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# Markovian Probabilistic Pavement Performance Prediction Models for a Developing Country

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**Abstract:** The research presented here is a part of a simplified Pavement Information and Management System (PIMS) constructed for a typical developing country. Pavement deterioration modeling based on historical record of the objective function (performance) variation with age (time) requires regular measurement of the condition rating of pavement sections over a period of some years. Based on the generated model curves using historical data, future condition rating could then be predicted. In the absence of such information and record in the country (Nigeria), such method cannot be used and the alternative is to use probabilistic modeling. With the aid of Matlab and Visual Basic application software, three models were developed to generate pavement deterioration profiles, accruable user costs and intervention maintenance costs. The developed models were applied to a case study road. The results proved that timely intervention to maintain pavements at appropriate times will significantly reduce the overall expenditure for both the road users and the government. This was also attested to by the results of the benefit-cost analysis carried out.

**Key words:** Pavement deterioration, user costs, probabilistic modeling, benefit-cost

## INTRODUCTION

Pavement performance prediction models are some of the most important components of a PIMS. Capabilities of a PIMS are largely dependent on these models. Prediction models are used in activities such as: to estimate future pavement conditions, to assess the type and timing of maintenance and rehabilitation actions, to optimize or prioritize maintenance and rehabilitation actions for single and multiple years, to analyze the impact of maintenance and rehabilitation on the future condition, to find out the life cycle cost and to provide feedback to the pavement design process (Smith, 1996).

According to Smith (1996), a prediction model can be developed by one of the following methods:

- Empirical method
- Mechanistic method
- Mechanistic-empirical method
- Bayesian method

Pavement deterioration modeling based on historical record of the objective function (performance) variation with age (time) requires regular measurement of the condition rating of pavement sections over a period of some years. Based on the generated model curves using historical data, future condition rating could then be predicted. In the absence of such information and record in the country (Nigeria), such method cannot be used and the alternative is to use probabilistic modeling. Thus, in this research, the Markov probabilistic modeling was used.

**Markov approach to predicting pavement performance:** A system, which can exist in one of a set of possible states and which, varies unpredictably over time is a candidate for description in Markovian Terms (Benjamin and Cornell, 1970). Road pavement is likened to such a system with a finite (N+1) number of states, labeled 1, 2, 3, ... N and it is assumed that the system is always in one of these states, while transition is in discrete steps. At discrete points in time, the system makes a transition from one state to another (or remains in the same state). If the probability of transition to other states depends only on the state currently occupied and not on the history of the system, the system is called a finite-state Markovian Chain.

Markov chains are conveniently represented in matrix notation. The state of the system is specified by a row vector of length (N+1), the elements of which, constitute a probability distribution over a set of possible states. The transition probabilities are arranged in an (1+N) × (N+1) matrix, the i, j element representing the probability that the system will undergo a transition from

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state i to j in a single step. If the 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.

## MATERIALS AND METHODS

**Proposed Markov modeling:** The first step in the modeling is the specification of the initial state of the pavement. In this research, following the earlier research in this area, the different states of a pavement are described by roughness measurement. For effective implementation of maintenance strategies, it is desirable that the pavement section be divided into different sections according to their specific state of disrepair.

In line with the recommendation of TRRL road note 5, 7 different states of any pavement were considered, to correspond to the seven M and R strategies adopted and shown in Table 1. For the application of the developed PIMS, the roughness data collected for Kano-Maiduguri Road in year 2005 by Pavement Evaluation Unit of the Federal Ministry of Works, Katabu-Kaduna was used. This case study road is 125.5 km long.

The steps to capture the proportions of a road section that fall within each condition rating, based on the supplied roughness data are indicated in the flowchart of Fig. 1. These steps are programmed into the PIMS such that for any pavement with known roughness data for any year, the initial probability vector, $P_0$, can be automatically generated.

The next step is the development of the transition probability matrix. Six TPMs (A-F) were conventionally developed using questionnaires that required the subjective judgement of experienced highway engineers in the Ministry of Transportation. These TPMs are based on past research carried out for their M.Sc Thesis at Ahmadu Bello University, Zaria, Nigeria.

These TPMs reflect two major road parameters affecting pavement deterioration-age and traffic volume. The ranges of values for age and traffic volume considered in this research are shown in Fig. 2. It is believed that specification of age spectrum for a road would have taken care of environmental effects on the road, while range of traffic volume would take care of road class. In addition, traffic growth rate is assumed constant for the analysis period.

Any pavement section in the network would be categorized into a specific combination of age and traffic volume spectra. The PIMS will automatically select and combine the TPMs corresponding to the specified age and ADT ranges of any selected road and utilize the combined TPM to perform the deterioration analysis. A typical transition probability matrix developed is shown in Eq. 1:

Table 1: States of pavement based on roughness measurement

| State of the road | Condition | Limiting roughness IRI (M/KM) | Mid values of roughness values IRI | BI (M/KM) |
|---|---|---|---|---|
| 1 | Excellent | 0.0-1.9 | 0.95 | 600 |
| 2 | Very good | 2.0-3.9 | 2.95 | 2140 |
| 3 | Good | 4.0-5.9 | 4.95 | 3830 |
| 4 | Fair | 6.01-7.9 | 6.95 | 5610 |
| 5 | Poor | 8.01-10.0 | 8.95 | 7460 |
| 6 | Very poor | 10.01-12.0 | 10.95 | 9360 |
| 7 | Failed | >12 | >11.95 | 10320 |

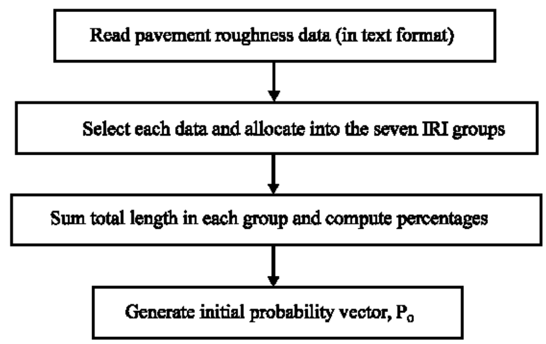



Fig. 1: System's flowchart to generate $P_0$ from known roughness data

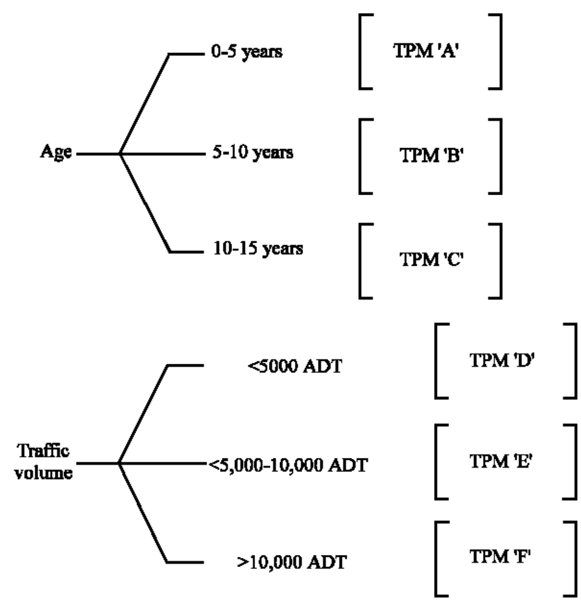



Fig. 2: Ranges for parameters considered in TPM development

$$\text{TPM } A_{ij} = \begin{bmatrix} 0.90 & 0.05 & 0.02 & 0.01 & 0.008 & 0.007 & 0.005 \\ 0 & 0.85 & 0.06 & 0.04 & 0.02 & 0.02 & 0.01 \\ 0 & 0 & 0.85 & 0.06 & 0.04 & 0.03 & 0.02 \\ 0 & 0 & 0 & 0.80 & 0.10 & 0.07 & 0.03 \\ 0 & 0 & 0 & 0 & 0.80 & 0.15 & 0.05 \\ 0 & 0 & 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Once, the initial state and transition matrices are specified, the new state of the pavement is calculated by matrix multiplication. Each multiplication of the state vector by the transition matrix represents one transition in the state of the pavement. The multiplication process continues until the required number of transitions has been completed or the system reaches a steady state.

For this research, one year has been adopted as the interval between transitions.

From the results of these proportions, an initial probability vector $P_o$, is obtained as:

$$P_o = [0.772908 \quad 0.227092 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$$

**User costs modeling:** The World Bank (Morosiur, 1986) has estimated that while, >10 thousand US million dollars are spent each year on highway construction, maintenance and administration by governments in developing countries of Africa, Asia and Latin America, the costs borne directly by the road users for vehicle operation might well be in the order of ten times this amount.

Basically, road user costs consist of time costs and vehicle operating costs. The time component of user cost in this research was ignored, primarily, because time costs in developing economies usually have low values. The user cost model therefore, considers the vehicle operating cost as the major component.

The components of vehicle operating cost normally considered are (Morosiur, 1986):

- Fuel consumption
- Lubricating oil consumption
- Spare parts consumption
- Vehicle maintenance labor hours
- Tyre consumption (wear and tear)
- Vehicle depreciation
- Crew cost
- Overheads

**Speeds:** These are major determinant of vehicle operation costs. In calculating speed, the following relationships exist for each class of vehicle (Parsley and Robinson, 1982):

$$\begin{aligned} V_C = S_c &+ (0.483 - 0.00833S_c) \\ &RS - (0.025 - 0.0005S_c) \\ &F + (0.115 - 0.0022S_c)C - 0.000087R \end{aligned} \quad (2)$$

$$\begin{aligned} V_T = 49.0 &+ (1.429 - 0.0286S_T) \\ &RS - (0.867 - 0.01318S_T) \\ &F + (0.177 - 0.00346S_T) \\ &C - (1.90 - 0.04346S_T)PW - 0.00106R \end{aligned} \quad (3)$$

where:

| | | |
|---|---|---|
| $V_C$ | = | Speed of cars (km $h^{-1}$) |
| $V_T$ | = | Speed of trucks (km $h^{-1}$) |
| $S_C$ | = | Observed free speed of cars (km $h^{-1}$) |
| $S_T$ | = | Observed free speed of trucks (km $h^{-1}$) |
| RS | = | Rise (km $h^{-1}$) |
| F | = | Fall (km $h^{-1}$) |
| C | = | Curvature (degrees $km^{-1}$) |
| R | = | Roughness (mm $km^{-1}$) |
| PW | = | Power to weight ratio in brake horsepower/ton (BHP $ton^{-1}$) |

**Fuel consumption:** Fuel consumption should be calculated for each half percent increment in road gradient and for the two directions of traffic in order to provide the mean value of each class of vehicle. The TRRL laboratory report 1057 gives the relationships to use:

$$FL_C = \begin{pmatrix} 24 + \dfrac{969}{V} + 0.0076V^2 + 1.33RS \\ -0.63F + 0.0029F^2 \end{pmatrix} 1.08 \quad (4)$$

$$FL_B = \begin{pmatrix} 29 + \dfrac{2219}{V} + 0.0203V^2 + 0.848 \\ (GVW \times RS) - 2.6F + 0.0132F^2 \end{pmatrix} 1.13 \quad (5)$$

where:

| | | |
|---|---|---|
| $FL_C$ | = | Fuel consumption of cars (mL $km^{-1}$) |
| $FL_B$ | = | Fuel consumption of buses and trucks(mL $km^{-1}$) |
| V | = | Speed (km $h^{-1}$) |
| Rsm | = | Rise (m $km^{-1}$) |
| F | = | Fall (m $km^{-1}$) |
| GVW | = | Gross vehicle weight (tons) |

**Tyre consumption (wear and tear):** The basic relationships used are (Parsley and Robinson, 1982):

$$TC_C = \left(\frac{0.0927 + 0.06275e^Z}{1 + e^Z}\right)10^{-3}; \quad Z = -3.753 + 0.000695R \quad (6)$$

$$TC_B = \left(\frac{0.1054 + 0.19215e^Z}{1 + e^Z}\right) \times GVW \times 10^{-4}; \quad Z = -4.302 + 0.00737R \quad (7)$$

where:

$TC_C$ = Tyre consumed per kilometer for cars
$TC_B$ = Tyre consumed per kilometer for buses and trucks
R = Roughness (mm $km^{-1}$)
GVW = Gross vehicle weight (tons)

Tyre consumption in cars is dependent only on road roughness while, gross vehicle weight is an additional factor for trucks.

**Spare parts consumption:** The basic relationships used are (Parsley and Robinson, 1982):

$$PC_C = \left(\frac{1.57 + 18.08e^Z}{1 + e^Z}\right) \times K \times VP \times 10^{-11}; \quad Z = -4.673 + 0.000812 \times R \tag{8}$$

$$PC_T = \left(\frac{1.22 + 6.0e^Z}{1 + e^Z}\right) \times K \times VP \times 10^{-11} \quad Z = -4.879 + 0.00984 \times R \tag{9}$$

where:

$PC_C$ = Spare parts costs per kilometer for cars
$PC_T$ = Spare parts costs per kilometer for trucks
R = Roughness (mm $km^{-1}$)
VP = Price of an equivalent new vehicle
K = Total kilometers run to date (this is determined from the product of the average annual kilometers run and the average age of the vehicle, which is, in turn, found from the age spectrum

**Maintenance labor hours:** The following basic relationships are used (Parsley and Robinson, 1982):

$$LH_C = \left(\frac{695 + 383e^Z}{1 + e^Z}\right) \times \frac{PC}{VP}; \; Z = -6.373 + 0.00159 \times R \tag{10}$$

$$LH_T = \left(\frac{2819 + 250e^Z}{1 + e^Z}\right) \times \frac{PC}{VP}; \; Z = -6.373 + 0.00159 \times R \tag{11}$$

where:

$LH_C$, $LH_T$ = Labor hours of maintenance for cars and trucks, respectively
PC = Spare parts (costs $km^{-1}$)
VP = Price of an equivalent new vehicle
R = Roughness (mm $km^{-1}$)

**Crew hours 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 (Cundil, 1983):

$$CC = \left(\frac{NC \times CW(100 - PP)}{100}\right) \times TI \tag{12}$$

where:

CC = Crew (cost $km^{-1}$)
NC = Number of crew
CW = Crew wages (per person per h)
PP = Percentage of private cars
TI = Travel time (h $km^{-1}$) = $1/V_T$
$V_T$ = Speed of trucks (km $h^{-1}$)

**Depreciation cost:** Depreciation means the gradual decrease in the value of an asset due to wear and tear with passage of time. Most assets (including vehicles) become less valuable each passing year, eventually requiring replacement. The following relationship is used for all vehicle types regardless of road types (Cundil, 1983):

$$DC = \frac{AD \times PN \times VP(100 - PP)}{10^6} \times \frac{TI}{WH} \tag{13}$$

where:

DC = Depreciation (cost $km^{-1}$)
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 an equivalent new vehicle
WH = Working hours per year
PP = Percentage of private vehicles
TI = Travel time (h $km^{-1}$)

**Lubricating oil consumption:** Average figures for total oil consumption on paved roads are given in Table 2.

**Overheads:** TRRL has found through studies that overhead costs is a fixed percentage of total running costs with 20% for trucks and buses and 10% for cars.

Table 2: Average figures for total oil consumption

| Class of vehicle | Oil consumption |
|---|---|
| Passenger cars | 1.2 L/1000 km |
| Light goods vehicle | 1.8 L/1000 km |
| Medium and heavy goods vehicles | 4.0 L/1000 km |

Source: Hide (1982)

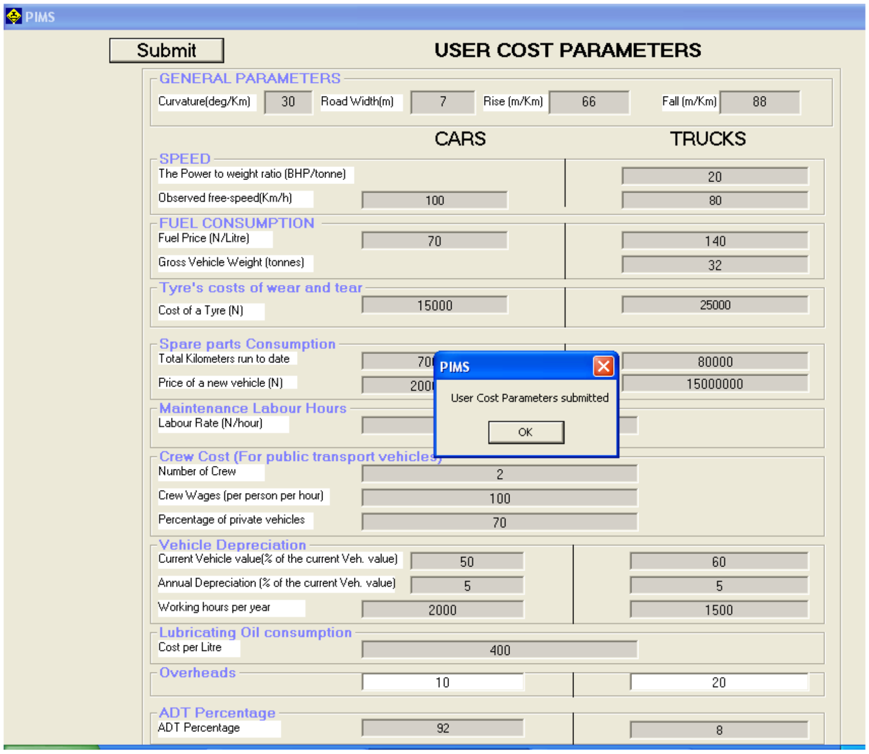



Fig. 3: User costs parameters form (with current default values)

Table 3: Contribution of different components of vehicle operating costs for cars

| State | A | B | C | D | E | F | G | H | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 10.05 | 1.67 | 23.17 | 0.57 | - | 0.60 | 0.48 | 3.65 | 40.19 |
| 2 | 9.96 | 2.14 | 30.63 | 0.74 | - | 0.61 | 0.48 | 4.46 | 49.02 |
| 3 | 9.86 | 3.41 | 56.48 | 1.19 | - | 0.62 | 0.48 | 7.20 | 79.24 |
| 4 | 9.77 | 5.69 | 119.08 | 1.71 | - | 0.63 | 0.48 | 13.74 | 151.10 |
| 5 | 9.67 | 7.87 | 188.36 | 2.56 | - | 0.65 | 0.48 | 20.96 | 230.55 |
| 6 | 9.57 | 8.93 | 219.82 | 2.97 | - | 0.66 | 0.48 | 24.24 | 266.67 |
| 7 | 9.52 | 9.16 | 225.47 | 3.05 | - | 0.67 | 0.48 | 24.84 | 273.19 |

Table 4: Contribution of different components of vehicle operating costs for trucks

| State | A | B | C | D | E | F | G | H | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 192.33 | 48.24 | 67.45 | 3.26 | 6.33 | 1.85 | 1.60 | 16.05 | 337.11 |
| 2 | 192.45 | 49.83 | 78.80 | 3.79 | 6.63 | 1.93 | 1.60 | 16.75 | 351.78 |
| 3 | 192.66 | 54.67 | 126.24 | 5.81 | 7.00 | 2.04 | 1.60 | 19.50 | 409.52 |
| 4 | 192.98 | 65.31 | 228.43 | 9.91 | 7.44 | 2.17 | 1.60 | 25.39 | 533.23 |
| 5 | 193.45 | 77.39 | 295.28 | 12.70 | 7.95 | 2.32 | 1.60 | 29.53 | 620.22 |
| 6 | 194.09 | 83.74 | 311.74 | 13.40 | 8.56 | 2.50 | 1.60 | 30.78 | 646.41 |
| 7 | 194.49 | 85.06 | 313.72 | 13.48 | 8.91 | 2.60 | 1.60 | 30.99 | 650.85 |

A: Fuel consumption, B: Tyre consumption (wear and tear), C: Spare parts consumption, D: Vehicle maintenance labor hours, E: Crew cost, F: Vehicle depreciation, G: Lubricating oil consumption and H: Overheads

**Evaluation of user cost model:** The user cost model is developed by generating values for each component of the vehicle operating cost using the given equations. The variable user-changeable components from the equations have been collated within the developed PIMS in the format of a form (Fig. 3). Default values, based on current year 2008 have been provided, through all the default values are user-changeable.

**Contribution of different components of vehicle operating costs:** The contribution of the different components of vehicle operating costs for cars and trucks, for the case study road are shown in Table 3 and 4.

The user costs for cars and trucks are then shown as column vectors corresponding to states 1-7 (expressed in Naira/km per vehicle), viz:

$$U_{Cars} = \begin{bmatrix} 40.19 \\ 49.02 \\ 79.24 \\ 151.10 \\ 230.55 \\ 266.67 \\ 273.19 \end{bmatrix} \text{ and } U_{Trucks} = \begin{bmatrix} 337.11 \\ 351.78 \\ 409.52 \\ 533.23 \\ 620.22 \\ 646.41 \\ 650.85 \end{bmatrix}$$

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)

The weighted mean user cost column vector was then obtained by utilizing the percentages of cars and trucks. Given a percentage of cars of 90.4 and that of trucks as 9.6, the weighted mean user cost column vector, $U_{WM}$, for the case study road was computed as:

$$U_{WM} = \begin{bmatrix} 68.69 \\ 78.08 \\ 110.95 \\ 187.78 \\ 267.96 \\ 303.14 \\ 309.45 \end{bmatrix}$$

**Maintenance intervention modeling:** The estimated intervention cost of each M and R activity was based on current rates from Ministry of Transportation (Highways Division) and shown in Table 5. An appropriate inflation rate was incorporated into the costing to make it realistic for the future years of prediction.

Thus, a maintenance intervention matrix can be obtained corresponding to different intervention levels and given as:

$$M_I = \begin{bmatrix} 0.00 \\ 150,000.00 \\ 350,000.00 \\ 1,000,000.00 \\ 3,000,000.00 \\ 15,000,000.00 \\ 60,000,000.00 \end{bmatrix}$$

Though, an infinite number of maintenance strategies can be evaluated, only three options will be considered in this research, namely:

Table 5: Estimated costs of M and R activities

| Conditions | M and R strategy | Estimated cost of M and R activity ($N\times10^6$ km$^{-1}$) |
|---|---|---|
| 1 | No action | 0.00 |
| 2 | Routine maintenance | 0.15 |
| 3 | Preventive maintenance | 0.35 |
| 4 | Corrective maintenance | 1.00 |
| 5 | Minor rehabilitation | 3.00 |
| 6 | Major rehabilitation | 15.0 |
| 7 | Reconstruction | 60.0 |

**Option 1**

**Deferred maintenance:** With this option, no form of maintenance intervention is undertaken for the period of study. Thus, the road is left unattended to from year 0, (which would be the beginning year of analysis), till year 20, which is total period covered by this study.

**Option 2**

**Repair failed sections only:** Here, due to budget constraint, the emphasis would be to repair only the failed sections (i.e., those in condition 7).

**Option 3**

**Repair all sections annually:** This option considers an ideal 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 optimum state (i.e., the best state)

**Analyses and results:** The different states of the case study road after the first year are given as:

$$P_1 = P_0 \times P'_{ij} \quad (14)$$

The case study road was surveyed in the year 2005 by PEU. The year when major rehabilitation was carried out the road was estimated by PEU to be 1999. Hence, the case study road is considered to be 6 years old (1999-2005) and the traffic volume falls into 5,001-10,000 ADT category. Thus, the system selects TPM $B_{ij}$ and TPM $E_{ij}$ corresponding to the age and traffic volume, computes their average to generate a new TPM $P'_{ij}$. Thus, $P_1$ becomes:

$$P_1 = [0.772908 \;\; 0.227092 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$
$$\begin{bmatrix} 0.825 & 0.065 & 0.045 & 0.030 & 0.019 & 0.011 & 0.005 \\ 0 & 0.775 & 0.085 & 0.060 & 0.045 & 0.025 & 0.010 \\ 0 & 0 & 0.775 & 0.090 & 0.070 & 0.040 & 0.025 \\ 0 & 0 & 0 & 0.725 & 0.150 & 0.080 & 0.045 \\ 0 & 0 & 0 & 0 & 0.725 & 0.175 & 0.100 \\ 0 & 0 & 0 & 0 & 0 & 0.675 & 0.325 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.000 \end{bmatrix} \quad (15)$$

$$P1 = \begin{bmatrix} 0.637 & 0.226 & 0.054 & 0.036 & 0.024 & 0.014 & 0.006 \end{bmatrix} \quad (16)$$

Traffic growth is thus, computed as:

$$Ft_n = V_o\,(1+r)^{n-1} = 9909 \times 365 \text{ days} = 3,616,785 \quad (17)$$

where:

$Ft_n$ = Future traffic volume in n years
$V_o$ = Initial traffic volume = 9909
r = Traffic growth rate = 3%
n = Number of years considered = 20

**Maintenance option 1 deferred maintenance:** The basic steps followed in generating the user costs, intervention costs and total system costs are highlighted as follows:

**User cost computations:** User cost $C_{u1}$ per km at the end of the first year is given as:

$$C_{u1} = P_1 \times U_{WM} \times FT_1 \quad (18)$$

$$C_{u1} = \begin{bmatrix} 0.637 & 0.226 & 0.054 & 0.036 \\ 0.024 & 0.014 & 0.006 & \end{bmatrix} \begin{bmatrix} 68.69 \\ 78.08 \\ 110.95 \\ 187.78 \\ 267.96 \\ 303.14 \\ 309.45 \end{bmatrix} 3,616,785 \quad (19)$$

$C_{u1}$ = N315,497,211.82, taking into consideration a 15% inflation rate, this becomes $C_{u1}$ = N362,821,793.59.

Similar procedure is followed for the other years of study where:

$$C_{u2} = P_2 \times U_{WM} \times FT_2$$
$$C_{u3} = P_3 \times U_{WM} \times FT_3$$

**Ideal intervention cost computations:** The cost of intervention represents the costs involved in executing maintenance activities. Intervention cost after one year, $C_{v1}$, is given as:

$$C_{v1} = P_1 \times M_I \quad (20)$$

For the deferred maintenance option, no activity is deemed to have taken place and thus, intervention cost is zero. However, if M and R activities are to be carried out, these become ideal intervention costs and would be calculated as follows:

Table 6: Cost computations for deferred maintenance option

| Years | User Cost/km (₦ ×10⁶) | Ideal intervention cost (₦ ×10⁶) | Total system cost (₦×10⁶) |
|---|---|---|---|
| 2005 | - | - | - |
| 2006 | 362.8218 | 0.8549 | 362.8218 |
| 2007 | 465.3963 | 2.7734 | 465.3963 |
| 2008 | 573.8952 | 5.5578 | 573.8952 |
| 2009 | 685.4869 | 9.0515 | 685.4869 |
| 2010 | 814.7334 | 13.5576 | 814.7334 |
| 2011 | 941.2118 | 18.5745 | 941.2118 |
| 2012 | 1,062.9360 | 23.8350 | 1,062.9360 |
| 2013 | 1,178.9660 | 29.1113 | 1,178.9660 |
| 2014 | 1,288.7650 | 34.2172 | 1,288.7650 |
| 2015 | 1,392.5390 | 39.0209 | 1,392.5390 |
| 2016 | 1,490.4360 | 43.4306 | 1,490.4360 |
| 2017 | 1,583.3090 | 47.4013 | 1,583.3090 |
| 2018 | 1,671.4670 | 50.9141 | 1,671.4670 |
| 2019 | 1,755.7120 | 53.9742 | 1,755.7120 |
| 2020 | 1,836.8930 | 56.6064 | 1,836.8930 |
| 2021 | 1,915.7420 | 58.8489 | 1,915.7420 |
| 2022 | 1,992.8240 | 60.7342 | 1,992.8240 |
| 2023 | 2,068.6880 | 62.3052 | 2,068.6880 |
| 2024 | 2,143.8750 | 63.6076 | 2,143.8750 |
| 2025 | 2,218.7960 | 64.6758 | 2,218.7960 |

$$C_{v1} = \begin{bmatrix} 0.637 & 0.226 & 0.054 & 0.036 \\ 0.024 & 0.014 & 0.006 & \end{bmatrix} \begin{bmatrix} 0.00 \\ 150,000.00 \\ 350,000.00 \\ 1,000,000.00 \\ 3,000,000.00 \\ 15,000,000.00 \\ 60,000,000.00 \end{bmatrix} \quad (21)$$

$C_{v1}$ = ₦743,365.00

Taking into consideration a 15% inflation rate, this becomes $C_{v1}$ = ₦854,869.80.

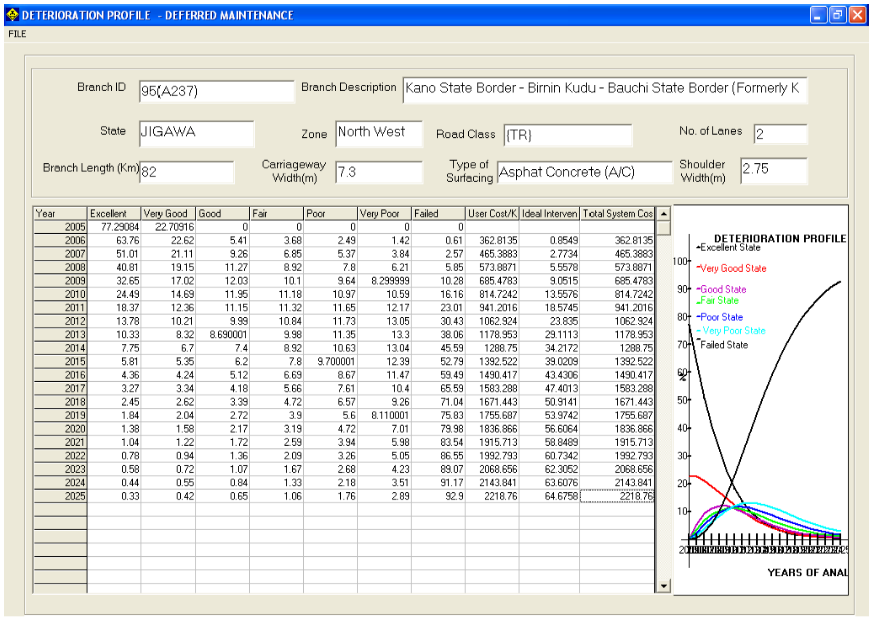
**Total system cost:** The total system cost, $C_s$ is defined as the sum of user cost and intervention cost, i.e.,

$$C_s = C_u + C_v$$

However, since intervention cost for deferred maintenance is zero (because of no activity), the user costs become the total system cost (Table 6).

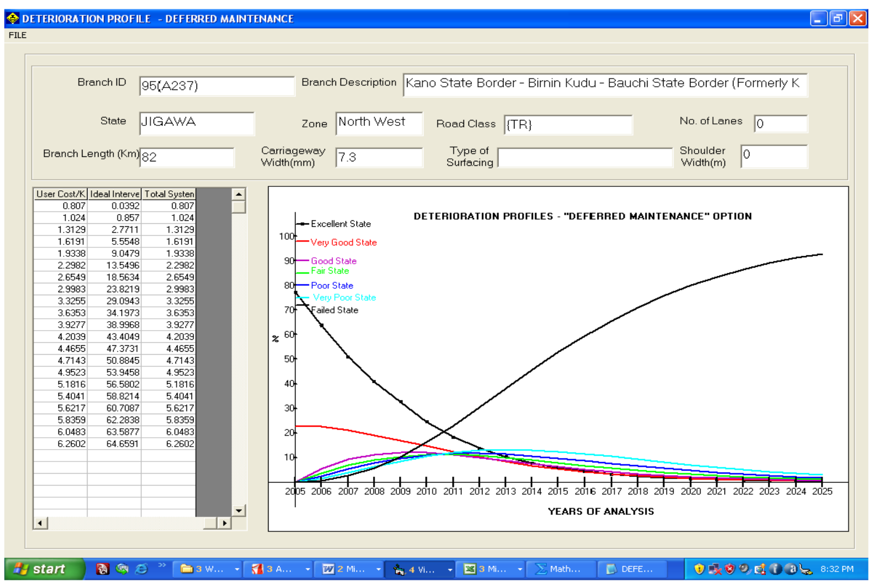
**Results from computational analyses for maintenance option 1:** For each of the three maintenance options adopted, results were obtained for user costs $km^{-1}$, ideal/actual intervention cost and total system cost $km^{-1}$ for each year of analysis (year 1-20). Results were also, obtained for the deterioration profiles under the three maintenance options adopted.

Figure 4 depicts the tabular and graphical PIMS display of the deterioration profile for deferred maintenance option while, Table 6 give the extracted deterioration profile and cost computation




| Year | Excellent | Very Good | Good | Fair | Poor | Very Poor | Failed | User Cost/K | Ideal Interven | Total System Cos |
|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 77.29084 | 22.70916 | 0 | 0 | 0 | 0 | 0 | | | |
| 2006 | 63.76 | 22.62 | 5.41 | 3.68 | 2.49 | 1.42 | 0.61 | 362.8135 | 0.8549 | 362.8135 |
| 2007 | 51.01 | 21.11 | 9.26 | 6.85 | 5.37 | 3.84 | 2.57 | 465.3883 | 2.7734 | 465.3883 |
| 2008 | 40.81 | 19.15 | 11.27 | 8.92 | 7.8 | 6.21 | 5.85 | 573.8871 | 5.5578 | 573.8871 |
| 2009 | 32.65 | 17.02 | 12.03 | 10.1 | 9.64 | 8.299999 | 10.28 | 685.4783 | 9.0515 | 685.4783 |
| 2010 | 24.49 | 14.69 | 11.95 | 11.18 | 10.97 | 10.59 | 16.16 | 814.7242 | 13.5576 | 814.7242 |
| 2011 | 18.37 | 12.36 | 11.15 | 11.32 | 11.65 | 12.17 | 23.01 | 941.2016 | 18.5745 | 941.2016 |
| 2012 | 13.78 | 10.21 | 9.99 | 10.84 | 11.73 | 13.05 | 30.43 | 1062.924 | 23.835 | 1062.924 |
| 2013 | 10.33 | 8.32 | 8.690001 | 9.98 | 11.35 | 13.3 | 38.06 | 1178.953 | 29.1113 | 1178.953 |
| 2014 | 7.75 | 6.7 | 7.4 | 8.92 | 10.63 | 13.04 | 45.59 | 1288.75 | 34.2172 | 1288.75 |
| 2015 | 5.81 | 5.35 | 6.2 | 7.8 | 9.700001 | 12.39 | 52.79 | 1392.522 | 39.0209 | 1392.522 |
| 2016 | 4.36 | 4.24 | 5.12 | 6.69 | 8.67 | 11.47 | 59.49 | 1490.417 | 43.4306 | 1490.417 |
| 2017 | 3.27 | 3.34 | 4.18 | 5.66 | 7.61 | 10.4 | 65.59 | 1583.288 | 47.4013 | 1583.288 |
| 2018 | 2.45 | 2.62 | 3.39 | 4.72 | 6.57 | 9.26 | 71.04 | 1671.443 | 50.9141 | 1671.443 |
| 2019 | 1.84 | 2.04 | 2.72 | 3.9 | 5.6 | 8.110001 | 75.83 | 1755.687 | 53.9742 | 1755.687 |
| 2020 | 1.38 | 1.58 | 2.17 | 3.19 | 4.72 | 7.01 | 79.98 | 1836.866 | 56.6064 | 1836.866 |
| 2021 | 1.04 | 1.22 | 1.72 | 2.59 | 3.94 | 5.98 | 83.54 | 1915.713 | 58.8489 | 1915.713 |
| 2022 | 0.78 | 0.94 | 1.36 | 2.09 | 3.26 | 5.05 | 86.55 | 1992.793 | 60.7342 | 1992.793 |
| 2023 | 0.58 | 0.72 | 1.07 | 1.67 | 2.68 | 4.23 | 89.07 | 2068.656 | 62.3052 | 2068.656 |
| 2024 | 0.44 | 0.55 | 0.84 | 1.33 | 2.18 | 3.51 | 91.17 | 2143.841 | 63.6076 | 2143.841 |
| 2025 | 0.33 | 0.42 | 0.65 | 1.06 | 1.76 | 2.89 | 92.9 | 2218.76 | 64.6758 | 2218.76 |

Fig. 4: Tabular and graphical PIMS display of the deterioration profile for deferred maintenance option for the case study road




| User Cost/K | Ideal Interve | Total Systen |
|---|---|---|
| 0.807 | 0.0392 | 0.807 |
| 1.024 | 0.857 | 1.024 |
| 1.3129 | 2.7711 | 1.3129 |
| 1.6191 | 5.5548 | 1.6191 |
| 1.9338 | 9.0479 | 1.9338 |
| 2.2982 | 13.5496 | 2.2982 |
| 2.6549 | 18.5634 | 2.6549 |
| 2.9983 | 23.8219 | 2.9983 |
| 3.3255 | 29.0943 | 3.3255 |
| 3.6353 | 34.1973 | 3.6353 |
| 3.9277 | 38.9968 | 3.9277 |
| 4.2039 | 43.4049 | 4.2039 |
| 4.4655 | 47.3731 | 4.4655 |
| 4.7143 | 50.8845 | 4.7143 |
| 4.9523 | 53.9458 | 4.9523 |
| 5.1816 | 56.5802 | 5.1816 |
| 5.4041 | 58.8214 | 5.4041 |
| 5.6217 | 60.7087 | 5.6217 |
| 5.8359 | 62.2838 | 5.8359 |
| 6.0483 | 63.5877 | 6.0483 |
| 6.2602 | 64.6591 | 6.2602 |

Fig. 5: Extracted full graphical display of the deterioration profile for deferred maintenance option for the case study road

results, respectively. The full, extracted graphical display of the deterioration profile is shown in Fig. 5.

**Results from computational analysis for maintenance option 2:** Figure 6 depicts the tabular and graphical PIMS display of the deterioration profile for repair failed sections only (option 2) while, Table 7 give the extracted deterioration profile and cost computation results, respectively.

**Results from computational analyses for maintenance option 3:** If all the sections are repaired, then all will upgrade to the excellent state. Thus, we have

$$P_1^1 = [1 \quad 0.0 \quad 0.0 \quad 0.0 \quad 0.0 \quad 0.0 \quad 0.0] \tag{21}$$

This value of $P_1^1$ is then used to generate for the second year of analysis, viz:

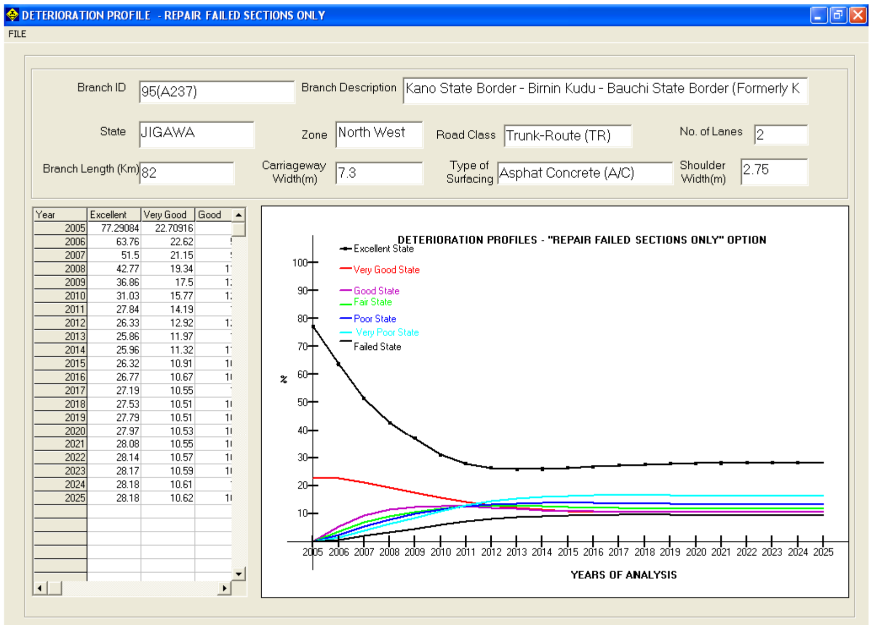



Fig. 6: Tabular and graphical PIMS display of the deterioration profile for repair failed sections only option for the case study road

Table 7: Cost computations for maintenance option 2 (repair failed sections only)

| Years | User cost $km^{-1}$ (₦ $\times 10^6$) | Actual intervention cost $km^{-1}$ (₦ $\times 10^6$) | Total system cost $km^{-1}$ (₦ $\times 10^6$) |
|---|---|---|---|
| 2005 | | | |
| 2006 | 362.8218 | 0.4209 | 363.2427 |
| 2007 | 459.4332 | 1.3524 | 460.7856 |
| 2008 | 549.0830 | 2.2839 | 551.3669 |
| 2009 | 628.5058 | 3.1119 | 631.6177 |
| 2010 | 716.2820 | 4.2021 | 720.4841 |
| 2011 | 787.3592 | 5.0163 | 792.3755 |
| 2012 | 844.8798 | 5.6235 | 850.5033 |
| 2013 | 891.1698 | 6.0444 | 897.2142 |
| 2014 | 929.2892 | 6.3066 | 935.5958 |
| 2015 | 962.2647 | 6.4653 | 968.7300 |
| 2016 | 992.0205 | 6.5412 | 998.5617 |
| 2017 | 1,020.3460 | 6.5688 | 1,026.9150 |
| 2018 | 1,048.6150 | 6.5688 | 1,055.1840 |
| 2019 | 1,077.6630 | 6.5550 | 1,084.2180 |
| 2020 | 1,107.7770 | 6.5343 | 1,114.3120 |
| 2021 | 1,139.0800 | 6.5136 | 1,145.5940 |
| 2022 | 1,171.8220 | 6.4998 | 1,178.3210 |
| 2023 | 1,206.0670 | 6.4860 | 1,212.5520 |
| 2024 | 1,241.7810 | 6.4791 | 1,248.2600 |
| 2025 | 1,278.7250 | 6.4722 | 1,285.1980 |

$$P_2 = \begin{bmatrix} 0.8000 & 0.0650 & 0.0500 & 0.0350 \\ 0.0250 & 0.0175 & 0.0075 & \end{bmatrix} \quad (22)$$

Figure 7 depicts the tabular and graphical PIMS display of the deterioration profile for 'Repair All Sections' (option 3) while, Table 8 and 9 give the extracted deterioration profile and cost computation results, respectively.

**Combined deterioration profile results:** The effects of the three maintenance options on the deterioration of a road are best captured when superimposed together as shown in Fig. 8. The plotted deterioration profiles for the three maintenance options considered for the case study road are shown in Fig. 8 while, the values are displayed in Table 10.

**Benefit-cost analysis of maintenance investments:** In order to justify the costs of intervention activities performed to restore a road, it is useful to calculate the benefit/cost ratio. In this regard, the derived user costs and intervention costs for the repair failed sections only and the repair all sections options are utilized to obtain the costs and benefits of bringing the different states of a road section to excellent state. The benefit/cost ratios are calculated as:

$$\frac{\sum_{i=1}^{n} \frac{B_n}{(1+r)^n}}{\sum_{i=1}^{n} \frac{C_n}{(1+r)^n}} \quad (23)$$

where:

$B_n$ = Benefits in each year
$C_n$ = Intervention cost in each year
n = Number of years
r = Interest (discount) rate

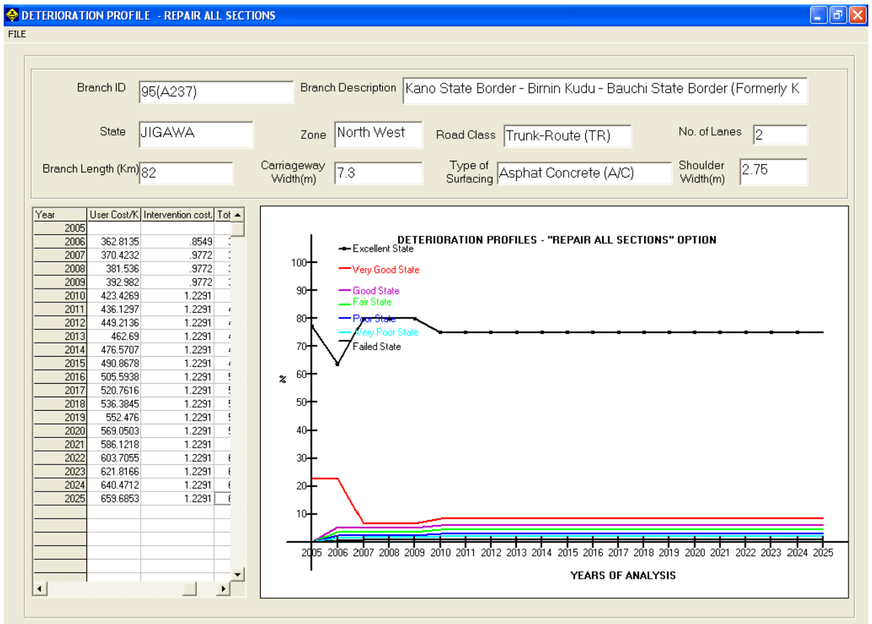



Fig. 7: Tabular and graphical PIMS display of the deterioration profile for 'repair all sections' option for the case study road

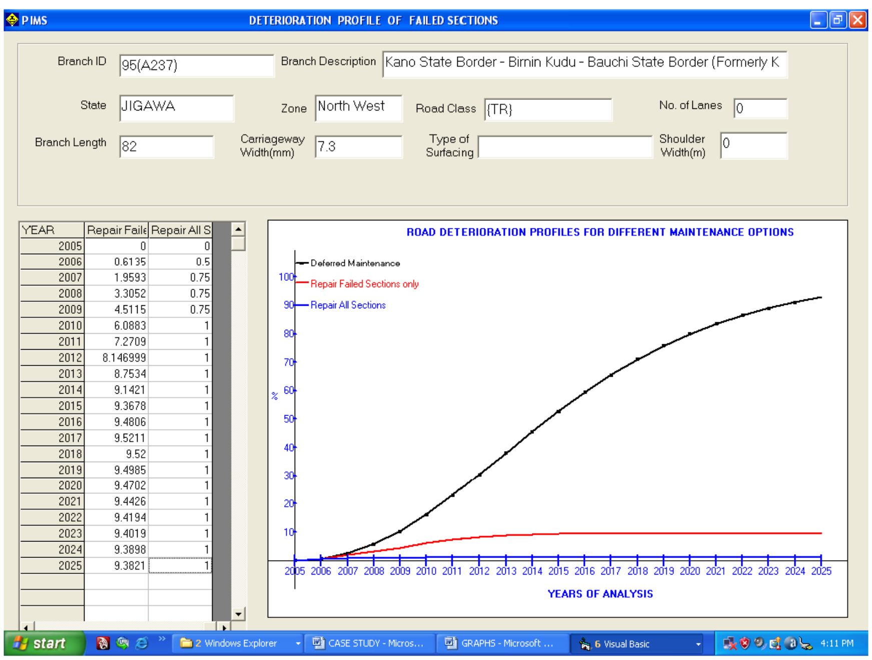



Fig. 8: Effects of the three maintenance options on case study road deterioration

$$\text{Discount factor} = \frac{1}{(1+r)^n}$$

The derived values from the analyses are shown in Table 11 and 12. Figure 9 displays two results. The first result displays the graphs of the generated user costs for all the three maintenance options for the analysis period of 20 years (2005-2025).

The second shows the graphs of benefit/cost plotted against time (period of analyses) for repair all sections and repair failed sections only.

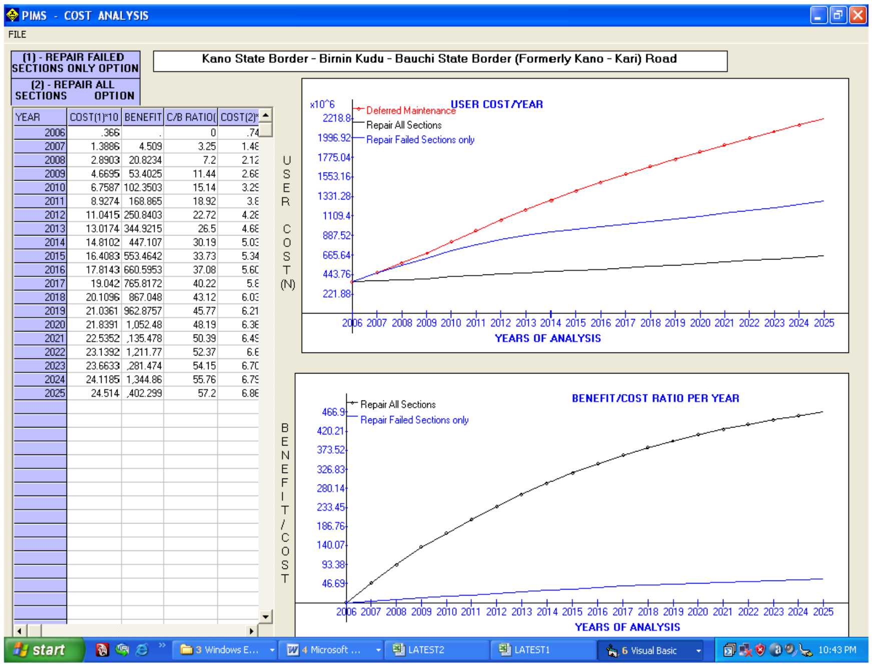



Fig. 9: Graphs of user costs and benefit/cost against time (years of analysis)

Table 8: Deterioration profile for maintenance option 3 (repair all sections)

| | Percentages of different states of the road | | | | | | |
|---|---|---|---|---|---|---|---|
| Years | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 2005 | 77.29 | 22.71 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2006 | 63.76 | 22.62 | 5.41 | 3.68 | 2.49 | 1.42 | 0.61 |
| 2007 | 80.00 | 6.50 | 5.00 | 3.50 | 2.50 | 1.75 | 0.75 |
| 2008 | 80.00 | 6.50 | 5.00 | 3.50 | 2.50 | 1.75 | 0.75 |
| 2009 | 80.00 | 6.50 | 5.00 | 3.50 | 2.50 | 1.75 | 0.75 |
| 2010 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2011 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2012 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2013 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2014 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2015 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2016 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2017 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2018 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2019 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2020 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2021 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2022 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2023 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2024 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |
| 2025 | 75.00 | 8.50 | 6.00 | 4.50 | 3.00 | 2.00 | 1.00 |

Table 9: Cost computations for maintenance option 3 (repair all sections)

| Years | User cost $km^{-1}$ (₦ $\times 10^6$) | Actual intervention cost $km^{-1}$ (₦ $\times 10^6$) | Total system cost/km (₦ $\times 10^6$) |
|---|---|---|---|
| 2005 | - | - | - |
| 2006 | 362.8218 | 0.8549 | 363.6767 |
| 2007 | 370.4355 | 0.9772 | 371.4127 |
| 2008 | 381.5486 | 0.9772 | 382.5258 |
| 2009 | 392.9951 | 0.9772 | 393.9723 |
| 2010 | 423.4396 | 1.2291 | 424.6687 |
| 2011 | 436.1428 | 1.2291 | 437.3719 |
| 2012 | 449.2270 | 1.2291 | 450.4561 |
| 2013 | 462.7039 | 1.2291 | 463.9330 |
| 2014 | 476.5850 | 1.2291 | 477.8141 |
| 2015 | 490.8825 | 1.2291 | 492.1116 |
| 2016 | 505.6090 | 1.2291 | 506.8381 |
| 2017 | 520.7773 | 1.2291 | 522.0064 |
| 2018 | 536.4006 | 1.2291 | 537.6297 |
| 2019 | 552.4926 | 1.2291 | 553.7217 |
| 2020 | 569.0674 | 1.2291 | 570.2965 |
| 2021 | 586.1394 | 1.2291 | 587.3685 |
| 2022 | 603.7236 | 1.2291 | 604.9527 |
| 2023 | 621.8353 | 1.2291 | 623.0645 |
| 2024 | 640.4904 | 1.2291 | 641.7195 |
| 2025 | 659.7051 | 1.2291 | 660.9342 |

## RESULTS AND DISCUSSION

The deterioration profiles for deferred maintenance option show that percentage of the pavement in the failed state increased exponentially from 0 to as high as 92.90% in 20 years (Table 7). On the other hand, the percentage of the pavement in excellent condition at year one, reduced drastically from 77.29 to a mere 0.33 at the end 20 years. Conversely, the accruable user costs $km^{-1}$ rose from ₦362 million after the 1st year to a stupendous amount of over ₦2.2 billion by the 20th year (Table 6). The graphical display of the deterioration profile (Fig. 5) lends glaring credence to these facts. Interestingly, it would have required the intervention sum of just ₦362.82 million at year one and ₦64.67 million at the 20th year to keep the road section at an ideal condition state.

The results of the analysis carried out for a situation, where only the failed sections are repaired annually are depicted in Fig. 6 and Table 7. Under this maintenance option, the percentage of the pavement in excellent condition (state 1) at year zero reduced significantly from 77.29-28.18, while those in failed state (state 7) increased in percentage from 0-9.38. The generated user cost km$^{-1}$ rose from ₦362.82 million at year one and increased significantly to ₦1.27 billion at the end of 20 years. The actual intervention cost km$^{-1}$ was ₦0.42 million at the 1st year, but stabilizes at about ₦6.0 million from the 8 years.

For the option, where all the sections of the pavement are brought to the best state annually, the percentage of the portion initially at best condition state increases slightly from 77.29-80.0 and thereafter becomes stable at 75% from the 5th year (Table 9). The portion in the failed state also rose marginally from 0-0.75% at the 5th year and thereafter, stabilizes at 1.0%. The actual intervention cost km$^{-1}$ required to achieve this feat is just N0.85 million by the 1st year and stabilizes at ₦1.22 million annually from the 5th year, while, the user cost km$^{-1}$ increased from ₦362.82 million at year one and stood at only ₦659.70 million at the end of the 20th year of analysis (Table 10).

The accruable benefits arising from timely injection of intervention repair funds are vividly shown in the benefit-cost ratio analysis for the repair all sections and repair failed sections only. For the repair failed sections only option (Table 12), the cumulative benefit stood at ₦1.40 billion with a benefit-cost ration of 57.2. On the other hand, the cumulative benefit for the repair all sections came to over ₦3.2 billion with a benefit-cost ratio of 466.9.

This research has been able to demonstrate the effects of different types of maintenance options on pavement in terms of deterioration and accruable user costs. Portions of the case study pavement (in the failed state) after year one of analysis rose from 0% to a staggering 92.9% at the end of 20 years, resulting in a corresponding user cost km$^{-1}$ over ₦2.2 billion. A paltry ideal intervention cost km$^{-1}$ of ₦0.85 million would have been required at the 1st year and only ₦64.67 million required at the 20th year. When, only the failed portions of the same road are annually upgraded to the excellent condition, the rate of deterioration increased from 0% to a moderate 9.38%. The corresponding user costs km$^{-1}$

Table 10: Deterioration profile data for all the three maintenance options

| Years | Deferred maintenance | Repair failed sections only | Repair all sections |
|---|---|---|---|
| 2005 | 0.00 | 0.00 | 0.00 |
| 2006 | 0.61 | 0.61 | 0.61 |
| 2007 | 2.57 | 1.96 | 0.75 |
| 2008 | 5.85 | 3.31 | 0.75 |
| 2009 | 10.28 | 4.51 | 0.75 |
| 2010 | 16.16 | 6.09 | 1.00 |
| 2011 | 23.01 | 7.27 | 1.00 |
| 2012 | 30.43 | 8.15 | 1.00 |
| 2013 | 38.06 | 8.76 | 1.00 |
| 2014 | 45.59 | 9.14 | 1.00 |
| 2015 | 52.79 | 9.37 | 1.00 |
| 2016 | 59.49 | 9.48 | 1.00 |
| 2017 | 65.59 | 9.52 | 1.00 |
| 2018 | 71.04 | 9.52 | 1.00 |
| 2019 | 75.83 | 9.50 | 1.00 |
| 2020 | 79.98 | 9.47 | 1.00 |
| 2021 | 83.54 | 9.44 | 1.00 |
| 2022 | 86.55 | 9.42 | 1.00 |
| 2023 | 89.07 | 9.40 | 1.00 |
| 2024 | 91.17 | 9.39 | 1.00 |
| 2025 | 92.90 | 9.38 | 1.00 |

Table 11: Derived results from benefit/cost analyses for case study road option 1-repair failed sections only

| Years | Deferred mainte-nance user cost ₦ ×10$^6$ (A) | Repair failed section only user cost ₦ ×10$^6$ (B) | Actual intervention cost ₦ ×10$^6$ (C) | Benefit ₦ ×10$^6$ (D) = (A-B) | Dis-count factor @ 15% (E) | Dis-counted cost ₦ ×10$^6$ (F) = C × E | Benefit ₦ ×10$^6$ (G) = D ×E | Dis-counted Cumula-tive cost ₦ ×10$^6$ (H) = $\sum_{i=1}^{n} F_n$ | Cumulative benefit ₦ ×10$^6$ (I) = $\sum_{i=1}^{n} G_n$ | B/C ratio (J) = I/H |
|---|---|---|---|---|---|---|---|---|---|---|
| 2006 | 362.8218 | 362.8218 | 0.4209 | 0.0000 | 0.8696 | 0.3660 | 0.0000 | 0.3660 | 0.0000 | 0.0000 |
| 2007 | 465.3963 | 459.4332 | 1.3524 | 5.9631 | 0.7561 | 1.0226 | 4.5090 | 1.3886 | 4.5090 | 3.2471 |
| 2008 | 573.8952 | 549.0830 | 2.2839 | 24.8122 | 0.6575 | 1.5017 | 16.3144 | 2.8903 | 20.8234 | 7.2046 |
| 2009 | 685.4869 | 628.5058 | 3.1119 | 56.9811 | 0.5718 | 1.7792 | 32.5791 | 4.6695 | 53.4025 | 11.4363 |
| 2010 | 814.7334 | 716.2820 | 4.2021 | 98.4514 | 0.4972 | 2.0892 | 48.9477 | 6.7587 | 102.3503 | 15.1434 |
| 2011 | 941.2118 | 787.3592 | 5.0163 | 153.8526 | 0.4323 | 2.1687 | 66.5147 | 8.9274 | 168.8650 | 18.9153 |
| 2012 | 1,062.9360 | 844.8798 | 5.6235 | 218.0562 | 0.3759 | 2.1141 | 81.9754 | 11.0415 | 250.8404 | 22.7180 |
| 2013 | 1,178.9660 | 891.1698 | 6.0444 | 287.7962 | 0.3269 | 1.9759 | 94.0811 | 13.0174 | 344.9215 | 26.4969 |
| 2014 | 1,288.7650 | 929.2892 | 6.3066 | 359.4758 | 0.2843 | 1.7927 | 102.1855 | 14.8102 | 447.1069 | 30.1892 |
| 2015 | 1,392.5390 | 962.2647 | 6.4653 | 430.2743 | 0.2472 | 1.5981 | 106.3572 | 16.4083 | 553.4642 | 33.7308 |
| 2016 | 1,490.4360 | 992.0205 | 6.5412 | 498.4155 | 0.2149 | 1.4060 | 107.1310 | 17.8143 | 660.5952 | 37.0824 |
| 2017 | 1,583.3090 | 1,020.3460 | 6.5688 | 562.9630 | 0.1869 | 1.2278 | 105.2218 | 19.0420 | 765.8170 | 40.2172 |
| 2018 | 1,671.4670 | 1,048.6150 | 6.5688 | 622.8520 | 0.1625 | 1.0676 | 101.2309 | 20.1096 | 867.0479 | 43.1160 |
| 2019 | 1,755.7120 | 1,077.6630 | 6.5550 | 678.0490 | 0.1413 | 0.9264 | 95.8278 | 21.0360 | 962.8756 | 45.7727 |
| 2020 | 1,836.8930 | 1,107.7770 | 6.5343 | 729.1160 | 0.1229 | 0.8030 | 89.6043 | 21.8391 | 1,052.4800 | 48.1925 |
| 2021 | 1,915.7420 | 1,139.0800 | 6.5136 | 776.6620 | 0.1069 | 0.6961 | 82.9978 | 22.5351 | 1,135.4778 | 50.3870 |
| 2022 | 1,992.8240 | 1,171.8220 | 6.4998 | 821.0020 | 0.0929 | 0.6040 | 76.2923 | 23.1391 | 1,211.7701 | 52.3688 |
| 2023 | 2,068.6880 | 1,206.0670 | 6.4860 | 862.6210 | 0.0808 | 0.5241 | 69.7042 | 23.6633 | 1,281.4743 | 54.1546 |
| 2024 | 2,143.8750 | 1,241.7810 | 6.4791 | 902.0940 | 0.0703 | 0.4553 | 63.3859 | 24.1185 | 1,344.8602 | 55.7605 |
| 2025 | 2,218.7960 | 1,278.7250 | 6.4722 | 940.0710 | 0.0611 | 0.3955 | 57.4386 | 24.5140 | 1,402.2988 | 57.2041 |

Table 12: Derived results from benefit/cost analysis for case study road option 2-repair all sections

| Years | Deferred maintenance user cost (₦ ×10$^6$) (A) | Repair all section user cost (₦ ×10$^6$) (B) | Actual intervention cost (₦ ×10$^6$) (C) | Benefit (₦ ×10$^6$) (D) = (A-B) | Discount factor @ 15% (E) | Discounted cost (₦ ×10$^6$) (F) =C × E | Discounted benefit (₦ ×10$^6$) (G) = D × E | Cumulative cost (₦ ×10$^6$) (H) = $\sum_{i=1}^{n} F_n$ | Cumulative benefit (₦ ×10$^6$) (I) = $\sum_{i=1}^{n} G_n$ | B/C ratio (J) = I/H |
|---|---|---|---|---|---|---|---|---|---|---|
| 2006 | 362.8218 | 362.8218 | 0.8549 | 0.0000 | 0.8696 | 0.7434 | 0.0000 | 0.7434 | 0.0000 | 0.0000 |
| 2007 | 465.3963 | 370.4355 | 0.9772 | 94.9608 | 0.7561 | 0.7389 | 71.8040 | 1.4823 | 71.8040 | 48.4411 |
| 2008 | 573.8952 | 381.5486 | 0.9772 | 192.3466 | 0.6575 | 0.6425 | 126.4710 | 2.1248 | 198.2750 | 93.3138 |
| 2009 | 685.4869 | 392.9951 | 0.9772 | 292.4918 | 0.5718 | 0.5587 | 167.2331 | 2.6835 | 365.5082 | 136.2039 |
| 2010 | 814.7334 | 423.4396 | 1.2291 | 391.2938 | 0.4972 | 0.6111 | 194.5422 | 3.2946 | 560.0503 | 169.9895 |
| 2011 | 941.2118 | 436.1428 | 1.2291 | 505.0690 | 0.4323 | 0.5314 | 218.3553 | 3.8260 | 778.4056 | 203.4520 |
| 2012 | 1,062.9360 | 449.2270 | 1.2291 | 613.7090 | 0.3759 | 0.4621 | 230.7159 | 4.2881 | 1,009.1215 | 235.3332 |
| 2013 | 1,178.9660 | 462.7039 | 1.2291 | 716.2621 | 0.3269 | 0.4018 | 234.1474 | 4.6898 | 1,243.2689 | 265.0978 |
| 2014 | 1,288.7650 | 476.5850 | 1.2291 | 812.1800 | 0.2843 | 0.3494 | 230.8722 | 5.0392 | 1,474.1411 | 292.5326 |
| 2015 | 1,392.5390 | 490.8825 | 1.2291 | 901.6565 | 0.2472 | 0.3038 | 222.8757 | 5.3431 | 1,697.0168 | 317.6119 |
| 2016 | 1,490.4360 | 505.6090 | 1.2291 | 984.8270 | 0.2149 | 0.2642 | 211.6819 | 5.6072 | 1,908.6987 | 340.3991 |
| 2017 | 1,583.3090 | 520.7773 | 1.2291 | 1,062.5317 | 0.1869 | 0.2297 | 198.5948 | 5.8370 | 2,107.2935 | 361.0255 |
| 2018 | 1,671.4670 | 536.4006 | 1.2291 | 1,135.0664 | 0.1625 | 0.1998 | 184.4800 | 6.0367 | 2,291.7735 | 379.6383 |
| 2019 | 1,755.7120 | 552.4926 | 1.2291 | 1,203.2194 | 0.1413 | 0.1737 | 170.0494 | 6.2104 | 2,461.8229 | 396.4010 |
| 2020 | 1,836.8930 | 569.0674 | 1.2291 | 1,267.8256 | 0.1229 | 0.1510 | 155.8088 | 6.3615 | 2,617.6317 | 411.4812 |
| 2021 | 1,915.7420 | 586.1394 | 1.2291 | 1,329.6026 | 0.1069 | 0.1313 | 142.0877 | 6.4928 | 2,759.7194 | 425.0409 |
| 2022 | 1,992.8240 | 603.7236 | 1.2291 | 1,389.1004 | 0.0929 | 0.1142 | 129.0834 | 6.6070 | 2,888.8027 | 437.2304 |
| 2023 | 2,068.6880 | 621.8353 | 1.2291 | 1,446.8527 | 0.0808 | 0.0993 | 116.9131 | 6.7064 | 3,005.7158 | 448.1885 |
| 2024 | 2,143.8750 | 640.4904 | 1.2291 | 1,503.3846 | 0.0703 | 0.0864 | 105.6358 | 6.7927 | 3,111.3516 | 458.0415 |
| 2025 | 2,218.7960 | 659.7051 | 1.2291 | 1,559.0909 | 0.0611 | 0.0751 | 95.26090 | 6.8678 | 3,206.6125 | 466.9035 |

increased from ₦362.82 million to over ₦1.27 billion requiring an annual actual expenditure km$^{-1}$ of around ₦6.0 million.

However, the biggest gain to both road users and pavement maintenance agency occurs when all sections of the pavement are upgraded to the best state. Under this condition, the percentage of failed state is kept at a very insignificant level 1.0%. The percentage rise of the accruable user cost km$^{-1}$, from ₦362.82 million to just over N650 million is due largely to the effect of inflation introduced.

The benefit-cost ratio (b/c) analysis gave an impressive b/c ratio of 466.9 when all sections of the road are constantly upgraded to the best state compared with a b/c ratio of only 57.2 when, only the failed portions of the road are constantly repaired. Clearly, this shows that expenditure on regular road maintenance and rehabilitation have high rate of return.

## CONCLUSION

From the foregoing detailed research, the following conclusions are made, viz:

- For developing countries that obviously cannot successfully utilize many of the sophisticated commercial software available in the market, a simpler, but equally effective computerized PIMS has been developed
- Timely intervention to maintain pavements at appropriate times will significantly reduce the overall expenditure from both the users and the government
- If properly utilized, the developed system would be very effective in managing the pavements in the federal road network, at the network level. It would also be very useful in assisting pavement engineers and decision makers in planning, programming and budgeting

## FURTHER RESEARCH

The determination of the transition matrices is still a weak area, as it was based on subjective opinions. However, since a simple, but computerized PIMS has been developed through this research; it is possible to incorporate pavement deterioration modeling based on historical record of the objective function (performance) variation with age (time). In order to achieve this, regular measurement of the condition rating of some selected pavement sections should be carried out over a period of some years. Based on the generated model curves using historical data, future condition rating could then be predicted.

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Mathematical Modeling for Evaluating Road Maintenance Needs and Interventions. Both research works were carried out at Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria.

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