The Optimal Time for Preventive Maintenance: Concepts and Practice

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SYNOPSIS

There is keen interest among highway agencies to manage their pavement networks using the concept of the "three rights:" applying the "right treatment, to the right roadway, at the right time." In recent years this concept has become synonymous with the increasingly widespread implementation of preventive maintenance programs by highway agencies. Under National Cooperative Highway Research Program (NCHRP) Project 14-14, an evaluation of highway agency pavement maintenance practices was performed to identify how treatment timing was being determined by those agencies that have implemented a preventive maintenance program.

From the initial phase of the project, it was clear that most agencies select the timing of preventive maintenance treatments based on expert opinion rather than using a methodical mathematical approach. Therefore, although many agencies have shown evidence of the benefits of implementing a preventive maintenance program, none of these agencies are truly optimizing the timing of their preventive maintenance treatments. Because of this discovery, the project emphasis was refocused on developing a methodology that would analyze an agency's own collected performance data in order to determine the most cost-effective treatment timing.

The first step was to define "optimal timing" in the context of preventive maintenance. A definition similar to that used in pavement management was selected as representative of what many highway agencies are trying to accomplish with their preventive maintenance practices. Next, a methodology for analyzing an agency's pavement performance data was developed. This methodology was then incorporated into an Excel®-based tool (using Visual Basic for Applications [VBA] macros) that can be used by agencies interested in analyzing their data. Because many agencies simply do not have preventive maintenance performance data, the tool also allows the analysis of expert opinion and assumed performance trends to assist those who wish to address the optimal timing question.

Finally, a validation effort was undertaken, in which data from four state highway agencies were used to evaluate both the methodology and the spreadsheet tool.

This paper offers an overview of the NCHRP 14-14 research into the optimal timing of preventive maintenance. It describes the optimal timing methodology that was developed as part of the research, presents the results of the analysis of agency preventive maintenance data, and makes recommendations for other agencies interested in determining the optimal time to apply their preventive maintenance treatments.

INTRODUCTION

As their budgets shrink, more and more highway agencies are moving toward a policy of pavement preventive maintenance and away from worst-first programming (in which pavements were allowed to deteriorate to a highly distressed condition before any restorative work was performed). Preventive maintenance is a systematic process of applying a series of treatments over the life of a pavement to maximize condition, extend pavement life, and minimize life-cycle costs. System-wide practice of pavement preventive maintenance is believed to result in benefits such as lower agency costs, improved pavement conditions, and increased customer satisfaction.

Experience with preventive maintenance in the United States spans a broad spectrum. Agencies such as Arizona (ADOT 2000) and Iowa (Jahren et al. 1999) have constructed test sections to evaluate the performance of certain preventive maintenance treatments, while others, such as Michigan, New York, and California, have well-established preventive maintenance programs which are documented in comprehensive manuals. In light of this broad range of experience, it is interesting to consider what is currently being reported about the status of pavement preservation in the United States. In a 1999 survey on pavement preservation in the United States, the American Association of State Highway and Transportation Officials (AASHTO) Lead States Team on Pavement Preservation (AASHTO 1999) surveyed transportation agencies in all 50 States, the District of Columbia, Puerto Rico, and six Canadian Provinces about their preventive maintenance programs. Of the 41 responding agencies, 36 reported having established pavement preventive maintenance programs, while 2 respondents were in the process of establishing a program. All 41 respondents reported using preventive treatments. Seventeen of the respondents had a program that had been in place for more than 10 years, and one agency reported practicing preventive maintenance for the past 75 years.

While these statistics suggest that preventive maintenance programs are mature in their development and widely used and accepted, actual practice is much more ambiguous. A 2000 survey of state highway agencies (SHAs) asked respondents to identify what they thought were the most important needs for their preventive maintenance program (FP2 2001). Some specific responses include the following: there is a "lack of research to specifically correlate maintenance treatments to extension of pavement life cycle," "we still don't have good answers about how often preventive maintenance treatments should be applied," "we aren't sure if we're using the right cycle times," we "need to be able to articulate definite cost savings and benefits to [the] state to obtain funds," and "we still rely on the 'expertise of experience' to determine appropriate preventive maintenance treatment timing."

Those responses are believed to more accurately represent the actual state of the practice.

PROJECT APPROACH

One of the initial challenges in this project was to attach some physical meaning to "optimal" timing in the context of preventive maintenance treatment applications. It could potentially mean getting the smoothest ride for the least money, delaying the need for rehabilitation the longest, or facilitating the attainment of some other agency objective. While the concept of "optimal" timing is closely linked to cost effectiveness, the definition of cost effectiveness also varies from agency to agency. Ultimately, a methodology very similar to the cost-effectiveness analyses used in pavement management systems was selected.

Optimal Timing Methodology

The chosen optimal timing methodology is built upon a number of fundamental benefit- and cost-related concepts. The approach assesses the effectiveness of a particular preventive maintenance application in terms of both the *benefit* it provides and the *cost* required to obtain that benefit. In this methodology, *benefit* is defined as the quantitative influence on pavement performance (i.e., any of one or more included condition indicators). Costs that may be included in the approach include:

- The agency cost to construct the treatment.
- Work zone-related user delay costs.
- The cost of a rehabilitation activity that would be considered at the point when the preventive maintenance treatment is considered failed.
- The cost of scheduled routine maintenance.

In the optimal timing methodology, the benefits associated with the use of a preventive maintenance treatment are evaluated in conjunction with its associated costs. The optimal timing of a preventive maintenance treatment is systematically defined as the pavement age at which the benefit associated with the treatment is greatest per unit cost.

Pavement Performance

The computation of benefit associated with an applied preventive maintenance treatment requires knowledge of the anticipated performance of the pavement. The performance of a treatment is determined by the change in condition indicators of interest to the agency, where condition indicators are defined as those measures of condition which define pavement performance. Any condition indicator used in the optimal timing methodology should have the following characteristics:

- Be measurable (able to be tracked over time).
- Indicate pavement performance (and especially functional performance, for preventive maintenance).
- Change value following the application of a preventive maintenance treatment.

Common condition indicators include the International Roughness Index (IRI), rutting, International Friction Index (IFI), raveling, bleeding, faulting, and so on.

The methodology permits the analysis of multiple condition indicators to determine in a comprehensive manner all of the benefits associated with the application of the treatment. However, to determine representative performance relationships, condition monitoring data are needed for any condition indicator that is used in the analysis.

Do-Nothing Relationships

The benefit associated with the application of a preventive maintenance treatment at any given time is based on the improvement in condition compared to the "do-nothing" performance. The do-nothing performance is defined as the performance over time (in terms of the condition indicators of interest) that would be expected if only minor routine maintenance were conducted on the pavement. When plotted in a graph of pavement condition versus time, these baseline performance relationships are referred to as "do-nothing" curves. Where benefit is defined in terms of multiple distress types, a "do-nothing" performance curve is required for each included condition indicator. Although the best source for do-nothing relationships is the performance data included in existing pavement management systems, the necessary relationships can also be approximated using engineering judgment if need be.

Post-Treatment Relationships

Determining optimal timing also requires an understanding of how performance is changed once the preventive maintenance treatment has been applied. A separate performance relationship (condition versus age) is needed for each unique combination of condition indicator and treatment application age; the assumption is that this relationship changes depending on when the treatment is applied. For example, if there are performance data for treatments applied at five application ages for three different measures of performance, 15 (3 x 5) different performance relationships must be defined.

Benefit Associated with Individual Condition Indicators

Within the methodology, *benefit* is the quantitative influence on any one or more condition indicators resulting from the application of a preventive maintenance treatment. Using this definition, many different *types* of benefit may be associated with an application of a given preventive maintenance treatment (applying a chip seal could result in benefits in the form of improved friction, retarded oxidation, or reduced rutting, for example). The benefit area for a given condition indicator is determined as the difference in computed areas associated with the post-treatment condition indicator curve and the do-nothing curve. For condition indicators that decrease over time (e.g., present serviceability, friction, or a typical composite index) it is the area <u>under</u> the curve that is important to the benefit computations, while for condition indicators that commonly increase over time (e.g., roughness, amount of cracking, rutting, faulting, and spalling) it is the area <u>above</u> the curve that is important to the benefit computations. Figure 1 illustrates the do-nothing area and the benefit resulting from the application of a preventive maintenance treatment.

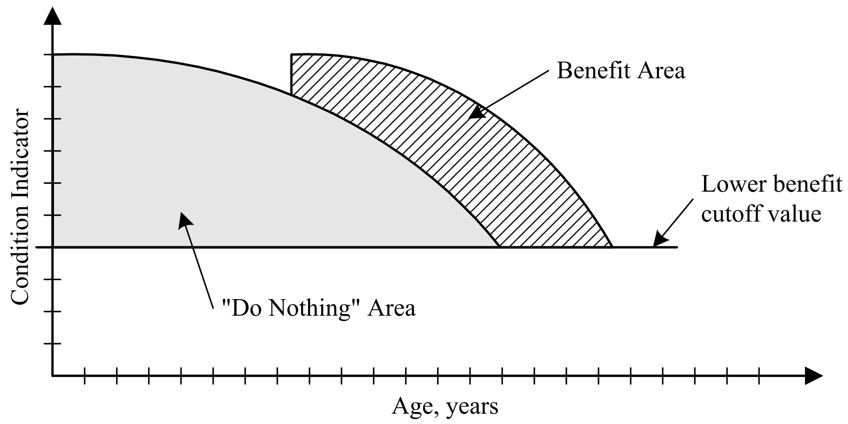

Figure 1 Conceptual illustration of the do-nothing and benefit areas.

Note that a defined lower benefit cutoff value limits these areas in the *y* direction. Benefit cutoff values are defined as the *y*-axis (condition indicator) boundary conditions for the performance curves that define the upper and lower limits for the benefit area calculations. More specifically, these user-defined values allow a user to define practical benefit limits within a given analysis. Figure 2 illustrates a benefit area that is bounded by both upper and lower benefit cutoff values. The inclusion of an upper limit is useful where it is possible to receive “excess” benefit from a treatment application. This might occur, for example, with a treatment applied to improve pavement smoothness. While a surface could be made increasingly smoother, the agency might determine that any smoothness beyond a specified value is not warranted. The use of a cutoff value (and the implied additional cost that would likely be incurred in achieving the uncounted benefit) is likely to make such a treatment not cost effective.

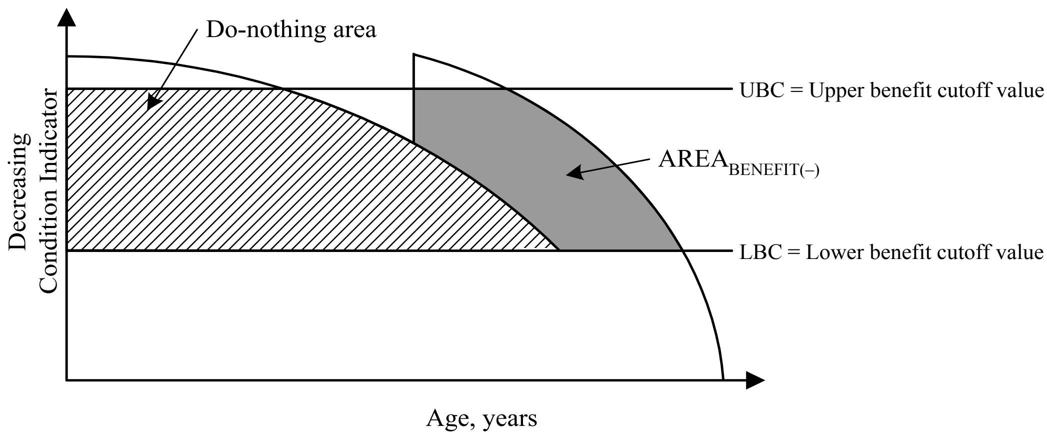

Figure 2 Benefit measures limited by upper and lower cutoff values.

The benefit (difference in areas) is generally *positive,* as a preventive maintenance treatment should improve condition or extend the time until the pavement needs rehabilitation; however, the methodology also calculates negative benefits (such as the decrease in friction that follows the application of a fog seal, or the increase in roughness that may accompany the application of a chip seal) if the conditions worsen due to the application of the treatment.

Because different condition indicators are expressed in different units, there is no easy way to directly add the benefits that are reflected by the different measures. The approach that is applied in this methodology is to normalize all individual condition indicator benefit values by dividing the benefit area by the original do-nothing area. The result is that all individual benefit values are similarly expressed in units of *percent*. For example, assume that the do-nothing and benefit areas in figure 1 are calculated to be 30 and 12, respectively. In this example, the individual benefit value associated with the increased performance that follows application of the treatment (in terms of the given condition indicator) is expressed as 12/30 = 0.4, or 40 percent.

Benefit Weighting Factors

When more than one condition indicator is included in the analysis, a method is needed to combine the individual benefit values associated with the different condition indicators. This is done by using *benefit weighting factors* and a normalization process. Benefit weighting factors are used to differentially weight the computed individual benefits associated with each included condition indicator. Each included condition indicator is assigned an integer weighting factor between 0 and 100, where all of the entered weighting factors must sum to 100 for a given analysis. Each chosen weighting factor is then converted to an associated *weighting percentage* by dividing each individual weighting factor by 100 (i.e., the sum of all assigned benefit weighting factors). The individual contributions to the overall benefit are then determined by multiplying the benefit weighting factor percentages by the individual benefit values. This approach is best explained with the following example.

Suppose that a particular preventive maintenance treatment timing results in individual benefit values of 27 percent for rutting, 12 percent for cracking, and 47 percent for friction. That is, the preventive maintenance treatment application increases performance by 27 percent over the rutting do-nothing benefit area, 12 percent more area over the cracking do-nothing benefit area, and 47 percent more area over the friction do-nothing benefit area. Next, assume that the agency chooses benefit weighting factors of 60, 30, and 10 for rutting, cracking, and friction, respectively (note that these factors add to 100). Using these weighting factors, overall benefit contributions are then determined by multiplying the benefit weighting factor percentages by the individual benefit values (e.g., for rutting 27 percent * 60/100 = 16.2 percent). The total overall benefit contribution is then the sum of those values calculated for each individual condition indicator; in this example the total overall benefit contribution is 24.5 percent (see table 1). By itself, this actual total benefit value is essentially meaningless; however, total benefit values computed for different timing scenarios are used (in combination with costs) to compare the effectiveness of those different timing scenarios.

Table 1 Example computation of overall benefit.

Condition Indicator	Individual Benefit Values, %	Assigned Benefit Weighting Factor	Benefit Weighting Factor Percentage	Overall Benefit Contribution, %
Rutting	27	60	60/100 = 0.6	16.2
Cracking	12	30	30/100 = 0.3	3.6
Friction	47	10	10/100 = 0.1	4.7
TOTAL	**—**	**100**	**1.0**	**24.5**

The optimal time to apply a treatment is based on a simultaneous analysis of benefit and costs. The application timing that maximizes benefit while minimizing costs (i.e., that timing with the largest benefit-to-cost ratio [B/C]) is labeled as the timing scenario that is most effective.

Costs

The second fundamental aspect of the proposed methodology is the inclusion of costs that are impacted by the application of preventive maintenance treatments. While an analysis can include any costs, the recommended life-cycle cost analysis considers preventive maintenance treatment costs (agency costs), rehabilitation costs, work zone-related user delay costs, and the costs of other routine maintenance activities. At least the treatment costs should be included, and any of the others can be added as desired.

Treatment Costs

Treatment costs include all agency costs associated with the placement of a preventive maintenance treatment. These include design, mobilization, materials, construction, and traffic control costs that the agency realizes during a particular preventive maintenance application.

Rehabilitation Activity Costs

Since the application of preventive maintenance should delay the need for major rehabilitation, the inclusion of the cost of such a rehabilitation activity is an option in the analysis. The cost of a required rehabilitation activity can be large in relation to the cost of a preventive maintenance treatment, so the timing of the expected rehabilitation activity can have a significant impact on a pavement's overall life-cycle cost.

Work Zone-Related User Delay Costs

In the optimal timing methodology, included user costs are limited to those associated with work zone delays (i.e., the cumulative delay cost recognized by all users who are subjected to the work zone during construction of the treatment). The methodology does not include other common types of condition-sensitive user costs (e.g., vehicle operating costs, discomfort, and accident costs) because the range in condition is assumed to be relatively small for pavements that are candidates for preventive maintenance. This approach favors those treatments that provide some benefit but can be placed comparatively quickly, with little disruption to the traveling public.

This cumulative delay cost is computed as a function of the average number of vehicles per day (AADT), work zone duration, average vehicle delay time, and cost per delay time per vehicle. As stated previously, the incorporation of user costs in the optimal timing analysis is optional.

This simplified process does introduce several sources of error. One obvious source of error is the accuracy of the user's estimates, but it is believed that even though these errors may be significant, they can still be used to make meaningful comparisons because it is the *relative* effects that are examined. Another source of error arises if a queue forms because of the work zone, because that generates considerable delay costs and it may not be accurately accounted for in the user's estimate of the number of vehicles affected by the work zone. However, given that the work zones associated with most preventive maintenance treatments are of relatively short duration and short length, queues are less likely to form and the error associated with this item is reduced.

Additional Routine Maintenance Costs

Different pavement structures and surfacing approaches generate different needs for routine maintenance. These are addressed in the methodology as a recurring cost for which the timing is not optimized. An example of such an activity is pothole patching, which may influence long term performance but does not fit the preventive maintenance model in that it is only done once the distress appears (i.e., its timing cannot be truly optimized). It should be noted that when choosing to include the costs of routine/reactive maintenance activities in an analysis, the do-nothing performance curves must include the expected effect on performance of this maintenance. When chosen, the routine maintenance schedule (and costs) are estimated and included in the analysis.

Effectiveness Index

To make the actual values of the benefit-to-cost ratios more meaningful, the concept of an *Effectiveness Index* is introduced. The Effectiveness Index (EI) normalizes all individually computed B/C ratios to a 0 to 100 scale by comparing all B/C ratios to the maximum individual B/C ratio (i.e., that ratio that is associated with the optimal timing scenario). The maximum individual B/C ratio is assigned an EI of 100, and all other B/C ratios are represented as a fraction of the maximum EI. The EI is computed for each timing scenario using equation 1.

$$EI_i = \left[\frac{(B/C)_i}{(B/C)_{\max}} \right] \times 100 \qquad \text{(Eq. 1)}$$

where:

- EI_i = Effectiveness Index associated with the i^{th} timing scenario (dimensionless).
- $(B/C)_i$ = Benefit-to-cost ratio associated with the i^{th} timing scenario.
- $(B/C)_{max}$ = Maximum of all of the benefit-to-cost ratios associated with the different timing scenarios.
- i = Index associated with the current timing scenario.

The application of the Effectiveness Index is best illustrated with an example. Assume that the performance of a preventive maintenance treatment applied on an HMA pavement 1, 2, 3, 4, 5, and 6 years after construction (i.e., six timing scenarios) is monitored. For each of the six timing scenarios, benefit, cost, and benefit-to-cost ratios are computed using the previously outlined procedures. The computed values used in this example are presented in table 2. An analysis of the data in this example shows that the B/C ratio associated with timing scenario 4 (i.e., application age at four years) is the largest B/C ratio of all investigated timing scenarios.

Table 2 Example computation of overall benefit ($BENEFIT_{OVERALL}$).

Year of Application	BENEFIT (B) Overall Benefit, %	COST (C) EUAC, $	BENEFIT-TO-COST RATIO (B/C), %/$	Effectiveness Index
1	52.7	$10,000	0.00527	47
2	65.5	$9,615	0.00681	61
3	102.4	$9,246	0.01108	99
4	99.8	$8,890	(Max) 0.01123	100
5	72.5	$8,548	0.00848	76
6	65.4	$8,219	0.00796	71

Using equation 1, each individually computed B/C ratio is then normalized by dividing by the largest observed B/C ratio (i.e., the 0.01123 value associated with an application age of four years after construction). As an example, the Effectiveness Index for application age 1 is 47 ([0.00527/0.01123] × 100 = 47). The overall Effectiveness Index results for this example are illustrated in figure 3.

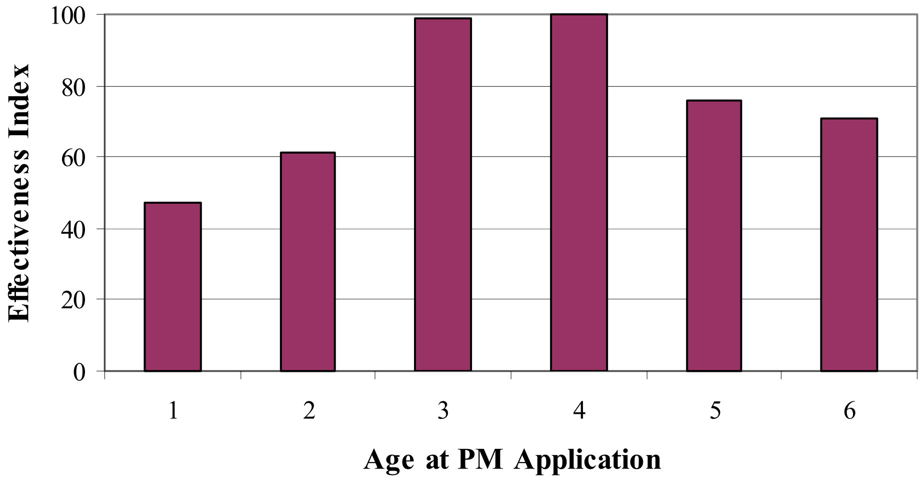

Figure 3 Example chart of Effectiveness Index versus timing of preventive maintenance application.

An agency that generates these results can conclude that the optimal time to apply this preventive maintenance treatment is in year 4, but that the results from an application in year 3 are very similar. Where there are minor differences in the Effectiveness Index, other output results such as total benefit, EUAC, or extension of life may help the user select the *most appropriate* timing scenario.

Introduction to the Analysis Tool

While the optimal timing methodology is conceptually simple, its application is complex. A macro-driven Microsoft® Excel-based tool, OPTime, was developed to make the methodology easier to apply. The resultant product is a versatile tool that allows users to analyze existing pavement treatment performance data applied over a span of years to identify the optimal time to apply that treatment. To maximize the number of users of the OPTime tool, two analysis approaches (referred to as *Detailed* and *Simple* approaches) are available within the tool. The *Detailed* approach is intended for those agencies who wish to base treatment timing on the analysis of actual historical performance data or trends. Recognizing that many agencies do not have the historical data needed to analyze optimal treatment timing, the *Simple* approach is included for those users that want to perform simplified “what if” analyses based on *estimated* performance trends.

The flow chart shown in figure 4 illustrates the major steps associated with the use of the tool. These steps also define the process of applying the optimal timing methodology, which would be extremely complex without the availability of such a tool.

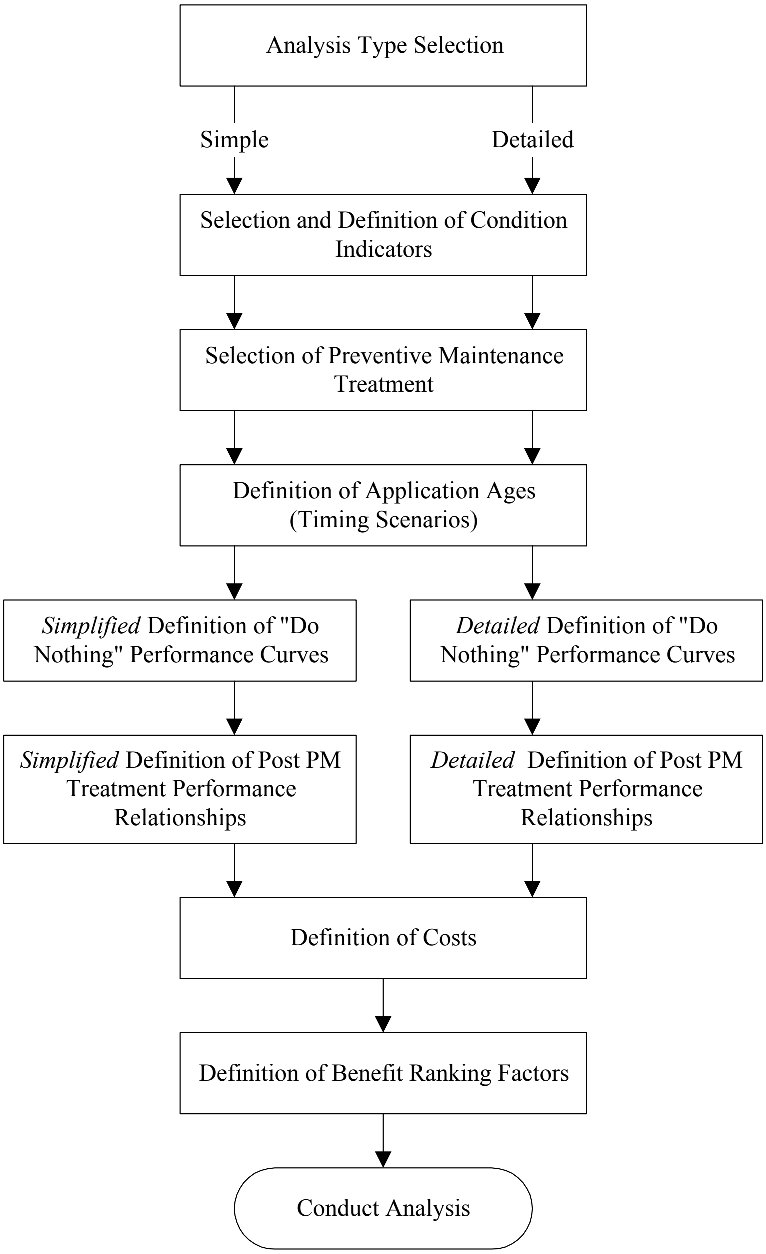

Figure 4 Outline of the data flow through the OPTime tool.

Validation of the Analysis Approach

Following the development of the optimal timing methodology and the analytical tool, the research team undertook a validation of the approach. Five state highway agencies (SHAs) — Arizona, California, Kansas, Michigan, and North Carolina — provided performance data for a range of treatments that were analyzed using OPTime.

At least one of the agencies was able to extract much of the required data from their pavement management database. Two other agencies had already compiled most of the required information for internal analyses; the other two undertook specific efforts to collect data that could be analyzed using the optimal timing methodology.

The following general observations are offered from the validation analysis:

- The performance of seal coats, chip seals, and crack sealing were evaluated using actual performance data obtained from the agencies.

- A wide range of performance measures are used to monitor pavement performance. The data examined included measures of IRI, friction, cracking, rutting, bleeding, equivalent transverse cracking, a Distress Index, and a Pavement Condition Rating (PCR). There are several instances in which the selected performance measures do not clearly reflect the benefits of these treatments.

- Few SHAs are tracking all of the information that is needed to evaluate the effectiveness of their treatments. Information that is needed but is not universally available includes the condition of the pavement prior to treatment, the results of doing nothing, the performance of the pavement after treatment application, and measures of pavement performance that reflect the benefit of applying preventive maintenance.

- Agencies continue to use their preventive maintenance treatments in "band-aid" applications. This complicated the data analysis in that treatment performance included both appropriate and inappropriate preventive maintenance applications. As such, the results did not always indicate a positive benefit from the treatment.

Nonetheless, the validation effort demonstrated the soundness of both the analytical approach and the usefulness of the OPTime tool. For two cases, the methodology clearly showed an optimal time to apply the treatment based on changes in treated pavement performance over time. In the other three cases, there were fundamental problems with the data sets that made an evaluation of the methodology ultimately unsuccessful.

SUMMARY AND RECOMMENDATIONS

For agencies that are interested in implementing a successful preventive maintenance program, there are many issues that need to be addressed. Among the most important issues are which treatments to use and under what conditions the use of the treatments is appropriate. Specific actions that can help to address these issues include the following:

- Identify objectives of the preventive maintenance program. These objectives can then serve as a guide to both the selection of preventive maintenance treatments and the measures used to monitor performance.

- Select treatments that are considered preventive applications and define guidelines on their appropriate use as preventive treatments. While the same treatments may be used as "band-aids" on pavements that have outlived their useful life, it is the conditions in which the treatment is used, rather than the treatment itself, that define a preventive use.

- Determine the expected performance of pavements when no treatment is applied (the "do-nothing" case) as well as the expected treatment performance. Expected treatment performance can either be analyzed from existing data or from test sections constructed specifically for that purpose.

- Select and collect measures of pavement performance in a regular monitoring process (such as a pavement management system) which is able to distinguish the effects of preventive maintenance treatments on performance.

When such processes are in place, the issue of treatment timing becomes of paramount importance. Previously, little guidance was available on what defined the optimal time to apply a preventive maintenance treatment. As described in this paper, the recommended optimal timing methodology considers the benefit (or benefits) of applying a preventive maintenance treatment, assuming that such benefits change over time as the pavement transitions from a relatively new structurally sound pavement to a pavement at the end of its life. The optimal timing methodology also considers associated costs of treatments applied at different times in the life of the pavement, concentrating on measurable user costs associated with work zone delays, as well as increased pavement maintenance costs and the delayed time until pavement rehabilitation is required.

Implementing an optimal timing analysis is facilitated through the use of OPTime, a macro-driven, Excel-based worksheet which permits both the analysis of agency data and the consideration of "what if" scenarios for those agencies that have yet to generate useful preventive maintenance performance data. For the agency that is seriously interested in developing optimal timing data for their own conditions, the final report for NCHRP project 14-14 includes an experimental plan that offers suggestions on how to set up and monitor preventive maintenance treatment sections that will generate data that can be used to determine locally appropriate optimal treatment timing guidance.

The evaluation of the optimal timing methodology and the spreadsheet tool using data provided by five different highway agencies suggests that the methodology is workable and that the spreadsheet tool is a useful means of carrying out optimal timing analyses. But, as outlined above, it also highlighted the need for agencies to carefully consider pavement management issues if there is interest in optimizing preventive maintenance treatment performance.

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Mr. Peshkin is a Principal and Vice President of Applied Pavement Technology, Inc. (APTech). His technical efforts focus on preventive maintenance research, technology transfer for pavement design, maintenance, and rehabilitation, and airfield pavement evaluation and design projects. He has been the Project Manager on the development of three training courses for the Federal Highway Administration (FHWA) through its National Highway Institute (NHI): *Pavement Preservation: The Preventive Maintenance Concept*, *Selecting Pavements for Preventive Maintenance*, and *Design and Construction of Quality Preventive Maintenance Treatments.* Mr. Peshkin is also an instructor for the FHWA/NHI workshop on design details for concrete pavements, and contributing author and instructor for two FHWA courses on pavement rehabilitation. Mr. Peshkin is an NHI-recognized Certified Instructor, and has assisted in the development and presentation of many successful training courses. He served as the Principal Investigator (PI) on NCHRP Project 14-14 on preventive maintenance optimal timing, and also served as the PI on a project for the South Dakota Department of Transportation evaluating the methods currently used by the Department for the collection of roadway data and making recommendations for improving the current practices.

Prior to joining APTech, Mr. Peshkin spent one year working as a consultant in the pavement engineering field. During that time, he developed presentation materials on pavement maintenance effectiveness for an FHWA project on innovative pavement materials, helped to develop guidelines for the design of rigid pavements, and assisted on a concrete pavement technology research effort. He served as an instructor for the NHI course *Hot Mix Asphalt Construction*, and presented the course seven times throughout the United States. Mr. Peshkin also spent almost 7 months in Malaysia on an Asian Development Bank-funded project to revise the World Bank's models for flexible pavement performance. As Principal Researcher–Roads, he was responsible for overseeing the pavement model development; he also had research and authorship responsibilities for several key sections of the final product.

Mr. Peshkin has over 17 years of experience in the pavement engineering field, is a registered professional engineer in four states, and is widely recognized for his research abilities and technology transfer skills.