KTC-98-24

Probabilistic Life Cycle Cost Analysis
FHWA Demonstration Project DP 115

by

R. Clark Graves, P.E., P.G.
Research Engineer

and

David L. Allen, P.E., P.G.
Chief Research Engineer

Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

December 1998

1.0 Introduction

Kentucky has been involved in several projects relating to the development of a Life Cycle Cost (LCC) analysis procedures of pavement structures. Research projects have been conducted by the Kentucky Transportation Center dealing with development of a more robust LCC procedures for pavement analysis. A research project has also been conducted developing network level LCC procedures. These procedures are currently in the evaluation phase and have not been implemented into current Kentucky Transportation Cabinet procedures. Life Cycle Costs analysis is utilized on various projects throughout Kentucky to evaluate various pavement construction and rehabilitation alternatives.

This report will outline the current procedures used in Kentucky for LCC analysis and will show how this procedure can be modified to include probabilistic analysis as presented in FHWA Demonstration Project 115 (DP 115) "Life Cycle Cost analysis in Pavement Design – A Probabilistic Approach."

1.1 Project Background

The construction project analyzed in during this project is one scenario which is included in a larger project to evaluate various reconstruction and rehabilitation alternatives for two interstate corridors in Kentucky. Kentucky is currently involved in a major effort to develop design plans to widen all of Interstates 65 and 75 to three lanes throughout the state. This involves more that 200 centerline miles of roadway of various pavement types and structural cross sections. One step in the process of developing these plans is to perform life cycle cost analysis on various alternatives based on the existing pavement type. To facilitate the pavement design process and the life cycle cost process, a catalog of pavement designs was developed based on project traffic levels and existing conditions. Pavement designs and subsequent life cycle cost analysis were performed for ESAL levels of 30, 50, and 70 million. For each ESAL level, subgrade CBR strengths of 2,4,7, and 11 were evaluated.

The typical pavement section consisted of a 4-lane interstate highway with a depressed median. The reconstruction consisted of rehabilitation of the existing mainline pavement and shoulders. One additional driving lane is also added, along with a 15 foot wide inside median. Concrete median barriers are also included as necessary.

Approximately 65 miles of the existing pavements are 9 to 11 inches of PCC pavement. The rehabilitation alternatives for this pavement type would be break-and-seat and asphalt overlay or an unbonded PCC overlay. The evaluation of the probabilistic procedure will evaluate these two alternatives for a given design thickness.

The structural cross section for each alternative evaluated is given in the following table. This section is designed for 30,000,000 ESAL's and a subgrade CBR of 2.

Pavement Structural Section

Alternate	Mainline Rehabilitation	Widening
Alt. 1A, AC Overlay	12" AC Overlay 10" Existing B/S PCC 6" Existing DGA	12" AC Base and Surface 6" AC Base 4" Asphalt Treated Drainage Blanket 6" DGA
Alt. 1B, PCC Overlay	10" PCC Overlay 1.5" AC Bond Breaker 10" Existing PCC 6" Existing DGA	10" PCC 1.5" AC Bond Breaker 6" AC Base 4" Asphalt Treated Drainage Blanket 6" DGA

Traffic will be maintained in two through lanes throughout the entire project during all construction and rehabilitation. For the analysis, work zones were limited to 1-mile lengths.

2.0. Life Cycle Cost Analysis Procedures

2.1 Current Kentucky Transportation Cabinet Procedure

Kentucky currently utilizes a procedure developed in a EXCEL spreadsheet. This procedure is utilized to compare various design and rehabilitation alternatives. It is a present-worth analysis based on estimates of construction and rehabilitation costs for various discount rates. The analysis will include the following input variables:

Analysis Period: 35 - 40 years
Discount Rate: 2 - 10 percent
Analysis Type: Present Worth

Traffic:
AADT – 55,000
80% Automobiles
17% Combination Units
3% Single Units

Construction Costs:
The construction costs are based on the unit price obtained from average unit bid prices of construction bid items. The spreadsheet calculates the necessary quantities based on pavement geometry provided by the designer. Based on these quantities, the total project cost for each bid item is determined.

Rehabilitation Costs:
Rehabilitation costs were determined based on typical strategies utilized in Kentucky. The spreadsheet calculates the cost for various bid items included in each strategy, based on standard alternatives. The rehabilitation strategies utilized for each alternate are as follows:

Asphaltic Concrete Pavement:
Year 10 – Mill 1.5 inches of AC, Overlay 1.5 inches of AC
Year 20 – Mill 1.5 inches of AC, Overlay 4.0 inches AC
Year 30 – Mill 1.5 inches of AC, Overlay 1.5 inches of AC

Portland Cement Concrete Pavements:
Year 15 – Clean and Reseal Joints
Year 30 – Clean and Reseal Joints

User Costs:
Fixed user costs are utilized for both initial construction and each rehabilitation alternative for both AC and PCC pavements. A cost of $5,000/day is utilized, the total user cost is determined by the number of days required to complete each phase of the project. Typically a value 120 days is utilized for initial construction and 30 days is used for each rehabilitation.

Traffic Control Costs:
The cost associated with traffic control are estimated based on costs associated with other construction projects of similar scope. For our example fixed values of $325,000 for initial construction and $100,000 for each rehabilitation were utilized.

Salvage Cost:

The salvage cost of the pavement structure at the end of the analysis period was determined by calculating the total quantity of materials (both original construction and rehabilitation) in-place on the roadway and giving them the value of in-place dense graded aggregate. The unit cost of dense graded aggregate was utilized to provide a total pavement salvage cost.

2.2 KyTC Model Results

The results of the current KyTC LCC procedure are contained in the following Table 1.

Table 1. KyTC Life Cycle Cost Analysis

Alternate 1A AC Pavement		Discount Rate											
		0		2		4		6		8		10	
Improvement	Improvement Year	Agency Cost	User Costs	Agency Cost	User Costs	Agency Cost	User Costs	Agency Cost	User Costs	Agency Cost	User Costs	Agency Cost	User Costs
Initial Construction	1998	2,639,300	600,000	2,639,300	600,000	2,639,300	600,000	2,639,300	600,000	2,639,300	600,000	2,639,300	600,000
Rehabilitation #1	2008	683,806	150,000	560,959	123,052	461,955	101,335	381,834	83,759	316,735	69,479	263,637	57,831
Rehabilitation #2	2028	1,173,130	150,000	789,483	100,946	535,401	68,458	365,788	46,771	251,693	32,182	174,378	22,297
Rehabilitation #3	2028	683,806	150,000	377,510	82,811	210,830	46,248	119,058	26,117	67,955	14,907	39,188	8,596
Salvage	2038	-1,713,702		-776,119		-356,945		-166,610		-78,883		-37,864	
		3,466,341	1,050,000	3,591,133	906,809	3,490,542	816,040	3,339,370	756,646	3,196,800	716,568	3,078,640	688,724
	Alt. 1A Total	**4,516,341**		**4,497,942**		**4,306,582**		**4,096,016**		**3,913,368**		**3,767,364**	

Alternate 1B PCC Pavement		Discount Rate											
		0		2		4		6		8		10	
Improvement	Improvement Year	Agency Cost	User Costs	Agency Cost	User Costs	Agency Cost	User Costs	Agency Cost	User Costs	Agency Cost	User Costs	Agency Cost	User Costs
Initial Construction	1998	3,471,297	600,000	3,471,297	600,000	3,471,297	600,000	3,471,297	600,000	3,471,297	600,000	3,471,297	600,000
Rehabilitation #1	2013	487,695	300,000	362,364	222,904	270,800	166,579	203,498	125,180	153,742	94,573	116,750	71,818
Rehabilitation #2	2028	487,695	300,000	269,242	165,621	150,365	92,496	84,913	52,233	48,466	29,813	27,949	17,193
Salvage	2038	-1,548,525		-701,312		-322,541		-150,551		-71,280		-34,215	
		2,898,162	1,200,000	3,401,592	988,526	3,569,921	859,075	3,609,157	777,413	3,602,225	724,386	3,581,782	689,010
	Alt. 1B Total	**4,098,162**		**4,390,117**		**4,428,996**		**4,386,569**		**4,326,610**		**4,270,792**	

It may be seen from this table that the costs of the two alternates are very close across various discount rates. Generally they are within 10% of each other. For discount rates below 4 percent, the PCC alternate is less expensive while for 4 percent and above the asphalt alternate is less expensive. This is due to the fact that the discount rate has a grater affect on the asphalt alternate since is has more rehabilitations in later years.

2.2 Probabilistic Life Cycle Cost Analysis

The KyTC procedure has been modified to incorporate various probabilistic parameters for inputs into the LCC process. Probabilistic parameters have been included for the following parameters: material properties utilized to calculate both the construction and rehabilitation costs, traffic growth rate, and life of initial construction and each rehabilitation. A summary of the various variables is as follows:

Analysis Period: 40 years
Discount Rate: 2 - 10 percent

Traffic:

AADT – 55,000
80% Automobiles
17% Combination Units
3% Single Units
Growth Rate: *Both a fixed 2 percent growth rate and a variable growth rate, modeled with a truncated normal distribution (average -- 2.0, standard deviation -- 0.2, maximum -- 3 and minimum – 1)*

Construction and Rehabilitation Costs:

Material unit costs for the various bid items were modeled with normal distributions with mean and standard deviations determined by analysis of historical bid prices. These values are given in the following table.

Item Code	Description	Unit	Cost $/unit Mean	Cost $/unit Standard Deviation
1	D G A BASE	TON	12.82	3.15
18	DRAINAGE BLANKET-TYPE II-ASPH	TON	23.37	4.67
134	BIT CONC BASE CLASS CK PG64-22	TON	28.34	4.72
137	BIT CONC BASE CLASS CI PG64-22	TON	30.22	2.87
139	BIT BASE CL CI PG76-22 W/50%ER	TON	38.34	5.04
190	BIT MIX FOR LEVELING & WEDGING	TON	31.01	3.65
243	BIT SURF CL AK/A PG76-22/50%ER	TON	45.71	10.08
246	BIT CONC SURFACE CLASS AK/S	TON	30.06	4.61
356	BITUMINOUS MATERIAL FOR TACK	TON	238.62	104.04
2069	PCC PAVEMENT-10 INCH NON-REINF	SQ YD	44.28	17.56
2070	PCC PAVEMENT-12 INCH NON-REINF	SQ YD	32.1	8.49
2071	PCC PAVEMENT-11 INCH NON-REINF	SQ YD	30.56	3.54
2073	PCC PAVEMENT-9 INCH NON-REINF	SQ YD	28.61	2
2084	PCC PAVEMENT-8 INCH NON-REINF	SQ YD	25.18	3.11
2107	BREAKING AND SEATING PAVEMENT	SQ YD	1	0.32
2115	SAW-CLEAN-RESEAL TVERSE JOINT	LIN FT	2.35	0.49
2116	SAW-CLEAN-RESEAL LONGIT JOINT	LIN FT	1.75	0.63
2677	BIT PAVE MILLING AND TEXTURING	TON	16.93	5.49

Initial Construction and Rehabilitation Life:

The expected life of initial construction and each rehabilitation were modeled using fixed construction and rehabilitation lives. The option of using variable life was also investigated. The concept of using probabilistic inputs of constuction and rehabilitation life produced very interesting results. Bi-modal distributions of projects costs were observed. This occurred due to the fact that during some simulations, more rehabilitation cycles were used. This concept produced results that were somewhat difficult to explain. It is anticipated that once further work is done to determine the actual life expectancy of each rehabilitation, better probabilistic functions can be developed. In addition, the concept of not allowing any rehabilitations during the last 5 years of the analysis period was also evaluated. This provided somewhat more reasonable results, however, further understanding of this concept as it relates to salvage value is needed for it to be a viable alternative. By introducing the variable rehabilitation life, user costs in the out years were extremely high with queue lengths of more than 50 miles. Based on this information, fixed rehabilitation intervals were used for the probabilistic model.

User Costs:

User costs were determined based on the increased travel time to transverse the work zone, the time associated with delays created by the work zone. Costs were determined based on both vehicle operating costs and the cost of travel time for various vehicles. The values used in this analysis are as follows:

Travel Time Values, $/vehicle
- Cars – $11.58
- Single Unit Trucks – $18.54
- Combination Unit Trucks – $22.31

Vehicle Operating Costs (hrs/1000 veh) and Added Time ($/1000 veh)

- Cars – 46.95 $/1000 veh, 4.9 hrs/1000 veh
- Single Unit Trucks – 65.76 $/1000 veh, 6.6 hrs/1000 veh
- Combination Unit Trucks – 305.07 $/1000 veh, 13.39 hrs/1000 veh

Traffic Control Costs and Salvage:

Determined in the same manner as the KyTC method.

Model Overview

The model developed during this study is somewhat project specific in that is was developed to evaluate the current interstate widening activities underway in Kentucky. Portions of the model are currently set to be generic in nature and the remainder of the model could also be modified to allow for its use on most projects. It is anticipated that these modifications may take place once the Kentucky Transportation Cabinet becomes more familiar with the procedure.

The model consists of seven separate worksheets within EXCEL. Two worksheets (one for the AC overlay alternate and one for the PCC overlay alternate) contain the thickness information for each of the design sections contained in the interstate design catalog along with the unit cost information for each of the constuction items. The model also contains a worksheet for each alternative for the calculation of actual constuction and rehabilitation costs. These sheets contain the actual risk functions which determine the distribution of the various probabilistic inputs. In addition, user costs for each alternative are calculated in separate sheets, these sheets contain the probabilistic inputs for the traffic growth rate. A summary sheet is also provided similar to Tables 1 and 2 which provides a summary of each alternate's construction, rehabilitation, salvage and user costs for discount rates of 0, 2, 4, 6, 8, and 10 percent. The calculation of cost at each discount rate allows for better comparison to the current Transportation Cabinet procedure.

Model Results

A similar table of results as those shown in Table 1 is given in Table 2 for the probabilistic model with mean inputs of each risk function. It may be seen that the change in methodology in calculating user costs has a dramatic effect on the overall life cycle cost of the project. The distribution of life cycle cost for each alternate for a fixed growth rate is given in Figure 1. It may be seen from this figure that there is considerable overlap in the distribution of total cost. A similar plot is given in Figure 2. utilizing the truncated normal distribution of the growth rate, it may be seen from this plot that the distributions are somewhat skewed and that they are virtually superimposed on one another. This comparison illustrates the sensitivity of this particular model to traffic parameters, in that the variation in the growth rate to 3.0 percent dramatically increases the user cost of each alternative.

A sensitivity analysis was also conducted for each alternate for both a fixed growth rate and a probabilistic growth rate. Regression sensitivity plots for a probabilistic growth rate are given in Figures 3 and 4. It may be seen from these figures that the growth rate has a very significant influence on the cost of each alternate. The regression sensitivity plots for a fixed growth rate are given in Figures 5 and 6. It is interesting to not that in both alternatives the unit cost of DGA has a negative effect on the resulting total project cost. This is not unexpected as the unit cost of DGA is used to determine the salvage value for each alternative.

Table 2. Probabilistic Life Cycle Cost Analysis

		Discount Rate											
		0		2		4		6		8		10	
		Cost ($)		Cost ($)		Cost ($)		Cost ($)		Cost ($)		Cost ($)	
Improvement	Improvement Year	Agency	User	Agency	User	Agency	User	Agency	User	Agency	User	Agency	User
Initial Construction	1998	2,639,300	1,872,657	2,639,300	1,872,657	2,639,300	1,872,657	2,639,300	1,872,657	2,639,300	1,872,657	2,639,300	1,872,657
Rehabilitation #1	2008	428,057	668,978	351,156	548,795	289,180	451,938	239,025	373,554	198,273	309,866	165,035	257,920
Rehabilitation #2	2018	789,941	1,724,815	531,608	1,160,751	360,519	787,183	246,307	537,805	169,480	370,056	117,420	256,383
Rehabilitation #3	2028	428,057	13,294,712	236,318	7,339,623	131,978	4,099,008	74,529	2,314,744	42,539	1,321,193	24,531	761,901
Salvage	2038	-1,713,702		-776,119		-356,945		-166,610		-78,883		-37,864	
	Alt1ASubtotal	2,571,654	17,561,162	2,982,263	10,921,826	3,064,032	7,210,786	3,032,552	5,098,760	2,970,710	3,873,772	2,908,422	3,148,861
	Alt 1A Total	**20,132,815**		**13,904,089**		**10,274,817**		**8,131,312**		**6,844,482**		**6,057,283**	

		Discount Rate											
		0		2		4		6		8		10	
		Cost ($)		Cost ($)		Cost ($)		Cost ($)		Cost ($)		Cost ($)	
Improvement	Improvement Year	Agency	User	Agency	User	Agency	User	Agency	User	Agency	User	Agency	User
Initial Construction	1998	3,433,711	1,872,657	3,433,711	1,872,657	3,433,711	1,872,657	3,433,711	1,872,657	3,433,711	1,872,657	3,433,711	1,872,657
Rehabilitation #1	2013	487,695	993,597	362,364	738,257	270,800	551,709	203,498	414,593	153,742	313,223	116,750	237,859
Rehabilitation #2	2028	487,695	13,294,746	269,242	7,339,642	150,365	4,099,018	84,913	2,314,750	48,466	1,321,196	27,949	761,903
Salvage	2038	-1,532,987		-694,275		-319,304		-149,040		-70,565		-4,815	
	Alt1BSubtotal	2,876,114	16,161,000	3,371,043	9,950,557	3,535,572	6,523,385	3,573,082	4,602,001	3,565,354	3,507,077	3,573,596	2,872,419
	Alt 1B Total	**19,037,115**		**13,321,600**		**10,058,957**		**8,175,082**		**7,072,431**		**6,446,015**	

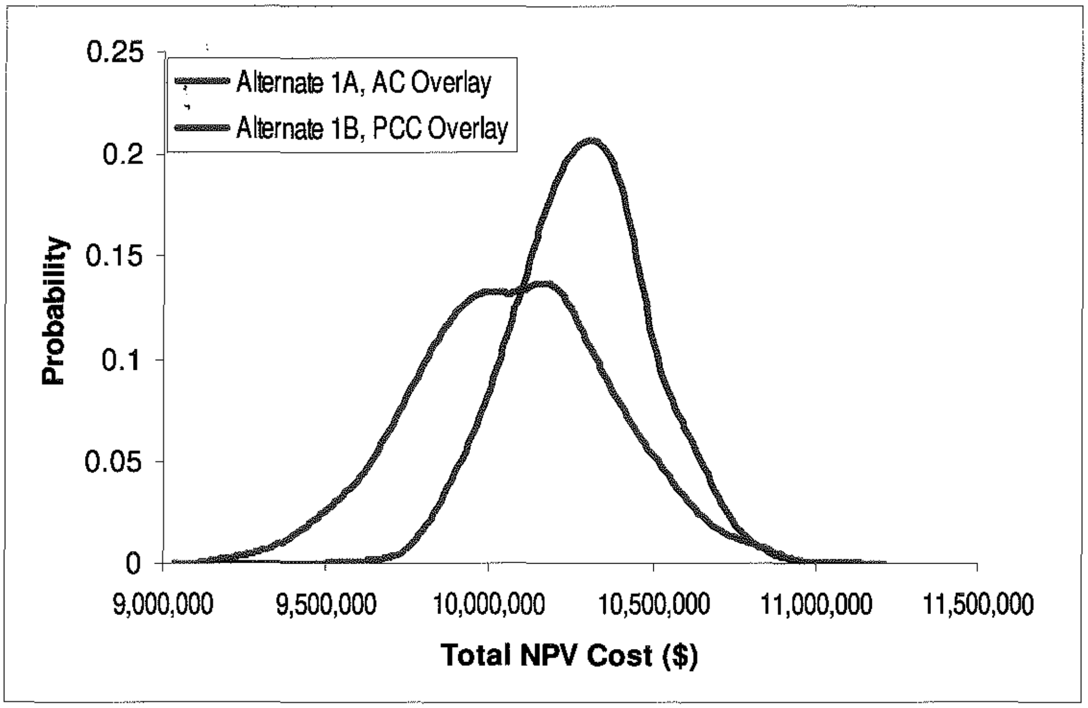

Figure 1. Distribution of Total NPV, Constant Growth Rate

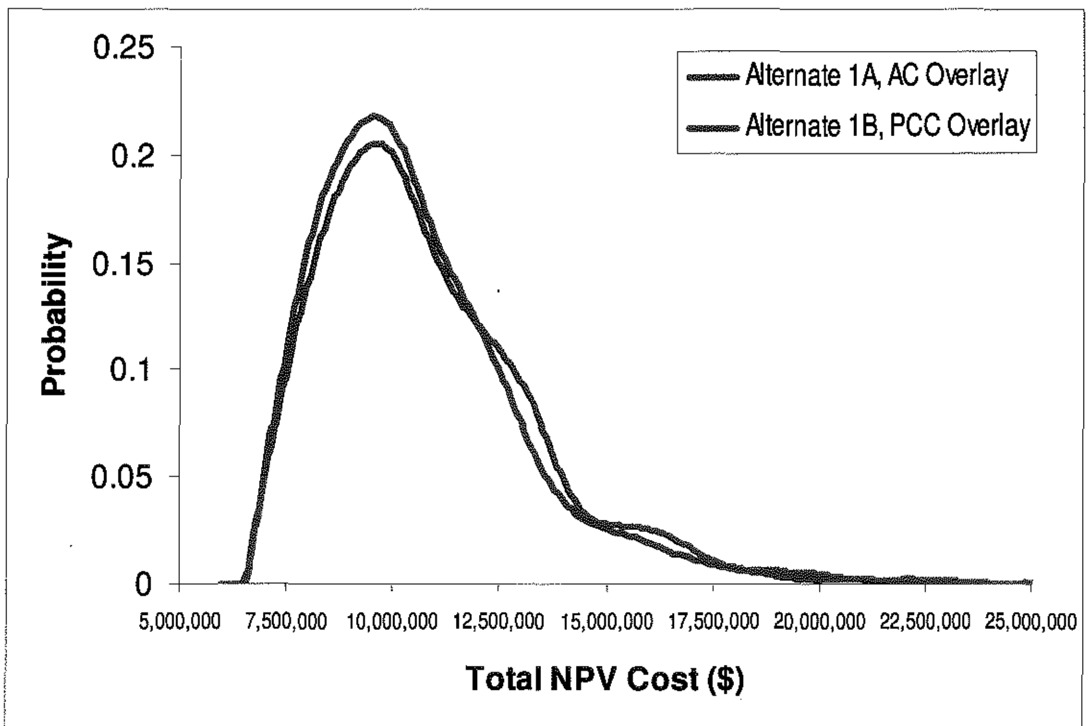

Figure 2. Distribution of Total NPV, Variable Growth Rate

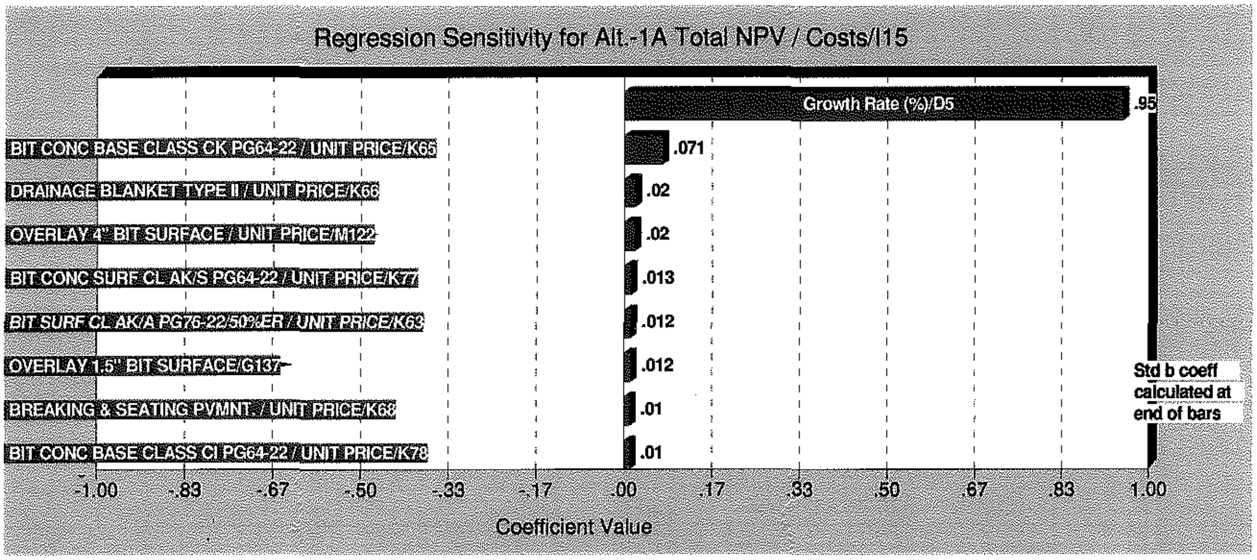

Figure 3. Regression Sensitivity, Alternate 1A, AC Overlay, Variable Growth Rate

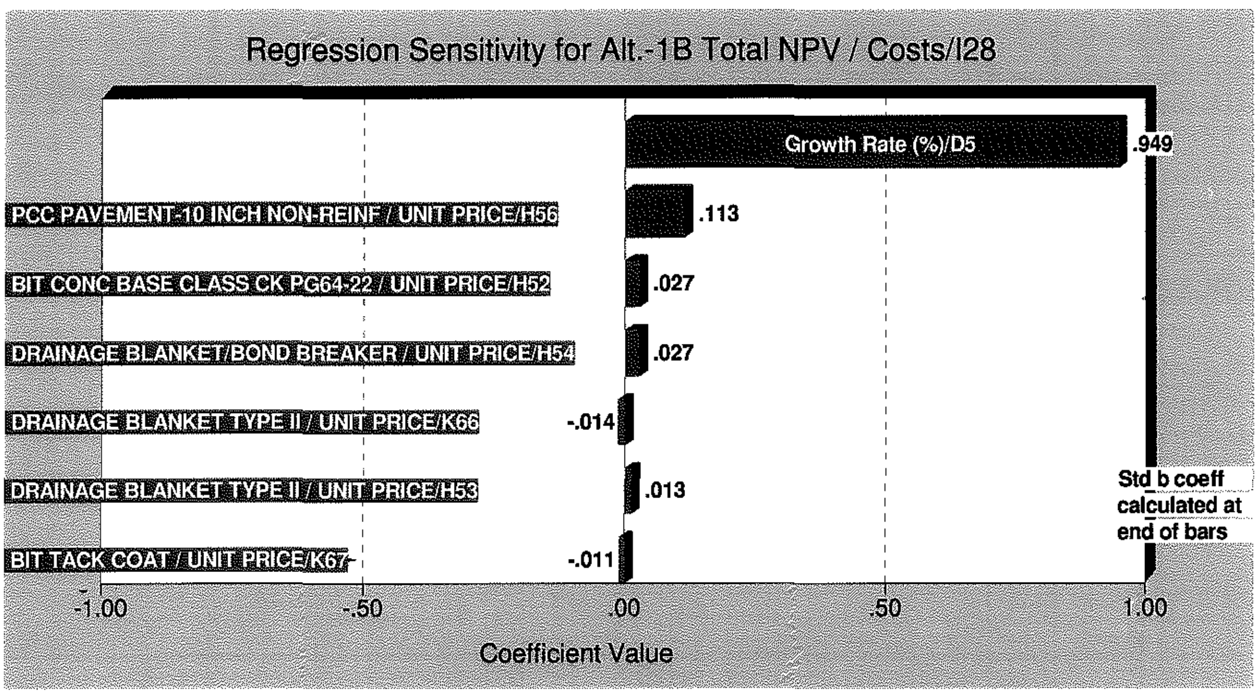

Figure 4. Regression Sensitivity, Alternate 1B, PCC Overlay, Variable Growth Rate

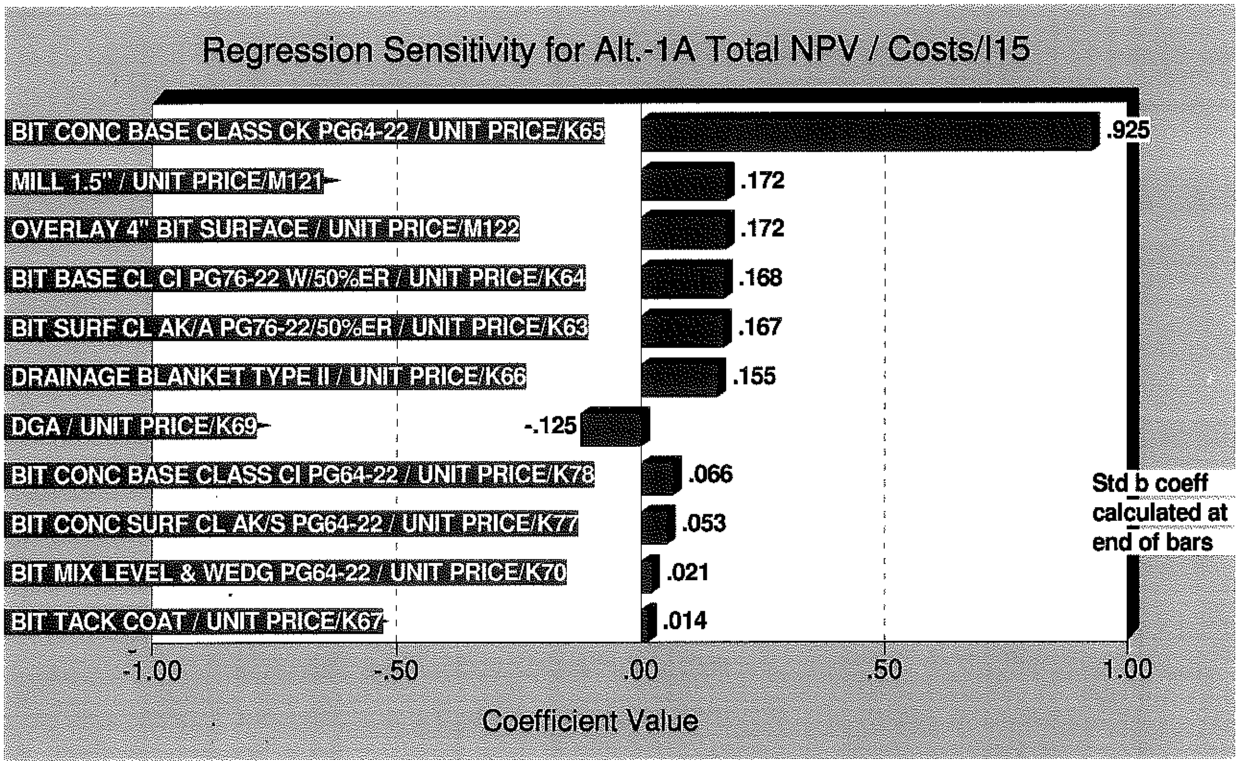

Figure 5. Regression Sensitivity, Alternate 1A, AC Overlay, Constant Growth Rate

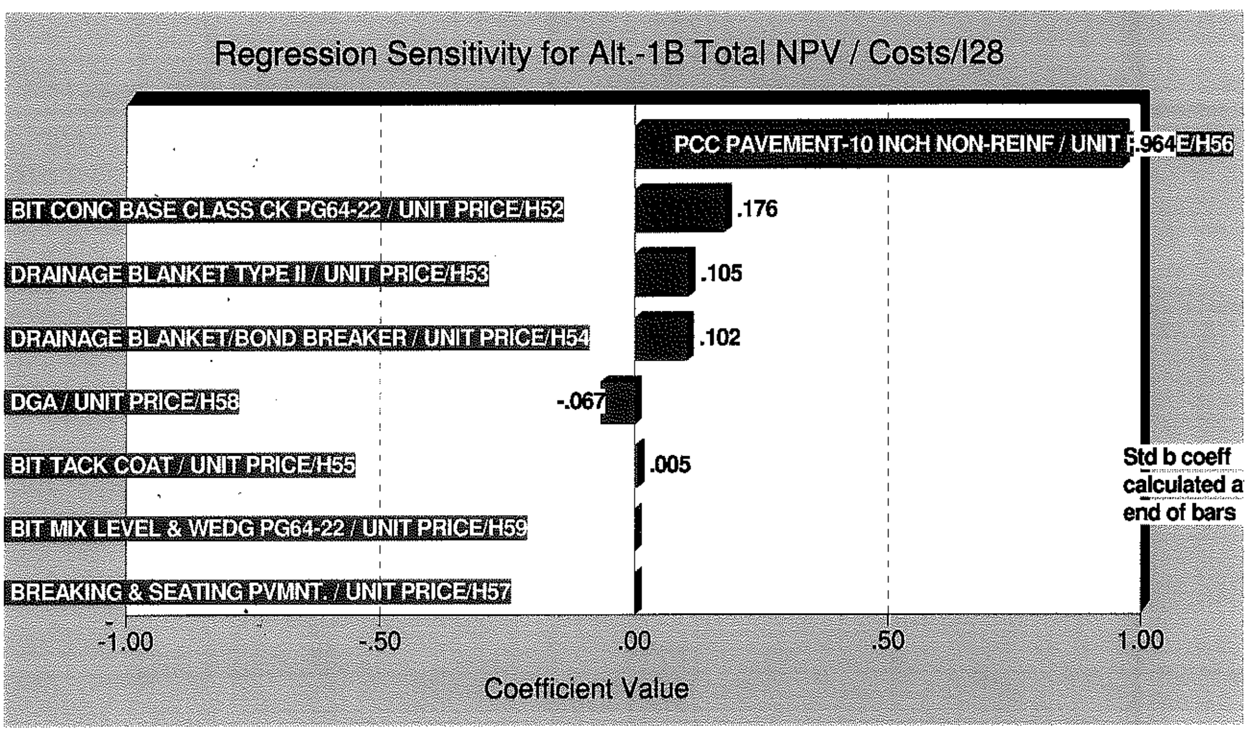

Figure 6. Regression Sensitivity, Alternate 1B, PCC Overlay, Constant Growth Rate

3.0 Summary and Conclusions

Based on the results of this analysis, either alternative could be a viable candidate for constuction, this is the same result which was obtained from Kentucky's conventional procedure. The actual selection of an alternate would include many other factors which would be evaluated by the design team for a specific project location.

The probabilistic procedures does show promise in providing decision makers with a more complete look at the total project cost, and the factors that affect that cost. There may be institutional barriers which will require education of the decision makers regarding the utilization and implementation of this procedure.

As has been previously noted, care should be taken in the utilization of probabilistic input values. Good information regarding the actual distribution of a particular variable is needed to insure the results are usable and understandable. There are several areas which will need further evaluation such as the variability in service life of the initial construction and subsequent rehabilitations. It is anticipated that this procedure will be expanded to include more probabilistic functionality as better input distributions are determined. Kentucky is currently conducting a research project dealing with construction delays and the cost of such delays. Once this project is completed, a better understanding of constuction delays and user costs will allow this model to be expanded.