Expected Performance of Pavement Repair Works in a Global Network Optimization Model

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Expected Performance of Pavement Repair Works in a Global Network Optimization Model

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Abstract: A global network optimization model has been developed for generating a pavement repair plan using expected performance of pavement repair works. The expected performance of pavement repair works is represented by the expected age (service life) associated with potential repair actions. The expected age defines the anticipated pavement condition improvement obtained from applying a particular repair action. The expected age for each repair action is usually known from either experience or assumed as part of a design procedure. A constrained linear optimization model is formulated with its main objective of optimizing the expected pavement condition improvement. Pavement condition improvement is defined as the age gain in year lane kilometer or average age in years extended to a pavement network as a result of applying potential repair actions. The global linear model is subjected to a single budget constraint enforcing the total budget available for the entire network and limitation constraints placing lower and upper limits on the repair variables. The optimum repair plan provides a macroscopic solution as the repair variables represent pavement proportions that should be treated by the corresponding repair actions. The pavement network is divided into a number of systems with similar pavement structures and loading conditions. Presented sample results have indicated that global network optimization of the pavement management problem may not result in a rational budget allocation among deployed pavement systems. This problem can be solved by enforcing system improvement requirement constraints.

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Introduction

The pavement management problem is considered extremely complex if it is to be solved in its totality. Some of the main reasons making it so are the need for an effective pavement performance prediction model, the need for extensive historical pavement distress records, the resulting large number of repair variables that should be considered in a reliable optimization method, an appropriate decision policy, and the effective integration of these main elements in a single entity called the pavement management system (Way et al. 1982; Harper and Majidzadeh 1991; Hill et al. 1991; Tavakoli et al. 1992; Shahin 1994; Abaza and Ashur 1999; Pilson et al. 1999; Abaza et al. 2001, 2004; Ferreira et al. 2002). Repair variables are typically introduced to represent potential pavement repair actions which are usually classified as either maintenance or rehabilitation actions. Maintenance actions are associated with shorter expected ages (service lives) compared to the rehabilitation actions which provide for much longer expected service lives. However, the cost rates associated with maintenance actions are much lower than the cost rates for rehabilitation actions.

Probably, the major drawback in solving the pavement management problem remains to be the associated large number of repair variables and the convergence of the deployed optimization method into a global optimum solution (Harper and Majidzadeh 1991; Pilson et al. 1999; Abaza et al. 2001, 2004; Ferreira et al. 2002). Therefore, some of the developed pavement management systems attempted to solve this problem by substantially reducing the number of deployed repair variables and/or utilizing a macroscopic approach rather than a microscopic one (Abaza and Ashur 1999; Abaza et al. 2001, 2004). In the macroscopic approach, the repair variables are introduced for each pavement class and they represent the proportions of pavement that should be treated by the applicable repair actions (Grivas et al. 1993; Chen et al. 1996; Liu and Wang 1996). The microscopic approach applies the repair actions to each pavement section or project resulting in a much larger number of variables, thus, making the optimization process extremely difficult (Shahin 1994; Pilson et al. 1999; Ferreira et al. 2002).

The optimization process can be further complicated if the formulated model is nonlinear in form, which restricts the number of repair variables to be used. Also, the number of deployed repair variables would substantially increase if a global solution at the network level is required. The resulting number of repair variables typically becomes large as different repair actions are applied to pavement classes in the various deployed pavement systems. In a global approach to pavement management, only the total budget projected for the entire pavement network is specified. But a key advantage is being able to obtain an optimum allocation of repair funds among the deployed pavement systems. In addition, a global optimum solution based on an effective decision policy may provide a pavement network with the best overall repair solution plan. Another major drawback associated with solving the pavement management problem is the need for a reliable performance prediction model if a long-term repair solution

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plan is sought at the network level. Such a prediction model requires extensive historical records of pavement distress to be effective (Pedigo et al. 1982; Way et al. 1982; Butt et al. 1987; Shahin et al. 1987; George et al. 1989; Abaza and Ashur 1999). However, a short-term repair plan as proposed in this paper can be achieved without the need for a pavement performance prediction model. A long-term repair plan comprises a number of time intervals, whereas a short-term repair plan only includes a one time interval preferably not to exceed 2 years as pavement conditions change with time.

Methodology

The developed global network optimization model (GNOM) applies the macroscopic approach in which the repair variables represent the proportions of pavement that should be treated by the corresponding repair actions. The developed global GNOM model generates a macroscopic repair solution plan and also yields optimum budget allocation for a given pavement network. The model uses a simple but very effective long-term measure of pavement condition improvement. The measure of pavement condition improvement used is the expected age of deployed repair actions, which is readily available. Therefore, the developed global GNOM model can be treated as a simple pavement management system since it does not require the incorporation of a complex pavement performance prediction model. This is a major advantage, especially to local governments that do not possess the needed resources and technologies to develop and maintain advanced pavement performance prediction models.

The developed global network optimization model is designed to solve the pavement management problem globally by formulating it as a constrained linear optimization model. Linear optimization methods can handle a much larger number of variables and provide more reliable solutions when compared to nonlinear methods of optimization (Phillips et al. 1976; Bazaraa and Shetty et al. 1979). The global GNOM model is mainly intended to generate an optimum repair plan that when applied produces the best overall pavement conditions. The required input data mainly consist of the total projected network budget, number of considered pavement systems, number of pavement classes in a given system, size of each deployed pavement system, present pavement distress condition of each class as obtained from one cycle of field inspection, number of repair actions to be applied to each class, cost rate of each repair action, and the expected age (service life) associated with each repair action.

GNOM Formulation

The developed global GNOM model is potentially designed to solve the pavement management problem considering the network level. Modeling the pavement management problem has been typically addressed using two different approaches (Harper and Majidzadeh 1991; Shahin 1994; Abaza and Ashur 1999; Abaza et al. 2004). The first approach aims to maximize the overall pavement conditions subjected to budget constraints, while the second approach aims to minimize the total repair cost subjected to certain pavement condition improvement constraints. Both management approaches are presented below as part of the global network optimization model formulation.

The global network optimization model is designed as a constrained linear optimization model subjected to linear constraints. In the formulation of the global GNOM model, separate models will be presented for the first management approach which maximizes pavement condition improvement and the second approach which minimizes total repair cost for a given network. The two proposed models require similar input parameters but they have different objective functions and constraints. Both models have linear objective functions and linear constraints.

Global Network Age-Gain Maximization Model

The objective of the first management approach is maximizing the pavement condition improvement that can take place on a given pavement network as a result of maintenance and rehabilitation works. The pavement condition improvement is defined as the net gain in age (i.e., extended service life) that can be added to a pavement network in the unit of year lane kilometer. The age gain unit of year lane kilometer is obtained from multiplying the expected age in years associated with a particular repair action by the length of the treated pavement in lane kilometers. The expected ages (A_{ijk}) of various deployed repair actions are the main pavement condition improvement indicators used in the formulation of the model objective function. The expected ages (service lives) of maintenance actions are estimated from experience and/or obtained by referring to maintenance files, whereas the expected ages of rehabilitation actions are typically assumed as required by the applied design procedure whether it involves the design of plain overlay or new design as in the case of reconstruction.

The pavement network is divided into a number of systems (n) with similar pavement structures and traffic conditions. The ith system is also divided into a number of pavement classes (s_i). A number of repair actions (m_{ij}) can be applied to the jth class in the ith system. The objective function of the first approach model represents the net age gain extended to the entire pavement network as indicated by Eq. (1) which is to be maximized. Each deployed repair action is represented by its own repair variable (X_{ijk}) which represents a proportion, in decimal form, of the pavement length (lane kilometer) in the jth class in the ith system that should be treated by the kth repair action. The existing proportion of pavement (P_{ij}) as a percentage associated with the jth class in the ith system, which can be obtained from conducting one cycle of field inspection of pavement distress, is used to determine the pavement length in the respective class by multiplying it by the system length (L_i). The existing pavement class length is then multiplied by the variable proportion (X_{ijk}) as a decimal to determine the class length portion to be treated by the corresponding repair action. Therefore, Eq. (1) simply provides a summation of the total age gain in year lane kilometer extended to a pavement network obtained from multiplying the expected ages (A_{ijk}) in years by the relevant class length portions in lane kilometers to be treated by the various applicable repair actions

$$G_N = \sum_{i=1}^{n} G_i = \sum_{i=1}^{n} \sum_{j=1}^{s_i} \sum_{k=1}^{m_{ij}} \left(\frac{L_i P_{ij}}{100}\right) A_{ijk} X_{ijk} \tag{1}$$

where G_N=total network age gain (year lane km); G_i=age gain (year lane km) extended to the ith system; L_i=length of the ith system in lane km; P_{ij}=proportion of pavement in the jth class in the ith system in percentage; A_{ijk}=expected age (years) associated with the kth repair action as applied to the jth class in the ith system; X_{ijk}=repair variable representing a proportion of the pavement length (lane km), in decimal form, in the jth class in the ith system to be treated by the kth repair action; n=number of deployed pavement systems; s_i=number of deployed pavement classes in the ith system; and m_{ij}=number of deployed repair actions (variables) for the jth class in the ith system.

The presented linear objective function, Eq. (1), can be subjected to five possible sets of linear constraints. The first set is the cost constraint set which represents the total cost associated with the repair actions applied to the entire pavement network. This total cost is required to be less than or equal to the total projected network budget (B_N), in United States dollars (USD), as provided in Eq. (2). This cost constraint involves most of the previously defined parameters plus the unit cost rate (C_{ijk}) associated with each repair action in USD per square meter of surface area, therefore, the system lane width (W_i), in meters, is introduced to Eq. (2). A set of budget constraints equal to the number of deployed systems can be used if the budget associated with each system is to be individually specified, but in a global optimization only one cost constraint is used representing the total projected repair budget

$$\sum_{i=1}^{n}\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{W_i(L_i\times 10^3)P_{ij}}{100}\right)C_{ijk}X_{ijk}\leqslant B_N \tag{2}$$

The age gain extended to a particular pavement system (G_i) is defined in Eq. (3). It represents the total improvement extended to a particular pavement system in year lane kilometer. The system age gain (G_i) is to be used in establishing pavement condition improvement requirement constraints among various deployed systems when a global optimum repair plan is sought at the network level. Alternatively, the system average age (A_i) can be used which is defined as the system age gain (G_i) divided by the system length (L_i) as indicated by Eq. (4). The system average age (A_i) represents the extension in service life that can be added to the ith pavement system in years as a result of implementing the derived optimum repair solution plan at the network level

$$G_i=\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{L_iP_{ij}}{100}\right)A_{ijk}X_{ijk}\quad (i=1,2,\ldots,n) \tag{3}$$

$$A_i=\frac{G_i}{L_i}=\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{P_{ij}}{100}\right)A_{ijk}X_{ijk}\quad (i=1,2,\ldots,n) \tag{4}$$

The second set of constraints is an optional one which specifies desired system condition improvement requirements either in terms of age gain or average age. Eq. (5) requires the system age gain to be greater than or equal to a specified desired age gain (SG_i). Similarly, Eq. (6) requires the system average age to be greater than or equal to a specified desired average age (SA_i)

$$\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{L_iP_{ij}}{100}\right)A_{ijk}X_{ijk}\geqslant \mathrm{SG}_i\quad (i=1,2,\ldots,n) \tag{5}$$

$$\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{P_{ij}}{100}\right)A_{ijk}X_{ijk}\geqslant \mathrm{SA}_i\quad (i=1,2,\ldots,n) \tag{6}$$

The third set of constraints is another optional one that requires equal condition improvements among the deployed pavement systems. This can be achieved by requiring equal age gain among the deployed systems as provided in Eq. (7). Alternatively, it can be achieved by requiring equal system average age as indicated by Eq. (8). The result is $(n-1)$ equality constraints which would assure equal condition improvements in age gain or average age for all pavement systems. Again, this is an optional constraint set that can be easily modified to include unequal system condition improvement constraints. Unequal system improvement constraints can be defined as required by multiplying the system improvement indicators (G_{i+1} and A_{i+1}) on the right side of Eqs. (7) and (8) by appropriate constant coefficients

$$G_i=G_{i+1}\quad (i=1,2,\ldots,n-1) \tag{7}$$

$$A_i=A_{i+1}\quad (i=1,2,\ldots,n-1) \tag{8}$$

The forth set of constraints is the limitation constraints placing upper limits on the deployed repair variables as indicated by Eq. (9). The sum of all repair variables as applied to the jth class in the ith system shall not exceed one as each variable represents a proportion of that pavement class length, in decimal form, to be treated by the corresponding repair action. The fifth set of constraints is the non-negativity constraints placed on all repair variables as defined in Eq. (10)

$$\sum_{k=1}^{m_{ij}}X_{ijk}\leqslant 1.0\quad (i=1,2,\ldots,n;\quad j=1,2,\ldots,s_i) \tag{9}$$

$$X_{ijk}\geqslant 0\quad (i=1,2,\ldots,n;\quad j=1,2,\ldots,s_i;\quad k=1,2,\ldots,m_{ij}) \tag{10}$$

Therefore, the presented optimization model has five possible sets of linear constraints. The formulated global network optimization model for the first management approach can be summarized as provided in Eq. (11). Logically, the model can only include one of the two optional constraint sets, namely, sets (2) and (3). Optimization of such a model can be easily obtained, even for a large number of repair variables, using commercially available linear programming software packages

Maximize

$$G_N=\sum_{i=1}^{n}G_i=\sum_{l=1}^{n}\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{L_iP_{ij}}{100}\right)A_{ijk}X_{ijk} \tag{11}$$

Subject to

$$(1)\quad \sum_{i=1}^{n}\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{W_i(L_i\times 10^3)P_{ij}}{100}\right)C_{ijk}X_{ijk}\leqslant B_N$$

$$(2)\quad \sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{L_iP_{ij}}{100}\right)A_{ijk}X_{ijk}\geqslant \mathrm{SG}_i\quad (i=1,2,\ldots,n)$$

or

$$\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{P_{ij}}{100}\right)A_{ijk}X_{ijk}\geqslant \mathrm{SA}_i\quad (i=1,2,\ldots,n)$$

$$(3)\quad G_i=G_{i+1}\quad (i=1,2,\ldots,n-1)$$

or

$$A_i=A_{i+1}\quad (i=1,2,\ldots,n-1)$$

$$(4)\quad \sum_{k=1}^{m_{ij}}X_{ijk}\leqslant 1.0\quad (i=1,2,\ldots,n;\quad j=1,2,\ldots,s_i)$$

$$(5)\quad X_{ijk}\geqslant 0\quad (i=1,2,\ldots,n;\quad j=1,2,\ldots,s_i;\quad k=1,2,\ldots,m_{ij})$$

Global Network Repair Cost Minimization Model

The objective in the second management approach used by the global GNOM model is minimizing the total network cost associated with the deployed repair actions subjected to certain pavement condition improvement constraints. The resulting optimization model has some similarities when compared to the first management approach model in which the objective function associated with the second approach model is the global cost constraint associated with the first approach model excluding the budget parameter. The constrained linear optimization model associated with the second management approach is presented in Eq. (12).

Minimize

$$C_N=\sum_{i=1}^{n}\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{W_i(L_i\times 10^3)P_{ij}}{100}\right)C_{ijk}X_{ijk} \tag{12}$$

Subject to

$$(1)\quad \sum_{i=1}^{n}G_i=\sum_{l=1}^{n}\sum_{j=1}^{S_i}\sum_{k=1}^{m_{ij}}\left(\frac{L_iP_{ij}}{100}\right)A_{ijk}X_{ijk}\geqslant \mathrm{SG}_N$$

$$(2)\quad \sum_{i=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{L_iP_{ij}}{100}\right)A_{ijk}X_{ijk}\geqslant \mathrm{SG}_i\quad (i=1,2,\ldots,n)$$

or

$$\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{P_{ij}}{100}\right)A_{ijk}X_{ijk}\geqslant \mathrm{SA}_i\quad (i=1,2,\ldots,n)$$

$$(3)\quad G_i=G_{i+1}\quad (i=1,2,\ldots,n-1)$$

or

$$A_i=A_{i+1}\quad (i=1,2\ldots,n-1)$$

$$(4)\quad \sum_{k=1}^{m_{ij}}X_{ijk}\leqslant 1.0\quad (i=1,2,\ldots,n;\quad j=1,2,\ldots,s_i)$$

$$(5)\quad X_{ijk}\geqslant 0\quad (i=1,2,\ldots,n;\quad j=1,2,\ldots,s_i;\quad k=1,2,\ldots,m_{ij})$$

where C_N=total network cost associated with the deployed repair actions in USD; and SG_N=specified desired network age gain in year lane km.

The first constraint set is a single improvement requirement constraint which has a form similar to the objective function used in the first management approach model except that a desired network age gain is specified. In the second set of constraints, a desired condition improvement is specified for each pavement system either in terms of age gain or average age. The third constraint set requires equal pavement condition improvements among the deployed systems either in terms of age gain or average age. Logically, the minimization model can only include one of the first three listed improvement constraint sets. The fourth and fifth constraint sets are the same ones used in the maximization model. The minimization model mainly used with its first listed constraint would be equivalent to the maximization model used with its first listed constraint.

Global Network Optimum Budget Allocation

A major outcome of applying the developed first management approach GNOM model is being able to make an optimal allocation of the projected repair funds among the deployed pavement systems. This can be readily obtained once the formulated constrained linear optimization model is solved. The optimum budget to be allocated for each system is obtained from the optimal values associated with the repair variables as stated in Eq. (13*a*). Similarly, the optimum budget allocated for a particular pavement class in a particular system can be determined as provided in Eq. (13*b*). The sum of the optimum system budgets must be equal to the optimum total network repair cost which is less than or equal to the total allocated network budget as indicated by Eq. (13*c*)

$$B_i^*=\sum_{j=1}^{s_i}\sum_{k=1}^{m_{ij}}\left(\frac{W_i(L_i\times 10^3)P_{ij}}{100}\right)C_{ijk}X_{ijk}^*\quad (i=1,2,\ldots,n) \tag{13a}$$

$$B_{ij}^*=\sum_{k=1}^{m_{ij}}\left(\frac{W_i(L_i\times 10^3)P_{ij}}{100}\right)C_{ijk}X_{ijk}^*\quad (i=1,2,\ldots,n;\ j=1,2,\ldots,s_i) \tag{13b}$$

$$C_N^*=\sum_{i=1}^{n}B_i^*=\sum_{i=1}^{n}\sum_{j=i}^{s_i}B_{ij}^*\leqslant B_N \tag{13c}$$

where B_i^*=optimum budget allocated to the ith system; B_{ij}^*=optimum budget allocated to the jth class in the ith system; C_N^*=optimum total network repair cost; and X_{ijk}^*=optimum values associated with the deployed repair variables.

Eq. (13) can also be solved using the optimal values of the repair variables obtained from the second management approach GNOM model. The optimal budget values in this case are the minimum values required for the implementation of the derived optimum repair solution plan determined according to specified pavement condition improvement requirements.

Global Network Optimization Model Requirements

Application of the developed global GNOM model to a given pavement network requires the local agency to prepare the needed input data as outlined in the formulation of the optimum models associated with the two presented management approaches. A summary of data requirements is provided in this section for a given pavement network.

1. The network is divided into a number of pavement systems consistent with the roadway classification systems used. The systems should have similar pavement structures and loading conditions. Therefore, designating a pavement system for each roadway classification system would greatly achieve that objective. Typically, a small local government may only need three pavement systems for the arterial, collector, and local road systems.
2. Each pavement system is to be divided into a number of pavement classes with each class containing pavements with similar distress conditions. The selected number of pavement classes should be appropriate for the proposed repair actions. The objective is to assign repair actions that would be appropriate for the state of distress in a particular pavement class. The expected number of pavement classes for a small local

Table 1. Pavement Class Proportions and Pavement System Dimensions

Pavement system	Pavement class proportion (P_{ij}) (%) $j=1$	$j=2$	$j=3$	ΣP_{ij}	L_i (lane km)	W_i (m)
Local ($i=1$)	21.0	22.0	24.0	67.0	350	3.6
Collector ($i=2$)	20.0	18.0	17.0	55.0	200	3.6
Arterial ($i=3$)	19.0	15.0	11.0	45.0	100	3.6

government is suggested to be about five classes designated very good, good, fair, poor, and bad. The pavement classes that qualify for repair actions may only be three or four classes out of five.

3. An appropriate number of repair actions should be specified for each pavement class. Different maintenance and rehabilitation actions are required for each pavement class. Maintenance actions have lower cost rates but provide smaller gain in age when compared to rehabilitation actions. Maintenance actions applied to classes with severe pavement distress are more costly and probably do not last that long, especially on heavily traveled roads. Similarly, rehabilitation actions appropriate for pavement classes with severe distress are much more costly but provide longer service life.
4. One cycle of field survey of pavement distress is required. The main outcome of this survey is estimating the proportion of pavement in each class as a percentage of the total system length. Assigning pavements to various classes must be done based on well-defined criteria that take into account the severity and extent of prevailing pavement defects, which can be determined using visual inspection and simple related measurements.
5. Estimating the unit cost rate, in USD per square meter of surface area, associated with each proposed repair action. The cost rates are to be estimated based on local market prices and similarly performed repair works.
6. Estimating the expected age (service life), in years, associated with each proposed repair action. The expected age associated with each maintenance action can be obtained from either experience or historical maintenance records. The expected age for most maintenance actions may not exceed 3 years, whereas, the expected age for rehabilitation actions typically exceeds 5 years as usually required by the United States government to qualify for federal aid. The expected age of a particular rehabilitation action is usually assumed for design purposes. A plain overlay is typically designed for 10 years and a new design may be for 15 or 20 years.
7. Applying the global GNOM model associated with maximizing the pavement network age gain requires allocating the total budget available for the entire network. This projected budget is used to implement the derived optimum repair solution plan within a limited short-time period not exceeding 2 years as pavement distress conditions change with time. However, the GNOM model can be applied as often as needed using new input data that would reflect the changes that have taken place on the pavement network, thus resulting in a revised optimum repair plan.
8. Applying the global GNOM model associated with minimizing the total network repair cost requires only specifying certain pavement condition improvement requirements. These improvement requirements can be done in three ways: (1) specifying a global network desired age gain; (2) specifying desired age gain or average age for each system; or (3) assigning age gain or average age relations among the deployed systems similar to the presented equal improvement relationships.
9. Formulating the corresponding constrained linear optimization problem can be performed using the general models presented earlier for the two management approaches. The optimal solution for a linear optimization problem can be obtained using one of the commercially available software packages for operations research. These software packages provide very effective solutions by applying the simplex method or revised simplex method to solve a particular problem (Phillips et al. 1976; Bazaraa and Shetty 1979).

Sample Presentation

A sample application of the global GNOM model at the network level is presented using the two outlined management approaches. A medium size pavement network is presented using reasonably estimated input data. The network is divided into three pavement systems representing the three typical local, collector, and arterial road classification systems and subscribed 1, 2, and 3, respectively. Three pavement classes requiring repair actions, donated fair, poor, and bad, and subscribed 1, 2, and 3, respectively, are assumed for each system. The very good and good pavement classes are not considered for repair works. Two repair actions are assumed for each pavement class with the first action being the maintenance one and the second action being the rehabilitation one, and subscribed 1 and 2, respectively. Typically, repair actions are associated with different cost rates and expected service lives as applied to each class depending on the severity and extent of pavement distress conditions. For example, potential rehabilitation actions are plain overlay, skin patch, and reconstruction, which are applicable to pavement Classes 1, 2, and 3, respectively.

The estimated input data for the presented sample network are provided in two tables. Table 1 provides the pavement proportion associated with each class in percentage as typically obtained from conducting one cycle of field inspection of pavement distress. The sum of pavement class proportions needing repair work is lower for systems with higher subscript numbers as would be expected. The table also provides the total length associated with each pavement system in lane kilometer (lane km) and the typical lane width of 3.6 m. Table 2 provides the expected age and cost rate associated with each repair action as estimated from local repair records and market prices, respectively. Generally, the expected ages for rehabilitation actions are much higher than the expected ages for maintenance actions, and the corresponding cost rates are substantially higher. It should be noted that for each system the expected age and cost rate are higher with higher

Table 2. Expected Ages and Cost Rates Associated with Deployed Repair Actions

Repair parameter		First action ($k=1$)			Second action ($k=2$)		
		$j=1$	$j=2$	$j=3$	$j=1$	$j=2$	$j=3$
Expected age (A_{ijk}) (years)	$i=1$	1.0	1.5	2.0	10.0	15.0	20.0
	$i=2$	1.0	1.5	2.0	10.0	15.0	20.0
	$i=3$	1.0	1.5	2.0	10.0	15.0	20.0
Cost rate (C_{ijk}) (United States dollars/m^2)	$i=1$	1.0	2.0	3.0	8.0	15.0	25.0
	$i=2$	1.5	2.5	3.5	10.0	20.0	35.0
	$i=3$	2.0	3.0	4.0	12.0	25.0	45.0

degree of pavement distress considering the same repair action. It is further noted that for each pavement class the expected ages are constant regardless of the system type, and the corresponding cost rates are higher for a higher system subscript number. The input data presented have been used to formulate sample global GNOM models for the first management approach which maximizes the pavement network age gain and for the second management approach which minimizes the total network repair cost.

Sample Global Network Age-Gain Maximization Model

The first sample global GNOM model is formulated to maximize the pavement network age gain as provided in Fig. 1. The associated objective function and constraints are presented in such a way that the variable coefficients and other constants can be easily traced to the input data presented in Tables 1 and 2. The model contains 18 repair variables, one global budget constraint with the allocated budget value (B_N) left variable, two equal system average improvement age constraints, nine upper limit constraints, and the non-negativity constraints. The last variable subscript number indicates "1" for maintenance action and "2" for rehabilitation action. The formulated model has been solved for different budget values with and without using the equal system improvement constraints.

Table 3 provides sample optimal solutions obtained excluding the two equal system average improvement age constraints. Examination of the optimal solutions reveals two key observations. The first one indicates that the variables representing rehabilitation actions have dominated the optimal solutions for all specified budget values. Table 3 shows that all optimal repair plans consist entirely of rehabilitation actions; those variables with "2" as the last subscript number, with the exception of one maintenance variable (X_{331}). This states that the expected network improvement based on the estimated expected ages and cost rates is best achieved if mostly rehabilitation actions are used. This trend can be changed if the expected ages associated with the deployed maintenance actions are increased and/or their corresponding cost rates are decreased. The second observation is the unreasonable allocation of repair works and consequently budget among the three deployed pavement systems. The optimum budget allocations among the three deployed systems are given in Table 4 based on the optimal solutions provided in Table 3. The table shows that the specified network budget is heavily allocated to the local system when generating a global solution for the pavement management problem. This is because most deployed input parameters favor the local system including its larger length, higher sum of pavement distress proportions, and lower repair cost rates. Therefore, a global optimal solution for budget allocation may not be a practical one given the input data used.

Table 5 provides optimal solutions similar to the ones presented in Table 3 but using the equal system average improvement age constraints as defined in Eq. (8). The result is two additional equality constraints which are represented by constraint set number (2) in Fig. 1. Table 5 shows that the rehabilitation variables have continued to dominate the optimal solutions but the number of contributing maintenance variables has increased to five. The feasible maximum network repair cost (C_N^*) as provided in Table 5 is 20.23 million USD obtained using a network budget of 25 million USD. Table 6 provides the corresponding optimum budget allocations among the three deployed systems which are much more reasonable than the ones provided in Table 4. The heaviest traveled arterial system, which is also associated with the highest repair cost rates, may now be getting its fair share of repair funds.

Tables 3 and 5 also provide at the bottom a summary of crucial optimal network improvement indicators. They include the optimal network age gain (G_N^*), the optimal network average improvement age (A_N^*) in years obtained from dividing the optimal network age gain by the network length (L_N=650 lane km, the optimal network repair cost (C_N^*), and the optimal network average repair cost ($\bar{C}_N^*$), in USD per year lane km, determined from dividing the optimal network repair cost by the optimal network age gain. It can be noted that the increase rate in the optimal network age gain or average improvement age is not proportional to the increase rate in the allocated budget. It can also be noted that the optimal network average repair cost (USD/lane km) increases with the increase in allocated budget. The explanation for these two observations is related to the optimization process which has generally resulted in an increase in the number of utilized repair variables with the increase in budget. The optimization process selects the most cost effective repair actions when lower budgets are assigned; however, the least cost effective repair actions are used when deploying higher budgets. Cost effec-

Maximize:

$$\begin{aligned} G_N = {} & 73.5(1X_{111}+10X_{112})+77.0(1.5X_{121}+15X_{122})+84.0(2X_{131}+20X_{132})+ \\ & 40.0(1X_{211}+10X_{212})+36.0(1.5X_{221}+15X_{222})+34.0(2X_{231}+20X_{232})+ \\ & 19.0(1X_{311}+10X_{312})+15.0(1.5X_{321}+15X_{322})+11.0(2X_{331}+20X_{332}) \end{aligned}$$

Subject to:

$$\begin{aligned} 1)\ & 73.5(1X_{111}+8X_{112})+77.0(2X_{121}+15X_{122})+84.0(3X_{131}+25X_{132})+ \\ & 40.0(1.5X_{211}+10X_{212})+36.0(2.5X_{221}+20X_{222})+34.0(3.5X_{231}+35X_{232})+ \\ & 19.0(2X_{311}+12X_{312})+15.0(3X_{321}+25X_{322})+11.0(4X_{331}+45X_{332}) \\ & \le B_N/(3.6 \times 1000) \end{aligned}$$

$$\begin{aligned} 2)\ & [73.5(1X_{111}+10X_{112})+77.0(1.5X_{121}+15X_{122})+84.0(2X_{131}+20X_{132})]/350 \\ & = [40.0(1X_{211}+10X_{212})+36.0(1.5X_{221}+15X_{222})+34.0(2X_{231}+20X_{232})]/150; \\ & [40.0(1X_{211}+10X_{212})+36.0(1.5X_{221}+15X_{222})+34.0(2X_{231}+20X_{232})]/150 \\ & = [19.0(1X_{311}+10X_{312})+15.0(1.5X_{321}+15X_{322})+11.0(2X_{331}+20X_{332})]/100 \end{aligned}$$

$$\begin{aligned} 3)\ & X_{111}+X_{112} \le 1.0; \quad X_{121}+X_{122} \le 1.0; \quad X_{131}+X_{132} \le 1.0 \\ & X_{211}+X_{212} \le 1.0; \quad X_{221}+X_{222} \le 1.0; \quad X_{231}+X_{232} \le 1.0 \\ & X_{311}+X_{312} \le 1.0; \quad X_{321}+X_{322} \le 1.0; \quad X_{331}+X_{332} \le 1.0 \end{aligned}$$

$$4)\ X_{ijk} \ge 0 \quad (\text{for } i=1,2,3;\ j=1,2,3; \text{ and } k=1,2)$$

Fig. 1. Sample global GNOM model for maximizing pavement network age gain

Table 3. Optimum Repair Solution Plans for Maximizing Network Age Gain without System Improvement Requirements

Repair variable	Network budget (B_N) (million United State dollars) 1.0	5.0	10.0	15.0	20.0	25.0
X_{111}	0.000	0.000	0.000	0.000	0.000	0.000
X_{112}	0.472	1.000	1.000	1.000	1.000	1.000
X_{121}	0.000	0.000	0.000	0.000	0.000	0.000
X_{122}	0.000	0.347	1.000	1.000	1.000	1.000
X_{131}	0.000	0.00	0.000	0.000	0.000	0.000
X_{132}	0.000	0.00	0.194	0.855	1.000	1.000
X_{211}	0.000	0.00	0.000	0.000	0.000	0.000
X_{212}	0.000	1.000	1.000	1.000	1.000	1.000
X_{221}	0.000	0.000	0.000	0.000	0.000	0.000
X_{222}	0.000	0.000	0.000	0.000	1.000	1.000
X_{231}	0.000	0.000	0.000	0.000	0.000	0.000
X_{232}	0.000	0.000	0.000	0.000	0.000	1.000
X_{311}	0.000	0.000	0.000	0.000	0.000	0.000
X_{312}	0.000	0.000	1.000	1.000	1.000	1.000
X_{321}	0.000	0.000	0.000	0.000	0.000	0.000
X_{322}	0.000	0.000	0.000	0.000	0.972	1.000
X_{331}	0.000	0.000	0.000	0.000	0.000	0.680
X_{332}	0.000	0.000	0.000	0.000	0.000	0.320
G_N^* (year lane km)	347	1,536	2,805	3,917	4,919	5,690
A_N^* (years)	0.534	2.363	4.315	6.026	7.569	8.754
C_N^* (million United States dollars)	1.0	5.0	10.0	15.0	20.0	25.0
$\bar{C}_N^*$ (United States dollars/year lane km)	2,882	3,255	3,565	3,829	4,066	4,394

tiveness for a particular repair action is defined as the ratio of its expected age (years) to its cost rate (USD/m^2). For example, the repair variable (X_{332}) representing the least cost effective repair action has only been used according to Table 3 when the assigned network budget reached 25 million USD. This is because it has the lowest cost effectiveness ratio of 0.444 year m^2/USD.

Sample Global Network Repair Cost Minimization Model

The second sample global GNOM model is formulated based on the outlined second management approach which minimizes the total repair cost associated with the presented pavement network. The formulated model is presented in Fig. 2 using the same input data provided in Tables 1 and 2. The model objective function is the cost constraint provided in Fig. 1 excluding the budget parameter, and the model is subjected to two pavement condition improvement constraint sets. The first constraint set consists of one global age gain constraint which requires the network age gain to be greater than or equal to a specified desired network age gain (SG_N) left variable. The second constraint set includes three system average age constraints which require the average improvement age of each system to be greater than or equal to a specified fixed average age (SA_i) left also variable. The minimization model is also subjected to two additional constraint sets placing limits on the repair variables which are the same ones used in the maximization model. The two improvement constraint sets are selected as outlined so that two minimization models compatible to the two maximization models presented in Tables 3 and 5 can be investigated.

The first sample minimization model is mainly subjected to one global network improvement constraint which requires the network age gain to be greater than or equal to a specified fixed age gain. This model has been solved by assuming the fixed net-

Table 4. Optimum System Budget Allocation for Maximizing Network Age Gain without System Improvement Requirements

Pavement system	Network budget (B_N) (million United States dollars) 1.0	5.0	10.0	15.0	20.0	25.0
Local (i=1)	1.00	3.56	7.74	12.74	13.84	13.84
Collector (i=2)	0.00	1.44	1.44	1.44	4.03	8.32
Arterial (i=3)	0.00	0.00	0.82	0.82	2.13	2.84
Total	1.0	5.0	10.0	15.0	20.0	25.0

Table 5. Optimum Repair Solution Plans for Maximizing Network Age Gain with Equal System Average Age Requirements

Repair variable	Network budget (B_N) (million United States dollar) 1.0	5.0	10.0	15.0	20.0	25.0
X_{111}	0.000	0.000	0.000	0.000	0.000	0.000
X_{112}	0.220	1.000	1.000	1.000	0.000	0.000
X_{121}	0.000	0.000	0.000	0.000	0.589	0.589
X_{122}	0.000	0.044	0.581	1.000	0.411	0.411
X_{131}	0.000	0.000	0.000	0.000	0.000	0.000
X_{132}	0.000	0.000	0.000	0.036	1.000	1.000
X_{211}	0.000	0.000	0.000	0.000	0.000	0.000
X_{212}	0.231	1.000	1.000	1.000	1.000	1.000
X_{221}	0.000	0.000	0.000	0.000	0.000	0.720
X_{222}	0.000	0.090	0.747	1.000	0.579	0.280
X_{231}	0.000	0.000	0.000	0.000	0.000	0.000
X_{232}	0.000	0.000	0.000	0.257	0.820	1.000
X_{311}	0.000	0.000	0.000	0.000	0.000	0.000
X_{312}	0.244	1.000	1.000	1.000	1.000	1.000
X_{321}	0.000	0.000	0.000	0.000	0.000	0.000
X_{322}	0.000	0.153	0.941	1.000	1.000	1.000
X_{331}	0.000	0.000	0.000	0.392	0.000	0.000
X_{332}	0.000	0.000	0.000	0.608	1.000	1.000
G_N^* (year lane km)	301	1,459	2,611	3,623	4,128	4,128
A_N^* (years)	0.463	2.244	4.017	5.574	6.351	6.351
C_N^* (million United States dollars)	1.00	5.00	10.0	15.0	20.00	20.23
$\bar{C}_N^*$ (United States dollars/year lane km)	3,322	3,427	3,830	4,140	4,845	4,901

work age gain (SG_N) to be equal to the optimal network age gain (G_N^*) values associated with the optimal repair solution plans provided in Table 3. The sample optimal repair solution plans for the first minimization model are provided in Table 7. Table 7 indicates that the resulting optimal repair plans are associated with the same identical solutions provided in Table 3 with the same optimal network age gains and total repair costs. The second sample minimization model is mainly subjected to three system average improvement age constraints with each constraint requiring the system fixed average age (SA_i) to be equal to the optimal system average age values (A_i^*) associated with the optimal repair solution plans provided in Table 5. Table 8 provides the resulting optimal repair plans which are again associated with the same identical solutions provided in Table 5 with the same optimal system average ages and total repair costs. The two presented sample minimization models clearly indicate that both maximization and minimization models can be formulated to be equivalent.

Implementation of a particular optimal repair variable will result in improving the pavement condition of only the relevant class portion receiving the corresponding repair action. For example, one of the optimal values of variable (X_{132}) provided in Table 3 is 0.194 which means the class 3 portion in system 1 that will be receiving the corresponding rehabilitation action is 19.4% of the total class length of 84 lane km. The corresponding rehabilitation action (reconstruction) has an expected age of 20 years which would result in a class age gain of 325.92 year lane km or a class average improvement age of 3.88 years. Similarly, the present network average age (service life) will be increased by an amount that is equal to the optimal network average improvement age (A_N^*). The presented optimal solutions associated with the sample formulated GNOM models have been obtained using a software package called Maple 8 developed by Waterloo Maple Inc. The computer time to solve a particular model with 18 vari-

Table 6. Optimum System Budget Allocation for Maximizing Network Age Gain with Equal System Average Age Requirements

Pavement system	Network budget (B_N) (million United States dollars) 1.0	5.0	10.0	15.0	20.0	25.0
Local (i=1)	0.47	2.30	4.53	6.55	9.60	9.60
Collector (i=2)	0.33	1.67	3.38	5.13	6.45	6.68
Arterial (i=3)	0.20	1.03	2.09	3.32	3.95	3.95
Total	1.0	5.0	10.0	15.0	20.0	20.23

$$\textbf{Minimize: } C_N = [73.5(1X_{111}+8X_{112})+77.0(2X_{121}+15X_{122})+84.0(3X_{131}+25X_{132})+$$
$$40.0(1.5X_{211}+10X_{212})+36.0(2.5X_{221}+20X_{222})+34.0(3.5X_{231}+35X_{232})+$$
$$19.0(2X_{311}+12X_{312})+15.0(3X_{321}+25X_{322})+11.0(4X_{331}+45X_{332})]$$
$$\times (3.6 \times 1000)$$

$$\textbf{Subject to: } 1)\ [73.5(1X_{111}+10X_{112})+77.0(1.5X_{121}+15X_{122})+84.0(2X_{131}+20X_{132})+$$
$$40.0(1X_{211}+10X_{212})+36.0(1.5X_{221}+15X_{222})+34.0(2X_{231}+20X_{232})+$$
$$19.0(1X_{311}+10X_{312})+15.0(1.5X_{321}+15X_{322})+11.0(2X_{331}+20X_{332})] \geq SG_N$$

$$2)\ [73.5(1X_{111}+10X_{112})+77.0(1.5X_{121}+15X_{122})+84.0(2X_{131}+20X_{132})]/350 \geq SA_i$$
$$[40.0(1X_{211}+10X_{212})+36.0(1.5X_{221}+15X_{222})+34.0(2X_{231}+20X_{232})]/150 \geq SA_i$$
$$[19.0(1X_{311}+10X_{312})+15.0(1.5X_{321}+15X_{322})+11.0(2X_{331}+20X_{332})]/100 \geq SA_i$$

$$3)\ X_{111}+X_{112} \leq 1.0;\quad X_{121}+X_{122} \leq 1.0;\quad X_{131}+X_{132} \leq 1.0$$
$$X_{211}+X_{212} \leq 1.0;\quad X_{221}+X_{222} \leq 1.0;\quad X_{231}+X_{232} \leq 1.0$$
$$X_{311}+X_{312} \leq 1.0;\quad X_{321}+X_{322} \leq 1.0;\quad X_{331}+X_{332} \leq 1.0$$

$$4)\ X_{ijk} \geq 0 \quad (\text{for } i = 1,2,3;\ j = 1,2,3; \text{ and } k = 1,2)$$

Fig. 2. Sample global GNOM model for minimizing pavement network repair cost

ables was about 1 s once the execution order was given. Therefore, it is expected that computer time will be very minimal even with a much larger number of repair variables.

Conclusions and Recommendations

The sample global network optimization models presented have all converged to optimal feasible solutions that would achieve the intended main objective, which is helping the pavement engineer make the best management decisions regarding the maintenance and rehabilitation works for a given pavement network. The presented sample results indicate that not all deployed repair variables have contributed to the optimal solutions. This can be attributed to the nature of the input data used, the fact that two repair variables are being assigned to each pavement class with the model selecting the best one of the two, and the amount of allocated budget. However, the objective of solving the pavement management problem can be achieved with only a limited number of repair actions. The sample results have also indicated that a global optimal repair plan at the network level may not result in a reasonable fund allocation among deployed pavement systems. Nevertheless, a rational fund allocation among deployed systems can be achieved once system improvement requirement constraints are used.

The global network optimization models presented are simple to apply with minimal data requirements, but yet considered very effective in solving the pavement management problem using the two outlined management approaches. The first approach is used to maximize the pavement network age gain if anticipated budget is known while the second approach is applied to minimize the total repair cost required to achieve certain pavement network improvement requirements. The two approaches offer the engineer a wide variety of options for selecting the model that best meets the needs of a given highway agency. They are also potentially useful to local governments which generally lack the resources and technical expertise to use highly sophisticated pavement management systems that are not as simple to apply and require extensive historical distress records for developing effective pavement performance prediction models.

The global network optimization models presented can be used as in the sample applications wherein maintenance and rehabilitation actions have been integrated together in the same

Table 7. Optimum Repair Solution Plans for Minimizing Network Repair Cost with Network Age-Gain Requirement

	Desired network age gain (SG_N) (year lane km)					
Repair variable	347	1536	2805	3917	4919	5690
X_{111}	0.000	0.000	0.000	0.000	0.000	0.000
X_{112}	0.472	1.000	1.000	1.000	1.000	1.000
X_{121}	0.000	0.000	0.000	0.000	0.000	0.000
X_{122}	0.000	0.347	1.000	1.000	1.000	1.000
X_{131}	0.000	0.00	0.000	0.000	0.000	0.000
X_{132}	0.000	0.00	0.194	0.855	1.000	1.000
X_{211}	0.000	0.00	0.000	0.000	0.000	0.000
X_{212}	0.000	1.000	1.000	1.000	1.000	1.000
X_{221}	0.000	0.000	0.000	0.000	0.000	0.000
X_{222}	0.000	0.000	0.000	0.000	1.000	1.000
X_{231}	0.000	0.000	0.000	0.000	0.000	0.000
X_{232}	0.000	0.000	0.000	0.000	0.000	1.000
X_{311}	0.000	0.000	0.000	0.000	0.000	0.000
X_{312}	0.000	0.000	1.000	1.000	1.000	1.000
X_{321}	0.000	0.000	0.000	0.000	0.000	0.000
X_{322}	0.000	0.000	0.000	0.000	0.972	1.000
X_{331}	0.000	0.000	0.000	0.000	0.000	0.680
X_{332}	0.000	0.000	0.000	0.000	0.000	0.320
G_N^* (year lane km)	347	1,536	2,805	3,917	4,919	5,690
C_N^* (million United States dollar)	1.0	5.0	10.0	15.0	20.0	25.0

Table 8. Optimum Repair Solution Plans for Minimizing Network Repair Cost with System Average Age Requirement

Repair variable	Desired system average improvement age (SA_i) (years)					
	0.463	2.244	4.017	5.574	6.351	6.351
X_{111}	0.000	0.000	0.000	0.000	0.000	0.000
X_{112}	0.220	1.000	1.000	1.000	0.000	0.000
X_{121}	0.000	0.000	0.000	0.000	0.589	0.589
X_{122}	0.000	0.044	0.581	1.000	0.411	0.411
X_{131}	0.000	0.000	0.000	0.000	0.000	0.000
X_{132}	0.000	0.000	0.000	0.036	1.000	1.000
X_{211}	0.000	0.000	0.000	0.000	0.000	0.000
X_{212}	0.231	1.000	1.000	1.000	1.000	1.000
X_{221}	0.000	0.000	0.000	0.000	0.000	0.720
X_{222}	0.000	0.090	0.747	1.000	0.579	0.280
X_{231}	0.000	0.000	0.000	0.000	0.000	0.000
X_{232}	0.000	0.000	0.000	0.257	0.820	1.000
X_{311}	0.000	0.000	0.000	0.000	0.000	0.000
X_{312}	0.244	1.000	1.000	1.000	1.000	1.000
X_{321}	0.000	0.000	0.000	0.000	0.000	0.000
X_{322}	0.000	0.153	0.941	1.000	1.000	1.000
X_{331}	0.000	0.000	0.000	0.392	0.000	0.000
X_{332}	0.000	0.000	0.000	0.608	1.000	1.000
A_i^* (years)	0.463	2.244	4.017	5.574	6.351	6.351
C_N^* (million United States dollars)	1.0	5.00	10.0	15.0	20.00	20.23

model or separate models can be formulated for both maintenance and rehabilitation works. The advantage of making separate models is eliminating the possibility that one type of repair works (i.e., maintenance or rehabilitation) dominates the optimal solutions which can occasionally take place as shown in the sample presentation. Of course, domination of one type of repair works may not be a problem as long as the input data used are considered reliable. Therefore, the required input data must be estimated with a high degree of reliability, a requirement that holds for any pavement management model, especially the expected ages and cost rates associated with the deployed repair actions as they are the most significant parameters for the global network optimization models presented.

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