Estimating Pavement Maintenance Costs under Performance-Based Contracts

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Abstract
Performance-based maintenance contracts differ significantly from method-based contracts that have been traditionally used to maintain roads. Road agencies around the world have moved towards a performance based contract approach because it offers several advantages like cost saving, better budgeting certainty, better customer satisfaction with better road services and conditions. Payments for the maintenance of road are explicitly linked to the contractor successfully meeting certain clearly defined minimum performance indicators. It is indeed a difficult task to estimate contract value of these maintenance works when no definite quantity of work is known. There is an abundance of literature when the objective function is to determine how much of the road section can be managed with the available funding. On the contrary, when the objective function is to determine how much money is required to maintain the road to certain specified performance conditions, there seems to be a dearth of knowledge. Estimating the value of these contracts based on the performance specified by the transportation agencies to maintain them over a certain period of time is the main aim of the research. For this, rather than evaluating the cost of maintaining the road based only on a single performance criteria such as pavement condition index, multiple performance criteria such as cracking, rutting and, roughness are taken into consideration in developing a model to estimate the cost of such maintenance contracts. Markov chain process has been utilized to model the stochastic degradation of the road condition over a certain period of time. Preventive and rehabilitative maintenance activities of varying amount are then proposed over the maintenance contract period so as to limit the distress condition within the specified threshold. Based on the proposed program of preventive and rehabilitative maintenance works over the period of the maintenance contract awarded to the contractor, cost is finally estimated.

Keywords
Performance-based contracts, Road, Risk, Transition probability matrix, Maintenance

1. Introduction

Performance-based contracts may be viewed as warranty contracts that specify the output or outcome required from the finished product. When the output or outcome required from such a product extends over a number of years, or when the performance is observed over an extended period of time, they become long term warranties or long term performance-based contracts. For infrastructure projects, for instance- highway projects, performance warranties for the procurement and management of transportation infrastructure can be classified into three categories (Federal Highway Agency, 2003):

short term warranties, long term warranties, and maintenance warranties. Short term warranties are usually implemented to safeguard against any defects shortly after construction. Contractors are liable to rectify any damage or defect within this short period without imposing any extra cost to the highway agencies. The other form of warranty, the long term warranty, on the other hand, covers the design, construction, and maintenance period even after several years post construction. This form of warranty is also known as the performance-based contract or performance specified maintenance contract. A very similar form of warranty as that of long term warranty but that covers only the maintenance part of the constructed transportation infrastructure in use is the maintenance performance warranty. Maintenance performance warranties consider the application of preventive maintenance as well as rehabilitations, and are also sometimes referred to as performance specified maintenance contracts or performance-based contracts (Damnjanovic, 2006). It is the intention of this study to explore this form of maintenance warranties or, simply referred to as the performance-based maintenance contracts in this paper.

Performance-based contracts differ significantly from method-based contracts that have been traditionally used to maintain roads. In traditional method-based contracts for road maintenance, highway agency usually specifies techniques, technologies, materials and quantities of materials to be used, together with the time period for which the maintenance works should be executed. The payments to the contractor is based on the amount of inputs (e.g. cubic meters of asphalt concrete, number of working hours) and the calculation is rather straight forward. However, in performance-based contracts, evaluation of payment to the contractor is difficult because payments are not based on the amount of inputs. Rather, a different approach of evaluating the amount of payment for the work scheduled or done by the contractor in the performance-based contracting is necessary. When these contract values are agreed in lump sum, which is often the case, it also becomes the burden of the contractor to evaluate the fair value of the contracts so that their bid price is competitive without putting them in a peril of losing money once they are awarded the contracts.

In performance-based maintenance contracts risk is shifted to the party who has more control over the project. Since the contractor has more control over the project, and therefore the risks, the contractor has to bear the risk of failure of the project. There have been numerous works in the area of risk management for new projects but there are very few for the maintenance projects under the performance-based environment. The risks that were earlier assumed by the agencies in pavement maintenance projects under traditional contracts now fall under contractors' responsibility in the performance-based contracts. There is a dearth of literature in the area of performance-based maintenance risks borne by the contractors. Most of the literatures discussing risks in performance-based maintenance contracts are subjective in nature focusing largely on the opportunities and importance of managing risk. Kostuk (2003) points this shortcoming and states that Gallagher and Mangan (1998) were the first to directly address risk in the context of long term maintenance contracts but that too without any methodology to quantify the risk. Gallagher and Mangan (1998) identified that the key to success in managing the risk associated with long term maintenance contracts is to be able to measure the condition state of the asset.

In this paper, study of the performance-based contracts for maintenance of road with a view of evaluating the fair value of the contracts is performed. For this, it is essential to accurately model future road condition based on the historical road conditions, and then link the future road conditions with the amount of work required to be done so as to maintain the road at the specified level of service for the agreed number of years. Once the amount of work to be done or, the program of work is determined, cost associated with such maintenance activities is easily evaluated.

2. Problem Statement

Eventual transition from in-house maintenance practice to off-shoring of the maintenance work has in turn necessitated, and brought about various contracting practices around the world including the United

States. As evident from the discussion in the previous paragraphs, one such form of contracting is the warranty contracting. A special form of warranty contracting is the performance-based contracts which are usually awarded on a long term basis, often exceeding ten years. Agreements of these contracts are complex not only because of length of the contract duration, but also because of the multiple performance criteria that is contractually imposed. Unlike the cost estimation in method-based contracts where the quantity of work is defined, it becomes the burden of the contracting party to estimate the cost of maintaining the road to a specified level of condition by predicting the future condition of the road. Linking performance to cost is often difficult, and it is this difficulty and uncertainty that makes the contractors more concerned about using the performance-based contracting in their future work. One of the most important concerns for the industry is the risks and liabilities posed by the use of long-term warranties. The contractor must maintain the warranted highway facilities above the required performance. Research by Bayraktar *et al*., (2004) indicated that the increase of bid price for such performance based contracts, or warranty projects in particular, is a function of project type and the warranty period. Short term warranties, with duration of one to three years, do not have significant impact on the cost. For warranties longer than five years, the resulting increase in the bid price varies dramatically. On average, a 5-year-warranty takes 10% of the total budget, and a 20-year warranty takes over 30% (Bayraktar *et al*., 2004). Contractors in many states are thus skeptical of warranty contracting. Cui *et al.,* (2007) reported that warranty cost estimating method ranked third among the main concerns in industry regarding warranty contracting.

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 account the uncertainty associated with the input variables in their modeling process. A comprehensive list of controllable variables and uncontrollable factors that have 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, roughness etc) rather than a single performance measure such as pavement condition index for the pavement, it is essential to predict the future road conditions in terms of all these performance indicators or criteria. Given the discussion above, there is therefore a need to develop a cost estimating model that can take into account the risk of achieving multiple performance criteria over an extended period of time as specified in the contract.

3. Research Purpose

The purpose of this research is to develop a methodology that can assist the contractors to estimate the cost of the performance-based road maintenance contracts based on the risks transferred to them by the highway agencies so that a fair value for executing the contract is obtained. Under varying contract specifications and contract durations, the risk transferred to the contractor also varies, and to accurately model the cost associated with maintaining the road within the specified level of service is the primary purpose of this research.

In order to accurately estimate the future pavement maintenance cost, it is essential to predict future road conditions. By developing a probabilistic performance model that can predict failure probabilities for multiple performance indicators such as roughness, rutting, and cracking, among others, cost estimate of maintenance activities is achieved.

4. Research Methodology and Approach

Since 1985, Pavement Materials System Section has been collecting, processing, and analyzing the information on the condition and the performance of the Florida State Roadway System on an annual basis. All roadway sections are rated in terms of varying severity and extent of specific distresses, namely, (1) cracking, (2) rutting, and (3) ride quality. Survey is conducted on state roads belonging to each county, which again belong to one of the six districts of the state of Florida. These are further categorized into Primary, Interstate, Turnpike, and Toll Roads based on the system.

In this paper, cracking, rutting, and ride quality conditions of the interstate highway of Florida are stochastically modeled to predict the future road condition using the data provided by Pavement Material System Section of Florida Department of Transportation (FDOT). The following steps describe the methodology in detail.

Step 1: Define the number of condition states
Although the condition states defined by the Florida Department of Transportation is rated on a scale of 0 to 10, for simplification purpose the condition of the distresses are categorized into three condition states as shown in Table 1. Since this research applied a three condition state model, FDOT condition state boundaries were modified on an arbitrary basis.

Table 1: Distress Indicators and their Limit

Distress	Distress Limit		
	Excellent (E)	**Good (G)**	**Poor (P)**
Cracking	10-9	8.9-7	6.9 & less
Rutting	10-9	8.9-7	6.9 & less
Ride (Roughness)	10-9	8.9-7	6.9 & less

Step 2: Generate transition probability matrices for pavement deterioration
Markov prediction models have been used to predict the probability of a length of a road being in a certain condition at a particular time. Transition Matrices are developed in the process of predicting future road conditions. Estimating a transition matrix is a relatively straight forward process if we can observe the sequence of states for each of the individual unit of observation. For example, if we observe the condition state of the pavement at the beginning of the year, and again at end of the year, then we can estimate the probability of the pavement section moving from one condition state to another. The probability of a pavement having a particular condition state at the end of the year, (e.g. Good) given their condition state at the beginning of the year (e.g. Excellent) is given by the simple ratio of the number of pavement sections that began the year with the same condition state (Excellent) and ended with Good condition state to the total number of pavement sections that began with an Excellent condition state. Suppose there are 100 pavement sections with an Excellent condition state at the beginning of the year, of which only 70 remain in an Excellent condition state, and the remaining 30 sections degrade to the next condition state , i.e., Good at the end of the year, then the transition probability can be estimated using the ratio as follows:

Transition probability from Excellent (E) to Excellent (E) condition state is given by the proportion:
$p_{E,E} = 70/100 = 0.7$

Transition probability from Excellent (E) to Good (G) condition state is given by the proportion:
$p_{E,G} = 30/100 = 0.3$.

Transition probabilities from one condition state to another condition state can be estimated in a similar manner using the count proportions obtained from historical record of pavement condition states.

Transition probability matrices are derived for three different distress indicators from the available pavement condition states.

Table 2: Cracking Condition State Distribution

Cracking Condition State	No. of Sections
Excellent (E) →Excellent (E)	198
Excellent (E) →Good (G)	13
Excellent (E)→ Poor (P)	2
Good (G)→ Good (G)	88
Good (G)→ Poor (P)	5
Poor(P) → Poor (P)	62
Total	368

Table 3: Transitional Probability Matrix Deterioration due to Cracking

	E	G	P
E	0.93	0.06	0.01
G	0	0.95	0.05
P	0	0	1

Table 4: Transitional Probability Matrix Deterioration due to Rutting

	E	G	P
E	0.92	0.08	0
G	0.214	0.786	0
P	0	0	1

Table 5: Transitional Probability Matrix Deterioration due to Ride (Roughness)

	E	G	P
E	0.51	0.49	0
G	0.04	0.94	0.02
P	0	0	1

Step 3: Generate transition probability matrices (TPM) for different maintenance activities
In step 2 above, transition matrix for deterioration for each of the three distress criteria are determined. These deteriorations are for pavements which are exposed to natural degradation process but where routine maintenance (minimal maintenance) is performed. In other words, these deterioration matrices are for pavements that may have received routine maintenance. These routine maintenance activities do not improve the condition of the pavement, but rather retard the degradation rate. On the other extreme of the maintenance process is the replacement of the pavement, which brings the state of the pavement to an excellent condition. Effects of all the other maintenance actions are somewhere in between these two extremes. Kostuk (2003) has methodologically defined a discrete continuum of deterioration matrix for other maintenance activities whose effects lie between these two extremes. The routine maintenance was defined as:

$$TPM_1 = \begin{vmatrix} a & b & c \\ 0 & d & e \\ 0 & 0 & 1 \end{vmatrix}$$

where a,b,c,d, and e are transitional probabilities for routine maintenance. The matrix describing full replacement (i.e. regardless of its initial condition state, the pavement is always returned to an excellent condition state) is then:

$$TPM_{10}= \begin{vmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{vmatrix}$$

Eight other transition probability matrices, which map the transition between these two matrices, are defined so that the incremental effects of these maintenance activities are of equal magnitude as much as possible. That is, if the maintenance activity-10 has 100% effectiveness, then maintenance activity-9 can be thought of as having maintenance effect of 90% effectiveness. These transitional probability matrices for all the maintenance activities, from maintenance action 1 to maintenance action 9, are as shown in Table 6.

Table 6: Generic Transitional Probability Matrices

Maintenance Action	Transitional Probability Matrices			
1	$TPM_1=$	a	b	c
		0	d	e
		0	0	1
2	$TPM_2=$	a	b	c
		0.6	4	0
		0.6	0.35	0.05
3	$TPM_3=$	a	b	c
		0.65	0.35	0
		0.65	0.30	0.05
4	$TPM_4=$	a	b	c
		0.7	0.3	0
		0.7	0.25	0.05
5	$TPM_5=$	a	b	c
		0.75	0.25	0
		0.75	0.20	0.05
6	$TPM_6=$	a	b	c
		0.8	0.2	0
		0.80	0.15	0.05
7	$TPM_7=$	a	b	c
		0.85	0.15	0
		0.85	0.10	0.05
8	$TPM_8=$	0.95	0.05	0
		0.9	0.1	0
		0.9	0.05	0.05
9	$TPM_9=$	1	0	0
		0.95	0.05	0
		0.9	0.1	0

		1	0	0
10	$TPM_{10}=$	1	0	0
		1	0	0

The unknown values a, b, c, d, and e are replaced by the actual values determined for distresses cracking, rutting, and ride from Table 3, 4, and 5 respectively. Once these values are substituted, generic transitional matrices of Table 6 become specific transitional matrices for each of the three distress criteria analyzed in this paper.

Step 4: Determine actual condition states distribution of pavement
The distribution of the actual condition states of the pavement throughout the analyzed length of the pavement under performance-based contract is required to obtain an average state of condition of the pavement before and after maintenance. This is calculated by finding proportion of the roadway in excellent, good, and poor condition states. The probability of finding the road in each of the three states, excellent, good, and poor, for three different distresses is shown in Table 7.

Table 7: Condition Distribution (Probability) and Average Distress Condition Value

	Condition State	Probability	Average Cracking
Cracking	Excellent	0.641	9.93
	Good	0.277	7.12
	Poor	0.082	6.50

	Condition State	Probability	Average Rutting
Rutting	Excellent	0.641	9.00
	Good	0.277	7.37
	Poor	0.082	3.50

	Condition State	Probability	Average Ride
	Excellent	0.641	9.00
Ride	Good	0.277	7.37
	Poor	0.082	3.50

Step 5: Identify maintenance actions and their effectiveness
Table 8 below shows different maintenance treatments available for this performance-based contract, and any one or combination of these maintenance actions could be chosen so that the condition of the pavement is maintained at the pre-specified level of service at the minimum cost. Result of the treatment actions, denoted by a number from one to ten, is the effectiveness of the maintenance treatments. One denotes least effective whereas, ten denotes that the maintenance action is the most effective.

Table 8: Maintenance Treatments and their Effectiveness (Kostuk, 2003)

Maintenance Action	Maintenance Treatment	Effectiveness on Rutting	Effectiveness on Ride	Effectiveness on Cracking
1	Routine maintenance	1	1	1
2	Thermo-patch	2	1	6
3	Flush seal	1	2	1
4	Spot seal	2	1	1

5	Strip seal	3	3	1
6	Micro-surfacing	5	7	6
7	Full seal	1	8	2
8	Spot overlay & seal	4	4	4
9	Thin overlay	7	9	8
10	Structural overlay	10	10	10

Step 6: Simulate the maintenance and rehabilitation (M&R) actions

Depending on the existing condition of the pavement when the contract is awarded to the contractors, different maintenance treatments may be needed to bring the condition of the pavement to an accepted level. These maintenance treatments are those numbered from 1 to 10 in Table 8. In the simulation process, maintenance activity that requires the least overall cost to maintain the pavement such that the specified level of condition is achieved is considered first. If this maintenance activity is unable to bring the condition of the pavement to the accepted level, maintenance treatment of the next higher level is considered. The intention of the simulation is to make sure that the pavements are maintained at least at the threshold level of performance specified. To get a better idea of how this is achieved, step-by-step calculations are presented for years 0 and 1 for rutting.

i) Year 0: Since no maintenance activity is performed in Year 0, the performance condition of the pavement is the initial condition determined in step 4. For rutting, this is determined to be $Y_0 =$ [0.641, 0.277, 0.082]. The distribution of excellent, good, and poor condition is 0.641, 0.277, and 0.082 respectively. Since this gives the average condition of the rutting in each condition state, the overall rutting condition of the pavement is determined by multiplying the rutting condition distribution by the respective mean level of rutting in each condition state. The overall rutting level of the initial condition at the time when the performance contract is awarded is calculated by multiplying the condition distribution by the mean level of rutting for each condition state. This overall rutting level comes out to be 8.80. When this rutting value is above the specified threshold level of 8.0 specified in the contract (assumed here), no maintenance activity is required in the succeeding year.

ii) Year 1: The performance condition in Year 1 is the product of condition distribution in Year 0, Y_0, and the deterioration matrix given in Table 4. This is represented by vector Y_1, and is calculated to be $Y_1 =$ [0.834, 0.166, 0]. The overall condition of the pavement in terms of rutting is found to be at 8.729, which is also above the contract specified threshold level of 8.0. Since there was no maintenance activity performed in Year 1, the rutting condition level of the pavement deteriorated from 8.80 to 8.72, although not significantly.

This simulation process is carried out in excel sheet from Year 0 to Year 10 (the performance contract period) such that the actual condition level of the rutting is maintained at or above the threshold rutting level of 8. In doing so, maintenance actions that are the least expensive, but good enough to maintain the pavement at the performance specified level are chosen.

This simulation is repeated for other two performance criteria, namely cracking, and ride by choosing maintenance activities from Table 8, which maintain the pavement at the pres-specified level of ride and cracking, and cost the least for the entire duration of the performance contract.
It should be noted here that, maintenance activity applied to remedy one distress may also improve the condition of the pavement in terms of other distress criteria and should be taken into account using Table 8 to calculate the overall pavement condition.

Step 7: Estimate cost associated with a long term maintenance contract

Once the overall program of maintenance actions is determined using steps 1 to 6, it is quite straight forward to quantify the cost associated with these maintenance activities from the unit cost data available. These costs, which are determined for annual maintenance, are added up for the entire contract duration,

and for the pavement length under performance-based contracts. This cost should be the least among the cost obtained from different combinations of maintenance operations during simulations. This cost is then the cost of executing the pavement maintenance under performance-based contracts.

6. Conclusion and Recommendation

The methodology described in this paper utilizes the available historical pavement condition records by stochastically modeling and predicting the future pavement condition. Pavement modeling techniques are inevitable part of managing pavement performance. Many of the existing pavement deterioration models are mechanistic and do not take into account the uncertainty associated with the input variables in their modeling process. The described methodology is a probabilistic pavement modeling technique, and therefore, takes uncertainty of different input variables such as weather in the pavement deterioration modeling. Although, pavement performance prediction is not the major purpose of this research, its role in pavement maintenance management cannot be overlooked.

The major task of the cost estimation methodology was to establish a program of maintenance treatments over the period of the maintenance contract, which in this case is taken to be ten years. Unlike the work of the previous researchers to establish a program of maintenance activities based on a single criteria, such as pavement condition index, or international roughness index (IRI), this research attempted to take multiple criteria, which is more common in performance-based contracts written in recent years. It was established that the described methodology fulfills the multiple performance criteria by taking each performance criteria, such as rutting, in determining maintenance treatments required so that the threshold performance values related to multiple criteria are not exceeded. At this stage of the research, simulation of different maintenance treatments, and their effects on performance level were tried out in excel spreadsheet, until a program of optimal combination of maintenance treatments were found such that they were the cheapest, yet had the ability to maintain the pavement at the pre-specified performance levels. Once these optimal maintenance programs are established, it is a straightforward process to estimate the cost of these maintenance activities based on the historical unit cost database available.

Although, the methodology here described the cost estimation for pavement maintenance for particular pavement type, that is asphalt pavement, this methodology can be adopted for other types of pavements. However, different types of pavements should be cost estimated separately as the pavement deterioration process, and the maintenance treatments for various types of pavements vary quite significantly. Moreover, pavements should be categorized based on various other factors such as geographical location, traffic load, pavement sub-grade, and so on. In this example, historical pavement conditions available for Interstate highway system of Miami-Dade County were used for developing a cost estimation methodology. The aim of the research was to develop a methodology to estimate the cost of performance-based maintenance contracts, and it was successfully illustrated in this paper. Although, some of the numbers in the cost estimation methodology were assumed, these numbers may be established easily from the actual contract documents, as well as from the historical database available from the Department of Transportation.

It is recommended that such a program of maintenance treatments may be established by using optimization techniques which were not utilized here. Rather, it was performed using a trial and error technique using the excel spreadsheet. Other performance criteria, which were not discussed in this paper but normally included in the performance-based maintenance contracts, can be taken into consideration in this methodology without much modification. Since, pavement performance condition for distresses other than rutting, cracking, and ride (roughness) were not publicly available from the Florida Department of Transportation, the pavement performance criteria were limited to these three distress criteria discussed.

7. References

Bayraktar, M.E., Cui, Q., Hastak, M., and Minkarah, I. (2004). "State-of-Practice of Warranty Contracting in the United States" *Journal of Infrastructure Systems,* ASCE, Vol.10, No.2, pp. 60-68.

Cui, Q. Johnson, P. W., and Sees, E. (2007). "Long-term warranties on highway projects", UTCA Report 06109, University Transportation Center for Alabama, Tuscaloosa, Alabama.

Damnjanovic, I. (2006). "A Risk-based Approach to Modeling Life-cycle Costs Associated withWarranty Specifications for Transportation Infrastructure" Ph.D. dissertation, University of Texas at Austin, Texas, USA.

Federal Highway Administration(2004). "Asphalt pavement warranties technology and practice in Europe", Report FHWA-PL-04-002, FHWA, Washington, D.C.,
http://international.fhwa.dot.gov/apw/apwscan.pdf

Gallagher, P. and Mangan, D. (1998). "Risk Issues in Performance-Specified Flexible Paving Contracts" *Conference of the Australian Road Research Board Transport Proceedings of the 1998 19th ARRB conference*, pp. 361-370.

Kostuk, K.J. (2003). "Quantifying the Uncertainty Associated with Long Term Maintenance Contracts" Ph.D. Dissertation, University of Saskatchewan, Saskatoon, Canada.

Ozbek, M.E. (2007). "Development of a Comprehensive Framework for the Efficiency Measurement of Road Maintenance Strategies using Data Envelopment Analysis" Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, USA.

Parkman, C., Hallet, J., Henning, T., and Tapper, M. (2003). "Pavement Deterioration Modeling in Long Term Performance-based Contracts: How Far Does it Mitigate the Risk for Client and Contractor?" *Twenty First ARRB and REAAA Conference*, Cairns, New Zealand,
http://www.transit.govt.nz/content_files/news/ConferencePaper34_PDFFile.pdf