Network-level optimization of pavement maintenance renewal strategies

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Abstract

Infrastructure systems in the US are in 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 USA is the transportation system. 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 simpler decision-making tools exacerbates the matter. This paper presents the development and implementation of a simpler, yet useful, network-level pavement maintenance optimization model, which is a Linear Program (LP) 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’ Risk Solver Platform 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 one of the Districts within a state DOT 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, network-level pavement performance targets, and available annual maintenance budget for a 15-year planning horizon are defined. The results presented show how an annual highway maintenance budget needs to be allocated or determined to achieve the District’s value proposition for various scenarios. Comparing the results of these varying scenarios provides insight on long-term strategies and the impact of target constraints on budget expenditures.

1. Introduction

Infrastructure systems are critical to sustaining and improving economic growth. Poor condition of infrastructure systems results in lost productivity and reduces the quality of life. Today’s global economy forces governments to sustain and renew infrastructure systems in order to remain competitive and productive [1]. Therefore, civil engineers and policymakers have been quite interested in the overall quality of the highways and bridges throughout the US [2]. Transportation networks are essential parts of the Nation’s infrastructure systems. Deterioration due to age and use is the main threat to the level of service observed in surface transportation networks. Thus, highway agencies throughout the United States strive to maintain, repair and renew transportation systems already in place [2]. The future prosperity of the USA and growth in the US economy highly depend on the nation’s highways, railways, transit systems, airports and ports [3].

Highway agencies in the United States have utilized their resources for the construction of new paved road networks for 40 years starting from 1950s until the late 1980s. Reign of this strategy mainly stemmed from the Traditional Federal Highway Program in that highway agencies could invest the monies provided by the Federal Highway Trust Fund only in the construction of new transportation systems. 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 [4]. Hence, highway agencies wanting to benefit from the Federal Highway Trust Fund used their available resources for new capital projects. 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 [4].

A report to 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 the priority in fiscal programs of highway agencies [5]. According to the same report, the amount of funding necessary...
to preserve the existing level of pavement serviceability was $50 billion while the amount spent was only $25 billion as of 1996. To aggravate the matter, this ever-lasting gap between re-
quired funding to maintain the existing infrastructure systems in
the US and available funding has been widening day by day. The
Infrastructure Report Card released by ASCE in 2009 points out this
widening gap. The aforementioned report dated 2009 shows that
available funding for highway improvement programs was
$70.3 billion, while required funding to improve the transportation
infrastructure condition nationally was $186 billion [3]. Finally, the
gap between required transportation surface program investment
and the available fund for maintenance and repairs through 2010
is $1.6 trillion [2]. These statistics clearly suggest that Federal
Highway Funding will continue to be insufficient to maintain and
rehabilitate highway infrastructures already in place.

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 maintenance and rehabil-
itation (M&R) budgets. Managers must allocate such limited bud-
gets among competing alternatives, which makes the situation
even more challenging. The Infrastructure 2007 report published
by The Urban Land Institute and Ernst and Young states that “the
programs in some areas do not employ the best tools and ap-
proaches to ensure effective and efficient investment decisions”
[2].

In short, infrastructure systems in the US are in urgent need of
maintenance and rehabilitation and therefore must be treated
immediately. Thus, infrastructure maintenance policies need to
be established and considered as a priority in spite of never ending
budget gaps. Therefore, it is essential to establish effective mainte-
nance programs to preserve aging infrastructure systems already
in place in the US. This paper proposes a simpler, but useful, net-
work-level optimization model through which State DOTs will be
able to select the best maintenance program for the road network,
that is, what proportion of available budget to spend on which
treatment type in each time period so that the network-level main-
tenance program will yield the most effective use of resources and
achieve the best pavement performance throughout the road net-
work. The proposed model will use a network-level optimization
subject to annual M&R budget constraints and net-
work-level performance targets.

2. Prior research in network-level optimization

Infrastructure systems deteriorate due to external effects such as
usage, climate and aging. This deterioration unfortunately cannot
be eliminated. However, maintenance strategies and their time
of application affect the long-term condition and performance of a
road network.

Various approaches for network-level optimization of mainte-
nance and rehabilitation programming have been proposed in re-
cent years. Common components of these approaches are as fol-
loows:

- Identification of network information system.
- Evaluation of current needs.
- Definition of treatment strategies.
- Prediction of future condition of assets.
- Development of an optimization algorithm.
- Selection of appropriate treatments.

Previously proposed optimization approaches have, in particular,
two essential elements, namely optimization algorithms and pave-
ment performance prediction models. Such elements vary remark-
ably depending on researchers’ approach to the problem.

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 pave-
mament condition due to its ability to integrate rehabilitation and
pavement deterioration rates in a single transition probability ma-
trix [6,7]. Abaza and Ashur [6] applied a Markov model to predict
future pavement performance and developed a nonlinear optimiza-
tion method to establish optimum pavement condition throughout
the network subject to budget constraints. The Markov model used
by Abaza and Ashur consisted of three main components.

- Five condition states, namely a, b, c, d and f, representing excel-
    lent, good, fair, poor and bad condition, respectively.
- Deterioration transition probabilities, $P_{\text{d}}$, representing pave-
    ment deterioration rate. $P_{\text{r}}$ represents the probabilities that a
    pavement section will deteriorate from state $i$ to state $j$ in a sin-
    gle time interval.
- Maintenance transition probabilities, $P_{\text{m}}$, representing the prob-
    abilities that a pavement section will improve from state $i$ to
    state $j$ in a single interval as a result of maintenance actions
    applied in a given interval.

The main objective of the research done by Abaza and Ashur [6] was
to determine the optimum future maintenance and rehabilitation
program to be implemented. The model proposed was able to pro-
vide decision makers with the amount of investment required for
each maintenance and rehabilitation treatment strategy in order
to achieve the most effective M&R program.

Mbwan and Turnquist [8] described a network-level pavement
management system using a large scale linear programming
algorithm, which was converted from a dynamic programming
formulation, in order to achieve network-level optimization [8].
Markov Transition Probabilities, as used in previous research in
this field such as those by Chen et al. [9], Liu and Wang [10] and
Abaza and Ashur [6], were employed in the model in order to pre-
dict future pavement condition. However, Mbwan and Turnquist's
formulation of the Markov decision process model assigned a spe-
cific identity to each individual section defined in the network.
Thus, maintaining identities related to each individual section is
unique for the problem of network-level optimization. Hence, this
approach aids in transition from network-level planning to project-
level actions, since section-specific pavement conditions are avail-
able [8]. The model developed was applied to a highway network
in Nassau County, New York; solutions produced were observed
and were compared with the practices followed in New York State.
However, Wang et al. [11] do not favor this approach due to its
complex and disputable assumptions.

Another approach used in modeling network-level optimization
problems is goal programming. Ravirala et al. [12] favored this ap-
proach due to its strength in considering problems encompassing
conflicting objectives with different degrees of importance. Prior
works published by Ravirala and Grivas [13] show that goal
programming is beneficial to attain conflicting objectives simulta-
aneously. However, goal programming sustains a few disadvantages
in that it is not easy to integrate Markov Transition Probabilities into
the optimization procedure. Furthermore, integer programming
used in this approach is inapplicable to large scale pavement net-
works due to high computational requirements [12]. Hence, the
model proposed by Ravirala et al. [12] uses linear programming in-
stead of integer programming to develop an optimal multi-year
maintenance schedule. A set of linear functions of the decision
variables is defined in order to create the goal program for the pave-
mament network optimization. However, this model entails up-front
effort in order to assess network condition and controls specifi-
cation. Assessment of network condition involves definition of pave-
ment states, inventory and inspection data, while controls
specification consists of three processes, namely treatment identification, condition-treatment matching and estimation of pavement state transition times.

Developing a reliable pavement performance prediction model is as essential as the algorithm used in the optimization model [14]. Thus, Li et al. [14] stresses the importance of producing a pavement deterioration model which considers the effect of a treatment on the pavement deterioration rate after maintenance actions take place. In contrast, homogenous (time-independent) Markov decision process disregards the effect of applying a treatment to a pavement section and assumes that application of a treatment has no effect on the deterioration rate of pavement, regardless of the treatment applied. This assumption conflicts with what occurs in the field. Therefore, a non-homogenous (Time-related) Markov decision process was introduced by Li et al. [14]. The model developed by Li et al. [14] assumes that application of a maintenance action to a pavement section will result in a new deterioration rate which is computed based on the Ontario Asphalt Deterioration Equation [14]. Furthermore, Li et al. [14] defined the unit cost of each treatment and quantified the effect of each treatment strategy on the pavement in terms of a jump in PCI [14]. Thus, cost-effectiveness based priority programming for a network-level optimization problem was established. This model adopts an integer programming approach in the pursuit of producing the most cost-effective maintenance program for each programming year. The objective of this model is to maximize the total benefit-cost ratio and to make comparisons among different treatments planned for each programming year as to select the best set of maintenance actions, given the available budget and other constraints [14]. This comparison is based on the unit cost of each treatment strategy as well as the particular effect of each treatment on the future pavement performance. The effectiveness of a particular treatment strategy is defined as the product of the area between the predicted performance curve and minimum serviceability level multiplied by the length and traffic volume of the section to which such particular treatment strategy is applied. The comparison made based on the cost effectiveness resulted in prioritization among treatment strategies, thus, producing a maintenance program for each year.

Another example of a network-level optimization model was established in Arizona, Arizona Department of Transportation used a network-level optimization model whose objective was to minimize the annual M&R cost over the planning period. Liu and Wang [10] proposed a new network optimization system where available annual budget for maintenance and rehabilitation was introduced as a constraint. The objective of the proposed model was to maximize the pavement network performance by effectively using the available M&R budget. Liu and Wang [10] used linear programming approach to perform network-level optimization. The objective function of the model proposed is as follows:

$$ Z = \sum_{i} \sum_{k} w_{ik} * f_i $$

where $w_{ik}$ denotes the proportion of roads that are in condition state $i$ at the beginning of the $k$th period of planning horizon $T$ and to which the preserving action $k$ is applied. Here $f_i$ denotes the performance rating for condition state $i$, $f_i$ is used in the model as an utility value to consider the impact of each condition state on overall pavement network performance [10]. The objective function maximizes the total pavement performance over the planning horizon $T$. The outcome of this network-level optimization model was:

- The allocation of the annual budget for different maintenance actions.
- Proportions of the pavements expected to be in each condition state at the beginning of each year.
- Recently, the genetic programming 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 [15] showed that a genetic algorithm based optimization proved beneficial in determining multiyear maintenance programs. The objective of the model was to bring about the highest average pavement condition level throughout the road network. Following the investigation for dynamic programming algorithm along with two different genetic algorithm techniques, namely simple (SGA) and preconstrained genetic algorithm (PCGA), Tack and Chou showed that SGA and PCGA techniques yield near optimal solutions. In addition, the degree of flexibility and scalability inherent in the genetic algorithm technique is of great advantage in that each pavement type may require different pavement deterioration models and repair types [15]. On the other hand, dynamic programming lacks such attributes as flexibility and scalability. Thus, dynamic programming has proved unsuccessful in adjusting to new variables introduced in the model. Therefore, Tack and Chou [15] concluded that dynamic programming was the most difficult to implement in comparison to SGA and PCGA. Furthermore, Cheu et al. [16] supported this argument by asserting that the genetic algorithm is suitable for problems with a substantial number of variables and constraints, since the coding of objective functions in the genetic algorithm is efficient and flexible.

In the USA, the Asset Management office of the Federal Highway Administration (FHWA) has developed tools to support the programming needs of the States and of the Federal government. The Highway Economic Requirement System-State Version (HERS-ST) software is a tool that performs network-level optimization based on the synthesis of engineering knowledge and applied microeconomics [20]. Relationship between parameters, such as traffic volumes, road capacity, pavement deterioration rates, speeds, crashes, travel time, curves and grades, and other highway attributes comprise the engineering aspect, while cost-benefit analysis used in HERS-ST is performed based on microeconomic theory. Engineering relationships are used for determining the benefit, such as travel time savings and operating cost reductions. HERS-ST also incorporates discount rate and life-cycle cost analysis in its analyses [20]. Moreover, the Federal Highway Administration’s (FHWA’s) Office of Legislation and Strategic Planning used The Highway Economic Requirement System (HERS) throughout the last decade as a decision-making tool in order to determine the most effective national highway investment level and strategy [21]. In summary, what we have in the literature is a robust set of linear and non-linear optimization approaches to the Maintenance-Repair-Rehabilitation (M&R) problem. Each of these has built in a comprehensive and stochastic engine to predict the future condition state of the pavement after a maintenance treatment is applied, or not. Like anything else in research, each proposed strategy, including the one proposed in this paper, has its contributions rooted on a set of assumptions and on the availability of specific data, information, and/or knowledge.

The optimization model developed within this paper differs from the ones introduced thus far in that it is very practical and easily reproducible since the number of components pertaining to the model is far less than in the models introduced previously. Hence, it is easy for any decision-maker, regardless of technical background, to study the model and make use of it. Furthermore, the model presented in this paper works with deterioration and renewal values that have been found deterministically, as opposed to the probabilistic approach; hence it does not require any rigorous probabilistic calculations. The overall architecture of the model presented in this paper is closest to that of Liu and Wang [10]. This research adds value to the body of knowledge in that the simpler (but not simple) and practical nature inherent in the model is likely to appeal to decision-makers in highway agencies since it does not
require investing substantial time and resources for doing pavement maintenance what-if analysis.

3. Methodology

The research presented in this paper builds upon prior research [22]. 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 performance. 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, in this research we developed a decision-making tool to perform network-level optimization for the pavement maintenance problem based on the LP framework. The biggest assumption required for this framework is that of linearity, and as we discuss below, the linear assumption is appropriate for this type of strategic analysis. Furthermore, linear programming allows us to examine the problem from many different perspectives, based on modification to the objective function and the feasible region, as we illustrate in this research using the various scenarios. Linear programming also lets the decision-maker easily perform sensitivity analysis for the solutions developed using this tool. Lastly, linear programming has solution algorithms that are tractable (can be solved quite quickly) and guarantee a global optimal solution. The outcome of the research presented herein aids highway maintenance managers in developing optimal alternative network-level pavement maintenance strategies through an automated, simpler, practical, and optimized process.

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

3.1. Component 1 evaluation of road network

Data pertaining to the pavement condition of the Interstate road network from one of the state DOT District’s 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.

3.2. Component 2 identification of performance targets

Pavement performance targets are the essential component of the proposed research, since such performance targets are introduced as constraints in the optimization model. The performance targets for the very poor, poor, and fair condition state at time 0 are equal to the baseline condition and then decrease linearly during the 15-year planning horizon. For example, at time 0, the performance target for very poor lane-miles is 25, whereas the target at time 15 is 10.

3.3. Component 3 identification of maintenance treatments

Fig. 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 [22].

3.4. 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 [23]. The pavement deterioration rates used in this research effort are adopted from the former research conducted by de la Garza and Krueger [22]. 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 [24]. 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. The specific deterioration rates embedded in our model are as follows: from Excellent to Good = 3 years; from Good to Fair = 5 years; from Fair to Poor = 3 years; and from Poor to Very Poor = 4 years. These deterioration rates are part of the input parameters to our model and can be easily changed to determine their effect on results. Innovations in materials, mix designs, additives, as well as in means and methods of maintenance can generate pavements with different deterioration patterns, which can easily be modeled by changing this input data.

3.5. 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 [25]. This section of the paper presents an overview of a network-level LP optimization model. The sets, parameters, decision variables, constraints and objective functions are defined as follows.

3.5.1. Definition of sets and parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Set of funding periods in the planning horizon</td>
</tr>
<tr>
<td>S</td>
<td>Set of all pavement condition states (1 = Very Poor, 2 = Poor, 3 = Fair, 4 = Good, 5 = Excellent)</td>
</tr>
<tr>
<td>S1</td>
<td>Set of undesirable pavement condition states (1 = Very Poor, 2 = Poor, 3 = Fair)</td>
</tr>
<tr>
<td>S2</td>
<td>Set of desirable pavement condition states (4 = Good, 5 = Excellent)</td>
</tr>
<tr>
<td>R</td>
<td>A set of treatments (1 = Reconstruction, 2 = Rehabilitation2, 3 = ThickOverlay3, 4 = ThinOverlay4, 5 = Rehabilitation1, 6 = ThickOverlay2, 7 = ThinOverlay3, 8 = OrdinaryMaintenance4, 9 = OrdinaryMaintenance4)</td>
</tr>
<tr>
<td>B</td>
<td>Highway Maintenance Budget available within period i, ∀i ∈ P</td>
</tr>
<tr>
<td>U</td>
<td>Unit (Per lane-mile) cost of treatment j within period i, ∀i ∈ P and ∀j ∈ R</td>
</tr>
<tr>
<td>N</td>
<td>Number of lane-miles in condition k at time 0 (initial condition), ∀k ∈ S</td>
</tr>
<tr>
<td>G</td>
<td>Required number of lane-miles (Performance Target) in condition k at the end of period i, ∀i ∈ P and ∀k ∈ S</td>
</tr>
<tr>
<td>D</td>
<td>Number of years it takes to deteriorate from condition state (k + 1) to condition state k, ∀k ∈ S</td>
</tr>
</tbody>
</table>

3.5.2. Definition of Decision Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xij</td>
<td>Amount of money spent on treatment j within period i, ∀i ∈ P and ∀j ∈ R</td>
</tr>
<tr>
<td>Nk</td>
<td>Number of lane-miles in condition k at the end of period i, ∀i ∈ P and ∀k ∈ S</td>
</tr>
</tbody>
</table>
3.5.3. Statement of the objective function
We now provide a generic LP formulation, which we modify for the various scenarios in Section 4.

\[ \text{Minimize } \sum_{i \in P} \sum_{j \in 1} w_i n_{ij} \]  

(1)

3.5.4. Subject to constraints

\[ n_{ij} = n_{ij-1} - \frac{N_{i,j-1}}{D_{ij}} + \frac{X_{1i}}{U_{ij}} + \frac{X_{2i}}{U_{ij}} + \frac{X_{3i}}{U_{ij}} + \frac{X_{4i}}{U_{ij}}, \forall i \in P \]  

(2)

\[ n_{ij} = n_{ij-1} - \frac{N_{i,j-1}}{D_{ij}} + \frac{X_{5i}}{U_{ij}} + \frac{X_{6i}}{U_{ij}} + \frac{X_{7i}}{U_{ij}} + \frac{X_{8i}}{U_{ij}}, \forall i \in P \]  

(3)

\[ n_{ij} = n_{ij-1} - \frac{N_{i,j-1}}{D_{ij}} + \frac{X_{9i}}{U_{ij}} + \frac{X_{10i}}{U_{ij}} - \frac{X_{11i}}{U_{ij}} + \frac{X_{12i}}{U_{ij}}, \forall i \in P \]  

(4)

\[ n_{ij} = n_{ij-1} - \frac{N_{i,j-1}}{D_{ij}} + \frac{X_{13i}}{U_{ij}} + \frac{X_{14i}}{U_{ij}}, \forall i \in P \]  

(5)

\[ \sum_{j \in R} x_{ij} \leq b_i, \forall i \in P \]  

(6)

Objective Function (1) allows for weights \(w_i\), unrestricted in sign, to define priorities for each pavement condition. Constraints (2) through (6) determine the number of lane-miles in each condition state in each period based on treatment choices and deterioration rates. For instance constraint (2) requires that the number of lane-miles in excellent condition at the end of period \(i\) is 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, ThickOverlay3, and ThinOverlay4, respectively; these treatments all restore the pavement condition to excellent (see Fig. 1).

Constraint (7) is the annual highway maintenance budget constraint. Money spent on the different renewal activities (treatments) in set \(R\) within the period \(i\) must be less than or equal to the budget available for period \(i\), which is \(B_i\). Constraint (8) forces the number of lane-miles in very poor, poor, and fair condition to be greater than or equal to the performance targets. Constraint (9) forces the number of lane-miles in good and excellent condition to be greater than or equal to the performance targets. Constraints (8) and (9) guarantee that the model will satisfy performance goals if there is any feasible solution to the problem. Constraint (10) and (11) are the logical non-negativity constraints.

This is a strategic-level planning model, and as such we believe any approximations made to fit the linear form are justified. For instance, the number of lane-miles to receive treatment \(j\) in period \(i\), \(x_{ij}\), is a continuous variable, while in practice it might be discrete, but for large systems this will produce very little error. Deterioration rates are often nonlinear and stochastic, but for a strategic-level planning model using a linear approximation is appropriate because it captures the expected behavior of the system, essentially the parameter \(D_{ij+1, j}\) is the expected deterioration rate for the system, for highway sections in condition state \(k + 1\) to condition \(k\). To model the nonlinear and stochastic behavior of roadway deterioration would require a much more complex model that would cloud the strategic-level insights available from the given methodology.

3.6. Scope and Limitations of the Model

The scope of this research consists of the following elements and limitations: (1) the objective is to create a network-level optimization model; hence it does not address the project-level maintenance programming problem; (2) this research considers only pavement maintenance programming, maintenance programming for other assets in highway facilities is not addressed; and (3) only the pavement condition data pertaining to 500 lane-miles of Interstate road network in a District are used in the analyses, pavement data pertaining to primary and secondary roads is not included.

4. Numerical case study

This case study is based on a state DOT highway planning District, which consists of 500 lane-miles of Interstate highway, over a 15-year planning horizon. Here we examine four scenarios: (1) minimize the number of lane-miles in very poor, poor, and fair conditions subject to a budget constraint; (2) minimize the number of lane-miles in very poor, poor, and fair conditions subject to performance targets and a budget constraint; (3) minimize the total...
budget required over the planning horizon to satisfy the target constraints; and (4) minimize the maximum yearly budget required to satisfy the target constraints with a not-to-exceed maximum budget. Additional scenarios may be found in [26]. The scenarios presented in this paper are based on 2010 prices. This case study is used to demonstrate the use of the models developed during this research effort and illustrate some important issues.

4.1. Scenario 1 – minimizing lane-miles in very poor, poor, and fair condition

In this scenario, we examine strategies for the District to allocate its annual highway maintenance budget for different renewal activities such that the number of lane-miles in very poor, poor, and fair condition will be minimized subject to a yearly budget constraint. Priority will be given for any excess budget to be used towards maximizing the number of lane-miles in excellent condition. To do this we use an LP that consists of the following: Objective Function (1) using weights \( w_1, w_2, \) and \( w_3 \) set to 500, \( w_4 = 0 \), and \( w_5 = -1 \); and Constraints (2) through (7), (10) and (11); the only constraints excluded are (8) and (9), i.e., the condition target constraints. The weight coefficients \( w_1, w_2, \) and \( w_3 \) are set to 500 (the number of lane-miles considered) to give priority to setting the number of highway lane-miles in the very poor, poor, and fair conditions to zero. This is not a lexicographic priority, but it does give high priority to eliminating these conditions from the system. For Constraint (7) the budget is set to $15 million per year.

Fig. 2 displays the results, i.e., the number of lane-miles in each condition state for each year in the planning horizon. This solution specifies that the District use the available annual highway maintenance budget in the first five periods in order to minimize the lane-miles in very poor, poor and fair condition. Then, the next four years are used to transition lane-miles in good condition into excellent condition. After that, for the remaining six years of the planning horizon the system is in equilibrium where all the roadway lane-miles cycle between the excellent and good condition states. This is the best that can be accomplished as every year some portion of the roadways in excellent condition deteriorates to good condition.

Fig. 2 also displays the fraction of the budget spent on each treatment each year. The budget in the first four years is allocated to ThinOverlay3, ThickOverlay2 and Rehabilitation1 to renew the lane-miles in fair, poor and very poor condition to good condition, respectively. For the next four years, a combination of ThickOverlay3 and ThinOverlay4 is used to maintain the lane-miles in fair and good condition, moving them into excellent condition. Starting on the ninth year, all lane-miles are in good or excellent condition and equilibrium has been reached. Here ThinOverlay4 is used to convert lane-miles in good condition to excellent condition. When the system is in equilibrium the whole yearly budget is not required; the average budget used in the last six years is $10.5 million. The total budget used over the 15-year planning horizon is $195.8 million. This behavior can be attributed to the fact that the objective function defined for the model favors having as many lane-miles as possible in excellent condition, i.e., \( w_5 = -1 \), but after the lane-miles in fair, poor, and very poor have been eliminated. This observation justifies the use of arbitrary weights included in the objective function.

To contrast these results, if we only emphasize putting lane-miles in excellent condition, in this case using weight coefficients \( w_1, w_2, w_3 \) and \( w_4 = 0 \), and \( w_5 = -1 \), we get the condition states transition graph displayed in Fig. 3. Here we see that the equilibrium is reached earlier, without the intermediate transition of roadways to good condition, before they are put into excellent condition, i.e., all downstream condition states are able to renew lane-miles directly into the excellent condition. This requires a slightly smaller overall budget of $188.1 million, but it has a disadvantage in that during the early years more lane-miles become very poor and poor, i.e., the highway system will get worse before it gets better. This is optimal given the budget and treatment costs, but perhaps not a desirable solution. To eliminate this behavior we consider the next scenario, which includes condition targets.

4.2. Scenario 2 – minimizing lane-miles in very poor, poor, and fair condition including targets

In this scenario, we modify the LP from Scenario 1 (using the original weights) by adding Constraint (8), which specifies performance targets for the maximum number of lane-miles in fair, poor, or very poor condition. One must be careful in setting these targets, as they can potentially conflict with the budget constraint, producing an infeasible LP. Here we specify the maximum number of lane-miles in each condition using a linearly decreasing function through time. We note that Constraint (9), which sets targets for good and excellent condition, is not used. If these targets are also included, they must also be used with care because if we were to set a target for lane-miles in good condition, for example, it could produce a worse solution by limiting the number of lane-miles that we can put into excellent condition. Fig. 4 shows the results for this scenario along with the targets.

Using the targets has the desired effect, the number of lane-miles in very poor and poor condition now decreases through time—tracking the targets downward and the number of lane-miles in fair condition drops rapidly to zero—the effect of the weights on the objective function and the effect of the targets constraint are evident. The condition targets also delay the equilibrium between good and excellent condition lane-miles and increase the overall budget for the planning horizon to $211.3 million. The condition targets are used to transition lane-miles in very poor and poor conditions to fair, poor and fair condition, moving them into excellent condition. Fig. 4 also shows that the available pavement maintenance budget for the first six years is spent on Rehabilitation1, ThickOverlay2, and ThinOverlay3 which restore lane-miles in very poor, poor, and fair condition to good condition, respectively. Initially, the solution exactly matches the target for very poor and poor lane-miles, while more aggressively reducing lane-miles in fair condition. After the seventh year, the budget is primarily allocated to ThickOverlay3 and ThinOverlay4, which restore the pavement to excellent condition—moving the system towards equilibrium, which is reached at approximately year 11, after which only ThinOverlay4 is used. Hence, the model first focuses on bringing the lane-miles in very poor, poor and fair condition to good condition in order to meet the pavement performance targets. Thus, the budget allocation pattern that materializes in the first 5–6 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 the first 11 periods was fully expended. The model reaches equilibrium after 11 years, as the objective function pertaining to the model strives towards minimizing and keeping below target 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 12 because the equilibrium requires less budgetary resources to maintain.

4.3. Scenario 3 – minimizing the total budget required to meet targets

In this scenario, we examine strategies for minimizing the total budget, over a 15-year planning horizon, required by the District in order to meet the performance targets pertaining to very poor, poor and fair condition. Here we use an LP consisting of Objective Function (12), introduced below, and Constraints (2) through (6), (8), (10), and (11).

\[
\text{Minimize } \sum_{i < p} \sum_{j < R} x_{ij} \quad (12)
\]
The goal of this objective function is to determine the minimum total budget spent over the 15-year analysis period while keeping the lane-miles in very poor, poor and fair condition below performance targets. Fig. 5 shows the budget allocation pattern and the level of service pertaining to each year.

The results shown indicate that the budget allocation that materialized based on this model significantly differs from that of the models presented earlier because a yearly budget limit is not included, and the objective focuses on total spending over the 15-year planning horizon. The results show that money to be spent in year 1 is significantly more than the following 14 years. This budget allocation pattern results from the fact that this model restores lane-miles in poor and fair condition immediately in the first year of analysis. This is the least expensive ($173 million) way to meet the targets because over the 15 years we can use relatively inexpensive treatments, namely ThickOverlay3 and...
ThinOverlay4 to try reaching equilibrium, while spending as little as possible on Rehabilitation1 to renew the lane-miles in very poor condition in the first five and last two years, respectively. The trend analysis charts also show that the lane-miles in very poor and poor condition begin to creep up in the last five years, but always stay under or at the specified performance targets. This is probably not a very desirable behavior; the end of the planning horizon is not necessarily the end of the infrastructures usefulness. To combat this, we could add a constraint that does not allow the number of lane-miles in very poor, poor, or fair to never increase year-to-year, and also that forces the number of lane-miles in excellent to never decrease.

This model is designed to determine the minimum budget required in order to meet the performance targets pertaining to very poor, poor and fair condition over 15 years of analysis. Highway agencies aiming to restore lane-miles in very poor, poor and fair condition may find this model useful. To illustrate the budget allocation pattern, we use Model 1.2.

Fig. 3. Scenario 1a: maximize lane-miles in excellent condition with a fixed budget.
condition in the first few years of the analysis can use this model not only to determine the minimum budget required to meet the performance targets, but also to realize visible and rapid improvements in terms of pavement performance throughout the network. However, the major drawback of this model is the practicality of being able to achieve such a level of maintenance in one year, since it will practically require closing the Interstate and paralyzing commerce.

4.4. Scenario 4 – minimizing the maximum yearly budget required to meet targets with a maximum cap

To address the impracticality of the previous scenario, in this scenario we minimize the maximum yearly budget required to meet the District targets over the 15-year planning horizon pertaining to very poor, poor and fair condition. Here we use an LP
consisting of Objective Function (12) subject to Constraints (2) through (6), (7), (8), (10), and (11).

Minimize \[ \sum_{i \in F} \sum_{j \in K} x_{ij} \]  

The main difference between Scenarios 3 and 4 is that the model developed for Scenario 4 places an upper limit on the yearly budget via constraint (7) which allows for a feasible solution given the potential conflict between the target constraints. Scenario 4 is useful because Highway agencies usually do not have unlimited amounts of money for maintenance in any given year. The budget allocation pattern demonstrated in Scenario 3 indicates that the District should spend over $46 million in year 1 in order to meet the performance targets and to minimize the cost for the 15-year analysis period. However, this budget allocation pattern is not very likely to materialize in practice. Hence, the maximum

Fig. 5. Scenario 3: minimize the total budget required to meet targets.
budget which can be allocated in any given year in Scenario 4 is fixed at $15 million.

**Fig. 6** illustrates the pavement condition results. We see that this model stays quite close to the targets for lane-miles in very poor and poor, while after an initial dip, the number of lane-miles in excellent condition steadily increases. The total expenditures over the planning horizon are $189.3 million.

There are striking similarities between Scenario 2 and 4. For example, the budget allocation to maintenance treatments in the first four years is almost identical, hence resulting in very similar

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**Fig. 6.** Scenario 4: minimize the maximum yearly budget required to meet targets with a maximum cap.
level of service patterns. Given that the model in Scenario 4 is trying to minimize the budget, it allows the lane-miles in very poor and poor condition to creep up and track the declining performance targets—this is in contrast to the patterns observed in Scenario 2 where the emphasis was on both: staying under targets and rapidly minimizing the very poor, poor, and fair lane-miles. This policy difference explains the differential in the total expenditures over the planning horizon, i.e., $22 million.

5. Observations

The results presented for Scenario 1 and 2 are significantly different. Recall that the major difference between Scenario 1 and 2 is the use of a constraint that sets a target (upper bound) for the number of the lane-miles in very poor, poor, and fair condition. The level of service resulting from Scenario 2 is higher than that of Scenario 1, but this comes at a higher level of expenditures as well. The difference between levels of service pertaining to each model is especially significant early on. This difference results from introducing performance constraints to the model which directs the type and magnitude of budget allocation that the model could generate. Hence, the presence of performance constraints reduces the feasible region.

Scenario 3 involves a very different approach as its emphasis is to determine the minimum budget needed to reach and maintain the performance targets for very poor, poor and fair lane-miles. Thus, it does not make sense to do a detailed comparison of Scenarios 1 and 2 with Scenario 3. However, given that Scenario 2 and 3 both required meeting the target number of lane-miles in very poor, poor and fair condition, we can comment on the impact of this constraint on the total budget expenditures over the 15-year simulation. Scenario 2 required a total 15-year budget of $211.3 million while Scenario 3 required $173 million of which $46 million was needed in year 1. While impractical, Scenario 3 does show and confirm what is widely known, i.e., over the long run, it is cheaper to maintain early.

Scenario 4 is also designed to determine the minimum budget required in order to meet the performance targets pertaining to very poor, poor, and fair condition over 15 years of analysis, while not exceeding a practical upper budget limit. Highway agencies aiming to restore lane-miles in very poor, poor, and fair condition in the long-term can use this model to simply meet the performance targets and to obtain a more practical investment strategy over 15 years of analysis. Scenario 2 and 4 are comparable in that both are constrained by having to meet the performance targets, but Scenario 2 also has the added dimension of rapidly minimizing the number lane-miles in very poor, poor, and fair condition. This begs a policy question, is it enough to meet the performance targets or should a Highway agency attempt to outperform them?

The Linear Program provided herein can be used as a decision making tool to assist highway maintenance managers in preserving an acceptable level of service given a highway maintenance budget. In addition, this Linear Program may be used to develop the highway maintenance budget necessary to reach a desired level of service. These objectives may be accomplished through running a variety of scenarios and performing what-if analysis.

The Virginia Department of Transportation (VDOT) utilizes a two-stage process [17,18] to determine the maintenance needs. In the first stage, the frequency and density of pavement distress data (fatigue cracking, transverse cracking, rutting, patching) is used in the form of a decision matrix along with the pavement critical condition index to initially determine a section’s preliminary maintenance needs (e.g., do nothing, preventive maintenance, corrective maintenance, restorative maintenance, rehabilitation) and the associated cost. In the second stage, the preliminary maintenance decision, which is mainly based on visual distresses, is further enhanced through the utilization of traffic, pavement structure and the section’s maintenance history information. The 6-year network-level maintenance needs estimates are derived through a multi-constraint optimization process whose objective is to minimize the cost while achieving condition-based performance targets, e.g., 18% or less of the network in a deficient condition, 10% or less of the network in need of rehabilitation, maintaining or improving the critical condition index over time. In related research, which utilizes these decision matrices, we have developed a framework to optimize highway maintenance budget allocation policy by developing a micro-level simulation model (using system dynamics) of the highway deterioration and renewal processes and coupling it with calibration and optimization using system dynamics techniques [19].

6. Conclusions

This LP framework allows for improved strategic level planning by enabling the highway maintenance managers to explore the feasible region, i.e., the set of all possible strategies, in an efficient manner. The simpler and practical nature inherent in the model is likely to appeal to decision-makers, as the model does not require investing substantial time or resources. The results presented show that incorporating a smart decision-making tool is beneficial in determining an effective pavement maintenance program. The results obtained from this optimization model are superior to those obtained by de la Garza and Krueger [22] which were based on a manual budget allocation.

One advantage of the LP framework is that Linear Programming has a well-developed theory for sensitivity analysis, thus we can easily examine how a given solution is impacted by changes in the input parameters (e.g., deterioration rates and treatment costs). For instance, part of the solution that is important is the selection of maintenance treatments for any particular year and over the whole planning horizon; in fact, we find that of the nine possible treatments, often only a subset is used. This can be important for planning. We can study, using sensitivity analysis, the range for the various input parameters where a certain treatment set remains optimal (even if the number of lane-miles to which each treatment is applied changes).

Insights from the scenarios presented show potential for developing new understanding into the MR&R problem. As the four scenarios studied here show, the solutions are complex, especially given the dynamic nature of the problem. For instance, in Scenario 3 we minimize the total budget over the 15-year planning horizon, given a set of targets, i.e., upper bounds, on the number of lane-miles in fair, poor, and very poor condition. The optimal strategy for accomplishing this is to spend a sizable budget in the first year. This might not be possible from a budgetary point of view, or even a maintenance point of view (too much work done in one construction season). This leads to Scenario 4, where we have the same objective, but add a constraint that limits the yearly budget permissible, which changes the maintenance strategy considerably.

The complexity of this problem stems from the conflicting objectives, one of maximizing the quality of the pavement and the other of minimizing the budget. These conflicting objectives are handled in the LP model by transforming one of the objectives into a constraint, i.e., the budget constraint or the pavement quality targets. The complexity is compounded by the dynamic nature of the problem. For example, we see from Scenario 1, where we seek to minimize the lane-miles in fair, poor, and very poor condition, with a budget constraint, but no performance targets that the optimal strategy actually increases the number of lane-miles in...
very poor condition for the first few years. While this is optimal for the given objective function, it might not be desirable. This leads to Scenario 2, which included performance targets to eliminate this behavior.

One of the major assumptions, and perhaps limitations of the model presented, has to do with how we have chosen to model pavement deterioration. Deterioration of the roadway is an important aspect of this problem, and there are some considerations when modeling roadway deterioration in an LP. First, the given LP framework discretizes the time horizon into periods of one year. While this is a very natural way to look at the problem as it matches budgeting and construction periods, in reality deterioration is continuous in nature. In this model we take a “deteriorate-first, treatment-second” modeling approach, but the opposite approach is also possible, so future research should examine the impact of these approaches. Deterioration is also non-linear. By linearizing it we ensure some level of error, although using a non-linear approach does not ensure better results given the stochastic nature of deterioration. Linearization can be a good approximation, given appropriate condition states. In our examples, we used five condition states, excellent, good, fair, poor, and very poor. If the deterioration rate between these states is highly non-linear, then we can add additional states to compensate. While this was not in the scope of our analysis, this can be done by analyzing the deterioration curves and finding the best piece-wise linear approximation. The last major complication presented by deterioration is, as mentioned above, uncertainty, i.e., its stochastic nature. There are various ways to handle this uncertainty, in this analysis we are using expected and deterministic deterioration rates, but we could be more risk averse and use more pessimistic estimates. Furthermore, we could use this same framework in a scenario-based stochastic linear program to examine a set of possible deterioration scenarios.

Continuing research is underway in three tracks. First, the model presented in this paper may be extended to measure the efficiency of the budget allocation process by optimizing a cost/benefit ratio. Krueger and de la Garza [27] developed a cost/benefit ratio by comparing the annual maintenance highway budget versus a weighted level of service index. Minimizing this cost/benefit ratio would further allow a highway maintenance manager to spend their budget in the most efficient manner.

Second, research is also underway to modify the structure of the five condition states to better account for the effects of ordinary maintenance (OM). Since the purpose of OM is to extend the life of the pavement without letting it go into the next condition state, we are considering adding a fork from the good condition state where one path continues as is (letting lane-miles deteriorate from good to fair) and the other path leads to an intermediate state between good and fair through the application of OrdinaryMaintenance4. This intermediate state can hold the lane-miles, say for example an additional 2 years, before they go into the fair condition state.

Third, the model present in this research focused on the network level. Another natural extension to this work is to focus on a project-level optimization, determining which specific segments of the whole highway network should be targeted. Research in underway to integrate this LP network-level framework with a Discrete Event Simulation project-level framework [28].

In conclusion, we believe the LP framework is well-suited for this type of strategic level planning; it models the system with enough fidelity to be useful for decision making and provides a straightforward methodology for exploring the set of possible solutions.

7. Future directions and challenges

As discussed in the previous section, this research is being extended in three directions, namely, (1) to develop a higher level optimization function which maximizes the Benefit/Cost ratio of the different maintenance policies; (2) to integrate this network-level decision support system with a project-level system so as to provide programmatic insights to the field highway maintenance engineers; and (3) to modify the structure of the deterioration/renovation engine to better account for the behavior of Ordinary Maintenance. The challenges posed by trying to optimize a Benefit/Cost index are related to the resulting non-linear properties of the new model and to the need to create an aggregated and weighted Level-of-Service index. The challenges posed by integrating a network- and project-level decision support system are related to determining pavement deterioration rates for each of the sections and to model such via a discrete-event simulation environment. The challenges posed by modifying the structure of the current engine relate to being able to quantify how much the life of the pavement is really extended by relatively inexpensive ordinary maintenance.

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