MAINTENANCE NEEDS AND INTERVENTIONS"

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SEPTEMBER, 1999

DEDICATION

This work is dedicated to my sister, Christy.

DECLARATION

I hereby declare that this thesis has been composed by myself and that it is a record of my own research work. It has not been accepted in any previous publication in a higher degree.

All sources of information are specifically acknowledged by means of references.



L.O. EZEMENARI

CERTIFICATION

This thesis entitled "Mathematical Modelling for Evaluating Road Maintenance Needs and Interventions" by Ezemenari Lawrence Obinani, meets the regulations governing the award of the degree of Master of Science of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

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EZEMENARI, L.O.

ABSTRACT

A mathematical model for prioritizing road maintenance in terms of the timing of maintenance intervention and scope of work done is developed. Three sub-models are incorporated namely, classification, performance and cost sub-models. The classification sub-model uses the roughness measurement to classify the road sections into one of six different states according to their degree of disrepair. The performance sub-model utilizes the first order MarKov Chain Process to simulate future states of the road pavement. The cost sub-model computes both the user cost and maintenance intervention costs. The models are then used to simulate the performance of Rano-Sumaila road in Kano State of Nigeria for a period of twenty years. Results indicate that prompt response to maintenance needs reduces overall expenditure on maintenance over time and also that maintenance expenditure has a high rate of return. The benefit-cost ratio of intervention expenditure on different maintenance activities was found to vary from about twenty eight to less than two, depending on the degree of disrepair on the road before the intervention. It was also confirmed that yearly upgrading of all road sections to the best state would cost less than half of yearly reconstruction of only the totally collapsed sections.

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PRINCIPAL SYMBOLS

BI	British Bump Integrator
C_U	User cost in option 1
C_U^1	User Cost at year 1 in option 1
Cu^m	User cost at year m in option 1
C_s	Total system cost in option 1
C_s^m	Total system cost at year m in option 1
C_I^m	Intervention cost at year m in option 1
C_I^*	Intervention cost in option 2
C_s^*	Total system cost in option 2
C_U^*	User cost in option 2
IRI	International Roughness Index
Km	Kilometer
M_I	Maintenance Intervention cost matrix
m	Number of years
$P_{(i,j)}$	Probabilities assigned to the transition of road between any two points i and j
P_{ij}	Probability transition matrix
P_{ij}^m	Probability transition matrix after m transitions
Po	Initial state vector
P_K	Final state vector
P_1	State vector after year 1 in option 1
P_m	State vector after year m in option 1
P_1^*	State vector after year 1 in option 2
$P_1^/$	State vector got as a result of a change in P_1^* due to an intervention that has taken place in option 2
P_m^*	State vector after year m in option 2
$P_{m-1}^/$	State vector got as a result of a change in P_{m-1}^* due to an intervention that has taken place in option 2
P_{m-1}^*	State vector after year (m-1) in option 2
P_2^*	State vector after year 2 in option 2
P_1^{**}	State vector after year 1 in option 3
$P_1^{//}$	State vector got as a result of a change in P_1^{**} due to an intervention that has taken place in option 3
P_2^{**}	State vector after year 2 in option 3
$P_2^{//}$	State vector got as a result of a change in P_2^{**} due to an intervention that has taken place in option 3
P_m^{**}	State vector after year m in option 3
$P_{m-1}^{//}$	State vector got as a result of a change in P_{m-1}^{**} due to an intervention that has taken place in option 3
P_{m-1}^{**}	State vector after year (m-1) in option 3
R	Traffic growth rate
T^m	Total annual traffic volume at year m
U_{CARS}	Average users cost column vector for cars

U_{TRUCKS}	Average users cost column vector for trucks
U_{WM}	Weighted mean user cost
V_o	Initial annual traffic volume
₦	Naira, Unit of money in Nigeria

CHAPTER ONE

INTRODUCTION

1.1 GENERAL

The construction of new highways, including the interstate system, has accounted for the majority of efforts expended by different tiers of governments in Nigeria since 1950s. As a result, the physical plant of the highway system, for practical purposes, is now complete and transportation agencies should, of necessity, shift their emphasis from new construction to maintenance, upgrading and rehabilitation. Unfortunately, this shift has been slow in coming and many of the nation's highways are approaching or have exceeded their serviceable lives.

Consequent upon the oil boom era of 1970s, the Nigerian economy was treated to considerable changes prompted by overwhelming investment allocations to the economic and social sectors. Unfortunately, maintenance of the economic infrastructural facilities, like roads, were given little attention. The construction of new projects was the vogue. The down turn came when there was dramatic reduction in the price of crude oil with subsequent sharp decline in government revenues. So, now that the expansive network of roads that were provided with oil revenues are in need of maintenance, available funds are not enough and optimal allocation of resources has become appropriate.

Maintenance, as it relates to highways, is the preservation of each roadway structure and facility, as near as possible, in its original condition as constructed or subsequently improved. Timely and periodic maintenance intervention is necessary to keep traffic moving safely and economically. Highway maintenance consists of correcting deficiencies in the highway network which might have developed as a result of age, wear, weather or damage arising from the effects of cumulative axle loads and exposure to the elements. Maintenance could also be designed to prevent or delay the development of

development of other deficiencies.

Among the several techniques for pavement maintenance that have been developed is the pavement management system (PMS). Pavement management system is a systematic strategy of maintaining road pavement. It is a broadly based process which incorporates the set of all activities required to provide and maintain road pavements. Its basic purpose is to achieve the best value possible for the available maintenance funds and to provide safe, comfortable and economic transportation. The essence of this system is to provide a consistent, reasonably objective, and systematic procedure for establishing priorities, scheduling and budgeting roadway maintenance and rehabilitation requirements. The procedure, when implemented, will provide the decision maker with the type of information necessary for planning and programming maintenance and rehabilitation of road pavements.

This research project is specifically designed to evolve working tools needed to adopt the principles of PMS in optimally allocating limited resources among competing highway maintenance needs.

1.2 Research Justification

In Nigeria, a review of past development efforts shows that one of the greatest investments of public funds is in the construction of roads. Hence, the cumulative length of roadways in the country has increased appreciably. The substantial increase of surfaced road has made it imperative that a systematic maintenance strategy be evolved. This can be achieved by establishing maintenance needs well ahead of time and rationally prioritizing maintenance needs in accordance with available funds. The benefits to be obtained from implementing such a system include effective planning of maintenance and a systematic as well as efficient pattern of utilizing the limited maintenance funds. Such a system would greatly facilitate a reliable projection of funds required, over time, to maintain various elements of roadway and thereby facilitate maintenance programming and budgeting.

Effective maintenance of roads in Nigeria has been frustrated because of the lack of scientific tools for programming and budgeting. The current tools such as The Transport and Road Research Laboratory Road Investment Model for Developing Countries (RTIM2) and The World Bank's Highway Design and Maintenance Standard Model (HDM-III) are useful but too sophisticated and costly for wide applications in Nigeria and hence the need for a less involved technique as proposed in this work. It is hoped that findings from this study would provide a basis for formulating such less involved technique that would be suitable for wide application in Nigeria.

1.3 Research Objectives

The primary objective of this study is to formulate a mathematical model that can be used to prioritize road maintenance without violating budgetary limitations and is sufficiently simple for wide applications in Nigeria. In doing this, the following secondary objectives will be attained:-

a) To be able to classify road pavement into different states of disrepair in accordance with the severity of distress;

b) To express, in probabilistic terms, the progressive deterioration of a road pavement as it transits from one state to another when left unimproved over time;

c) To set up cost models that capture user costs on the road as well as maintenance intervention costs;

d) To determine the optimal road maintenance strategy in accordance with prevailing circumstances.

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1.4 Research Methodology

In order to achieve the objectives set for the study, the following steps are taken:

a) A theoretical framework that captures the road deterioration profile over time as well as the associated cost is proposed and developed;

b) A case study of Rano-Sumaila road will be presented;

c) By using pavement attributes, the road will be divided into different states of disrepair;

b) A case study of Rano-Sumaila road will be presented;

c) By using pavement attributes, the road will be divided into different states of disrepair;

d) An initial probability vector will be obtained by determining the proportions of the road length lying in different states of distress;

e) A transition matrix will be developed for the study by interviewing highway engineers;

f) Traffic survey on Rano-Sumaila road will be carried out and the Average Daily Traffic determined for analysis;

g) Cost models that capture user costs on the road will be developed with temporal changes in traffic and road conditions incorporated;

h) Based on (a) to (g), pavement deterioration and maintenance requirement will be predicted with the attendant life cycle maintenance costs determined. This will then facilitate a rational evaluation of candidate maintenance strategies as well as optimization within budget limitations.

1.5 Organisation of the Thesis

The thesis is divided into six chapters. Chapter one gives the introduction to the studied problem, its importance, the research objectives and summary of research methodology while chapter two reviews a number of procedures that have been or are being developed for the management of highway pavements. Chapter three focuses on the theory underlying pavement deterioration, maintenance requirements and all matters pertaining to life cycle costs whereas chapter four dwells on the development of the models for the case study (i.e. Rano-Sumaila road in Kano State). The evaluation of the model and analysis of results using the case study is treated in chapter five while chapter six gives the conclusion, research constraints and recommendations.

CHAPTER TWO
LITERATURE REVIEW

2.1 Pavement Failures

A pavement is considered to have failed at a point when certain of its characteristics, such as riding quality, reaches unacceptable limits, as a result of both environmental and traffic effects or when the distress from the system exceeds an acceptable level. There are, however, two major types of pavement failure, namely:

a) Structural failure

b) Functional failure.

Structural Failure is the type whose manifestation is a breakdown of one or more of the pavement components of such a magnitude to make the pavement incapable of sustaining the loads imposed upon it.

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Functional failure, on the other hand, occur when pavements can no longer sustain or carry out their functions. This type of failure may or may not, be accompanied by structural failure but is such that pavement is unable to carry out its intended functions without causing high stresses in the plane of any vehicle that passed over it due to its roughness. It is, therefore, usual to periodically undertake pavement condition survey as a means of assessing the physical condition of pavement structure.

2.2 Pavement Condition Survey

Condition surveys are designed to measure the presence of various types as well as degrees or severity of distress. The aim of the survey is to classify a road pavement into various states of disrepair. Such identification of distress on a highway pavement is used in planning for effective maintenance and rehabilitation strategies. The visual pavement distresses are normally grouped into the following categories:-

a) Cracking

b) Surface deformation

c) Surface defects

d) Other pavement failures

2.2.1 Cracking

The two most important types of cracking commonly observed on Nigerian roads are allegator cracking and edge cracking.

Alligator cracking is caused by repeated traffic loading and is also sometimes called chicken wire due to its distinctive shape. The American Association of State Highway and Transportation Officials (AASHTO) has categorized this cracking into three levels of severity as follows:-

a) Class I: These are longitudinal cracks in the wheelparts. They are not interconnected with short transverse cracks. They are many and often criss-cross.

b) Class II: These are the cracks which have progressed into being interconnected and exhibit a good pattern. They form a chicken wire or alligator skin pattern with numerous small paragon and octagon shaped pieces. At this point, however, the pieces are still together and disintegration has not yet begun.

c) Class III: This is progression of Class II cracking resulting in spalling occurring at the edges of the cracks. The segment of the pavement surface loosen and pieces may usually move under traffic loads. Ingress of water starts resulting in eventual potholing and total failure.

Edge cracking is associated with the deterioration of the pavement-shoulder interface. Its occurrence is associated with trucks partially clearing from the pavement to permit passing. They are generally longitudinal cracks located along the outside of the pavement out of the wheelpaths and run approximately parallel with the pavement-shoulder joints.

2.2.2 Surface Deformations

The most important distress in this category is the wheel path rutting. This distress has been associated with such problems as mix instability, excessive traffic loading and/or poor base and sub-base compaction. Ruts are longitudinal depressions in the wheel paths. The severity is evaluated in terms of the depth of ruts. This deformation aggravates pavement disfunction as water accumulates in the ruts and causes spray and hydroplane problems affecting traffic safety. The water can also enter pavement structure and weaken pavement materials.

2.2.3 Surface Defects

The commonly encountered defects are:

a) Ravelling

b) Surface separations

c) Bleeding

Ravelling is sometimes referred to as stripping and it is a condition where many aggregates peel off the pavement. Its occurrence is mainly due to the insufficiency of asphaltic bitumen, dirty aggregates, inadequate compaction or faulty asphalt distribution, among other things.

Surface Separations are localized holes in the surface of a pavement caused by dislodgement of the surface layer from an underlying layer. Surface separations appear as potholes but differ from potholes in that the bottom of the surface separation is an asphaltic pavement layer. Base or sub-base material is normally found in the bottom of potholes.

Bleeding is characterized by black discoloration in the wheelpaths. Asphalt bleeding or the excess of asphaltic bitumen on the pavement surface is not only a waste of very costly material, it is also an indication that pavement would deform shortly.

2.2.4 Other Pavement Failures

The other types of pavement failures, besides those already discussed, include potholes and patched areas. These are briefly commented upon as follows:

Potholes are small, localised, but deep pavement failures characterised by a round shape. Potholes are caused by the effects of rain and traffic on a weak subbase/or subgrade.

Patched Areas of the pavement, whether surface depth potholes or otherwise indicate prior areas of distress. They are generally an indication of the amount of maintenance required to keep the pavement in service. If a patched are has failed or exhibits any of the other distresses then the area should be rated both as a patch and as distress under appropriate category.

2.3 Pavement Condition Rating

In the preceding section, the physical surface distresses were described. In this section, the discussion focusses on how the distresses are used to develop the pavement condition rating. Developing such a condition rating entails a framework for converting the various distress types into a common metric or distress index. Shown in Table 2.1 is the framework currently being used by the Pavement Evaluation Unit (P.E.U) of Federal Ministry of Works and Housing, Kaduna, in evaluating Nigerian road network. The main distress types incorporated are cracking, rutting, potholes and patched areas and they are categorized into three levels according to density or severity.

Table 2.1: CHARACTERIZATION OF PAVEMENT FAILURE CATEGORIES AND DENSITY OR SEVERITY LEVELS

TYPE OF DISTRESS	LEVEL	DENSITY OR SEVERITY
CRACKING	a) None	No cracking visually detectable
	b) Moderate	AASHTO Class I and II cracks seen at riding speed.
	c) Severe	AASHTO Class III cracks seen at riding speed.
RUTTING	a) None	Not visually detectable (less than 10mm in depth).
	b) Moderate	Between 10 and 30mm in depth.
	c) Severe	Greater than 30mm in depth.
POTHOLES	a) None	Not visually detectable.
	b) Moderate	One hole at 400/500mm average intervals.
	c) Frequent	Constant over an area and considerably concentrated.
PATCHES	a) None	Not visually detectable.
	b) Moderate	One patch at 400/500m average intervals.
	c) Frequent	Constant over an area and considerably concentrated.

Typically, in undertaking a pavement condition rating, the road links are surveyed by dividing them into 5km elements. In order to fully categorize the different sections, the condition survey data for each section has to be converted into a value in a convenient scale. The scale used is the Condition Survey Score (CSS) which combines, in a systematic manner, density and severity levels of the distress types occurring within the given road section. A density/severity level description has to be defined for each distress category on a scale from zero to five. The description is given a grade of 1 for all low levels of the distress types characterized as levels denoted as levels a in Table 2.1. All intermediate levels, denoted as levels b, in Table 2.1 receive a grade of 3. Likewise, the extensive and severe occurrence of the distress categories, characterized as levels c, in Table 2.1 receive a grade of 5. These descriptions are then entered into a parabolic functions, defined as equation 2.1, and used to calculate the corresponding condition survey score (CSS) (1) for the section, ie:

$$CSS = \Sigma^{K}_{i=0} W_i(1 - X_i^2/25) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

where

X_i = density/severity descriptors for each distress category.

W_i = maximum weighting factors for each distress category.

K = number of distress categories

Equation 2.1 was developed by Pavement Evaluation Unit design and research engineers. It distributes maximum weighting factors according to a parabolic relationship. A parabolic function is considered ideal for use as it is fairly sensitive to high density/severity levels and, at the same time, allows proper discrimination between sections with intermediate and low distress levels. The efficacy of equation 2.1 in helping to distinguish among distress severity levels is illustrated from data reduction undertaken in Table 2.2. The weighting factors incorporated in the calculations presented in Table 2.2 is that used by P.E.U.

At the moment, in Nigeria the convention adopted by the P.E.U. is to use the following weighting factors:

Potholes: W_{PH} = 40%, Cracking: W_{CR} = 30%

Rutting: W_R = 20%, Patching: W_P = 10%

TABLE 2.2: CSS FOR SEVERAL DISTRESS COMBINATION CONDITIONS

Value of description X_i for all distress categories i

Potholes	Cracking	Rut depth	Patches	CSS Score
5	5	5	5	0
5	5	5	3	6.4
5	5	5	1	9.6
5	5	3	5	12.6
5	5	3	3	19.2
5	5	1	5	19.2
5	3	5	5	19.2
5	5	3	1	22.4
5	3	5	3	25.6
5	5	1	3	25.6
3	5	5	5	25.6
5	3	3	5	32.0
3	5	5	3	32.0
3	5	5	1	35.2
3	5	3	3	44.8
3	5	1	5	44.8
1	5	5	3	44.8
3	5	1	3	51.2
3	3	5	3	51.2
1	5	3	5	51.2
1	3	5	5	57.6
3	1	5	3	60.8
1	5	3	1	60.8

Thus, the highest maximum weighting factor is given to potholes. Potholes, which are frequent on most highly trafficked Nigerian roads, represent a very progressed stage of deterioration of a badly cracked flexible pavement surface. Such a distress manifestation

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is characterized by a very rough and uneven surface and leads to poor rideability. Potholes typify a structurally inadequate and fatigued pavement that requires prompt rehabilitation. The second highest maximum weighting factor is assigned to cracking. This distress manifestation typically arises from structural deficiencies in the pavement and fatigue. Once it appears, chances are high that accelerated damage on the structure may take place as a result of water percolation that brings about loss of strength of the pavement layers. Lastly, rutting and patching received lower maximum weighting factors than potholes and cracking as they are mainly important from serviceability standpoint. If their density/severity levels are such that do not pose serious safety hazards to the road users, their rehabilitation importance is not very high.

Equation 2.1 is such that for a road section (typically of 5km length) in poor condition, high density/severity levels will probably be recorded at the survey for the different distress categories. The corresponding descriptions will then receive ratings of 5 and CSS will tend towards a minimum value of zero. Alternatively, low density/severity levels will be characteristic of road sections in good condition. In this case, the descriptors will most likely receive ratings of 1 and CSS will tend toward a maximum possible value of 100. CSS, in essence, represents a summation of fractions of the maximum weighting factors for each distress category, determined from their density/severity levels.

There is also a five scale rating of roads which is convertible to the CSS of the road. This rating describes precisely the exact condition of the road and is as in Table 2.3.

TABLE 2.3: FIVE-SCALE RATING OF ROADS

GRADE OF ROAD	CONDITION OF PAVEMENT
1	Excellent
2	Good
3	Fair
4	Poor
5	Fail

The approach (i.e. CSS calculation) as illustrated here is quite simple but requires a substantial length of time and resources to accumulate the data needed to arrive at reasonable results. This drawback is likely to hinder its wide acceptability and is the reason why it was not used in this work.

2.4 Ride Quality (Roughness)

The underlying principle for this pavement rating index is that the primary operating characteristics of a pavement at any particular time is the level of service provided to the users. Variation of the level of service with time is thus a measure of pavement deterioration profile. Pavement ride quality or roughness is evaluated on the basis of how well the road is serving the user. Road users enjoy the pleasant ride of a smooth pavement and dislike the uncomfortable ride they experience on rough and bumpy pavements.

Pavement roughness cannot be easily defined because of the diversity of the factors involved. Basically, roughness can be considered as the distortions and variations of the road surface. For most engineering purposes, a definition of pavement roughness including local pavement disturbances and distortions which directly influence passenger comfort, safety and vehicle operation should be sufficient. These are the characteristics which can be quantified and used to measure the pavement serviceability to the public.

There are many methods for measuring serviceability of a road at any particular time. In Canada, the Riding Comfort Index (RCI) is used while most agencies in the United States of America use the concept of the present serviceability index to characterize the rideability of the pavements.

The Mays Ridemeter (Maysmeter) has been used extensively as a mechanical measure of roughness of the pavement surface. It is a device mounted on a station wagon and is a simple electromechanical device that measures the number and magnitude of vertical deviations between the body of the automobile and the centre of its rear axle by means of a flexible cable passing over a pulley and restrained by a tension spring.

The results of Maysmeter roughness are in units of counts/horizontal distance. This roughness counts must be convertible to some set roughness standard in order to be useful in highway pavement rating. Determining what the conversion should be is achieved by a correlation calibration of the Maysmeter to the desired standard. The World Bank uses a standard roughness measure known as the Quarter Car Index (QI) in its Highway Design and Maintenance Model (HDM)(2).

The Transport and Road Research Laboratory (TRRL) has recommended broad guidelines by which pavements can be demarcated into different distress conditions in terms of roughness (3). The British Guidelines are summarized in Table 2.3 wherein the terms IRI and BI have been introduced. The term IRI (International Roughness Index) is a reference measure of the road surface shape that resulted from an international co-operative study, through the World Bank. In the past, roughness has been measured in units of 'mm/km' based on a BI (Bump Integrator) trailer towed at 32km/hr. A relationship exists between the standard roughness index IRI (m/km) and the roughness measure based on the British Bump Integrator (BI), ie.

$$BI = 630\ (IRI)^{1.12} \quad \text{.....(2.2)}$$

where BI is expressed in mm/km
and IRI is expressed in m/km.

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TABLE 2.4 ROAD ROUGHNESS VALUES FOR DIFFERENT SERVICEABILITY LEVELS

LEVEL	SERVICEABILITY DESCRIPTION	ROUGHNESS MEASURE	
		IRI m/km	BI mm/km
I	Ride comfortable over 120 km/hr. Undulation barely perceptible at 80km/hr in range 1.3-1.8. No depressions, potholes or corrugations are noticeable: depressions less than 2mm at 3m interval. Typical high quality asphalt 1.4-2.3. High quality surface treatment 2.0-3.0.	1.5-2.5	1000-2000
II	Ride comfortable up to 100km/hr - 120km/hr. At 80km/hr, moderately perceptible movements or large undulations may be felt. Defective surface: occasional depressions, patches or potholes (e.g. 5-15mm/3m or 10-20mm/5m with frequency 1-2 per 5m) or many shallow potholes (e.g. on surface treatment showing extensive ravelling). Surface without defects: moderate corrugations or large undulations.	4.0-5.5	3000-4000
III	Ride comfortable to 70-90km/hr, strongly perceptible movements and swaying. Usually associated with defects: frequent moderate and uneven depressions or patches (e.g. 15mm-20mm/3m or 20-40mm/5m) or occasionally potholes (e.g. 1-3 per 50m). Surface without defects: strong undulations or corrugations.	7.0-8.0	5500-6500
IV	Ride comfortable up to 50-60km/hr, frequent sharp movements or swaying. Associated with severe defects: frequent deep and uneven depressions and patches (e.g. 20-40mm/3m or 40-80mm/5m with frequent 5-3 per 50m) or frequent potholes (e.g. 4-6 per 50m).	9.0-10.0	7000-8500
V	Necessary to reduce velocity below 50km/hr. Many deep depressions, potholes and severe disintegration (e.g. 40-80mm deep with frequency of 8-16 per 50m).	11.0-12.0	9000-10,000

Also world Bank Organisation for Economic Co-operation and Development (O.E.C.D.) in their report on Road Monitoring for Maintenance Management recommended broad guidelines by which pavements can be demarcated into different distress conditions in terms of roughness (4). This is summarized in table 2.5.

TABLE 2.5: ROAD ROUGHNESS VALUES FOR DIFFERENT SERVICEABILITY LEVELS WITH RESPECT TO O.E.C.D. CLASSIFICATION

IRI CLASSIFICATION (m/Km)	SERVICEABILITY DESCRIPTION	OECD CLASSIFICATION
0 2	V > 120Km/hr. Undulations hardly noticeable at 80Km/hr. Visual inspection: No deformations or potholes. *Depressions < 2mm/3m* Asphalt concrete or high quality surface treatment.	1
4 5 6	V = 100-120Km/hr. Aware of slight movements or gentle undulations at 80Km/hr. Surface degraded by depressions (5.15mm/3m), repairs and potholes (1-5 per 100m). Surface not damaged, but undulations and corrugations exist.	2
7	V = 70 - 90Km/hr. Sharp movements and swaying. Depressions (10-20mm) or frequent repairs, or occasional potholes; or surface not damaged, but strong undulations and corrugations exist.	3
9 10	V = 50 - 60Km/hr. Frequent and sudden movements and swaying. Serious faults; or frequent and deep depressions (20-35mm at a frequency of 6-10 per 100m); or frequent poor repairs and potholes (6-20 per 100m).	4
11	V < 50Km/hr. *Frequent and deep depressions and potholes (>40mm,* frequency 16-30 per 100m)	5

where V = "comfortable" speed.

Findings from another study carried out by TRRL to rate pavements have been used to set limits for different levels of pavements serviceability in terms of the roughness values. The results are shown in Table 2.6.

TABLE 2.6: LIMITS OF PAVEMENT SERVICEABILITY IN TERMS OF ROUGHNESS VALUES (mm/Km)

PAVED ROADS		UNPAVED ROADS	
Serviceability	Upper value of Roughness (BI measure)	Serviceability	Upper value of Roughness (BI measure)
Good	2500	Good	5000
Start of potholing	4000	Potholes	10000
Badly broken	10000	Corrugations	15000

2.5 **Stochastic Modelling**

Stochastic systems are those that display random behaviour over time. A stochastic process varies unpredictably with time and most engineering systems exhibit such features. A good example of such a system is road deterioration over time. Therefore, in mathematical modelling of such systems, they could be formulated in terms of probabilistic statements rather than deterministic statements.

Atume (5) in his work described a stochastic modelling of road maintenance strategies using Rano-Garko road in Kano State as a case study. In the study, he formulated a mathematical model that could be used for optimising spread of maintenance budget on roads within a specified jurisdiction. Roughness measurement was used as the main parameter in categorizing the pavement into six different states of disrepair. A transition matrix was developed using mainly subjective opinions of experienced highway engineers. Submodels of the priority model, cost model and performance model was developed and three maintenance strategies were evaluated; no maintenance intervention, maintenance of failed sections and ideal maintenance. Using the user cost, maintenance

intervention and performance models, different states of the road were simulated for a period of 20 years and costs to the road users and maintenance agencies were estimated for different maintenance strategies. Results from the research showed that timely response to maintenance needs reduces overall expenditure on maintenance over time as well as minimized user costs. Also, maintenance expenditure over time was found to have a high rate of return in that reduction in user cost far outweighs investment on maintenance.

The Transport and Road Research Laboratory Road Investment Model for Developing Countries (RTIM 2) is designed to aid investment decisions within the roads sector in developing countries (6). It calculates the construction cost of a road and predicts the condition of the road as time passes and vehicles travel over it. It also estimates the costs of road maintenance and the vehicle operating costs. The model simulates the performance of a road over time including traffic patterns. The effect on vehicle operating cost of changing conditions of the road surface is taken into account in the determination of cost and benefits. The model was developed with data from a study carried out in Kenya, a tropical and developing country like Nigeria.

A detailed diagram of the model's flow chart is shown in Figure 2.1. Operation of the model starts by the user specifying the analysis period and defining the road alignment. Construction details are then input and the cost of construction determined. For each year, the road is open to traffic, road deterioration, road user costs and road maintenance costs are predicted. Road deterioration is calculated as a function of the construction specification, the maintenance policy, the rainfall and traffic. Road geometry and road surface conditions are used to predict vehicles' speeds, and fuel consumption. Costs of oil, fuel, tyres, vehicle maintenance, depreciation, etc, are then determined to give the total vehicle operating costs. Road maintenance requirements are then found from the condition of the road surface in conjunction with the maintenance policy specified by the user and these are used to calculate the maintenance cost. The model then continues with its year-by-year analysis. This model has proved to be quite versatile but its drawback is in its sophistication.

The World Bank's Highway Design and Maintenance Standard Model (HDM-III) (7) is designed with the same basic objectives as RTIM2. The major differences between them are in the number of road links each can evaluate simultaneously. The road deterioration and road user costs relationships assumed in the HDM-III model are also more extensively researched over a wider range of conditions and are thus more mechanistically and behaviourally compatible with empirical situations than the RTIM 2 model.

There is also The Road Transport Investment Model (RTIM3) (8), User's Manual. The vehicle operating costs calculated in RTIM3 are based closely on those of RTIM2. The concept of 'free speed' is replaced by a "speed constant" and parts consumption is calculated for vehicles of average age rather than spectrum of ages. Parts consumption equations have been adjusted so that vehicle age is expressed as vehicle travel to date and not year end travel. Also the calculation of interest and depreciation costs has been simplified in RTIM 3.

2.6 Other Studies on Road Maintenance

Oguara (9) in his work proposed a pavement management system for roadway maintenance in Nigeria. In the model, pavement were prioritized using pavement distress score and ride score. The concept of pavement distress score (PDS) was used to rate the pavement. A pavement without any distress would have a perfect score of 100, conversely, a pavement in a very poor condition could have a PDS of zero. Thus, the higher the score, the better the performance of the pavement. In general, the pavement distress score is given by equation 2.2, ie.:

$$PDS = 100 - \sum_{i=1}^{n} \sum_{j=1}^{m} a(T_i, S_j, E_{ij}) \quad \ldots\ldots (2.3)$$

where

a(Ti,Sj, Eij) = weighing factor depending upon distress type Ti, Severity Sj, and extent of distress Eij.

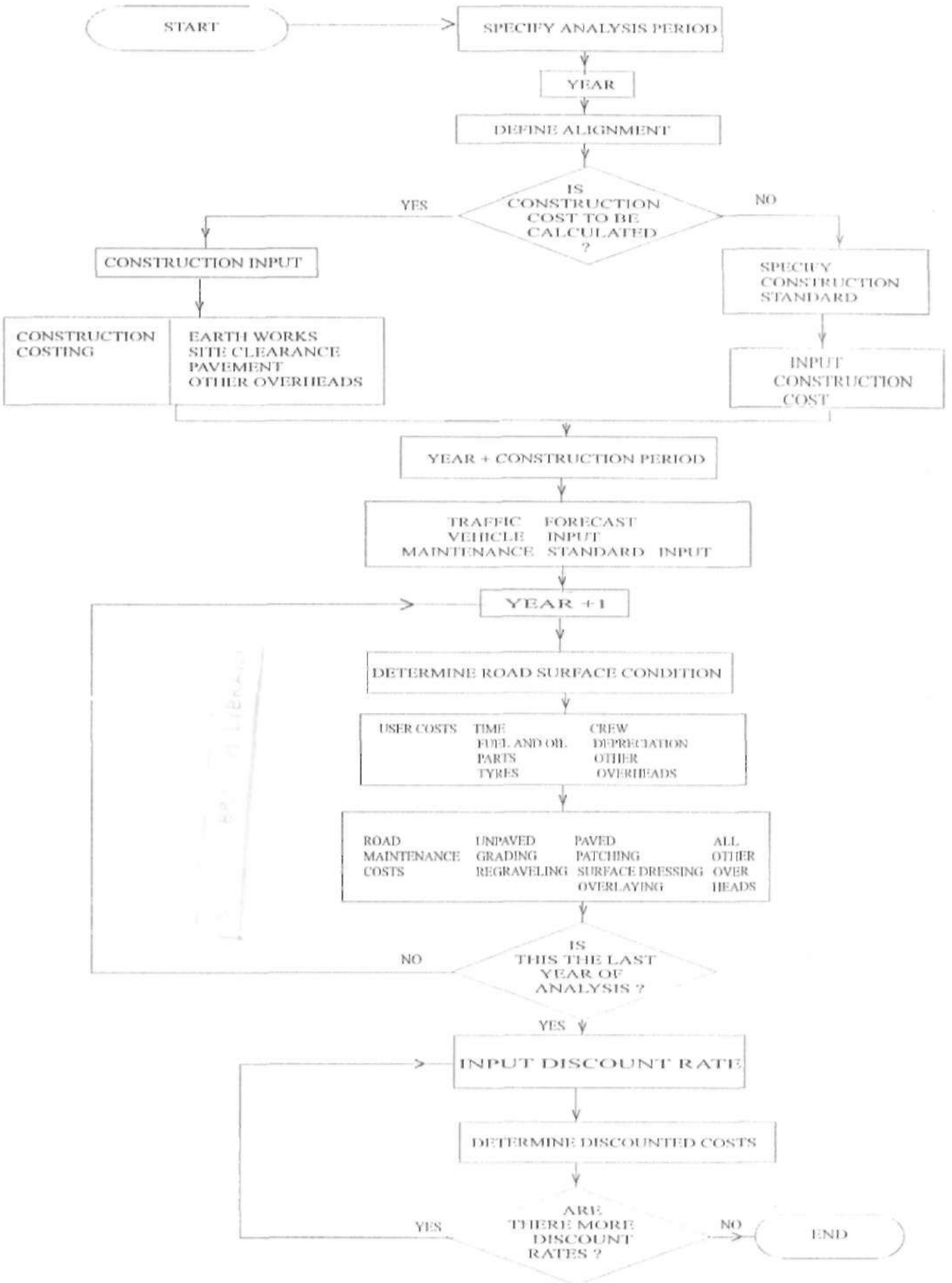


FIG. 2.1 DETAILED FLOW-DIAGRAM OF TRRL ROAD INVESTMENT MODEL

The ride score which is a measure of the roughness was determined using a subjective method of present serviceability index. Ride score ranges from 0 to 10, with smaller values indicating poor ride quality. The two scores are combined and a pavement condition index (PCI) is obtained to rate the pavement.

A performance model which utilizes the PCI values determined, and predicts the future condition of the roadway using a Markov chain process was developed. The Markov chain process utilizes a one step probability transition matrix using mainly subjective opinions of experienced highway engineers. A cost model was used to determine the maintenance cost and optimum strategy was obtained.

Finn (10) in his work described a pavement maintenance management system developed for the city of Palo Alto, California. The city has approximately 320km of paved roads. While the primary objective of the project was to identify maintenance requirements, additional data files were developed which were considered useful for design and construction and to provide life cycle information for various maintenance and rehabilitation alternatives. Three data files were developed. The information available in the three data file reports and two special reports that were developed served the following primary purposes:

(1) to establish priorities for pavement maintenance;
(2) to develop life cycle maintenance and rehabilitation costs estimates;
(3) to provide a data base of information for estimating future maintenance needs;
(4) to estimate the cost effectiveness of various rehabilitation procedures; and
(5) to schedule routine maintenance.

Special pavement inventory and threshold reports were used to establish maintenance priorities for the roads. The study focussed on scheduling maintenance and rehabilitation for the roads considered.

In South Africa, around 1988, both rural and urban authorities showed increased interest in developing a more formal approach to the management of their pavement networks. Curtayne and Scullion (11), reported the first stage in the implementation of a pavement management system for the city of Johannesburg. The municipality of Johannesburg then had an extensive pavement network made up of some 2700Km. The work was centered on assisting the road authority in identifying roads that require resealing or overlays. It was based on a model that relates pavement condition to maintenance requirements and to the timing of future inspections.

The method of establishing the model involved the assessment of the maintenance requirements of a set of pavements by a panel of raters and the correlation of these assessments with quantitative descriptions of the pavement distress. The summary of the maintenance requirements gave the total amounts for the various types of maintenance treatment for each priority level. The subjective manner in which the model was developed made the system simple.

Kilareski and Churilla (12) reported a special study conducted by the office of Research and Special Studies of the Pennsylvania Department of Transportation to evaluate the need for a pavement management system for Pennsylvania. Pennsylvania is a large industrial state with more than 75,450Km of paved roadway. The study consisted of an evaluation of what other states had done to implement a pavement management system and how their work could be expanded for Pennsylvania's purpose. The study also assessed pavement evaluation techniques which were being used by the department, such as MaysMeter roughness, Road Rater deflections, and distress surveys. It was arranged that a Pavement Management System Development Group oversee the implementation of the system with the following modules:

(a) Complete inventory of serviceability of the pavement network by Present Serviceability Index;
(b) Development of a distress survey for prioritizing projects; and

2.7 General and Concluding Remarks

In conclusion, it is necessary to highlight the basic elements of mathematical models needed for pavement management system. The first part is the 'classification' sub-model wherein the prevailing state of the road network is characterized. A second key element is the 'performance' sub-model wherein the future states of the network are simulated. This sub-model should make provision for various maintenance interventions and be capable of predicting the consequent behaviour of the network. As maintenance interventions are undertaken, the consequent behaviour of the network over time should also be predicted by the 'performance' sub-model. Another key element is the 'cost' sub-model wherein maintenance costs at different points in time are estimated on the basis of the prevailing states of the network. The 'cost' sub-model should be capable of also predicting road user costs at the prevailing states of the road at different points in time. The overall picture is then got by the sub-models working together.

From the system reviewed for developed countries, it can be deduced that some of the pavement attributes are site specific to their country of derivation. For instance, distress type and severity, besides being traffic volume related, is certainly a function of the local climatic condition and the materials used for the construction of the pavement. This means that the patterns of behaviour of pavements studied in these countries may not be directly replicated in the Nigerian environment. Another area of concern relates to the sophistication of some of the models. The data requirements are likely to render them almost impossible for adaptation in Nigeria considering our level of technological development, personnel capability and equipment availability.

The approach adopted in modelling of road maintenance strategies by Atume (5) seems quite convenient for the Nigerian situation. However, the order of calibration of maintenance intervention which he adopted is not very good. For instance, surface dressing is normally a method of resealing and therefore by taking surface dressing as a distinct method coming after resealing as a different operation does not look good. Also to bring state 3 (i.e. roughness of 7381 mm/km) and state 4 (i.e. roughness of 9241

mm/km) to the best state, there is need to repair the potholes before resealing operations.

The pavement maintenance program outlined by Oguara (9) is also convenient for the Nigerian situation but its emphasis was more on the maintenance cost sub-model without relating it to user cost sub-model. Thus, the returns from investments to maintenance intervention cannot be deduced.

This work continues along the framework outlined by Atume (5). The main pavement attribute used to model pavement performance and to develop both the classification and user cost sub-models is roughness index. Although use of roughness alone in this context has some limitations, it is probably the best method currently available for measuring riding quality used for carrying out road ranking surveys.

CHAPTER THREE

THEORETICAL CONSIDERATIONS

3.0 PREAMBLE

Having reviewed previous works on road maintenance in the preceding chapter, this chapter brings into light the theory underlying pavement deterioration, maintenance requirements and all matters pertaining to life cycle costs. In the consideration, the local situation in Nigeria, is taken as the model in as much as possible.

3.1 Performance Sub-Model

The performance sub-model focuses on the prediction of future ride qualities experienced by users of the roadway at different points in time. The prediction is necessary to estimate the performance trends of the original pavement, the changes which are likely to occur as a result of maintenance or lack of maintenance and the performance trends after maintenance has been effected. This model would utilize the initial vector determined by roughness measure in predicting the future conditions of the roadway using a Markov chain process.

3.1.1 Markov Chain Process

Markov chain process offers a very convenient approach to the prediction of pavement performance over time. A system which can exist in one of a set of possible states and which varies unpredictably over time is a condition for description in Markovian terms. Road pavement is likened to such system by idealizing that it can only exist in a specified number of states at a time. It is further assumed that the transition from one state to another is instantaneous. Thus, it is idealized that the pavement existing in a specified initial state makes transitions, at discrete points in time, from one state to another or remains in the same state. Of course, practical realities are reflected to impose some restrictions on the transitions.

A newly well-constructed pavement is said to be in its possible best state. After the road pavement is opened to traffic and exposed to the elements of weather, the condition will generally deteriorate with time. This deterioration involves a decrease in serviceability, an increase in distress, increase in user costs and, as maintenance is delayed, higher costs would be required to restore the road to its initial condition. In this formulation, the process of gradual deterioration is idealized as a series of transitions of pavement states from the initially excellent condition to less desirable conditions. This concept of a transition of pavement states is a basis for modelling the deterioration of pavement condition. Once deterioration starts, the pavement cannot transit to a better state unless there is some maintenance intervention.

A state in a Markov process is specified by the value of the variable which describes the behaviour of the system. In this work, the road pavement is classified into six different states of disrepair, in accordance with the severity of distresses, from state zero to state five with state zero as the best state and state five as the worst state. State zero is assumed to be the excellent condition of the road which requires no maintenance and state five is when the road has failed and requires reconstruction to bring it back to the best state.

The state of a pavement can be described by the values of the performance parameters (e.g. roughness) which reflect the condition of the pavement. The variable used to characterize the states of pavement is roughness but with some arbitrary grouping as indicated in Table 3.1. International Roughness Index (IRI) has been used in this grouping. IRI is a standard roughness measure and describes a scale of roughness which is zero for a true planar surface, increasing to about 6 for moderately rough roads, and 12 to 15 for extremely rough roads. In state zero, it is assumed that the road is excellent and roughness values very low. In state one, the pavement is still in a very good condition and the roughness values are still low. In state two, though the condition of the pavement is good, minor cracks (AASHTO Class 1 cracks) have started forming with spot potholes, hence roughness is moderate. In state three, the condition of the road is

fair with progressed cracks formation and occasional potholes, hence higher roughness values. In state four, the condition of the road is poor with fully developed cracks and major potholes, hence high roughness values. In state five, the road has collapsed exhibiting deep potholes and severe disintegration, hence very high roughness values.

TABLE 3.1 ARBITRARY CATEGORIZATION OF ROAD PAVEMENT INTO DIFFERENT STATES

STATE OF THE ROAD	CONDITION	LIMITING ROUGHNESS
0 (best state)	Excellent	0 - 2
1	Very good	2 - 4
2	Good	4 - 6
3	Fair	6 - 9
4	Poor	9 - 12
5 (worst state)	Fail	> 12

To be able to describe the probabilistic behaviour of the Markov chain process, there is need to have two sets of information which represent the parameter of the process.

(i) The state from which the system originates at time zero. This is specified, in matrix notation, by a row vector of length (N + 1) with elements of which constitutes a probability distribution over a set of possible states, where N is number of states. The initial state of the system, P_o is given as:

$$P_o = (X_0, X_1, X_2, X_3, X_4 \ldots\ldots\ldots\ldots X_N)$$

(ii) The transition probabilities, $P_{ij}^{(n)}$, ie. the probability of the system going from state i to state j in n steps. This expresses the probability that a road in state i

will transit to a state j within a specified unit time period. The transition probabilities are arranged in an (1 + N) x (1 + N) matrix (14) e.g.

$$P_{ij} = \begin{Vmatrix} X_{00} & X_{01} & X_{02} & X_{03} & \ldots\ldots\ldots\ldots & X_{0N} \\ X_{10} & X_{11} & X_{12} & X_{13} & \ldots\ldots\ldots\ldots & X_{1N} \\ X_{20} & X_{21} & X_{22} & X_{23} & \ldots\ldots\ldots\ldots & X_{2N} \\ X_{30} & X_{31} & X_{32} & X_{33} & \ldots\ldots\ldots\ldots & X_{3N} \\ & & & & & \\ X_{N0} & X_{N1} & X_{N2} & X_{N3} & \ldots\ldots\ldots\ldots & X_{NN} \end{Vmatrix}$$

If a system is initially described by a specific probability distribution over the N states (the row vector) and if the transition matrix is also specified, the state of the system after one transition may be obtained directly by matrix multiplication.

$$P_K = P_0 \; P_{ij}$$

The mathematics of a MarKov Chain is silent about how much time elapses between transitions. In order to compare predictions with the real world, it is therefore necessary to set a time scale. This implies specifying the average length of time in some convenient units, that is to be associated with the interval between transitions. For the purpose of this work, one year has been adopted as the interval between transitions.

3.2 Maintenance Intervention Activities

These are routine and major maintenance activities carried out by the highway agency in order to preserve the roadway structure. Maintenance is the preservation of each roadway structure and facility, as near as possible, in its original condition as constructed or as subsequently improved. It is necessary to classify maintenance activities according to frequency of operation, as used in TRRL road note 1 (15).

(a) Routine Maintenance

This is required regardless of the engineering characteristics of the road or the density of traffic it carries. Typical activities in this category include, clearing

of side drains, grass cutting, cleaning of culverts and maintenance of road furniture among other things.

(b) Recurrent Maintenance

This is undertaken at intervals throughout the year, but the frequency varies with traffic and weather severity. Activities in this category include sealing of potholes, sealing of cracks, etc.

(c) Periodic Maintenance

This is undertaken only at intervals of several years. Activities in this category include strengthening by overlays and surface dressing.

(d) Upgrading

Upgrading is undertaken to provide increased capacity when a road is nearing the end of its design life or because there has been an unforeseen change in the use of the road. Typical examples of upgrading projects are paving of gravel roads, widening of existing roads, etc.

(e) Rehabilitation

Rehabilitation is required either because a road has outlived its design life or, more usually, because the road has received insufficient maintenance to enable it provide an appropriate level of service to the end of its design life.

3.3 Cost Models

The pavement behaviour and performance have economic significance which can be measured in terms of costs. The cost models consists of maintenance intervention costs and user costs sub-models.

3.3.1 Users Costs Sub-Model

Road construction and maintenance activities consume a large proportion of the annual budgets of all tiers of government in Nigeria. The costs borne by the road users for vehicle operation and depreciation are even greater. Road-user costs are, by far, the largest cost element in road transport.

The World Bank has estimated that more than 10,000 million dollars are spent each year on highway construction, maintenance, and administration by governments in the developing countries of Africa, Asia and Latin America. In the industrial economies of Europe, North America and Japan, the total is something more than 10 times as great. The costs borne by the road-users for vehicle operation and depreciation are of a much larger magnitude, typically 8 to 10 times those borne by governments (7). Improvements in road conditions, although costly, can yet pay substantial dividends by reducing vehicle operating cost and hence generate large net benefits to the national economy as a whole.

User costs incurred by highway users consist of vehicle operating costs, travel time delays and accident costs. Vehicle operating costs account for the largest cost component in low-income developing countries because they are relatively sensitive to variations in road design and surface conditions. In comparism to developed countries, traffic volumes are typically much lower, incomes and values attached to travel time savings are far lower and therefore not very significant. Accident costs, although quite large in aggregate, are quite small in relation to vehicle operating costs and are, in general, not as sensitive to variations in road characteristics (7).

Vehicle operating costs depend on the number and type of vehicles using the road, the geometric design standards of the road, particularly of the curvature, gradient and road width, the condition of the surface of the road and driver behaviour. Roughness, at any time, will depend on whether the road surface is earth, gravel or paved, on the climate in the vicinity of the road, on the traffic it has carried and on the type and level of maintenance that has been carried out in the past. The value of roughness will change

with time depending on traffic loading, the performance of the materials with which the road is built and the type and amount of maintenance that is carried out. The change in roughness can have an appreciable effect on the vehicle operating cost throughout the life of a road. The components of vehicle operating costs, are very sensitive to speeds of travel and they are outlined by TRRL (6) as follows:

(a) Fuel consumption

(b) Tyres' costs of wear and tear

(c) Spare parts consumption

(d) Maintenance labour hours

(e) Crew cost (for public transport vehicles)

(f) Vehicle depreciation

(g) Lubricating oil consumption

(h) Overheads.

3.3-1.0 Speeds

These are a major determinant of vehicle operating costs. In calculating speed, the following relationships exist for each class of vehicle (6):

(i) CARS:

$$V = S_c + (0.483 - 0.00833\ S_c)RS - (0.025 - 0.0005S_c)F + (0.115 - 0.0022S_c)\ C - 0.00087R \quad \ldots\ldots\ldots(3.1)$$

(ii) TRUCKS:

$$V = 49.0 + (1.429 - 0.0286S_T)\ RS - (0.867 - 0.01318S_T)F + (0.177 - 0.00346S_T)\ C - (1.90 - 0.04346S_T)\ PW - 0.00106R \quad \ldots\ldots\ldots(3.2)$$

where,

V = speed (Km/hr)

RS = rise in m/Km

F = fall in m/Km

S_C = observed free-speed of passenger cars in Km/h

S_T = observed free-speed of trucks in Km/h

C = Curvature in degrees/km

R = Roughness in mm/Km

W = Road width (m)

PW = The power to weight ratio (BHP/tonne)

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3.3-1.1 Fuel Consumption Costs

There is considerable evidence supporting that at constant speed, on other than steep grades, the relationship between fuel consumption (per unit distance) and vehicle speed is approximately U-shaped. Several design codes assume such a relationship. However, other factors besides speed influence vehicles' fuel consumption costs. The following relationships exist for each class of vehicle (6):

(i) CARS

$$FL = \left(24 + \frac{969}{V} + 0.0076V^2 + 1.33RS - 0.63F + 0.029F^2\right) \frac{1.08}{10^3} \quad \ldots\ldots\ldots(3.3)$$

(ii) TRUCKS

$$FL = \left(29 + \frac{2219}{V} + 0.0203V^2 + 0.848GVW \times RS - 2.60F + 0.0132F^2\right) \frac{1.13}{10^3} \quad \ldots\ldots\ldots\ldots(3.4)$$

where

FL = Fuel consumption (litres/Km)

GVW = Gross vehicle weight (tonnes)

and the other variables are as defined before.

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3.3-1.2 Tyres' Costs of Wear and Tear

Tyre cost is an important element of vehicle operating costs, particularly in developing countries, and they are sensitive to highway conditions. Like fuel and oil, tyres are subjected to wear and tear continuously as vehicles travel. Each kilometer travelled results in material being removed from the tyres and, if for no other reasons, the tyres will eventually wear out from this type of abrasive wear. In addition, like the vehicle itself, tyres are stressed and strained as they travel so that, as time passes, the tyre's carcass is also weakened.

The incidence of tyre failure and the rate of tread loss are much greater in developing countries than in most developed nations. This is partly because of the prevalence of relatively low quality tyres. It is also due to travel on poor quality roads, often unpaved which cause increased carcass stress and tread wear and accelerate normal tread loss. Increased incidence of overloading causes greater carcass flexing and increases the risk of premature failure particularly for tyres placed on drive axles. And where ambient temperatures are high, tyres overheat and are more likely to blowout or strip their tread.

The following relationships exist for each class of vehicle (6)

(i) CARS

$$T = \frac{0.0927 + 0.6275e^{Z}}{1 + e^{Z}} \times \frac{1}{10^{3}} \quad \text{.....(3.5)}$$

where

$Z = 0.000695R - 3.753$

(ii) TRUCKS

$$T = \frac{0.1054 + 0.1921e^{Z}}{1 + e^{Z}} \times \frac{GVW}{10^{4}} \quad \text{.....(3.6)}$$

where $Z = 0.000737R - 4.302$

and T = Number of tyres consumed per Km

R = Roughness in mm/Km

GVW = Gross vehicle weight (tonnes)

It is pertinent to note here that tyre consumption in cars is dependent only on road roughness while gross vehicle weight becomes an additional factor for trucks.

3.3-1.3 Spare Parts Consumption

Spare parts consumption is crucially important in the calculation of benefits to highway improvements. It is a large component of total vehicle operating costs. It is sensitive to highway conditions, particularly surface condition, and their progression as vehicles age is influential in determining vehicle replacement expenditures. Spare parts consumption depends upon the characteristics of the routes over which vehicles travel, on the way in which vehicles are used and on the characteristics of the vehicles. The following relationships are used for each class of vehicle (8):

(i) CARS:

$$PC = (2.319R' \times LK' - 9.87R' - 841) \times VPR \times 10^{-9} \quad \ldots\ldots (3.7)$$

where

$$R' = \frac{500 + 14500e^{W}}{1 + e^{W}}$$

$$W = 415R \times 10^{-6} - 2.9$$

$$LK' = \frac{5.301e^{Y}}{1 + e^{Y}}$$

$$Y = 1.579 \log_{10}(K + HY) - 5.332$$

(minimum value of PC = 0)

(ii) TRUCKS

$$PC = \frac{3[(4.484 + 106R^{l} \times 10^{-6})\log_{10}(K + HY) + 24.86G \times C \times 10^{-6} - 22.07]VP}{10^{6}}$$

.....(3.8)

(minimum value of PC = 0)

where R is as defined before.

and PC = Maintenance parts cost per Km

R = roughness in mm/Km

K = vehicle age in Km

VP = Price of a new vehicle

G = gradient in m/Km

C = Curvature in degrees/Km

HY = equivalent half-year travel (km) as determined for case study.

3.3-1.4 Maintenance Labour Hours

Maintenance labour hours is necessary in calculating benefits to highway improvements. In the calculation of maintenance labour hours, the ratio of spare parts consumption to the price of an equivalent new vehicle is considered as one of the influencing factors. The following relationships are used for each class of vehicle (6):

(i) CARS

$$LH = \frac{695 + 383e^{z}}{1 + e^{z}} \times \frac{PC_{c}}{VP} \text{.....(3.9)}$$

(ii) TRUCKS

$$LH = \frac{2819 + 2507e^{z}}{1 + e^{z}} \times \frac{PC_{T}}{VP} \text{.....(3.10)}$$

where Z = -6.373 + 0.00159R

and LH = Labour hours per Km

PC_c = Maintenance parts cost per Km for cars

PC_T = Maintenance parts cost per Km for trucks

VP and R are as defined before.

3.3-1.5 Crew Cost

This is the cost of maintaining the crew of the vehicle. This involves light passenger vehicles, buses and trucks. There are normally no crew costs for private cars. It is determined by the number of crew that a vehicle carries, their wages and the overheads of employing them. The following relationship is used for all vehicle types (except private cars) regardless of road types used (8):

$$CC = \frac{NC.CW(100 - PP)}{100} \times TI \quad \text{.....(3.11)}$$

and CC = Crew cost per Km

NC = Number of crew

CW = Crew wages (per person per hour)

PP = Percentage of private vehicles

TI = Travel time (hours per Km)

V = Speed (Km/hr)

3.3-1.6 Depreciation

Depreciation as a concept has different meanings to different people. Nevertheless, it means the gradual decrease in the value of an asset due to wear and tear with passage of time. There is hardly any asset that has a permanent nature which does not become of less value each year, eventually requiring replacement. Vehicles suffer severely from wear and tear. The following relationship is used for all vehicle types regardless of road types used (8):

$$DC = \frac{AD.PN.VP(100 - PP)}{10^6} \times \frac{TI}{WH} \quad \ldots\ldots\ldots\ldots (3.12)$$

where

DC = depreciation cost per Km

AD = annual depreciation as a percentage of the current vehicle value

PN = current vehicle value as a percentage of the price of a new vehicle

VP = price of a new vehicle

WH = working hours per year

PP and TI are as defined before.

3.3-1.7 Lubricating Oil Consumption

Just as fuel is being consumed for running vehicles, lubricating oil is also consumed. The quantities of lubricating oil consumed are given in Table 3.2 as average values for paved and unpaved roads for four classes of vehicles (6). These quantities include both maintenance oil changes and oil consumed during vehicle running.

TABLE 3.2: AVERAGE FIGURES FOR TOTAL OIL CONSUMPTION (Litres/1000Km)

CLASS OF VEHICLE	PAVED	UNPAVED
Cars	1.2	2.4
Light vehicles	1.8	3.6
Trucks and buses	4.0	8.0

3.3.-1.8 Overheads

This component of vehicle operating cost includes such items as interest on capital, insurance and garaging. These costs vary from country to country and depending

on the size of the transport operation, vary from company to company. However, TRRL has found through studies that overhead costs is a fixed percentage of total running costs with twenty percent for trucks and buses and ten percent for cars (5). This is a very important cost component of vehicle operating costs which should not be neglected.

in excess of what the pavement was meant to sustain. The area of the pavement covered by alligator cracks was about 55%. Average Daily Traffic on this road was 414 vehicles per day.

Very few patches were observed on this road. This observation confirms the fact that the road had undergone little maintenance since construction. Patches indicate prior areas of distress or pavement failure. Drainage along the road was fairly adequate in some sections and poor in others. With respect to pavement condition rating described in section 2.3, the road is rated to have a Condition Survey Score of 86.85%, which when converted to five scale rating, is 4 indicating that the condition of the road is poor with some sections severely deteriorated.

Rano-Sumaila road is one of the roads earmarked for rehabilitation by the Kano State Government under Multi-State Roads Projects.

4.2 Development of Models for Case Study

4.2-1 Determination of Initial Probability Vector

Based on the data of roughness index gathered by PEU in 1995 (see Appendix A) and using the roughness values of Tables 2.4 recommended by TRRL, 2.5 recommended by OECD's Road Transport Research Programme and the World Bank and 2.6 as well as the categorization format outlined in Table 3.1, Rano-Sumaila road was neatly demarcated into six different states of disrepair in accordance with the severity of distress:

(a)	State 0 (the best state)	0 - 1.9 IRI
(b)	State 1	2.0 - 4.4 IRI
(c)	State 2	4.5 - 6.4 IRI
(d)	State 3	6.5 - 8.9 IRI
(e)	State 4	9.0 - 10.9 IRI
(f)	State 5 (the worst state)	>11.0 IRI

It is further categorized as shown in Table 4.1.

TABLE 4.1: CATEGORIZATION OF RANO-SUMAILA ROAD INTO DIFFERENT STATES OF DISREPAIR

STATE OF ROAD	ROUGHNESS (mid-values)	
	IRI, m/Km	BI, mm/Km
0	1.0	630
1	3.2	2320
2	5.5	4250
3	7.7	6200
4	10.0	8300
5	>11.0	9240

With the foregoing, the road pavement was sub-divided into different sections according to their specific state of disrepair for effective maintenance. This approach has the main advantage of efficient budget allocation to repair sections in urgent maintenance needs first. It conforms also to the model specifications outlined in chapter three. From the data collected by PEU, the total length of the road is 66Km. In measuring the roughness, right hand side (RHS) lane and left hand side (LHS) lane were measured and recorded separately, therefore, the overall length used in the calculation of road proportion is 66 x 2 = 132 Km, after which all the corresponding road lengths were divided by two to get the actual length of the road.

TABLE 4.2: THE PROPORTIONS OF THE ROAD UNDER DIFFERENT STATES

STATE	LENGTH OF THE ROAD FALLING INTO STATE, Km	PROPORTION OF THE TOTAL LENGTH
0	0	0
1	12.00	0.18
2	30.25	0.46
3	20.75	0.32
4	2.25	0.03
5	0.75	0.01
TOTAL	66.00	1.00

From these proportions given in Table 4.2, an initial probability vector P_o was obtained as:

$$P_o = (0.0\ 0.18\ \ 0.46\ \ 0.32\ \ 0.03\ \ 0.01)$$

Thus, the initial state assumed for the work corresponds to the year 1995 which was the most recent data on the road that was available.

4.2-2 Determination of Transition Matrix

The probability transition matrix was determined using a questionnaire that required the subjective judgement of experienced highway engineers in the Ministry of Works.

Different transition matrices got from the questionnaire were used to analyse a newly constructed road that is in its best state (state zero) and road deterioration profiles

were got assuming no maintenance intervention on the road. Three of the transition matrices were chosen because the nature of their road deterioration profiles were close to reality. These road profiles show that about 50% of the road has collapsed at the 8th year of analysis and about 99% at 27th year of analysis.

The three transition matrices were then averaged to get the final transition matrix, P_{ij} which was used for the study:

$$P_{ij} = \begin{Vmatrix} 0.78 & 0.08 & 0.05 & 0.04 & 0.03 & 0.02 \\ 0 & 0.72 & 0.10 & 0.09 & 0.06 & 0.03 \\ 0 & 0 & 0.67 & 0.20 & 0.09 & 0.04 \\ 0 & 0 & 0 & 0.62 & 0.23 & 0.15 \\ 0 & 0 & 0 & 0 & 0.58 & 0.42 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{Vmatrix}$$

Details of the questionnaire used in the formulation of the transition matrix have been included in Appendix B.

4.2-3 Evaluation of User Cost Sub-Model Using Case Study

4.2-3.0 Vehicle Speed

By adopting equations 3.1, 3.2 and making use of Table 4.1, the mean speeds of cars and trucks were obtained.

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TABLE 4.3: ESTIMATES OF MEAN SPEEDS OF CARS AND TRUCKS

STATE	SPEED OF CARS IN KM/HR	SPEED OF TRUCKS IN KM/HR
0	59.63	51.50
1	58.16	49.70
2	56.49	47.66
3	54.79	45.59
4	52.96	43.37
5	52.14	42.37

4.2-3.1 Fuel Consumption Costs

By adopting equations 3.3 and 3.4 and making use of Table 4.3 as well as taking the cost of fuel as N11/litre, the fuel consumption costs for cars and trucks were obtained as shown in Table 4.4.

TABLE 4.4: FUEL CONSUMPTION COSTS FOR CARS AND TRUCKS

STATE	FUEL CONSUMPTION COSTS FOR CARS, ₦ PER KM	FUEL CONSUMPTION COSTS FOR TRUCKS, ₦ PER KM
0	0.96	2.40
1	0.95	2.37
2	0.94	2.35
3	0.93	2.33
4	0.92	2.31
5	0.92	2.30

TABLE 4.6: SPARE PARTS CONSUMPTION FOR CARS AND TRUCKS

STATE	SPARE PARTS CONSUMPTION FOR CARS, ₦ PER KM	SPARE PARTS CONSUMPTION FOR TRUCKS, ₦ PER KM
0	3.54	35.14
1	6.62	39.98
2	12.32	49.53
3	21.81	63.90
4	32.90	81.37
5	37.31	88.32

4.2-3.4 Maintenance Labour Hours

By adopting equations 3.9 and 3.10 and making use of Table 4.6, Table 4.7 which shows the maintenance labour costs for cars and trucks was obtained.

TABLE 4.7: MAINTENANCE LABOUR COSTS FOR CARS AND TRUCKS

STATE	CARS ₦ PER KM	TRUCKS ₦ PER KM
0	0.008	0.069
1	0.015	0.078
2	0.021	0.091
3	0.029	0.113
4	0.042	0.143
5	0.048	0.155

Labour rate approved by the Federal Government of Nigeria = ₦7/hr.

4.2-3.5 Crew Cost

From equation 3.11, and making use of Table 4.3, the crew cost for running trucks was obtained as shown in Table 4.8.

TABLE 4.8: CREW HOUR COSTS

STATE	TRUCKS ₦ PER KM
0	0.23
1	0.24
2	0.25
3	0.26
4	0.28
5	0.28

4.2-3.6 Depreciation Costs

From equation 3.12, Table 4.9 which shows depreciation costs for cars and trucks was obtained.

TABLE 4.9: DEPRECIATION COSTS

STATE	CARS ₦ PER KM	TRUCKS ₦ PER KM
0	0.097	0.638
1	0.099	0.662
2	0.101	0.690
3	0.105	0.721
4	0.109	0.758
5	0.111	0.776

4.2-3.7 Lubricating Oil Consumption

From Table 3.1 and assuming the cost of engine oil is N150 per litre, Table 4.10 was obtained for cars and trucks.

TABLE 4.10: LUBRICATING OIL CONSUMPTION COSTS

STATE	CARS ₦ PER KM	TRUCKS ₦ PER KM
0	0.18	0.60
1	0.18	0.60
2	0.18	0.60
3	0.18	0.60
4	0.18	0.60
5	0.18	0.60

4.2-3.8 Overheads

Overhead cost is a fixed percentage of total running costs with 20% for trucks and 10% for cars. This was carefully calculated and included as item H in Tables 4.11 and 4.12 for cars and trucks respectively.

Tables 4.11 and 4.12 show the contribution of different components of vehicle operating costs for cars and trucks respectively.

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TABLE 4.11: CONTRIBUTION OF DIFFERENT COMPONENTS OF VEHICLE OPERATING COSTS FOR CARS

STATE	A	B	C	D	E	F	G	H	TOTAL
0	0.96	0.56	3.54	0.008	-	0.097	0.18	0.54	5.89
1	0.95	0.75	6.62	0.015	-	0.099	0.18	0.86	9.48
2	0.94	1.29	12.32	0.021	-	0.101	0.18	1.49	16.34
3	0.93	2.16	21.81	0.029	-	0.105	0.18	2.52	27.74
4	0.92	2.82	32.90	0.042	-	0.109	0.18	3.70	40.67
5	0.92	2.96	37.31	0.048	-	0.111	0.18	4.15	45.68

TABLE 4.12: CONTRIBUTION OF DIFFERENT COMPONENTS OF VEHICLE OPERATING COSTS FOR TRUCKS

STATE	A	B	C	D	E	F	G	H	TOTAL
0	2.40	2.45	35.14	0.069	0.23	0.638	0.60	8.31	49.84
1	2.37	2.55	39.98	0.078	0.24	0.662	0.60	9.30	55.78
2	2.35	2.89	49.53	0.091	0.25	0.690	0.60	11.28	67.68
3	2.33	3.54	63.90	0.113	0.26	0.721	0.60	14.29	85.76
4	2.31	4.13	81.37	0.143	0.28	0.758	0.60	17.92	107.51
5	2.30	4.25	88.32	0.155	0.28	0.776	0.60	19.34	116.02

where

A = FUEL CONSUMPTION

B = TYRES' COSTS

C = SPARE PARTS CONSUMPTION

D = VEHICLE MAINTENANCE LABOUR

E = CREW COSTS

F = VEHICLE DEPRECIATION

G = LUBRICATING OIL CONSUMPTION

H = OVERHEADS.

The user costs for cars and trucks are then shown as column vector corresponding to states zero to five and these are expressed in naira per kilometer per vehicle.

$$U_{CARS} = \begin{Vmatrix} 5.89 \\ 9.48 \\ 16.34 \\ 27.74 \\ 40.67 \\ 45.68 \end{Vmatrix} \qquad U_{TRUCKS} = \begin{Vmatrix} 49.84 \\ 55.78 \\ 67.68 \\ 85.76 \\ 107.51 \\ 116.02 \end{Vmatrix}$$

where;

U_{CARS} = Average user cost column vector for cars (Naira/veh-Km)

U_{TRUCKS} = Average user cost column vector for trucks (Naira/veh-Km)

With the percentage of cars for the case study which was 92% and that of trucks 8%, the weighted mean User cost, U_{WM} is therefore;

$$U_{WM} = \begin{Vmatrix} 9.41 \\ 13.18 \\ 20.45 \\ 32.38 \\ 46.02 \\ 51.31 \end{Vmatrix}$$

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The units of U_{WM} are Naira/veh-Km.

A simple observation of Tables 4.11 and 4.12 indicates that C, spare parts consumption cost, constitutes the major cost components. This cost component is about 81% of the total costs. This is followed by overhead costs which is about 10%. Tyres' cost and fuel consumption cost are also significant. The values of depreciation, lubricating oil, vehicle maintenance labour and crew costs are relatively small with vehicle maintenance labour costs as the least cost.

This in essence shows that spare parts consumption cost is the largest component of total vehicle operating costs. It is very sensitive to highway conditions, particularly surface condition. The values of this component are highly sensitive to the initial vehicle price. The obvious conclusion from the results is that the surface condition of a road has great influence on the vehicle operating cost.

4.2-4 Calibration of the Maintenance Intervention Sub-Model for Case Study

Even with proper maintenance, roads deteriorate with time. The rate depends on the climate, the type and strength of the pavement materials, the volume of traffic using the road and the axle loads of commercial vehicles. For all roads, there will eventually come a time when they will reach the end of their design lives and they will need strengthening or improvement. Strengthening, rehabilitation and reconstruction are all high cost maintenance activities and it is cost-effective to delay them for as long as possible by effecting appropriate and timely maintenance.

In this work, each or combination of two of the five different maintenance operations, outlined in section 3.2, is considered to be appropriate for the different states of the road disrepair to bring the road to its best condition. For example, road in state zero is assumed to be excellent and needs no maintenance. Road in state one is in a very good condition and needs only routine maintenance to bring it back to the best state. Road in state two, though in a good condition, cracks have started forming with spot potholes and therefore needs crack sealing, and minor pothole repairs to bring it back to the best state. Road in state three is fair with progressed crack formation and occasional potholes and therefore needs crack sealing and moderate pothole repairs to bring it back to the best state. Road in state four is in a poor condition with fully developed cracks and needs major pothole repairs and resealing to bring it back to the best state. Road in state five has failed and the only solution is to reconstruct the road to bring it back to the best state. Maintenance intervention calibration for the road is as shown in table 4.13.

TABLE 4.13: CALIBRATION OF MAINTENANCE INTERVENTION

STATE	CONDITION	MAINTENANCE INTERVENTION
0	Excellent	No maintenance
1	Very good	Routine maintenance
2	Good	Crackseal + minor pothole repairs
3	Fair	Crackseal + moderate pothole repairs
4	Poor	Major pothole repairs + resealing
5	Fail	Reconstruction/complete rehabilitation

4.2-4.1 Available Data on Rano-Sumaila Road

A traffic census carried out in 1995 by PEU showed that the Average Daily Traffic on Rano-Sumaila road was 414 vehicles per day. With the present growth rate of three percent for roads in Nigeria, the future traffic was determined from the relationship shown in equation 4.1.

$$V = V_o (1+R)^{m-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

$$= 414 \times 365 (1 + 0.03)^{m-1}$$

$$= 151110 (1.03)^{m-1}$$

where

R = Traffic growth rate which is 3% per annum

m = number of years considered

V_o = initial traffic, in vehicles per year

V = future traffic, in vehicles per year

Details of the studied road are:

(a) Length of road = 66km

(b) Pavement type = surface dressing

(c) Pavement width = 7.30m

(d) Shoulder width = 1.50m (unpaved)

(e) ADT = 414 vehicles per day.

4.2-4.2 Estimates of Costs of Maintenance Operations

Table 4.14 gives current rates for maintenance operations and materials as approved by the Federal Government of Nigeria.

TABLE 4.14: APPROVED FEDERAL GOVERNMENT RATES

STATE	DESCRIPTION	UNIT	RATE (₦)
1	Scarification	m^2	66.00
2	Sub-base materials	m^3	570.00
3	Base materials	m^3	618.00
4	MC1	m^2	57.00
5	Tack coat	m^2	50.00
6	Surface dressing	m^2	125.00
7	Asphaltic concrete	m^3	12,000.00

Labour rate = N54.55/day - 5 day - 40hr week.

The maintenance operations to be carried out are as follows:-

(a) Costs of Pavement Reconstruction

The road sections that fall in state five would require pavement reconstruction to bring them to the best state.

Total width of the road including shoulders

7.3 + (1.5)2 = 10.3m

Area/Km = 10.3 x 1000 = 10,300m^2

i) Scarification

Total cost of scarification

= 66 x 10300 = N679,800.00/Km

ii) Pavement reconstruction

Assuming a thickness of 150mm for road base and sub-base,

Quantity of materials = 10300 x 0.15

= 1,545m^3/Km

Estimated cost of materials

Sub-base	= 1545 x 570	=	880,650
Base	= 1545 x 618	=	954,810
Total	= ₦1,835,460.00/Km		

iii) Prime Coat

Prime coat would give a total cost of 57 x 10300 = N587,100.00/Km

iv) Surface dressing

Surface dressing treatment would give a total cost of 125 x 10300 = N1,287,500.00/Km

Hence, estimated total cost of reconstruction per Km = N4,389,860.00.

(b) Cost of Major Pothole Repairs and Resealing

The road sections that fall in state four would require major pothole repairs and surface dressing treatment to upgrade them to the best state.

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i) Pothole Patching

This has been estimated at N75,000.00/Km.

ii) Surface dressing

Cost of tack coat = 7300 x 50 = N365,000.00/Km

Cost of surface dressing treatment = 7300 x 125 = N912,500.00/Km.

Total cost of (b) = N1,352,500.00/Km.

(c) Cost of Crack Sealing and Moderate Pothole Repairs

The road sections that fall in state three would require crack sealing and moderate pothole repairs to bring them to the best state.

i) Moderate Pothole Repairs

This would be 50% of major pothole repairs i.e. 0.5 x 75000 = N37,500.00/Km.

ii) Crack Sealing

Cost of seal coat = 7300 x 50 = N365,000.00/Km

Total cost (c) = N402,500.00/Km.

(d) Cost of Minor Crack Sealing and Minor Pothole Repairs

The road sections that fall in state two would require minor crack sealing and minor pothole patching to bring them to the best state.

i) Minor Crack Sealing

This would be 25% of the cost of crack sealing = 0.25 x 365,000 = N91,250.00/Km.

ii) Minor pothole patching

This would be 25% of the cost of major pothole patching = 0.25 x 75,000 = N18,750.00/Km

Total cost of (d) = N110,000.00/Km.

(e) Routine Maintenance

The road sections that fall in state one would require routine maintenance to bring them to the best state.

An average routine maintenance would cost N20,000.00/Km for paved roads and N12,500.00/Km for gravel roads (A.S. Bhandari - World Bank).

The maintenance intervention matrix is therefore obtained corresponding to different intervention levels, i.e.

$$M_I = \begin{Vmatrix} 0 & \text{No maintenance} \\ 20{,}000 & \text{Routine maintenance} \\ 110{,}000 & \text{Crack seal + Minor pothole repairs} \\ 402{,}500 & \text{Crack seal + Moderate pothole repairs} \\ 1{,}352{,}500 & \text{Major pothole repairs + Resealing} \\ 4{,}389{,}860 & \text{Reconstruction/Complete rehabilitation} \end{Vmatrix}$$

The units of M_I are Naira per Km.

CHAPTER FIVE

APPLICATION OF DEVELOPED MODEL TO CASE STUDY

5.0 PREAMBLE

The model developed in this work can be used to evaluate different maintenance strategies. Three options have been specially considered in this work, ie.:

(a) No maintenance intervention

(b) Maintenance of failed sections only

(c) Maintenance of all sections.

The options considered constitute widely different maintenance strategies such that results obtained would facilitate drawing of conclusions on implications of maintenance as well as timely intervention in a road system. Three computer programs were developed to simulate the three different maintenance strategies. The computer programs are subsequently referred to as JKE.1, FMT.40, and GEM.260. Details of the programs have been included in appendix C.

5.1 Description of the Maintenance Options

5.1.-1 Option 1: No Maintenance Intervention

The assumption here is that no form of maintenance is undertaken. Thus, the road is left unattended to from year 0, whose state was earlier described in section 4.1-1, till year 20 which is the total period covered by this investigation. The computer program developed for this option is JKE.1.

5.1-2 Option 2: Maintenance of Failed Sections Only

The assumption here is to maintain sufficiently only completely failed sections (i.e. those in state 5), bringing them to the best state. The computer program developed for this option is FMT.40.

5.1-3 Option 3: Maintenance of all Sections

This option considers a situation in which all necessary maintenance is undertaken. The assumption here is that at the end of every year, adequate provision is made for all sections of the road to be taken to the best state (i.e. state zero) through appropriate maintenance intervention. The compute program developed for this option is GEM.260.

5.2 Basic Steps in the Computation

Details of computations involved in the computer simulations of investigated maintenance options are given in the computer programs. However, basic steps involved in the computations are described in subsequent sub-sections.

5.2-1 Option 1 (Program JKE.1)

This program computes the user cost for all sections of the road based on the strategy of no maintenance intervention. The different states of the road at year, m is thus:

$$P_m = P_o P_{ij}^m \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

where,

P_o = initial state probability vector

P_{ij}^m = probability transition matrix after m transitions

P_m = state vector at end of year, m; 1, 2, ...20

Thus, at end of the first year,

$$P_1 = (0.0 \;\; 0.18 \;\; 0.46 \;\; 0.32 \;\; 0.03 \;\; 0.01) \begin{Vmatrix} 0.78 & 0.08 & 0.05 & 0.04 & 0.03 & 0.02 \\ 0 & 0.72 & 0.10 & 0.09 & 0.06 & 0.03 \\ 0 & 0 & 0.67 & 0.20 & 0.09 & 0.04 \\ 0 & 0 & 0 & 0.62 & 0.23 & 0.15 \\ 0 & 0 & 0 & 0 & 0.58 & 0.42 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{Vmatrix}$$

P_1 = (0.0 0.1296 0.3262 0.3066 0.1432 0.0944)

5.2-1.1 User Cost Computation

Future traffic is computed as T^m, where

$T^m = V_o (1 + R)^{m-1}$ .....(5.2)

$= 414 \times 365 (1 + 0.03)^{m-1}$

$= 151110 (1.03)^{m-1}$

where,

V_o = Initial annual traffic volume

R = Traffic growth rate (assumed to be 3%)

m = number of years considered

T^m = Total annual traffic volume at year, m.

Total User cost C_u per Kilometer at the end of the first year is:

$C_u^1 = P_1 U_{wm} \times T^1$ .....(5.3)

where,

P_1 = State of the road after first year

U_{wm} = Weighted mean user cost matrix

T^1 = Total annual traffic volume at year,1.

$$C_u^1 = (0.0\ \ 0.1296\ \ 0.3262\ \ 0.3066\ \ 0.1432\ \ 0.0944) \begin{Vmatrix} 9.41 \\ 13.18 \\ 20.45 \\ 32.38 \\ 46.02 \\ 51.31 \end{Vmatrix} \times 151110$$

C_u^1 = N4,494,064.89/Km

TABLE 5.1: COST PROFILE WHEN NO MAINTENANCE IS UNDERTAKEN

YEAR OF OPERATION	USER COST/KM ₦ X 10^6	ACTUAL INTERVENTION COST/KM ₦ X 10^6	TOTAL SYSTEM COST/KM ₦ X 10^6
1	4.49406	-	4.49406
2	5.37661	-	5.37661
3	6.16474	-	6.16474
4	6.86242	-	6.86242
5	7.47997	-	7.47997
6	8.03017	-	8.03017
7	8.52595	-	8.52595
8	8.97929	-	8.97929
9	9.40063	-	9.40063
10	9.79882	-	9.79882
11	10.18110	-	10.18110
12	10.55340	-	10.55340
13	10.92050	-	10.92050
14	11.28600	-	11.28600
15	11.65310	-	11.65310
16	12.02400	-	12.02400
17	12.40060	-	12.40060
18	12.78450	-	12.78450
19	13.17690	-	13.17690
20	13.57870	-	13.57870
TOTAL	193.67146	-	193.67146

TABLE 5.2: ACTUAL ROAD PROFILE DETERIORATION WHEN NO MAINTENANCE IS UNDERTAKEN

YEAR OF OPERATION	PERCENTAGE OF DIFFERENT STATES OF THE ROAD AT END OF YEAR					
	0	1	2	3	4	5
1	0.0	12.960	32.620	30.660	14.320	9.440
2	0.0	9.331	23.151	26.700	19.071	21.747
3	0.0	6.718	16.445	22.024	19.845	34.968
4	0.0	4.837	11.690	17.548	18.459	47.466
5	0.0	3.483	8.316	13.653	16.085	58.463
6	0.0	2.508	5.920	10.442	13.427	67.704
7	0.0	1.806	4.217	7.883	10.872	75.222
8	0.0	1.300	3.006	5.894	8.607	81.193
9	0.0	0.936	2.144	4.372	6.696	85.852
10	0.0	0.674	1.530	3.224	5.139	89.434
11	0.0	0.485	1.093	2.365	3.900	92.157
12	0.0	0.349	0.781	1.729	2.933	94.208
13	0.0	0.252	0.558	1.259	2.190	95.741
14	0.0	0.181	0.399	0.915	1.625	96.880
15	0.0	0.130	0.285	0.663	1.200	97.721
16	0.0	0.094	0.204	0.480	0.882	98.340
17	0.0	0.068	0.146	0.347	0.646	98.793
18	0.0	0.049	0.105	0.250	0.472	99.124
19	0.0	0.035	0.075	0.181	0.344	99.366
20	0.0	0.025	0.054	0.130	0.250	99.541

Similar procedure is followed for other years.

The total system cost, C_s^m, is defined as the sum of user cost and intervention cost, ie.

$$C_s^m = C_u^m + C_I^m \quad \text{.....(5.4)}$$

where

C_u^m = user cost at year, m.

C_I^m = intervention cost at year, m.

Since the intervention cost for this option is zero, and m = 1.

C_S = ₦4,494,064.89/Km

Table 5.1 is the result of program JKE.1 (option 1) for all other values of m under this option. Similarly, Table 5.2 shows the actual road deterioration profile when no maintenance operation is undertaken, where the percentages of the road in the different states over the 20-year period considered are shown.

5.2-2 Option 2 (Program FMT.40)

This program computes the user costs and intervention costs based on the strategy that all failed sections of the road (ie. state 5) would be rehabilitated every year of analysis. The first step is the determination of the state vector from where the user costs and intervention costs are computed.

In the first year (ie. m = 1)

$P_1^* = P_o P_{ij}$

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As before

$P_1^* = (0.0 \quad 0.1296 \quad 0.3262 \quad 0.3066 \quad 0.1432 \quad 0.0944)$

The user cost is determined as described in option 1.

Intervention cost, $C_I^* = P_I^* \times M_I$ .....(5.5)

where,

M_I is the intervention matrix.

P_I^* is the state of the road after first year in option 2.

Since only sections in state 5 (worst state) are to be maintained each year, and making use of the value of M_I, as obtained in section 4.2-4.2, the intervention cost is given as;

$$C_I^* = (0, 0, 0, 0, 0, 0.0944) \begin{Vmatrix} 0 \\ 20{,}000 \\ 110{,}000 \\ 402{,}500 \\ 1{,}352{,}500 \\ 4{,}389{,}860 \end{Vmatrix}$$

$C_I^* = N414,402.78/Km$

Hence, total system cost C_S^* is given as;

$C_S^* = C_U^* + C_I^*$ .....(5.6)

Having maintained the road sections in state 5, the new state vector will change from P_1^* to P_1' because of the maintenance intervention, i.e.

$P_1' = (0.0 + 0.0944\ 0.1296\ 0.3262\ 0.3066\ 0.1432, 0.0)$

$P_1' = (0.0944\ 0.1296\ 0.3262\ 0.3066\ 0.1432\ 0.0)$

where,

P_1^* = state vector realized after intervention for the first year.

P_1' = state vector got as a result of the change in P_1^* due to the intervention that has taken place.

This new state vector is then used to compute the next state vector, P_2^*, as;

$$P_2^* = P_1 / P_{ij}$$

$$P_2^* = (0.0944\ \ 0.1296\ \ 0.3262\ \ 0.3066\ \ 0.1432\ \ 0.0) \begin{Vmatrix} 0.78 & 0.08 & 0.05 & 0.04 & 0.03 & 0.02 \\ 0 & 0.72 & 0.10 & 0.09 & 0.06 & 0.03 \\ 0 & 0 & 0.67 & 0.20 & 0.09 & 0.04 \\ 0 & 0 & 0 & 0.62 & 0.23 & 0.15 \\ 0 & 0 & 0 & 0 & 0.58 & 0.42 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{Vmatrix}$$

$$P_2^* = (0.07363\ \ 0.10086\ \ 0.23623\ \ 0.27077\ \ 0.19354\ \ 0.12496)$$

Similar procedure is followed for other years and the state vector for the m^{th} year is thus:

$$P_m^* = P_{m-1} / P_{ij};\ m = 1, 2, \ldots\ldots 20 \ldots\ldots\ldots\ldots (5.7)$$

Table 5.3 summarises the results of program FMT.40 (option 2) by showing the user costs and intervention costs based on maintenance of failed sections only. Similarly, Table 5.4 shows actual road deterioration profiles when the option is in effect.

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TABLE 5.3: USER COST AND INTERVENTION COST BASED ON MAINTENANCE OF FAILED SECTIONS ONLY

YEAR OF OPERATION	USER COST/KM ₦ X 10^6	ACTUAL INTERVENTION COST/KM ₦ X 10^6	TOTAL SYSTEM COST/KM ₦ X 10^6
1	4.49406	0.414403	4.908463
2	4.81547	0.548548	5.364018
3	4.88134	0.607336	5.488676
4	4.81125	0.604706	5.415956
5	4.71137	0.576246	5.287616
6	4.63558	0.541706	5.177286
7	4.60515	0.510590	5.11574
8	4.62316	0.486370	5.10953
9	4.68389	0.469337	5.153227
10	4.77855	0.458372	5.236922
11	4.89840	0.451947	5.350347
12	5.03610	0.448618	5.484718
13	5.18619	0.447228	5.633418
14	5.34490	0.446939	5.791839
15	5.50991	0.447196	5.957106
16	5.67995	0.447661	6.127611
17	5.85445	0.448149	6.302599
18	6.03329	0.448572	6.481862
19	6.21662	0.448900	6.66552
20	9.40470	0.449135	6.853835
TOTAL	103.20433	9.701959	112.906289

TABLE 5.4: ACTUAL ROAD DETERIORATION PROFILE WHEN MAINTENANCE IS UNDERTAKEN FOR SECTIONS IN STATE 5

YEAR OF OPERATION	PERCENTAGE OF DIFFERENT STATES OF THE ROAD AT END OF YEAR					
	0	1	2	3	4	5
1	0.0	12.960	32.620	30.660	14.320	9.440
2	7.363	10.086	23.623	27.077	19.354	12.496
3	15.490	8.851	17.829	23.215	20.780	13.835
4	22.873	8.719	14.297	19.929	20.407	13.775
5	28.586	9.209	12.283	17.466	19.329	13.127
6	32.536	9.968	11.236	15.783	18.137	12.340
7	35.003	10.767	10.769	14.725	17.105	11.631
8	36.375	11.483	10.624	14.117	16.322	11.079
9	37.014	12.064	10.639	13.809	15.783	10.691
10	37.210	12.503	10.720	13.683	15.442	10.442
11	37.169	12.814	10.815	13.659	15.248	10.295
12	37.022	13.023	10.901	13.683	15.152	10.219
13	36.848	13.156	10.968	13.726	15.115	10.188
14	36.688	13.235	11.016	13.769	15.111	10.181
15	36.558	13.279	11.048	13.806	15.123	10.187
16	36.461	13.300	11.067	13.834	15.140	10.198
17	36.394	13.309	11.078	13.854	15.157	10.209
18	36.350	13.311	11.083	13.867	15.171	10.218
19	36.323	13.309	11.085	13.875	15.182	10.226
20	36.308	13.307	11.085	13.879	15.189	10.231

5.2-3 Option 3 (program GEM.260)

In this option, all required maintenance intervention is undertaken at the end of every year on all sections of the road to bring them to the best state (state zero). The state vector, P_1^{**} after the first year is then used to compute the user cost and intervention cost for that year as before:

$$P_1^{**} = P_o\, P_{ij} = (0.0 \;\; 0.1296 \;\; 0.3262 \;\; 0.3066 \;\; 0.1432 \;\; 0.0944)$$

The state vector after maintenance of all the sections of the road is thus:

$$P_1^{//} = (1, 0, 0, 0, 0, 0)$$

where,

P_1^{**} = state vector realized after intervention for the first year

$P_1^{//}$ = state vector got as a result of the change in P_1^{**} due to the intervention that has taken place.

The new state vector, $P_1^{//}$ is used to compute the next state vector P_2^{**} as;

$$P_2^{**} = (1, \;\; 0, \;\; 0, \;\; 0, \;\; 0, \;\; 0) \quad \left\| \begin{array}{cccccc} 0.78 & 0.08 & 0.05 & 0.04 & 0.03 & 0.02 \\ 0 & 0.72 & 0.10 & 0.09 & 0.06 & 0.03 \\ 0 & 0 & 0.67 & 0.20 & 0.09 & 0.04 \\ 0 & 0 & 0 & 0.62 & 0.23 & 0.15 \\ 0 & 0 & 0 & 0 & 0.58 & 0.42 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{array} \right\|$$

$$P_2^{**} = (0.78 \;\; 0.08 \;\; 0.05 \;\; 0.04 \;\; 0.03 \;\; 0.02)$$

A similar procedure is followed for other years and the state vector for the m^{th} year is thus;

$$P_m^{**} = P_{m-1}^{//}\, P_{ij};\ m = 1, 2, 3, \ldots\ldots 20 \ldots\ldots\ldots\ldots\ldots (5.8)$$

Table 5.5 gives the result of program GEM.260 (option 3) showing the user costs and intervention costs based on maintenance of all sections. Similarly, Table 5.6 shows the corresponding actual road deterioration profile.

Highlights of the results on deterioration patterns, user costs and total system costs for all the options are graphically displayed in Figures 5.1, 5.2 and 5.3.

TABLE 5.5: USER COST AND INTERVENTION COST BASED ON MAINTENANCE OF ALL SECTIONS

YEAR OF OPERATION	USER COST/KM ₦ X 10^6	ACTUAL INTERVENTION COST/KM ₦ X 10^6	TOTAL SYSTEM COST/KM ₦ X 10^6
1	4.494	0.7700	5.2640
2	2.042	0.1516	2.1936
3	2.103	0.1516	2.2546
4	2.166	0.1516	2.3176
5	2.231	0.1516	2.3826
6	2.298	0.1516	2.4496
7	2.367	0.1516	2.5186
8	2.438	0.1516	2.5896
9	2.511	0.1516	2.6625
10	2.587	0.1516	2.7386
11	2.664	0.1516	2.8156
12	2.744	0.1516	2.8956
13	2.826	0.1516	2.9776
14	2.911	0.1516	3.0626
15	2.999	0.1516	3.1506
16	3.088	0.1516	3.2396
17	3.181	0.1516	3.3326
18	3.277	0.1516	3.4286
19	3.375	0.1516	3.5266
20	3.476	0.1516	3.6276
TOTAL	55.778	3.6504	59.4284

TABLE 5.6: ACTUAL ROAD DETERIORATION PROFILE WHEN MAINTENANCE IS UNDERTAKEN ON ALL SECTIONS

YEAR OF OPERATION	PERCENTAGE OF DIFFERENT STATES OF THE ROAD AT END OF YEAR					
	0	1	2	3	4	5
1	0.0	12.96	32.62	30.66	14.32	9.44
2	78.00	8.00	5.00	4.00	3.00	2.00
3	78.00	8.00	5.00	4.00	3.00	2.00
4	78.00	8.00	5.00	4.00	3.00	2.00
5	78.00	8.00	5.00	4.00	3.00	2.00
6	78.00	8.00	5.00	4.00	3.00	2.00
7	78.00	8.00	5.00	4.00	3.00	2.00
8	78.00	8.00	5.00	4.00	3.00	2.00
9	78.00	8.00	5.00	4.00	3.00	2.00
10	78.00	8.00	5.00	4.00	3.00	2.00
11	78.00	8.00	5.00	4.00	3.00	2.00
12	78.00	8.00	5.00	4.00	3.00	2.00
13	78.00	8.00	5.00	4.00	3.00	2.00
14	78.00	8.00	5.00	4.00	3.00	2.00
15	78.00	8.00	5.00	4.00	3.00	2.00
16	78.00	8.00	5.00	4.00	3.00	2.00
17	78.00	8.00	5.00	4.00	3.00	2.00
18	78.00	8.00	5.00	4.00	3.00	2.00
19	78.00	8.00	5.00	4.00	3.00	2.00
20	78.00	8.00	5.00	4.00	3.00	2.00

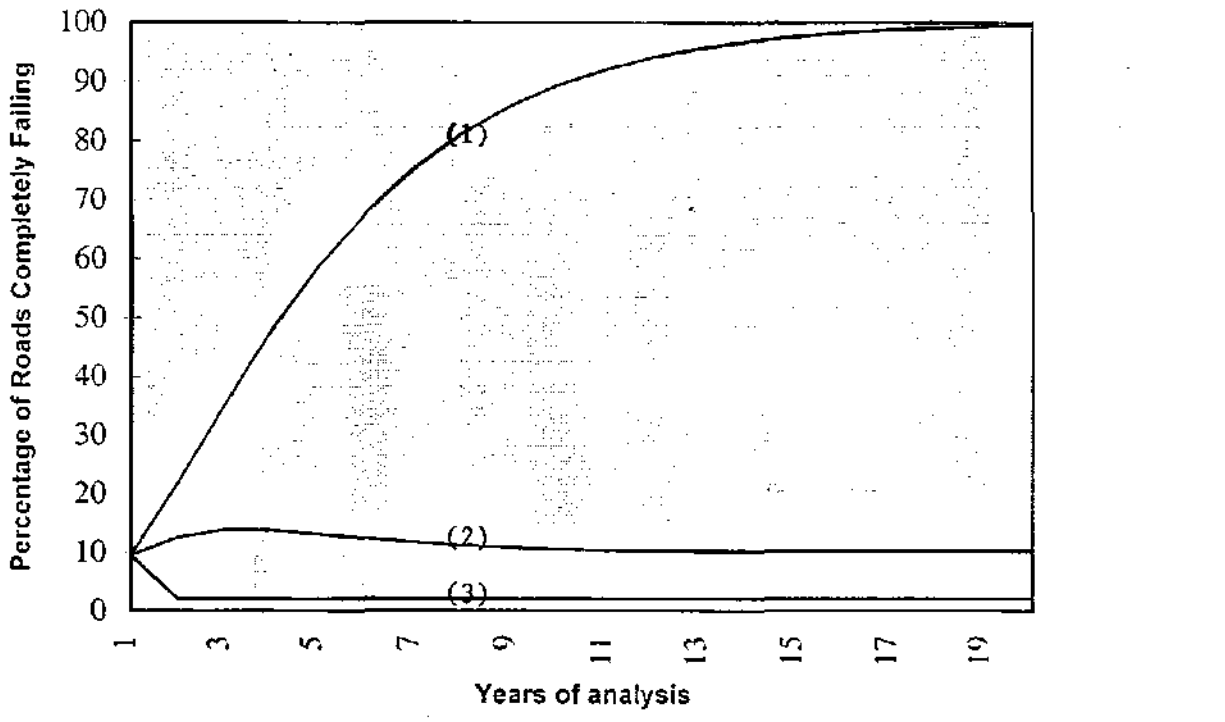


Fig. 5.1 Road Deterioration profiles for the Different Maintenance Strategies

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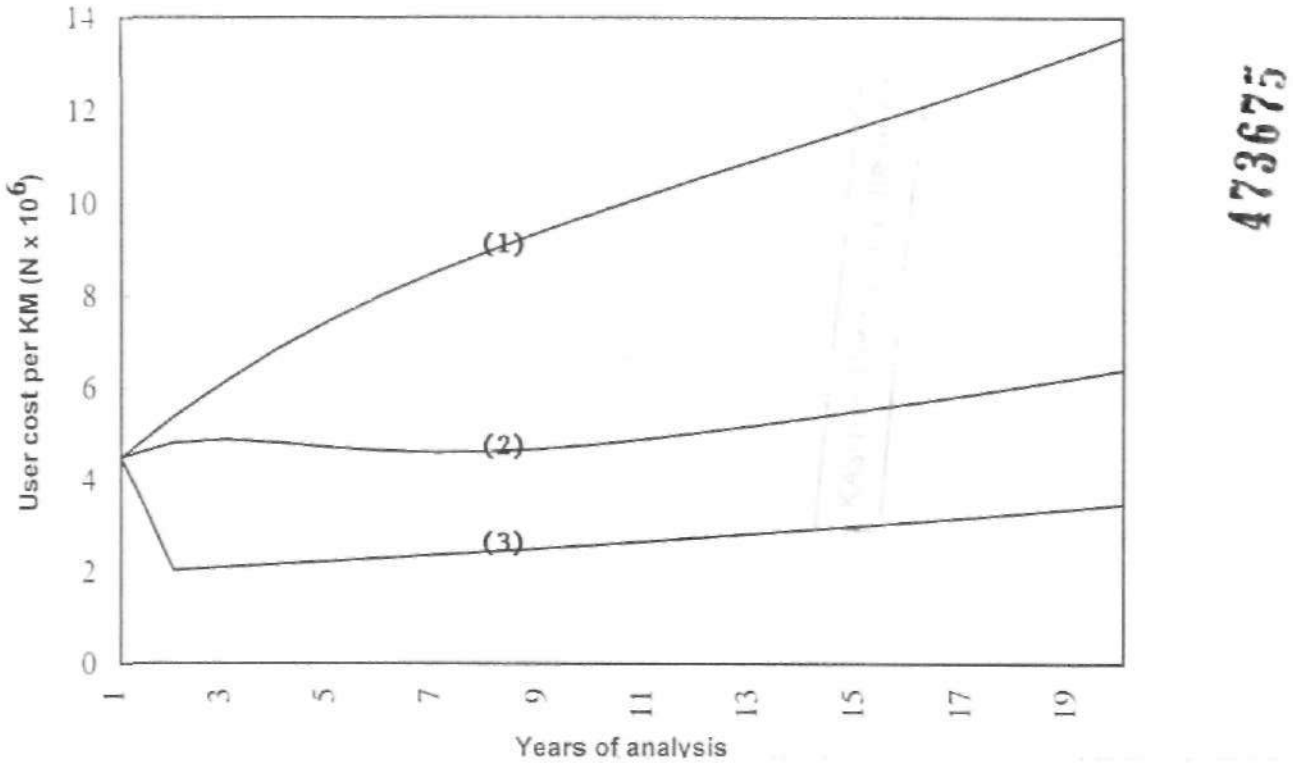


Fig. 5.2 User Cost Versus Years of Analysis for Different Strategies

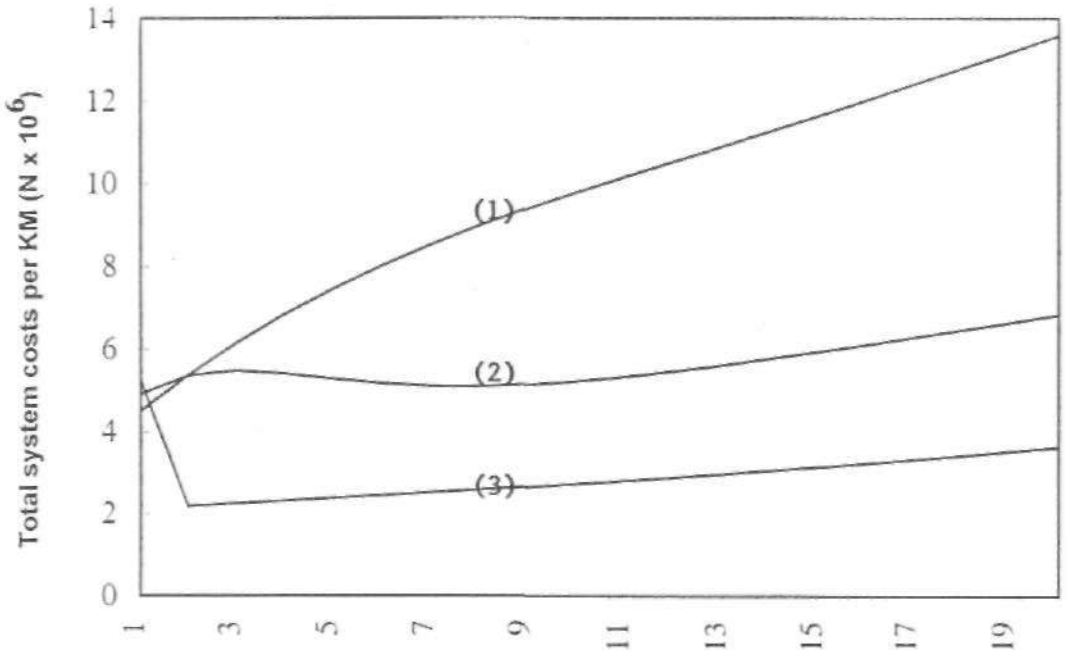


Fig. 5.3 Total System Cost Versus Years of Analysis for Different Strategies

5.3 Analysis of Results

5.3-1 General

Results of situation when no maintenance (ie. option 1) was undertaken are given in Tables 5.1 and 5.2. Here, the total annual user costs rose from about N4.5 million/Km, at the beginning of the analysis period to about N13.5 million/Km at the end of the 20th year. The road deterioration profile during the same period shows that at the end of the 20th year, about 95.5% of the road would have collapsed completely requiring total reconstruction to bring it back to the best state. Cumulatively, user costs per Km for the 20 year period is about N193.6 million/Km.

Option 2 assumes sufficient maintenance to repair only completely failed sections (ie. those in state 5). From Tables 5.3 and 5.4 it can be seen that this maintenance strategy reduces the vehicle operating cost considerably as compared to option 1. The user cost increased from about N4.5 million/Km at the initial state to about N9.4 million/Km at the 20th year with a cumulative total value of about N103 million/Km. The road deterioration profile during the same period shows an initial 0% of roads in the best state while from about 9th year of analysis, the percentage of roads in the best state stabilized at about 37%. Similarly, percentage of roads in the worst state rose from initial 9.4% and stabilized at about 10% at the 9th year of analysis. This shows a very negligible increase in the proportion of sections in the worst state.

In option 3, all the different sections of the road are maintained and brought to the best state annually. Table 5.5 shows that it would require an initial average amount of N770,000.00 per Km to upgrade all road sections to the best state at the end of the first year of analysis and subsequently only an average of N151,600.00/Km would be required yearly to sustain the roads in the best state throughout the analysis period. The user cost is about N4.5 million/Km for the first year but falls to about N2 million/Km at the end of the second year and rises to about N3.4 million/Km at the end of the 20th year. Table 5.6 shows that this strategy will keep 78% of the road in the best state with only 2% in the worst state throughout the period of analysis.

Figure 5.1 is a graphical representation of the rate of deterioration of sections of the road with time. It shows that roads deteriorate most under option 1 while there is least deterioration of roads under option 3. Figures 5.2 and 5.3 graphically illustrate user cost variation over time and total system cost variation also. They show that, over time, the user costs and total system costs are highest under option 1 but give least values under option 3. Option 2 is in between the two in all cases, in terms of performance.

The results clearly show that timely response to maintenance needs reduces overall expenditure on maintenance. They also show that expenditure on road maintenance have high rate of return. These deductions arise by comparing Tables 5.1, 5.3 and 5.5. In Table 5.3, where only totally collapsed road sections are rehabilitated, a total of N9.7 million/Km would be required to maintain the road for the 20-year period of analysis. In Table 5.5, where all road sections are attended to yearly, only a total of N3.6 million/Km would be required for the 20-year period of analysis.

Furthermore, results in Table 5.1 show that under option 1, the user costs incurred at the end of the 10th year amounted to about N75 million/Km. In Table 5.3 (ie option 2), the user cost at the end of the 10th year amounted to about N47 million/Km. The major difference between the two cases is that in option 1, no maintenance is undertaken whereas a total of about N5.2 million/Km had been cumulatively spent on maintenance at the end of 10th year in option 2. Thus by investing about N5.2 million/Km there is a saving of about N28 million/Km (i.e. N75M - N47M). If option 3 is considered, at the end of the 10th year, about N2.1 million/Km would have been cumulatively spent on maintenance and about N25.2 million/Km incurred as user cost. This implies that about N2.1 million/Km would have been spent to reduce the user cost from N75 million/Km to N25.2 million/Km bringing about a saving of about N49.8 million/Km. Among the three options analysed, option 3, maintenance of all sections, is therefore taken as the optimum strategy. These deductions come out even more clearly from a benefit/cost analysis which is presented in the next section.

5.3-2 Benefit/Cost Analysis of Maintenance Investments

Making use of the user cost and intervention cost matrices, the benefits and costs of bringing different states to state zero were obtained. The results are summarized on Table 5.7. The results relate to different states of the road, in terms of annual intervention costs of improving them to state zero and the benefits in terms of reduced user costs that accrue from such interventions. It shows that benefit cost ratio is highest

TABLE 5.7: BENEFIT/COST VALUES IN ₦ PER KM

STATE	COST, * N/KM	BENEFIT,** N/KM	BENEFIT COST RATIO
0	0.0	0.0	0.0
1	20,000.00	569,685.00	28.5
2	110,000.00	1,668,254.00	15.2
3	402,500.00	3,470,997.00	8.6
4	1,352,500.00	5,532,137.00	4.1
5	4,389,860.00	6,331,509.00	1.4

* intervention costs of improving to state zero.

** reduction in annual user costs that accrue from the maintenance interventions.

when the road is not allowed to deteriorate to the worst state, ie. benefit cost ratio reduces as maintenance is delayed. The results clearly show that if the road is maintained while in state 1, the benefit to be realized would be 28.5 times the investment on the maintenance. If the road is allowed to deteriorate to state 2 before being maintained, the benefit would be 15.2 times the maintenance investment on the road. Similarly, if the road is allowed to deteriorate to state 5 before being maintained, the benefit would be 1.4 times the maintenance investment on the road. This goes a long way to confirm that timely response to maintenance needs not only reduces overall expenditure on maintenance over time but also ensures highest rate of return.

CHAPTER SIX

SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.1 Summary

A rather simple mathematical model for prioritizing road maintenance has been developed and its applications illustrated. It has been demonstrated in this work that a simpler approach to maintenance management system is possible. The stochastic model developed in this work, though relatively crude, seems quite appropriate for Nigeria and indeed other developing countries. This is because the existing international models, TRRL'S RTIM2 and World Bank's HDM-III, though very versatile cannot be used effectively in Nigeria due to lack of adequate data and limited use of computers. However, this model does not render the international models obsolete, but instead limits their use to only special cases.

The study has reviewed a number of procedures that have been or are being developed for the management of highway pavements. In general, all these procedures have the main objective of providing a consistent and systematic procedure from which priorities can be clearly defined and budgeting for road maintenance properly scheduled. Pavement attributes or parameters are necessary for the development of a Pavement Management System. Quite a number of these attributes were mentioned in this work, for instance, rutting, ravelling, cracking, bleeding, patching, potholing, etc. In this work, roughness data was the parameter chosen for prioritizing the road into different states of disrepair. The data was derived from Maysride meter (Maysmeter) readings of surface roughness.

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Three sub-models were developed for this work, namely, classification, performance and cost sub-models. The classification sub-model used the roughness measurement to classify the road sections into one of different states according to their degree of disrepair, with state 0 as the best state and state 5 as the worst. The

performance sub-model utilized the first order MarKov Chain Process to predict future condition of the road pavement. In the MarKov chain process probabilities, $P_{(i,j)}$, are assigned to the transition of the road between any two states i and j. These probabilities form a matrix, P_{ij}, known as the probability transition matrix which expresses the probability that a road in state i will transit to a state j within a specified time period.

The cost sub-model is subdivided into user cost and maintenance intervention cost sub-models. The user cost sub-model was obtained based on the components of fuel consumption, cost of tyres wear and tear, crew costs, vehicle depreciation, vehicle maintenance labour costs, spare parts consumption, lubricating oil consumption and overheads. The maintenance intervention on the other hand considered routine maintenance, crack sealing, patching of potholes, resealing and reconstruction/complete rehabilitation.

Using the user cost, maintenance intervention cost and performance sub-models, different states of the road were simulated for a period of 20 years and the costs to road users and maintenance agencies were accurately determined for different maintenance strategies.

6.2 Research Constraints

The main weakness of the model formulated appears to be the determination of the transition matrix. The transition matrix applied in this work was based on a subjective approach, making use of experienced highway engineers. This was definitely based only on the experience of these engineers and, in this regard, could constitute a major source of errors. It is hoped that future research efforts would be geared towards deriving a transition matrix that is reflective of a wider group and less prone to errors. Similarly, in discretizing possible states to only six, gross simplifications are embodied. Larger states may, perhaps, also improve the accuracy.

6.3 Conclusion and Recommendations

The output from different maintenance strategies adopted has shown that timely response to maintenance needs reduces overall expenditure on maintenance and also that expenditure on road maintenance has a high rate of return. For instance, in option 3 (yearly maintenance of all sections), a maintenance cost of N2.1 million/Km over a period of ten years brought about a saving of N49.8 million/Km in user costs whereas option 2 (maintenance of failed sections only) brought about a saving of only N28 million/Km in user costs over a period of ten years with a maintenance input of N5.2 million/Km. This shows that yearly upgrading of all road sections to the best state would cost less than half of yearly reconstruction of only the totally collapsed sections. It has also been shown from the benefit/cost analysis that benefit cost ratio is higher when the road is not allowed to deteriorate to the worst state, ie. the benefit cost ratio reduces as maintenance is delayed. This goes a long way to confirm that timely response to maintenance needs not only reduces overall expenditure on maintenance over time but also ensures highest rate of return.

From the summary of findings derived from this work, it is recommended that timely intervention by the maintenance agencies be encouraged. The results have also indicated that cost-recovery measures that make adequate funds available for timely maintenance are in the best interests of road users as the returns far outweigh the charges.

In conclusion, one should, in applying the proposed model, consider the usual limitations of mathematical models which derive from the fact that they are based on idealized conditions. The proposed model is no exception. In its present form, the model is far from being perfect and it is hoped that future researches on the subject would improve on it. It is also hoped that the results' sensitiveness to unit prices of items covered would be undertaken so as to identify key variables that need to be very accurately determined.

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APPENDIX A

ROUGHNESS MEASUREMENT FOR RANO-SUMAILA ROAD

	STATION	KPH	IRI
RANO	0.00 - 0.50	50	5.20
RHS	0.50 - 1.00	50	4.24
	1.00 - 1.50	50	5.52
	1.50 - 2.00	50	6.18
	2.00 - 2.50	50	5.12
	2.50 - 3.00	50	5.72
	3.00 - 3.50	50	3.63
	3.50 - 4.00	50	5.37
	4.00 - 4.50	50	5.55
	4.50 - 5.00	50	7.10
	5.00 = 5.50	50	4.96
	5.50 - 6.00	50	5.88
	6.00 - 6.50	50	3.43
	6.50 - 7.00	50	5.41
	7.00 = 7.50	50	4.58
	7.50 - 8.00	50	3.85
	8.00 - 8.50	50	4.86
	8.50 - 9.00	50	5.49
	9.00 - 9.50	50	5.91
	9.50 - 10.00	50	4.26
	10.00 - 10.50	50	4.07
	10.50 - 11.00	50	4.97
	11.00 - 11.50	50	5.60
	11.50 - 12.00	50	6.42
	12.00 - 12.50	50	5.07
	12.50 - 13.00	50	6.92
	13.00 - 13.50	50	6.82
	13.50 - 14.00	50	5.20
	14.00 - 14.50	50	5.43
	14,50 - 15.00	50	6.53
	15.00 - 15.50	50	4.99
	15.50 - 16.00	50	5.43
	16.00 - 16.50	50	10.79
	16.50 - 17.00	50	4.90

	STATION	KPH	IRI
	17.00 - 17.50	50	5.12
	17.50 - 18.00	50	5.42
	18.00 - 18.50	50	5.80
	18.50 - 19.00	50	5.11
	19.00 - 19.50	50	7.39
	19.50 - 20.00	50	6.46
	20.00 - 20.50	50	6.38
	20.50 - 21.00	50	6.47
	21.00 - 21.50	50	5.67
	21.50 - 22.00	50	6.82
	22.00 - 22.50	50	6.51
	22.50 - 23.00	50	6.29
	23.00 - 23.50	50	4.79
	23.50 - 24.00	50	4.56
	24.00 - 24.50	50	6.81
	24.50 - 25.00	50	5.68
	25.00 - 25.50	50	5.49
	25.50 - 26.00	50	4.27
	26.00 - 26.50	50	5.00
	26.50 - 27.00	50	5.61
	27.00 - 27.50	50	4.26
	27.50 - 28.00	50	3.46
	28.00 - 28.50	50	4.60
	28.50 - 29.00	50	3.67
	29.00 - 29.50	50	5.02
	29.50 - 30.00	50	5.45
	30.00 - 30.50	50	5.58
	30.50 - 31.00	50	4.40
	31.00 - 31.50	50	3.46
	31.50 - 32.00	50	4.36
	32.00 - 32.50	50	5.06
	32.50 - 33.00	50	6.22
	33.00 - 33.50	50	7.00
	33.50 - 34.00	50	5.04
	34.00 - 34.50	50	6.23
	34.50 - 35.00	50	3.89
	35.00 - 35.50	50	3.37
	35.50 - 36.00	50	3.25
	36.00 - 36.50	50	4.98

	STATION	KPH	IRI
	36.50 - 37.00	50	2.67
	37.00 - 37.50	50	4.06
	37.50 - 38.00	50	2.84
	38.00 - 38.50	50	6.40
	38.50 - 39.00	50	7.27
	39.00 - 39.50	50	6.44
	39.50 - 40.00	50	8.00
	40.00 - 40.50	50	6.74
	40.50 - 41.00	50	7.22
	41.00 - 41.50	50	8.54
	41.50 - 42.00	50	7.10
	42.00 - 42.50	50	6.85
	42.50 - 43.00	50	6.80
	43.00 - 43.50	50	10.71
	43.50 - 44.00	50	5.49
	44.00 - 44.50	50	4.39
	44.50 - 45.00	50	4.12
	45.00 - 45.50	50	6.29
	45.50 - 46.00	50	4.53
	46.00 - 46.50	50	3.97
	46.50 - 47.00	50	5.20
	47.00 - 47.50	50	3.92
	47.50 - 48.00	50	4.02
	48.00 - 48.50	50	5.44
	48.50 - 49.00	50	3.88
	49.00 - 49.50	50	3.90
	49.50 - 50.00	50	5.20
	50.00 - 50.50	50	3.80
	50.50 - 51.00	50	4.62
	51.00 - 51.50	50	5.69
	51.50 - 52.00	50	5.66
	52.00 - 52.50	50	6.56
	52.50 - 53.00	50	5.36
	53.00 - 53.50	50	6.11
	53.50 - 54.00	50	4.62
	54.00 - 54.50	50	5.58
	54.50 - 55.00	50	6.88
	55.00 - 55.50	50	7.18

	STATION	KPH	IRI
	55.50 - 56.00	50	5.00
	56.00 - 56.50	50	5.70
	56.50 - 57.00	50	7.17
	57.00 - 57.50	50	6.81
	57.50 - 58.00	50	6.65
	58.00 - 58.50	50	6.91
	58.50 - 59.00	50	5.95
	59.00 - 59.50	50	5.75
	59.50 - 60.00	50	6.28
	60.00 - 60.50	50	7.27
	60.50 - 61.00	50	6.09
	61.00 - 61.50	50	5.42
	61.50 - 62.00	50	7.19
	62.00 - 62.50	50	5.05
	62.50 - 63.00	50	5.79
	63.00 - 63.50	50	7.13
	63.50 - 64.00	50	5.32
	64.00 - 64.50	50	4.83
	64.50 - 65.00	50	5.15
SUMAILA	65.00 - 65.50	50	6.11
RHS	65.50 - 66.00	50	5.62

	STATION	KPH	IRI
SUMAILA LHS	0.00 - 0.50	50	6.54
	0.50 - 1.00	50	6.36
	1.00 - 1.50	50	6.75
	1.50 - 2.00	50	6.92
	2.00 - 2.50	50	6.36
	2.50 - 3.00	50	8.31
	3.00 - 3.50	50	5.48
	3.50 - 4.00	50	7.79
	4.00 - 4.50	50	7.20
	4.50 - 5.00	50	9.35
	5.00 = 5.50	50	6.97
	5.50 - 6.00	50	6.27
	6.00 - 6.50	50	8.01
	6.50 - 7.00	50	7.67
	7.00 = 7.50	50	6.37
	7.50 - 8.00	50	6.33
	8.00 - 8.50	50	6.92
	8.50 - 9.00	50	6.92
	9.00 - 9.50	50	5.53
	9.50 - 10.00	50	4.41
	10.00 - 10.50	50	5.60
	10.50 - 11.00	50	6.47
	11.00 - 11.50	50	6.98
	11.50 - 12.00	50	6.38
	12.00 - 12.50	50	4.99
	12.50 - 13.00	50	5.65
	13.00 - 13.50	50	6.70
	13.50 - 14.00	50	3.36
	14.00 - 14.50	50	6.48
	14,50 - 15.00	50	6.72
	15.00 - 15.50	50	4.58
	15.50 - 16.00	50	3.26
	16.00 - 16.50	50	4.44
	16.50 - 17.00	50	4.79
	17.00 - 17.50	50	6.78
	17.50 - 18.00	50	4.30
	18.00 - 18.50	50	3.91
	18.50 - 19.00	50	6.82
	19.00 - 19.50	50	4.65
	19.50 - 20.00	50	7.21

	STATION	KPH	IRI
	20.00 - 20.50	50	5.76
	20.50 - 21.00	50	4.00
	21.00 - 21.50	50	4.36
	21.50 - 22.00	50	6.46
	22.00 - 22.50	50	3.36
	22.50 - 23.00	50	4.51
	23.00 - 23.50	50	5.80
	23.50 - 24.00	50	7.42
	24.00 - 24.50	50	4.79
	24.50 - 25.00	50	5.06
	25.00 - 25.50	50	4.36
	25.50 - 26.00	50	3.78
	26.00 - 26.50	50	5.19
	26.50 - 27.00	50	3.98
	27.00 - 27.50	50	4.60
	27.50 - 28.00	50	5.52
	28.00 - 28.50	50	4.05
	28.50 - 29.00	50	2.80
	29.00 - 29.50	50	4.20
	29.50 - 30.00	50	7.96
	30.00 - 30.50	50	6.62
	30.50 - 31.00	50	6.64
	31.00 - 31.50	50	5.74
	31.50 - 32.00	50	4.39
	32.00 - 32.50	50	10.65
	32.50 - 33.00	50	8.66
	33.00 - 33.50	50	8.87
	33.50 - 34.00	50	8.01
	34.00 - 34.50	50	7.57
	34.50 - 35.00	50	6.14
	35.00 - 35.50	50	8.86
	35.50 - 36.00	50	7.95
	36.00 - 36.50	50	6.70
	36.50 - 37.00	50	8.18
	37.00 - 37.50	50	12.53
	37.50 - 38.00	50	12.28
	38.00 - 38.50	50	7.57
	38.50 - 39.00	50	7.10
	39.00 - 39.50	50	9.02
	39.50 - 40.00	50	7.34

	STATION	KPH	IRI
	40.00 - 40.50	50	5.07
	40.50 - 41.00	50	5.61
	41.00 - 41.50	50	6.72
	41.50 - 42.00	50	7.81
	42.00 - 42.50	50	6.77
	42.50 - 43.00	50	7.53
	43.00 - 43.50	50	8.31
	43.50 - 44.00	50	5.18
	44.00 - 44.50	50	7.44
	44.50 - 45.00	50	8.21
	45.00 - 45.50	50	6.66
	45.50 - 46.00	50	6.32
	46.00 - 46.50	50	6.38
	46.50 - 47.00	50	8.35
	47.00 - 47.50	50	6.43
	47.50 - 48.00	50	6.81
	48.00 - 48.50	50	4.18
	48.50 - 49.00	50	6.69
	49.00 - 49.50	50	7.04
	49.50 - 50.00	50	9.58
	50.00 - 50.50	50	7.84
	50.50 - 51.00	50	6.88
	51.00 - 51.50	50	8.62
	51.50 - 52.00	50	6.24
	52.00 - 52.50	50	7.27
	52.50 - 53.00	50	7.47
	53.00 - 53.50	50	8.31
	53.50 - 54.00	50	8.56
	54.00 - 54.50	50	7.70
	54.50 - 55.00	50	5.30
	55.00 - 55.50	50	4.16
	55.50 - 56.00	50	5.61
	56.00 - 56.50	50	5.26
	56.50 - 57.00	50	9.77
	57.00 - 57.50	50	7.17
	57.50 - 58.00	50	7.97
	58.00 - 58.50	50	4.77
	58.50 - 59.00	50	6.30
	59.00 - 59.50	50	4.06

	STATION	KPH	IRI
	59.50 - 60.00	50	6.10
	60.00 - 60.50	50	7.80
	60.50 - 61.00	50	6.59
	61.00 - 61.50	50	5.06
	61.50 - 62.00	50	9.66
	62.00 - 62.50	50	11.39
	62.50 - 63.00	50	6.38
	63.00 - 63.50	50	9.49
	63.50 - 64.00	50	6.35
	64.00 - 64.50	50	5.78
	64.50 - 65.00	50	5.58
RANO	65.00 - 65.50	50	3.94
LHS	65.50 - 66.00	50	3.98

APPENDIX B

DETERMINATION OF TRANSITION MATRIX BY PERSONAL INTERVIEW

NAME OF RATER:.....
RANK (IN THE MINISTRY):.....
AGE:.....

1. How many years have you been actively involved in road maintenance?.....

2. How many of these years in (1) were used in the maintenance of flexible pavement?.....

3. What major maintenance activities have you been executing during these years
   (a) Patching of pot holes.....
   (b) Overlaying.....
   (c) Reconstruction.....

4. Highway traffic class under consideration (tick the appropriate class)
   ☐ Class I (ADT = 0 - 300)
   ☐ Class II (ADT = 300 - 1000)
   ☐ Class III (ADT = 1000 - 3000)
   ☐ Class IV (ADT = 3000 and above)

5. Road deterioration progresses in stages if the road is not maintained over a given period of time. From your experience, is it easy to predict these different stages of deterioration with time?.....

6. For a newly constructed road in Nigeria, based on your experience, how many years will it take for the whole road to completely collapse if left unmaintained?.....

7. For maintenance purposes, an engineer has classified a road into six different states of disrepair using roughness only as the easiest index of measurement. The possible states have been modelled as 0, 1, 2, 3, 4 and 5 with state 0 representing the best possible and state 5 the worst, indicating total collapse. One can assume that the gradation from state 0 to state 5 uniformly covers the possible states. You are kindly requested to assign a score of 0 to 1 probability to indicate deterioration from one state to another between inspections. For example, the probability that a road in state 0 (the best state) will remain in the same state after one year, if left unmaintained, indicates the relative frequency of lengths of the road that will satisfy the stated conditions.
   Based on the above, answer the following questions:
   A. i) What is the probability of the road remaining in state 0 after one year?.....
      ii) State 0 to state 1.....
      iii) State 0 to state 2.....

iv) State 0 to state 3.....

v) State 0 to state 4.....

vi) State 0 to state 5.....

B. i) Suppose the road length was in state 1 at the beginning of the year, what is the probability of the road remaining in state 1 after one year?.....

ii) State 1 to state 2.....

iii) State 1 to state 3.....

iv) State 1 to state 4.....

v) State 1 to state 5.....

C. i) Similarly, suppose the road length was in state 2 at the beginning of the year, what is the probability of the road remaining in state 2 after one year?.....

ii) State 2 to state 3.....

iii) State 2 to state 4.....

iv) State 2 to state 5.....

D. i) Suppose the road length was in state 3 at the beginning of the year, what is the probability of the road remaining in state 3 after one year?.....

ii) State 3 to state 4.....

iii) State 3 to state 5.....

E. i) Suppose the road length was in state 4 at the beginning of the year, what is the probability of the road remaining in state 4 after one year?

ii) State 4 to state 5.....

F. The chance of the road being in state 5 is 1

APPENDIX C

OPTION 1: PROGRAM JKE.1

```
      dimension A(1,6), b(6,6), c(1,6), d(1,6),tcu(20),
      *           dd(6,1),cu(20),ci(50),ff(6,1),cp(1,6)
      data a/0.0,0.18,0.46,0.32,0.03,0.01/
      data dd/9.41,13.18,20.45,32.38, 46.02,51.31/
      data ff/0.0,20000.,110000.,402500.,1352500.,4389860./
      data b/0.78,5*0.0,
      +          0.08,0.72,4*0.0,
      +          0.05,0.10,0.67,3*0.0,
      +          0.04,0.09,0.20,0.62,2*0.0,
      +          0.03,0.06,0.09,0.23,0.58,0.0,
      +          0.02,0.03,0.04,0.15,0.42,1.0/
      open(2,file='law1.res',status='old',err=55)
      goto 1111
55    open(2,file='law1.res',status='new')
1111  open(4,file='law1.out',status='old',err=1112)
      goto 111
1112  open(4,file='law1.out',status='new')
111   m = 0
1     m = m + 1
      do 20 i = 1,6
           x = 0.0
           do 10 j = 1,6
10              x = x + a(1,j)*b(j,i)
20              d(1,i) = x
      tcu(m) = 0.0
      tt = 151110.0*1.03**(m-1)
c     write(*,*)tt
      do 30 k = 1,6
      c(1,k) = d(1,k)
30    tcu(m) = tcu(m) + c(1,k)*dd(k,1)
      write(*,*) tt,tcu(m)
c No Maintenance and user's cost
      cu(m) = tcu(m)*tt
c Maintenance of failed sections and intervention Cost
      Ci(m) = c(1,6)*ff(6,1)
c p primes
      cp(1,1) = c(1,1)+c(1,6)
      cp(1,6) = 0.
      do 88 mm = 2,5
88    cp(1,mm) = c(1,mm)
      write(4,112)(cp(1,k),k=1,6)
      if(m.eq.1) then
      write(2,444)
      write(2,555)m,(c(1,i),i=1,6),cu(m)
      else
      write(2,555)m,(c(1,i),i=1,6),cu(m)
      endif
      if(m.lt.20) then
           do 40 kk = 1,6
40         a(1,kk) = c(1,kk)
```

```
          goto 1
      endif
112   format(3x,6(2x,f8.5))
444   format(4x,'S/N',18x,'row vector',42x,'User Cost'/
     *        2x,90('*'))
555   format(3x,i3,3x,6(2x,f8.5),3x,e15.6)
44    stop
      end
```

```
      dimension A(1,6), b(6,6), c(1,6), d(1,6),tcu(20),
     *           dd(6,1),cu(20),ci(50),ff(6,1),cp(1,6)
      data a/0.00,0.18,0.46,0.32,0.03,0.01/
      data dd/9.41,13.18,20.45,32.38, 46.02,51.31/
      data ff/0.0,20000.,110000.,402500.,1352500.,4339860./
      data b/0.78,5*0.0,
     +         0.08,0.72,4*0.0,
     +         0.05,0.10,0.67,3*0.0,
     +         0.04,0.09,0.20,0.62,2*0.0,
     +         0.03,0.06,0.09,0.23,0.58,0.0,
     +         0.02,0.03,0.04,0.15,0.42,1.0/

      open(2,file='law2.res',status='old',err=55)
      goto 111
55    open(2,file='law2.res',status='new')
111   m = 0
1     m = m + 1
      do 20 i = 1,6
           x = 0.0
           do 10 j = 1,6
10              x = x + a(1,j)*b(j,i)
20              d(1,i) = x
      tcu(m) = 0.0
      tt = 151110.0*1.03**(m-1)
      do 30 k = 1,6
      c(1,k) = d(1,k)
30    tcu(m) = tcu(m) + c(1,k)*dd(k,1)
c     write(*,*)(c(1,ll),ll=1,6)
c No Maintenance and user's cost
      cu(m) = tcu(m)*tt
c Maintenance of failed sections and intervention Cost
      Ci(m) = c(1,6)*ff(6,1)
c p primes
      cp(1,1) = c(1,1)+c(1,6)
      cp(1,6) = 0.
      do 88 mm = 2,5
88    cp(1,mm) = c(1,mm)
c     if(m.eq.1) then
c     write(2,444)
c     else
c     write(2,112)m,(cp(1,k),k=1,6)
c     endif
      if(m.eq.1) then
      write(2,444)
      write(2,555)m,(c(1,i),i=1,6),cu(m),ci(m)
      else
      write(2,555)m,(c(1,i),i=1,6),cu(m),ci(m)
      endif
      if(m.lt.20) then
           do 40 kk = 1,6
c note the change here for p'
40         a(1,kk) = cp(1,kk)
           goto 1
      endif
```

```
112   format(3x,i3,3x,6(2x,f9.5))
444   format(4x,'S/N',18x,'row vector',47x,'user
     *cost',8x,'int. cost'/
     *        2x,105('*'))
555   format(3x,i3,3x,6(2x,f9.5),3x,2e15.6)
44    stop
      end
```

```
      dimension A(1,6), b(6,6), c(1,6), d(1,6),
     * es(150),tcu(20),
     * dd(6,1),cu(20),ci(50),ff(6,1),cp(1,6),cpp(1,6)
      data a/0.0,0.18,0.46,0.32,0.03,0.01/
      data dd/9.41,13.18,20.45,32.38, 46.02,51.31/
      data ff/0.0,20000.,110000.,402500.,1352500.,4389860./
      data b/0.78,5*0.0,
     +         0.08,0.72,4*0.0,
     +         0.05,0.10,0.67,3*0.0,
     +         0.04,0.09,0.20,0.62,2*0.0,
     +         0.03,0.06,0.09,0.23,0.58,0.0,
     +         0.02,0.03,0.04,0.15,0.42,1.0/

      open(3,file='law3.out',status='old',err= 77)
      goto 802
77    open(3,file='law3.out',status='new')
802   open(2,file='law3.res',status='old',err=55)
      goto 111
55    open(2,file='law3.res',status='new')
111   m = 0
1     m = m + 1
      do 20 i = 1,6
           x = 0.0
           do 10 j = 1,6
10              x = x + a(1,j)*b(j,i)
20              d(1,i) = x
      do 50 jj = 1, 6
50    c(1,jj) = d(1,jj)
      cpp(1,1) = 1.0
      do 51 jj = 2,6
51    cpp(1,jj) = 0.0
      tcu(m) = 0.0
      tt = 151110.0*1.03**(m-1)
      do 30 k = 1,6
      c(1,k) = d(1,k)
30    tcu(m) = tcu(m) + c(1,k)*dd(k,1)
c No   Maintenance   and   user's   cost
      cu(m) = tcu(m)*tt
c Maintenance   of    failed   sections
c a n d   i n t e r v e n t i o n   C o s t
      ci(m) = 0.0
      do 777 nl = 1,6
777   Ci(m) = ci(m)+c(1,nl)*ff(nl,1)
      if(m.eq.1) then
      write(2,444)
      write(2,555)m,(c(1,l),l=1,6),cu(m),ci(m)
      else
      write(2,555)m,(c(1,l),l=1,6),cu(m),ci(m)
      endif
      write(3,112)m,(c(1,ll),ll=1,6)
      if(m.lt.20) then
           do 40 kk = 1,6
c note  the change here   for   p  prime
40           a(1,kk) = cpp(1,kk)
```

```
            goto 1
         endif
112      format(3x,i3,3x,6(2x,f5.2))
444      format(4x,'S/N',25x,'row vector',32x,'user
     *  cost',4x,'int. cost'/
     *         2x,100('*'))
555      format(3x,i3,3x,6(2x,f8.4),3x,2e12.4)
44       stop
         end
```