Reliability-based Model for Estimating Long Term Pavement Maintenance Contracts Under Performance Specifications

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Abstract
This paper presents a model through which the cost associated with pavement warranty in performance based maintenance contracts are analyzed and quantified. Performance based maintenance contracts are eventually getting popular among the Highway agencies. These are long term pavement warranty contracts where the contractors are responsible for maintaining the pavement condition up to a certain specified level over the period of warranty. The trend now is to award the maintenance contracts for a longer period of time, generally up to ten years or even more in some cases unlike the short warranty contracts. With the evolution of these new form of contracts, the challenge is to estimate the cost associated with these contracts for a specified performance period. Unlike the deterministic approach of cost estimation for new products, the maintenance contracts have probabilistic cost estimation approach. Since maintenance action is required when the performance threshold is exceeded, the time to failure of the product (when the performance threshold level is exceeded) is a random variable. This necessitates a different cost estimation approach for maintenance contracts of product (pavement) which is presented in this paper. The developed model can be used by the Highway Agencies as well as the contractors to estimate the cost of performing such long term pavement performance contracts based on stipulated performance criteria.

Keywords
Performance, Contract, Pavement, Warranty, Specification

1. Introduction
Studies made by the World Bank have shown that contracting out road maintenance to the private sector can reduce maintenance cost by between 30 and 50% (Queiroz, 1999). Some of the benefits of outsourcing maintenance include external expertise, improvement in monitoring and flexible use of labor and equipments. In the international arena, countries such as Argentina (1990), Uruguay (1995), Australia
Performance specified maintenance contracts use performance and life cycle cost models to specify the desired materials and construction quality and measure the acceptability of the as-constructed product. A framework for performance-related specifications (PRS) has been established and sufficient research has been completed (Ozbek, 2004). Although considerable research has been conducted in the area of life cycle cost modeling of the infrastructure, there is however very limited literature related to modeling cost in Performance-based environments. Virtually, no research has been completed till date to the knowledge of this author that comprehensively deals with the product performance risk faced by the contractors under the Pavement Specified Maintenance Contract (PSMC). This research will fulfill this vacuum by developing a model that considers risk of achieving multiple performance indicators under different contract conditions. The major party that would benefit from this research would be the contractors that are new to the performance based contracting environment in pavement maintenance business.

Experience confirms that the only credible means of managing pavement performance is through the use of pavement modeling techniques like the pavement deterioration models (Parkman et al., 2003). However, many of the existing pavement deterioration models are mechanistic and do not take into uncertainty associated with the input variables in their modeling process. A comprehensive list of controllable variables and uncontrollable factors that impact on the performance of the road has been listed by Ozbek for developing a framework for measuring the efficiency of highway maintenance strategies (Ozbek, 2007) but there has been no attempt to quantify the effect of these risks on the total cost of these maintenance projects. Since the agencies specify multiple performance indicators (such as cracking, rutting etc) rather than a single performance measure such as roughness index for the pavement, it is essential to predict the failure probabilities and expected number of failures due to various distress indicators within the maintenance contract period. Given the discussion above, there is therefore a need to develop and implement a comprehensive product risk assessment model that can take into account the risk of achieving multiple performance criteria as specified in the contract.

2. Performance Specifications/Warranty Specifications

A warranty is either an implied or an expressed (written or oral) agreement made by the seller to the buyer to provide satisfactory or expected performance during a given period of time after the purchase (Thomas & Rao, 1999). This concept of warranty in manufacturing industry is finding its application in the construction industry in the warranty based contracts. In products warranty, a warranty policy is defined mainly by two elements: (1) the period of coverage, and (2) the terms of payment or compensation to the buyer. This policy is analogous to the one applied in pavement warranty contracts where the agencies contract the maintenance work for certain period of time, known as the warranty period. If the pavement fails within this warranty period, the contractor has to repair or rehabilitate the pavement section and may also have to pay penalty for the failure of the pavement. Reliability of products is an important concept in manufacturing industry in order to predict the time to failure of products so that suitable premium for this risk is taken into account in product pricing. In a similar manner, in the warranty based contracts in the pavement maintenance, this risk premium needs to be estimated by the contractors before they bid for the job. Warranty specifications/ performance specifications are therefore very important to be defined well as what defines failure in these contracts is the inability of the performance indicators of the pavement to achieve the stated level of performance standard. Some of these performance specifications as mentioned in many papers and texts are potholes, cracking, rutting, ravelling, roughness (Zietlow & Bull, 1999; Pradhan, 2001; Attoh-Okine, 2001). However, depending on the risks that the highway agencies want to assume, performance criteria and their target levels vary accordingly. In that case, it becomes the burden of the contractor to model their risk premium based on the target level of these performance specifications. It is felt during this preliminary literature search that
such mechanism of allocating risk premium based on the level of performance standard demanded is very scarcely covered.

Warranty Analysis represents a new development in the Construction and Management of transportation infrastructure facilities. There are no published studies for determining the optimal schedule of rehabilitation during the warranty period. Most of the pertinent literature deals with the life cycle costing of pavements in the viewpoint of state highway agencies. However, with the changing roles of the contractor assuming more maintenance work in the performance based environment, a need has been created to estimate the value of these maintenance contracts in the viewpoint of the contractors.

3. Quantification of risk in Performance-based maintenance contracts

Performance-based maintenance contracts are different from the asset management contracts in a sense that when modeling for Performance-based maintenance contract the objective is to determine how much funding is required to meet the target conditions as opposed to how much can be achieved with the available funding in asset management. For tendering purpose, it has become necessary to modify the ‘typical’ modeling methodology to meet the tender requirements. For this reason the task of modeling for the tendering process tends to be more complicated and requires a greater understanding of modeling principles than if modeling for asset management purpose (Hatcher, 2001). Moreover, since the input variables in determining service life of the pavement is stochastic rather than deterministic, modeling cost of Performance-based pavement maintenance is a complex process and requires greater understanding.

Probability theory has been used for assessing life-cycle costs for infrastructures. Piyatrapoomi et al. note that there are several researches done in this area (Kong and Frangopol; Zayed et al.; Kong and Frangopol; Liu and Frangopol; Noortwijk and Frangopol; and Novick, as cited in Piyatrapoomi, 2004). However it is evident from the literature that there is very limited information on the methodology that uses the stochastic characteristics of asset condition data for assessing costs for pavement maintenance. Salem et al. (2003) have used a risk-based approach using probability theory and data input modeling to predict probabilities of occurrence of different life cycle costs associated with the construction/rehabilitation of an infrastructure unit. Markovian Decision Process has been a popular tool among various researchers modeling asset management decision problems because of its ability to include stochastic nature of pavement deterioration (Golabi et al., 1982; Kostuk, 2003). It has been widely accepted now that pavement deterioration must be represented probabilistically and not deterministically because of the following reasons as outlined by Kostuk (2003).

The mechanistic causes of pavement distress are not well known; one can model stress, strain, and deflection but not fatigue, cracking, rutting and other pavement characteristics. Pavement is under a continuous influence of random variables such as traffic loads, utilization and weather conditions. Pavement being a heterogeneous material performs differently at different sections.

Most of these pavement management models are based on the concept of asset management where the objective is to find how much of maintenance work can be done with the available budget by the agencies. However, if the same work has to be performed by the private parties, the objective of the modeling would be to find how much investment is required by them in order to execute the work in the Performance-based contracts. Not only this, equally important is the influence of key performance measures or level of service on the quantum and quality of maintenance work that the contractors have to achieve within the contract period.
4. Proposed Approach

In the light of the discussions in the preceding paragraphs, it is evident that there is a lack of literature that deals with the quantification of risks faced by contractors in determining the total cost of the performance specified maintenance contracts. It is proposed in this research that quantification of long term warranty is modeled using the system approach. System components in the performance specified maintenance contracts are the highway agencies, contractors and the external variables that influence the critical factors that describe the system behavior. While highway agencies define performance specifications, contractors control the schedule and the type of preventive maintenance and rehabilitation work. Equally important in the system is the influence of external factor that determines the pavement behavior and thus risk associated with pavement maintenance activities. So the effect of all these factors on the pricing of the contracts is proposed to be modeled using the system approach as to be discussed in the following chapter.

4.1 Performance Cost Estimation Methodology

An overview of the approach to performance cost analysis is shown in Figure 1. In order to estimate and predict performance costs, a cost model is required. Analysis of the model will provide the estimates. Proper formulation of the model requires an understanding of the warranty process. This begins with an appropriate system characterization. Each aspect of the methodology is described in the following sections.

![Figure 1: Performance Cost Estimation Methodology](image)

4.1.1 System characterization

In analyzing cost related to long term warranties in performance based maintenance contracts, the appropriate framework for system characterization is a stochastic framework with time treated as a continuum. In order to calculate the costs associated with warranty, it is necessary to model the random elements underlying the warranty process. Here, warranty process is considered the system. An appropriate characterization of the warranty process is required which means that characterization of each element in Figure 2 is needed in order to formulate a working cost model. From Figure 2 it can be seen that the direct cost of warranty is primarily a result of two key determinants: i) the structure of the warranty policy (performance based maintenance specifications) and ii) the failure pattern of the
pavement. Each of these is a function of many factors but the cost models that will be discussed in this chapter require precisely these two inputs.

![Figure 2: System Characterization](image)

4.1.2 Modeling
The cost model will be considered from the contractor’s point of view. As noted, cost models for warranty analysis depend on the type of warranty offered and the failure distribution of the product under warranty which in this case is the pavement. The type of warranty affects the cost in that it specifies the terms of rectification, that is, the type of maintenance action to be taken in case of failure under warranty, the preventive measures and their schedule. For example, the performance specifications will mention what distress indicators of the pavement need to be considered and what actions (both preventive and reactive) are required to bring the pavement to a required level of performance. A number of probability distributions are used to model the failure distribution of items. These range from quite simple to quite complex. Based on the actual plots of the failure data obtained from the pavement management systems, the type of distribution, whether it is normal, lognormal, and exponential or weibull is determined and appropriate mathematical expression for each of these failure distributions is determined.

Repair costs are uncertain, as they depend on the type of repair being done. The repair cost is therefore a random variable and needs to be modeled by a suitable distribution function. In general, it is very difficult to obtain the distribution function for the warranty cost for unit product, even for the simplest model formulations, because of mathematical intractability. Hence, expressions for the expected value of this cost will be used instead.

Data Structure and Analysis
The basic data on pavement performance in the US are usually available through the Pavement Management System. Long Term Pavement Performance (LTPP) is a 20-year research program developed by the Federal Highway Agency (FHWA) as part of the Strategic Highway Research Program.
LTPP is a collection of information on pavement performance such as rut depth, transverse crack, longitudinal crack, alligator crack, potholes and many other distress indicators and their influencing factors. LTPP has been monitoring more than 2400 pavement test sections across the United States and Canada since 1987 (FHWA, 2004). For performance-based contracts or warranty specifications, various distress indicators, their threshold levels and the remedial actions are usually agreed upon while drafting the contract document. Different modes of failure in asphalt pavement are as follows (WisDOT, 2001):

1. Alligator Cracking
2. Block Cracking
3. Edge Revealing
4. Flushing
5. Longitudinal Cracking
6. Longitudinal Distortion
7. Rutting
8. Surface Raveling
9. Transverse Cracking
10. Transverse Distortion
11. Patching
12. Potholes, Slippage areas and other disintegrated areas.

Probability-failure distributions for all these failure modes are plotted. These graphs are nothing but the plot of probability of failure on the y-axis and the time to failure on the x-axis. Different forms of failure distribution curves that can be plotted are: Normal, Lognormal, Exponential and Weibull. Goodness-of-fit tests can be applied to check which of the failure distribution plots are most applicable to the data at hand. Once it is determined which failure distribution curves are the best fit for the available LTPP data, parameters such as mean time to failure (MTTF), standard deviation of MTTF, shape parameters can be estimated for each failure mode.

Estimation of Warranty Costs
As discussed previously, reliability analysis approaches are used for estimating the probability of pavement failures caused by different distress failures. We assume here that the condition of the pavement after corrective repair is as good as new. We can then apply an ordinary renewal process to model the cost associated with warranty based on the pavement performance specifications. This ordinary renewal process has been used in warranty cost estimation of several manufacturing products such as aircraft windshields (Blischke and Murthy, 2000).

For the manufacturing products, expected cost of warranty for the product is given by Expression (1).

$$E[C(W)] = C + C_r M(W)$$

Where,
- $E[C(W)]$ is the Expected Cost of Warranty
- $C$= Cost of the product
- $C_r$= Cost of repairing the product
- $M(W)$= Renewal function of the product.

Slight modification of the Expression (1) is required to apply it to maintenance of pavement (which can be viewed as a product) by removing the cost of the product from the Expression (1).

Expression (1) is reduced to:

$$E[C(W)] = C_r M(W)$$

For the normal distribution probability of failure, the renewal function is evaluated by using the expression,
\[ M(W) = \sum_{n=1}^{\infty} F^{(n)}(W) \]  

(3)

Where \( F(n)(\cdot) \) is the \( n \)-fold convolution of \( F(\cdot) \) with itself, i.e., is the distribution of the sum of \( n \) random variables. Since the distribution of the sum of \( n \) random variables is normal with mean \( n\mu \) and variance \( n\sigma^2 \), the sum in Expression (2) is easily calculated. For the Weibull distribution, numerical methods and tables are required. A detailed mathematical derivation of the renewal function is explained in Blishchke and Murthy (1994).

Cost factor, \( C_r \) is available to the contractors for different types of corrective actions for different modes of pavement failures. For different warranty or performance period \( W \), the expected cost of pavement maintenance is obtained by multiplying the cost factor \( C_r \) with the renewal function, \( M(W) \) as in Expression (2). Contractors usually have a record of cost per unit repair for different repair actions based on their past projects. The final cost associated with long term warranties is thus estimated based on the mathematical model proposed. However, when the pavement fails due to several modes at the same time, a single repair action may rectify several failure modes. In this case it is not necessary to calculate the repair cost for all the failed distress indicators. A best course of repair action that can bring the distress indicators to the acceptable level of performance is decided by the estimator and an estimate is based on this action taken.

5. Conclusion

In this paper, a mathematical model is developed to estimate the pavement maintenance cost for long term pavement maintenance contracts using reliability concept. Reliability is nothing but the measure of how long a product or a system would last without failing. Reliability concept is a backbone of warranty cost calculation in manufacturing products. Manufacturing industries maintain a long term record of the failure data of the products that they manufacture. Similarly, Highway Agencies also have started to maintain a performance record of the pavements that they construct and maintain. When pavement maintenance contracts are awarded to the contractors based on performance specifications for certain time, reliability concept can be used for estimating the cost associated with the pavement maintenance. When we assume that the pavement returns to “as good as new” condition after the corrective repair, pavement failures can be viewed as an ordinary renewal process, similar to what is done for an industrial product. The renewal function is derived from the pavement failure distributions. The mathematical formulae to calculate the warranty cost associated with any product can be used in the case of maintaining a pavement over a warranty period with slight modification as explained in section 4. Considering pavement as a form of product, the mathematical expressions developed for industrial product are adapted in this paper so as to apply it to estimate the cost of long term warranties of pavement maintenance. In the next phase of the research, the plan is apply this concept to a real pavement obtained from LTPP data base.

6. References


