Springer

Chinese Society of Pavement Engineering

International Journal of
Pavement Research and Technology

Journal homepage: www.springer.com/42947

Decision Support System for the Maintenance Management of Road Network Considering Multi-Criteria

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Received 14 May 2019; received in revised form 6 June 2019; accepted 10 June 2019

Abstract

Maintenance management of a large road network with limited resources is a challenging task in developing countries like India. Road agencies expect that the condition of their road infrastructure should always above the desired level of performance even under restricted resources. This requires an integrated decision support system considering all aspects of maintenance. In this paper, a framework for optimal maintenance decisions by multi-objective approach is formulated for a road network by considering functional condition of the pavement quantified in terms of roughness and structural condition quantified in terms of rebound deflection. A multiobjective optimization model is developed using Integer Linear Programming (ILP). A novel approach to track the age of pavement is applied in the formulation of the mathematical model. The ε-constraint method is adopted to generate non-dominated solutions. Budget bound optimizing model is formulated and implemented for a typical road network of four roads and optimal maintenance scheduling is arrived.

Keywords: Road network; Deterioration; Multi-objective optimization; Optimal maintenance decision; Integer linear programming; Non-dominated solutions.

1. Introduction

India has the second largest road network in the world, spanning a total of over 5.4 million km [1]. According to the Ministry of Road Transport and Highways [2], Government of India, the length of National highways and Expressways in India is 100,475 km, carrying more than 40% of the total traffic. The volume of traffic is increasing at a fast rate of 10.16% per annum. About US$ 745 million is spent annually for the maintenance of the National Highways network in the country. Managing a large transportation network with limited resources is a challenging task. The decision makers have to estimate the optimal budget needed for the preservation and maintenance management of the existing highway networks vis-à-vis construction of new highways/additional lanes to augment the capacity of the existing highways to cope up with the demand. Such decisions always consider a number of criteria such as options for different maintenance strategies, choice of materials and techniques, traffic volume, load spectrum and composition, desired performance level, timing of the maintenance, etc. Hence, the need for the present study arises to plan effective maintenance strategies/ tools for the management of road networks at the appropriate time duly considering the structural and functional condition of the pavements.

1.1. Background

Pavement maintenance includes various types of corrective and preventive maintenance strategies. The basic purpose of pavement maintenance is to extend the service life of the pavements, so that the timing for major rehabilitation can be delayed (Fig. 1). Appropriate pavement maintenance measures retard the rate of deterioration, lower the vehicle operation cost and keeps the road open for vehicle movements.

Pavement maintenance may be classified as routine and periodic maintenance like resurfacing. The up-gradation or strengthening aims at providing additional structural capacity to the pavement by major rehabilitation, when it is nearing its design life or when there is an unforeseen increase in traffic load repetitions.

Maintenance planning can be classified as Routine maintenance, Preventive maintenance and corrective maintenance. Routine maintenance consist of simple periodical maintenance actions such as, clearing cross drainage structures like culverts and bridges, providing/cleaning side drains, filling of pot holes, sealing cracks, maintaining earthen shoulder , marking the lanes etc., It is provided for proper functioning of pavement. Actually, this maintenance does not prevent deterioration of the pavement, but it is provided to retard the rate of deterioration of the pavement.

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Peer review under responsibility of Chinese Society of Pavement Engineering.

ISSN: 1996-6814 DOI: https://doi.org/10.1007/s42947-019-0039-7
Chinese Society of Pavement Engineering. Production and hosting by Springer Nature

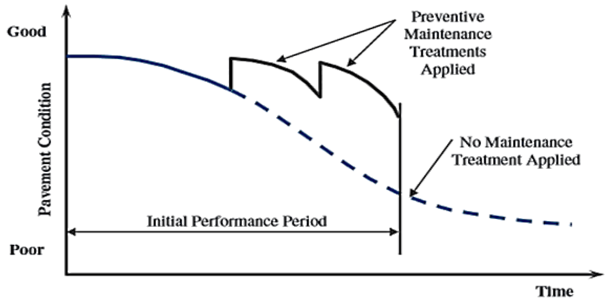

Fig. 1. Pavement Maintenance [3].

By the way preventive maintenance avoids advancement of failure or initiates alternate distress or premature failure. Preventive maintenance is applied to pavement sections that are in good structural condition but when they are functionally deficient. The preventive maintenance treatments extend the life of pavements and minimize the life cycle cost through a sequence of maintenance interventions if applied at the optimal timing duly considering the structural condition of the pavement and the traffic levels [3]. Corrective maintenance treatments are applied at the later parts of the pavement life when the pavement is structurally deficient. It enhances the structural capacity of the pavement and correspondingly the cost of corrective maintenances is also high. Depending upon the condition of the pavement, suitable maintenance is to be planned. Delaying the maintenance causes not only a risk of failure but also increases the user and maintenance cost. This in turn requires larger maintenance investments over time. Delay in application of maintenance treatment has contributed to three the times cost of rehabilitation and vehicle operating cost [4].

Maintenance planning is done by three methods, viz., (a) ranking different projects for maintenance [5], (b) prioritization of project sections duly considering the economic benefits of maintenance and the budget [6], and (c) optimization of the different maintenance strategies [7], viz., optimal timing for the maintenance considering different treatment types, as well as the desired level of performance for different categories of roads carrying different volumes of traffic under budget constraints. In ranking procedure, single year planning is scheduled whereas in practice, multi-year prioritization is usually done [8,9]. Many often, prioritization of pavement maintenance is performed using Analytical Hierarchy Process (AHP) where in the relative importance (on Saaty's scale) between alternatives are assigned subjectively [10]. Pair wise comparison between alternate pavement sections is done in the hierarchy to derive the prioritized list of pavement sections. Maintenance planning can be applied at (a) network level, and (b) project level [11]. In network level Pavement Management System (PMS), the objectives are towards framing policies, assessment of budget requirements, setting maintenance priorities and schedule of the projects for maintenance. At the project level, the system provides optimal techniques for maintenance of specific segment/project.

This paper presents an operation-research model to evolve the optimal solution for the maintenance scheduling of a road network considering multiple distresses and agency cost. A multi-objective optimization model is formulated using Integer Linear Programming (ILP). An efficient $\varepsilon -$ constraint algorithm is proposed to generate a set of non-dominated solution. The paper demonstrates the application of $\varepsilon -$constraint algorithm on Integer Linear Program in road maintenance scheduling to identify treatment choices that simultaneously minimize both the rebound deflection of the pavements and also the roughness of the road network. The rebound deflection is an indicator of the structural condition of the pavement and the roughness is an indicator of the functional condition of the pavement.

2. Review of literature

Optimization of pavement maintenance shall be done by either using mathematical modelling or by heuristic/meta-heuristic algorithms. Optimization models are the only way available as of now that can scientifically justify the decisions on maintenance [12].

The optimization models are needed for the following reasons:

1. Computers and softwares are cheap. More sophisticated computing machines are available in the market with latest softwares.
2. Capital investment on road infrastructure is increasing. Hence maintenance cost will also increase. There will be tremendous need to use optimization model to bring the economic maintenance.

Mathematical models use application tool technology (both soft- and hardware) that is available at low costs and are rapidly developing.

In general, the optimization modelling are categorised into two fundamental approaches namely, top-down and bottom- up approach. In top-down methods, the roads are analysed in groups and all roads in a group are treated as identical in terms of deterioration (e.g. [13]). These methods are independent of the number of roads and thus very efficient for large-scale networks.

In contrast, bottom-up approaches consider distress information and deterioration rates for each section. This method can be one-stage and two-stage solution approaches. One-stage bottom-up approaches simultaneously consider all possible combinations of roads, maintenance and rehabilitation treatment types and intervention years. Treatment intervention is represented by a binary decision variable 1 or 0 depending on the treatment is selected or not, respectively.

Due to the exceptional complexity and non linearity of the objectives, the solution will take long time and hence, many authors have adopted a heuristic technique (Genetic Algorithm) in their solution [14-18].

In two-stage bottom-up approaches, a set of optimal and sub-optimal treatment choices are selected for each road. The objective of the problem is to identify the optimal combination of treatment choices at the network level, under the budget constraint. Yeo et al. [19] and Lee & Medanat [20] formulated the network-level problem as a constrained combinatorial problem, which they solve with evolutionary algorithm or pattern search heuristic. For both approaches, the objectives shall be set as minimizing cost, maximizing the performance, and maximizing remaining life. Depending on the number of objectives, the optimization models shall be Single Objective Optimization (SOO) or Multi-Objection Optimization (MOO) problem.

Following approaches are used while handling multiple objectives [21]:

1. Multi Criteria Decision Making (MCDM) method: Transformation of multiple objectives into single objective. Decision makers' preference is considered in advance.

2. Multi-objective optimization: Identification of non-dominated solutions (Pareto solutions).

Several approaches have been developed to solve MOO problems, which include, among others, Simple Aggregate Method [7], Weighted aggregate method [22], Weighted Metric Methods (Compromise programming methods) [17], Goal programming method, achievement functions method, goal attainment method, ε-constraint method [23], dominance- based approaches [17,24]. A complete review of the application of MOO techniques to the highway asset management problems can be referred at [25].

Wang et al. [26] proposed a multi-objective optimization to maximize maintenance effectiveness and minimize the disturbance cost. The problem is simplified by a single objective problem by simple weighted sum method. Chowdhury and Tan [23] proposed Surrogate Worth Trade-off (SWT) analysis for a static problem wherein he had generated non dominated solution from ε - constraint method. Gao et al. [27] proposed a bi-objective problem and generated Pareto solutions with different weights used for objectives.

Chen et al. [28] compared $\varepsilon -$ Constraint Method (ECM), Weighted Sum Method (WSM), Dichotomic Approach (DA) and Revised Normal Boundary Intersection (RNBI) method for a road network having three groups of roads. Integer Programming was implemented in Gurobi software. RNBI was found to take longer time and WSM and DA took lesser time. ECM required a reasonable time and provided many Pareto solutions. Yu et al. [29] proposed three objective problems but he generated solution from Genetic algorithm. Meneses et al. [24,30,31] proposed multi-objective problem and scalarised by Weighted Sum Method. Santos et al. [32] development of a three objective problem for pavement management that has the ability to involve road users and environmental concerns with highway agency cost of maintenance. Multi-objective Genetic algorithm (MOGA) was attempted to solve the problem.

Not much work done in mathematical model in multi-objective optimization applicable to pavement maintenance due to:

1. The objective function must be differentiable or continuous or the reasonable region must be convex. This affects the efficiency of the mathematical model [33]. In contrast, the population-based meta-heuristic approaches produce different classes of non-dominated solutions simultaneously in every iteration.
2. Exact solution for large net work is time consuming. At network level, algorithms for multi-objective optimization may require impractically high computational times to solve them to the exact optimum [17,31].

2.1. *Summary of literature review and research gap*

Many mathematical models are single objective problems. When it comes to multi-objective optimization, either simple aggregate method or weighted sum method is applied and solved as single objective problem. Surrogate Worth Trade-off (SWT) method was used once for a static problem. In other cases, the problems are solved by meta-heuristic approach (Genetic algorithm).

Therefore, this motivates to explore other approaches of multi-objective optimization algorithms in mathematical modelling. Among the different approaches, the ε - constraint method is the efficient algorithm that provide all non dominated solutions. The algorithm is simple and provides exact Pareto-optimal solution. In addition, this approach can be used for non-convex problems. Hence, the ε - constraint method is used in present work to arrive different Pareto-optimal solutions.

In the past works in multi-objective optimization, distress values are not referred in the optimization model instead distress indices (like Present Serviceability Index, PSI) are used to identify the distress. Treatment effectiveness for different treatment is related to distress indices. Distresses are not directly represented as objectives or constraints. To characterize the pavement condition as a whole in optimization model, distresses should represent both structural condition and functional condition of pavements. In the proposed approach, deflection and roughness values, measure directly the distresses.

Only scant literature is available on the multi-objective optimization process in the pavement management considering both structural and functional condition of the pavements at network level. In general, two types of models are used: (1) Budget Bound Model (BBM), and (2) Necessary Fund Model (NFM) [34].

In this paper, formulation of the Budget Bound Model is presented. Maintenance treatment scheduling is proposed duly considering multiple criteria viz., functional and structural condition of the pavements in the optimization process. A framework for multi-objective optimization is formulated to derive the optimal timing for maintenance duly considering different traffic (volume) levels, threshold level for maintenance, desired level of performance and budget constraints.

Another significant initiative in this study is that while calculating the progression of distress, the age of the pavement will be reset to 1 when a treatment (corrective maintenance treatment) is performed. This will yield a close and realistic prediction of distress. Moreover, this provides a hand on information about the time elapsed from the previous intervention. The model is precisely formulated to account the above distress progression mechanism.

2.2. *Objectives*

1. Development of a framework for the selection of appropriate maintenance treatments of a highway network duly considering the structural and functional condition of the pavements in a network of roads,
2. Formulation of a multi-objective optimization algorithm for maintenance management of a highway network, and
3. Development of a decision support system, viz., optimal timing and selection of appropriate maintenance strategies, for a highway network through multi-criteria approach.

3. Framework and formulation

3.1. *Problem statement*

To formulate and implement multi-objective optimization to select the optimal treatment choices by minimizing the distress levels (multi-objective) under budget constraint using Integer Linear Programming (ILP) integrating with $\varepsilon -$ constraint algorithm.

3.2. *Assumptions*

Structural condition of the pavement is considered to be represented by the rebound deflection of the pavement measured using Benkelman beam. The roughness of the pavement considers the extent and severity of the various distresses affecting the ride quality, like rutting, cracking, ravelling, pothole etc., and hence roughness is considered as the parameter to represent the functional condition of the pavement. The improvement in the condition of the pavement due to treatment is termed as treatment effectiveness. The treatment effectiveness is considered from the data available from literature. Discrete time of one year is considered in this work.

3.3. Notations

Sets and Indices:

T	Time period; $t = 1, 2, 3,...., T$.
i	Roughness levels; $i = 1, 2, 3,...., I$.
j	Deflection levels; $j = 1, 2, 3,...., J$.
n	Index for road; $n = 1, 2, 3,...., N$.
a	Index for treatment choice; $a = 1, 2, 3,...., A$.
τ	Index with respect to year of the last treatment (i.e., age since last treatment); $1 \leq \tau \leq$ maximum age of a road; when no intervention of a treatment takes place over the planning horizon, the maximum age is encountered.

Parameters:

B	Budget for the entire planning horizon.
T	Finite Planning Horizon.
I	Total number of roughness levels.
J	Total number of deflection levels.
N	Total number of roads.
A	Total number of treatment choices.
$R'^{b}_{i,n}$	Beginning roughness with respect to roughness level *i* of road *n*.
$D'^{b}_{j,n}$	Beginning deflection with respect to deflection level *j* of road *n*.
$R^{end}_{i,j,\tau,n}$	End roughness of road n, given the level of beginning roughness being i, the level of beginning roughness being j and the beginning age being (τ-1).
$D^{end}_{i,j,\tau,n}$	End deflection of road n, given the level of beginning roughness being i, the level of beginning roughness being j and the beginning age being (τ-1).
$R'^{e}_{i,n}$	End roughness with respect to level *i* and road *n*.
$D'^{e}_{j,n}$	End deflection with respect to level *j* and road *n*.
$R^{new}_{i,j,a,n}$	Roughness of road *n* after the intervention or treatment choice of level *a,* with respect to roughness level *i* and deflection level *j*.
$D^{new}_{i,j,a,n}$	Deflection of road *n* after the intervention or treatment choice of level *a*, with respect to roughness level *i* and deflection level *j*.
$C'_{a,n}$	Maintenance cost for road *n* by treatment choice of level *a*.
ζ_n	Age of road *n* at the beginning of planning period.

Decision variables:

$R^{b}_{t,n}$	Beginning roughness at time *t*, for road *n*.
$D^{b}_{t,n}$	Beginning deflection at time *t*, for road *n*.
$R^{e}_{t,n}$	End roughness at time *t*, for road *n*.
$D^{e}_{t,n}$	End deflection at time *t*, for road *n*.
$C_{t,n}$	Maintenance cost at time *t*, for road *n*.
$Max_{t,n}$	A variable that tracks the number of years since the last treatment on road *n,* with respect to beginning of year *t*.
$\delta_{i,j,\tau,t,n}$	= 1, if roughness level i and deflection level j with age since last intervention being τ for road *n,* are present at the beginning of period *t*. = 0, otherwise.
$\Delta_{i,j,a,t,n}$	= 1, if treatment choice a is given to road n with roughness level i and deflection level j at the end of period t. = 0, otherwise.

Input conditions:

B	Budget for entire planning horizon.
$D^{b}_{1,n}$ and $R^{b}_{1,n}$	Initial deflection and initial roughness of road *n,* at the beginning of year 1(i.e., *t*=1).
$Max_{1,n}$	Age of road *n* at beginning of time *t*=1.

3.4. Mathematical programming model

$$Minimize \quad Z = \left(\sum_{n=1}^{N}\sum_{t=2}^{T}(R^{b}_{t,n} + R^{e}_{t,n})/2\right)/((T-1) \times N) \tag{1}$$

$$Minimize \quad Z = \left(\sum_{n=1}^{N}\sum_{t=2}^{T}(D^{b}_{t,n} + D^{e}_{t,n})/2\right)/((\mathrm{T}-1) \times \mathrm{N}) \tag{2}$$

subject to the following:

Eqs. (3), (4), (5) and (6) compute respectively the state of road *n*; beginning roughness, beginning deflection and the age (since the last treatment) at the beginning of year *t*.

$$\{$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{\tau=1}^{t+\zeta_n}\left(\delta_{i,j,\tau,t,n}\right) = 1\,, \tag{3}$$

$$\sum_{i=1}^{I}\left(R'^{b}_{i,n} \times \left(\sum_{j=1}^{J}\sum_{\tau=1}^{t+\zeta_n}\delta_{i,j,\tau,t,n}\right)\right) = R^{b}_{t,n}\,, \tag{4}$$

$$\sum_{j=1}^{J}\left(D'^{b}_{j,n} \times \left(\sum_{i=1}^{I}\sum_{\tau=1}^{t+\zeta_n}\delta_{i,j,\tau,t,n}\right)\right) = D^{b}_{t,n}\,, and \tag{5}$$

$$\sum_{\tau=1}^{t+\zeta_n}\left(\tau \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\delta_{i,j,\tau,t,n}\right)\right) = Max_{t,n} \tag{6}$$

$$\}, \forall t \text{ and } \forall n.$$

Eqs. (7) and (8) compute respectively the roughness and deflection of road *n* at the end of year *t*.

$$\{$$

$$R^{e}_{t,n} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{\tau=1}^{t+\zeta_n}\left(R^{end}_{i,j,\tau,n} \times \delta_{i,j,\tau,t,n}\right),\ and \tag{7}$$

$$D^{e}_{t,n} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{\tau=1}^{t+\zeta_n}\left(D^{end}_{i,j,\tau,n} \times \delta_{i,j,\tau,t,n}\right) \tag{8}$$

$$\}, \forall t \text{ and } \forall n.$$

Eqs. (9), (10) and (11) compute respectively the end state of road *n*; end roughness and end deflection at the end of year *t*.

$$\{$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{a=1}^{A}\left(\Delta_{i,j,a,t,n}\right) = 1, \tag{9}$$

$$\sum_{i=1}^{I}\left(R'^{e}_{i,n} \times \left(\sum_{j=1}^{J}\sum_{a=1}^{A}\Delta_{i,j,a,t,n}\right)\right) = R^{e}_{t,n},\ and \tag{10}$$

$$\sum_{j=1}^{J}\left(D'^{e}_{j,n} \times \left(\sum_{i=1}^{I}\sum_{a=1}^{A}\Delta_{i,j,a,t,n}\right)\right) = D^{e}_{t,n} \tag{11}$$

$$\}, \forall t \text{ and } \forall n.$$

Due to treatment choice a implemented on road *n* at the end of year *t*, the beginning roughness and the beginning deflection at the beginning of the year (*t*+1) of implementation and the treatment cost of road *n* at the end of year *t* are computed from Eqs. (12), (13) and (14).

$$\{$$

$$R^{b}_{t+1,n} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{a=1}^{A}\left(R^{new}_{i,j,a,n} \times \Delta_{i,j,a,t,n}\right), \tag{12}$$

$$D^{b}_{t+1,n} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{a=1}^{A}\left(D^{new}_{i,j,a,n} \times \Delta_{i,j,a,t,n}\right), and \tag{13}$$

$$C_{t,n} = \sum_{a=1}^{A} C'_{a,n} \times \sum_{i=1}^{I}\sum_{j=1}^{J}\left(\Delta_{i,j,a,t,n}\right) \tag{14}$$

}, for $t = 1, 2, 3, ..., T$ and $\forall n$.

$Max_{t+1,n}$ tracks the age at the beginning of the year (t+1) from the last treatment for road n at the end of time t. $Max_{t+1,n}$ is set to 1, if the treatment level a other than 1 is implemented or $Max_{t+1,n}$ increases by one, if treatment level 1 is implemented, at end of time t on road n.

{

$$Max_{t+1,n} \leq 1 + M\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\Delta_{i,j,1,t,n}\right)\right), \tag{15}$$

$$Max_{t+1,n} \geq 1 - M\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\Delta_{i,j,1,t,n}\right)\right) \tag{16}$$

$$Max_{t+1,n} \geq \left(Max_{t,n} + 1\right) - M\left(1 - \sum_{i=1}^{I}\sum_{j=1}^{J}\left(\Delta_{i,j,1,t,n}\right)\right), \tag{17}$$

$$Max_{t+1,n} \leq \left(Max_{t,n} + 1\right) + M\left(1 - \sum_{i=1}^{I}\sum_{j=1}^{J}\left(\Delta_{i,j,1,t,n}\right)\right) \tag{18}$$

}, for t = 2, 3,...., T and $\forall n$.

$$\sum_{t=1}^{T}\sum_{n=1}^{N} C_{t,n} \leq B \tag{19}$$

Eq. (1) is the first objective function to minimize the average roughness over the period of planning horizons and Eq. (2) is the second objective function to minimize the average deflection over the period of planning horizons. Binary variables are used for selection of roughness and deflection at the end of a given year. Eq. (3) ensures that only one binary variable takes the value of 1 and the rest of the binary variables turn to zero. Eq. (6) represents the selection of age after the treatment with the above principle. Eqs. (7) and (8) identify the roughness and deflection at the end of a given year from the binary variable obtained from Eqs. (3), (4) and (5). This incorporates the roughness and deflection progression over age.

Eq. (9) represents a binary variable for selection of treatment level and resultant roughness and deflection due to implementation of the selected treatment level. This equation ensures that only one of these binary variables takes the value 1 and other variables turn to zero.

Eqs. (10) and (11) identify the treatment options from the binary variable and Eqs. (12) and (13) are used to compute the roughness and deflection values after the implementation of the selected treatment. The roughness and deflection values after the treatment are considered as the beginning roughness and beginning deflection values for the next year. Eq. (14) considers the cost of the treatment.

Constraints (15) to (18) track the age of the pavement and add age by 1 every year, if treatment is 'do-nothing' viz., only routine maintenance is applied. At the same period, if any other treatments viz., preventive or corrective maintenance is applied, then the age is reset to 1. For this purpose a large constant value M is deliberately added in the constraints (17) and (18). The assumption behind the principle is that the road after any treatment, except do-nothing treatment with routine maintenance is considered to enhance the structural and functional condition of the pavement. Constraint 19 ensures that the total maintenance cost is less than the budgetary provision of planning horizon.

3.5. Algorithm to generate a set of non-dominated Pareto-optimal solutions by ε− constraint method

There are many approaches to solve multi-objective optimization. Among the different approaches, $\varepsilon -$ constraint algorithm is simple and efficient to generate non-dominated solutions. A solution is said to be non-dominated (Pareto optimal), if no other feasible solution that can improve one of the objective without degrading any other objective.

3.5.1. Generation of non-dominated solution

In this problem, two minimization objectives are laid down. (1) To minimize the average network deflection over planning horizon (Eq. (1)); (2) To minimize the average roughness over planning horizon (Eq. (2)).

Initially, Minimum roughness ruf_1^* is created from the ILP formulation without deflection constraint as per step 1.1 and kept $ruf_1^1 = ruf_1^*$

Then, Minimum deflection def_1^1 is created from the ILP formulation keeping ruf_1^* as add-on constraint (Eq. (20)) as per step 1.2.

After this, Minimum deflection def^* is created from the ILP formulation without roughness constraint as per step 1.3.

This is the procedure for iteration 1 (Fig. 2) which yields a non-dominated solution ruf_1^1 *and* def_1^1.

To generate subsequent non-dominated solutions, deflection decrement approach is followed. For each consecutive iteration, a deflection $\boldsymbol{\varepsilon_d}$ will be reduced from final deflection value of previous iterations ($def_{iter-1}^1 - \boldsymbol{\varepsilon}_d$) and set as def_{iter}^1. This will be an add-on constraint for minimizing the roughness to ruf_{iter}^1 (Eqs. (21) and (22)).

Similar to step 1.2, minimum deflection def_{iter}^1 is created from the ILP formulation keeping ruf_{iter}^1 as add-on constraint (Eq. (23)).

The procedure is repeated for each $\boldsymbol{\varepsilon_d}$ decrement of deflection and non-dominated solutions are arrived until $def_{iter}^1 = def^*$

3.5.2. Terminology

Iter	Index for Iteration
ruf_{iter}^1	Minimum Average roughness obtained in the iteration *iter.*
def_{iter}^1	Minimum Average deflection obtained in the iteration *iter,* corresponding to ruf_{iter}^1
def^*	Minimum Average deflection (without roughness constraint)

/* note: rest of terminologies are already introduced in sub-section 3.3*/

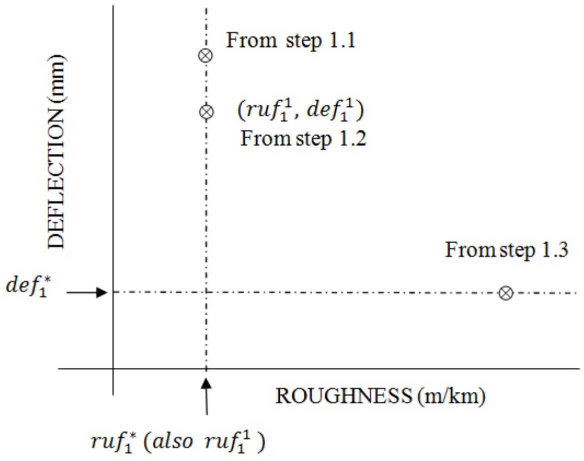

Fig. 2. Iteration principle.

3.5.3. Step-by-step procedure to generate a set of non-dominated (Pareto-optimal) solutions

/* Step 1 is to obtain an efficient solution with the minimum average roughness and corresponding minimum average deflection of all roads for the entire planning period; */
Step 1: Set *iter* =1.
Step 1.1: Execute the following ILP, called ILP-1.

$$Minimize\ Z = ruf^{*}_{iter} = \sum_{n=1}^{N}\sum_{t=1}^{T}(R^{b}_{t,n} + R^{e}_{t,n})/(2 \times (T-1) \times N)$$

with the MILP originally given in model (see sub-section 3.4). Thereafter,

Set $ruf^{1}_{iter} = ruf^{*}_{iter}$

Step 1.2: Generate the following ILP, called ILP-2.

$$Minimize\ Z = def^{1}_{iter} = \sum_{n=1}^{N}\sum_{t=1}^{T}(D^{b}_{t,n} + D^{e}_{t,n})/(2 \times (T-1) \times N)$$

and subject to all constraints in the ILP given in model, and with the following add-on constraint, derived from Step 1.1:

$$\sum_{n=1}^{N}\sum_{t=1}^{T}(R^{b}_{t,n} + R^{e}_{t,n})/(2 \times (T-1) \times N) = ruf^{1}_{iter} \quad (20)$$

Denote this solution for the ILP as $\{\delta el^{iter}\}$ associated with def^{1}_{iter} and ruf^{1}_{iter}.
/* note: $\{\delta el^{iter}\}$ denotes the solution with the minimum average deflection and the associated average roughness */
Step 1.3: Execute the MILP given in model with the following objective function:

$$Minimize\ Z = def^{*} = \sum_{n=1}^{N}\sum_{t=2}^{T}(D^{b}_{t,n} + D^{e}_{t,n})/(2 \times (T-1) \times N)$$

subject to all constraints given in the ILP originally presented in Sub-section 3.4.
Step 2:
/* Do this step to get further Pareto-optimal solutions by ε-constraint (with respect to deflection decrement) approach */
/* note: skip Step 2 if $def^{1}_{iter} = def^{*}$ */
Step 2.1: Set *iter* = *iter* +1;
with respect to the original ILP given in sub-section 3.4, do the following:

(1) set : $Minimize\ Z = ruf^{1}_{iter} = \sum_{n=1}^{N}\sum_{t=1}^{T}(R^{b}_{t,n} + R^{e}_{t,n})/(2 \times (T-1) \times N)$;
(2) if $(def^{1}_{iter-1} - \varepsilon_{d} > def^{*})$
then,
{
add:

$$\sum_{n=1}^{N}\sum_{t=1}^{T}(D^{b}_{t,n} + D^{e}_{t,n})/(2 \times (T-1) \times N) \le def^{1}_{iter-1} - \varepsilon_{d} \quad (21)$$

and set $def^{1}_{iter} = def^{1}_{iter-1} - \varepsilon_{d}$,
and execute the resultant ILP.
}
Else
{
add : $\sum_{n=1}^{N}\sum_{t=1}^{T}(D^{b}_{t,n} + D^{e}_{t,n})/(2 \times (T-1) \times N) = def^{*} \quad (22)$
and set $def^{1}_{iter} = def,^{*}$
and execute the resultant ILP.
}

Step 2.2: Execute the following ILP:

$$Minimize\ Z = def^{1}_{iter} = \sum_{n=1}^{N}\sum_{t=1}^{T}(D^{b}_{t,n} + D^{e}_{t,n})/(2 \times (T-1) \times N)$$

and subject to all constraints in the original ILP in Sub-section 4.3, and with the following constraint addition :

$$\sum_{n=1}^{N}\sum_{t=1}^{T}(R^{b}_{t,n} + R^{e}_{t,n})/(2 \times (T-1) \times N) = ruf^{1}_{iter} \quad (23)$$

Denote the solution from the ILP as $\{\delta el^{iter}\}$, associated with def^{1}_{iter} and ruf^{1}_{iter}, and the related binary variables
Step 3: If
$def^{1}_{iter} = def^{*}$
then proceed to Step 4
else return to Step 2.
Step 4: STOP: the set of Pareto-optimal solutions is obtained, denoted by $\{\delta el^{iter}\}$ and the corresponding def^{1}_{iter} and ruf^{1}_{iter} for given ε_{d}, and over all *iter.*

4. Model implementation

4.1. Road network

A typical network consist of four road sections with varied traffic levels expressed in million standard axles (msa), and having different initial distress conditions is considered for the implementation of the proposed model.

The details of road (traffic level, sections, length of road) and Initial distress level (roughness and deflection) are summarised in Table 1.

Table 1
Details of road network.

Road	Road 1	Road 2	Road 3	Road 4
Traffic level *(msa)	100	30	20	10
Length of road (km)	8	12	24	16
Number of lanes	2	2	2	2
Age, years	1	1	1	1
Initial Roughness (m/km)	2	2.2	2.0	2.2
Initial deflection (mm)	0.25	0.25	0.35	0.35

(*the design traffic is expressed in terms of 'Million Standard Axle' repetitions (msa).

The data required for implementing the formulation are: selection of deterioration criteria, historic deterioration data, identification of treatment choices, work effect or treatment effectiveness and treatment cost.

4.1.1. Selection of deterioration criteria

Two distress criteria considered are structural condition quantified in terms of rebound deflection and functional condition quantified in terms of roughness.

4.1.2. Historic deterioration data

It is important to quantify the performance of the pavement in terms of distress. The distress propagation could be identified from the past data from the field tests. Roughness test is conducted by Fifth Wheel Bump Integrator (FWBI) test and rebound deflection is evaluated from Benkelman Beam Deflection test. These tests are to be performed on the pavements periodically to assess the condition of pavements over time with different traffic level. The deterioration models are considered from available earlier research work carried out in India [35,36,37]. The deflection and roughness growth depend explicitly on parameters viz., initial roughness, initial deflection, traffic level (msa) and age. The deflection and the roughness data are derived for different traffic levels ranging from 10 to 100 msa considering the rate of traffic growth as 5 % per year from the models below. The deflection level varies from 0.25 mm (minimum value) to 2.5 mm (maximum value).

4.1.3. Deflection progression model [35]

$$For\ iDef \le 0.66\,mm:$$
$$D_t = iDef + 0.07884\,(N_t \times age)^{iDef} \quad (24)$$
$$For\ \ 0.66\,mm < iDef \le 0.84\,mm:$$
$$D_t = iDef + 0.0027\,exp[(iDef \times N_t)^{iDef}] + 0.0859(age) \quad (25)$$
$$For\ \ 0.84\,mm < iDef \le 1.10mm:$$
$$D_t = iDef + 0.04513\,[exp(N_t)]^{0.45} + 0.0924[exp(age)]^{\log(iDef)} \quad (26)$$
$$For\ iDef > 1.10\,mm:$$
$$D_t = iDef + 0.03658\,[exp(iDef \times N_t)]^{0.5} + 0.19864(age)^{0.26} \quad (27)$$

where $iDef$ = initial deflection (mm),
D_t = Deflection (mm) at time t,
N_t = Cumulated standard axles (msa) at time t, and
age = Age of pavement at t years.

4.1.4. Roughness progression model [36]

$$UI_t = UI_0 + 9.09(csa)^{idef} + 15.575(age)^{2.244} \quad (28)$$

where UI_t = Roughness Index (mm / km) at time t,
UI_0 = Initial Roughness Index (mm/km),
csa = Cumulated standard axles (million), and
$iDef$ = Initial deflection (mm).

4.1.5. Identification of treatment choices

Five treatment choices are considered viz., (1) Do-nothing with routine maintenance, (2) Thin overlay - 25mm Hot Mix Asphalt (HMA), (3) Thick overlay (75mm HMA), (4) Major Rehabilitation (150mm HMA), and (5) Reconstruction.

4.1.6. Treatment effectiveness

The deflection effectiveness for treatment choices are taken from [38]. The deflection effectiveness for thin overlay is considered to be zero and for reconstruction, the deflection is assumed to have minimum value of 0.25 mm. The maximum deflection is considered as 2.5 mm, based on the field performance data and the pavement has deemed to be reached its terminal stage.

Similarly, roughness effectiveness (m/km) is taken from [39], as below:

For Thin overlay:
$$1.057\times \ln(InitialRoughness) + 0.116 \text{ m/km} \quad (29)$$
For Thick overlay:
$$1.843\times \ln(InitialRoughness) - 0.144 \text{ m/km} \quad (30)$$
For Rehabilitation:
$$1.087\times \ln(InitialRoughness) + 0.318 \text{ m/km} \quad (31)$$
For Reconstruction:
Roughness reaches minimum value (2.0 m/km) (32)

The minimum roughness of pavement is taken as 2.0 m/km and maximum roughness is considered as 5.2 m/km. It is assumed that when the roughness of the pavement reached 5.2 m/km the pavement section has reached the terminal stage.

4.1.7. Treatment cost

Unit cost of each treatment is obtained from Highways Department of the Government of Tamil Nadu. The unit cost is worked out for two lane roads. This is used for calculation of treatment cost for each roads having different length for all five treatment choices (Table 2).

4.2. Description of data

The data required for the formulation is described in two segments namely, distress progression and treatment effectiveness. The format for the distress progression data for a hypothetical road *n* is shown in Table 3 for the purpose of illustration. This forms the first segment of problem to incorporate the distress progression over year. For different values of deflection ($D^b_{t,n}$ in columns) and roughness ($R^b_{t,n}$ in rows), the deflection($D^e_{t,n}$) and roughness($R^e_{t,n}$) progression are marked for each year after construction. Deflection and roughness progression are marked to values rounded to nearest

Table 2
Unit cost of treatment.

Treatment choice (a)	Treatment	Unit cost in Rupees (million /km/two lane)			
		Road 1	Road 2	Road 3	Road 4
1	Do-nothing viz., Routine maintenance	1.0	0.9	0.6	0.6
2	Thin Overlay	6.0	5.0	4.0	4.0
3	Thick Overlay	9.0	8.0	7.5	7.5
4	Rehabilitation	15.0	14.0	13.0	13.0
5	Reconstruction	18.0	16.0	15.0	15.0

1 US $ = Rs.65 (approx.)

Table 3
Deflection and roughness progression over time.

Age ⟶	$(\tau = 1)$				$(\tau = 2)$						$(\tau = 3)$							
$D^b_{t,n}$ ⟶	25		35		25		35		45		25		35		45		55	
$R^b_{t,n}$ ↓	$D^e_{t,n}$	$R^e_{t,n}$	$D^e_{t,n}$	$R^e_{t,n}$	$D^e_{t,n}$	$R^e_{t,n}$	$D^e_{t,n}$	$R^e_{t,n}$	$D^e_{t,n}$	$R^e_{t,n}$	$D^e_{t,n}$	$R^e_{t,n}$	$D^e_{t,n}$	$R^e_{t,n}$	$D^e_{t,n}$	$R^e_{t,n}$	$D^e_{t,n}$	$R^e_{t,n}$
2.00	**35**	**2.20**	45	2.20														
2.20	35	2.40	45	2.40			**45**	**2.40**	55	2.40								
2.40	35	2.60	45	2.60			45	2.60	55	2.60							**55**	**2.60**
2.60	35	2.80	45	2.80			45	2.80	55	2.80							55	2.80
2.80	35	3.00	45	3.00			45	2.80	55	3.00							55	3.00

deflection and roughness levels. Set of such data is prepared for every incremental time (one year). Deflection values are represented in 1/100 values and therefore 0.25 mm, 0.35 mm, 0.45 mm, 0.55 mm are represented as 25, 35, 45, 55 and so on, as integer values. In this case deflection levels (*I*) are 4, similarly roughness levels (*J*) are 5 viz., 2.00, 2.20, 2.40, 2.60 and 2.80 m/km.

If the beginning deflection and roughness values are 25 (0.25mm) and 2.00 m/km, deflection and roughness values at the end of year (τ =1 year after construction) is 35 (0.35mm) and 2.20 m/km. For next year ($\tau = 2$ year after construction) the progression is read against 35 (0.35mm) in column and 2.20 m/km in row. The values are 45 (0.45mm) and 2.40 m/km two years after construction. For subsequent year ($\tau = 3$ year after construction) this will be 55 (0.55mm) and 2.60 m/km. The same procedure will be repeated for the design period. The data required for each road are planning horizon period and the age of the road at beginning of planning period. As the age increases, the right bottom fields will contain values, indicating the deterioration process and other field are empty indicating the condition of pavement that will not be reached.

The second segment of the problem is to incorporate the effectiveness of the different treatments on distress reductions. Total number of treatment choice A is 5. Table 4 shows typical deflection and roughness values after the treatment as well as their corresponding values before the treatment. For example, if a road has beginning deflection value of 25 (0.25mm) and roughness value of 2.00 m/km (previous example), at the end of 3 year, the end deflection and end roughness will be 55 (0.55mm) and 2.60m/km under a do-nothing scenario. If a treatment choice 3 (thick overlay) is proposed, the deflection and roughness values after the treatment are 35 (0.35mm) and 2.20 m/km. The treatments are proposed at (after) the end of each year and hence, deflection and roughness values after the treatment are considered as beginning deflection and roughness for next year ($D^b_{t+1,n}$ and $R^b_{t+1,n}$).

Cost of treatment of level *a* for road *n*, ($C'_{a,n}$) are calculated from the unit cost of treatment (Table 2) and road lane length (Table 1).

Another interesting element of the problem is to consider the pavement as to perform like a newly constructed pavement, when a maintenance treatment is carried out other than do-nothing (treatment choice *a*=1). If do-nothing treatment is performed (only routine maintenance action is done), the deflection and roughness values after the treatment are not expected to improve. In this case, age is increased by one. Some authors will consider, the pavement can be treated as new only on application of corrective maintenance treatment. In such case, in constraint 15 to 18, the decision variable $\Delta_{i,j,1,t,n}$ shall be replaced as $\Delta_{i,j,1,t,n} + \Delta_{i,j,2,t,n}$, which is self explanaory. This concept of tracking the age (number of years after previous intervention) is incorporated by a variable $Max_{t,n}$. It is implicit that $Max_{1,n}$ is the age of pavement n known at the beginning of planning horizon and hence this will be given as input like beginning deflection and beginning roughness.

At beginning of planning period, let $Max_{1,n} = 1$ be the input. At the end of the year, no maintenance action (only do nothing) is done and hence $a = 1$. For the next year, $Max_{2,n}$ will be (From constraints (17) and (18)) $Max_{1,n} + 1 = 2$. If no maintenance is carried out in the following year, $Max_{3,n} = Max_{2,n} + 1 = 3$. On the other hand, if any maintenance treatments (other than do-nothing) is performed $ie.a \neq 1$, (From constraints (15) and (16)), $Max_{3,n}$will be 1.

4.3. Optimization

For the given problem, four year planning horizon period is considered. A typical network of four roads with different traffic levels having different roughness and deflection progression are considered. The age at the beginning of planning period for each road is kept as one year. In the models, the deflection values are approximated to nearest 0.05 mm and roughness values are approximated to nearest 0.08 m/km. It is ensured that the threshold values of deflection and roughness values are not exceeded in any year during the analysis period. The budgetary constraints are duly considered. For this purpose a typical budget provision of Rs. 450 million allotted for the whole planning period.

The problem is formulated as a Integer Linear Programming and solved using the CPLEX Solver. The problem is formulated as multi-objective problem and solved by ε - constraint method. A set of non-dominated solutions (Pareto solutions) are generated by the algorithm specified section 3.5. The Pareto solutions (Fig. 3) provide a trade-off between the two objectives, viz., average network deflection values and average network roughness values.

5. Results and discussion

In this study, budget bound model with objectives to minimize average network deflection and average network roughness is implemented. A budget of Rupees 450 million is considered for the planning period of 4 years. To obtain the bounds of non-dominated solutions, the extreme ordinates are determined as single objective problem. This is done by minimizing roughnessalone (R^*) and corresponding deflection is obtained (Solution 1 of Table 5). Similarly minimize deflection (D^*) alone and corresponding roughness is obtained (Solution 4 of Table 5). For the intermediate ordinates (non-dominated solutions 2 and 3), with the objective function to minimize the deflection, the roughness constraint is added with $\varepsilon_r = 0.05$ m/km for each iterations in the algorithm stated in section 3.5.

Table 4
Deflection and roughness before and after treatment.

Treatment level	a=3							
$D^e_{t,n}$ →	25		35		45		55	
$R^b_{t,n}$ ↓	$D^b_{t+1,n}$	$R^b_{t+1,n}$	$D^b_{t+1,n}$	$R^b_{t+1,n}$	$D^b_{t+1,n}$	$R^b_{t+1,n}$	$D^b_{t+1,n}$	$R^b_{t+1,n}$
2.00	25	2.00	25	2.00	25	2.00	25	2.00
2.20	25	2.00	25	2.00	25	2.00	25	2.00
2.40	25	2.00	25	2.00	25	2.00	25	2.00
2.60	25	2.00	25	2.00	25	2.00	35	2.20
2.80	25	2.00	25	2.00	25	2.20	35	2.20

Table 5
Ordinates for non-dominated solutions.

Non-dominated solution	*Roughness (m/km)	*Deflection (mm)	Maintenance Cost (Rupees in million)
1	2.035	0.397	436.4
2	2.050	0.377	420.4
3	2.100	0.355	430.8
4	2.130	0.351	448.4

(* The Roughness and Deflection are the average network roughness and average network deflection during four year analysis period respectively.

Table 6
Optimal Maintenance Strategies.

Solution	Solution 1				Solution 2				Solution 3				Solution 4			
Time (years)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Road 1	1	2	2	1	1	3	1	1	1	3	1	1	3	3	3	1
Road 2	1	2	1	1	1	1	2	1	1	3	1	1	1	3	1	1
Road 3	1	2	1	1	1	1	2	1	1	1	1	1	1	1	1	1
Road 4	1	2	1	1	1	1	2	1	1	3	1	1	1	1	1	1

(For solutions 1 to 4, the values in the table shown against roads and the time, are treatment choice *a,* where, 1: do- nothing 2: thin overlay 3: thick overlay 4: rehabilitation 5: reconstruction, in the present analysis, the maximum treatment choice is only 3).

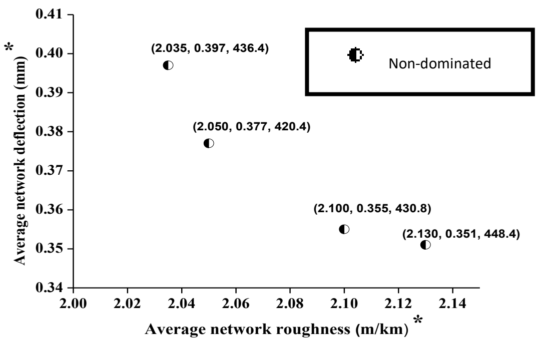

Fig. 3. Pareto curve.

(* The average network deflection is average deflection for all the four roads during four year analysis period and average network roughness is average roughness for all four roads for four year analysis period. The values shown in the parenthesis are average network roughness (m/km), average network deflection (mm) and total treatment cost (million rupees). Origin of the plot is kept as 0.34 mm and 2.00 m/km).

Table 5 shows the ordinates of non-dominated solutions and Fig. 3 shows the Pareto curve for a budget of Rupees 450 million. It may be observed that the maintenance cost for each solution (maintenance strategies) is less than the budget bound of Rupees 450 million.

Table 6 shows the optimum maintenance strategies (treatment scheduling for all four roads over the planning period of 4 years) corresponding to Pareto optimal solutions. The numbers indicated (1 through 3) in Table 6 are treatment choice. It may be noted that the treatment choice 4 and 5 do not find place in the solution set. It means that the pavements can be maintained within the desired distress level with three treatment choices viz., 1, 2 and 3 and the roads do not warrant higher level treatments like rehabilitation (Treatment choice 4) or reconstruction (Treatment choice 5) within 4 years, as the pavements are structurally adequate during the analysis period.

Fig. 4 shows the maintenance cost distribution for solution 3 over the planning period of 4 years having minimum average network

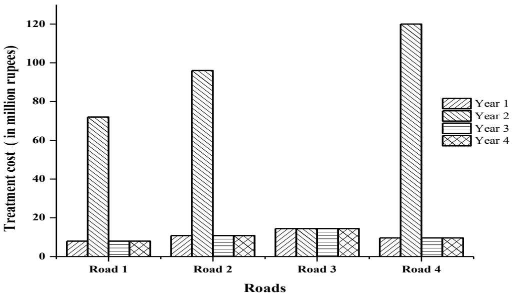

Fig. 4. Maintenance cost distribution (Solution 3).

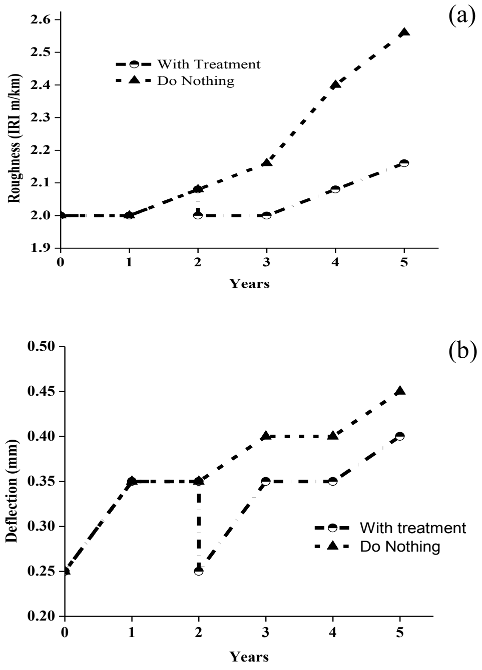

Fig. 5. Performance curve for (a) roughness and (b) deflection (For road 2 - Solution 3).

deflection of 0.354 mm and minimum average network roughness of 2.1 m/km. Fig. 5 shows the performance curve for roughness and deflection for road 2 with treatments as per solution 3 and do-nothing condition.

5.1. Conclusions

1. A framework for selection of projects and scheduling of optimal maintenance strategies for a network of roads is formulated under budgetary constraints scenario.
2. The optimization procedure is formulated using Integer Linear programming (ILP) method. A novel tracking procedure is formulated to track the age of the pavement as the age is reset to 1 on application of treatment. This captures the behaviour of the pavement that behaves as a new pavement whenever a treatment action is performed. In some cases, the pavement deemed to behave as new only after corrective/rehabilitation treatment action. Any such cases can be precisely incorporated into existing formulation.
3. Multi-objective optimization is implemented considering two performance criteria, namely roughness and deflection values. For generating non-dominated solutions, $\varepsilon -$constraint method is implemented.
4. Budget bound formulation is adopted for a typical road network comprising new roads in fairly good condition with different traffic levels and the solution reveals that higher level treatments are not warranted in the initial 5 years of service life.

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