A Framework for Network Level Pavement Maintenance Planning for Low Volume Roads

H. R. Pasindu, R. M. K. Sandamal, and M. Y. I. Perera

Abstract Low volume roads (LVRs) play a pivotal role in the economic development of rural areas especially by providing connectivity for the communities to access markets, education and social needs in an efficient manner. They serve as the link between the local road network to the arterial and collector road network designed at providing accessibility to residential, agricultural or industrial areas. Lack of funding, subjective and ad hoc decision making has resulted in an ineffcient utilization of resources in the local road agencies. Lack of a sound analytical process is a major impediment to maintain these roads in cost effective manner under the resource constraints prevalent. Existing pavement management systems (PMS) require extensive data collection and complex analysis processes, which makes them impractical to be deployed in local agencies. The core attributes of the proposed system are, reduced the data requirements, simplified the analytical tools and allowing users to customize considering the resource constraints. In this study, a relationship between International Roughness Index (IRI) and relevant distresses for LVR is established and based on that cost estimation model is developed for distress repair. Furthermore, the strategy which provide maximum condition for preventive maintenance is found by using decision tree approach in the network level optimization. A case study illustrated that the use of proposed PMS provides better overall network condition with compare to conventional decision making for same budget level.

Keywords Pavement management system · Low volume roads · Optimization · International Roughness Index · Cost estimation model

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1 Introduction

The classification of low volume road (LVR) is typically based on average daily traffic (ADT) and approximately less than 1000 vehicles/day, however the definition is differs from country to country significantly (Gamage et al. 2016). Low volume roads play an important role in providing accessibility to communities to fulfill their social and economic needs. Road pavement deteriorate with time, under traffic and environment effects and the condition of those pavements are generally in unsatisfactory condition, resulting in increase of vehicle operating cost, delay among several other issues to the road users. Therefore, it is imperative to maintain those roads at the satisfactory condition to meet the road user needs. In developing countries, the LVRs are maintained by local authorities (e.g. provincial councils, municipal councils) and typically, there is no comprehensive maintenance strategy in place mainly due to the lack of technical expertise and financial limitations. Conventional pavement management systems (PMS) require a certain level of technical knowledge to collect and analyze data, which may not always be available in local road agencies. Moreover, the data collection processes in PMS are time consuming and costly Therefore an alternative system with the capability to overcome those issues and be adoptive for the local authorities is required. In maintenance planning, several factors are to be considered, namely pavement structural and functional condition, social-economic importance, traffic volume etc. Moreover, in the decision making stage, selection of roads for different maintenance activities, strategies to be applied and post condition prediction must be accurately incorporated into the system to achieve optimum solution for the particular road network.

The main objective of this study is to develop a user-friendly and customizable system, with low data requirement with the capability of providing an optimal maitenance strategy within the budget and other constraints.

2 Pavement Management Systems for Low Volume Roads

Road asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively as defined by United State Department of Transportation (USDOT) in 1999 (Shah et al. 2017). It focuses on combining engineering principles with business practices and economic considerations, by providing a tool to facilitate a more organized, logical approach to decision-making. The existing PMS are consisted with different analytical tools, resource management methods, prioritization techniques. Ferreira et al. (2009) developed a PMS with road network database, quality evaluation tool, cost model, decision aid tool and a pavement performance model with incorporating Geographical Information System (GIS) for data collection.

Pavement condition evaluation is consisting of four aspects, i.e. distress condition evaluation, pavement roughness measurement, skid resistance and structural capacity evaluation (Hass et al. 1994). Among those aspects, pavement roughness is effective to use for network level evaluation due to its repeatability, productivity and ease of collection. Gamage et al. (2016), Islam et al. (2014) have developed models to evaluate road condition using roughness data based on a mobile phone application and a cost model is also developed to forecast maintenance cost with respect to International Roughness Index (IRI). Several researchers have shown that the applicability of roughness measurement is high in PMS for network level evaluation (Tai et al. 1998; Eriksson et al. 2008; Bisconsini et al. 2018; Buttlar and Islam 2014).

The maintenance and rehabilitation (M&R) strategies are incorporated in PMS based on the user defined threshold and trigger values. Prior to budget optimization process roads are categorized into routine maintenance, preventive maintenance, rehabilitation or reconstruction (Mane et al. 2016). In the budget optimization, performance jump for different operation types must be defined accurately. Islam et al. (2014) investigated pavement roughness improvement can be achieved by different maintenance treatment types such as slurry seal, chip seal, crack seal for flexible pavement. Moreover, Dwaikat and Haider (2012) estimated the pre-treatment pavement performance, jump and slope adjustment factors for various treatment types while showing that slurry and chip seal can be applied when rutting is minimal and thin overlay is cost-effective when the rutting is high.

Leanne et al. (2011) conducted a study on challenges and successes of implementing a PMS and identified that in the decision making, higher the number of decisions and higher the number of roads, make the output time longer. To reduce the output time and simplify the decision-making process, prioritization and optimization model can be implemented. Perera et al. (2019) shown that with the use of integer programming, average network condition can be reduced with the increasing of budget level and accuracy of optimization model. The challenges in optimizing large networks can be overcome with the using cost model, decision tree approach to solve the objective functions and prediction models with combining to a proper internal database (Mahoney et al. 1978; Swei et al. 2016). Scheinberg and Anastasopoulos (2010) shown that significant cost saving can be achieved with the use of year-by-year multi-constraint technique at network-level optimization using integer programming by a case study on the State of Virginia.

3 Proposed Pavement Management System

3.1 Condition Evaluation Method

In the system, pavement roughness is measured in terms of IRI and is used as the default road condition measurement parameter. Based on the results from the detail distress survey along with IRI measurement on selected low volume roads in Sri Lanka, a relationship is established between IRI and distresses as shown in Eq. (1). This suggests that IRI can accurately represent the relevant distress condition of rural

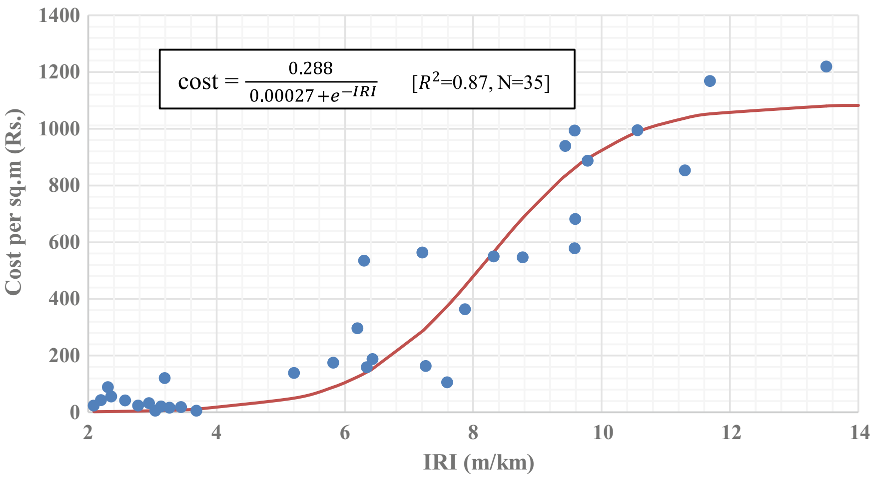

Fig. 1 IRI vs major distresses repair cost plot

roads. Moreover, by using these distress density a cost estimation model is developed for distress repair as shown in Fig. 1.

$$IRI = 2.90 + 0.16RAV\% + 0.29CRA\% + 0.40EDG\% \quad \left[R^2 = 0.75, N = 95\right] \tag{1}$$

where *RAV%* is the raveling area as a percentage of total pavement area, *CRA%* is the cracking area as a percentage of total pavement area, *EDG%* is the linear length of edge gap (more than 10 cm gap between carriageway and shoulder in both side of the pavement section) as a percentage of total length of road section.

Further, potholes are considered as a condition evaluation parameter due to its usage of identify priority roads to be repaired by local agencies. Pothole identification is relatively easy, and it can also be incorporated in the roughness measurement apps developed. Thus, it would not be a major issue for the local road agencies. In addition to roughness and number of potholes, basic road characteristics (e.g. pavement type, length of the section, average width) are the main component of the data required for the proposed system.

3.2 *Screening and Selection for Corrective Maintenance*

The software framework of the proposed PMS is developed by using Java programming language and MySQL software which provide the user interaction and data base respectively. In the system, following steps are performed in the screening and corrective maintenance prioritization process.

Step 1: Screening - If $IRI_i < IRI_{Prev}$ then road 'i' (i = 1, 2, 3…n) is filtered from the analysis step.

Step 2: Selection of roads for corrective maintenance - If $IRI_i > IRI_{Corr}$ then road 'i' (i = 1, 2, 3…n) is selected for the corrective maintenance/overlay in worst first ranking method until the allocated corrective maintenance budget is fully utilized.

Where IRI_i is the IRI of road 'i', IRI_{Prev} is the threshold IRI value used for screening, IRI_{Corr} is the threshold IRI value used for selecting roads for corrective maintenance, n is the number of roads in the network.

Based on the engineers' judgement and resource availability IRI_{Prev} and IRI_{Corr} can be defined in the selection criteria. The corrective maintenance cost is consisting of two components namely distress repair and overlay. The user must be input the unit value of overlay maintenance. Distress repair must be performed prior to the overlay and cost is based on IRI (see Fig. 1) and number of potholes per kilometer (NP). The most appropriate transfer function for cost estimation model is selected among the linear and non-linear regression analysis and among those sigmoid function is found to be the best representative of the data as shown in Fig. 1. Finally, by adding abovementioned two components, total cost of overlay is calculated.

3.3 *Preventive Maintenance Activities*

After selecting roads for corrective maintenance, the remaining road sections are performed under preventive maintenance for a given budget using the optimization approach. This optimization approach adopts a decision tree considering all possible combinations of operations. The operation type which are used for LVRs are identified by the opinion survey from engineers in local authorities. The representative cost values are shown in Table 1 using the Highway Schedule of Rates (HSR) (Provincial 2019).

Table 1 Selected preventive maintenance types used in decision tree approach with unit cost

Operation no. (r)	Preventive maintenance operation	HSR-2019 item no.	Cost (LKR.)
1	Minimum maintenance	DR-009 + DR-010 + MS1-021	33 per sq.m + 20 per L.m. + 40 per sq.m
2	Major distress repair + Pothole patching	Fig. 1 + MS1-007	Fig. 1 + 1404 per sq.m
3	Pothole patching + Double Bitumen Surface Treatment (DBST)	MS1-007 + S1-030B	1404 per sq.m + 477 per sq.m

Where DR is the drain work, MS is the miscellaneous, S is the surface treatment, sq.m is the square meter, L.m. is the linear meter, and LKR is the Sri Lankan rupee (1 US \$ = 190 LKR)

In the decision tree approach, cost of each operation for respective section is calculate based on the pavement condition and road inventories as described below.

1. Minimum maintenance - Based on the length/area of the section and no distress repairing is considered in this operation.
2. Major distress repair - Based on the existing IRI value, cost is calculated for this operation. The unit value from Fig. 1 is multiply by the total area to calculate total cost for the entire section.
3. Pothole patching - NP is converted into the pothole repair cost by the system and a representative area of a pothole must be defined by the user.
4. DBST- Based on the HSR rates, using the unit values, total cost for DBST is calculated by multiplying by total area of the section.

IRI, NP, unit rates and road inventories (e.g. length, width etc.) used as the inputs and respective cost of operation for each section is calculated in the cost estimation model by following the described procedures. This would allow the cost estimation to be made for the maintenance activities based on IRI alone with NP, which would minimize the cost for extensive distress data collection.

3.4 Post Repair Condition Prediction

Performance jump (condition of each section after applying each repair) should be input by the user to the system prior to running optimization model. Minimum maintenance is not affected to change of IRI significantly while major distress repair is reduced roughness slightly. Applying DBST is restored IRI to the range of 2.5–3.4 m/km (Montenegro and Minc 1992).

3.5 Optimization Model

Step 3: Optimization Model for Preventive Maintenance Selection - Accepted preventive maintenance combination is selected by the combination which minimize overall network IRI under the budget constraint. The objective function and the constraint used in the system are represented in Eq. (2) to Eq. (4).

$$\text{Objective function;} \quad Condition;\ Minimize\ Q = \frac{\sum_{s=1}^{n} \sum_{r=1}^{m} Qrs.Ls.Xrs}{L} \tag{2}$$

$$\text{Constraints;} \quad Budget;\ B \geq \sum_{s=1}^{n} \sum_{r=1}^{m} Crs.Ls.Xrs \tag{3}$$

$$Annual\ operation; \sum_{r=1}^{m} Xrs = 1 \tag{4}$$

where Q is the average network IRI value, Qrs is the IRI of road section 's' after applying the operation 'r', Ls is the length of road section 's' in km, Xrs is the decision variable (if operation 'r' is applied to road section 's' then $Xrs = 1$ and operation 'r' is not applied to road section 's' then $Xrs = 0$, L is the total length of the road network, B is the total budget available for the financial year, Crs is the cost per km for applying operation 'r' to road section 's', n is the number of road sections in the network, and m is the number of operation used for road section 's'.

4 Illustrative Example

To illustrate the developed system, a sample of 27 road sections each having length of 1 km were selected. The budget for corrective maintenance works is Rs. 115 million and preventive maintenance budget is Rs. 15 million.

Step 1: Screening - IRI_{Prev} of 4 m/km were used in the case study and 9 sections were screened from the maintenance process based on the value of IRI_{Prev}.

Step 2: Selection of roads for corrective maintenance - 11 road sections were identified for the corrective maintenance under IRI_{Corr} value of 7 m/km and are prioritized based on IRI value. Total cost of corrective maintenance is Rs. 113.13Mn and out of 11 only 9 sections were selected due to budget constraint. The selected sections for corrective maintenance are shown in Table 2.

Step 3: Optimization Model for Preventive Maintenance Selection - The remaining 11 road sections are selected for the preventive maintenance process. Rs.15Mn budget allocation is used for the preventive maintenance and it was found that total cost of Rs. 14.62Mn and average network IRI of 3.98 m/km obtained from the optimization as shown in Table 3.

Table 2 Road sections prioritized under corrective maintenance

Rank	Road Id (s)	Existing IRI values (m/km)	Number of potholes per km (NP)	IRI after overlay (m/km)
1	C300/Sec004	10.3	41	2.5
2	C300/Sec003	9.1	37	2.4
3	C300/Sec002	9.0	21	2.4
4	C301/Sec004	8.8	32	2.4
5	C301/Sec003	8.6	17	2.3
6	C301/Sec002	8.5	07	2.3
7	D002/Sec001	8.1	32	2.2
8	D002/Sec002	7.5	21	2.1
9	C300/Sec001	7.4	15	2.1

Table 3 Summary of results in preventive maintenance process

Road Id (s)	Existing IRI values (m/km)	Number of potholes per km (NP)	Applied operation (r)	IRI after applying (m/km) (Qrs)	Cost (Crs) (Rs.)
C003/Sec001	5.7	10	3	3.5	1,697,600
C003/Sec002	5.4	10	3	3.5	1,697,600
C002/Sec002	5.3	7	3	3.4	1,689,170
C002/Sec001	5.2	7	1	5.2	311,000
C301/Sec001	7.1	14	3	3.8	1,708,840
C004/Sec002	4.4	3	1	4.4	311,000
D002/Sec004	7.3	22	3	3.9	1,731,320
D005/Sec001	6.6	17	3	3.8	1,717,270
D002/Sec003	6.1	21	3	3.7	1,728,510
D005/Sec002	5.0	4	1	2.7	311,000
D005/Sec003	5.9	17	3	3.6	1,717,270

Where r = 1 is the minimum maintenance, r = 2 is the major distress repair + pothole patching, r = 3 is the pothole patching + DBST

From the proposed PMS, overall network IRI of 3.16 m/km is obtained under total cost of Rs.127.75Mn (Budget constraint is Rs.130Mn).

The comparison of average network condition and total cost between different treatment strategies (minimum maintenance all, distress repair all, DBST all, overlay all) used for the selected road network and output from the developed PMS is shown in Fig. 2. In the PMS, 85% of total budget for corrective maintenance and other 15% for preventive maintenance is allocated for different budget limit.

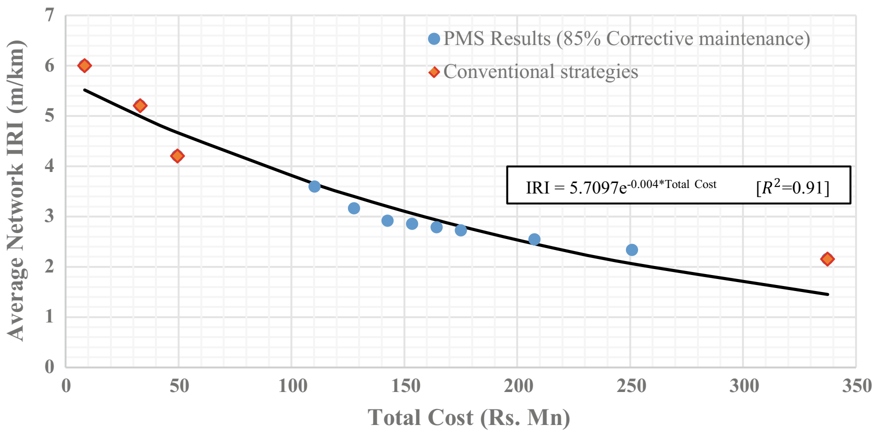

Fig. 2 Average network condition and total cost for different treatment strategies

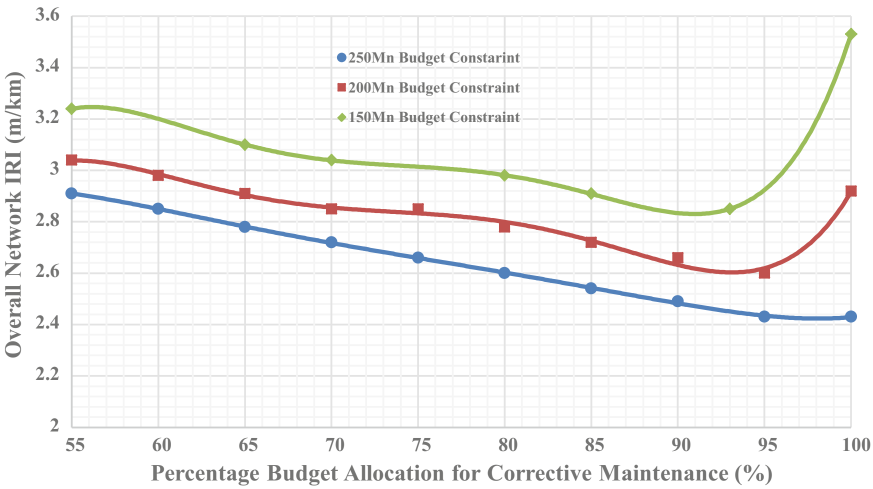

Fig. 3 Overall network condition under different budget allocation levels for corrective maintenance

Furthermore, for this network, total budget is fixed and the combination which gives the minimum overall IRI is found under that budget constraint is shown in Fig. 3.

From the comparison shown in Fig. 3, it can be concluded that when the budget limit is increasing, overall network IRI is reduced and the optimum combination is move towards the higher corrective maintenance percentage. Further, it refers that when the available budget is limited, by allocating relatively higher budget for the preventive maintenance will be provide a better overall network condition rather than allocating more to the corrective maintenance.

5 Conclusions

The research was focused into developing a system which requires minimum data and optimize the maintenance strategy within the available budget. This model can be customized based on road agency decision making strategy. By using the developed system's optimization model, an engineer could be able to decide the preliminary budget requirement for preventive and corrective maintenance. The research provides a decision support system which doesn't require intensive data collection and a systematic process which would yield better results than subjective decision making. Illustrated example shown that, the system has the capability to find the maximum overall network condition under the given budget. Moreover, for a given budget, the combination between preventive and corrective maintenance which gives the minimum network IRI can be found by running the analysis process for several iterations.

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