Pavement Performance Modeling Using Piecewise Approximation

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A successful pavement management system requires an accurate pavement performance prediction model. A novel pavement performance model using the piecewise approximation approach was developed to estimate the pavement serviceable life. It can be broadly applied to estimate pavement performance of any distress types or indexes. The basic theory of the piecewise approximation is to divide the whole pavement serviceable life into three zones: Zone 1 for early age pavement distress, Zone 2 in rehabilitation stage, and Zone 3 for overdistressed situations. Historical pavement performance data are regressed independently in each time zone. This approach can accurately predict pavement distress progression trends in each individual zone by eliminating possible impacts from biased data in other zones. This paper describes the theoretical piecewise approximation process of data classification and model regression and then demonstrates an implementation for a group of Washington State Department of Transportation asphalt concrete pavements. The results are compared with the *Mechanistic–Empirical Pavement Design Guide* incremental damage approach, the current Washington State Pavement Management System (WSPMS) exponential model, and ordinary regression on all data points. Results indicate that the proposed approach is able to estimate the most accurate rehabilitation due year and to predict the performance trends for each divided zone. The piecewise approximation approach is planned for implementation into the WSPMS and will play an important role in decision making for future pavement rehabilitations.

The scheduling of pavement maintenance and rehabilitation is a critically important task for any state department of transportation. It is probably the key decision variable in any asset management system. This decision process relies upon the capability to predict future pavement distress condition as a function of time. If the pavement performance prediction model can be developed to accurately reflect real pavement performance, the remaining service lives for pavements can be more accurately estimated, which helps to

1. Optimize the pavement programming work plan. The models are used to predict the future road conditions and determine when maintenance or rehabilitation is required for individual pavement sections.
2. Determine the funding level to achieve a predetermined level of performance. With the model predictions, road agencies are able to estimate the long-term funding level required to maintain the road under reasonable performance objectives.
3. Improve pavement design methods and life-cycle cost analysis. The models relate the pavement service life and distresses to existing conditions, so they can improve pavement design and other cost analyses (*1*).

Empirical performance models based on evaluations of pavement conditions and traffic loads have been used for 40 years for pavement design and evaluation (*2*). In the past 20 years mechanistic–empirical models have been developed on the basis of field performance data, lab characterization of materials, pavement parameters, and performance (*3*). These models have been established on the basis of incremental damage approach, Markov process, Bayesian analysis, or other types of analysis (*3–7*). However, the attempts to develop general pavement performance forecasting models have not been generally successful in accurately estimating the pavement service life, as compared with the actual field performance.

The approach of the Washington State Pavement Management System (WSPMS) is not attempting to predict pavement performance broadly, because of the overwhelming nature of the variability of pavement performance. Instead, the performance of small (typically 0.1 mi) pavement sections is monitored until the data show they are projected to reach the optimum time for rehabilitation. For asphalt concrete pavement (ACP), performance monitoring is based on tracking three condition indexes that range in value from 100 (perfect) to 0 (complete failure). The three indexes are PSC (pavement structural condition), PRC (pavement rutting condition), and PPC (pavement profile condition). When any of these indexes reaches a value of 50, it has reached the "trigger" value for rehabilitation and is termed the due year. The development of this process was discussed in detail in previous reports (*8, 9*).

The small sections and their associated due years based on performance monitoring are then aggregated into project units, called preservation units, that are programmed for maintenance or rehabilitation. The key parameter for this pavement management process is, therefore, the due year for each preservation unit.

The research summarized in this paper involved implementing a novel pavement performance model using piecewise approximation (*10*). In this approach, the pavement performance trend over time is divided into three zones: Zone 1 for the early age pavement distress, Zone 2 for the rehabilitation stage, and Zone 3 for excessively distressed situations, which are well past the terminal serviceability level. The historical pavement performance data are regressed independently in each time zone, because most pavement distress types and indexes exhibit different progression trends in each zone, as observed in the 40 years of WSPMS performance data (*8*). The historical performance data are regressed in each zone independently, and integrated models are recommended for the transition areas between zones. This approach is able to more accurately predict the pavement distress progression in each individual zone by eliminating

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the possible influence from other zones. The method can also be broadly applied to estimate pavement performance for any distress type or index.

This paper describes the process of classifying data into zones and the associated piecewise approximation regression method. The results are compared with the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) incremental damage approach, the current WSPMS exponential performance model, and an ordinary regression model of all data points. The results indicate that the piecewise approximation is able to estimate the most accurate rehabilitation due year and to effectively regress the trends in each zone. This piecewise approximation approach is planned for implementation into the WSPMS, and it will play an important role in improving the decision-making process for pavement maintenance and rehabilitation.

REVIEW OF PERFORMANCE PREDICTION MODELS

Pavement performance is a general term used to describe how pavement conditions progress throughout the service life. Many approaches have been developed and applied to predicting pavement performance. These performance models can be separated into two categories: deterministic and probabilistic. The deterministic models are used to estimate the pavement response, structure performance, and damage models in a straightforward process using single estimates for the input variables. Typical probabilistic models use the "before" pavement conditions in a statistical method to predict the "after" conditions. The uncertainties are characterized by a proper reliability level (*1*). A reliability level of 50% was adopted in this study to represent the average conditions of the historical performance. Both types of models have been widely applied to empirical and mechanistic–empirical processes to estimate the pavement distress.

MEPDG is a typical mechanistic–empirical approach for pavement design and evaluation. The performance calculation is based on an incremental damage approach. Pavement damage is estimated and accumulated for each analysis interval. An analysis interval is defined as the basic unit for estimating the damage. The total cumulative pavement distresses at the end of interval i are applied to the beginning of the next interval, $i + 1$, until the end of the analysis period. It is a continual process that relies on the accuracy of estimation for each time interval. The model is required to fit all observed data throughout the entire analysis period.

If the entire pavement service life is divided into three continuous zones (Zone 1 for the early age pavement distress, Zone 2 for the middle, and Zone 3 for excessively distressed situations), Zone 2 is more important than Zone 1 and 3 for estimating the service life, because rehabilitation is most likely to occur in this zone. Thus, the shortcomings of using the MEPDG incremental damage approach can be summarized as follows:

1. The trend line in Zone 2 is more likely to be driven by data in Zones 1 and 3 (which possess more data points because the regression model is targeted to fit all measured data over the entire pavement service life);
2. The accuracy of the damage estimate in time Zone 2 is highly dependent on the accuracy of the damage in Zone 1, the early age of pavement life (where more measurement errors may exist because the distresses are too tiny to be measured precisely); and
3. There are fewer data points in the excessively distressed Zone 3 because most sections are rehabilitated in Zone 2, when rehabilitation is triggered. The fewer data points will affect the accuracy of models derived on Zone 3 data.

Above all, the performance models that attempt to model the entire service life lack accuracy to either estimate the rehabilitation year in Zone 2 or model the real distress conditions in all three zones. Therefore, an approach using piecewise approximation was implemented to improve the prediction accuracy in Zone 2—the most important zone for predicting the time to rehabilitation.

To illustrate this concept, Figure 1 shows the PSC of one 0.1-mi pavement section. This section is located in a preservation unit on State Route 82 from Milepost 0.63 to 1.78 (which contains 22 0.1-mi survey unit segments in both directions). The mean of the due year values is 10.1 years, and the standard deviation is 2.8 years. The mean minus one standard deviation defines the border between Zones 1 and 2, and the mean plus 1 standard deviation defines the border between Zones 2 and 3. Accordingly, Zones 1, 2, and 3 are defined

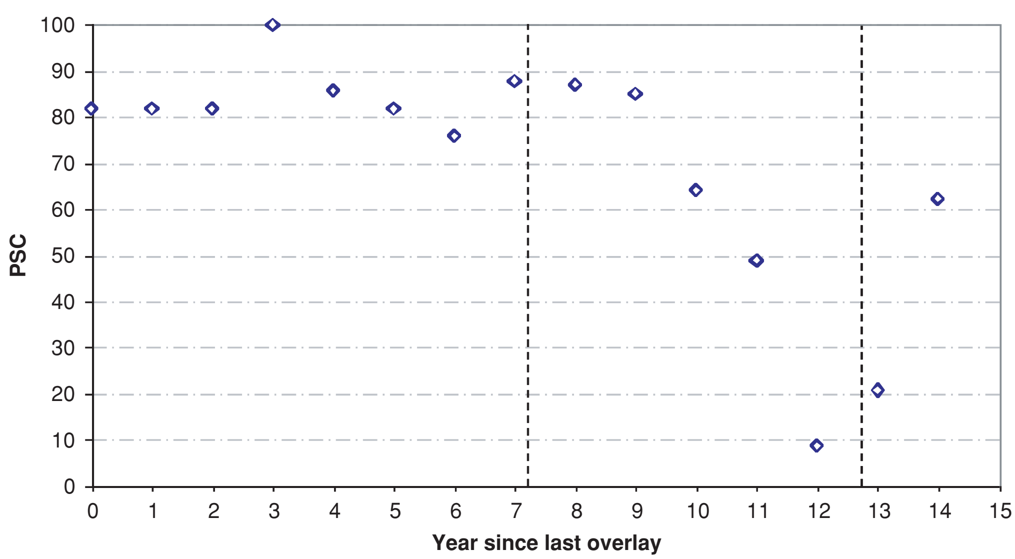

FIGURE 1 Example of pavement distress versus time data, divided into three zones.

as 0 to 7 years, 8 to 12 years, and 13 to 15 years, respectively. This section was overlaid in the 16th year.

DEVELOPMENT OF PAVEMENT PREDICTION MODEL USING PIECEWISE APPROXIMATION

The major characteristics of the piecewise approximation approach are as follows:

1. The life span can be separated into several analysis zones according to various pavement evaluation purposes. Typically, three zones are recommended: early stage of the pavement life zone, rehabilitation zone, and excessive distress zone.
2. The boundaries of each zone can be dynamic. Separations defined by the mean and one standard deviation of the real due year in the selected data sample are recommended, because this results in a more than 68% chance that the rehabilitation year is located in the middle zone.
3. The development of the performance models in each zone are independent, and their mathematical functions may differ. Each zone performance modeling can be used for different purposes: Zone 1 modeling for the early stage of pavement distresses; Zone 2 modeling for pavement rehabilitation plans; and Zone 3 modeling for pavement conditions by the end of the service life.
4. Integrated models are recommended near boundary areas between analysis zones.
5. This method has the objective of eliminating the impact of the data between zones and providing the most accurate models for each independent zone. The most important zone with regard to pavement management is Zone 2, in which the due year is determined.

Data Analysis

Because WSPMS predicts the pavement performance of short, relatively homogeneous sections, the performance modeling is primarily a process of monitoring the performance of a section as it deteriorates toward the due year. Because pavement condition data are collected each year, the due year prediction is updated every year.

For analysis of pavement serviceability, age is the most significant predictor, and the cumulative traffic loading in terms of equivalent single-axle loads (ESALs) plays a secondary role because the pavement has been designed to support the traffic loads throughout an expected service life with a reasonable pavement performance.

Data classification is a major issue for piecewise approximation. The Washington State Department of Transportation (DOT) has more than 19,000 lane miles of pavements, and the distress data are summarized annually for each 0.1-mi segment in WSPMS (*8, 11*). The performance model can be regressed for each survey segment, as discussed above, or larger sections of the network can be modeled in the same manner, depending on the purpose of the evaluation. Observations of the WSPMS data over 40 years reveal that pavement performance is significantly influenced by surface materials, base type, climate, and traffic loading. Thus, for ordinary analysis purposes, all WSPMS data could be categorized by the following groups:

- Surface materials of portland cement concrete (PCC), ACP, or bituminous surface treatment (BST);
- Base types of granular base, asphalt treated base, and cement treated base;
- Climates of western Washington, eastern Washington, and mountain passes; and
- Traffic levels of low (≤25 million in 50 years), medium (from 25 to 50 million), and high (≥50 million) ESAL levels.

Another major issue is how to separate the pavement life span into a number of analysis zones. The separation should be determined according to specific local pavement situations. For the Washington State DOT, the majority of the state pavements were built during the late 1950s and 1960s. Although they were not originally designed as perpetual pavements, deformations on base and subgrade layers were rarely observed. It is the philosophy of the Washington State DOT to keep the pavement structure in a reasonably good condition with proper maintenance and rehabilitation efforts.

ACP or BST pavements normally undertake several overlay cycles throughout the designed structure life. This overlay cycle is defined as a performance period. Distresses on the previous layers should be repaired before the next layer is placed; hence the performances of successive overlays are similar. Thus, the model regressed on the previous layer can accurately estimate the performance for the current or future layers. The assumptions are that the pavement base and subgrade layers have been designed to be relatively permanent and the material aging issues can be compensated by the continuous overlays to maintain the same structural support for the traffic loads. The analysis zones can be defined by the real data distribution of the previous layers.

However, for PCC pavements, the analysis period should be the pavement design life. Most of Washington State DOT's PCC pavements have far exceeded the original 20-year design life and have carried several times the traffic loading originally anticipated. The Washington State DOT is undertaking a major effort to identify both rehabilitation and reconstruction projects by estimating the future performance based on current and historical performance. Under these circumstances, researchers decided to define the analysis zones as within design life of 20 years, 20 to 40 years, and more than 40 years (as the overdistressed condition). Models developed on basis of the historical performance data can be applied to slabs under similar data categories of traffic level, climate, base type, and slab thickness.

Model Regression Using Piecewise Approximation Approach

As explained previously, WSPMS uses three condition indexes to monitor pavement performance. PSC is derived from all types of cracking for ACP pavements. It is the most important condition indicator and triggers more than 80% of ACP pavement rehabilitation projects.

An example showing the PSC performance trends versus pavement age, using the piecewise approximation approach in the WSPMS analysis on a group of 0.1-mi pavement segments, is demonstrated below. The historical PSC data throughout the service life of the previous layer on State Route 3 Milepost 30.5 to 31.5 were analyzed. This ACP segment is located in western Washington with a medium traffic level and a granular base. There are a total of 55 data points, resulting in 13.4 years of average service life and 2.6 years standard deviation. Accordingly, the pavement life span is divided into three zones using the mean and one standard deviation: 0 to 10 years, 11 to

16 years, and 17 to 25 years. The PSC data for each zone were regressed independently using econometric software, NLOGIT 3.0 (*12*). The results of the piecewise approximation were compared with three different models:

- MEPDG. This guide is an advanced pavement design tool that uses an incremental damage approach to estimate pavement distresses in a defined analysis period. The Washington State DOT has calibrated the models to local conditions (*13–15*). The estimated alligator, longitudinal, and transverse cracking were converted to PSC scores according to the WSPMS PSC equations (*9*).
- WSPMS curves. WSPMS currently uses exponential functions to fit regression curves to all data points and estimates the rehabilitation year when PSC is 50. The coefficients are determined using the selected data group (*8*).
- Regression for all 55 data points. All data were regressed in NLOGIT 3.0, and cosine function was found to be the best fit for the selected data.

The model functions, coefficient of determination (*R*-square), and estimated due year for rehabilitation as determined by the piecewise approximation, and the results for the three model types above, are listed in Table 1. Performance trends in the three zones are compared in Figure 2.

As Table 1 and Figure 2 indicate, the MEPDG estimation, WSPMS method, and regression of all data approaches are driven by Zone 1 and Zone 3, from which more data points are evaluated. The result is reduced accuracy in Zone 2, which is the most critical time period for due year estimation. However, the piecewise approximation approach analyzed the three zones of data independently and provided the most accurate estimation for Zone 2.

- The best fit progression trends and model functions for each zone in the piecewise approximation approach are significantly different from each other. This result indicates the need to separate the data into three analysis zones.

TABLE 1 Results of Four Selected Model Types

Model Type	Model Function	R^2	Estimated Due Year
MEPDG estimation	Incremental damage model	.64	15
WSPMS curves	$97.819 - 2.708 * \text{age}^{1.038}$	.78	16
Regression all data	$59.946 + 32.505 * \cos(0.127 * \text{age})$	.81	15
Piecewise approximation	Zone 1 $93.245 - 0.2621\ \text{age}^2 + 0.7329\text{age}$	.33	—
	Zone 2 $738.03 * \text{age}^{-1.0559}$	.94	13
	Zone 3 $264.06 + 0.396 * \text{age}^2 - 19.435\text{age}$	.38	—

- The piecewise approximation also provides the most accurate progression trend in Zone 2. The estimated due year is 13, which is the closest to 13.4 years (the average of the real data). The MEPDG estimation, the WSPMS exponential approach, and regression of all data estimates were 15 to 16 years.
- The MEPDG incremental damage models were calibrated to fit the trigger values around the rehabilitation period for all selected sections. Therefore, more bias exists in Zone 1 and Zone 3.
- The overall goodness-of-fit factors are fairly good for the WSPMS exponential approach and the regression of all data method, but the models are driven mostly by the Zone 1 and 3 data, and easily lost accuracy in Zone 2 for both progression trends and due year estimation.

The *R*-square of the piecewise approximation in Zone 1 and 3 are significantly lower. It is because of the errors of the measured data; no single model can fit the scattered data well. The improved accuracy of the piecewise approximation indicates that those data should be excluded from estimation of the rehabilitation due year in Zone 2.

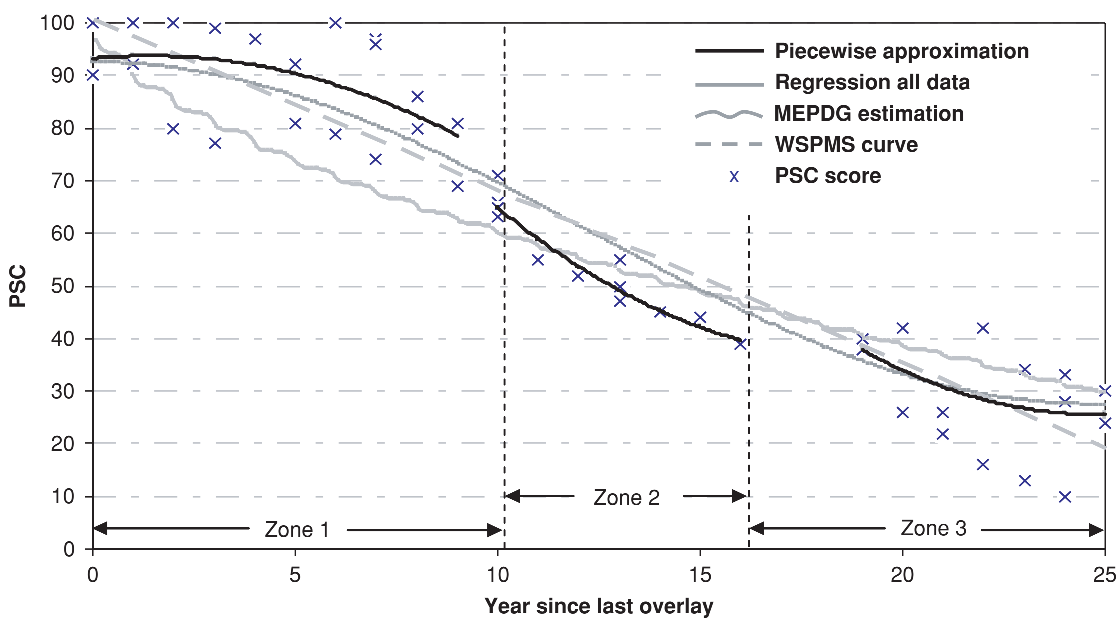

FIGURE 2 Progression trends generated by piecewise approximation approach and three other model types.

DISCUSSION OF RESULTS

The piecewise approximation method has demonstrated the benefits of modeling pavement performance independently in different zones, according to the data distribution.

Data Category

It is recommended to group data by surface material, traffic loads, climate, and base type. The approach can be applied to all possible pavement units or lengths, from project to strategic levels, according to various evaluation purposes. It could include a single pavement section, a group of projects, or the entire state route system.

Zone Partition

The primary characteristic of the piecewise approximation approach is the analysis zone partition. As the previous example shows, it is recommended to define the zones by the sample mean and standard deviation if the distribution form is known. Otherwise, an adaptive optimization algorithm can be used, in which data populations that are not normally distributed can be analyzed and partitioned (*16*). In the adaptive optimization algorithm, the partition of the analysis input space into a number of zones is not predefined, but obtained in the piecewise approximation process. The classification is improved step by step with improving data classification with changing zone definitions. The elaboration of the algorithms and the investigation of the possible convergence should be able to obtain the best goodness-of-fit factors. An example would be where the piecewise approximation is reduced to the special case of cluster analysis (*17*).

For boundary areas between the time zones, the model outputs may be different from the adjacent zones with various model functions. Integrated models can be applied if performance on a specific year needs to be estimated that is near a zone boundary.

Model Application

The piecewise approximation approach can be applied to, but is not limited to, estimating pavement distresses or indexes versus age or cumulative traffic loads. The methodology can also be used to investigate the impacts of possible factors, such as material properties, climate conditions, or pavement structures, on related pavement distresses. It is shown that the piecewise approximation approach can be induced to the classification problem. In these cases, the idea is to approximate pavement distress conditions in a set of functions defined in separate regions of the input parameters.

CONCLUSIONS AND RECOMMENDATIONS

This paper proposed the implementation of a new pavement performance model that uses piecewise approximation. The approach theory was used to investigate the PSC progression versus pavement age for a specific group of ACP sections from WSPMS and compared with the MEPDG incremental damage approach, the current WSPMS exponential model, and ordinary regression on all data points. Major findings follow:

- The progression trends and model functions for each analysis zone in the piecewise approximation approach differ. This result emphasizes the need to analyze the zones independently, as with the piecewise approximation approach.
- Neither the progression trend nor model function in each analysis zone of the piecewise approximation approach is similar to the other three types of traditional models.
- The zone partition is the primary characteristic of the piecewise approximation approach. The analysis zones can be defined according to the data distribution or an adaptive optimization algorithm during the approximation process.
- The method was developed to estimate the pavement serviceable life (due year), and can be broadly applied to any type of pavement distresses or pavement indexes.
- The other three types of traditional models that were examined are biased in their estimate of the rehabilitation due year because they are all heavily influenced by the Zone 1 and 3 data, which reduced accuracy in Zone 2 for both regression trends and due year estimation.

Recommendations for using the piecewise approximation approach:

- Good models must be established using accurate data. Pavement performance models involve a large amount of historical data, and improving the data measurement and accuracy is fundamental.
- Model functions are different in each analysis zone. Bias in a reasonable range should be allowed between boundary areas. Integrated models are recommended for estimates near the partition boundaries.
- The piecewise approximation can be applied to, but should not be limited to, pavement performance versus time or cumulative traffic loads. The methodology could also be used to explore some unknown area or extreme values that may present.

The pavement performance prediction models using piecewise approximation are planned for implementation into WSPMS to estimate the pavement rehabilitation due year and will play an important role in decision making for pavement maintenance and rehabilitation scheduling.

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