Development of network-level linear programming optimization for pavement maintenance programming

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Abstract

Infrastructure systems in the US are in an urgent need of maintenance and rehabilitation. According to the most recent factsheet published by the American Society of Civil Engineers, one of the top five infrastructure concerns of today in the US is transportation systems. The major challenge facing maintenance managers in state Departments of Transportation (DOTs) today is to preserve the road networks at an acceptable level of serviceability subject to the stringent yearly maintenance and rehabilitation (M&R) budgets. Maintenance managers must allocate such limited budgets among competing alternatives. Absence of decision-making tools exacerbates the matter. This paper presents the development and implementation of a network-level pavement maintenance optimization model, which is established with the application of the Linear Programming algorithm and is subject to budget constraints and the agencies’ pavement performance goals in terms of total lane-miles in each pavement condition state. A decision-making tool is developed using Frontline Systems’ Premium Solver add-in for Microsoft Office Excel. This decision-making tool can compute the optimal amount of investment for each pavement treatment type in a given funding period. Pavement condition data pertaining to the Salem District within the Virginia Department of Transportation (VDOT) is used to test the model presented herein. Within this context, nine treatment types along with their corresponding unit prices ($/Lane-Mile), five pavement condition states, pavement deterioration rates, VDOT’s pavement performance goals, and available annual maintenance budget for the next fifteen years are defined. The results show that the network-level optimization model developed herein yields more efficient pavement maintenance programming than that obtained from the manual budget allocation process.

Keywords: highway, maintenance and rehabilitation, optimization, pavement management systems

1 Introduction

Highway agencies in the United States have utilized their resources for the construction of new paved road networks for 40 years starting from the 1950s until the late 1980s. Decision-makers in highway agencies viewed M&R costs as “sunk costs” in that there was no mechanism that held them accountable for preserving infrastructures already in place (Dornan, 2002). Disregarding the paramount importance of maintaining existing infrastructure systems in a timely manner and omitting the long term consequences of deferred maintenance resulted in increasing needs for renewal and replacement of highway infrastructure assets (Dornan, 2002).
A report to the Federal Highway Administration (FHWA) dated 1996 shows that investment in new highway construction projects has declined since 1989, while rehabilitation work and preventive maintenance projects started to have added priority in fiscal programs of highway agencies (Hicks et al., 1997). Consequently, the major challenge facing State DOT managers today is to preserve state road networks at an acceptable level of serviceability under the stringent yearly M&R budgets. Managers must allocate such limited budgets among competing alternatives which makes the situation even more challenging. Absence of decision-making tools and accurate data exacerbates the matter. Thus, it is essential to establish effective maintenance programs to preserve aging infrastructure systems already in place in the USA.

The objective of this paper is to address this need by developing a decision-making tool which is capable of performing network-level optimization for the pavement maintenance programming problem through the application of the Linear Programming (LP) methodology. The decision-making tool presented herein aids highway maintenance managers in developing alternative network-level pavement maintenance strategies through an automated process. Subsequently, decision-makers are able to compare the impact of each strategy and identify a strategy such that the most effective use of scarce resources will materialize.

2 Prior research in network-level optimization

Previously proposed optimization approaches have, in particular, two essential elements, namely optimization algorithms and pavement performance prediction models. Such elements could vary remarkably depending on the researchers’ approach to the problem.

Developing a reliable pavement performance prediction model is as essential as the algorithm used in the optimization model (Li et al., 1997). Rohde et al. emphasize the essence of predicting the pavement deterioration accurately by stating that it is important to use reliable performance prediction models to see the long-term consequences of various maintenance strategies (Rohde et al., 1997). Investigation of mathematical models in order to predict the future pavement performance is still getting a lot of attention from researchers. Particularly, the Markov prediction model seems to be the most frequently used approach in predicting future pavement condition due to its ability to integrate rehabilitation and pavement deterioration rates in a single transition probability matrix (Abaza and Ashur, 1999, Chen et al., 1996, Liu and Wang, 1996).

Turnquist and Mbwana described a network-level pavement management system using a large-scale LP algorithm, converted from dynamic programming formulation, in order to achieve network-level optimization (Mbwana and Turnquist, 1996). Another approach used in modeling the network-level optimization problem is goal-programming. Raviarala et al. favored this approach due to its strength in considering problems encompassing conflicting objectives with different degrees of importance (Raviarala et al., 1997).

The genetic algorithm has been of great interest to researchers striving to improve the current available optimization models used for network-level M&R programming. Tack and Chou recently showed that a genetic-based optimization algorithm proved beneficial in determining multiyear maintenance programs (Tack and Chou, 2002). Cheu et al. asserts that genetic algorithms are suitable for problems with a substantial number of variables and constraints, since coding objective functions in a genetic algorithm is efficient and flexible (Cheu et al., 2004).

3 Specific objectives

The research presented in this paper builds upon prior research (de la Garza and Krueger, 2007). In their research, highway maintenance managers, through what-if analysis, allocate the available budget manually and then observe how this new budget allocation strategy influences the overall network
Thus, there was an opportunity to improve on this research by developing a model which is capable of performing such budget allocation processes *optimally*. Therefore, this research effort strived towards developing a decision-making tool to perform network-level optimization for the pavement maintenance programming problem through application of the LP methodology. The outcome of the research presented herein aids highway maintenance managers in developing optimal alternative network-level pavement maintenance strategies through an automated and optimized process.

4 Methodology

The methodology that the authors use within this research consists of the following components.

4.1 Component 1 evaluation of road network

Data pertaining to the pavement condition of the Interstate road network (I-81 and I-581) in the Salem District has been collected by VDOT regularly for the last 8 years and is analyzed within this research. This database is analyzed with a focus on pavement condition ratings. The baseline number of lane-miles in each of the five condition states is computed based on the Combined Condition Index (CCI) values.

4.2 Component 2 identification VDOT’s performance targets

Pavement performance targets set by VDOT are the essential component of the proposed research, since such performance targets are introduced as either constraints or objectives in the optimization model.

4.3 Component 3 Identification of Maintenance Treatments

Figure 1 shows the 5 condition states and the 9 renewal activities which restore the condition of lane-miles from a downstream condition (worse) to an upstream condition (better). Expected performance targets for each condition state can be achieved through balancing upward and downward flows of lane miles, i.e., by determining how much money to invest in each maintenance treatment type (de la Garza and Krueger, 2007).

Figure 1. Pavement condition states & highway maintenance activities (de la Garza and Krueger, 2007)
4.4 Component 4 identification of pavement deterioration model

Reliable pavement deterioration prediction models are beneficial for pavement management systems in that highway agencies can predict the optimal time for applying maintenance and rehabilitation treatments and determine the required long-term financial requirements (Sadek et al., 1996). Pavement deterioration rates used in this research effort are adopted from the former research conducted by de la Garza and Krueger (de la Garza and Krueger, 2007). The pavement deterioration rates, which were computed deterministically based on historical data, are fixed for each pavement condition state. Liu et al. favor this assumption by stating that it is reasonable to assume fixed yearly deterioration rates since values of many parameters used in nonlinear deterioration models are not readily available, hence nonlinear deterioration models are not practical in real problems (Liu et al., 1997). The network-level optimization model developed herein assumes that pavement deterioration materializes in increments of one condition state per year, that is, deterioration from an upstream condition to the next downstream condition only, e.g., pavement in good condition can deteriorate only to fair condition each period.

4.5 Component 5 development of network-level LP optimization model

An objective function and a set of constraints in the form of a system of equations or inequalities form mathematical optimization models. Optimization models facilitate the decision making process and therefore are used very often in almost all areas of engineering (Arsham, 2007). This section of the paper presents an overview of a network-level optimization model developed through the LP approach. The sets, parameters, decision variables, constraints and objective functions are defined in the following sections.

4.5.1 Definition of Sets

P: a Set of Funding Periods (1, 2, 3, 4, ………, i, ………, 15)
S: a Set of Pavement Condition States (Very Poor, Poor, Fair, Good, Excellent)
R: a Set of Treatments (Reconstruction, Rehabilitation1, Rehabilitation2, Thick Overlay2, Thick Overlay3, Thin Overlay3, Thin Overlay4, Ordinary Maintenance3, Ordinary Maintenance4)

4.5.2 Definition of Parameters

B_i: Highway Maintenance Budget available within period i, \( \forall i \in P \)
U_{ij}: Unit (Per lane-mile) cost of treatment j within period i, \( \forall i \in P \) and \( \forall j \in R \)
N_{ki0}: Number of lane-miles in condition k at the beginning of year 1 (Baseline condition), \( \forall i \in P \) and \( \forall k \in S \)
G_{ki}: Required number of lane-miles (Target specified by VDOT) in condition k at the end of period i, \( \forall i \in P \) and \( \forall k \in S \)
D_{(k+1)k}: Deterioration Rate from condition state \((k+1)\) to condition state \(k\), \( \forall k \in S \)

4.5.3 Definition of Decision Variables

X_{ij}: Amount of money spent on treatment j within period i, \( \forall i \in P \) and \( \forall j \in R \)
N_{ki}: Number of lane-miles in condition k at the end of period i, \( \forall i \in P \) and \( \forall k \in S \)

4.5.4 Statement of the Objective Function

The objective function stated below is a generic objective function. The terms \(w_1, w_2, w_3, w_4\) and \(w_5\) represent possible weighting coefficients pertaining to each condition state.

Minimize \[ \sum_{i \in P} \left( \left( w_1 \cdot N_{i1} \right) \pm \left( w_2 \cdot N_{i2} \right) \pm \left( w_3 \cdot N_{i3} \right) \pm \left( w_4 \cdot N_{i4} \right) \pm \left( w_5 \cdot N_{i5} \right) \right) \] (1)
5 Problem statement

The problem statement given below is included in this paper for demonstrating the results of the models developed during this research effort. Additional optimization scenarios may be found in (Akyildiz, 2008).

How should VDOT allocate its annual highway maintenance budget for different renewal activities such that number of lane-miles in very poor, poor, and fair condition will be minimized while excess budget will be used towards maximizing the number of lane-miles in excellent condition?

5.1 Objective Function

Minimize \[ \sum_{i \in P} \left( (N_{1i} + N_{2i} + N_{3i}) - (N_{4i} + 5 \cdot N_{5i}) \right) \] (2)

5.2 Subject to:

Constraint 1

\[ G_{ki} - N_{ki} \geq 0, \forall i \in P, \forall k \in S_1, k=1, 2, 3, i=3, 4, 5 \ldots 15 \]

This constraint represents the performance targets being greater than or equal to the number of lane-miles in very poor, poor and fair condition.

Constraint 2

\[ \sum_{j=1}^{9} X_{ij} \leq B_i, \forall i \in P, i=1, 2, 3 \ldots, 15 \]

This constraint represents the annual highway maintenance budget constraint. Money spent on 9 different renewal activities (treatments) within the period \( i \) must be less than or equal to the budget available for period \( i \), which is \( B_i \).

Constraint 3

\[ N_{5i} = N_{5(i-1)} \cdot \frac{N_{5(i-1)} - X_{ii}}{D_{54} + \frac{X_{i1}}{U_{i1}} + \frac{X_{i2}}{U_{i2}} + \frac{X_{i3}}{U_{i3}} + \frac{X_{i4}}{U_{i4}}} \geq 0, \forall i \in P, i=1, 2, 3 \ldots, 15 \]

This constraint represents the requirement that the number of lane-miles in excellent condition at the end of period \( i \) have to be equal to the sum of the following components:

The number of lane-miles in excellent condition at the end of period \((i-1)\) or beginning of the period \( i \); minus the number of lane-miles in excellent condition deteriorating to good condition; plus the number of lane miles restored through Reconstruction, Rehabilitation2, Thick Overlay3, Thin Overlay4 respectively.

Constraints 4 through 7 are developed in a similar manner for the other four condition states.

Constraint 8

\[ N_{ki} \geq 0, \forall i \in P, \forall k \in S \]

\[ X_{ij} \geq 0, \forall i \in P, \forall j \in R \]

These inequalities denote the non-negativity constraints.
6 Results

6.1 Budget allocation

Table 1. Budget allocation that materializes based on the model

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Recon</th>
<th>Rehab 2</th>
<th>Thick Overlay 3</th>
<th>Thin Overlay 3</th>
<th>Thick Overlay 2</th>
<th>Rehabilitation 1</th>
<th>Thick Overlay 2</th>
<th>Rehabilitation 1</th>
<th>Thick Overlay 3</th>
<th>Ordinary Maintenance 3</th>
<th>Ordinary Maintenance 4</th>
<th>Total Budget Spent</th>
<th>Available Budget</th>
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<td>$6,075,216</td>
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Total Budget $113,996,861 $130,500,000

6.2 Pavement condition trend analysis

Table 2. Number of lane-miles in each condition state

<table>
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<tr>
<th>Condition State</th>
<th>Baseline</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
<th>Year 6</th>
<th>Year 7</th>
<th>Year 8</th>
<th>Year 9</th>
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<th>Year 11</th>
<th>Year 12</th>
<th>Year 13</th>
<th>Year 14</th>
<th>Year 15</th>
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<tr>
<td>Target Very Poor Condition</td>
<td>25.0</td>
<td>43.7</td>
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<td>25.0</td>
<td>25.0</td>
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<td>25.0</td>
<td>24.0</td>
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<tr>
<td>Target Poor Condition</td>
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<td>106.3</td>
<td>47.4</td>
<td>50.0</td>
<td>50.0</td>
<td>50.0</td>
<td>23.0</td>
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<td>Target Fair Condition</td>
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<td>43.4</td>
<td>76.6</td>
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<td>37.5</td>
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<tr>
<td>Target Excellent Condition</td>
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<td>75.3</td>
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</tbody>
</table>

7 Observations

The goal of the objective function defined in the problem is to minimize the lane-miles in very poor, poor and fair condition while excess budget will be used towards maximizing the number of lane-miles in excellent condition. Table 1 and Table 2 show the budget allocation pattern and the level of service pertaining to each year respectively, which resulted from the parameters, pavement performance constraints and the objective function used in the model. The results show that the available pavement maintenance budget for the first 3 years should be spent on renewal activities which restore lane-miles in very poor and fair condition to good and excellent condition. Thus, the model allocates the whole budget into Thick Overlay 3 in the first year of the analysis, while available pavement maintenance budget is split between Thick Overlay 3, Rehabilitation 1 and Thick Overlay 2 renewal activities for the following 3 years. Moreover, Rehabilitation 1 consumes the available money in year 3 in an effort to bring number of lane-miles in very poor condition down to an acceptable level. Hence, the model first focuses on bringing the lane-miles in very poor, poor and fair condition to good and excellent condition in order to meet the pavement performance targets set by Virginia Department of Transportation Thus, the budget allocation pattern that materializes in the first three years clearly shows that the model works as expected resulting in a feasible and optimal solution.

It should be noted that the available budget in first 9 periods was fully expended in the model. Hence, the model restores all the lane-miles to excellent condition in 10 years as the objective function pertaining to the model strives towards minimizing the number of lane-miles in very poor, poor and fair condition, and then excess budget is invested in order to maximize the number of lane-
miles in excellent condition. One interesting observation is that the model cannot fully spend the available budget after year 9 in that all the lane-miles in the road network is in excellent condition after year 9, resulting in unspent money. Results shown in this paper indicate that incorporating a decision-making tool is beneficial in determining a pavement maintenance program. Thus, it has been found that results obtained based on manual budget allocation are inferior to what is presented in this paper. The network-level optimization problem developed herein searched for the optimal pavement maintenance program considering 15 years of analysis, whereas in a manual budget allocation process, the decision-maker arbitrarily allocates money into renewal activities in the first year, and then reiterates the same process for the following 14 years.

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References


