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Optimizing Pavement Preservation: An Urgent Demand for Every Highway Agency

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Preventive maintenance is a tool that has the potential to both improve quality and reduce expenditures for a pavement network. Preventive maintenance is based on the concept that periodic, inexpensive treatments, such as seals, are more economical than infrequent, high-cost procedures, such as reconstruction. The paper presents a step-by-step procedure for selecting the appropriate preventive maintenance treatment for asphalt pavement and evaluating the optimal timing for that treatment under different pavement, traffic, and climatic conditions. The information presented in this paper is a useful tool for highway engineers and superintendents at various governmental levels throughout the world to develop a preventive maintenance program that would maximize the cost-effectiveness of maintenance treatments. Typical examples of pavement distresses are presented showing appropriate treatments that can be used. A model is presented to provide the basis for the analysis of the cost-effectiveness of a pavement preventive maintenance program.

Keywords: Pavement, Preservation, Maintenance, Preventive maintenance, Cost effectiveness

INTRODUCTION

Highway agencies throughout the world face increasing demands on their highway networks and decreasing resources to maintain and preserve them. The demand to "do more with less" has become an operating slogan for many highway agencies. Historically, the emphasis of highway agencies has focused on new construction of new facilities. However, restoration, rehabilitation and reconstruction (the 3R program), along with preventive maintenance, are now required. Highway agencies are currently in a maintenance and preservation mode of operation. This trend can be expected to continue into the foreseeable future.

The importance of highway maintenance was demonstrated in a study by the World Bank (1985). After concentrating on the construction of new facilities in developing countries, the Bank found that the transportation situation was not improving to meet their expectations. An investigation of the problem found that due to countries diverting funds from highway maintenance to construction, roads were deteriorating into an unserviceable condition more rapidly than

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new roads were being constructed. As a result there were fewer kilometers of roads in several countries than there were before the construction program was initiated. "If we cannot afford to take care of the roads we have, how can we afford to build new roads?"

Statistics in the U.S. indicate that current funding is less than that required to maintain pavements in their current condition (FHWA 1998). Therefore, under current policies and funding levels, further deterioration in the quality of the nation's pavements is expected. Since funding levels are not likely to significantly increase, highway agencies must seek more cost-effective methods of pavement preservation.

Pavement preventive maintenance is a tool that has the potential to both improve quality and reduce expenditures for a pavement network. Preventive maintenance is based on the concept that periodic, inexpensive treatments, such as seals, are more economical than infrequent, high-cost procedures, such as reconstruction. The potential for preventive maintenance to improve cost effectiveness through pavement preservation was recognized in several congressional bills in the United States in 1991, 1995 and 1998. These bills allow, for the first time, the use of federal funds for pavement maintenance.

Several efforts have recently been undertaken to increase the awareness of pavement preventive maintenance (Gichaga and Parker 1988, Smith et al. 1993, Raza 1994, Geoffroy 1996, Hicks et al. 2000). Although various preventive maintenance treatments have been employed by highway agencies, information on the cost-effectiveness of these treatments under different conditions is not well documented. Without this information, the determination of the optimal timing for applying a specific preventive maintenance treatment cannot be accurately identified.

Research and documentation are needed to guide highway agencies in determining the optimal timing of pavement preventive maintenance treatments under different pavement, traffic, and climatic conditions. This would help highway agencies effectively manage investments in pavement maintenance and achieve the best value for the public fund.

OBJECTIVE

The main objective of this paper is to provide guidance and present an approach for determining the optimal timing for the application of preventive maintenance treatments for flexible pavements that can be used by various highway agencies. Determining the optimum interval for preventive maintenance is a distinctly different problem than determining the optimal timing of rehabilitation treatments, which is the focus of many pavement management systems. Timing of rehabilitation treatments can be triggered by failure of the pavement that requires treatment in order to maintain the service of the facility. On the other hand, timing of preventive maintenance can only be determined through economic analysis with consideration of other constraints to the optimization problem. The paper also discusses typical pavement conditions and appropriate maintenance treatments under different conditions.

DEFINITION OF PAVEMENT PREVENTIVE MAINTENANCE

Preventive maintenance is defined as a planned strategy of cost-effective treatments to an existing roadway system that preserves the system, retards future deterioration, and maintains and improves the functional condition of the system (without substantially increasing structural capacity). One of the difficulties in describing and developing a preventive maintenance program is that the same pavement treatments can be used for preventive, corrective, or emergency maintenance. As shown on Figure 1, the differences between preventive, corrective, and emergency repair is the condition of the pavement when the treatment is applied, rather than the type of treatment (Zaniewski and Mamlouk 1996).

Several types of treatments can be used for preventive maintenance of flexible pavement including crack treatment, fog seal, chip seal, thin overlay, slurry seal, and micro-surfacing. An effective preventive maintenance program must include the periodic application of the preventive maintenance treatments,

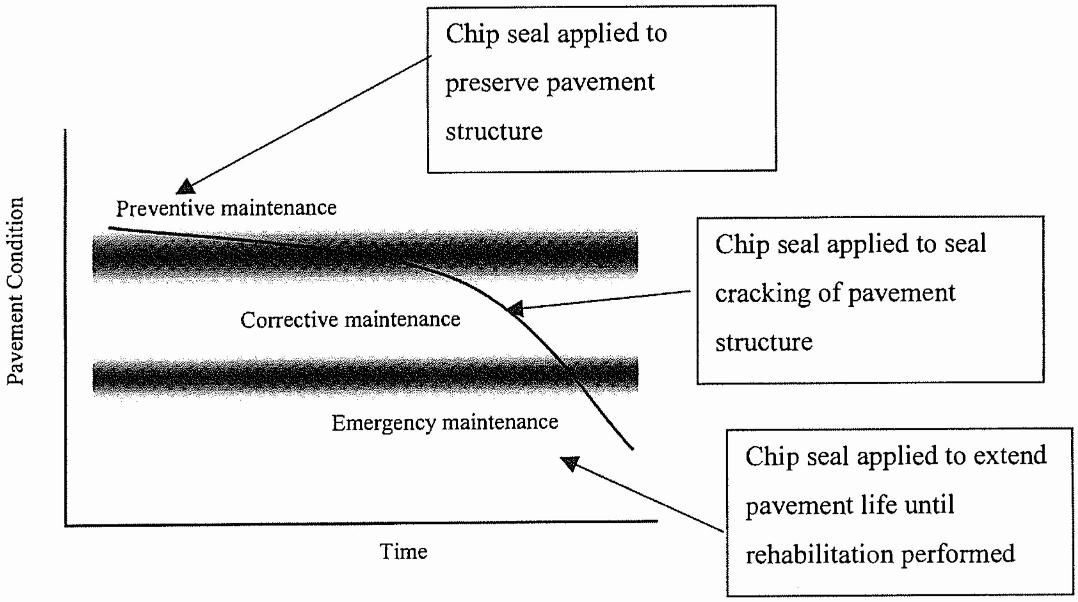

FIGURE 1 Definition of categories of maintenance

as demonstrated in Figure 2. This program can be a mixture of various preventive maintenance treatments. For example, a preventive maintenance program in one of the cities in the U.S. uses a fog seal 3 and 6 years after construction or rehabilitation. In the eighth year a rubber-asphalt crack sealer is applied to all cracks. In the ninth year, either a chip seal or slurry seal is placed on the pavement. This sequence of treatments generally proved to be cost-effective for asphalt pavements in that city for its specific climate and traffic levels.

Pavement preventive maintenance is not a new idea; the concept of preserving the condition of pavements has been available for decades. However, few highway agencies practice good pavement preventive maintenance. Several reasons for this lack of preventive maintenance include: 1) lack of information on the long-term benefits of preventive maintenance and 2) lack of information on the optimal timing for maintenance to make it more cost-effective. Since the consequences of deferring preventive maintenance do not immediately affect pavement quality or the traveling public, preventive maintenance is often the first activity to cut when budgets are tight.

Many personnel in highway agencies perceive that they are using preventive maintenance because they are using preventive maintenance type treatments, such as chip seals and microsurfacing. However, it is often discovered that the treatments are being applied to deteriorated pavements as a means of extending the pavement life for a limited time period. This limits the effective life of the treatment due to failure of the underlying pavement structure. This limited performance period is a function of the manner in which the treatment was used; it does not identify a limitation in the life of the treatment type when the treatment is placed under more favorable conditions.

COST-EFFECTIVENESS

One of the measurements of the effectiveness of different pavement treatment strategies is the area under a pavement condition versus time curve as shown in

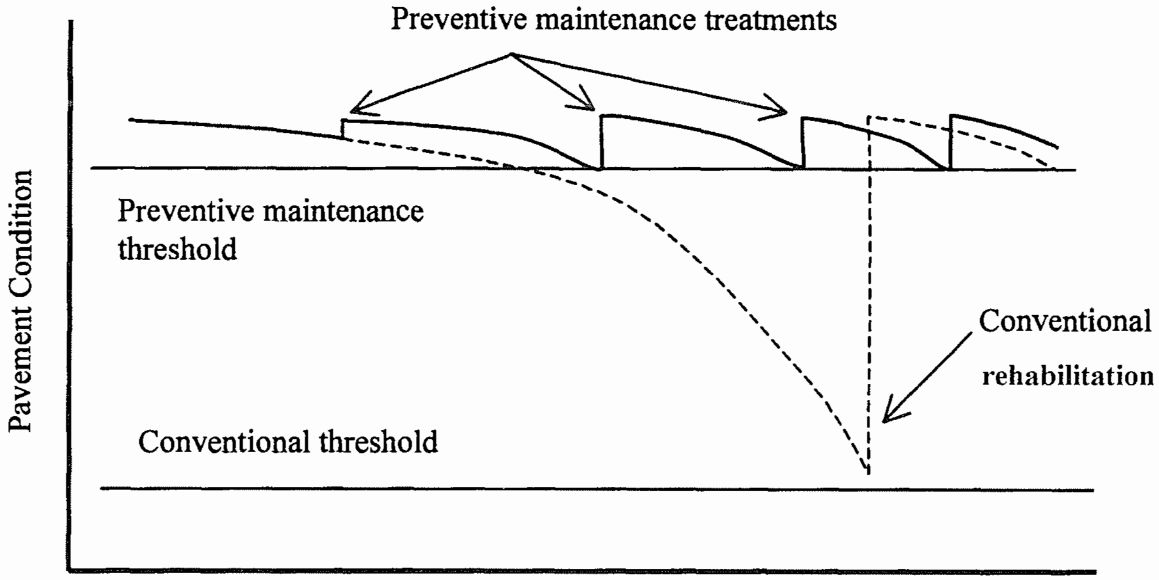

FIGURE 2 Conceptual performance of periodic application of preventive maintenance treatments

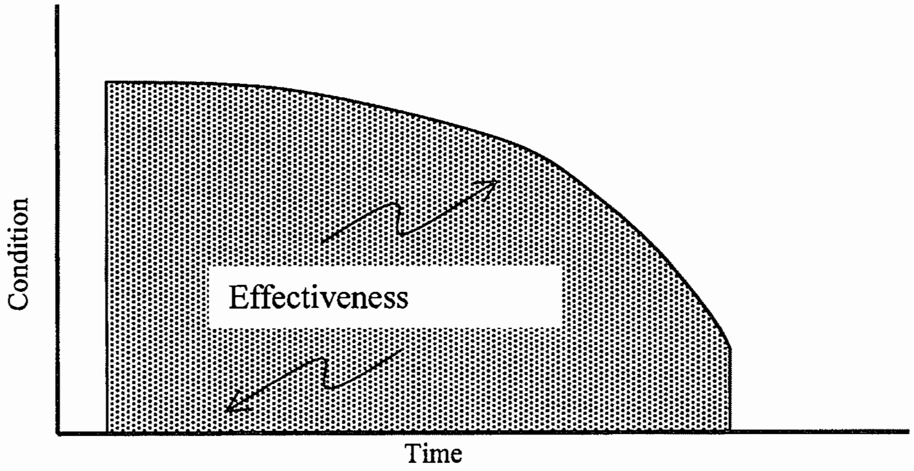

FIGURE 3 Definition of treatment effectiveness

Figure 3. A large area under the pavement condition versus time curve indicates a good pavement condition for a long period of time, and therefore greater effectiveness. However, effectiveness only is not a complete measure since treatments with different effectiveness might have different costs. A cost-effective treatment is that which has high effectiveness and low cost. Several studies have evaluated the cost-effectiveness of pavement preservation treatments under different conditions (Al-Mansour and Sinha 1994, Hicks et al. 2000, O'Brien 1989, Sharaf et al. 1988). However, information is still needed to determine the optimal timing of the treatment that produces the maximum cost-effectiveness.

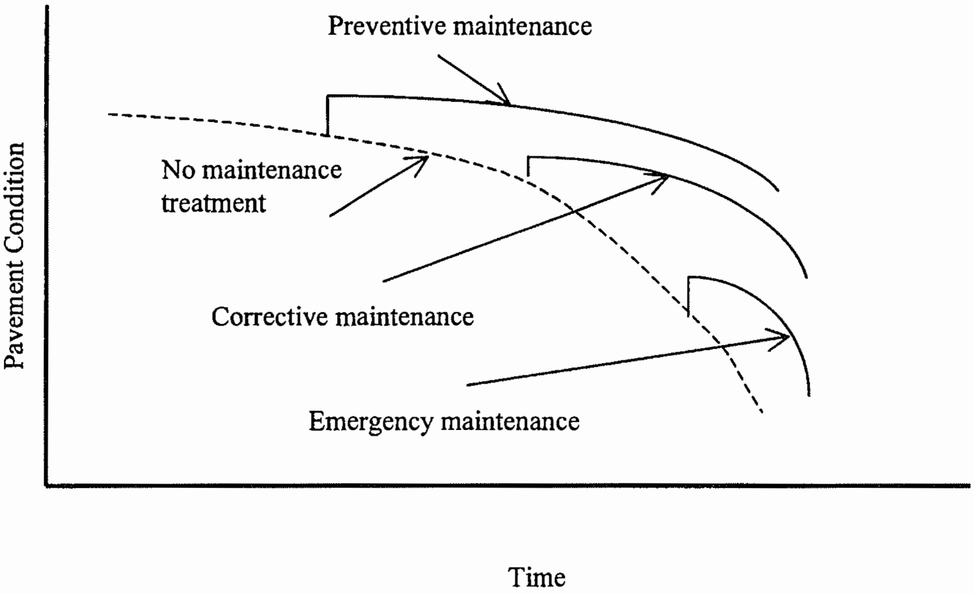

FIGURE 4 Conceptual performance of maintenance treatments applied to pavements with different pre-treatment conditions

TIMING OF PREVENTIVE MAINTENANCE

Pavement preventive maintenance treatments preserve, rather than improve, the structural capacity of the pavement structure. Thus, preventive maintenance treatments are limited to pavements in sound structural condition. In addition, in order to be effective, preventive maintenance should be applied before pavements display significant amounts of environmental distress such as raveling, oxidation, and block cracking. Pavement preventive maintenance treatments should be applied before most engineers, or project decision-makers, would normally consider their use. Currently, there are no specific guidelines on the optimal timing for preventive maintenance. Fundamentally sound statistical evidence is needed in order to persuade engineers, maintenance personnel, upper management, elected officials, and the traveling public that money should be spent on roads in "good" condition rather than roads in "poor" condition.

One of the questions raised by highway agencies evaluating the development of a pavement preventive maintenance program is, *"At what level of distress should a preventive maintenance treatment be applied?"* There is no single answer to this question, and research is still being performed to better answer the question. Peterson states, "Timing is crucial in preventive maintenance: it should be performed *before* a failure occurs" (Peterson 1985). Waiting to maintain a pavement until after a failure occurs is analogous to waiting to wax a car until the paint has begun to flake off.

Figure 4 shows conceptual performance of maintenance treatments applied to pavements with different pre-treatment conditions. The better the pre-treatment condition, the longer the treatment would last and the better the pavement condition after the treatment. At the same time, if the treatment is applied too early, unnecessary expenses will be wasted. An optimum timing is needed to obtain the highest effectiveness with the least cost.

Geoffroy (1996) conducted a survey of 60 highway agencies on the benefits of preventive maintenance. The results of this survey were based primarily on

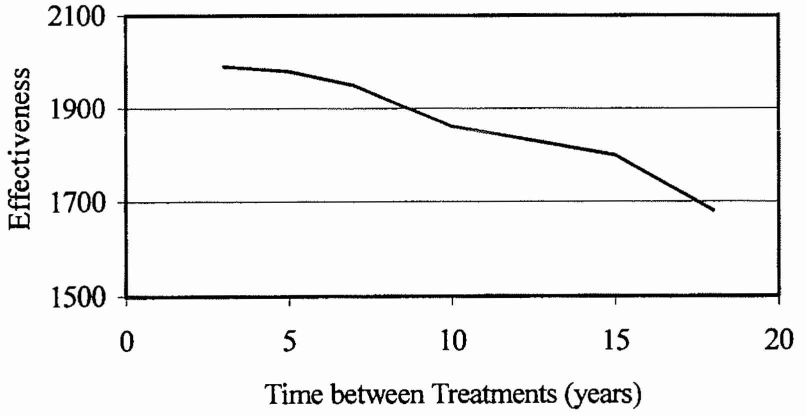

FIGURE 5 Effectiveness of treatments placed at different intervals

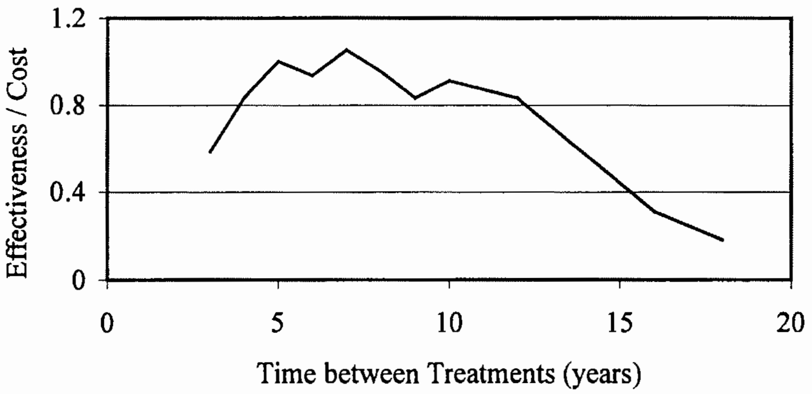

FIGURE 6 Cost-effectiveness of maintenance treatments placed at different intervals

observed performance of the pavements rather than from data from a pavement management system. The frequency of application for treatments of asphalt pavement, other than crack sealing and thin hot-mix asphalt overlays, was 5 to 6 years with a corresponding extension of effective pavement life. Zaniewski and Mamlouk (1996) used limited typical performance and cost data and showed that the effectiveness of the treatment (area under the condition curve) decreases when the time between treatments increases as shown in Figure 5. They concluded that placing treatments at frequencies of 5 to 8 years is the most cost-effective strategy as shown in Figure 6.

Mamlouk (2000) observed the performance of several pavement test sites in four states, which were treated with different preventive maintenance treatments. In order to be within the preventive maintenance mode, sites in good condition before applying the treatments were selected. Based on the evaluation made within three years of service of different sites, it was found that treated pavement sections perform better than untreated sections. Treatments applied on good pavements showed better performance than treatments applied on bad pavements. Research is still underway to observe the long-term performance of treatments.

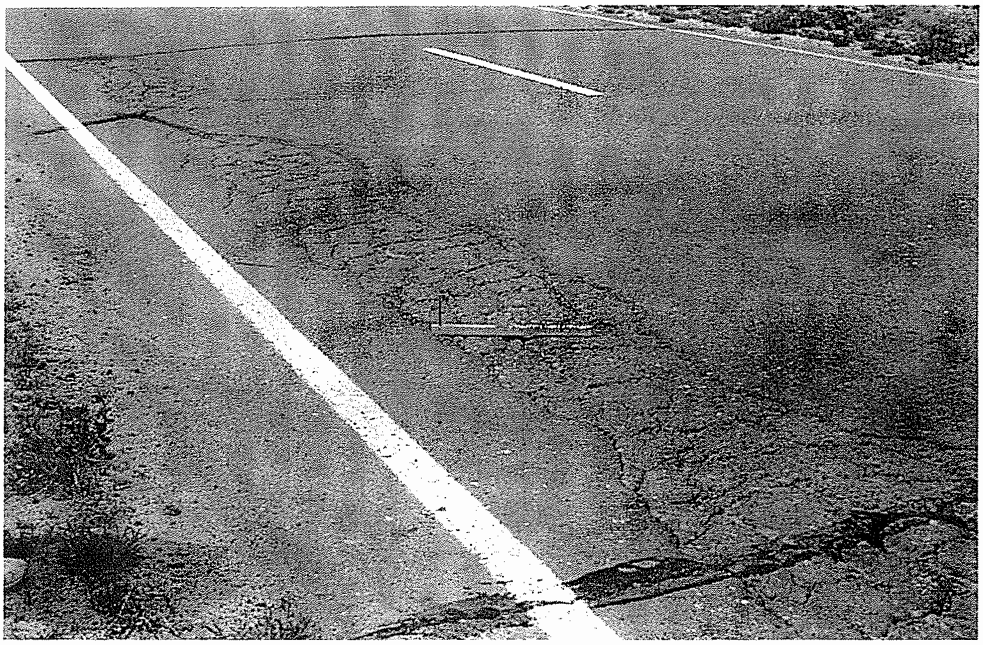

FIGURE 7 Fatigue cracking indicating weak pavement structure (Not candidate for preventive maintenance)

APPROACH FOR OPTIMIZING PREVENTIVE MAINTENANCE

This section outlines an approach that can be used by highway agencies to determine the optimal timing of applying preventive maintenance treatments to obtain the most cost-effective preservation program.

Step 1 – Data Collection and Information Review

Various highway agencies have either formal or informal pavement management systems from which information on previous maintenance projects can be obtained. Detailed information that can be obtained about each project includes type of treatment, materials, cost, pre-treatment pavement age and condition, treatment age and condition, climatic condition, traffic level, and performance indicators. Collected data can be summarized and documented in different computerized forms for use and analysis. For establishing a preventive maintenance program, the pavement management data screens should be used to identify pavements that are in good condition and would therefore benefit from a preventive maintenance treatment. Since it is generally not acceptable to place treatments on new pavements, a second screen could be used to identify pavements that have a minimum amount of time since construction or rehabilitation, such as three or four years.

Step 2 – Selection of Appropriate Preventive Maintenance Treatment

The preventive maintenance treatment selected for a section of pavement should consider the condition of the existing pavement, traffic volumes using the pavement, and environmental conditions. Other factors managers must consider include experience with treatments, budget constraints, political reality, etc. Research to date has not produced detailed rules for selecting one treatment over another for high-volume, high-speed highways. However, some general guidelines can be presented.

TABLE I Pavement distresses and candidate preventive maintenance treatments

Type of Distress	*Potential Preventive Maintenance Action*
Fatigue cracking (Figure 7)	Not candidate for preventive maintenance
Edge, longitudinal, transverse, or reflection cracking	• Crack treatment for low to medium density and edge deterioration • High crack density and/or high edge deterioration are not candidate for preventive maintenance
Patch/patch deterioration	Extensively patched pavements are not good candidates for preventive maintenance
Potholes	Not good candidates for preventive maintenance
Rutting (Figure 8)	
• Unstable asphalt concrete	• Not candidate for preventive maintenance
• Densification of asphalt concrete	• Fill ruts with microsurfacing or strip chip seal, then microsurfacing, or chip seal
• Deep settlement	• Not candidate for preventive maintenance
Shoving	Not candidate for preventive maintenance
Bleeding (Figure 9)	Sand seal, chip seal, slurry seal, or microsurfacing
Polished aggregate	Chip seal, Microsurfacing, slurry seal, or thin overlay
Raveling	Fog seal, chip seal, microsurfacing, slurry seal or thin overlay

Existing Pavement Condition

Pavement condition should be evaluated with respect to distress, structural capacity, roughness, and skid resistance. *Pavement distresses* are flaws in the surface condition of the pavement. *Structural capacity* refers to the ability of the pavement to carry the anticipated traffic loads. *Roughness* is defined as variations in the longitudinal profile of the pavement surface that affect ride quality. *Skid resistance* is an interaction between the vehicle tire and the pavement surface. The pavement's contribution to skid resistance is a function of surface texture and is particularly important in reducing wet weather accidents.

The number one rule for selecting a preventive maintenance treatment based on pavement condition is that **only pavements in reasonably good structural condition are candidates for preventive maintenance**. Preventive maintenance treatments can be used to improve non-load-associated distresses, roughness, and skid resistance. The structural condition of a pavement can be assessed by surface distress evaluation and analysis of deflection data.

The surface of the pavement can be evaluated with a standard distress evaluation method such as that developed as a part of SHRP (National Research Council 1993). The types of distresses are identified in Table I, along with potential preventive maintenance actions.

Traffic

Traditionally preventive maintenance treatments have not been applied to high-volume, high-speed roads in the United States. Many State highway agencies for example limit application of chip seals to pavements carrying less than 1000 to 5000 ADT. Tradition not withstanding, there is now evidence that preventive maintenance treatments can be applied to high-volume, high-speed highways (Zaniewski and Mamlouk 1996). However, care must be taken in the choice of pavements to receive the treatments and in their design and construction. For example, if a chip seal is applied to a high-volume, high-speed road, care must be taken to determine the proper amount of chips, calibrate the chip spreader to place the design amount, and control traffic speeds during the initial curing period. Without these precautions, chips can be dislodged from the pavement surface, reducing the effectiveness of the treatment and potentially causing vehicle damage.

Traffic volumes are also important during the construction of the treatment. Most preventive maintenance treatments need a curing period. The construction plans and specifications need to identify

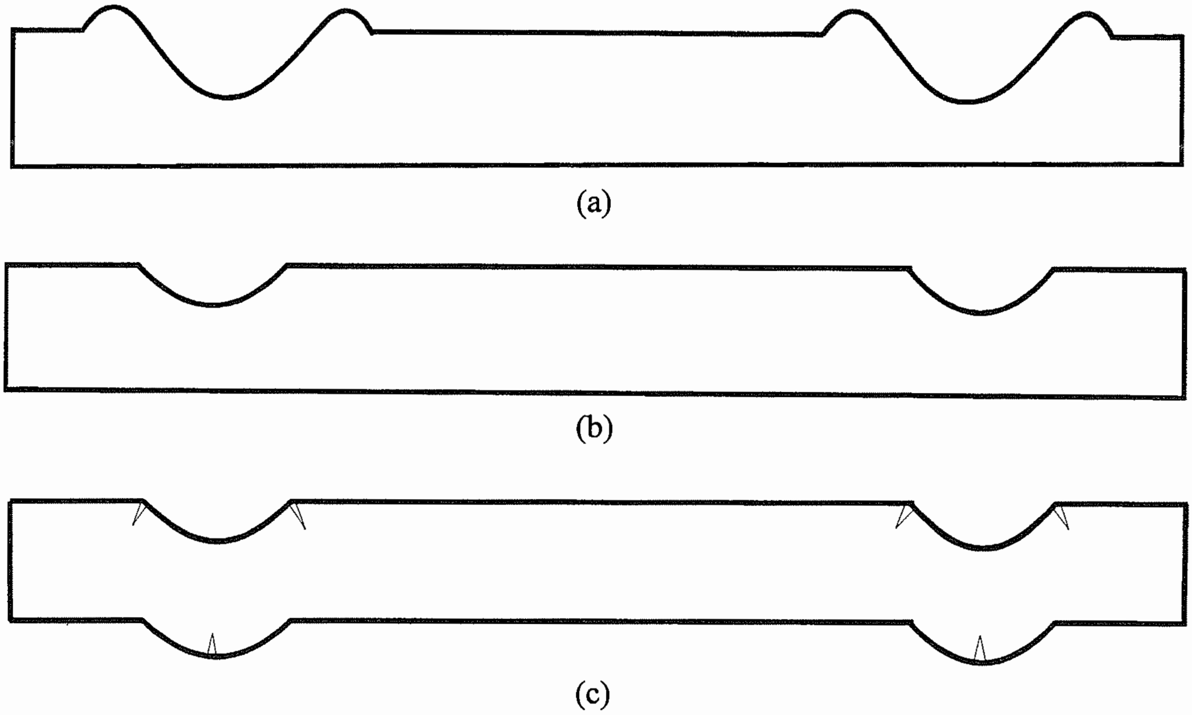

FIGURE 8 Rutting due to: (a) Unstable asphalt concrete, (b) Densification of asphalt concrete, and (c) Deep settlement

the type and duration of the traffic control, both during the construction and the curing period.

Environment

To a large extent, preventive maintenance treatments are designed to mitigate the damage that results from environmental conditions. Periodic renewal of the pavement surface provides several benefits. The two most important with respect to pavement performance are that it:

- Seals the pavement surface, preventing water from penetrating into the pavement structure, and
- Provides a new pavement surface controlling the effects of oxidation, raveling and surface cracking.

Traffic volumes and environmental conditions remain fairly consistent over time. Hence, the *maximum* time between preventive maintenance treatments should be based on time rather than on the amount of traffic the pavement carries. For example, a chip-sealing program may specify placing treatments every 7 years unless the pavement conditions indicate at an earlier time treatment is required.

Other Considerations

Construction is one of the most important considerations in determining the quality and life of a preventive maintenance treatment. Maintenance treatments can be broadly classified as either conventional or emerging treatments. Highway agencies are familiar with the construction of the conventional treatments. However, since these treatments were traditionally limited to low-volume roads, there may be a tendency to not be as precise in the material specifications and construction of the treatments as will be required for high-speed, high-volume roads. For example, a major problem that has limited the use of chip seals to high-volume roads is the possibility of vehicle damage due to loose chips. Loose chips can result from several factors that can be controlled in the design and

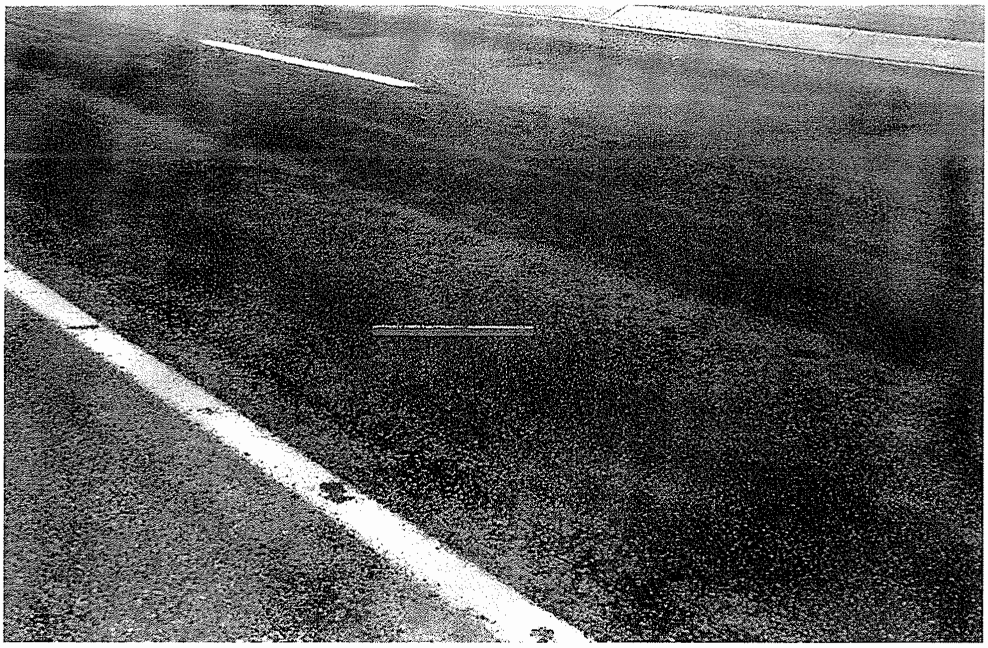

FIGURE 9 Bleeding (Candidate for preventive maintenance)

construction process. During design, the exact quantity of aggregate required to cover the pavement without excess can be determined. For construction the design chip application rate is frequently increased to allow for waste and inaccurate distribution of the chips. Hence, the probability of loose chips is increased. The quality of the chip sealing job can be improved by accurately calibrating the chip distributor and constructing the treatment with a minimum of wastage. This not only increases the quality of the treatment, but also decreases the probability of vehicle damage by loose chips.

Step 3 -Optimal Timing

In order to identify the optimal timing of treatments for flexible pavement, the following process can be used.

Factors Affecting Performance

A statistical study can be designed to determine the optimal timing of various treatments under different conditions. The following factors can be considered:

1. Treatment type (Categorical): Chip seal, slurry seal, microsurfacing, thin overlay, etc.
2. Climatic zone (Categorical): One or more depending on the available climate
3. Traffic level (Categorical): low and high
4. Pre-treatment pavement age (Numerical): 3, 6, and 9 years. (Alternatively, pavement condition could be considered.)
5. Treatment age (Numerical): 3, 6, and 9 years (or end of service life)

Measure of Effectiveness

The responses that can be collected from various pavement sections include treatment condition, distress type and severity, roughness, skid resistance, service life, etc. Distress data may be converted into a single measure of condition, such as the Pavement Condition Index (PCI) developed by the Corps of Engineers for the PAVER system (Shahin and Kohn 1979). The PCI value reflects the functional and structural condition and ranges from bad to good (0 to 100). The PAVER manual utilizes most of the SHRP

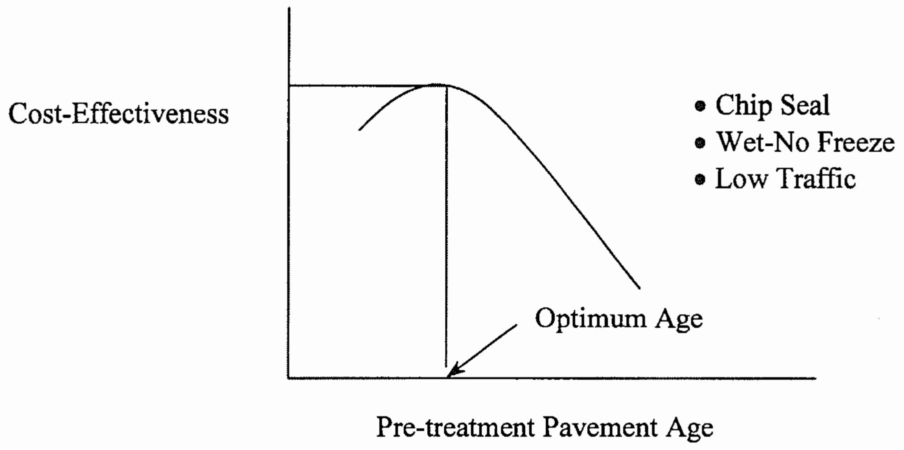

FIGURE 10 Example of relation between cost-effectiveness and pre-treatment age

LTPP distresses directly, although some measures have to be converted (National Research Council 1993).

The PCI value for each pavement section can be determined and plotted against the treatment age. The area under the curve at the end of the service life of the treatment can be calculated and designated as the effectiveness as shown in Figure 3. A large effectiveness value indicates good treatment performance. The effectiveness/cost ratio can be computed and designated as cost-effectiveness. A typical cost for each treatment can be used with an appropriate discount rate.

Statistical analysis may be performed to determine the significance of each factor on the cost-effectiveness of each treatment under different conditions. In addition, a regression equation can be developed to predict the cost-effectiveness of each treatment as a function of various factors, such as:

$$Cost - Effectiveness = f\left(\begin{array}{c} treatment\ type, climatic\ zone, \\ traffic\ level, pre-treatment\ pavement\ age, \\ condition, treatment\ age \end{array}\right)$$

Cost-effectiveness can be plotted against pre-treatment pavement ages (or condition) for each factor combination as illustrated in Figure 10. The figure shows that an optimum pre-treatment pavement age that corresponds to the maximum cost-effectiveness can be determined for a specific combination of preventive maintenance treatment, climatic zone, and traffic level. This process can be repeated for different factor combinations.

The results of the statistical analysis need to be carefully reviewed and compared with common practice and limitations to develop practical conclusions. Table II shows typical frequencies of application of different preventive maintenance treatments based on previous experience. The procedure described earlier can refine the data shown in Table II for the specific conditions of the highway agency.

TABLE II Typical frequency of preventive maintenance treatment application

Treatment	*Frequency of Application (year)*
Crack Treatment	2 to 4
Fog seal/rejuvenator	1 to 3
Single chip seal	4 to 7
Multiple chip seal	5 to 8
Slurry seal	4 to 6
Micro-surfacing	5 to 8
Thin hot-mix overlay	9 to 10

Step 4 – Monitoring Performance and Feedback

It is important to monitor the performance of different treatments and adjust the results obtained earlier. Usually these data can be collected within the scope of a pavement management system. Data that should be collected for evaluating the effectiveness of a preventive maintenance program include:

- As-built data for the existing pavement, thickness, and material type of each layer.
- Traffic data, both historical and loads applied to the treatment, including the number of 80 kN equivalent single axle loads.
- Condition of the pavement prior to the preventive maintenance treatment and periodically afterward.
- Design features of the preventive maintenance treatment such as the material type and thickness of the layer or application rates.
- As-built construction data.

Many preventive maintenance treatments involve new or emerging technologies. When these treatments are applied, there should be a program of more intensive evaluation of the performance of the treatments over time. This should include a detailed survey of pavement distresses prior to application of the treatment as well as subsequent periodic evaluations. When a new type of treatment is used, extra care should be taken to document the quality of the construction. For example, during the construction of one of the SHRP test sections, the slurry machine ran out of binder and deposited loose sand on the pavement surface. Even though the contractor cleaned up the construction site before correctly placing the treatment, the section failed prematurely. The researchers believed that this failure was related to the error in the construction process rather than a systemic problem with slurry seals. If a highway agency had such an experience, it could incorrectly lead to the rejection of slurry seals since the “experiment” failed.

MODELING COST EFFECTIVENESS OF PREVENTIVE MAINTENANCE

Once the data are collected for identifying the performance of preventive maintenance treatments, a model is needed for evaluating the cost effectiveness of the treatments. Due to the many variables that affect the decision to perform preventive maintenance, this model will be quite complex. Figure 11 presents a concept for the systematic analysis of the cost-effectiveness of pavements considering the entire life cycle and both conventional, rehabilitation-based, strategies and preventive maintenance. Due to the uncertainties associated with pavement design in general, and the performance of preventative maintenance treatments specifically, this model was formulated using risk analysis. Under a risk analysis approach, each of the input variables in the analysis is treated as a random variable described by a suitable distribution. A Monte Carlo simulation is then used to select values for the input parameters. An analysis is performed and the results are stored. The simulation is repeated by selecting another set of input parameters. The process is repeated until there are a sufficient number of simulations to quantify the output parameters for the simulation.

As demonstrated above, there is a considerable amount of uncertainty associated with the use of preventive maintenance treatments. Developing a sufficient database for establishing quality empirical models of preventive maintenance treatment performance will take years of observation. This is a particularly timely issue for preventive maintenance as the true benefit of preventive maintenance comes through the application of multiple treatments over the life of the pavement. The risk analysis approach presented in Figure 11 provides a tool that can be used to derive the maximum benefit from the available information.

SUMMARY AND CONCLUSIONS

The paper presents a step-by-step procedure for selecting the appropriate preventive maintenance treatment for asphalt pavement and evaluating the optimal timing for that treatment under different pavement, traffic, and climatic conditions. Also, it serves as a useful reference for seeking basic information of specific issues concerning preventive maintenance that needs to be assessed critically. The

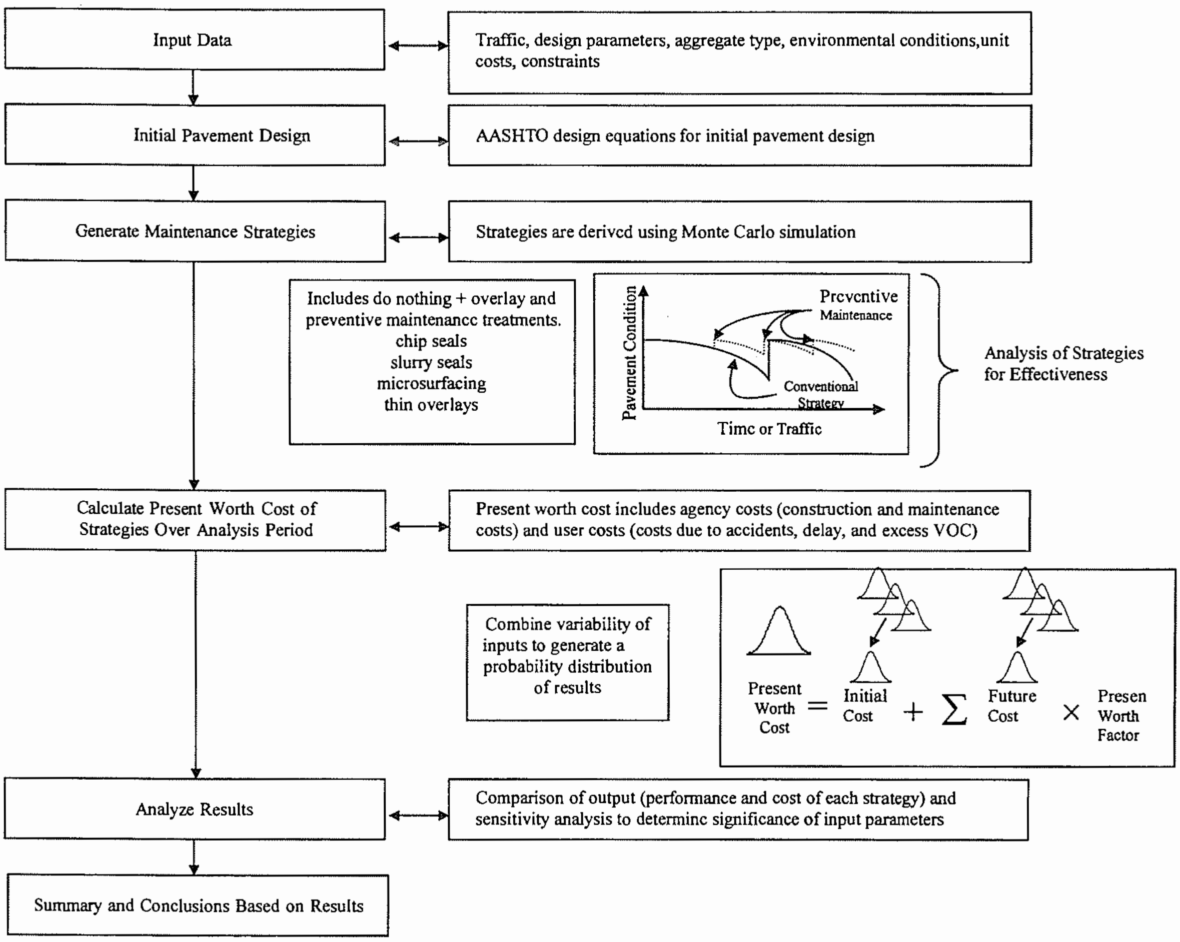

FIGURE 11 Concept for systematic analysis for pavement design including preventive maintenance

information presented in this paper is a useful tool for highway engineers and superintendents at the state, county, and city levels to develop a preventive maintenance program that would maximize the cost-effectiveness of maintenance treatments. Typical examples of pavement distresses are presented showing appropriate treatments that can be used. The approach discussed in this paper will help the highway agency understand the benefit of preventive maintenance and the need to invest money and use preventive maintenance. The model presented in Figure 11 provides the basis for the analysis of the cost-effectiveness of a pavement preventive maintenance program.

References

Al-Mansour, A.I. and Sinha, K.C. (1994) "Economic Analysis of Pavement Preventive Maintenance." *Transportation Research Board, Record 1442*, Washington, DC.

Federal Highway Administration (1998) "Status of the Nation's Surface Transportation System." *Report to Congress*, Washington, DC.

"Distress Identification Manual for the Long-Term Pavement Performance Project," (1993) *Report SHRP-P-338*, National Research Council, Washington, DC.

Geoffroy, D.N. (1996) "Cost Effective Preventive Maintenance." *NCHRP Synthesis 223*, Transportation Research Board, Washington, DC.

Gichaga, F.J. and Parker, N.A. (1988), "*Essentials of Highway Engineering with Reference to Warm Climates*," Macmillan Publishers, London, U.K.

Hicks, R.G., Seeds, S.B., and Peshkin, D.G. (2000), "*Selecting a Preventive Maintenance Treatment for Flexible Pavements*," Publication No. FHWA-IF-00–027, FHWA, Washington, DC.

Mamlouk, M.S. (2000) "*Preventive Maintenance of Flexible Pavement – Case Studies*." Presented at the Annual Transportation Research Board Meeting, Washington, DC.

O'Brien, L.G. (1989) "Evolution and Benefits of Preventive Maintenance Strategies." *NCHRP Synthesis of Highway Practices 153*, Transportation Research Board, Washington, DC.

Peterson, D.E. (1985) "Life Cycle Cost Analysis of Pavements." *NCHRP Synthesis 122*, Transportation Research Board, Washington, DC.

Raza, H. (1994) "Summary Report – 1993 Field Evaluations of SPS-3 and SPS-4 Test Sites." *Report No. FHWA-SA-94–078*, FHWA, Washington, DC.

Reigle, J. (2000) "*Risk Analysis Applied to a Pavement Design System*." Ph. D. Dissertation (in preparation), West Virginia University, Morgantown, WV.

Shahin, M. Y. and Kohn, S. D. (1979) "Development of a Pavement Condition Rating Procedure for Roads, Streets, and Parking Lots." *Technical Report M-268*, U.S. Army Construction Engineering Research Laboratory, Champaign, IL.

Sharaf, E.A., Shahin, M.Y., and Sinha, K.C. (1988) "Analysis of the Effect of Deferring Pavement Maintenance." *Transportation Research Board, Record 1205*, Washington, DC.

Smith, R., Freeman, T. and O. Pendleton (1993) "Pavement Maintenance Effectiveness." *Report SHRP-H-358*, National Research Council, Washington, DC.

The World Bank (1985) "*The Highway Design and Maintenance Model: HDM-III*," Vol. IV, Washington, DC.

Zaniewski, J.P. and Mamlouk, M.S. (1996) "*Preventive Maintenance Effectiveness – Preventive Maintenance Treatments*." Participant's Handbook, FHWA-SA-96–027, FHWA, Washington, DC.