ABSTRACT

The Georgia Department of Transportation (GDOT) is one of the leading state departments of transportation (DOTs) that has been performing pavement preservation since the 1980’s. Because of the current funding shortfall, many of GDOT’s pavement maintenance and preservation projects have been delayed or canceled, which will severely impact meeting long-term pavement condition and preservation needs. To effectively communicate with top management and stakeholders about the impacts of funding shortfalls, a Markov-process-based pavement management system was developed to forecast the network-level, long-term pavement conditions and the annual budget need. Historical pavement condition data were used to establish the pavement transition probabilities, which has been calibrated and verified. The ten-year pavement condition forecast showed that the current budget level is insufficient and can extend the pavement condition for only three more years. Even though the current funding allocation is reasonable and comparable to an optimal method, the need analysis showed that the 85-10% requirements for desirable pavement conditions are hard to achieve because of a budget shortfall—$426.4 million—in FY 2008, which is two times more than the current budget (if the total available budget is $185.1 million). Considering the escalation rate of construction costs (assumed to be 18.1%), $1.668 billion will be needed in FY 2017. The methodology proposed in this paper can be used by DOTs to communicate with top management and stakeholders as they seek to secure necessary pavement preservation budgets. Recommendations on future research were also discussed.

KEYWORDS

Pavement Maintenance and Preservation, Pavement Management System, Markov Process-based Optimization, Pavement Condition Forecasting
INTRODUCTION

The Georgia Department of Transportation (GDOT) is a leading state DOT that has been performing pavement maintenance and preservation since the 1980’s. To maintain the highway system at a serviceable level, GDOT strategically resurfaces 10% of its 18,000-mile (28,968 km) state route system each year; i.e. each pavement is resurfaced once every ten years. However, this goal is hard to achieve due to the current funding shortfall. In 2008, a financial audit revealed that there was a $456 million budget deficit. Compounded by today’s budget environment, the budget shortfall is causing delay or cancellation of road construction projects and will severely and negatively impact long-term pavement conditions.

GDOT’s budget shortfall is a common issue faced by highway agencies throughout the United States. Due to the indispensable role that the highway system plays in the economy, it is crucial for GDOT to justify to legislatures and stakeholders the importance of timely pavement maintenance and preservation and the consequences of inadequate funding. To address this need, this paper proposes a methodology to assess the network-level, long-term pavement conditions and the budget need in order to maintain the pavement conditions at a desirable level. Hopefully, it will help decision makers address the question of paying for roadway preservation now at a lower cost or later at a much higher cost.

In this paper, a network-level Markov-process-based pavement management system (PMS), which has been developed for and implemented by GDOT, is presented. To address different concerns regarding funding allocation, three types of funding allocation methods were devised. Optimization models were also developed for forecasting long-term pavement performance and need analysis. Case studies are performed on Georgia’s non-interstate highways to illustrate the flexibility and capability of the developed system.

The remainder of this paper is organized as follows. Following the introduction, the framework of the developed system is introduced, as well as the Markov model and analysis strategies. After that, three case studies are performed to address different concerns highway agencies might have. Finally, conclusions are drawn and recommendations for future research are presented.

DEVELOPMENT OF NETWORK-LEVEL PAVEMENT MANAGEMENT SYSTEM

In this section, the framework and the development of the proposed network-level PMS is briefly introduced. Then, the Markov model and different analysis strategies are presented, which are the kernel of the developed system.

System Framework

The developed PMS is used by GDOT to support its long-term pavement condition forecasting, long-term pavement maintenance and preservation need analyses, and other what-if analyses. As a decision support system, it enables GDOT to justify its budget needs to legislatures. This data-driven system is a modular computer program that is newly added to the whole Georgia Pavement Management Systems (GPAM) (Tsai, & Lai, 2002), which consists of many modules for data acquisition, data management and decision support. GPAM was developed by Georgia Institute of Technology and has been used by GDOT since the late 1990s to manage its pavement maintenance and preservation activities.

Figure 1 illustrates the framework of the developed system. The Markov process model is the core of the system, which is introduced in the following section. The input parameters are designed to fit in with this model. Analysis duration is the time horizon of the analysis, which can be ten to twenty years. Markov
transition probability matrices (TPMs) depict the deterioration characteristics of the pavement network. Initial states are the pavement conditions at the initial year; they consist of the percents of the total mileage in different condition categories (Excellent, Good, Fair, Poor and Bad) for each pavement group (also known as a “family”). Maintenance and rehabilitation (M&R) TPMs depict the performance of different M&R activities in recovering pavement conditions. M&R unit costs are calculated from the actual costs of different M&R activities divided by the treated centerline miles. The escalation rate reflects the average rate of the increasing construction cost, which can be analyzed using historical M&R expenditure. The annual budget is used when the long-term pavement conditions are to be forecast. When need analysis is performed, this parameter can be omitted.

The developed system provides great flexibility by presenting several strategies for meeting different requirements. Two major types of analyses can be performed: long-term pavement condition forecast analysis and M&R need analysis. If the future annual budget is known, the long-term pavement conditions can be forecast. The forecast is affected by different funding allocation methods. To handle different situations, three types of funding allocation methods are provided: Worst First, User Specified and Optimized. Worst First treats pavements in the worst condition first. Pavements in better condition will be treated in priority order. When the User Specified method is applied, the funding allocation can be manually adjusted based on highway agencies’ practices. It can also be used by highway agencies to do what-if analysis for evaluating the effect of different funding allocations. The Optimized method allocates funding by solving a mathematical programming model with a pre-set objective. In this system, the objective function is defined to maximize the annual pavement network composite rating. M&R need analysis deals with another issue that concerns highway agencies: the funding need for M&R activities in the future to maintain the pavement conditions at a desirable level. The results of this analysis are very important for highway agencies to justify to legislatures.

With given input parameters and a selected analysis strategy, the developed program runs and generates reports for further study. For better management and re-use of input parameters, a built-in database is used to store the data.

Figure 2 shows the major screen of the developed system. It is designed as a hierarchical structure. A database can store several simulations, in each of which several scenarios can be built. Each scenario consists of a set of input parameters, a selected analysis strategy, and the analysis result. This design is very convenient for end users to perform different what-if analyses and save lots of time for data preparation. The on-screen help shortens the learning curve. This system was developed using Microsoft Visual Basic, Microsoft Access and a third-party optimization solver.
Figure 1. System framework of the developed PMS

- Analysis duration
- Markov TPMs
- Initial States
- M&R TPMs
- M&R Unit Costs
- Escalation Rate
- Annual Budget

- Pavement Condition Forecasting
  - Worst First
  - User Specified
  - Optimized
- Need Analysis

Figure 2. Main screen of the developed PMS
Markov Model and Analysis Strategies

Markov process is used in the developed system to describe the evolution of pavement conditions over time. It is the core of all analysis strategies. The following briefly introduced the implementation of Markov model and the analysis strategies for GDOT pavement management at network level.

Markov Model

Pavement deterioration is very uncertain and experiences a stochastic nature, which is affected by such factors as pavement structures, traffic, weather conditions, and the history of M&R applications. Due to the importance in implementing a PMS, much study has been done in literature to model the pavement deterioration characteristics, such as the deterministic model (Ouyang, & Madanat, 2006), Markov model (Ferreira, Antunes, & Picado-Santos, 2002) and generic stochastic model (Chootinan, Horrocks, & Bolling, 2006). Markov model is the most popular one that was used in a network-level PMS and can be found in many studies (Butt, Shahin, Carpenter, & Carnahan, 1994; Wang, Zaniewski, & Way, 1994; Abaza, Ashur, & Al-Khatib, 2004). It is a special stochastic process that depicts the probabilistic status transition of a random variable over time. Under this model, the current status only depends on its previous status and has no “historical memory”. In our developed PMS, Markov model was chosen to depict the pavement deterioration.

In our Markov-process-based PMS model, the analysis horizon is discretized at an interval of one year. The pavement conditions at the beginning of a year are defined as the states of that year. The ending states of a year are considered as the states of the next year, which are the result of pavement condition changes due to the pavement deterioration and applied M&R actions in this year. Pavement conditions are discretized into several states. In our models, they are categorized as five states (Excellent, Good, Fair, Poor and Bad) in terms of the different ranges of PACES (Pavement Condition Evaluation System) ratings (GDOT, 2007). GDOT uses a PACES rating from 0 to 100 to rate a pavement condition. A higher score means a better condition. Table 1 summarizes the definition for each state. All pavement sections of the whole network are aggregated as fourteen families. Each family belongs to one of seven working districts and is either interstate or non-interstate highway. In the meantime, M&R actions are simplified into three categories: minor preventive maintenance, major preventive maintenance, and major rehab/reconstruction, which are used to treat pavements in the state of Fair, Poor, or Bad respectively.

Table 1. Definition of pavement condition states

<table>
<thead>
<tr>
<th>States</th>
<th>Excellent</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Bad</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACES rating ranges</td>
<td>91 to 100</td>
<td>81 to 90</td>
<td>71 to 80</td>
<td>55 to 70</td>
<td>Less than 55</td>
</tr>
</tbody>
</table>

With the above discretization of a continuous Markov model, the pavement condition evolution over time can be expressed as the following equation (Eq. 1).

\[ s_{t+1} = (s_t - X_t U_t^{-1})P + X_t U_t^{-1}P' \]

where \( s_t \) is the state vector for family \( f \) at the beginning of time period \( t \).

\( s_{t+1} \) is the corresponding state vector at \( t+1 \), which can be derived from the previous state vector.
in considering natural pavement deterioration (first part of the right hand side in Eq. 1) and applied M&R actions (second part of the right hand side in Eq. 1). As defined in Eq. 2, the value of an element, which represents a state with 1 being Excellent, 2 being Good, etc., is the percent of pavement centerline miles in this state out of the total pavement centerline miles in the family \( s_i^f = \left( s_i^{f1} \ s_i^{f2} \ s_i^{f3} \ s_i^{f4} \ s_i^{f5} \right) , \ f = 1, 2, \ldots, 14, \ t = 1, 2, \ldots, T \) (2)

Two types of TPMs are used to model the pavement deterioration with or without M&R action. \( P^f \) is the TPM for family \( f \) without treatment (Eq. 3). The entry \( p_{ij}^f \) represents the probability that a pavement in state \( i \) will transit to state \( j \) at the end of the current time period, i.e. the beginning of the next time period. It is assumed that each state cannot shift to more than the next adjacent state in one year. One simplification is made that the pavement deterioration characteristics stays the same after treatment. This simplification is valid because it is difficult to strictly separate the historical pavement condition data with or without previous M&R actions. \( P^f \) is actually a compound matrix in the course of generation using statistical methods on the historical pavement condition data.

\[
P^f = \begin{bmatrix}
p_{11}^f & p_{12}^f & 0 & 0 & 0 \\
0 & p_{22}^f & p_{23}^f & 0 & 0 \\
0 & 0 & p_{33}^f & p_{34}^f & 0 \\
0 & 0 & 0 & p_{44}^f & p_{45}^f \\
0 & 0 & 0 & 0 & p_{55}^f
\end{bmatrix} , \ f = 1, 2, \ldots, 14 \tag{3}
\]

\[
\sum_{j=1}^{5} p_{ij}^f = 1
\]

Another TPM \( P' \) is defined for pavement performance under each M&R action (Eq. 4). For simplicity, only one \( P' \) is constructed, which applies to the pavements for all families.

\[
P' = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
p_{31}^f & p_{32}^f & p_{33}^f & 0 & 0 \\
p_{41}^f & p_{42}^f & p_{43}^f & p_{44}^f & 0 \\
p_{51}^f & p_{52}^f & p_{53}^f & p_{54}^f & p_{55}^f
\end{bmatrix} \tag{4}
\]

\[
\sum_{j=1}^{5} p_{ij}' = 1
\]

\( X_i^f \) (Eq. 4) are defined as the funds spent for each family, each M&R action, and at each time period. It is the direct result for different analysis strategies.

\[
X_i^f = \left( 0 \ 0 \ X_i^{f1} \ X_i^{f2} \ X_i^{f5} \right) , \ f = 1, 2, \ldots, 14, \ t = 1, 2, \ldots, T \tag{5}
\]
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Analysis Strategies

As introduced above, two categories of analysis strategies are developed, long-term pavement condition forecasting and M&R need analysis. These strategies are based on the developed Markov model to solve the decision variables $X_t$, which are the annual funding allocations.

Worst First and User Specified methods for long-term pavement condition forecasting are still widely used in highway agencies. The funding allocation in these two methods is straightforward. Worst First treats pavements in the worst condition first. Then, the ones in a better condition can be treated. After that, Eq. 1 can be used to derive the pavement conditions in the next year. Repeat the same process and the long-term pavement conditions can be forecast. The process for the User Specified method is almost same. The difference is how to apply M&R actions on pavements in different conditions. Using this method, the funding allocation can be manually adjusted. For example, GDOT often allocates 10%, 80%, and 10% of its total budget on pavements in Fair, Poor and Bad conditions respectively.

Though the manual funding allocation methods are widely used, optimization based methods are still of great interest to highway agencies and researchers. The use of optimization models for pavement management can be traced back to the early 1980s when the Arizona PMS was successfully implemented (Golabi, Kulkarni, & Way, 1982). Thereafter, much study has been done to build different mathematical programming models to address pavement management issues. The objective is to solve the optimal M&R programming for purpose of either achieving the best pavement performance with a given annual budget or minimizing the total budget with given pavement performance (Zimmerman, 1995). One reason for the existence of various models is transportation agencies have different pavement management purposes, pavement performance indicators,

$$U_r = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & u_3 & 0 & 0 \\
0 & 0 & 0 & u_4 & 0 \\
0 & 0 & 0 & 0 & u_5
\end{bmatrix} \cdot r^{t-1}, \quad t=1, 2, ..., T$$

(6)

In GDOT, the network composite rating $R_t$ (Eq. 7), a weighted PACES rating, is used to quantify the overall pavement condition at network level. The weighting factors $m_f$ can be the middle value of a state or the mean value at the initial states of each family. The composite rating is computed as follows:

$$R_t = \left[ \sum_{f=1}^{14} (s_f \cdot m_f) \cdot l^f \right] / \sum_{f=1}^{14} l^f, \quad f=1, 2, ..., 14, \quad t=1, 2, ..., T$$

(7)

in which

$$m_f = \left( m_1^f, m_2^f, m_3^f, m_4^f, m_5^f \right), \quad f=1, 2, ..., 14$$

$$l^f = \text{total mileage in family } f$$

Analysis Strategies

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pavement maintenance criteria, and targeted pavement performance. It is difficult to build a model that can meet the requirements of all transportation agencies.

Depending on the way the individual pavement sections composing the network are accounted for, optimization models can be divided into two categories: 1) segment-linked models in which each pavement section can be explicitly considered, and 2) aggregate models in which pavement sections are grouped as several families (Gendreau, & Soriano, 1998). Both methods have advantages and disadvantages. Segment-linked optimization models can be used at the operation level because the decision variables are the detailed M&R programs on all pavement sections during the planning horizon (Li, Hass, & Huot, 1998; Fwa, Chan, & Hoque, 2000; Ferreira et al., 2002; Ouyang, & Madanat, 2004; Chootinan et al., 2006; Ouyang, 2007). However, due to the solution difficulty for an integer programming or a mixed integer programming, the problem size is very limited. That’s why only a small number of pavement sections are often used for case studies in most related literature. In contrast, aggregate models can be used at a high management level, by which the overall pavement network condition and its evolution over time can be solved (Chen, Hudson, Pajoh, & Dickinson, 1996; Gharaibeh, & Darter, 1999; Abaza et al., 2004; Madanat, Park, & Kuhn, 2006). This type of model can be used to solve the problem of large-sized pavement network.

In our developed PMS, both Optimized forecasting method and need analysis use the Markov-process-based aggregate optimization model. The objective of Optimized method is to maximize the annual pavement network composite rating (Eq. 7); while the annual available budget is used as one of the constraints. Need analysis is an optimization model with the objective to minimize the annual total budget while meeting the desirable pavement conditions. In GDOT, the desirable pavement conditions are defined so that the pavement network composite rating is greater than 85 and the percent of pavements below 70, i.e. pavements in Poor or Bad, is less than 10% (for abbreviation, it is called 85-10% requirements in this paper). The detailed development of these two optimization models can be found in the study by Wang, Tsai, Pitts, and Wu (2009).

CASE STUDIES

With the developed PMS models and the computer programs, different strategies can be used to forecast long-term pavement conditions and identify long-term annual budget need at network level. These strategies can be used individually or combined to address the different concerns in GDOT. In this section, several case studies are performed to demonstrate the flexibility and capability of the PMS program. The studies are performed on Georgia’s non-interstate highway network and answer the following questions:

• How long will the current pavement network last if no maintenance and preservation is applied in the following ten years (fiscal year (FY) 2009 to 2018)?
• If the current funding level remains the same for the following ten years, what will annual pavement conditions be? What is the best preservation strategy, Worst First, User Specified, or Optimized?
• Are the current funds sufficient for maintaining the pavement network at a desirable level? If not, how much money will be needed for the next ten years?

Before the case study can be done, the following parameters are needed: 1) Markov TPMs, 2) treatment unit costs and 3) average escalation rate of construction cost. As a common method applied in literature (Wang et al., 1994; Abaza et al. 2004; Baik, Jeong, & Abraham, 2006), the historical pavement condition data is used to establish the pavement condition transition probabilities. GDOT has maintained the annual condition data of its 18,000 centerline miles (28,968 km) highway pavements, including interstate and non-interstate highway, since FY 1986. GDOT uses approximately 80 engineers in 7 working districts to do the field condition survey annually. The collected data is stored in a centralized Oracle database. Up to FY 2008,
there were more than 60,000 records for projects and 390,000 records for pavement segments stored in the database, which increases year by year.

In this paper, we only focus on the non-interstate highway maintained by GDOT because: 1) there are fewer interstate highway records than non-interstate highway records, and, thus, the accuracy of transition probabilities for interstate highway are not sufficient, 2) the historical treatment expenditure can be only obtained for non-interstate highways to this point, and 3) the length of non-interstate highways is much greater than the length of interstate highways. The transition probabilities of pavement deterioration are established by statistical analysis of the pavement condition data from FY 1999 to 2007. For non-interstate highway, there are total seven TPMs for seven working districts. Due to the lack of treatment information in the current database, the transition probabilities for various treatments are estimated based on engineers’ experience. The estimate is based on the following facts: a) minor preventive maintenance, such as crack sealing, cannot improve pavement condition, but it can lengthen the duration of the current state to the following year; b) major preventive maintenance, such as resurfacing, and major rehab/reconstruction, can bring the pavement condition back to the Excellent. The detailed information regarding all TPMs can be found in the technical report (Tsai, & Wang, 2008). The unit costs and the annual average escalation rate are estimated according to the historical treatment expenditures from FY 1999 to 2007. With the computed 18.1% escalation rate, the projected unit cost in FY 2008 is listed in Table 2. The research by Wang et al. (2009) has done the calibration and validation on the established TPMs and the corresponding Markov models.

<table>
<thead>
<tr>
<th>Table 2. Treatment unit costs for non-interstate highway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
</tr>
<tr>
<td>Minor Preventive Maintenance</td>
</tr>
<tr>
<td>Major Preventive Maintenance</td>
</tr>
<tr>
<td>Major Rehab/Reconstruction</td>
</tr>
</tbody>
</table>

In the following case study, FY 2008 was used as the initial year and the corresponding pavement conditions are listed in Table 3. The total centerline miles of non-interstate highway pavements is 16,857 miles (27,129 km), which is more than 90% of the whole roadway network. The pavement conditions among seven working districts vary by composite ratings from 79 to 87. The overall composite rating is 83 and the percent of pavements below 70 (Poor + Bad) is 17%, which is already under the GDOT’s 85-10% performance requirements.

<table>
<thead>
<tr>
<th>Table 3. Initial pavement conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>District 1</td>
</tr>
<tr>
<td>22</td>
</tr>
<tr>
<td>District 2</td>
</tr>
<tr>
<td>District 3</td>
</tr>
<tr>
<td>District 4</td>
</tr>
<tr>
<td>District 5</td>
</tr>
<tr>
<td>District 6</td>
</tr>
<tr>
<td>District 7</td>
</tr>
<tr>
<td>Overall</td>
</tr>
</tbody>
</table>
Case I: Pavement Condition Forecasting without any M&R Activity

The objective of this case study is to assess the status of the current pavement network. Without any M&R activity, the pavement conditions will constantly deteriorate. If the average pavement conditions quickly reach a failure point, the current pavement network cannot withstand the traffic load. For this purpose, any method among Worst First, User Specified or Optimized can be used without any difference because budget allocation is not involved since the initial year FY 2008. Pavement conditions can be forecast through FY 2018.

Figure 3 (a) shows the trend of pavement composite ratings from FY 2008 to FY 2018. Figure 3(b) shows the corresponding percents of pavements below 70, which are Poor or Bad. From Figure 3(a) and (b), in FY 2008, the composite rating is 83, and the percent of pavements below 70 is approximately 17%. Therefore, the initial pavement conditions are already below the GDOT’s 85-10% pavement condition requirements.

Without any maintenance applied, the pavement conditions drop very fast. On average, 2.5 points in composite rating are lost each year (see Figure 3 (a)). In FY 2012, the pavement composite rating drops to 70, which means the average pavement conditions fall into Poor (see the dotted line in Figure 3(a)). At the same time, the percent of pavements below 70 is approximately 57%, which is 3 times more than the status in FY 2008 (see the dotted line in Figure 3 (b)). By the end of 10 years, in FY 2018, the composite rating is 58, and the percent of pavement below 70 is 89%, 54% of which is under 55 (in Bad) and in need of major rehab/reconstruction.

Using the above analysis, we can conclude that the pavement conditions of non-interstate highways in Georgia are not good. With the current traffic load and the pavement deterioration characteristics, the average pavement network will reach poor condition in 4 years if no significant maintenance is applied.

Figure 3. Pavement condition forecasting without preservation
Case II: Pavement Condition Forecasting with M&R Activities

Case I shows that pavement conditions will reach poor condition quickly if no M&R activity is applied. In Case II, pavements are maintained at the current funding level for the next ten years. With different funding allocation methods, the forecast for the long-term pavement conditions changes. The study is to assess if the current funding level is sufficient to maintain the pavement conditions at a desirable level. The difference among Worst First, User Specified, or Optimized can be analyzed and a proper strategy can then be established. The available annual budget from FY 2008 to 2017 remains $185.1 million. Because the pavement conditions in FY 2018 can be derived by the pavement conditions in FY 2017 and the M&R activities applied in FY 2017, the funding is only allocated to FY 2017, just as in case I, for which, FY 2008 is the initial year.

In the study, User Specified is used to forecast the long-term pavement conditions. The method is currently used by GDOT to allocate 10%, 80%, and 10% of total budget for minor preventive maintenance, major preventive maintenance and major rehab/reconstruction respectively (see Figure 6 (b)). Figure 4 (a) and (b) show the trend of pavement composite ratings and the percent of pavements below 70. If the current funding level remains same for the next 10 years, the pavement conditions still keep dropping, though the dropping rate is slower than in Case I. Approximately 2 points of composite rating are lost each year. In FY 2015, the composite rating will drop below 70 and the corresponding percentage is 57% (see the dotted lines in Figure 4 (a) and (b)), which is almost same as the condition in FY 2012 of Case I. In FY 2018, the composite rating is 64 and the percent of pavements below 70 is 73%. Clearly, the current funding level is insufficient to maintain the pavement conditions at a desirable level in the following 10 years. Compared with Case I, the pavement conditions can be extended 3 more years.

Figure 4. Pavement condition forecasting with maintenance
It should be noted that different funding allocation methods have different effects on pavement performance. In the developed PMS models, three methods are developed for pavement performance forecasting: Worst First, User Specified and Optimized. With the Worst First method, the worst pavement gets treated first. The User Specified method allocates funds according to transportation agencies’ experience. Otherwise, the optimization-based method tries to allocate funds by obtaining the maximal network composite rating. Figure 5 compares the results of different strategies with the same input parameters.

As expected, the composite rating drops faster under the Worst First method than other two methods (see Figure 5 (a)). The Optimized method has the best result. The result of User Specified method is in the between, but close to the Optimized one in the first 3 years, after that, the difference is also obvious. As a comparison, in FY 2013, the composite ratings are 70.4, 73.4 and 75.1 for Worst First, User Specified and Optimized respectively (see the dotted line in Figure 5 (a)). The corresponding values for the percent of pavements below 70 are 58%, 43% and 33% (see the dotted line in Figure 5 (b)).

The cause of the difference in pavement performance with different funding allocation methods can be explained from Figure 6. With the Worst First method, after FY 2009, all funds is allocated for the expensive major rehab/reconstruction because the funds are insufficient for recovering all Bad pavements (see Figure 6 (a)). In contrast, the Optimized method always tries to do minor preventive maintenance and major preven-
tive maintenance because they are low-cost compared to major rehab/reconstruction and can outcome higher network composite ratings (see Figure 6 (c)).

Due to the objective of achieving maximal network composite rating, under the Optimized method, Bad pavements cannot get treated because they are too expensive. However, in reality, pavements are not allowed to become unserviceable because of the unacceptable user cost. So, the current optimization model has limitation because the user cost was not considered. Pavement maintenance and preservation is a complicated decision-making process, and it is impossible for a mathematical model to fully handle it. The currently used User Specified method by GDOT is reasonable and practical, although it results in lower pavement composite ratings than the Optimized method. However, the result of the Optimized method can be considered as the upper bound of the network composite rating that can be achieved.

Figure 6. Funding allocations
Case III: Analysis on Pavement M&R Need

The analysis above shows that the current funding level is insufficient to maintain the pavement conditions at a desirable level. In this study, another question is to be answered: how much funding is needed in the following ten years to meet the GDOT’s 85-10% requirements? The objective of this case study is to determine the annual funds needed to maintain the pavements. The initial year is still FY 2008, and the input parameters for Markov TPMs, treatment unit cost, and the average escalation rate are same as in Cases I and II.

Figure 7 shows the analysis results. The initial percent of pavements below 70 in FY 2008 is 17%. So, some pavements in Bad need to be treated in FY 2009 and FY 2010 to decrease the percentage (see Figure 7 (a)).

![Figure 7. Pavement M&R need in 10 years](image)
Consequently, the pavement composite rating increases to 85 in FY 2009 (see Figure 7 (b)) and the percent of pavement below 70 decreases below 10% (see Figure 7 (c)). From Figure 7, it is found that the trend for each figure becomes stable after FY 2012, which is called the steady status in a Markov process. It means that after FY 2012, the pavement condition becomes stable with the unchanged percents of pavements in each state if the available funding can meet the requirements.

Table 4 details the funds needed annually. Apparently, the annual funds increasing rate after FY 2012 is close to 18.1%, which is the average construction cost escalation rate applied in the case study. So, if no escalating rate is considered, the annual funds will also become stable. To bring back the pavement condition to the desirable level, $611.5 million is needed, a $426.4 million shortfall compared to the assumed $185.1 million current budget. Due to construction cost increases, $1.668 billion is needed in FY 2017.

Table 4. Funds needed to meet the 85-10% requirements in ten years

<table>
<thead>
<tr>
<th>Year</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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<tr>
<td>Fund (Million $)</td>
<td>611.5</td>
<td>500.9</td>
<td>412.3</td>
<td>469.1</td>
<td>684.9</td>
<td>836.3</td>
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<table>
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<tr>
<th>Year</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fund (Million $)</td>
<td>1,004.9</td>
<td>1,194.8</td>
<td>1,413.3</td>
<td>1,668.0</td>
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**CONCLUSIONS AND RECOMMENDATIONS**

This paper presents a network-level PMS that was developed for GDOT to forecast long-term pavement conditions and efficiently justify to legislatures the highway pavement maintenance and preservation need. Pavement deterioration is characterized by employing a Markov process model, which is calibrated and verified using the historical pavement condition data and M&R expenditure. Several funding allocation methods are designed and implemented as a computer program, which provides the flexibility for GDOT to perform long-term pavement condition forecasting, long-term pavement M&R need analysis, and other what-if analyses. Though the models and programs are specific for GDOT’s need, their underlying principle and methodology can be extended to other highway agencies’ practice.

Pavement maintenance and preservation is indispensable to extend the pavement service life. Without any M&R activity applied, the Georgia’s non-interstate highway pavement conditions drop very fast, losing almost 2.5 points of composite rating each year. Four years later (FY 2012), with FY 2008 as the initial year, the pavement composite rating will drop to 70. In the meantime, the percent of pavements below 70 is around 57%.

If the current funding level and funding allocation remains same in the following ten years, the pavement conditions still keep dropping, about 2 points per year. Around FY 2015, the composite rating will drop to below 70, and the corresponding percent of pavements below 70 is 57%. Therefore, the current funding level can sustain the pavement conditions for three years longer than the case without any M&R activity. Current funding is seriously insufficient to maintain the pavement network at a constantly serviceable level for a long-term period. The comparison among three funding allocation methods, Worst First, User Specified, and
Optimized, shows that Worst First is the most inefficient method for pavement maintenance and preservation. Optimized shows the best result. However, because some factors, such as user cost, cannot be considered in the mathematical model due to the lack of data support at the current stage, the User Specified strategy currently used by GDOT should be comparable to an optimal solution.

The need analysis shows that the 85-10% requirements are hard to achieve because there is a $426.4 million shortfall in FY 2008 alone, which is two times more than the available budget of $185.1 million. Considering the escalation rate of construction cost (18.1% is assumed in this case), $1.668 billion will be needed in FY 2017.

Pavement maintenance and preservation is a complicated decision-making process. The case studies based on the developed PMS model and the computer program demonstrates the capability to help the decision-making process. Otherwise, further study is still needed. The following suggests some future research:

- The current PMS optimization model uses annual-based linear programming. The results cannot guarantee the optimality during the entire analysis time horizon. To solve this issue, a multi-year optimization model that considers funding allocation for the whole analysis period is needed.
- The accuracy of the long-term pavement performance forecasting and funding need analysis largely depends on the accuracy of the input parameters of the computation model. Further study of the generation of Markov TPMs, the accurate modeling of construction cost escalation, and the unit costs of alternative M&R actions is needed.
- Without considering user cost, cheaper treatments are always the first selection by an optimization model, which in some cases, make less sense in transportation agencies’ practice. It is needed to incorporate a proper user cost model and the corresponding data analysis in the PMS model.
- The current PMS model can be used for network-level planning and programming. However, the detailed project-level programming cannot be handled. To link the project-level programming and the network-level planning, a segment-linked PMS model is needed.

**REFERENCES**


