Analysis and Design Optimization of Flexible Pavement

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(Reviewed by the Highway Division)

Abstract: A project-level optimization approach was developed to minimize total pavement cost within an analysis period. Using this approach, the designer is able to select the optimum initial pavement thickness, overlay thickness, and overlay timing. The model in this approach is capable of predicting both pavement performance and condition in terms of roughness, fatigue cracking, and rutting. The developed model combines the American Association of State Highway and Transportation Officials (AASHTO) design procedure and the mechanistic multilayer elastic solution. The Optimization for Pavement Analysis (OPA) computer program was developed using the prescribed approach. The OPA program incorporates the AASHTO equations, the multilayer elastic system ELSYM5 model, and the nonlinear dynamic programming optimization technique. The program is PC-based and can run in either a Windows 3.1 or a Windows 95 environment. Using the OPA program, a typical pavement section was analyzed under different traffic volumes and material properties. The optimum design strategy that produces the minimum total pavement cost in each case was determined. The initial construction cost, overlay cost, highway user cost, and total pavement cost were also calculated. The methodology developed during this research should lead to more cost-effective pavements for agencies adopting the recommended analysis methods.

INTRODUCTION

In the United States, as the national economy and population increase, travel demand increases. Concurrently, the trend of budgetary pressures on highway agencies is increasing. Many highway projects are delayed because of budget constraints. To meet these challenges highway agencies are looking for more cost-effective ways to better manage their pavement network. Thus, the significance of modern pavement management practices and new pavement technologies, which allow highway agencies to improve the allocation of resources and performance of pavements, has become increasingly important.

Pavements are complex structures affected by many factors and stochastic processes such as traffic volume and load, material properties, environment, change of roadbed soil support, pavement aging process, construction practices, and maintenance procedures. Capturing these issues with project-level management requires complete and detailed data and precise models to predict the impact of treatment strategies on pavement performance.

Currently, available project-level pavement management systems that incorporate modern optimization methods in conducting life-cycle design and economic analysis are limited. For example, flexible pavements can be designed with many possible combinations of construction, maintenance, and rehabilitation strategies. It is desirable to find the optimal solution, in terms of minimum cost while satisfying the engineering constraint, by modern mathematical methods and new computer technology. Thus, there is a need to develop a new optimization technique to provide highway agencies with a better and more efficient decision tool for pavement project planning, programming, maintenance, and rehabilitation.

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RESEARCH OBJECTIVE

The objective of this research is to develop a project-level optimization and analysis method for flexible pavements. The aim of the method is to improve pavement management at the project level by minimizing highway agency and user costs, while satisfying the constraints of performance criteria. Using this approach, the designer would be able to select the optimum initial pavement thickness, overlay thickness, and overlay timing. The model would be capable of predicting both pavement performance and condition in terms of roughness, fatigue cracking, and rutting. The developed model would combine empirical design procedure and the mechanistic multilayer elastic solution.

CURRENT PROJECT-LEVEL PAVEMENT MANAGEMENT MODELS

Several project-level pavement management and cost allocation systems have been developed, such as the Flexible Pavement Design System (Hudson and McCullough 1973), the Systems Analysis Model for Pavements (Hudson and McCullough 1973), the Ontario Pavement Analysis of Cost (Haas et al. 1994), and the Highway Design and Maintenance model (HDM-III) (*Highway* 1985; Paterson 1989). None of the available project-level management systems uses state-of-the-art optimization methods for determining the best pavement treatment strategy to meet specified objectives. Existing systems were developed in a more constrained computer environment as compared to current technology. Advances in computers and optimization methods make it feasible to blend optimization and project-level pavement management, a situation which did not previously exist.

OPTIMIZATION TECHNIQUES

Modern optimization technologies, especially operation research and system methods, have been extensively used in industry and management. They provide a scientific basis for decision-makers to increase productivity, efficiency, resource utilization, profit, and performance, and to decrease capital cost, labor force turnover, time, and environment pollution. A pavement management system with an optimization capability can asssist the decision-making process and provide better management. The optimum objective can be to maximize ben-

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efit, minimize cost, or minimize the cost-benefit ratio. Through the optimization process, the best set of alternative strategies for construction and rehabilitation can be selected based on specified criteria. Several techniques can be used for optimization, such as linear programming, integer programming, nonlinear programming, and dynamic programming (Li and Qian 1982; French et al. 1986; Sniedovich 1992; Holsapple and Jacob 1994).

Optimization techniques can provide tools that are capable of giving the best possible solutions in the decision-making process of many engineering applications. Linear programming is a widely used optimization technique because of its simplicity. In the real world, however, most physical and mechanical phenomena cannot be modeled by linear functions. The American Association of State Highway and Transportation Officials (AASHTO) and mechanistic pavement models, for example, are nonlinear functions. Moreover, the pavement project management is a multistage decision process. Therefore, nonlinear dynamic programming is a suitable tool for solving the life-cycle optimization problems.

PAVEMENT DESIGN AND PERFORMANCE MODELS

In the past several decades, many models have been developed to predict pavement performance and condition and to design pavement structures. Among the commonly used models are the AASHTO pavement design and the mechanistic structural and distress models.

AASHTO Pavement Design Model

The AASHTO model has been widely used in pavement design for several decades. It is based on actual field conditions and has been modified several times to accommodate new conditions. However, the AASHTO model is limited, since it satisfies the serviceability requirement only and cannot be used to predict various modes of pavement distress. Thus, the strategies selected for construction and rehabilitation using the AASHTO model only may not be the optimal strategies. Pavements may fail due to fatigue cracking or rutting before the present serviceability index (*PSI*) reaches the specified terminal value. Another shortcoming is that although the AASHTO method recommends the consideration of life-cycle cost in pavement design, there is not any optimization method used for the cost of either the initial construction or later overlays. Due to the large amount of investment in initial pavement construction and overlay activities, an optimal design can reduce the cost for both the highway agency and highway users.

Mechanistic Response and Distress Models

Since the 1970s, accompanying the development of empirical models for pavement management, many mechanistic-empirical models have been developed based on elastic and viscoelastic theories and the finite element analysis technique. BISAR, CHEVRON, ELSYM5, VESYS, and KENLAYER are examples of computer programs that incorporate these types of models. These programs compute the structural response of the pavement in terms of stresses and strains for a given combination of loading, materials, and layer thicknesses.

Using the structural response of the pavement to traffic load, major load related distresses, such as fatigue cracking and rutting, could be predicted using fatigue cracking and rutting distress models. The horizontal tensile strain at the bottom of the asphalt surface layer is usually assumed to be the major cause of fatigue cracking, whereas the vertical compressive strain on the top of the subgrade is used as the limiting criterion for rutting (Monismith 1992; Huang 1993). Although current mechanistic models are more fundamental than empirical models, they use assumptions that are different than field conditions.

DEVELOPMENT OF PAVEMENT OPTIMIZATION MODEL

In this study, the methodology for developing a project-level pavement management model is presented. The optimization model incorporates the following distinctive features:

- AASHTO design model
- Mechanistic-empirical performance models
- Life-cycle cost optimization and analysis

Design Strategies

For ease of description, the following terms are defined:

- Minimum initial design life—the shortest amount of time that the initial construction should last without the need for rehabilitation. For example, it may be desirable that the initial pavement construction lasts at least five years before a rehabilitation operation is performed.
- Maximum initial design life—the longest amount of time that the initial construction can last before it needs rehabilitation
- Intermediate initial design life—any initial pavement life between the minimum and maximum initial design lives
- Minimum overlay life—the shortest amount of time that an overlay should last. For example, it may be desirable that the overlay lasts at least five years before the next overlay is constructed.
- Maximum overlay life—the longest amount of time that an overlay rehabilitation can last before it needs another overlay.
- Analysis period—the period of time for which the analysis is to be conducted, i.e., the length of time that any design strategy must cover. It may range from one initial design life only to an initial construction followed by one or more overlays.

Fig. 1 demonstrates the design concept applied in this research. The figure shows that there are many combinations of initial pavement and overlay designs to meet the needs of any analysis period. The design strategy can consist of an initial design with or without one or more overlays. Obviously, the costs of different design strategies are different. An optimum design strategy exists that has minimum cost while meeting all design constraints.

Design Model

The design model developed in this study combines the empirical AASHTO model (*Guide* 1993) and mechanistic-empirical models. The input data needed to design the pavement consist of traffic parameters, environmental factors, material properties, economic factors, and control variables. Traffic data include average daily traffic (ADT), annual traffic growth rate, percentages of different vehicle types, truck factors, traffic directional distribution, and lane distribution factors. Environmental factors are the roadbed soil swell and frost heave properties. Material properties include the modulus of each pavement layer, layer coefficients, and drainage coefficients. Economic factors include the discount rate and unit costs of pavement materials. The control parameters consist of the analysis period, performance and condition damage criteria, minimum and maximum layer thicknesses, minimum and maximum initial design and overlay lives, and reliability variables.

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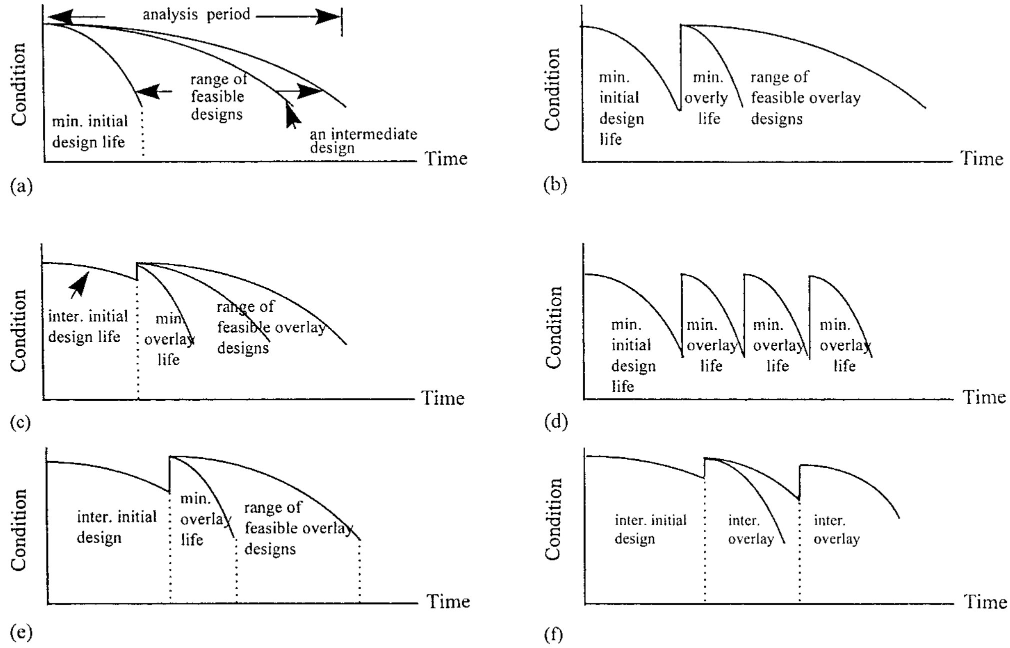

FIG. 1. Alternate Design Strategies: (a) Range of Feasible Initial Designs; (b) Range of Feasible Overlay Designs for Minimum Initial Design; (c) Range of Feasible Overlay Designs for Intermediate Initial Design—Earliest Application; (d) Minimum Design Strategies; (e) Range of Feasible Overlay Designs for Intermediate Initial Design—Intermediate Application; (f) Intermediate Initial and Overlay Design Strategy

The AASHTO model is used to compute the required structural number (*SN*) and the thickness of each pavement layer. This model is also transformed to calculate the *PSI* in order to predict pavement performance. The Newton-Raphson algorithm (Nie 1982) is employed to solve AASHTO design equations. Using the layer thicknesses obtained from the AASHTO model along with material properties and traffic data, the ELSYM5 elastic mechanistic model is used to calculate the horizontal tensile strain at the bottom of the asphalt layer and the vertical compressive strain on top of the subgrade. These strains are then used to predict the pavement performance.

The pavement overlay and analysis model uses the AASHTO remaining life overlay procedure. The same performance model and distress models are used as the initial design. The damage checking procedure is also used in the same way as for the initial design.

Distress Models and Failure Criteria

Three distress models and failure criteria are used—roughness, fatigue cracking, and rutting. The AASHTO design equation, which uses the roughness mode of distress in terms of the present serviceability index, is used to design the pavement layers. The Asphalt Institute fatigue and rutting distress equations are used to check the AASHTO design (Huang 1993). The AASHTO and the Asphalt Institute fatigue and rutting distress equations used are as follows:

$$\log_{10} W_{18} = Z_R S_0 + 9.36 \log_{10}(SN + 1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2 - 1.5}\right)}{0.40 + \frac{1{,}094}{(SN + 1)^{5.19}}} + 2.32 \log_{10}(0.145 M_R) - 8.07 \quad (1)$$

$$N_c = 0.0796(\varepsilon_t)^{-3.291}(0.145E)^{-0.854} \quad (2)$$

$$N_r = 1.365 \times 10^{-9}(\varepsilon_c)^{-4.477} \quad (3)$$

where W_{18} = predicted future cumulative traffic 80-kN (18-kip) equivalent single axle load (ESAL) in the design lane in the design period; Z_R = Z statistic for a corresponding level of reliability; S_0 = combined standard error of the traffic prediction and performance prediction; SN = structural number; ΔPSI = difference between the initial and terminal serviceability in the design period; M_R = resilient modulus of roadbed soil (kPa); N_c = allowable number of ESAL repetitions to fatigue failure; ε_t = tensile strain at the bottom of the asphalt layer; E = asphalt concrete modulus (kPa); N_r = allowable number of ESAL repetitions to rutting failure; and ε_c = vertical compressive strain on top of the subgrade.

Three failure criteria for roughness, fatigue cracking, and rutting used in the analysis are as follows:

$$PSI = f(Z_R, S_0, SN, M_R) \geq PSI^* \quad (4)$$

$$CI = \frac{n}{N_c} \leq CI^* \quad (5)$$

$$RI = \frac{n}{N_r} \leq RI^* \quad (6)$$

where PSI = present serviceability index; PSI^* = terminal PSI; n = number of actual ESAL applications; CI = cracking index (damage index of fatigue cracking); CI^* = terminal CI; RI = rutting index (damage index of rutting); and RI^* = terminal RI.

When the serviceability reaches its terminal level, an overlay is triggered. During the design period, the fatigue cracking index and rutting index are checked. Also, if one or more of these indexes reach the limits, an overlay is triggered.

Dynamic Programming Optimization

Project-level pavement management is a multistage decision-making process. A stage is assumed to be a number of years. The analysis period of a pavement project can be divided into several stages that interact with each other. At each stage, a decision has to be made regarding whether an overlay is needed or not based on traffic, environment, or pavement condition. The state of the condition of a pavement at each stage can be described by its *PSI*, *CI*, and *RI* values. Since a

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decision to overlay causes the pavement condition to change, the decision made at any stage will affect the decision at the next stage, and consequently it will affect the whole future decision-making process. All decisions made throughout the process constitute a decision series, called a policy. Usually, there is more than one alternative (layer thicknesses and overlay timing) available for a decision-maker to select. Therefore, there are many policies that can be selected for the multistage decision-making process, and each will produce different outcomes.

Thus, a large number of combinations of initial construction and overlay strategy alternatives exist during the decision-making process. The goal of the multistage decision-making process is to select the optimum policy or a set of optimum policies that will produce the best performance during the entire life of a pavement project. As pavements deteriorate with time under traffic and environment, dynamic programming is an appropriate mathematical tool to solve this multistage decision-making problem. For the pavement project optimization and analysis in this study, the dynamic programming optimum algorithm that minimizes the total pavement cost was used (Sniedovich 1992; Holsapple and Jacob 1994). The sum of the initial construction and overlay costs is designated as the agency cost, whereas the sum of the agency and user costs is designated as the total pavement cost. The user cost was calculated using available prediction methods (Zaniewski et al. 1985; Zaniewski and Hudson 1994).

Thus, the optimization objective function is as follows:

$$C(T_a) = w_a C_a(T_a) + w_u C_u(T_a) \tag{7}$$

where T_a = pavement analysis period; $C(T_a)$ = present worth of total pavement cost; $C_a(T_a)$ = present worth of agency cost; $C_u(T_a)$ = present worth of user cost; and w_a, w_u = weight factors for agency cost and user cost, respectively.

The output of the dynamic programming process includes

- Layer thickness for initial construction and overlay
- Optimum initial construction design period
- Optimum overlay strategies and intervals
- Present worth of agency cost over the analysis period
- Present worth of user cost over the analysis period
- Present worth of pavement construction and overlay cost (sum of the agency and user costs)

In this study, the only form of rehabilitation used was an overlay. In addition, the objective was to minimize the total pavement cost (sum of agency and user costs). The method, however, is equally applicable to other forms of rehabilitation as well as different types of maintenance treatments. Also, the method can be adapted to achieve other objectives, such as minimizing only the user cost.

COMPUTER PROGRAM DEVELOPMENT

The Optimization for Pavement Analysis (OPA) computer program was developed in this study using the research approach discussed previously. The OPA program is written using PowerBuilder, Visual C++, and structured language. The program incorporates the AASHTO equations, the multilayer elastic system ELSYM5 model (rewritten in C++ language), and the dynamic programming optimization technique. The program is a PC-based Windows program, and can run in either the Windows 3.1 or the Windows 95 environment.

To validate the results of the OPA computer program, manual calculations were performed and compared with the results of the program. Very close agreement was found between the manual and computer results.

CASE STUDIES

Conditions and Variables

Using the OPA program, a six-lane road was analyzed under different traffic volumes and material properties. Two alternate solutions were used: (1) considering user cost; and (2) ignoring user cost. Since the user cost typically represents a large portion of the total cost, a weight factor of 0.1 was used for the user cost to reduce its domination. The combination of variables used in the analysis is marked ''X,'' as shown in Fig. 2.

The data used for the case studies consist of fixed and variable data. The fixed data used in this analysis are shown in Tables 1–4. They are traffic, environment, material, cost, and control data. The base and subbase drainage coefficients used

User Cost \ Traffic Volume / Materials	Low		Medium		High	
	Weak	Strong	Weak	Strong	Weak	Strong
Considered		X	X	X		X
Not Considered		X	X	X		X

FIG. 2. Factors and Levels Used in Case Studies

TABLE 1. Traffic Fixed Data

Parameter (1)	Value (2)
Annual traffic growth rate	5
Percent of cars	80
Percent of truck 1	10
Percent of truck 2	4
Percent of truck 3	3
Percent of truck 4	2
Percent of truck 5	1
Directional distribution factor (%)	50
Lane distribution factor (%)	70
Truck factor[a] for cars (ESAL/truck)	0.0003
Truck factor[a] for truck 1 (ESAL/truck)	0.005
Truck factor[a] for truck 2 (ESAL/truck)	1.5
Truck factor[a] for truck 3 (ESAL/truck)	3.0
Truck factor[a] for truck 4 (ESAL/truck)	4.0
Truck factor[a] for truck 5 (ESAL/truck)	4.5

[a]Truck factor is the number of equivalent single axle loads (ESAL) per vehicle.

TABLE 2. Environment Fixed Data

Parameter[a] (1)	Value (2)
Vertical rise (mm)	50
Swell probability (%)	60
Swell rate	0.05
Frost heave probability (%)	30
Maximum *PSI* loss	1.9
Frost heave rate (mm/day)	5

Note: *PSI* = present serviceability index.
[a]Parameters are defined elsewhere (*Guide* 1993).

TABLE 3. Cost Fixed Data

Parameter (1)	Value (2)
Asphalt concrete cost (dollars/m^3)	63
Base material cost (dollars/m^3)	20
Subbase material cost (dollars/m^3)	11
Discount rate (%)	4.5

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TABLE 4. Control Fixed Data

Parameter (1)	Value (2)
Analysis period (years)	20
Maximum initial life (years)	15
Minimum initial life (years)	5
Maximum overlay life (years)	15
Minimum overlay life (years)	5
Design reliability (%)	95
Overall standard deviation	0.4
Initial *PSI*	4.4
Terminal *PSI*	2.5
Terminal *CI*	1
Terminal *RI*	1
Minimum surface layer thickness (mm)	50
Maximum surface layer thickness (mm)	250
Minimum base thickness (mm)	150
Maximum base thickness (mm)	375
Minimum subbase thickness (mm)	150
Maximum subbase thickness (mm)	500

Note: *PSI* = present serviceability index; *CI* = cracking index; *RI* = rutting index.

TABLE 5. Material Property Variables

Material property (1)	Weak materials (2)	Strong materials (3)
Surface modulus (MPa)	2,758	4,137
a_1	0.42	0.44
Base modulus (MPa)	138	138
a_2	0.10	0.20
Subbase modulus (MPa)	69	138
$a1_3$	0.08	0.14
Subgrade modulus (MPa)	34	69

in the AASHTO equation were assumed to be 1.2. An analysis period of 20 years was used.

Three levels of traffic volumes (low, medium, and high) were assumed to study the effect of traffic on the analysis output. Average daily traffic values of 5,000, 30,000, and 60,000 vehicles/day in the two directions were assumed for the three traffic levels, respectively. Two sets of material properties were used, which are designated as weak and strong materials, shown in Table 5.

Analysis of Results

Using the data presented earlier and the OPA computer program, the optimum design strategy that produces the minimum total pavement cost in each case was determined. The initial construction cost, overlay cost, highway user cost, and total pavement cost were also calculated.

Effect of Traffic

Fig. 3 shows the optimal design strategies at the three traffic levels in the analysis period when the user cost is considered in the optimization. This bar chart represents the duration of initial design and overlay designs for each traffic level. Note that the first overlay is not necessarily constructed at the end of the design period of the initial construction. Similarly, the second overlay is not necessarily constructed at the end of the design period of the first overlay, and so on. Also, the design period of the last overlay always ends at the end of the analysis period. In this example, the design strategy at low traffic volume has three stages, i.e., one initial design and two overlays. For the medium and high traffic volumes, the designs have four stages, one initial and three overlays. For the medium and high traffic volumes, the overlay application times are earlier than that of the low traffic level. Table 6 shows layer thicknesses and various costs associated with the optimal design strategies shown in Fig. 3. As traffic volume increases, layer thicknesses increase.

Fig. 4 shows the agency cost, broken down into initial construction cost and overlay cost, using the optimum design strategies for the three traffic levels when the user cost is considered. The initial cost, overlay cost, and their sum (agency cost) increase as traffic increases. Fig. 5 shows the agency cost, user cost, and the total pavement cost for the three levels of

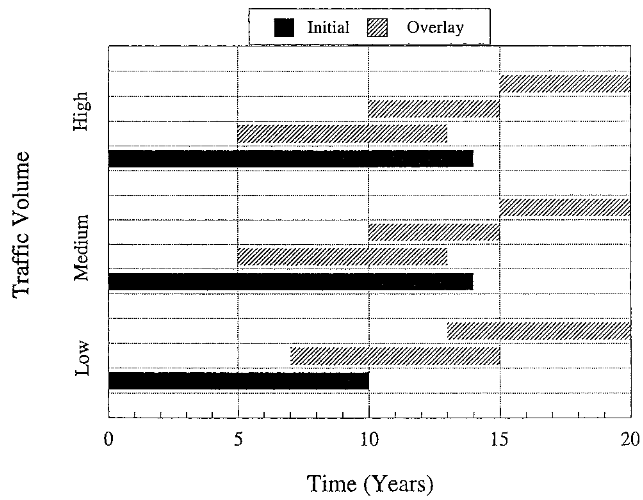

FIG. 3. Optimal Design Strategies for Three Traffic Levels (Strong Materials, User Cost Considered) (Note: Overlaps Indicate Remaining Lives)

TABLE 6. Life-Cycle Analysis for Different Traffic Volumes (Strong Materials, User Cost Considered)

Parameter (1)	Traffic Volume Low (2)	Medium (3)	High (4)
Initial surface thickness (mm)	125	180	215
Base thickness (mm)	75	150	150
Subbase thickness (mm)	180	200	200
First overlay thickness (mm)	50	50	50
Second overlay thickness (mm)	50	50	50
Third overlay thickness (mm)	—	115	140
Initial cost ($1,000/lane · km)	44	63	73
First overlay cost ($1,000/lane · km)	9	10	10
Second overlay cost ($1,000/lane · km)	7	7	7
Third overlay cost ($1,000/lane · km)	—	14	17
Agency cost ($1,000/lane · km)	60	95	107
User cost ($1,000/lane · km)	45	263	528
Total pavement cost ($1,000/lane · km)	104	358	635

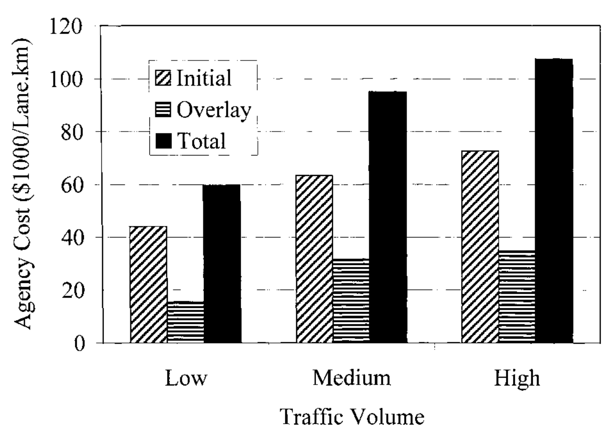

FIG. 4. Agency Cost for Three Traffic Levels (Strong Materials, User Cost Considered)

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traffic. The figure shows that as traffic volume increases, the agency cost, user cost, and total pavement cost increase. In addition, the user cost increases more rapidly than the agency cost does when the traffic volume increases.

Fig. 6 shows the traffic effect on the design strategies in the analysis period when the user cost is not considered. In this case, the optimization is used to minimize the agency cost, since the user cost is ignored. Each of the design strategies has three stages. Table 7 shows layer thicknesses and various costs associated with the optimal design strategies shown in Fig. 6. Table 7 shows that as traffic volume increases, both the initial cost and the total cost increase significantly, but the overlay cost increases only slightly. The initial cost represents the major part of the total cost for all traffic levels.

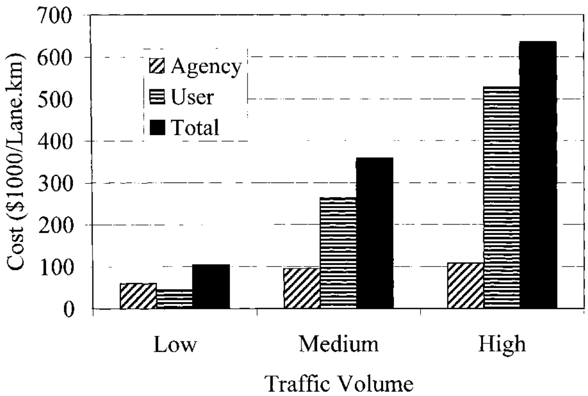

FIG. 5. Pavement Cost for Three Traffic Levels (Strong Materials, User Cost Considered)

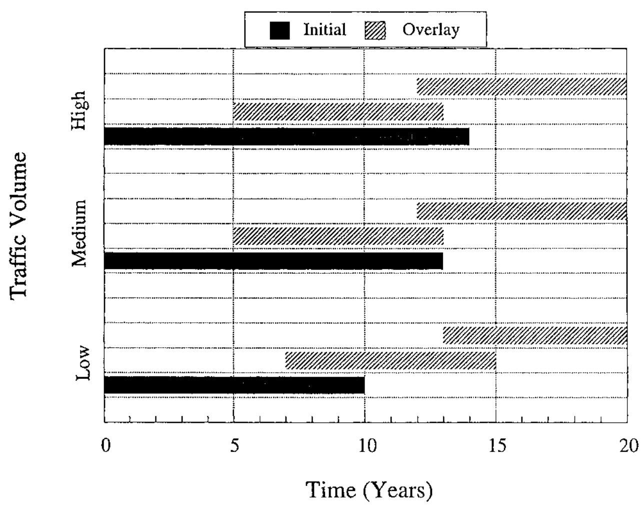

FIG. 6. Optimal Design Strategies for Three Traffic Levels (Strong Materials, User Cost Not Considered) (Note: Overlaps Indicate Remaining Lives)

TABLE 7. Life-Cycle Analysis for Different Traffic Volumes (Strong Materials, User Cost Note Considered)

Parameter (1)	Traffic Volume Low (2)	Medium (3)	High (4)
Initial surface thickness (mm)	125	180	215
Base thickness (mm)	75	150	150
Subbase thickness (mm)	180	200	200
First overlay thickness (mm)	50	50	50
Second overlay thickness (mm)	50	65	75
Initial cost ($1,000/lane·km)	44	63	73
First overlay cost ($1,000/lane·km)	9	10	10
Second overlay cost ($1,000/lane·km)	7	7	11
Agency cost ($1,000/lane·km)	60	82	93

Effect of Material Strength

Fig. 7 shows the optimal design strategies for the weak and strong materials in the analysis period when the user cost is considered in the optimization. As shown in the figure, the strategy for the strong materials has four stages, whereas only three stages are needed during the analysis period for the weak materials. Table 8 shows layer thicknesses and various costs associated with the optimal design strategies shown in Fig. 7.

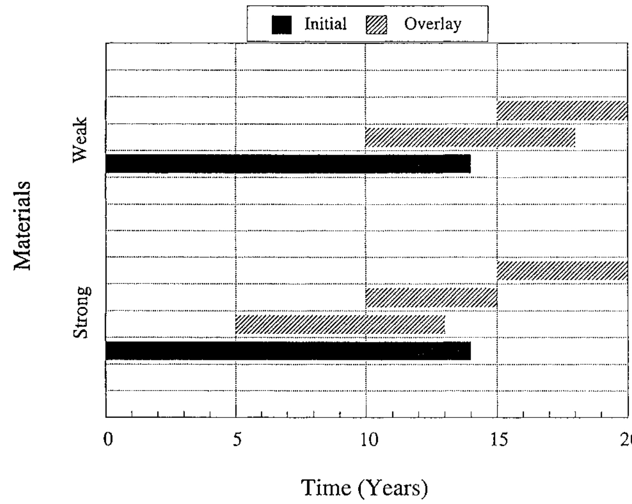

FIG. 7. Optimal Design Strategies for Two Sets of Materials (Medium Traffic, User Cost Considered) (Note: Overlaps Indicate Remaining Lives)

TABLE 8. Life-Cycle Analysis for Different Materials (Medium Traffic, User Cost Considered)

Parameter (1)	Materials Weak (2)	Strong (3)
Initial surface thickness (mm)	290	180
Base thickness (mm)	230	150
Subbase thickness (mm)	380	200
First overlay thickness (mm)	50	50
Second overlay thickness (mm)	50	50
Third overlay thickness (mm)	—	115
Initial cost ($1,000/lane·km)	105	63
First overlay cost ($1,000/lane·km)	7	10
Second overlay cost ($1,000/lane·km)	6	7
Third overlay cost ($1,000/lane·km)	—	14
Agency cost ($1,000/lane·km)	119	95
User cost ($1,000/lane·lkm)	251	263
Total pavement cost ($1,000/lane·km)	370	358

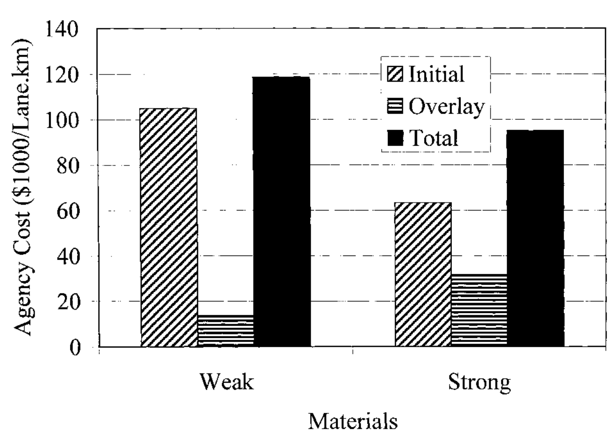

FIG. 8. Agency Cost for Two Sets of Materials (Medium Traffic, User Cost Considered)

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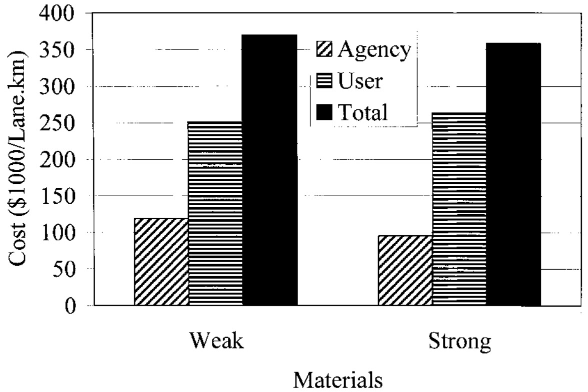

FIG. 9. Pavement Cost for Two Sets of Materials (Medium Traffic, User Cost Considered)

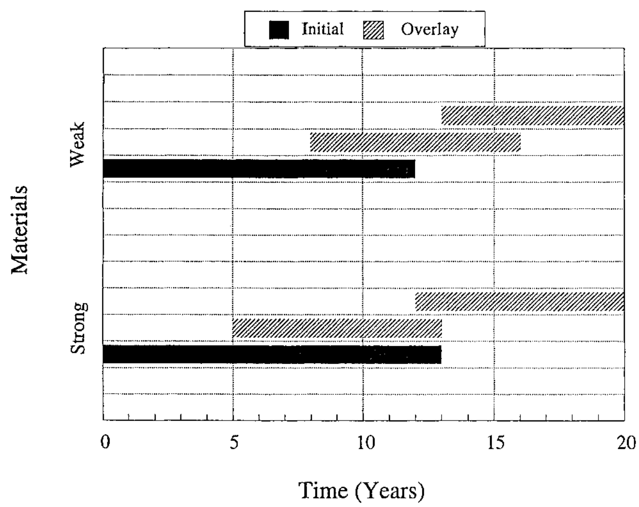

FIG. 10. Optimal Design Strategies for Two Sets of Materials (Medium Traffic, User Cost Not Considered) (Note: Overlaps Indicate Remaining Lives)

TABLE 9. Life-Cycle Analysis for Different Materials (Medium Traffic, User Cost Not Considered)

Parameter (1)	Materials Weak (2)	Strong (3)
Initial surface thickness (mm)	280	180
Base thickness (mm)	230	150
Subbase thickness (mm)	380	200
First overlay thickness (mm)	50	50
Second overlay thickness (mm)	50	65
Initial cost ($1,000/lane · km)	102	63
First overlay cost ($1,000/lane · km)	9	10
Second overlay cost ($1,000/lane · km)	7	9
Agency cost ($1,000/lane · km)	117	82

As expected, weak materials required thicker layers as compared to strong materials.

Fig. 8 shows the agency cost for the weak and strong materials when the user cost is considered in the optimization. The cost of initial design is higher and the cost of overlay is lower for the weak materials than for the strong materials. On the other hand, the total agency cost for the weak materials is higher than that for strong materials. For both materials, the initial cost takes the major part of the total agency cost. For the weak materials, the initial cost is 88% of the total agency cost, whereas the initial cost is 67% of the total agency cost for the strong materials. Fig. 9 shows the agency cost, user cost, and total pavement cost for the weak and strong materials when the user cost is considered.

Fig. 10 shows the optimal design strategies for the two materials in the analysis period when user cost is not considered. As shown in the figure, the strategies for each set of materials need three design stages, one initial construction and two overlays. For the strong materials, the first overlay is applied five years after the initial construction. For the weak materials, the first overlay is applied eight years after the initial construction. Table 9 shows layer thicknesses and various costs associated with the optimal design strategies shown in Fig. 10. The cost of initial design for the weak materials is 61% higher than that for the strong materials, as shown in Table 9. The cost of overlay for the weak materials is slightly lower than that for the strong materials. The total agency cost for weak materials is 43% higher than that of the strong materials.

CONCLUSIONS

This research demonstrates the feasibility of applying optimization methods for project-level pavement management. The combination of empirical and mechanistic methods improves the predictive capacity of the design method as compared to conventional approaches. The inclusion of user costs allows the agency to consider the impact of different pavement designs on the highway user. The methodology developed during this research should lead to more cost-effective pavements for agencies adopting the recommended analysis methods.

APPENDIX. REFERENCES

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