Decision Support Models for Asset Management of Low-Volume Roads

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Pavement maintenance decisions are based on skimpy rules and rules of thumb. Generally, the selection of roads for maintenance is based on a worst-first policy. The timing of maintenance intervention and standards adopted for maintenance govern the service life of the pavement. The rate of pavement deterioration depends on the timing of maintenance intervention, choice of the type of maintenance treatment, and the quality of the construction. In the present investigation, the periodic performance data of typical low-volume rural roads constructed under the rural road development programs in India are considered. Performance prediction models are developed. The models are used to predict the performance during the design life. Different maintenance interventions are considered at different pavement conditions. The effect of the timing of maintenance on agency costs and vehicle operation costs is quantified and presented.

In the new millennium, the demands on the road network and available transportation funding are greater than ever. These demands, combined with growing public expectations for safety, quality, and performance, require road infrastructure agencies to maintain the highest level of service practical. To meet these demands, road agencies are redefining their objectives and focusing on preservation and maintenance of road assets already created rather than on expanding the existing road network system. India has taken up several ambitious road development programs, including the Pradhan Mantri Gram Sadak Yojana of the Bharat Nirman program. Several hundred thousand kilometers of roads have already been constructed, and the performance of these roads varies from good to fair. These roads have created a sea change in the economy of the rural villages. The traffic on the roads has increased manyfold. The prediction of traffic on many roads was much lower than the present-day traffic. The rural roads have provided an all-weather connectivity to the villages. Consequently, the economy level increased manyfold, resulting in increased vehicle ownership. The road assets that have been created with a huge investment need to be preserved and maintained periodically. Unless the roads are periodically maintained, the pavement will deteriorate quickly and the cost of maintenance will increase manyfold. Rural roads have become a lifeline for the villages in India.

Pavement preservation is needed to enhance pavement performance; the use of an integrated, cost-effective set of practices will extend pavement life, improve safety, and meet road users' expectations. An effective pavement preservation program will address pavements while they are still in good condition and before the onset of serious distresses. By applying a cost-effective treatment at the right time, the pavement can be restored almost to its original condition. The cumulative effect of systematic, successive preservation treatments is to postpone costly rehabilitation and reconstruction. During the life of a pavement, the cumulative discount value of a series of pavement preservation treatments is substantially less than the discounted value of the more extensive, higher cost of reconstruction and generally more economical than the cost of major rehabilitation. In addition, performing a series of successive pavement preservation treatments during the life of a pavement is less disruptive to uniform traffic flow than the long closures normally associated with reconstruction projects, which increase agency costs significantly.

CHALLENGE OF MAINTENANCE

Maintaining India's present highway network to full maintenance standards will require annual funding of about US$1,514 million, three times the current level of expenditure. The economic road user costs are 23% higher on roads in poor condition than on good roads and 55% higher if the roads are in very poor condition. The quantifiable benefits accruing from the improvements and better maintenance of roads consist of savings in vehicle operating costs and travel time, which will reduce overall transport costs. Although the direct beneficiaries are road users and transport operators, the benefits of transport cost savings will be passed on to end users. For every U.S. dollar spent on maintaining the road network, there are net benefits (net present value) in excess of US$7. The Indian road network at nearly 3.2 million km is one of the world's largest road networks. Out of that length, less than 1% of the roads are being developed under various schemes by central and state governments. A considerable amount of manpower, technology, and expertise are being used for these roads at various levels from inception to completion. According to the World Bank, the loss in vehicle operation costs from poor road maintenance in India is estimated to be about US$4,328 million per year.

IMPORTANCE OF TIMELY MAINTENANCE

Often pavement maintenance decisions are based on skimpy rules and rules of thumb. The selection of the roads for maintenance is generally based on the worst-first policy. The functional condition parameters of the roads (namely, roughness, cracking, and raveling) generally are not considered while timing and choice of maintenance treatment are being decided, that is, type of maintenance strategy and thickness of the treatment. The timing of maintenance

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intervention and the maintenance standards govern the service life of a pavement. The rate of pavement deterioration depends on the timing, type, and quality of the maintenance treatment. If the maintenance is not carried out with due consideration for the structural and functional condition of the pavement section, the pavement may not offer the desired level of performance. If the maintenance of the pavement is deferred by 2 to 3 years, the condition of the pavement will further deteriorate, causing discomfort to users and loss in monetary value. Because of pavement deterioration during the deferred period, there will be a substantial increase in agency cost as a result of the additional rehabilitation required to achieve the desired level of serviceability. It is reported that even construction of overlays thicker than that required based on the structural requirements will result in lower economic benefits.

The roads that are already constructed and open to traffic have started showing signs of premature failure and distresses as a result of the increased number of load repetitions as well as environmental and construction quality effects. These roads require preventive maintenance now. The preventive maintenance is a systematic process of applying a series of preventive maintenance treatments during the life of the pavement to maintain a good condition. The treatments extend the life of the pavement and minimize life-cycle costs without substantially increasing the structural aspects. It is believed to result in lowered agency cost, improved pavement condition, and increased road user satisfaction. Preventive maintenance is applying the right treatment to the right pavement at the right time. The experience with pavement preventive maintenance demonstrates that each U.S. dollar spent now is estimated to save up to US$6 in the future. An effective pavement preservation program encompasses a full range of preventive maintenance techniques and strategies, such as crack sealing, fog seals, slurry seals, surface dressing, and thin overlays. A traditional rehabilitative approach allows the original pavement section to deteriorate to fair to poor condition in regard to ride quality and structural condition. At this stage, structural damage occurs and the objective of the rehabilitation treatment is to repair that damage and restore the pavement. Thus, the traditional approach is reactive and can be a costly and time-consuming process when compared with preventive maintenance, which is a proactive and less expensive approach.

REVIEW OF EARLIER WORK

The NCHRP report on optimal timing of preventive maintenance treatment applications describes the procedure to calculate the optimal timing scenario by considering benefit–cost values and effectiveness criteria (*1*). Haas and Hudson highlighted the importance of pavement preservation on highways by considering extension of the life of the pavement, delay in rate of deterioration, and enhanced safety of road users (*2*). Sood and Sharma collected performance data from existing pavement sections during a period of about 6 years for expeditious development of pavement deterioration models (*3*). These models can be used to predict the initiation and progression of cracking, potholes, rutting, and so forth on highway pavements considering several influencing parameters such as traffic, pavement strength, and construction quality. Reddy and Veeraragavan studied the structural performance of in-service flexible pavements and developed predictive models for structural and functional condition deterioration based on empirical modeling of performance data (*4*). Mechanistic–empirical models for rut depth, crack area, and unevenness of in-service flexible pavements have been developed on the basis of performance data collected during a period of 10 years. The allowable traffic loads for critical value of rut depth, crack area, and unevenness based on deflection criteria were also developed.

Mamlouk and Zaniewski reported that pavement preventive maintenance has been found to be successful for low- as well as high-volume roads (*5*). They emphasize that the selection of preventive maintenance treatment should be based on the condition of the existing pavement, traffic volume, and environmental conditions. Labi and Sinha investigated the cost-effectiveness of preventive maintenance (*6*). The field data for validation from in-service state highway pavements in Indiana were used. The strategy formulated in the present study consists of various treatment types applied at different timings. The effectiveness of the maintenance is defined as the increase in service life relative to a base case (do-nothing strategy). The study suggests that generally preventive maintenance cost-effectiveness increases with an increase in preventive maintenance effort up to a certain maximum, after which it declines with increasing effort. Singh and Veeraragavan quantified the benefits of timely maintenance on the highways (*7*). Priya et al. studied the sensitivity of design parameters on optimal pavement maintenance decisions at the project level (*8*). However, the benefits of preventive maintenance have not been studied and reported in India so far. Thus, there is an urgent need to preserve the already constructed road pavements through timely maintenance intervention.

OBJECTIVES OF THE PRESENT STUDY

1. Develop models for the prediction of the performance of rural roads.
2. Study the effect of time of maintenance on the performance of the roads.
3. Quantify penalties resulting from deferred maintenance on agency costs.
4. Quantify the cost-effectiveness of different maintenance strategies.

STUDY SECTIONS

The present study is taken up to predict the performance of typical low-volume, single-lane rural roads constructed under the Pradhan Mantri Gram Sadaj Yojana program. The pavement in general has a composition of a 200-mm granular subbase over a prepared subgrade, 225 mm of a granular base course, and a 20-mm premix carpet surface. The modified structural number (MSN) for the pavement section is found by using the following equation:

$$\text{MSN} = \text{SN} + 3.51(\log \text{CBR}) - 0.85(\log\ \text{CBR})^2 - 1.43$$

where SN is the structural number and CBR is the California bearing ratio. With the appropriate structural layer coefficients, MSN = 3.21. The traffic volumes on typical rural roads in Tamilnadu, India, after the opening of traffic are given in Table 1.

PERFORMANCE PREDICTION

A flexible pavement is a structure whose condition changes with the passage of time as a result of the combined effects of structural adequacy, volume, composition, and loading characteristics of traf-

TABLE 1 Classified Volume Counts on Various Rural Roads in 2008

Road District	Two-Wheelers	Auto	Car	Bus	Truck
Kanchipuram	242	0	15	8	4
Villupuram	138	1	11	5	6
Thoothukudi	205	0	57	6	3
Trichy	140	0	9	9	7
Madurai	159	1	50	5	7
Karur	216	2	13	6	3
Coimbatore	134	14	11	7	2
Namakkal	137	1	4	4	8
Average	175	2	21	6	5

fic, the environment, and maintenance inputs provided. The failure of a pavement structure is not abrupt like the collapse of any other structure. The failure occurs as a result of internal damage caused by traffic loads and environmental effects during a period of time. The process of accumulation of damage is called deterioration. It is essential to predict the deterioration in regard to distresses to estimate the remaining service life of the pavement, which in turn is helpful for suggesting appropriate maintenance interventions at defined trigger levels. The pavement deterioration models were developed on the basis of the performance data collected from selected roads constructed under the Pradhan Mantri Gram Sadak Yojana in Tamilnadu. The models developed by the Central Road Research Institute were used to predict the progression of various distresses of the pavement for which data were not available from the rural roads laid in Tamilnadu. The analysis period considered in the present study is 20 years.

Deflection Prediction

The structural performance of the pavement section is predicted by using deflection progression models; the deflection progression equation developed is as follows:

$$\text{Def}t = 0.006\ \exp(i\text{Def}) + 0.153\ \text{CSA}^{0.317} + 0.171\ \text{age} \quad [N = 90;\ R^2 = 0.841;\ \text{SE} = 0.24]$$

where

Def$t$ = rebound deflection at time t (mm),
iDef = initial rebound deflection (mm),
CSA = cumulative standard axles (millions), and
age = age of pavement from the time of construction (years).

Roughness Prediction

The functional performance of the pavement section is predicted by using roughness progression models. A roughness prediction equation was developed considering the traffic, age, and initial roughness of the pavement surface. The critical values of initial roughness for various types of bituminous surfacing are as per the Special Publications of the Codes published by the Indian Roads Congress (IRC): 16-2004. The roughness progression model is a function of initial roughness, age, and CSA load repetitions.

$$\text{IRI}_t = \text{IRI}_0 + 0.838\ N_t^{(0.224\text{age})} \quad [n = 24,\ R^2 = 0.77,\ \text{SE} = 0.313]$$

where

IRI_t = international roughness index (m/km) at any time t,
IRI_0 = initial international roughness index (m/km) at time $t = 0$,
N_t = cumulative standard axles (millions) at time t, and
age = age of pavement at t (years).

Rutting Prediction

Rut depth progression was developed by using the periodic pavement performance data considering initial structural condition of the pavement and traffic load repetitions. The model is as follows:

$$\text{RD}_t = \text{RD}_0 + 534.36\ (i\text{Def} * \text{CSA})^{0.855} + \log \text{CSA} \quad [n = 36,\ R^2 = 0.66,\ \text{SE} = 0.289]$$

where RD_t is rut depth at time t (years) and RD_0 is initial rut depth (mm).

Cracking Criteria

The crack in the bituminous surfacing occurs as a result of the combined action of traffic loading and the environment. The cracking initiation model by Sood and Sharma is as follows (*3*):

For premix carpet surfacing:

$$\text{AGECRIN} = 2.74\text{EXP}\left[-2.57\frac{\text{CSALYR}}{\text{MSN}^2}\right] \quad [n = 20,\ R^2 = 0.45,\ \text{SE} = 0.43]$$

where AGECRIN is the age of pavement at time of cracking initiation (years) and CSALYR is cumulative standard axles per year (millions).

The cracking progression model is given by

$$\frac{\Delta \text{CR}_t}{t_i} = 5.41\left[\frac{\text{CSALYR}}{\text{MSN}}\right]^{0.54} * \text{SCR}_i^{0.32} \quad [n = 124,\ R^2 = .25,\ \text{SE} = 1.14]$$

where

MSN = $3.28(\text{Def}_0)^{-0.23}$,
ΔCR_t = percentage change in crack area over time t in years (%),
SCR_i = initial crack area (%), and
t_i = time interval (years).

For the purpose of analysis, the initial crack area is assumed to be 2% of the whole area.

Raveling Criteria

Raveling occurs as a result of the loss of fines or stone particles from the surfacing or as a result of the loss of adhesion–bonding between

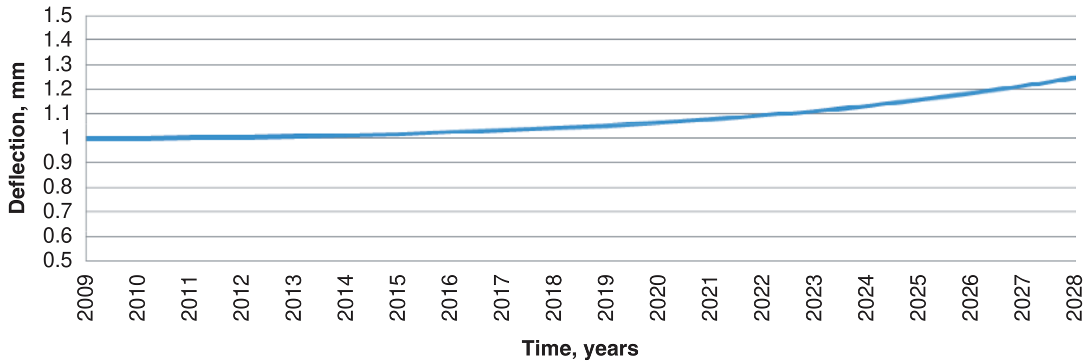

FIGURE 1 Deflection progression.

binder and aggregates. The general form of raveling initiation model by Sood and Sharma is as follows (*3*):

$$\text{AGERVIN} = 3.18\ \text{AXLEYR}^{-0.138} * (\text{CQ}+1)^{-0.38}$$

$$[n = 26,\ R^2 = 0.43,\ \text{SE} = 0.38]$$

where

AGERVIN = age of pavement at time of raveling initiation,
AXLEYR = number of vehicle axles per year (million), and
CQ = construction quality (for national highway = 0, for state highway = 1).

The model for raveling progression is

$$\frac{\text{RV}_t}{t_i} = 3.94\ \text{AXLEYR}^{0.32} * \text{SRV}_i^{0.46}$$

$$[n = 82,\ R^2 = 0.28,\ \text{SE} = 1.02]$$

where RV_t = raveling at time t (%), and SRV_i = initial raveling (%). For analysis purposes, the initial raveling is assumed to be 1% of the whole area.

ANALYSIS

The progression of deflection, roughness, rutting, cracking, and raveling for the 20-year analysis period can be seen in Figures 1 through 5. The initial roughness in regard to the international roughness index (IRI) of premix carpet is assumed to be 4 m/km. For the do-nothing strategy, the maximum roughness value at the end of the analysis period is 14.5 m/km as can be seen in Figure 2. Cracks will initiate in the pavement surface in 2011 and reach a maximum value of 3% by the end of the analysis period, as can be seen in Figure 4. Raveling is likely to initiate on the pavement in 2015 and to reach a maximum value of 4% at the end of the analysis period, as can be seen in Figure 5.

MAINTENANCE TREATMENTS AT DIFFERENT TRIGGER LEVELS

The maintenance treatments that are considered in the analysis at different trigger levels are shown in Table 2. By using initial roughness values of different treatments and unit costs that are given in Tables 3 and 4, the analysis was carried out to quantify the extra funds needed as a result of the delayed maintenance period. The discounted agency costs needed in the 20-year analysis period for different treatments are calculated by assuming the discount rate to be 12% and the inflation rate to be 5%.

The schedule for different maintenance interventions is shown in Table 5. From the results given in Table 6, it can be seen that the agency cost increases as a result of the delayed maintenance intervention. If preventive maintenance treatment (surface dressing) is applied, the agency cost is US$9,739 per lane kilometer, whereas if corrective maintenance treatment (i.e., 50 mm bituminous macadam + 20 mm bituminous concrete) is applied, the agency costs will be as high as US$19,478 per lane kilometer in 2022. Table 7 shows the effect of delayed maintenance on agency costs. From the results, it

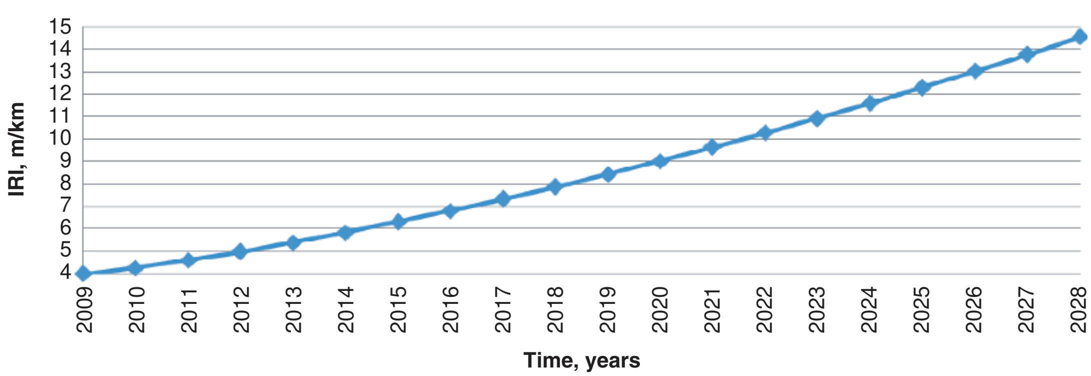

FIGURE 2 Roughness progression.

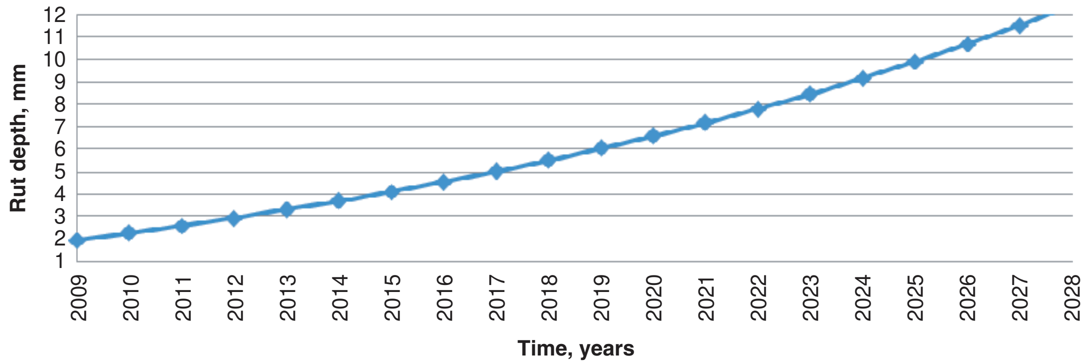

FIGURE 3 Rutting progression.

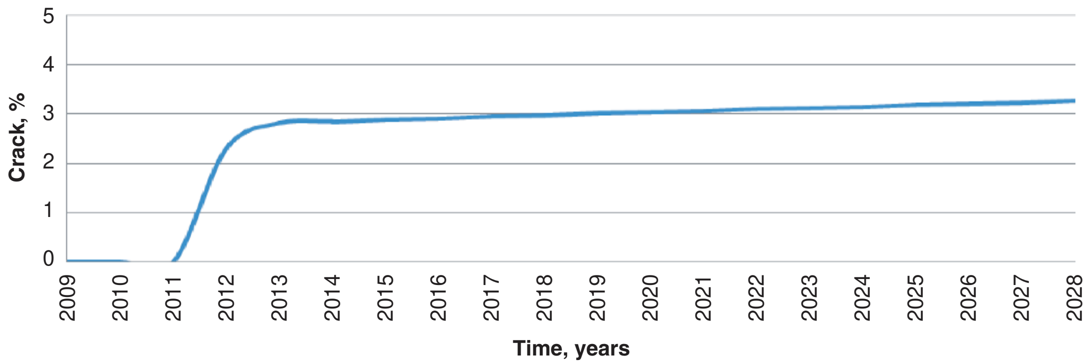

FIGURE 4 Cracking progression.

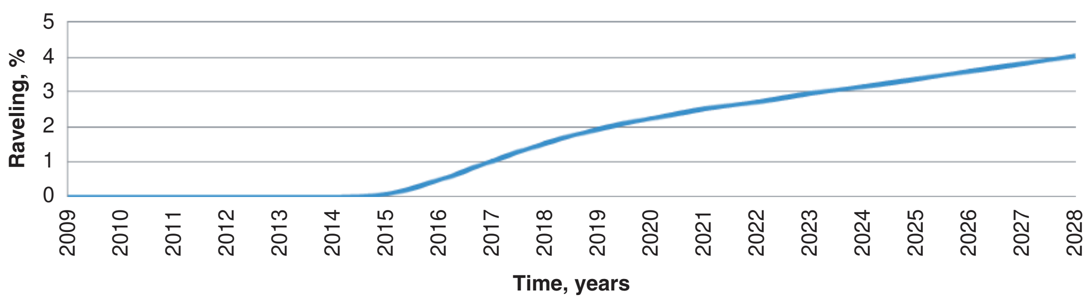

FIGURE 5 Raveling progression.

TABLE 2 Selected Treatments in Analysis at Different Trigger Levels

Serial Number	Trigger Level	Treatment
1	IRI = 6 m/km	Single-coat surface dressing, 20-mm premixed carpet, 20-mm mix seal surfacing
2	IRI = 8 m/km	40-mm semidense bituminous concrete
3	IRI = 10 m/km	50-mm bituminous macadam + 25-mm semidense bituminous concrete

TABLE 3 Initial Roughness Values

Serial Number	Treatment	Initial Roughness After Treatment (m/km), IRI
1	Thick overlay viz., (50-mm BM + 25-mm SDBC)	2.5
2	Semidense bituminous concrete	3.5
3	Surface dressing	4.5
4	Mix seal surfacing	4
5	Premix carpet	4

NOTE: See IRC 16-2004.

TABLE 4 Schedule of Rates

Serial Number	Treatment	Cost (US$)/Unit
1	Bituminous concrete	156/m^3
2	Bituminous macadam	110/m^3
3	Semidense bituminous concrete	143/m^3
4	Routine maintenance	325/lane km
5	Surface dressing	1.5/m^2
6	Premix carpet	2.5/m^2

NOTE: Rate schedule according to Government of Karnataka, Public Works Department, schedule of rates.

TABLE 5 Year(s) of Maintenance Intervention

Trigger Value, IRI	Treatment	Years of Application
6	Two-coat surface dressing	2015, 2019, 2023, 2026
6	Premix carpet	2015, 2020, 2025
8	40-mm semidense bituminous concrete	2019, 2028
10	50-mm bituminous macadam + 25-mm semidense bituminous concrete	2022

can be inferred that delay in maintenance by 4 years is likely to result in an additional maintenance cost of US$7,791 per kilometer to the agency, and further delay in maintenance is likely to increase the maintenance cost by US$9,739 per kilometer.

EFFECT OF DELAYED MAINTENANCE ON VEHICLE OPERATION COST

From Figure 6 it can be seen that there is a reduction in roughness value after the maintenance intervention at an IRI value of 6 m/km, resulting in significant influence on vehicle operation costs (VOC). The total VOC at the end of the analysis period for the do-nothing strategy is US$86,569/km whereas total VOC at the end of the analysis period by considering timely maintenance is US$71,419/km, resulting in a savings of more than US$15,150/km during the analysis period. Similarly, comparison of the roughness progression and the effect of different maintenance interventions at IRI values of 8 m/km and 10 m/km are shown in Figures 7 and 8, respectively. VOC savings of US$10,816/km can be obtained as a result of effective maintenance at an IRI value of 8 m/km, and VOC savings of only US$4,326/km can be obtained as a result of maintenance at an IRI value of 10 m/km.

SENSITIVITY ANALYSIS

Sensitivity analysis was carried out to understand the effect of an increase in unit rates on an increase in agency costs resulting from a delay in maintenance. It is observed from Figure 9 that an increase in the unit rate of various maintenance treatments from 0% to 20% causes the agency cost to increase from US$7,790 to US$9,517 if the delay in maintenance intervention is 4 years.

CONCLUSIONS

1. The increased maintenance costs to the agency resulting from a delay in maintenance of 4 years and 7 years are US$7,790 per lane kilometer and US$15,148 per lane kilometer, respectively. The increased maintenance cost is due to deterioration of the pavement and costly maintenance intervention strategies to be applied to the pavement later in the design life.

TABLE 6 Agency Costs for Different Maintenance Alternatives

Trigger	6 IRI	6 IRI	8 IRI	10 IRI
Year	2015	2015	2019	2022
Treatment	Surface dressing	Premix carpet	40-mm semidense bituminous concrete	50-mm bituminous macadam + 25-mm semidense bituminous concrete
Discounted agency costs (US$/ lane kilometer)	9,739	14,067	17,530	19,478

TABLE 7 Effect of Delayed Maintenance on Agency Costs

Treatment	Years of Maintenance	Discounted Agency Costs (US$/km)	Delay Time (years)	Extra Cost Needed (US$/km)
Two-coat surface dressing	2015, 2019, 2023, 2026	9,739	0	0
40-mm semidense bituminous concrete	2019, 2028	17,530	4	7,791
50-mm bituminous macadam + 25-mm semidense bituminous concrete	2022	19,478	7	9,739

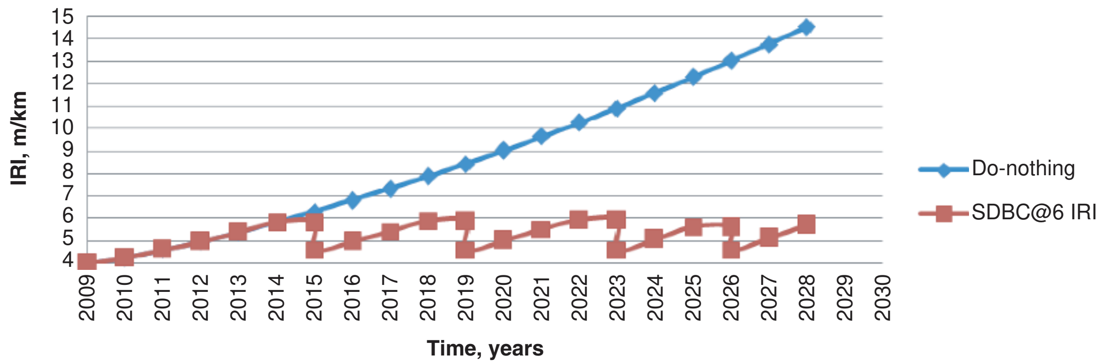

FIGURE 6 Comparison of roughness progression for doing nothing and maintenance with semidense bituminous concrete (SDBC) at 6 IRI.

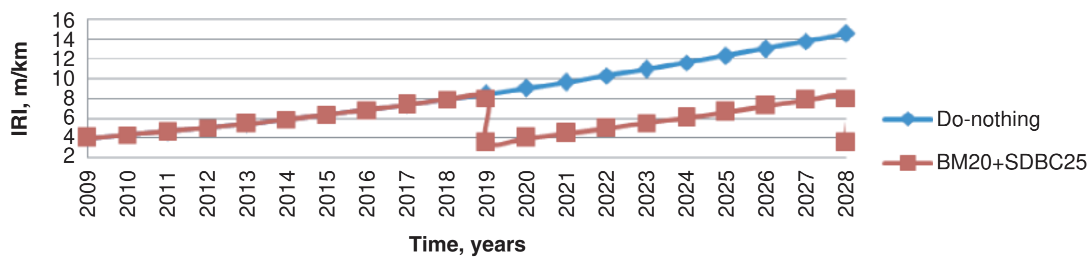

FIGURE 7 Comparison of roughness progression for doing nothing and maintenance with bituminous macadam (BM)20 + SDBC25 at 8 IRI.

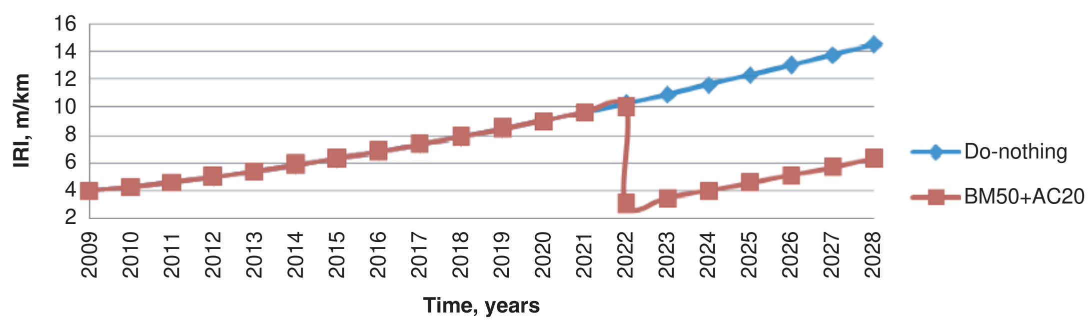

FIGURE 8 Comparison of roughness progression for doing nothing and maintenance with BM50 + asphalt concrete (AC) 20 at 10 IRI.

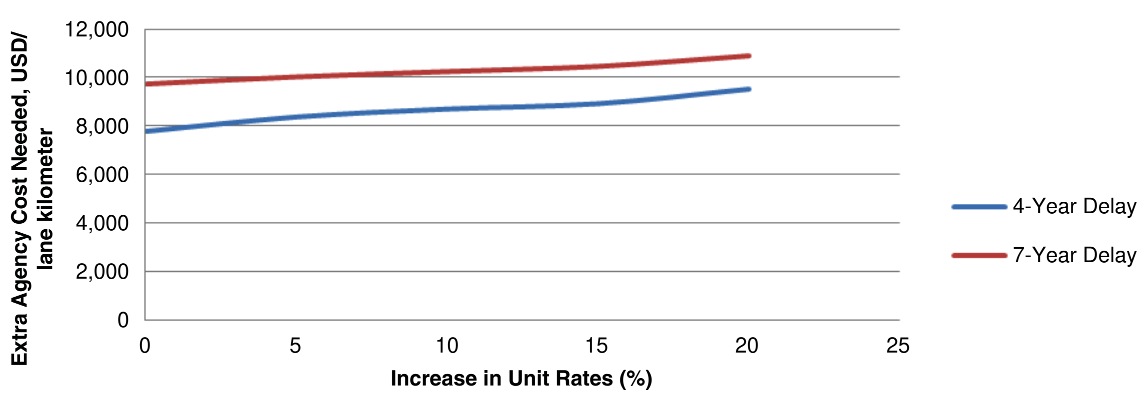

FIGURE 9 Sensitivity analysis.

2. Timely maintenance can significantly reduce agency cost and road user cost.

3. The vehicle operation cost can be significantly higher as a result of delayed pavement maintenance.

4. Substantial benefits can be obtained by adopting a preventive maintenance strategy for all pavement sections when they are still in good condition.

5. There is an urgent need to take up research schemes to determine the optimal preventive maintenance interventions for rural roads under varying traffic, climate, and environmental conditions.

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