Advanced Quality Systems: Probabilistic Optimization for Profit (Prob.O.Prof) Software

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FOREWORD

Like all highway construction specifications, statistical quality assurance specifications containing pay adjustment provisions for quality let the contractor decide what levels of quality to target during construction. However, as these specifications are couched in statistical terms requiring a good understanding of risks, making the best decision is seldom a simple process.

Prob.O.Prof 2.0 is a software tool that can be used by contractors and agencies alike to make keen business decisions regarding pavement quality. For the contractor, Prob.O.Prof 2.0 can help during bid preparation and/or during construction to answer the question, "What target quality levels will lead to maximum profit in my specific situation?" For the agency, Prob.O.Prof 2.0 can help validate the specifications by answering the question, "What quality levels are our specifications encouraging our contractors to achieve?"

This report describes the research and development work that was done to create Prob.O.Prof 2.0. It also contains the Prob.O.Prof 2.0 user's manual as an appendix.

This report corresponds to the TechBrief titled "Probabilistic Optimization for Profit (Prob.O.Prof) Software" (FHWA-HRT-10-057). This report is being distributed through the National Technical Information Service for informational purposes. The content in this report is being distributed "as is" and may contain editorial or grammatical errors.

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16. Abstract

Contractors constantly have to make decisions regarding how to maximize profit and minimize risk on paving projects. With more and more States adopting incentive/disincentive pay adjustment provisions for quality, as measured by various acceptance quality characteristics (AQCs), a contractor likely has to evaluate several options before selecting an optimum target quality that accomplishes this goal. The greater the number of AQCs, the more complex the assessment the contractor is required to perform, and the less intuition and experience can be relied upon.

Highway agencies also need to evaluate their specifications to determine the appropriateness of the process and criteria, and to ensure that the specifications do not have any undesirable consequences. If, for example, an agency learns that there is an economic benefit for contractors to construct pavements at substandard quality levels because of inadequate disincentives, then the agency may need to adjust the specification pay schedule accordingly.

Prob.O.Prof 2.0 is a newly developed software tool that can be used by contractors and agencies alike to make keen business decisions regarding the levels of pavement quality to target. This probabilistic, Microsoft Excel®-based program is an enhancement of the original Prob.O.Prof program, developed as part of a Ph.D. dissertation at the University of Florida (Vidalis et al., 2006). It entails a major expansion of the original program through the incorporation of three additional State department of transportation (DOT) portland cement concrete (PCC) pavement specifications and the introduction of four State DOT hot mix asphalt (HMA) pavement specifications. As a result of this expansion, other forms of quality measures besides percent within limits (PWL), such as average absolute deviation (AAD), averages, and average minus standard deviation, can be evaluated, along with other AQCs and pay factor schedules.

This report corresponds to the TechBrief titled "Probabilistic Optimization for Profit (Prob.O.Prof) Software" (FHWA-HRT-10-057) and to the Prob.O.Prof 2.0 CD-ROM (NTIS PB2010-500014).

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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CHAPTER 1. INTRODUCTION

BACKGROUND

Contractors constantly have to make decisions about how to maximize profit and minimize risk when undertaking paving projects. With more and more States adopting incentive/disincentive pay adjustment provisions for quality, as measured by various acceptance quality characteristics (AQCs), a contractor likely has to evaluate several options before selecting an optimum target quality that accomplishes this goal. The greater the number of AQCs, the more complex the assessment that the contractor must perform, and the less he/she can rely on intuition and experience. In addition, the contractor can use this analysis while determining the bid price.

On the client side, highway agencies also need to evaluate their specifications to determine the appropriateness of the process and criteria, and to ensure that the specifications do not have any undesirable consequences. For example, a contractor may opt to construct a pavement at the minimum quality level for a particular AQC (such as thickness), because the cost savings is greater than the disincentive pay adjustment. In this case, the highway agency may want to adjust the pay factors accordingly while developing the specifications to discourage a contractor from selecting such an option.

Prob.O.Prof (Probabilistic Optimization for Profit) is a probabilistic-based tool to assist both the contractor and the highway agency in the evaluation of statistical quality assurance (QA) specifications with an eye towards maximizing contractor profits while minimizing risks. This spreadsheet-based computer program was developed as part of a Ph.D. dissertation at the University of Florida (Vidalis et al., 2006). The original program has its limitations and needs to be improved to allow analyses of all commonly used pay-related AQCs for both asphalt and concrete paving applications, other common measures of quality, and other pay equations or pay schedules. The software also needs to be made more user-friendly, particularly with respect to output, units, usefulness, ease-of-use, and consistency of results.

OBJECTIVE

The objective of this Task Order is to develop an expanded, improved, and upgraded version of Prob.O.Prof that will address the limitations of the software tool by incorporating additional AQCs for both asphalt and concrete paving operations, other pay equations and schedules, and generally making it more user-friendly with respect to output, units, usefulness, ease-of-use, and consistency of results.

SCOPE OF RESEARCH

This research was focused on the development of the next version of the Prob.O.Prof software program. The basis for developing the new Microsoft® Excel-based program included:

- A critical review of the current version of Prob.O.Prof and related documentation.
- A detailed review of literature and highway agency hot-mix asphalt (HMA) and Portland cement concrete (PCC) specifications to identify representative specific elements and features to be incorporated into the software.
- A limited survey of paving contractors and selected analyses to help establish default costs associated with achieving various levels of quality.
- Use of Visual Basic for Applications (VBA) programming tools to provide user-friendly graphical interfaces and perform probabilistic computations of pay factors and profit amounts.

The following tasks and subtasks were performed to accomplish the project goals:

- Task A: Review Software and Related Research
  - Subtask A-1: Kickoff Meeting
  - Subtask A-2: Review Prob.O.Prof
  - Subtask A-3: Review Literature and Agency Specifications
  - Subtask A-4: Contractor Survey on Costs
  - Subtasks A-5 and A-6: Prepare Initial and Revised Informal Papers on Prob.O.Prof
- Task B: Develop New Prob.O.Prof Software
  - Subtask B-1: Develop Screen Shots
  - Subtask B-2: Develop Alpha Version
  - Subtask B-3: Develop Beta Version
  - Subtask B-4: Identify and Eliminate Bugs and Develop First Release
- Task C: Perform Analyses
  - Subtask C-1: Comparative Analyses
  - Subtask C-2: Sensitivity Testing
- Task D: Prepare Reports
  - Subtask D-1: Draft Final Report
  - Subtask D-2: User's Manual
  - Subtask D-3: Revised Final Report and User's Manual

ORGANIZATION OF THE REPORT

This report is divided into five chapters and two appendices. Chapter 1 (this chapter) provides a brief introduction, including the background for the study and its objectives and scope. Chapter 2 provides an overview of the current Prob.O.Prof program and a critical evaluation of the program to identify areas of needed improvement.

Chapter 3 provides a detailed review of HMA and PCC pavement specifications, with emphasis on the AQCs, quality measures, and pay schedules used. Summary tables of the American

Association of State Highway and Transportation Officials (AASHTO) Quality Assurance Guide Specifications for asphalt and concrete pavements are presented, along with review summaries of 27 State specifications.

Chapter 4 discusses the development of the next-generation Prob.O.Prof program (version 2.0). It describes and illustrates the various features incorporated into the program from the standpoints of inputs, execution/computation, and outputs.

Chapter 5 summarizes the entire work effort and presents various recommendations regarding future upgrades of the Prob.O.Prof program.

Appendix A contains a list of key terms and definitions pertaining to QA specifications, as well as a list of the various acronyms and abbreviations used throughout the report.

Appendix B contains summary tables of pavement specifications from 27 States. These include various asphalt and concrete pavements.

Appendix C contains the User's Manual for the new Prob.O.Prof program. This manual describes and illustrates how to use the program and interpret its outputs. It also includes discussions of sensitivity testing that was performed using the new program.

CHAPTER 2. PROB.O.PROF REVIEW

PROGRAM OVERVIEW

The current Prob.O.Prof software is a probabilistic-based tool that allows a concrete pavement contractor (software user) to evaluate various options with respect to target quality levels and to select the optimum quality levels that will result in the greatest expected profit at a specified reliability level (expressed as risk percentiles). The three AQCs included in the software are PCC thickness, PCC strength, and initial smoothness. The acceptance plans included in the software are those specified in the AASHTO Quality Assurance Guide Specifications (AASHTO, 1996) for the three AQCs.

The software allows the user to enter necessary information (in the "Input" sheet), such as target values, lower specification limits, and standard deviations, for the three AQCs. For thickness and strength, the user enters the number of samples per Lot; for smoothness, the user enters the total number of sublots. Based on the entered target value increments and the standard deviations, Monte Carlo simulations are performed by the software at five quality levels for each AQC. Default costs percentage increment and decrements relative to the design values are computed by the program and displayed on the input screen. The user has the ability to change these default cost values.

For each AQC, and at each of the five quality levels, the results from the Monte Carlo simulation are used along with the AASHTO pay schedule to compute the average pay and the pay at 25, 50, 75, and 95 percent reliability levels. The profits are computed as the difference between the pays and the costs. These results are displayed in the "Output" sheet. User-selected composite pay factor method and user-entered composite pay factor cap are used to compute and display the relative rankings of various combinations of AQCs. The top three combinations resulting in maximum profit are highlighted. Details of the software and its functionalities are included in this section.

PROGRAM EVALUATION

The current Prob.O.Prof was primarily developed to analyze the AASHTO Guide Specifications resulting in the following capabilities and limitations of the software:

General

- Can be used only for PCC pavements, primarily jointed plain concrete (JPC) pavement.
- Only three PCC AQCs are included—thickness, strength (flexural or compressive), and initial smoothness (profile index with 0.2-in blanking band [$PI_{0.2}$] or International Roughness Index [IRI]).
- Four methods of composite pay adjustment computations are included—product, summation, average, and weighted average.

Input Screen

- The "Input" sheet has CLEAR, SAVE, PRINT, and HELP buttons as shown in figure 1. Clicking on the CLEAR button clears the input sheet. Clicking on the SAVE button brings up the file save dialog box. Clicking on the PRINT button prints the input and output sheets. Clicking on the HELP button brings up a drop down menu. The user can then select from a list of items to get additional information.
- The user enters the number of AQCs (1 to 3) to be included in the analysis.
- For slab thickness and concrete strength, the user enters the target values (compressive or flexural strength), the lower specification limit (LSL), the standard deviation (σ), and the constant number of samples per Lot (n). A Lot is divided into equal size sublots, and one sample is taken from each sublot. For thickness, one thickness sample is taken from each sublot. For compressive strength, one sample usually consists of two test specimens and a strength test result is the average of the two strength values. The number of samples per Lot is limited to 30.
- For initial surface smoothness, the user enters the target value (profile index or IRI), the standard deviation, and the total number of sublots. Each sublot is 0.1 mi. One and only one sample is taken from each sublot. This sample smoothness value for a sublot is the average of runs conducted on the inside and outside wheel path of a lane. The total number of sublots is limited to 70.
- For each AQC, the user can enter and must enter five target values. This can be done by either entering all target values or entering a target value increment.
- When all target values are manually entered in the "Input" sheet, for each of the five target values, the percentage increment or decrement costs relative to the design value, must also be manually entered.
- When a target value increment is entered the five target values are computed relative to the design value as:
  - Design Value – (2×Increment)
  - Design Value – Increment
  - Design Value
  - Design Value + Increment
  - Design Value + (2×Increment)

  In this case, the default percentage increment or decrement costs for the five target values are computed by the program. These default values are generated based on average values computed from contractor and agency surveys.
- The analyses for each of the three AQCs have to be performed separately by clicking on the corresponding individual "RUN" buttons.

Functionality

- If all three AQCs are included in the analyses, the five target values for each AQC results in 15 total target values and 125 unique combinations of target values.
- At each target quality level, a Monte Carlo simulation is performed to model statistical variability. The number of samples per Lot, n (entered by user), are randomly generated 2,000 times using a normal probability distribution with the mean value set at the target value (μ) and the standard deviation (σ) entered by the user. These 2,000 sample values are written to 2,000 Excel® cells on the "Input" sheet.

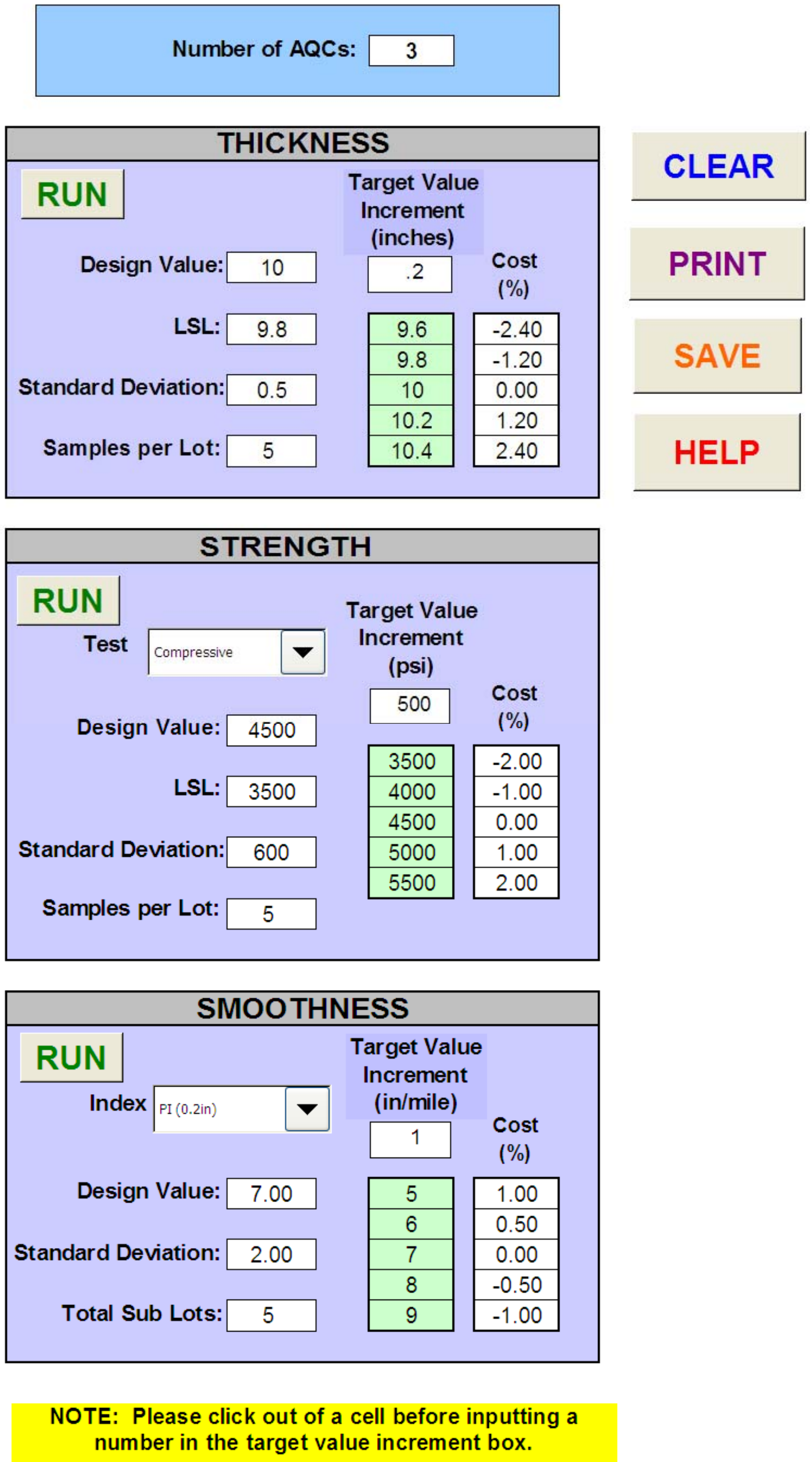

Figure 1. Prob.O.Prof input screen.

- For thickness and strength, for each of the 2,000 simulated Lots, the sample mean ($\bar{x}$) and standard deviation (s) are computed. The quality index, QI, is computed as:

$$QI = \frac{\bar{x} - LSL}{s} \qquad \text{Eq. 1}$$

  The QI is used to compute the PWL using the QI table provided in the AASHTO Guide.[2] The PWL is the area under the symmetrical Beta distribution function between –QI and +∞. The functionality of computing the PWL is performed in the program by using the table functions INDEX and MATCH, which are used to lookup the values from an Excel® cell array.
- The thickness and strength acceptance plans are based on the PWL quality measure tied to a standard pay equation shown below and in table 1. This pay equation is used to compute the pay factor if PWL > 60.

$$\text{Percent Pay} = 55 + 0.5\ \text{PWL} \qquad \text{Eq. 2}$$

Table 1. AASHTO thickness and strength pay adjustments.

PWL	Percent Pay
100	105
90	100
80	95
70	90
60	85
< 60	Engineer Determination

- If PWL ≤ 60, the AASHTO Guide specifies "Engineer Determination." However, in Prob.O.Prof, the pay factor is computed using the following equation.

$$\text{Percent Pay} = 0.75\ (55 + 0.5\ \text{PWL}) \qquad \text{Eq. 3}$$

- For smoothness, for each of the 2,000 simulated Lots, the mean ($\bar{x}$) is computed. The quality measure used for surface smoothness is the average value of all sublots within the Lot. The surface smoothness acceptance plan is based on a daily average profile index tied to the graduated pay adjustment schedule shown in table 2.
- If $PI_{0.2}$ > 12 in/mi, the AASHTO Guide specifies "Corrective Work Required." However, in Prob.O.Prof, a default pay factor of 89 percent is used.
- The functionality of computing the pay factor is performed in the program using the table functions INDEX and MATCH, which are used to lookup the values from an Excel® cell array.

Table 2. AASHTO smoothness pay adjustment schedule.

Profile Index $PI_{0.2}$, in/mi per 0.1-mi section	Price Adjustment, % of Pavement Unit Bid Price
3 or less	105
Over 3 to 4	104
Over 4 to 5	102
Over 5 to 7	100
Over 7 to 8	98
Over 8 to 9	96
Over 9 to 10	94
Over 10 to 11	92
Over 11 to 12	90
Over 12	Corrective work required

- The current version of Prob.O.Prof contains a bug wherein "n" smoothness pay factors are computed for each of the "n" sublots, and the average of these "n" pay factors are used as the average pay factor for the Lot. The average smoothness for the Lot should be computed first, which should then be used to compute a single pay factor for the Lot.
- Once the pay factors are computed for the 2,000 simulated Lots for each target quality level, they are sorted in descending order and the average pay factor and the 25th percentile, 50th percentile, 75th percentile, and 95th percentile pay factors are computed.
- For each target quality level, the profit is computed as the difference between the pay and the percentage cost increment/decrement.

<u>Output</u>

- The "Output" sheet has SAVE, PRINT, and HELP buttons as shown in figure 2. Clicking on the SAVE button brings up the file save dialog box. Clicking on the PRINT button prints the output sheet. Clicking on the HELP button brings up a drop down menu. The user can then select from a list of items to get additional information.
- For each AQC, the results for all five target quality levels are displayed in the "Output" sheet in a tabular form. The table includes cost (increment or decrement), pay and profit at the 25th percentile, 50th percentile, 75th percentile, and 95th percentile levels, and average pay and profit.
- If the user has analyzed more than one AQC, they can then select one of four composite pay factor methods (weighted average, average, sum, and product) and enter a pay factor cap. If weighted average is selected, the user must enter the weighted percentage for each AQC.
- These inputs are used to rank the 125 unique target value combinations, and the top 60 combinations are displayed on the "Output" sheet, as shown in figure 3. Five tables are displayed corresponding to the average, 25th percentile, 50th percentile, 75th percentile, and 95th percentile level results from each AQC.
- The tables include the values of the three target quality factors, the cost, the pay, and the profit, computed for that combination of target quality levels. The top three ranked target value combinations are highlighted for easy identification.

Target Thickness (inches)	COST (%)	PAY				PROFIT				EXPECTED	
		95%	75%	50%	25%	95%	75%	50%	25%	PAY	PROFIT
9.60	-2.40	-58.16	-50.43	-45.55	-41.07	-55.76	-48.03	-43.15	-38.67	-43.93	-41.53
9.80	-1.20	-52.83	-44.38	-40.00	-13.98	-51.63	-43.18	-38.80	-12.78	-33.64	-32.44
10.00	0.00	-45.35	-38.93	-13.11	-6.73	-45.35	-38.93	-13.11	-6.73	-20.61	-20.61
10.20	1.20	-39.40	-10.71	-5.46	1.38	-40.60	-11.91	-6.66	0.18	-7.65	-8.85
10.40	2.40	-11.56	-4.84	0.52	5.00	-13.96	-7.24	-1.88	2.60	-1.08	-3.48

PRINT

SAVE

HELP

Target Strength (psi)	COST (%)	PAY				PROFIT				EXPECTED	
		95%	75%	50%	25%	95%	75%	50%	25%	PAY	PROFIT
3500.00	-2.00	-52.17	-44.77	-40.27	-14.33	-50.17	-42.77	-38.27	-12.33	-34.04	-32.04
4000.00	-1.00	-38.66	-10.62	-4.84	1.49	-37.66	-9.62	-3.84	2.49	-7.73	-6.73
4500.00	0.00	-5.31	0.71	4.94	5.00	-5.31	0.71	4.94	5.00	2.43	2.43
5000.00	1.00	2.65	5.00	5.00	5.00	1.65	4.00	4.00	4.00	4.69	3.69
5500.00	2.00	5.00	5.00	5.00	5.00	3.00	3.00	3.00	3.00	4.97	2.97

Target Smoothness (in/mile)	COST (%)	PAY				PROFIT				EXPECTED	
		95%	75%	50%	25%	95%	75%	50%	25%	PAY	PROFIT
5.00	1.00	-0.80	0.60	1.40	2.20	-1.80	-0.40	0.40	1.20	1.39	0.39
6.00	0.50	-2.00	-0.80	0.00	1.00	-2.50	-1.30	-0.50	0.50	0.08	-0.42
7.00	0.00	-3.80	-2.40	-1.60	-0.40	-3.80	-2.40	-1.60	-0.40	-1.49	-1.49
8.00	-0.50	-5.80	-4.00	-3.20	-2.00	-5.30	-3.50	-2.70	-1.50	-3.15	-2.65
9.00	-1.00	-7.60	-6.00	-4.80	-4.00	-6.60	-5.00	-3.80	-3.00	-4.89	-3.89

Cap:

Composite Pay Factor:

Note: For Weighted Average Method only

Thickness Weight (%):

Strength Weight (%):

Smoothness Weight (%):

NOTE: A contractor can not get more than the specified cap

Figure 2. Prob.O.Prof output screen.

Rank	Target Quality Factor			Cost	CPF	Profit
	T	St	Sm	(%)	(%)	(%)
19	10.4	5500	5	5.40	110.00	4.60
15	10.4	5500	6	4.90	110.00	5.10
13	10.4	5500	7	4.40	109.81	5.41
22	10.4	5500	8	3.90	108.05	4.15
32	10.4	5500	9	3.40	105.84	2.44
11	10.4	5000	5	4.40	110.00	5.60
8	10.4	5000	6	3.90	110.00	6.10
6	10.4	5000	7	3.40	109.81	6.41
14	10.4	5000	8	2.90	108.05	5.15
28	10.4	5000	9	2.40	105.84	3.44
3	10.4	4500	5	3.40	110.00	6.60
2	10.4	4500	6	2.90	110.00	7.10
1	10.4	4500	7	2.40	109.81	7.41
7	10.4	4500	8	1.90	108.05	6.15
21	10.4	4500	9	1.40	105.84	4.44
20	10.2	5500	5	4.20	108.79	4.59
25	10.2	5500	6	3.70	107.51	3.81
30	10.2	5500	7	3.20	106.02	2.82
35	10.2	5500	8	2.70	104.32	1.62
38	10.2	5500	9	2.20	102.19	-0.01
12	10.2	5000	5	3.20	108.79	5.59
17	10.2	5000	6	2.70	107.51	4.81
24	10.2	5000	7	2.20	106.02	3.82
31	10.2	5000	8	1.70	104.32	2.62
37	10.2	5000	9	1.20	102.19	0.99
4	10.2	4500	5	2.20	108.79	6.59
9	10.2	4500	6	1.70	107.51	5.81
16	10.2	4500	7	1.20	106.02	4.82
26	10.2	4500	8	0.70	104.32	3.62
34	10.2	4500	9	0.20	102.19	1.99
44	10	5500	5	3.00	100.09	-2.91
47	10	5500	6	2.50	98.91	-3.59
48	10	5500	7	2.00	97.54	-4.46
51	10	5500	8	1.50	95.97	-5.53
53	10	5500	9	1.00	94.02	-6.98
41	10	5000	5	2.00	100.09	-1.91
43	10	5000	6	1.50	98.91	-2.59
45	10	5000	7	1.00	97.54	-3.46
49	10	5000	8	0.50	95.97	-4.53
52	10	5000	9	0.00	94.02	-5.98
39	10	4500	5	1.00	100.09	-0.91
40	10	4500	6	0.50	98.91	-1.59
42	10	4500	7	0.00	97.54	-2.46
46	10	4500	8	-0.50	95.97	-3.53
50	10	4500	9	-1.00	94.02	-4.98
56	9.8	5500	5	1.80	92.31	-9.49
58	9.8	5500	6	1.30	91.22	-10.08
60	9.8	5500	7	0.80	89.96	-10.84
54	9.8	5000	5	0.80	92.31	-8.49
55	9.8	5000	6	0.30	91.22	-9.08
5	10.4	4000	5	2.40	108.91	6.51
10	10.4	4000	6	1.90	107.63	5.73
18	10.4	4000	7	1.40	106.14	4.74
27	10.4	4000	8	0.90	104.43	3.53
23	10.2	4000	5	1.20	105.15	3.95
29	10.2	4000	6	0.70	103.92	3.22
33	10.2	4000	7	0.20	102.48	2.28
36	10.2	4000	8	-0.30	100.83	1.13
57	9.8	4000	5	-1.20	89.22	-9.58
59	9.8	4000	6	-1.70	88.17	-10.13

Figure 3. Relative rank, cost, pay, and profit for the top 60 (of 125) target value combinations.

- Because the AQCs are combined, the percentile values do not represent the overall probability of attaining (as a minimum) the displayed profit for a particular combination of target quality levels.

The complete Prob.O.Prof flow chart is shown in figure 4.

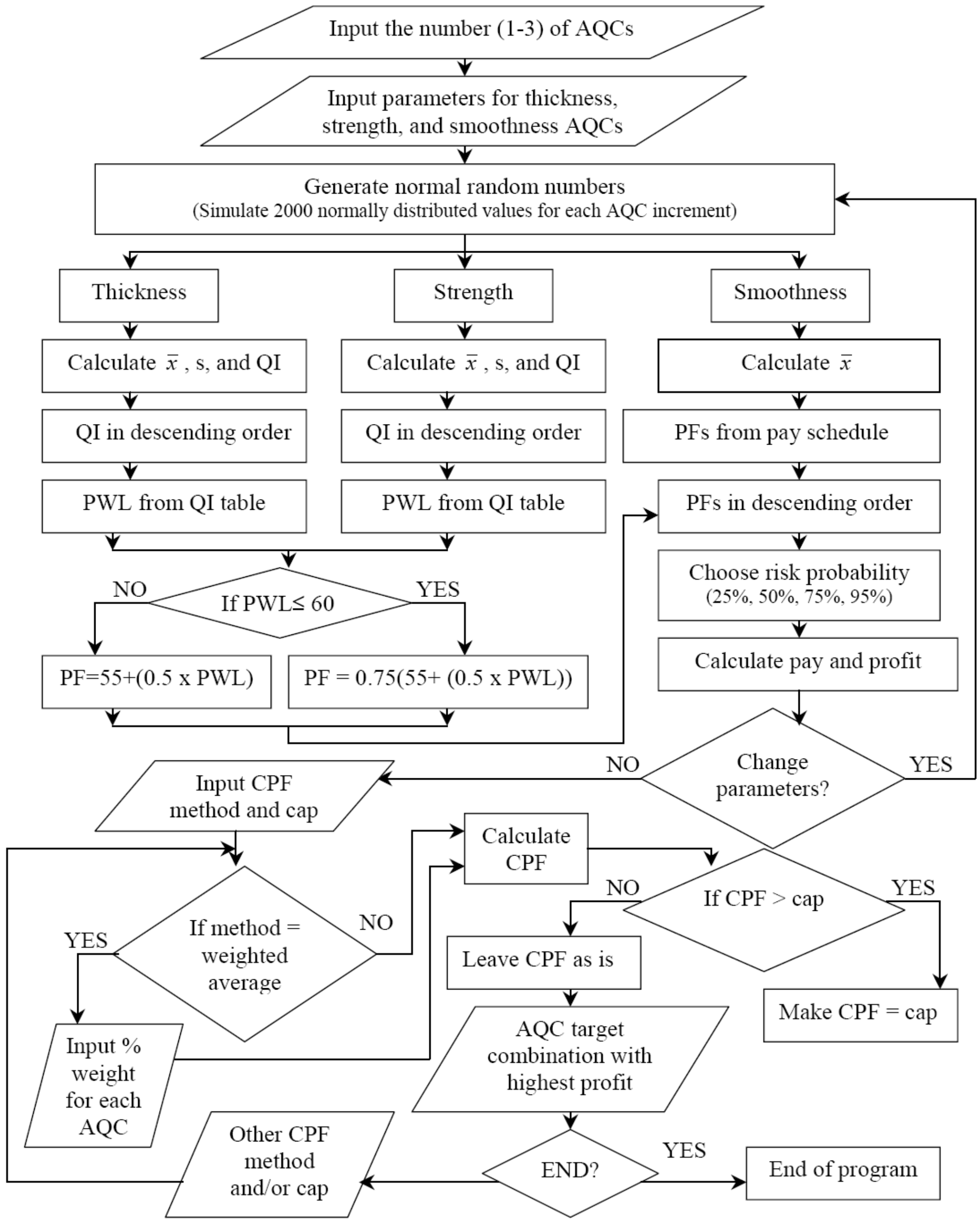

Figure 4. Prob.O.Prof flowchart.

CHAPTER 3. PAVEMENT SPECIFICATIONS REVIEW

INTRODUCTION

To develop a sense of the types of specifications that the new Prob.O.Prof program would need to accommodate, an investigation was made into the nature and content of today's HMA and PCC pavement specifications. This investigation began with a review of key pieces of literature and was followed by a detailed review of several States' current HMA and PCC specifications. The primary focus of this undertaking was information concerning the following aspects of pavement QA practices and specifications:

- Agency and Contractor Responsibilities.
- Quality Control (QC) Quality Characteristics.
- AQCs.
- Sampling/Testing Procedures.
- Use of Contractor Test Results.
- Acceptance Measures and Requirements.
- Pay Adjustment Procedures.
- Application of Pay.

REVIEW OF LITERATURE

A search of literature relating to current or fairly recent QA practices/specifications revealed the following key documents:

- Federal Highway Administration (FHWA) Report FHWA-HRT-04-046, *Evaluation of Procedures for Quality Assurance Specifications* (Burati et al., 2004).
- *National Cooperative Highway Research Program (NCHRP) Synthesis 346*, "State Construction Quality Assurance Programs" (Hughes, 2005).
- AASHTO *Quality Assurance Guide Specification* (AASHTO, 1996) (in conjunction with AASHTO *Guide Specifications for Highway Construction* [AASHTO, 1998]).

Summaries of the information pertinent to the enhancement of the Prob.O.Prof software program are provided below.

FHWA *Evaluation of Procedures for Quality Assurance Specifications*

As part of this project, HMA and PCC specifications were requested from all State agencies. A total of 23 HMA specifications, 8 Superpave specifications, and 9 PCC specifications were received as follows:

- HMA—Alaska, Arkansas, Colorado, Idaho, Illinois, Iowa, Maryland, Michigan, Minnesota, Montana, Nebraska, North Dakota, Nevada, Ohio, Ontario, Oregon, Pennsylvania, South Carolina, Texas, Virginia, Washington, Wisconsin, and Wyoming.

- Superpave—Connecticut, Kansas, Louisiana, Maine, Minnesota, Mississippi, New York, and North Carolina.
- PCC—Illinois, Iowa, Kansas, New Jersey, North Carolina, Oregon, Pennsylvania, Texas, and Wisconsin.

Reviews of the specifications were summarized as follows (Burati et al., 2004):

> HMA—*Examination of the specifications revealed that the majority of the agencies use the Marshall mix design and therefore the quality characteristics evaluated for QC and acceptance are similar. The most significant difference is in the number of quality characteristics that the contractor is responsible for controlling. Some agencies require the contractor to control a few common characteristics, such as gradation, asphalt content, density, voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and total air voids. Almost all of the agencies use these characteristics for QC or acceptance. However, some agencies require control over many more characteristics, including Hveem stability, Marshall stability, Marshall flow, dust-to-asphalt ratio, maximum specific gravity (MSG), bulk specific gravity (BSG), moisture content, binder temperature, liquid limit, plastic index, fractured faces, absorption, indirect tensile strength (ITS), and tensile strength ratio (TSR). Additionally, differences in the Lot sizes for testing varied widely from agency to agency. Testing frequencies are also significantly different for the various agencies. This review indicated that with the exception of a few commonly measured characteristics, the QC and acceptance procedures varied widely among the responding agencies.*
>
> *The methods for determining acceptance were also investigated. The method for acceptance of material varies from agency to agency, but can be grouped into four general categories:*
>
> - *Acceptance testing by the department.*
> - *Verification of the contractor's QC tests by the department's assurance tests.*
> - *Acceptance testing by the contractor under departmental supervision.*
> - *Some combination of contractor and departmental testing.*
>
> *The final aspects of the specifications examined were the properties evaluated and the methods for determining payment factors. Most of the responding agencies evaluate only a few properties for determining payment factors. The most common properties used are gradation, in-place density, asphalt content, VMA, and air voids. Additional properties evaluated by some agencies include Marshall stability, crushed particle count, thickness, moisture content, theoretical maximum density (TMD), laboratory-molded density, and smoothness.*
>
> Superpave—*Examination of the specifications indicated that verification of the mix design is similar for all of the agencies. Additionally, the quality characteristics evaluated for QC and acceptance do not differ substantially from agency to agency. However, there is a significant difference in the quality characteristics evaluated for acceptance. Most of the agencies evaluate the following characteristics: asphalt content,*

gradation, air voids, VMA, and in-place density. In addition to these commonly evaluated characteristics, three agencies evaluate mix moisture, VFA, and BSG, and two agencies evaluate TMD, dust-to-asphalt ratio, and G_{mb}@N_{des}. At least one agency evaluates a number of other quality characteristics, such as TSR, sand equivalent, percent crushed aggregate, N_{ini}, N_{des}, and N_{max}. Four of the eight agencies use smoothness as an acceptance quality characteristic.

The methods used to determine acceptance can be grouped into two categories: acceptance testing by the agency and verification of the contractor's tests by the agency's verification tests. The most common quality characteristics used in determining payment factors are gradation, asphalt content, air voids, in-place density, and smoothness.

PCC—*The review of the PCC specifications revealed similarities in the quality characteristics that the contractor is responsible for controlling. Each of the agencies requires the contractor to conduct QC tests for aggregate gradation, air content, slump, unit weight/yield, and compressive or flexural strength. A majority of the agencies also require the contractor to control thickness, temperature, and smoothness. Additional characteristics evaluated by at least one agency include water-cement ratio, percent passing the 75-micrometer (µ m) sieve, moisture content of the aggregate, fineness modulus, sand equivalent, fine aggregate organic impurity, and admixture dosage. The QC testing frequency requirements vary widely from agency to agency. The quality characteristics evaluated for the acceptance of material vary only slightly from agency to agency. Most of the agencies evaluate aggregate gradation, slump, temperature, smoothness, unit weight/yield, thickness, air content, and compressive or flexural strength. The method for determining the acceptance of material varies from agency to agency, with either agency verification testing of the contractor's tests or acceptance testing by the agency. The responding agencies assigned payment factors for one or more of the following quality characteristics: smoothness, thickness, air content, compressive strength, and flexural strength.*

Detailed information on each of these States' specifications is provided in the appendices of the project report. As discussed in the next section, some of this information has been compiled and summarized with more recent specification data.

NCHRP *Synthesis 346*

This synthesis presented the results of a 2004 State survey of QA practices performed under NCHRP Project 20-5. It showed a variety of quality characteristics being used for QC and acceptance of HMA and PCC paving materials. As seen in table 3, gradation, asphalt content (P_b), compaction, voids in the mineral aggregate (VMA), and aggregate fractured faces were found to be the most common QC quality characteristics for HMA, while compaction, P_b, ride quality, and gradation were identified as the most common acceptance characteristics. As table 4 shows, gradation, air content, and slump were found to be the most common QC quality characteristics for PCC, while thickness, air content, cylinder strength, slump, and gradation were identified as the most common acceptance characteristics.

Table 3. Quality attributes used for QC and acceptance of HMA paving (Hughes, 2005).

Attribute	No. of Responses	
	QC	**Acceptance**
Asphalt content (P_b)	40	**40**
Gradation	43	**33**
Compaction	28	**44**
Ride Quality	16	**39**
Air Voids (V_a)/Voids in Total Mix (VTM)	20	**26**
Voids in the Mineral Aggregate (VMA)	26	**23**
Aggregate Fractured Faces	25	**23**
Thickness	13	**22**
Voids Filled with Asphalt (VFA)	**19**	**13**

Note: 44 total responses

Table 4. Quality attributes used for QC and acceptance of PCC paving (Hughes, 2005).

Attribute	No. of Responses	
	QC	**Acceptance**
Air content	25	**38**
Thickness	14	**36**
Slump	24	**33**
Cylinder strength	18	**31**
Gradation	25	**26**
Beam strength	14	**18**
Water-cement ratio	12	**16**
Ride quality	1	**15**
Aggregate fractured faces	7	**6**
Sand equivalence	0	**3**
Permeability	0	**3**
Core strength	**0**	**2**

Note: 40 total responses

As table 5 shows, the same 2004 survey showed that the most commonly used HMA quality measures are PWL/Percent Defective (PD) (27 States), Range (15), Average (13), Individual Values (4), and Average Absolute Deviation (AAD) (4). For PCC (table 6), the most commonly used quality measures are PWL/PD (16 States), Range (15), Average (12), and Individual Values (10).

Table 5. Quality measures used for QC and acceptance of HMA paving (Hughes, 2005).

QUALITY MEASURE	NO. OF AGENCIES
Percent Within Limits (PWL)	26
Range	15
Average	13
Individual Values	4
Average Absolute Deviation (AAD)	4
Standard Deviation	3
Percent Defective (PD)	1
Moving Average	1

Note: 45 total responses

Table 6. Quality measures used for QC and acceptance of PCC paving (Hughes, 2005).

QUALITY MEASURE	NO. OF AGENCIES
Percent Within Limits (PWL)	13
Range	15
Average	12
Individual Values	10
Standard Deviation	3
Percent Defective (PD)	3

Note: 40 total responses

AASHTO *Quality Assurance Guide Specification*

As noted earlier, the current version of Prob.O.Prof utilizes the PCC pavement acceptance plan outlined in the 1996 AASHTO *Quality Assurance Guide Specification*. A summary of the key aspects/ features (QC quality characteristics, sampling/testing plans, AQCs, quality measures, pay adjustment methods) of that plan, as well as those of the asphalt concrete (AC) pavement acceptance plan, is provided in table 7.

It should be noted that the 1996 AASHTO *Quality Assurance Guide Specification* references the smoothness testing procedures and pay factors contained in the 1993 AASHTO *Guide Specifications for Highway Construction*. The 1993 *Guide* specified the PCC smoothness pay ranges and factors shown in table 7; these are included in the current Prob.O.Prof program.

An updated version of the AASHTO *Guide Specifications for Highway Construction* was made available in 2008. It specifies the PCC and AC smoothness pay ranges and factors also shown in table 7. As can be seen, the criteria for both pavement types are the same.

Table 7. Summary of AASHTO Quality Assurance Guide Specification (AASHTO, 1996).

SPECIFICATION	**FEATURE**	**PCC PAVEMENT**	**AC PAVEMENT**
Contractor QC	**QC Quality Characteristics**	Agg Gradation, Agg Moisture, Slump, Air Content, Temperature, Yield, Comp Strength, Thickness	Agg Gradation, P_b, Marshall Flow & Stability, V_a, VMA, Thickness, Mat Density
Agency QA	**Type/Nature**	Contractor QC Inspection, Sampling, and Testing	Contractor QC Inspection, Sampling, and Testing
	Sampling & Testing Procedure	Lot (strength, thickness) =As defined by Agency Sublot (strength, thickness) = 500 lane-ft Lot (smoothness) = 528 ft	Lot & Sublot (mix properties) = As defined by Agency Lot & Sublot (density) = As defined by Agency Lot (smoothness) = 528 ft
Acceptance	**Basis**	Agency-based acceptance procedures (i.e., Agency acceptance testing and/or verification testing of contractor test results)	Agency-based acceptance procedures (i.e., Agency acceptance testing and/or verification testing of contractor test results)
	Acceptance Quality Characteristics (AQCs)	Comp Strength: 1 core/sublot Thickness: 1 core/sublot Smoothness/$PI_{0.2}$: 2 profile tests; one in each wheelpath	Mixture Properties (Agg Gradation, P_b, Marshall Flow & Stability, V_a, VMA): As chosen by Agency Mat Density (%TMD): As defined by Agency Smoothness/$PI_{0.2}$: 2 profile tests; one in each wheelpath
	AQC Measure Types	Comp Strength: PWL $Q_S = (\bar{X}-LSL)/S$ LSL = As specified by Agency PWL_S from statistical table using Q_S and n Thickness: Ind & PWL Ind: If T(sublot) ≤ 1.0 in deficient from T_{DES}, then full acceptance. If T(sublot) > 1.0 in deficient from T_{DES}, sublot not accepted PWL: $Q_T = (\bar{X}-LSL)/S$ $LSL=T_{DES} - 0.2$ in PWL_T from statistical table using Q_T and n Smoothness/$PI_{0.2}$: Avg	Agg Gradation: PWL $Q_L = (\bar{X}-LSL)/S$ $LSL=JMF_{Targ} - z$ (z=2 to 7% depending on sieve size) $Q_U = (USL-\bar{X})/S$ $USL=JMF_{Targ} + z$ (z=2 to 7% depending on sieve size) PWL_L and PWL_U from statistical table using Q_L, Q_U, n $PWL_T = (PWL_L + PWL_U) - 100$ P_b: PWL $Q_L = (\bar{X}-LSL)/S$ $LSL = JMF_{Targ} - 0.4\%$ $Q_U = (USL-\bar{X})/S$ $USL = JMF_{Targ} + 0.4\%$ PWL_L and PWL_U from statistical table using Q_L, Q_U, n $PWL_T = (PWL_L + PWL_U) - 100$ Marshall Flow/Stability: PWL (using Agency tolerances) V_a: PWL (using Agency tolerances) VMA: PWL (using Agency tolerances) Mat Density: PWL $Q_L = (\bar{X}-LSL)/S$ LSL = 91% $Q_U = (97.5\%-\bar{X})/S$ USL = 96% PWL_L and PWL_U from statistical table using Q_L, Q_U, n $PWL_T = (PWL_L + PWL_U) - 100$ Smoothness/$PI_{0.2}$: Avg
Basis for Pay	**Pay Adjustment Procedures**	Thickness $PF_{LOT} = 55 + 0.5\times PWL$ For PWL≤60, Agency determines appropriate action Comp Strength $PF_{LOT} = 55 + 0.5\times PWL$ For PWL≤60, Agency determines appropriate action Smoothness/$PI_{0.2}$, in/mi (Method 3 in 1993 *Guide Spec for Hwy Const*)* ≤3.0 105% 3.1 to 4.0 104% 4.1 to 5.0 102% 5.1 to 7.0 100% (Method 2: ≤7.0 100%) 7.1 to 8.0 98% 8.1 to 9.0 96% 9.1 to 10.0 94% 10.1 to 11.0 92% 11.1 to 12.0 90% >12.0 Corrective Action Smoothness/$PI_{0.2}$, in/mi (2008 *Guide Spec for Hwy Const*)** ≤1.0 105% 1.1 to 2.0 103% 2.1 to 3.0 102% 3.1 to 4.0 101% 4.1 to 7.0 100% (Based on initial PI measurements) 7.1 to 8.0 98% 8.1 to 9.0 96% 9.1 to 10.0 94% 10.1 to 11.0 92% 11.1 to 12.0 90% (Based on post-corrective work PI measurements) >12.0 Corrective Action	Agg Gradation $PF_{LOT} = 55 + 0.5\times PWL$ For PWL≤60, Agency determines appropriate action P_b $PF_{LOT} = 55 + 0.5\times PWL$ For PWL≤60, Agency determines appropriate action Marshall Flow & Stability $PF_{LOT} = 55 + 0.5\times PWL$ For PWL≤60, Agency determines appropriate action V_a $PF_{LOT} = 55 + 0.5\times PWL$ For PWL≤60, Agency determines appropriate action VMA $PF_{LOT} = 55 + 0.5\times PWL$ For PWL≤60, Agency determines appropriate action Mat Density $PF_{LOT} = 55 + 0.5\times PWL$ For PWL≤60, Agency determines appropriate action Smoothness/$PI_{0.2}$, in/mi (2008 *Guide Spec for Hwy Const*)** ≤1.0 105% 1.1 to 2.0 103% 2.1 to 3.0 102% 3.1 to 4.0 101% 4.1 to 7.0 100% 7.1 to 8.0 98% 8.1 to 9.0 96% 9.1 to 10.0 94% 10.1 to 11.0 92% 11.1 to 12.0 90% (Based on post-corrective work PI measurements) >12.0 Corrective Action
	Application of Pay Factors	Composite (unspecified type) for Comp Strength and Thickness Individual for Smoothness	Composite (unspecified type) for Agency-chosen Mixture Properties and Mat Density Individual for Smoothness

* Smoothness pay ranges and factors based on the 1993 AASHTO *Guide Specifications for Highway Construction* (method 3 using incentives)
** Smoothness pay ranges and factors based on the 2008 AASHTO *Guide Specifications for Highway Construction*.

SELECTED STATE AGENCY HMA PAVEMENT SPECIFICATIONS

Tables 17 through 24 in appendix B summarize key aspects/features (QC quality characteristics, sampling/testing plans, AQCs, quality measures, pay adjustment methods) of 12 States' HMA (Hveem, Marshall, Superpave, and stone matrix [SMA] mixes) specifications. The information provided in these tables is derived from the FHWA report, *Evaluation of Procedures for Quality Assurance Specifications* (Burati et al., 2004), but it has been verified and/or updated based on each agency's most current specifications and prevailing special provisions.

Many different abbreviations and acronyms are used throughout the specifications in appendix B. Their complete designations are provided in appendix A.

The States selected for in-depth specification review represent a wide geographical sampling of States that do a substantive amount of HMA paving. Thus, it is believed the information presented in this section covers a majority of the types of HMA pavement specifications that are currently in use throughout the country.

In general, it can be said that while there are many different quality characteristics that are closely monitored during HMA production and placement, only a few are frequently used as the basis for acceptance by the State highway agency (SHA). These AQCs and their forms of measurement include:

- Gradation—retainage on key sieves (e.g., nominal max size sieve, No. 8, No. 40, No. 200), as determined by gradation analysis (AASHTO T 30) of extracted mix samples taken from the truck, paver hopper, or roadway (prior to rolling) (AASHTO T 168).
- Asphalt content (P_b)—percentage of asphalt binder, as determined by ignition testing (AASHTO T 308) of mix samples taken from the truck, paver, or roadway (prior to rolling) (AASHTO T 168/modified T 168).
- V_a—percentage of air voids, as determined by G_{mm} and G_{mb} (AASHTO T 269) or Superpave Gyratory testing (AASHTO T 312) using mix samples taken from the truck, paver, or roadway (prior to rolling) (AASHTO T 168).
- VMA—percent voids in mineral aggregate, as computed from G_{mm} and G_{mb} (AI MS-2, SP-2).
- VFA—percent voids filled with asphalt binder, as computed from V_a and VMA.
- Dust to Asphalt Ratio—Dust to asphalt ratio, as computed from P_b (AASHTO T 308), gradation analysis (AASHTO T 30), and aggregate bulk specific gravity (G_{sb}) testing.
- Mat Density—percent theoretical maximum density (%TMD) or percent theoretical maximum specific gravity (%G_{mm}) using mix samples and core samples (AASHTO T 168) for determining G_{mm} and G_{mb} (AASHTO T 166, T 209, T 269, T 312, ASTM D 6752); or percent target density using nuclear density gauge calibrated to G_{mm} and G_{mb} (ASTM D 2950).
- Smoothness—$PI_{0.0}$, $PI_{0.2}$, or IRI, as determined from California profilograph or inertial profiler.

The way the quality of these AQCs is assessed varies from characteristic to characteristic, but the typical measures for each AQC are as follows:

- Gradation—PWL, PD, Average, Range, Individual.
- P_b—PWL, PD, Average, Individual, AAD.
- V_a—PWL, AAD, Average, Individual.
- VMA—PWL, Average, Individual.
- VFA and Dust to Asphalt Ratio—PWL.
- Mat Density—PWL, AAD, PD, Average, Individual, Range.
- Smoothness—Individual Profile, Averaged Profile, PWL.

As described below, acceptance provisions vary widely among and within the individual AQCs.

- Gradation—In general, acceptance of gradation for Marshall mixes is based on individual test results or average or moving average test results, whereas acceptance of gradation for Superpave mixes is typically based on PWL/PD. In this procedure, lower-limit and upper-limit quality indexes (Q_L and Q_U) are computed for key sieve sizes based on specified lower and upper control limits. PWL/PD is subsequently determined for each key sieve using Q_L, Q_U, the number of samples (n), and statistical tables. A composite PWL/PD for gradation is then computed by applying weighting factors (f) to the PWL/PD for each key sieve. Equations are used or values are assigned to convert PWL/PD into a pay factor or pay adjustment value, frequently in conjunction with volumetric properties (e.g., P_b, V_a, VMA, VFA).
- P_b, V_a, VMA, VFA, and Dust to Asphalt Ratio—Although individual, average, moving average, and AAD approaches are used, acceptance of mixes with respect to these volumetric properties is generally based on PWL/PD. In this procedure, lower and upper control limits are typically specified (exception for VMA, whereby only a lower limit is frequently specified) from which lower-limit and upper-limit quality indexes (Q_L and Q_U) are computed. PWL/PD is subsequently determined using Q_L, Q_U, the number of samples (n), and statistical tables. Equations are used or values are assigned to convert PWL/PD into a pay factor or pay adjustment value, frequently in conjunction with gradation and other volumetric properties.
- Mat Density—A variety of methods are used in accepting HMA based on mat density. These include individual, average, weighted average, AAD, and both single- and double-limit PWL/PD, as determined from core samples or nuclear density test results. Typically, for the PWL/PD approach, a pay factor equation is utilized, whereas for the other methods, a pay factor schedule is employed. Although the pay factor for mat density is applied individually in some cases, it is frequently applied on a weighted average basis with gradation and volumetric properties.
- Smoothness—In most cases, acceptance is based on a bottom-line smoothness value, with incentives and/or disincentives applied to levels above that value. In some cases, however, no pay adjustment schedule is used; the pavement either satisfies the bottom-line criterion or must be corrected so that it does. Where incentives/disincentives are used, either stepped pay schedules or mathematical formulas are used to adjust pay as a percentage of the contract unit price or as a dollar amount adjustment. In most cases, application of the smoothness pay factor is separate from the pay factors for gradation, volumetric properties, and mat density.

The establishment of evaluation units for sampling and testing of the different AQCs varies considerably. The evaluation units are typically established according to tons of mix for gradation, volumetric properties, and mat density. However, the mix amounts constituting a Lot or sublot are sometimes different for gradation/volumetric properties and mat density. Also, in some cases, the Lot/sublot for mat density is defined according to paved area (e.g., lane-mi).

Lot sizes are defined in terms of 1 day's production or unsuspended production of a particular job mix formula (JMF) or anywhere from 2,400 to 6,000 plus tons of mix. Each Lot is subdivided into a minimum number of sublots (usually three to six), from which a specified number of samples or tests are taken. For smoothness, the most common evaluation unit is a 0.1-mi long traffic lane.

SELECTED STATE AGENCY PCC PAVEMENT SPECIFICATIONS

Tables 25 through 29 in appendix B summarize key aspects/features (QC quality characteristics, sampling/ testing plans, AQCs, quality measures, pay adjustment methods) of 15 States' PCC pavement specifications. Again, the information provided in these tables is derived from the FHWA report, *Evaluation of Procedures for Quality Assurance Specifications* (Burati et al., 2004), but it has been verified and/or updated based on each agency's most current specifications and prevailing special provisions.

Designations for the various abbreviations and acronyms appearing in the concrete pavement specifications in appendix B are given in appendix A.

The States selected for in-depth specification review represent a wide geographical sampling of States that do a substantive amount of concrete paving. Thus, it is believed the information presented in this section covers a majority of the types of PCC pavement specifications that are currently in use throughout the country.

In general, it can be said that while there are many different quality characteristics that are closely monitored during PCC production and placement, only a few are frequently used as the basis for acceptance by the SHA. These AQCs and their forms of measurement include:

- Thickness—cores, probes, survey elevation differentials.
- Smoothness—$PI_{0.0}$, $PI_{0.2}$, IRI.
- Strength—28-day compressive using cores or cylinders, 28-day flexural using beams.
- Air Content—percent air.

The way the quality of these AQCs is assessed varies from characteristic to characteristic, but the typical measures for each AQC are as follows:

- Thickness—Individual Deficiency, Average Deficiency, PWL, Average minus Standard Deviation.
- Strength—PWL, PD, Average minus Standard Deviation.
- Smoothness—Individual Profile, Averaged Profile.

- Air Content—Individual, PWL.

As described below, acceptance provisions vary widely among and within the individual AQCs.

- Thickness—Acceptance for thickness typically has two components. First, significantly deficient areas are identified and either removed/replaced or not paid. Second, areas of slightly deficient or acceptable levels of thickness are accepted and adjusted accordingly for pay. The incentives and/or disincentives are typically applied according to stepped pay schedules or mathematical formulas, such as the AASHTO pay factor equation ($PF_{LOT} = 55 + 0.5 \times PWL$) given earlier.
- Strength—Acceptance for strength is typically based on computation of the lower-limit quality index (Q_L) and determination of PWL/PD using Q_L, the number of samples (n), and statistical tables. Equations are then sometimes used to convert PWL/PD into a pay factor or pay adjustment value. In one case, acceptance and corresponding pay adjustments are based on the Average−Standard Deviation.
- Smoothness—In most cases, acceptance is based on a bottom-line smoothness value, with incentives and/or disincentives applied to levels above that value. In some cases, however, no pay adjustment schedule is used; the pavement either satisfies the bottom-line criterion or must be corrected so that it does. Where incentives/disincentives are used, either stepped pay schedules or mathematical formulas are used to adjust pay as a percentage of the contract unit price or as a dollar amount adjustment.
- Air Content—Acceptance is typically based on conformance of individual and/or averaged values to a defined range. In one case, lower-limit and upper-limit quality indexes (Q_L and Q_U) are computed, from which PWL is determined and used in a composite pay factor.

The establishment of evaluation units for sampling and testing of the different AQCs varies considerably. The evaluation units are typically defined as sublots, two or more of which comprise a Lot. Lot sizes for thickness, strength, and air content are often defined in terms of 1 day's production, a certain volume of PCC placed, or a certain area of in-place PCC. Each Lot is then subdivided into a certain number of sublots, from which a specified number of samples or tests are taken. In some cases, the Lot is not subdivided and therefore serves as the evaluation unit. For smoothness, the most common evaluation unit is a 0.1-mi long traffic lane. In one case, the entire day's production (i.e., the Lot) is tested as one unit.

CHAPTER 4. NEXT-GENERATION PROB.O.PROF

INTRODUCTION

Development of the next generation of Prob.O.Prof (version 2.0) focused on expanding, improving, and upgrading current Prob.O.Prof functionality so as to attract greater use by contractors and highway agencies alike. Because of the significant changes proposed for the program, it was determined that developing a completely new system would be more efficient and effective than modifying the visual interfaces and programming code of the existing spreadsheet program. Thus, a Microsoft® Excel spreadsheet-based system was built using the VBA coding tools and other built-in design and computational tools.

The primary goal in developing the new Prob.O.Prof 2.0 was to install it with the capability of evaluating optimal levels of quality for both HMA and PCC paving projects. Like its predecessor, the new program needed to utilize probabilistic simulation as the basis for the evaluation. However, for expanded application/use, it would need to feature the sampling/testing protocol and acceptance criteria of multiple specifications rather than just that of the AASHTO *QA Guide Specification* for PCC pavement.

Other goals of the new program included the following:

- Inclusion of specifications that cover a range of different AQCs and quality measure types.
- User-defined AQC target levels, with a maximum of seven target levels per AQC.
- User-defined number of probabilistic simulations.
- User-defined sample sizes.
- Capability of multiple-Lot analysis to offset risk associated with single-Lot analysis.
- Tabular displays of simulation results, including relative cost of paving at various target quality levels, the resulting relative pay, and the resulting net gain/loss (i.e., profit).
- Graphical displays of probability for profit associated with paving at various specified quality levels.
- Capability of testing/evaluating the effects of changes in specification and pay schedule criteria and composite pay factor computation method.

Details of the development process are provided in the sections below.

INPUTS

Users of the new Prob.O.Prof 2.0 program must input a variety of data in order to evaluate the optimal levels of pavement quality for a particular project. Several of the inputs are the same as those in the original Prob.O.Prof, but others are the result of the enhancements made to the program in this study. A complete listing of the inputs, with asterisk designations given for those that are new, is as follows:

- Pavement type (HMA or PCC)*.
- Project information.
  - Size/dimensions.
  - Estimated average bid price for HMA or PCC*.
  - No. of Lots*.
  - Samples per Lot.
  - AQC standard deviation.
- Specification (chosen from the following)*.
  - AASHTO PCC.
  - Arizona PCC*.
  - Iowa PCC*.
  - Wisconsin PCC*.
  - Alabama Superpave HMA*.
  - Missouri SMA*.
  - South Carolina Marshall HMA surface mix*.
  - South Carolina Marshall HMA binder mix*.
- AQCs (corresponding to chosen specification)*.
  - PCC compressive strength.
  - PCC thickness.
  - PCC smoothness.
  - PCC air content*.
  - HMA P_b*.
  - HMA V_a*.
  - HMA VMA*.
  - HMA mat density*.
  - HMA smoothness*.
- Number of simulations.
- Costs of achieving quality levels.
- Target values and increments for each AQC.
- Composite pay method.
  - Sum.
  - Product.
  - Average.
  - Weighted average.
  - Minimum*.
- Maximum composite pay factor.
- Number of top AQC combinations to be displayed.
- Minimum profit goal*.
- Confidence levels for displaying profit.
- Confidence intervals around median profit*.

Specifications

One of the first steps in developing the next-generation Prob.O.Prof was selecting a suite of specifications to be included in the program. The original program allowed the evaluation of quality in terms of only one specification (*AASHTO Guide Specification for PCC Pavement*) comprised of three AQCs (compressive strength, thickness, and smoothness). To expand the capabilities of the program, the various state specifications reviewed in chapter 3 and summarized in appendix B were considered for inclusion. It should be noted that one of the original intentions was to create a set of generic specifications that would reflect a commonality of the quality assessment approaches/procedures comprising the state specifications. The diversity and uniqueness of the specifications, however, prevented this work from happening.

Table 8 shows the specifications chosen for inclusion in Prob.O.Prof 2.0. It lists the AQCs represented in each specification along with the quality measures utilized with each AQC. Additional information on each specification is contained in tables 17 through 29 in appendix B. As a matter of note, for cases where an agency uses a PWL process similar to the AASHTO Guide Specification for PCC, this specification can be modified in Prob.O.Prof 2.0 to reflect that agency's specification.

Table 8. Pavement specifications selected for inclusion in next-generation Prob.O.Prof.

SPECIFICATION	AQCS	QUALITY MEASURE
AASHTO Guide Spec for PCC	Compressive Strength (28-day, cores) Thickness (cores) Smoothness ($PI_{0.2}$)	PWL PWL Average
Arizona PCC	Compressive Strength (28-day, cylinders) Thickness (cores) Smoothness ($PI_{0.2}$)	PWL PWL Individual
Iowa PCC	Thickness (cores) Smoothness ($PI_{0.2}$)	Average − Std Dev Average
Wisconsin PCC	Compressive Strength (28-day, cylinders) Thickness (probes) Smoothness ($PI_{0.0}$)	Average − Std Dev Average Average
Alabama Superpave HMA	P_b (nuclear gauge) V_a Mat Density (cores, %TMD) Smoothness ($PI_{0.0}$)	AAD AAD AAD Individual
Missouri SMA	P_b (nuclear gauge) $V_a{}^{@}N_{des}$ $VMA^{@}N_{des}$ Mat Density (cores, %TMD) Smoothness ($PI_{0.0}$)	PWL PWL PWL PWL Individual
South Carolina Marshall HMA (surface and binder mixes)	P_b (extraction or ignition loss) V_a VMA Mat Density (cores, %G_{mb}) Smoothness (MRN)	PWL PWL PWL PWL Average

Pay Schedules

The pay schedules used with each specification are those contained in appendix B. The schedules include graduated/step-type pay adjustments, linear equation pay adjustments, and combinations of the two. Additionally, while the pay schedules are often expressed as percentages or factors of the pay item unit cost, they sometimes are given in terms of pay amounts for a specified area.

Composite Pay

With the exception of the AASHTO Guide Specification for PCC pavement, each specification stipulates the method for computing composite pay and the AQCs included in the composite pay. Table 9 summarizes the composite pay criteria for each specification.

Table 9. Composite pay methods used in selected pavement specifications.

SPECIFICATION	COMPOSITE PAY METHOD (AQCS INCLUDED)
AASHTO Guide Spec for PCC	Unspecified/Optional (Compressive Strength, Thickness, Smoothness)
Arizona PCC	N/A—Individual pay factors for each AQC
Iowa PCC	N/A—Individual pay factors for each AQC
Wisconsin PCC	N/A—Individual pay factors for each AQC
Alabama Superpave HMA	Lowest (P_b, V_a, Mat Density)
Missouri SMA	Average (25% P_b, 25% V_a@N_{des}, 25% VMA@N_{des}, and 25% Mat Density)
South Carolina Marshall HMA	Weighted Average (25% P_b, 30% V_a, 10% VMA, and 35% Mat Density)

Only the *AASHTO Guide Specification for PCC Pavement* includes a maximum composite pay amount. The amount can be specified by the user.

Quality Costs

A key component in the evaluation of the optimal levels of pavement quality is the estimate of the contractor's cost of achieving a certain level of quality. Like the original Prob.O.Prof program, the next-generation system leaves it to the user to define, for each AQC, the contractor's relative costs of attaining various levels of quality. The relative costs are expressed as percentages of the cost associated with achieving the Agency Design/Specified Value for the particular AQC.

In the event the user is unable to define the costs, a set of default values has been developed and included in the program. Discussions on how these values were developed are given in the paragraphs below.

PCC Mixture Properties

The PCC mixture properties embodied by the suite of specifications included in the new Prob.O.Prof 2.0 program include compressive strength. A fairly comprehensive assessment of the contractor's cost of producing PCC mixes with different strengths was made in the development of the original Prob.O.Prof program. This included a survey of both SHAs and PCC paving contractors as a means of generating estimates of these values (Vidalis, 2005), combined with data from a recent FHWA study on incremental costs of PCC design elements (Hoerner et al., 2004). The relative costs developed for the original Prob.O.Prof are as follows:

Compressive Strength, lb/in^2	Relative Cost, %
2,825	−2
3,325	−1
3,825	0
4,325	+1
4,825	+2

These values represent a linear relationship in which a change in strength of 500 lb/in^2 entails a 1 percent change in the contractor's cost of PCC production and placement. For the Prob.O.Prof 2.0 relative costs, a review of Engineering News Record ready-mix concrete cost trends also was made (ENR, 2005). This review was combined with the original Prob.O.Prof data and resulted in a linear relationship in which a change in strength of 500 lb/in^2 entails a 1.5 percent change in the contractor's cost of PCC production and placement.

PCC Thickness

The relative costs of PCC thickness developed for the original Prob.O.Prof, based on the SHA and contractor surveys and data from the FHWA incremental costs report, are as follows:

Thickness, in	Relative Cost, %
8.90	−12
9.90	−6
10.90	0
11.90	+6
12.90	+12

These values also represent a linear relationship in which a change in thickness of 1 in entails a 6 percent change in the contractor's cost of PCC production and placement. This same relationship has been incorporated into the new Prob.O.Prof 2.0 program.

HMA Mixture Properties

Three mixture properties represent key AQCs in the HMA specifications utilized by the new Prob.O.Prof program. They include asphalt binder content (P_b), air voids (V_a), and voids in the mineral aggregate (VMA). Brief discussions of each parameter are provided below.

Asphalt Binder Content

P_b is the measure of the weight of asphalt binder in compacted HMA, expressed as a percentage of the total mix weight. For Superpave mixes and typically for Marshall mixes, an optimum asphalt binder content is identified in the mix design process as that content that results in 4 percent air voids at the design laboratory compaction level (e.g., Superpave N_{des}, Marshall 50- or 75-blow). This optimum content then serves as the job mix formula (JMF) target.

Changes in P_b have a direct impact on the overall cost of HMA production and placement. The impact is represented by the sum cost of less asphalt and more aggregate (corresponding to a lower P_b than the JMF target) or more asphalt and less aggregate (corresponding to a higher P_b than the JMF target).

The contractor's relative cost of HMA as a function of P_b will vary somewhat, depending on the prices of asphalt binder and aggregate, and the JMF target. In recent years, the price of binder has increased dramatically, from about \$400/ton in 2006 to about \$650/ton currently. Aggregate costs have remained fairly steady, typically ranging from \$12 to \$18/ton.

Using these ranges of asphalt and aggregate costs and variations of P_b from three JMF target values (4%, 5%, and 6%), plots of relative cost as a function of asphalt content were developed and are shown in figure 5. The rate of change in relative cost varies from 9.34 to 17 percent per 1 percentage point change in P_b.

For Prob.O.Prof 2.0 default costs, a rate of 12 percent change in relative cost per 1 percentage point change in P_b was selected. However, recognizing that labor and equipment costs are a considerable portion of the costs described above and would not change based on changes in asphalt content, the 12 percent change in relative cost per 1 percentage point change in P_b was reduced to 6 percent.

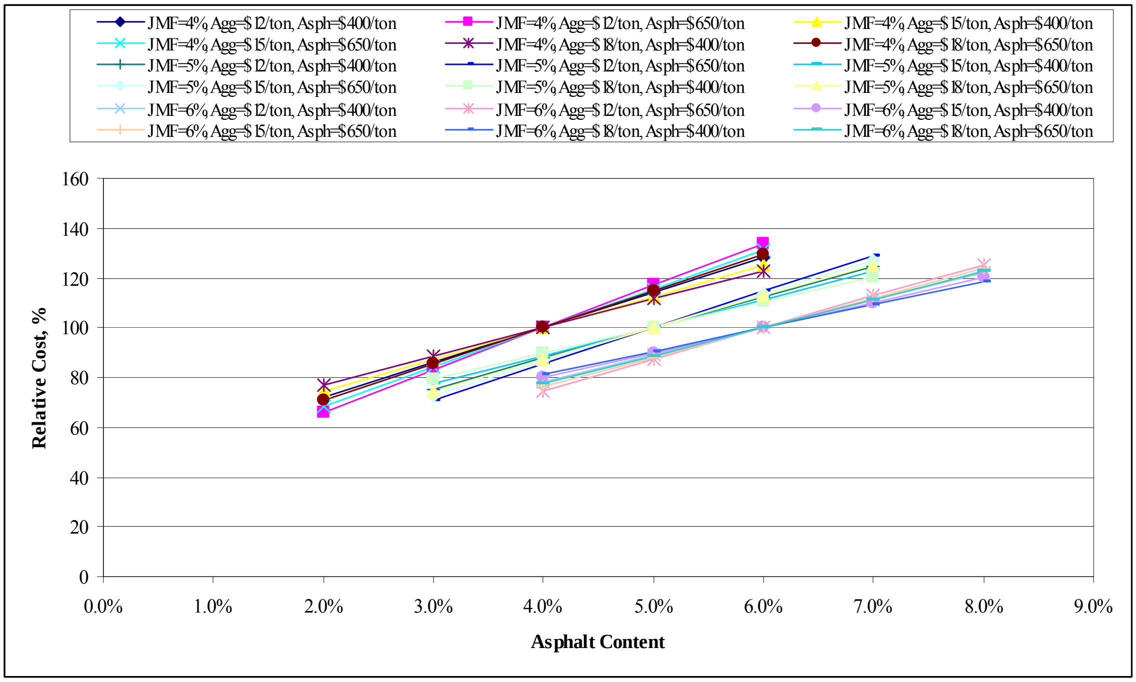

Figure 5. Relative cost of HMA as function of asphalt content.

Air Voids and Voids in the Mineral Aggregate

V_a is the measure of the volume of entrapped air in compacted HMA, expressed as a percentage of total mix volume. In general, air voids in dense-graded Superpave and Marshall mixes are designed at around 3 to 5 percent, with 4 percent typically specified. Air voids are largely a function of the asphalt binder content, but also are influenced by the gradation/size of the aggregate and the aggregate particle shape/angularity.

VMA is the measure of the volume of void space between aggregate particles in compacted HMA, also expressed as a percentage of total mix volume. It is the sum of the volume of air voids and the effective (i.e., unabsorbed) asphalt binder content (P_{be}). VMA is a function of V_a, P_b, aggregate gradation/size, aggregate particle shape/angularity, and aggregate absorption characteristics.

Because V_a and VMA are highly interrelated with P_b and the characteristics of the aggregate, it is impossible to establish any meaningful independent relationship between production cost and quality level for each of these parameters. With inadequate time and resources available to evaluate and develop an interdependent cost–quality relationship covering P_b, V_a, and VMA, it was determined that only very crude estimates of default relative costs could be developed for V_a and VMA. Such estimates can be derived from the default relative costs developed previously for P_b (i.e., 6 percent change in relative cost per 1 percentage point change in asphalt content).

While contractors/producers can vary aggregate types, gradations, and particle shapes to help achieve certain percentages of air and VMA, binder content is the primary means in effecting changes in these parameters. For simplistic purposes, a 2 percentage point change in air voids corresponding to a 1 percentage point change in P_b was assumed. Linking this with the incremental change of 6 percent change in relative cost for a 1 percentage point change in asphalt content, an estimate of 3 percent change in relative cost for a 1 percentage point change in V_a was derived. Table 10 illustrates this cost–quality relationship for a typical range of V_a.

Table 10. Relative cost of HMA as function of V_a.

Air Voids (V_a), %	**Relative Cost of Attaining Quality Level, %**
2.0	+6.0
2.5	+4.5
3.0	+3.0
3.5	+1.5
4.0 (typical JMF target)	0
4.5	−1.5
5.0	−3.0
5.5	−4.5
6.0	−6.0

While the relationship between VMA and P_b is a little more involved than the relationship between V_a and P_b, the assumption was made that a 3 percentage point change in VMA corresponds with a 1 percentage point change in P_b. Linking this again with the incremental change of 6 percent change in relative cost for a 1 percentage point change in asphalt content, an estimate of 2 percent change in relative cost for a 1 percentage point change in VMA was derived. Table 11 illustrates this cost–quality relationship for a typical range of VMA.

Table 11. Relative cost of HMA as function of VMA.

Voids in the Mineral Aggregate (VMA), %	**Relative Cost of Attaining Quality Level, %**
14.0	−4.0
14.5	−3.0
15.0	−2.0
15.5	−1.0
16.0 (typical JMF target)	0
16.5	+1.0
17.0	+2.0
17.5	+3.0
18.0	+4.0

HMA Mat Density

There are many factors that affect the compactability of HMA mixes and, subsequently, the cost of achieving a certain level of density. Key factors include the properties of the mix, type and density of the underlying base course material, thickness of the asphalt layer being compacted, environmental conditions at the time of placement, and the type and number of rollers and associated rolling patterns.

In the absence of detailed information concerning these factors, a general relationship between relative cost and each of three density measures has been developed. The relationship assumes a compaction level of 84 percent of Rice theoretical maximum density (TMD) can be achieved post-screed without rolling. An arbitrary cost value of 90 percent of the HMA unit price was assigned at this level. At 92 percent TMD, which can be readily achieved with the typical roller regime and patterns, the full cost (100 percent) of the HMA unit price was assigned. And, at the highest possible compaction level (100 percent TMD), an arbitrary cost value of 110 percent of the HMA unit price was assigned. Thus, for Prob.O.Prof 2.0 default costs, a rate of 1.25 percent change in relative cost per 1 percentage point change in TMD was utilized.

HMA and PCC Pavement Smoothness

It is generally believed that most asphalt paving is done at an IRI level of 60 to 80 in/mi and concrete paving at an IRI level of 75 to 100 in/mi. As seen in table 12, these levels are fairly well supported by the full-pay (100 percent) smoothness levels given in the suite of specifications made part of the new Prob.O.Prof. The equivalent IRI full-pay levels shown in this table were computed using established pavement smoothness index relationships from a recent FHWA study (Smith et al, 2002).

Table 12. Full-pay smoothness levels for new Prob.O.Prof 2.0 specification suite.

SPECIFICATION	FULL-PAY SMOOTHNESS LEVELS				EQUIVALENT IRI, IN/MI
	IRI, in/mi	$PI_{0.0}$, in/mi	$PI_{0.1}$, in/mi	$PI_{0.2}$, in/mi	
1993 AASHTO PCC				5.1 to 7.0	90.4 to 95.9
2008 AASHTO PCC and HMA				4.1 to 7.0	87.7 to 95.9
Arizona PCC				7.0	95.9
Iowa PCC				3.1 to 7.0	84.9 to 95.9
Wisconsin PCC		25.3 to 44.3			82.1 to 123.9
Alabama Superpave HMA		10.0 to 20.0			41.7 to 67.5
Missouri SMA		15.0 to 20.0			54.6 to 67.5

Based on this information, IRI levels of 70 in/mi for HMA and 87.5 in/mi for PCC were chosen to serve as the reference value for default relative costs. Using the same established smoothness index relationships in determining equivalent IRI values, the following reference values for the other smoothness index parameters were computed:

- HMA: IRI=70.0 in/mi, $PI_{0.2}$=3.5 in/mi, $PI_{0.1}$=9.5 in/mi, $PI_{0.0}$=21.0 in/mi
- PCC: IRI=87.5 in/mi, $PI_{0.2}$=4.0 in/mi, $PI_{0.1}$=12.5 in/mi, $PI_{0.0}$=28.0 in/mi

It should be noted that, although the $PI_{0.2}$ reference level of 4.0 in/mi for PCC is considerably lower than the 7.0 in/mi used in the original Prob.O.Prof, PCC paving technologies have improved substantially in recent years, allowing contractors to readily attain this level.

To develop relative contractor costs for levels smoother and rougher than the reference levels established above, a linear cost trend similar to the one in the current Prob.O.Prof was applied. The current Prob.O.Prof cost trend is shown below and essentially entails a 1 percent change in relative cost for every 2.0 in/mi change in $PI_{0.2}$.

SMOOTHNESS/$PI_{0.2}$, IN/MI	**RELATIVE CONTRACTOR COST, %**
3.0	+2.0
5.0	+1.0
7.0	0.0
9.0	−1.0
11.0	−2.0

For the enhanced Prob.O.Prof, a trend of 1 percent change in relative cost for every 5.0 in/mi change in IRI was used. The corresponding equivalent $PI_{0.0}$, $PI_{0.1}$, and $PI_{0.2}$ values were then determined, such that the array of relative cost values listed in tables 13 and 14 now serve as the default costs for smoothness in the new program.

Table 13. Default relative contractor costs for HMA smoothness.

% RELATIVE CONTRACTOR COST	**IRI, IN/MI**	**$PI_{0.0}$, IN/MI**	**$PI_{0.1}$, IN/MI**	**$PI_{0.2}$, IN/MI**
+5	45.0	11.3	1.1	—
+4	50.0	13.2	2.8	—
+3	55.0	15.1	4.5	—
+2	60.0	17.1	6.2	0.8
+1	65.0	19.0	7.9	2.1
0	70.0	21.0	9.5	3.5
−1	75.0	22.9	11.3	4.8
−2	80.0	24.8	13.1	6.1
−3	85.0	26.8	14.8	7.4
−4	90.0	28.7	16.5	8.7
−5	95.0	30.6	18.2	10.0

%Cost = 14.00 – 0.20×IRI
%Cost = 10.84 – 0.517×$PI_{0.0}$
%Cost = 5.63 – 0.58×$PI_{0.1}$
%Cost = 2.63 – 0.76× $PI_{0.2}$

Table 14. Default relative contractor costs for PCC smoothness.

% RELATIVE CONTRACTOR COST	IRI, IN/MI	$PI_{0.0}$, IN/MI	$PI_{0.1}$, IN/MI	$PI_{0.2}$, IN/MI
+5	62.5	16.4	1.2	—
+4	67.5	18.7	3.5	—
+3	72.5	20.9	5.7	—
+2	77.5	23.2	8.0	0.3
+1	82.5	25.5	10.2	2.1
0	87.5	27.5	12.5	4.0
−1	92.5	30.0	14.7	5.8
−2	97.5	32.3	16.9	7.6
−3	102.5	34.6	19.1	9.4
−4	107.5	36.8	21.4	11.2
−5	112.5	39.1	23.6	13.1

$\%Cost = 17.50 - 0.20 \times IRI$
$\%Cost = 12.22 - 0.44 \times PI_{0.0}$
$\%Cost = 5.55 - 0.45 \times PI_{0.1}$
$\%Cost = 2.16 - 0.55 \times PI_{0.2}$

Target Values and Increments

For each AQC, analysis at the agency design level will always be performed. In addition, the user has been given the flexibility of specifying between one and six additional target levels, thus making the total number of possible target levels for analysis between two and seven. As in the current Prob.O.Prof program, the user can enter increment/decrement values relative to the design level or can manually enter all target levels. For instance, in the case of Iowa DOT's PCC smoothness specification, which has a full-pay $PI_{0.2}$ range of 3.1 to 7.0 in/mi, a design value of $PI_{0.2}$ = 5.0 in/mi might be specified, along with four additional target levels given in 1.0-in/mi increments/decrements. The resulting set of target levels for analysis would be 3.0, 4.0, 5.0 (design), 6.0, and 7.0 in/mi.

Standard Deviation and Sample Sizes

The Prob.O.Prof user is prompted to provide specific details for each AQC depending on the quality measure chosen. One such detail is the standard deviation. The standard deviation entered is the population standard deviation and corresponds to one sample unit per sublot. This value can be obtained through historical data collected by the contractor or agency. Only one value is simulated per sublot, irrespective of the number of individual specimens per sublot. Thus, if the mean values of two or more replicate specimens are used to represent an AQC for an individual sublot, the standard deviation entered is that of these mean values and not of the specimen values. For example, if Agency A requires the mean value of two samples to be the representative value for a sublot (e.g. mean value of inner and outer wheelpath smoothness measurements, replicate strength or thickness measurements within a sublot, replicate asphalt content or density measurements within a sublot), then the standard deviation used is that of the historical mean values and not the historical individual values.

For each AQC requiring the computation of standard deviation, the user is allowed to enter the sample size or number of sublots per Lot (3 to 50). Because composite pay combines various AQCs, the overall Lot size should be consistent between the various AQCs and the Lot sizes for all AQCs should be normalized to have the same sizes. This is especially important when considering smoothness as an AQC, and the payment is based on individual profile measurements over a fixed distance (e.g., 0.1 mi). More details are provided in the User's Guide portion of this document.

Probabilistic Simulation Parameters

Levels of Confidence

In Prob.O.Prof 2.0, the level of confidence is defined as the probability that a certain amount of pay or profit will be achieved based on the level of quality targeted. For example, for a 75 percent confidence level, it could be stated that there is a 75 percent probability of achieving a pay amount of at least 2 percent (i.e., a minimum bonus of 2 percent).

Like the original program, Prob.O.Prof 2.0 was developed to allow the user to evaluate pay and profit at four specified levels of confidence. However, unlike the original program which uses set levels of 25, 50, 75, and 95 percent, the new program allows users to define their own desired levels. Default values of 50, 75, 90, and 95 percent are provided.

Confidence Intervals Around Median Profit

Another added feature of the program relating to simulation is the inclusion of confidence intervals around the median profit. This feature allows the user to specify four confidence intervals (typically, values of 90 percent or higher are used) for examining the probabilities of profit falling within a certain range about the median profit value. For instance, for a given targeted level of quality, if median profit is determined to be 3.5 percent and the 90 percent confidence interval shows a profit range of 0.5 to 6.0, then the user could be 90 percent confident that the targeted level of quality would result with a profit between 0.5 and 6.0 percent.

Minimum Profit Goal

The Prob.O.Prof 2.0 program has also been developed to include a minimum profit goal. With this feature, the user can specify a certain profit goal that will be used to highlight profits obtained through the simulation that meet or exceed the specified goal. The highlighted values will bring to the attention of the user the various AQC combinations in which the goal was met.

EXECUTION/COMPUTATION

The Monte Carlo sampling procedure was chosen for use as the probabilistic simulation tool in the new Prob.O.Prof 2.0. This procedure uses random numbers to sample from the pre-defined probability distributions of the AQCs included in the analysis. A description and illustration of the procedure was provided in the FHWA's *Interim Technical Bulletin on Life-Cycle Cost Analysis* (Walls and Smith, 1998) and is repeated below.

> *As shown in figure 6, a series of random numbers between 0 and 1 are generated by the computer along the cumulative probability scale of the input distribution. Values corresponding to each random number are sampled along the x-scale. For the example shown, when the computer generates the random number 0.65 in figure 4.8, a corresponding value of* $X_{.65}$ *is sampled. The sampled value is then combined with other distribution samples to compute a single result. It is important to note that the computer uses a uniform distribution to generate the random numbers and all values along the cumulative scale of the y-axis have equal probability of being selected. Therefore, x-axis values corresponding to portions of the distribution curve where the slope is steeper (more vertical) have a greater likelihood of being sampled compared to x-axis values that correspond to portions of the curve with flatter slopes.*

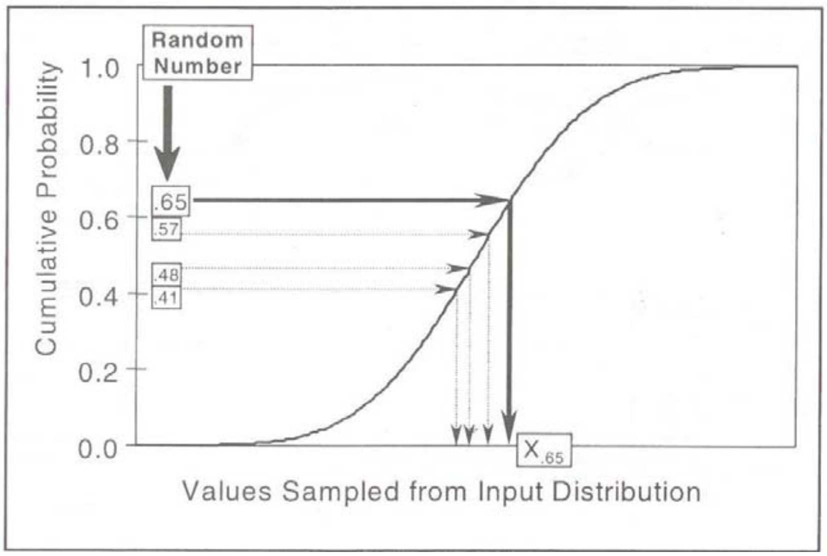

Figure 6. Monte Carlo sampling procedure (figure 4.8 in Walls and Smith, 1998).

As an example of how the simulation process works, consider the following analysis of three AQCs using the *AASHTO Guide Specification for PCC Pavements*:

- PCC Thickness Design/Target Value: 10.0 in.
- PCC LSL: 9.8 in.
- PCC Thickness Standard Deviation: 0.3 in.
- Samples per Lot: 5.
- Target Values for Simulation: 9.50 in, 9.75 in, 10.00 in, 10.25 in, and 10.50 in.

- PCC Compressive Strength Design/Target Value: 4,500 lb/in^2.
- PCC Compressive Strength LSL: 3,800 lb/in^2.
- PCC Compressive Strength Standard Deviation: 600 lb/in^2.

- Samples per Lot: 5.
- Target Values for Simulation: 4,000 lb/in^2, 4,250 lb/in^2, 4,500 lb/in^2, 4,750 lb/in^2, and 5,000 lb/in^2.

- PCC $PI_{0.2}$ Design/Target Value: 7.0 in/mi.
- PCC $PI_{0.2}$ Standard Deviation: 1.0 in/mi.
- Total number of sublots: 5.
- Target Values for Simulation: 5 in/mi, 6 in/mi, 7 in/mi, 8 in/mi, and 9 in/mi.

In this example, there are 5^3 or 125 target value combinations, as illustrated in table 15. For each target value combination, the user-specified number of simulations is performed. Each simulation consists of the following sequence of steps:

1. Based on the thickness target value (9.5 in for AQC target value combination #1) and standard deviation (0.3 in), and assuming a normal distribution, generate five random samples for the Lot.
2. Compute the sample mean and standard deviation for the simulated Lot.
3. Compute QI, PWL, and percent pay for the simulated Lot.
4. Based on the compressive strength target value (4,000 lb/in^2 for AQC target value combination #1) and standard deviation (600 lb/in^2), and assuming a normal distribution, generate five random samples for the Lot.
5. Compute sample mean and standard deviation for the simulated Lot.
6. Compute QI, PWL, and percent pay for the simulated Lot.
7. Based on the smoothness target value (8 in/mi for AQC target value combination #1) and standard deviation (1 in/mi), generate five random sublot values.
8. Compute sample mean and percent pay for the simulated Lot.
9. Combine the individual pay factors into a composite pay factor, based on the user-specified composite pay method (e.g., product, sum, average, weighted average, or minimum) and limited by the maximum pay factor.
10. Compute the contractor's relative cost of producing a pavement having the simulated AQC Lot values.
11. Compute the profit (i.e., net gain/loss) by subtracting the contractor's relative cost from the composite pay factor.

For a user-specified 1,000 simulations, completion of steps 1 through 11 for a given target value combination results in 1,000 simulated profit amounts, which can then be statistically analyzed and interpreted along with the simulated profits from the other 124 target value combinations.

Table 15. Example of AQC target value combinations used in probabilistic simulation.

AQC Target Value Combination	Target PCC Thickness, in	Target PCC Compressive Strength, lb/in^2	Target PCC Smoothness, in/mi
1	9.5	4,000	5
2	9.5	4,000	6
3	9.5	4,000	7
4	9.5	4,000	8
5	9.5	4,000	9
6	9.5	4,250	5
7	9.5	4,250	6
…	…	…	…
…	…	…	…
119	10.5	4,750	8
120	10.5	4,750	9
121	10.5	5,000	5
122	10.5	5,000	6
123	10.5	5,000	7
124	10.5	5,000	8
125	10.5	5,000	9

OUTPUTS

The new Prob.O.Prof 2.0 program has been equipped to display simulation results in both tabular and graphical form. Because a simulation can entail many thousands of computations based on millions of randomly generated input values, only the summary output information needed for interpretation is provided.

For a given AQC target value combination, the simulated pay factors and profit amounts are sorted to obtain the pay factors and profit amounts for each of the four user-specified confidence levels (or four default levels of 50, 75, 90, and 95 percent). Also computed are the mean (expected) pay factor and profit amount.

An example illustration of the tabular results for multiple AQC target value combinations is given in table 16. In the Prob.O.Prof 2.0 output table, the five target value combinations with the highest-ranked profit amounts have the cells containing those profits shaded, as shown in table 16. Also, all profit amounts equal to or greater than the user-specified minimum profit goal, have the profit values highlighted. In the illustration in table 16, a user-specified goal of 3.5 percent was used, resulting in one profit value (3.75 percent for AQC target value combination #45) being highlighted.

Table 16. Example of tabular display of probabilistic simulation results.

AQC Target Value Comb.	Relative Cost, %	Mean Pay, %	Median Pay, %	Min. Pay, %	Max. Pay, %	Mean Net Gain/Loss, %	Median Net Gain/Loss, %	Pay Factor (%) @				Net Gain/Loss (%) @			
								CL1 =50	CL2 =75	CL3 =90	CL4 =95	CL1 =50	CL2 =75	CL3 =90	CL4 =95
40	0.06	-9.25	-8.66	-26.5	4.91	-9.31	-8.72	-8.67	-13.14	-16.53	-18.54	-8.73	-13.2	-16.59	-18.6
41	-0.49	-10.42	-10.18	-29.85	3.31	-9.93	-9.69	-10.18	-14.11	-17.46	-20.61	-9.69	-13.62	-16.97	-20.12
42	-1.04	-9.85	-9.54	-28.44	2.96	-8.81	-8.5	-9.57	-13.55	-16.97	-19.13	-8.53	-12.51	-15.93	-18.09
43	0.66	3.15	3.5	-8.16	9.6	2.49	2.84	3.5	1.78	-0.55	-2.43	2.84	1.12	-1.21	-3.09
44	0.11	2.79	3.25	-10.21	8.9	2.68	3.14	3.24	1.18	-1.25	-2.83	3.13	1.07	-1.36	-2.94
45	-0.44	2.79	3.31	-10.2	9.55	3.23	3.75	3.31	1.24	-1.24	-2.57	**3.75**	1.68	-0.8	-2.13

CL = Confidence Level.

Probability distributions of profit for each AQC target quality combination can be developed and displayed in Prob.O.Prof 2.0 using the raw simulation data. Figures 7 and 8 provide example illustrations of these distributions using target value combination #42 in the table above. Figure 7, which gives the probability distribution in histogram form, shows that the simulated profit amounts range from −30 to +5 percent. It also shows that the −10 to −5 percent profit range has the greatest likelihood of occurring, and that there is a low probability of achieving a positive profit for this targeted combination.

Figure 8 shows the cumulative form of the probability distribution for the same target value combination. As can be seen, there is about a 5 percent probability that the contractor will achieve a positive profit if it targets the quality levels associated with target value combination #42. It also shows that the contractor has a 50 percent chance of achieving a profit greater than −8.53 percent. This corresponds to the value given for this combination in column 13 of table 29.

Further descriptions and illustrations of the outputs are provided in the Prof.O.Prof 2.0 User's Manual contained in appendix C of this report. This includes discussion of single-Lot versus multiple-Lot simulation analysis.

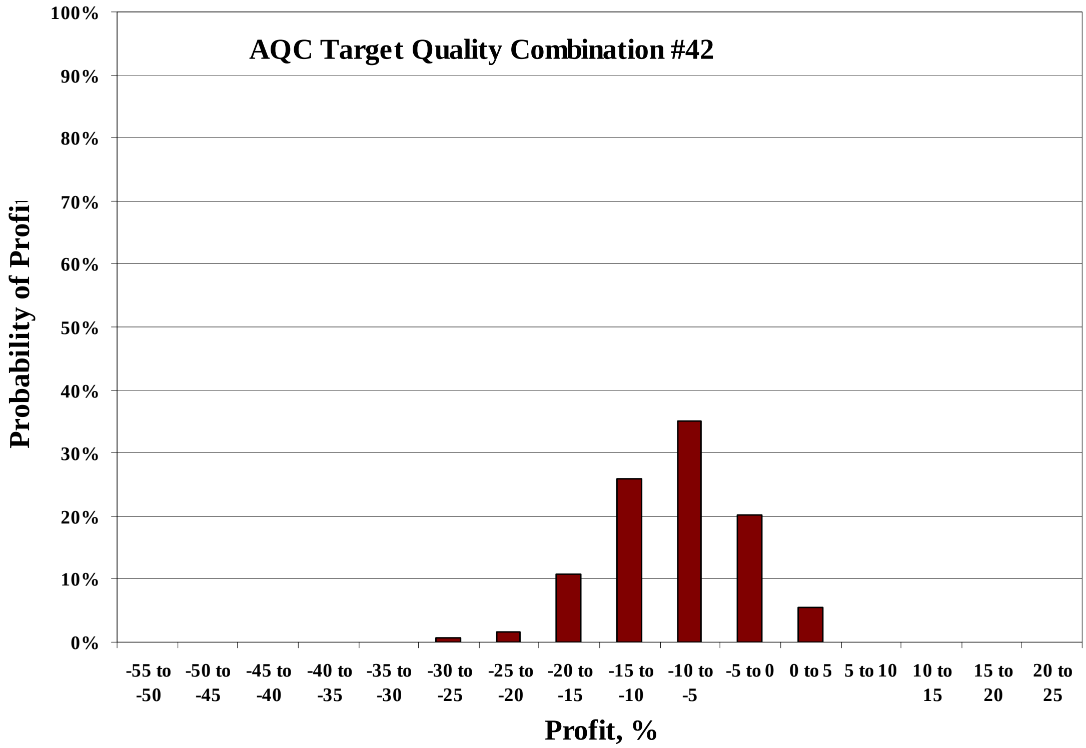

Figure 7. Example probability distribution resulting from probabilistic simulation.

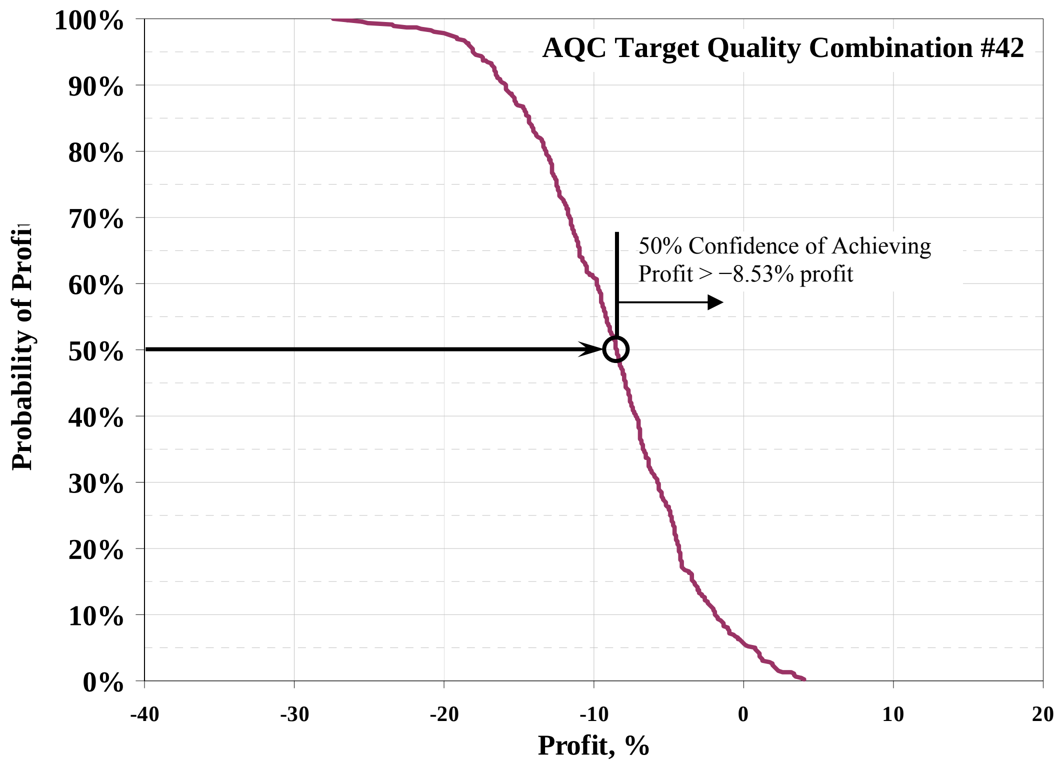

Figure 8. Example cumulative probability distribution resulting from probabilistic simulation.

CHAPTER 5. SUMMARY AND RECOMMENDATIONS

SUMMARY

Contractors constantly have to make decisions regarding how to maximize profit and minimize risk on paving projects. With more and more States adopting incentive/disincentive pay adjustment provisions for quality, as measured by various AQCs, a contractor likely has to evaluate several options before selecting an optimum target quality that accomplishes this goal. The greater the number of AQCs, the more complex the assessment the contractor is required to perform, and the less intuition and experience can be relied upon.

On the client side of the aisle, highway agencies also need to evaluate their specifications to determine the appropriateness of the process and criteria, and to ensure that the specifications do not have any undesirable consequences. If, for example, an agency learns that there is an economic benefit for contractors to construct pavements at substandard quality levels because of inadequate disincentives, then the agency may need to adjust the specification pay schedule accordingly.

Prob.O.Prof 2.0 is a newly developed software tool that can be used by contractors and agencies alike to make keen business decisions regarding pavement quality. This probabilistic, Microsoft Excel®-based program is an enhancement of the original Prob.O.Prof program, developed as part of a Ph.D. dissertation at the University of Florida (Vidalis et al., 2006). It entails a major expansion of the original program through the incorporation of three additional state DOT PCC pavement specifications and the introduction of four state DOT HMA pavement specifications. As a result of this expansion, other forms of quality measures besides PWL, such as AAD, averages, and average minus standard deviation, can be evaluated, along with other AQCs and pay factor schedules.

The new Prob.O.Prof 2.0 is more user-friendly with regard to both the establishment of inputs and the selection and display of outputs. Probabilistic simulation techniques are used to evaluate pay factor and profit amounts for specific target quality combinations. Graphical simulated probability distributions are available along with tabular displays of the results to assist the user (whether with a contractor or the highway agency) in interpreting the results.

This report described all aspects of the development of the new Prob.O.Prof 2.0 program. It also includes a User's Manual (appendix B) that details the use of the program and presents the results of limited sensitivity testing of the program.

RECOMMENDATIONS

The development of Prob.O.Prof 2.0 represents a significant advancement in the area of highway pavement QA specifications. Through the expansion and improvement of the original program—multiple HMA and PCC specifications are now included, featuring additional AQCs, quality measures, and pay schedules—contractors and highway agencies now have greater opportunities to examine the impacts of selected specifications on targeted levels of pavement quality. If seized upon, these opportunities should lead to a better overall understanding of the optimal quality levels in the interests of both parties.

Despite the great strides made to the program in this study, there is much more that can and needs to be done in the future. Listed below are some of the key recommendations for further improvement and enhancement of the Prob.O.Prof program.

- Inclusion of many more States' specifications, so that the market for potential users is broadened.
- Inclusion of HMA specifications that include aggregate gradation as an AQC. Although an attempt was made in this study to incorporate one such specification, the complexity associated with modeling the quality measure of this AQC was too great.
- Improved default relative costs, particularly for HMA volumetric parameters that are inter-related.
- Improved modeling of the cost consequences of non-conformance of some AQCs (e.g., PCC air content).
- Improved modeling of special provisions and/or exceptions in various States' specifications.
- More stable programming environment, such as C++ for a stand-alone application not connected to MS Excel®.
- Improved ability to edit States' specifications for modeling if/then scenarios.

APPENDIX A. TERMINOLOGY

HIGHWAY QUALITY ASSURANCE TERMS

The Transportation Research Board (TRB) released a circular (TRB, 2005) containing a glossary of highway QA terms. This document was developed to provide a uniform understanding of technical terms that have specific meanings in the highway engineering field. Definitions for these terms are cited below, to introduce and clearly distinguish among them.

- ***QA****—All those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service. QA addresses the overall problem of obtaining the quality of a service, product, or facility in the most efficient, economical, and satisfactory manner possible. Within this broad context, QA involves continued evaluation of the activities of planning, design, development of plans and specifications, advertising and awarding of contracts, construction, and maintenance, and the interactions of these activities.*

  In summary, QA is a process to ensure that the quality of the finished product meets specifications. It is the responsibility of the highway agency and is comprised of QC, inspection and acceptance, and IA.

- ***QC****—Also called process control, QC includes those QA actions and considerations necessary to assess and adjust production and construction processes so as to control the level of quality being produced in the end product.*

  QC is motivated by QA and acceptance procedures, and typically is the responsibility of the contractor and/or producer.

- ***Inspection*** *—The act of examining, measuring, or testing to determine the degree of compliance with requirements.*

- ***Acceptance****—The process of deciding, through inspection, whether to accept or reject a product, including what pay factor to apply. Where contractor test results are used in the agency's acceptance decision, the acceptance process includes contractor testing, agency verification, and possible dispute resolution.*

- ***IA****—A management tool that requires a third party, not directly responsible for process control or acceptance, to provide an independent assessment of the product or the reliability of test results, or both, obtained from process control and acceptance. The results of IA tests are not to be used as a basis of product acceptance.*

ABBREVIATIONS AND ACRONYMS

Many different abbreviations and acronyms are used in pavement specifications. A complete listing of the ones contained throughout this report (including the appendixes) is provided below.

a=Variable Factor for Sample Size
AAD=Average Absolute Deviation
CAA=Coarse Aggregate Angularity
CDS=Class Design Strength
Cp=Contract Price per Lot
CPF=Composite Pay Factor
CUP=Contract Unit Price
ESAL=Equivalent Single Axle Load
f=Pay Adjustment Factor
FAA=Fine Aggregate Angularity
f_I=Weighting Factor
G_{mb}=Bulk Specific Gravity (mix) (Marshall)
G_{mm}=Theoretical Maximum Specific Gravity of HMA mix (Rice)
G_{sb}=Bulk Specific Gravity (aggregate)
IRI=International Roughness Index
JMF=Job Mix Formula
JMF_{Targ}=JMF Target Value for a given Property
LOT=Lot size
L_p=Lot Payment
LSL=Lower Spec Limit
L_{TOT}=Total length tested
MRN=Mays Ride Number
N_{Des}=Design No. of Gyrations (SHRP Compactor)
N_{Init}=Initial No. of Gyrations (SHRP Compactor) (early densification indicator)
N_{Max}=Max No. of Gyrations (SHRP Compactor) (long-term densification indicator)
P_b=Asphalt Content
P_{be}=Effective Asphalt Content
PD_L=Lower Percent Defective
PD=Total Percent Defective
PD_U=Upper Percent Defective
PF=Pay Factor
$PI_{0.0}$=Profile Index, zero blanking band
$PI_{0.1}$=Profile Index, 0.1-in blanking band
$PI_{0.2}$=Profile Index, 0.2-in blanking band
PPA=Percent Pay Adjustment
PR=Pay Reduction
PWL_L=Lower Percent Within Limits
PWL=Total Percent Within Limits
PWL_U=Upper Percent Within Limits
QI (or Q)=Quality Index
QL=Quality Index for Lower Spec Limit

QU=Quality Index for Upper Spec Limit
RQI=Ride Quality Index
T (or D)=Thickness
TI=Thickness Index
TMD = Theoretical Maximum Density of HMA mix
TPF=Total Pay Factor
TSR=Tensile Strength Ratio
USL=Upper Spec Limit
V_a or VTM=Air Voids or Voids in Total Mix
VFA (or VFB)=Voids Filled with Asphalt (or with Binder)
VMA=Voids in Mineral Aggregate
WPF=Weighted Pay Factor

APPENDIX B. STATE AGENCY PAVEMENT SPECIFICATIONS

Table 17. Summary of HMA pavement specifications from Alabama.

SPECIFICATION	FEATURE	AL (MARSHALL & SMA MIXES) ('06 STD SPECS)	AL (SUPERPAVE MIXES) ('06 STD SPECS & '06 SUPP SPECS)
Contractor QC	**QC Quality Characteristics**	Marshall Mixes FAA, CAA, Gradation, P_b, VTM, VMA, Dust to Asphalt Ratio, Marshall Stability & Flow, TSR, Mat Density (%TMD via mix and core samples and G_{mm} and G_{mb} determination) SMA Mixes Gradation, P_b, G_{mm}, VTM, VMA, TSR, Mat Density (%TMD via mix and core samples and G_{mm} and G_{mb} determination)	FAA, Gradation, P_b, G_{mm}, VTM, VMA, $\%G_{mm}{}^{@}N_{Des}$, Dust to Asphalt Ratio, TSR, Mat Density (%TMD via mix and core samples and G_{mm} and G_{mb} determination)
Agency QA	**Type/Nature**	Observation of Contractor QC, Verification Testing	Observation of Contractor QC, Verification Testing
	Sampling & Testing Procedure	Lot (mix properties)=2,800 tons of mix, with four equal sublots/Lot (1 sublot=700 tons of mix) Sublot (mat density)~12,000 lane-ft, with 1 density test/3,000 lane-ft	Lot (mix properties)=2,800 tons of mix, with four equal sublots/Lot (1 sublot=700 tons of mix) Sublot (mat density)~12,000 lane-ft, with 1 density test/3,000 lane-ft
Acceptance	**Basis**	Contractor acceptance test results and Agency verification test results	Contractor acceptance test results and Agency verification test results
	Acceptance Quality Characteristics (AQCs)	P_b (1 test/sublot) VTM (1 test/sublot) Gradation (1 test/sublot) Mat Density (%TMD) (4 cores/sublot) Smoothness/$PI_{0.0}$ (1 test per lane per 0.1-mi section using profile of right wheelpath of right lane or left wheelpath of left lane, as measured with California profilograph)	P_b (1 test/sublot) VTM (1 test/sublot) Gradation (1 test/sublot) Mat Density (%TMD) (4 cores/sublot) Smoothness/$PI_{0.0}$ (1 test per lane per 0.1-mi section using profile of right wheelpath of right lane or left wheelpath of left lane, as measured with California profilograph)
	AQC Measure Types	P_b: AAD $AAD=\sum\lvert Xi-JMF_{Targ}\rvert/n$ VTM: AAD $AAD=\sum\lvert Xi-4.0\rvert/n$ Density(%TMD): AAD & Weighted Avg Smoothness/$PI_{0.0}$: Ind	P_b: AAD $AAD=\sum\lvert Xi-JMF_{Targ}\rvert/n$ VTM: AAD $AAD=\sum\lvert Xi-4.0\rvert/n$ Density(%TMD): AAD & Weighted Avg Smoothness/$PI_{0.0}$: Ind
Basis for Pay	**Pay Adjustment Procedures**	P_b (based on 4 tests/Lot) 0.00≤AAD≤0.14 PF=1.02 0.15≤AAD≤0.24 1.00 0.25≤AAD≤0.26 0.98 0.27≤AAD≤0.28 0.95 0.29≤AAD≤0.33 0.90 AAD>0.33 0.80 and/or remove/replace VTM (based on 4 tests/Lot) 0.00≤AAD≤0.45 PF=1.02 0.46≤AAD≤0.75 1.00 0.76≤AAD≤0.81 0.98 0.82≤AAD≤0.90 0.95 0.91≤AAD≤1.05 0.90 AAD>1.05 0.80 and/or remove/replace Mat Density (%TMD) 0.00≤AAD≤1.00 PF_{Sublot}=1.02 1.01≤AAD≤1.67 1.00 1.68≤AAD≤1.80 0.98 1.81≤AAD≤2.00 0.95 2.01≤AAD≤2.33 0.90 AAD>2.33 0.80 and/or remove/replace $PF_{Lot}=[(PF_{Sublot\ 1}\times L_{Sublot\ 1})+(PF_{Sublot\ 2}\times L_{Sublot\ 2})+\ldots+(PF_{Sublot\ j}\times L_{Sublot\ j})]/(L_{Sublot\ 1}+L_{Sublot\ 2}+\ldots+L_{Sublot\ j})$ Smoothness, in/mi $PI_{0.0}$<10.0 PF=105−($PI_{0.0}$/2) 10.0≤$PI_{0.0}$<20.0 100% 20.0≤$PI_{0.0}$≤50.0 100−($PI_{0.0}$−20)/1.5 $PI_{0.0}$>50 Unacceptable	P_b (based on 4 tests/Lot) 0.00≤AAD≤0.19 PF=1.02 0.20≤AAD≤0.31 1.00 0.32≤AAD≤0.34 0.98 0.35≤AAD≤0.38 0.95 0.39≤AAD≤0.44 0.90 AAD>0.44 0.80 and/or remove/replace VTM (based on 4 tests/Lot) 0.00≤AAD≤0.75 PF=1.02 0.76≤AAD≤1.25 1.00 1.26≤AAD≤1.35 0.98 1.36≤AAD≤1.50 0.95 1.51≤AAD≤1.75 0.90 AAD>1.75 0.80 and/or remove/replace Mat Density (%TMD) 0.00≤AAD≤1.12 PF_{Sublot}=1.02 1.13≤AAD≤1.88 1.00 1.89≤AAD≤2.02 0.98 2.03≤AAD≤2.25 0.95 2.26≤AAD≤2.62 0.90 AAD>2.62 0.80 and/or remove/replace $PF_{Lot}=[(PF_{Sublot\ 1}\times L_{Sublot\ 1})+(PF_{Sublot\ 2}\times L_{Sublot\ 2})+\ldots+(PF_{Sublot\ j}\times L_{Sublot\ j})]/(L_{Sublot\ 1}+L_{Sublot\ 2}+\ldots+L_{Sublot\ j})$ Smoothness, in/mi $PI_{0.0}$<10.0 PF=105−($PI_{0.0}$/2) 10.0≤$PI_{0.0}$<20.0 100% 20.0≤$PI_{0.0}$≤50.0 100−($PI_{0.0}$−20)/1.5 $PI_{0.0}$>50 Unacceptable
	Application of Pay Factors	Lowest Pay Factor for P_b, VTM, and Mat Density Individual for Smoothness/$PI_{0.0}$	Lowest Pay Factor for P_b, VTM, and Mat Density Individual for Smoothness/$PI_{0.0}$

Note: Marshall Mixes used when design ESALs≤10 million. Superpave and SMA mixes used when design ESALs>10 million.

Table 18. Summary of HMA pavement specifications from Arkansas and Maine.

SPECIFICATION	FEATURE	AR (SUPERPAVE MIXES) ('03 STD SPECS)	ME (SUPERPAVE MIXES) ('02 STD SPECS & '07 SUPP SPECS)
Contractor QC	**QC Quality Characteristics**	Gradation, V_a, P_b, VMA, Density (TMD), Mat Density (%TMD via calibrated nuclear density gauge), Stability	FAA, CAA, Flat/Elongated Particles, Gradation, P_b. Rice Specific Gravity, $V_a{}^{@}N_{Des}$, $VMA^{@}N_{Des}$, Fines to Effective Binder Ratio, Mat Density (%TMD via mix and core samples and G_{mm} and G_{mb} determination), Temperature (mix and mat)
Agency QA	**Type/Nature**	Observation of Contractor QC, Verification Testing	Observation of Contractor QC, Acceptance Testing
	Sampling & Testing Procedure	Lot (mix properties & density) = 3,000 tons of mix, with 4 sublots/Lot (sublot=750 tons of mix)	Lot (mix properties & density)≤6,600 tons of mix, with min of 4 sublots/Lot for mix properties (gradation, P_b, $V_a{}^{@}N_{Des}$, $VMA^{@}N_{Des}$, fines to binder ratio, VFB) and 5 sublots/Lot for mat density (%TMD) Mix properties sublot=1,100 tons Density sublot=275 tons (surface), 500 tons (base/binder) Lot (smoothness)=3,000 lane-ft, with sublots=50 lane-ft
Acceptance	**Basis**	Contractor acceptance test results (performed under supervision of Agency) and Agency verification and acceptance test results	Agency acceptance test results
	Acceptance Quality Characteristics (AQCs)	P_b (1 test/sublot by Contractor plus 1 test/Lot by Agency→5 total tests/Lot) V_a (1 test/sublot by Contractor plus 1 test/Lot by Agency→5 total tests/Lot) VMA (1 test/sublot by Contractor plus 1 test/Lot by Agency→5 total tests/Lot) Mat Density (%TMD) (1 nuclear test/sublot by Contractor and 1 nuclear test/Lot by Agency→5 total tests/Lot) Surface Course Smoothness/$PI_{0.1}$ (Contractor's option) (1 test per lane per 0.1-mi section using center-of-lane profile measured by California profilograph or lightweight inertial profiler calibrated to California profilograph)	Gradation (1 test/sublot) P_b (1 test/sublot) V_a (1 test/sublot) $VMA^{@}N_{Des}$ (1 test/sublot) Fines to Eff Binder Ratio (1 test/sublot) VFB (1 test/sublot) Mat Density (%TMD) (5 cores/sublot min) Smoothness/IRI (2 tests per wheelpath per lane as measured by inertial profiler)
	AQC Measure Types	P_b: Avg Compliance Limits=JMF_{Targ} ± 0.3% Reject Limits (Lot): <JMF_{Targ}−0.6% & >JMF_{Targ}+0.6% Reject Limits (sublot): <JMF_{Targ}−0.8% & >JMF_{Targ}+0.8% V_a: Avg Compliance Limits=3.0 to 5.0% Reject Limits (Lot)≤2.4% or ≥5.6% Reject Limits (sublot)≤1.9% or ≥6.1% VMA: Avg Compliance Limits=11.0 to 13.0% (base course) =12.0 to 14.0% (binder course) =13.5 to 16.0% (0.5-in surf course) =14.5 to 17.0% (0.38-in surf course) Reject Limits (Lot)≤10.4% or ≥13.6% (base course) ≤11.4% or ≥14.6% (binder course) ≤12.9% or ≥16.6% (0.5-in surf course) ≤13.9% or ≥17.6% (0.38-in surf course) Reject Limits (sublot)≤9.9% or ≥14.1% (base course) ≤10.9% or ≥15.1% (binder course) ≤12.4% or ≥17.1% (0.5-in surf course) ≤13.4% or ≥18.1% (0.38-in surf course) Mat Density (%TMD): Avg Compliance Limits=92.0 to 96.0% Reject Limits (Lot)≤90.9% or ≥97.1% Reject Limits (sublot)≤89.9% or ≥98.1% Surface Course Smoothness/$PI_{0.1}$: Ind	Gradation: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - z$) (z=2 to 7% depending on sieve size) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + z$) (z=2 to 7% depending on sieve size) Composite PWL_L and PWL_U from statistical table using Q_L and Q_U and n Comp PWL_T = (Comp PWL_L + Comp PWL_U) − 100 Fines to Effective Binder Ratio: PWL $Q_L = (\bar{X}-0.6)/S$ $Q_U = (1.2-\bar{X})/S$ PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ VFB: PWL $Q_U = (80-\bar{X})/S$ (high-volume, 0.19-in top size mix) $Q_U = (76-\bar{X})/S$ (high-volume, 0.38-in top-size mix) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ P_b: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 0.4\%$) $Q_U = (5.5\%-\bar{X})/S$ ($USL=JMF_{Targ} + 0.4\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ V_a: PWL $Q_L = (\bar{X}-2.5\%)/S$ $Q_U = (5.5\%-\bar{X})/S$ PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ $VMA^{@}N_{Des}$: PWL $Q_L = (\bar{X}-LSL)/S$ (LSL=12 to 16%, depending on max agg size) PWL_L from statistical table using Q_L and n PWL_U = 100% $PWL_T = (PWL_L + PWL_U) - 100$ Mat Density (%TMD): PWL $Q_L = (\bar{X}-92.5\%)/S$ (75+ gyration mix) $Q_U = (97.5\%-\bar{X})/S$ (75+ gyration mix)

			PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Smoothness/IRI: PWL $Q_U = (USL-\bar{X})/S$ (USL=79.15 in/mi for interstates and 88.65 in/mi for other highways) PWL_U from statistical table using Q_U and n $PWL_L = 100\%$ $PWL_T = (PWL_L + PWL_U) - 100$

Table 18. Summary of HMA pavement specifications from Arkansas and Maine (continued).

SPECIFICATION	FEATURE	AR (SUPERPAVE MIXES) ('03 STD SPECS)	ME (SUPERPAVE MIXES) ('02 STD SPECS & '07 SUPP SPECS)
Basis for Pay	**Pay Adjustment Procedures**	P_b PR_{AC} (Lot)=12% for each 0.1% deviation outside compliance limits, up to a maximum of three deviations (i.e., 0.3%) V_a PR_{AV} (Lot)=10% for each 0.1% deviation outside compliance limits, up to a maximum of five deviations (i.e., 0.5%) VMA PR_{VMA} (Lot)=10% for each 0.1% deviation outside compliance limits, up to a maximum of five deviations (i.e., 0.5%) Mat Density (%TMD) PR_{Den} (Lot)=4% for each 0.1% deviation outside compliance limits, up to a maximum of ten deviations (i.e., 1.0%) Surface Course Smoothness/$PI_{0.1}$ $PI_{0.1} \leq 3.0$ in/mi to receive incentive	Gradation (used only as basis for shutting down plant [PF<0.85]; no pay adjustment applied) $PF_{Grad} = 0.01\times(55 + 0.5\times PWL_T)$ Fines to Effective Binder Ratio (used only as basis for shutting down plant [PF<0.85]; no pay adjustment applied) $PF_{Fines/Binder} = 0.01\times(55 + 0.5\times PWL_T)$ VFB (used only as basis for shutting down plant [PF<0.85]; no pay adjustment applied) $PF_{VFB} = 0.01\times(55 + 0.5\times PWL_T)$ P_b $PF_{AC} = 0.01\times(55 + 0.5\times PWL_T)$ (If PF_{AC} <0.85, then shut down plant) V_a $PF_{AV} = 0.01\times(55 + 0.5\times PWL_T)$ (If PF_{AV} <0.85, then shut down plant) $VMA^{@}N_{Des}$ $PF_{VMA} = 0.01\times(55 + 0.5\times PWL_T)$ (If PF_{VMA} <0.85, then shut down plant) Mat Density (%TMD) $PF_{\%TMD} = 0.01\times(55 + 0.5\times PWL_T)$ (If $PF_{\%TMD}$<0.80, then additional cores and tests; if $PF_{\%TMD}$ still <0.80, remove and replace) Smoothness/IRI $PF_{IRI} = 0.01\times(55 + 0.5\times PWL_T)$
	Application of Pay Factors	Summation Composite Pay Factor (PR) for P_b, V_a, VMA, and Mat Density (%TMD) If any of the four AQCs fall into reject limits or if PR_{COMP}>50%, then Lot not accepted Incentive payment of 6% applied if: P_b is within ±0.2% of JMF_{Targ}, and Range in V_a is ≤0.6%, with none outside compliance limits, and All densities fall between 92.0 and 96.0%, and No areas of segregation Additional incentive payment of 2% if: All requirements above are met, and VMA are within compliance limits If Contractor elects, additional incentive payment of 1% if: All requirements above are met, and surface course smoothness/$PI_{0.1}$ requirement is met, and No corrective patches needed	Avg or Weighted-Avg Composite Pay Factor for P_b, V_a, $VMA^{@}N_{Des}$, Mat Density (%TMD), and Smoothness/IRI $CPF_{LOT} = ([f_1\times PF_1] + [f_2\times PF_2] + \ldots + [f_j\times PF_j]) / \sum f$

Table 19. Summary of HMA pavement specifications from Maryland and Montana.

SPECIFICATION	FEATURE	MD (SUPERPAVE MIXES) ('01 STD SPECS & '05 PROVISIONS)	MT (MARSHALL MIXES) ('06 SPECS)
Contractor QC	**QC Quality Characteristics**	Gradation, P_b, G_{mm}, G_{mb}, G_{mb}@N_{max}, VTM, VMA, VFA, Dust to Asphalt Ratio, Temperature (mix), Mat Density (%G_{mm} via cores or nuclear density gauge)	Coarse Agg Fractured Particles, Gradation, Mat Density (%Target Marshall via nuclear density tests calibrated to lab densities of extracted cores)
Agency QA	**Type/Nature**	Observation of Contractor QC, Verification Testing	Observation of QC, Acceptance Testing
	Sampling & Testing Procedure	Lot (mix properties) ≈ 6,000 tons of mix, with sublot≤1,000 tons of mix Lot (density)=1 Day's production, with five equal sublots/Lot (sublot≤500 tons of mix)	Lot (mix properties, density)=3,000 tons of mix, with 5 sublots/Lot (sublot=600 tons of mix)
Acceptance	**Basis**	Contractor acceptance test results (performed by Agency-certified technicians) and Agency verification and acceptance test results	Agency acceptance test results
	Acceptance Quality Characteristics (AQCs)	Gradation (1 test/sublot) P_b (1 test/sublot) VTM (1 test/sublot) Mat Density Option A (%G_{mm}) (1 core/sublot by Contractor plus 1 core/sublot by Agency→%G_{mm} results for Lot compared; if statistically similar, Contractor's results used for acceptance; if not, Agency's results used) Mat Density Option B (%G_{mm}) (2 cores/sublot by Agency)	Gradation (1 test/sublot) Coarse Agg Fractured Particles (1 test/sublot) Mat Density (%Target) (1 nuclear density test/sublot)
	AQC Measure Types	Gradation: PWL $Q_L = (\bar{X} - LSL)/S$ ($LSL = JMF_{Targ} - z$) (z=2 to 7% depending on sieve size) $Q_U = (USL - \bar{X})/S$ ($USL = JMF_{Targ} + z$) (z=2 to 7% depending on sieve size) Composite PWL_L and PWL_U from statistical table using Q_L, Q_U and n Comp PWL_T = (Comp PWL_L + Comp PWL_U) − 100 P_b: PWL $Q_L = (\bar{X} - LSL)/S$ ($LSL = JMF_{Targ} - 0.4\%$) $Q_U = (USL - \bar{X})/S$ ($USL = JMF_{Targ} + 0.4\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ VTM: PWL $Q_L = (\bar{X} - LSL)/S$ (LSL=2.3%) $Q_U = (USL - \bar{X})/S$ (USL=4.7%) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Mat Density Options A&B (%G_{mm}): Ind & Avg Full acceptance if both: $91.0 \le \%G_{mm} \le 97.0$ (individual sublots) $92.0 \le \overline{\%G_{mm}} \le 97.0$ (Lot average) Rejection possible if one individual $\%G_{mm} \le 89.0$ and/or $\overline{\%G_{mm}} < 89.0$	Gradation: Avg & Range Determine $\bar{X}$ and Range for each of seven sieve sizes for a given Lot and use in pay reduction (PR) equation shown below Agg Fractured Particles: Avg & Range Determine $\bar{X}$ and Range for a given Lot and use in pay reduction (PR) equation shown below Mat Density (%Target): Avg & Range Determine $\bar{X}$ and Range for a given Lot and use in pay reduction (PR) equation shown below If PR percentage of an individual element (e.g., gradation, fractured particles, asphalt binder penetration, compaction, etc.) is <3 or a negative value, Lot is accepted as being in conformance. If sum of PR values of individual elements is between 3 and 25, Lot may require correction or acceptance at a reduced price. If sum of PR values is > 25, remove and replace.
Basis for Pay	**Pay Adjustment Procedures**	<u>Gradation, P_b, and VTM</u> Compute Composite PWL_{Comp} as: $(52 \times PWL_{AC} + 6 \times PWL_{VTM} + 32 \times PWL_{Grad})/90$ If $PWL_{Comp} < 90\%$, then $PF = 55 + 0.5 \times PWL_{Comp}$ If $PWL_{Comp} \ge 90\%$, then PF=100% <u>Mat Density Options A&B (%G_{mm})</u> $\overline{\%G_{mm}}$ — Ind %G_{mm} — PF_{Den} 94.0 to 97.0 — ≥94.0 — 105% 94.0 to 97.0 — ≥93.0 — 104% 93.0 to 97.0 — ≥93.0 — 103% 93.0 to 97.0 — ≥92.0 — 102% 92.0 to 97.0 — ≥92.0 — 101% 92.0 to 97.0 — ≥91.0 — 100% 91.0 to 97.0 — ≥90.0 — 95% 90.0 to 97.0 — ≥90.0 — 90% 89.0 to 97.0 — ≥89.0 — 85% <89.0 — 88.0 — 75% (or reject) $Pay_{Lot} = CUP \times PF_{Den} \times Tonnage_{Lot}$	<u>Gradation</u> $PR = F \times (LSL + a \times Range - \bar{X})$ or $PR = F \times (\bar{X} + a \times Range - USL)$ F = 1, 3, or 6, depending on sieve LSL and USL = vary depending on sieve a = 0.28 to 0.45, depending on number of samples, n Incentive Pay Factor of 1.05 allowed when aggregate gradation for #4, #40, and #200 sieves is not more than one-half the allowable tolerance from the JMF_{Targ} <u>Coarse Agg Fractured Particles</u> $PR = F \times (LSL + a \times Range - \bar{X})$ F = 2 LSL = 60% for Class D mix a = 0.28 to 0.45, depending on number of samples, n <u>Mat Density (%Target)</u> $PR = F \times (LSL + a \times Range - \bar{X})$ F = 12 LSL = 95% a = 0.28 to 0.45, depending on number of samples, n Incentive Pay Factor of 1.05 allowed when average density of the Lot is between 97 and 98 percent of the target Marshall density and Range is ≤3
	Application of Pay Factors	Weighted-Avg Composite Pay Factor for Gradation, P_b, and VTM Individual for Density (%G_{mm})	Individual for Gradation, Coarse Agg Fractured Particles, and Mat Density (%Target)

Table 20. Summary of HMA pavement specifications from Minnesota.

SPECIFICATION FEATURE		MN (MARSHALL MIXES) ('05 STD SPECS & '06/'07 PROVISIONS)	MN (SUPERPAVE MIXES) ('05 STD SPECS & '06/'07 PROVISIONS)
Contractor QC	**QC Quality Characteristics**	FAA, CAA, Gradation, G_{sb}, G_{mb}, G_{mm}, V_a, P_b, VMA, Moisture, TSR, Mat Density (%G_{mm} via mix and core samples and G_{mm} and G_{mb} determination)	FAA, CAA, Gradation, G_{sb}, G_{mb}, %$G_{mm}{}^{@}N_{init}$, %$G_{mm}{}^{@}N_{max}$, %$G_{mm}{}^{@}N_{des}$, V_a, P_b, VMA, Moisture, TSR, Mat Density (%G_{mm} via mix and core samples and G_{mm} and G_{mb} determination)
Agency QA	**Type/Nature**	Observation of Contractor QC, Verification Testing	Observation of Contractor QC, Verification Testing
	Sampling & Testing Procedure	Lot (density) depends on daily production 300 to 600 tons→1 Lot 601 to 1,000 tons→2 Lots 1,001 to 1,600 tons→3 Lots 1,601 to 3,600 tons→4 Lots 3,601 to 5,000 tons→5 Lots 5,001+ tons→6 Lots	Lot (density) depends on daily production 300 to 600 tons→1 Lot 601 to 1,000 tons→2 Lots 1,001 to 1,600 tons→3 Lots 1,601 to 3,600 tons→4 Lots 3,601 to 5,000 tons→5 Lots 5,001+ tons→6 Lots
Acceptance	**Basis**	Contractor QC test results and Agency verification test results	Contractor QC test results and Agency verification test results
	Acceptance Quality Characteristics (AQCs)	Gradation, VMA, P_b, V_a (number of tests = 1 day's planned production divided by 1000, then rounded up to next whole number) FAA & CAA (1 test/day) Mat Density (%G_{mm}) (3 cores/Lot) Smoothness/IRI (1 test per lane per 0.1-mi section using right wheelpath profile measured by inertial profiler)	Gradation, VMA, P_b, %$G_{mm}{}^{@}N_{des}$ (number of tests = 1 day's planned production divided by 1000, then rounded up to next whole number) FAA & CAA (1 test/day) Mat Density (%G_{mm}) (3 cores/Lot) Smoothness/IRI (1 test per lane per 0.1-mi section using right wheelpath profile measured by inertial profiler)
	AQC Measure Types	Gradation: Ind & Moving Avg Out of JMF Limits FAA & CAA: Ind Out of JMF Limits VMA: Ind & Moving Avg Out of JMF Limits P_b: Ind & Moving Avg Out of JMF Limits V_a: Ind & Moving Avg Out of JMF Limits Mat Density (%G_{mm}): Avg For all courses, min requirement is 92.0% of G_{mm} If Avg > 93.0% → Bonus If Avg < 92.0% → Penalty If Avg < 89.0% → Remove/Replace is possibility, with limits determined through additional cores Thickness: Avg If $(T_{DES} - 0.25) \leq \overline{T} \leq (T_{DES} + 0.25)$ → full acceptance If $(T_{DES} - 0.25) > \overline{T} > (T_{DES} + 0.25)$ → 2 additional cores required and average recalculated (remove/replace possible). Smoothness/IRI: Ind Corrective action may be required for: IRI>65.0 in/mi (3-lift+ paving) IRI>75.0 in/mi (2-lift paving) IRI>85.0 in/mi (1-lift paving)	Gradation: Ind & Moving Avg Out of JMF Limits FAA & CAA: Ind Out of JMF Limits VMA: Ind & Moving Avg Out of JMF Limits P_b: Ind & Moving Avg Out of JMF Limits %$G_{mm}{}^{@}N_{des}$: Ind & Moving Avg Out of JMF Limits Mat Density (%G_{mm}): Avg For wearing courses, min requirement is 92.0% of G_{mm} If Avg > 93.0% → Bonus If Avg < 92.0% → Penalty If Avg < 89.0% → Remove/Replace is possibility, with limits determined through additional cores For nonwearing courses, min requirement is 93.0% of G_{mm} If Avg > 94.0% → Bonus If Avg < 93.0% → Penalty If Avg < 90.0% → Remove/Replace is possibility, with limits determined through additional cores Thickness: Avg If $(T_{DES} - 0.25) \leq \overline{T} \leq (T_{DES} + 0.25)$ → full acceptance If $(T_{DES} - 0.25) > \overline{T} > (T_{DES} + 0.25)$ → 2 additional cores required and average recalculated (remove/replace possible). Smoothness/IRI: Ind Corrective action may be required for: IRI>65.0 in/mi (3-lift+ paving) IRI>75.0 in/mi (2-lift paving) IRI>85.0 in/mi (1-lift paving)

Table 20. Summary of HMA pavement specifications from Minnesota (continued).

SPECIFICATION	FEATURE	MN (MARSHALL MIXES) ('05 STD SPECS & '06/'07 PROVISIONS)	MN (SUPERPAVE MIXES) ('05 STD SPECS & '06/'07 PROVISIONS)
Basis for Pay	**Pay Adjustment Procedures**	Gradation Ind PF=95% Moving Avg 75% FAA & CAA Ind PF=90% VMA Ind PF=85% Moving Avg 75% P_b Ind PF=85% Moving Avg 75% V_a Ind PF=70% Moving Avg 50% Mat Density of all courses, $\%G_{mm}$ $\geq$ 93.6 PF=104% 93.1 to 93.5 102% 92.0 to 93.0 100% 91.0 to 91.9 98% 90.5 to 90.9 95% 90.0 to 90.4 91% 89.5 to 89.9 85% 89.0 to 89.4 70% < 89.0 50% or remove/replace Smoothness/IRI (3-lift+ paving), in/mi < 30.0 PA=+$400 (per 0.1-mi sect) 30.0 to 65.0 $850 − (15×IRI) > 65.0 −$900 Smoothness/IRI (2-lift paving), in/mi < 33.0 PA=+$270 33.0 to 75.0 $600 − (10×IRI) > 75.0 −$675 Smoothness/IRI (1-lift paving), in/mi < 36.0 PA=+$180 36.0 to 85.0 $414 − (6.5×IRI) > 85.0 −$450	Gradation Ind PF=95% Moving Avg 75% FAA & CAA Ind PF=90% VMA Ind PF=85% Moving Avg 75% P_b Ind PF=85% Moving Avg 75% $\%G_{mm}{}^{@}N_{des}$ Ind PF=70% Moving Avg 50% Mat Density of wearing course, $\%G_{mm}$ $\geq$ 93.6 PF=104% 93.1 to 93.5 102% 92.0 to 93.0 100% 91.0 to 91.9 98% 90.5 to 90.9 95% 90.0 to 90.4 91% 89.5 to 89.9 85% 89.0 to 89.4 70% < 89.0 50% or remove/replace Mat Density of nonwearing course, % of G_{mm} $\geq$ 94.6 PF=104% 94.1 to 94.5 102% 93.0 to 94.0 100% 92.0 to 92.9 98% 91.5 to 91.9 95% 91.0 to 91.4 91% 90.5 to 90.9 85% 90.0 to 90.4 70% < 90.0 50% or remove/replace Smoothness/IRI (3-lift+ paving), in/mi < 30.0 PA=+$400 (per 0.1-mi sect) 30.0 to 65.0 $850 − (15×IRI) > 65.0 −$900 Smoothness/IRI (2-lift paving), in/mi < 33.0 PA=+$270 33.0 to 75.0 $600 − (10×IRI) > 75.0 −$675 Smoothness/IRI (1-lift paving), in/mi < 36.0 PA=+$180 36.0 to 85.0 $414 − (6.5×IRI) > 85.0 −$450
	Application of Pay Factors	Lowest Pay Factor for Gradation, VMA, P_b, V_a, FAA and CAA Individual for Mat Density ($\%G_{mm}$) Individual for Smoothness/IRI, except no incentive for smoothness if more than 25% of all density lots fail to meet density requirements	Lowest Pay Factor for Gradation, VMA, P_b, V_a, FAA and CAA Individual for Mat Density ($\%G_{mm}$) Individual for Smoothness/IRI, except no incentive for smoothness if more than 25% of all density lots fail to meet density requirements

Table 21. Summary of HMA pavement specifications from South Carolina and Washington.

SPECIFICATION	FEATURE	SC (MARSHALL MIXES) ('00 STD SPECS & '03 SUPP SPECS)	WA (SUPERPAVE MIXES) ('06 SPECS)
Contractor QC	**QC Quality Characteristics**	Gradation (aggregate stockpile and mixture), G_{mm} (Rice method), Marshall Stability, Lime Rate, Temperature (mix, ambient, and mat), Mat Density (%Target Marshall density via mix and core samples and G_{mm} and G_{mb} determination)	Coarse Agg Fractured Faces & % Fracture, Fine Agg Uncompacted Void Content, Agg Sand Equivalent, Gradation, P_b, V_a, VMA, VFA, Dust to Asphalt Ratio, $\%G_{mm}{}^{@}N_{init}$, $\%G_{mm}{}^{@}N_{max}$, $\%G_{mm}{}^{@}N_{des}$, Temperature, Mat Density ($\%G_{mm}$ via nuclear density tests calibrated to lab densities of extracted cores)
Agency QA	**Type/Nature**	Observation of Contractor QC, Verification Testing	Observation of Contractor QC, Acceptance Testing
	Sampling & Testing Procedure	Lot (mix properties [P_b, V_a, VMA])=1 Day's Production, 3 sublots (500 tons of mix) min per Lot Lot (density)=1 Day's Production	Lot (mix properties)=All material produced using same JMF, with min of three equal sublots ≤ 800 tons of mix Lot (density)=1 Day's Production or 400 tons of mix (whichever is less), with 5 sublots/Lot
Acceptance	**Basis**	Contractor QC test results and Agency verification test results	Agency acceptance test results
	Acceptance Quality Characteristics (AQCs)	P_b (1 test/sublot) V_a (1 test/sublot) VMA (1 test/sublot) Mat Density (%Target) (5 cores/Lot for high-type mixes, 10 nuclear tests/Lot for low-type mixes) Smoothness/MRN (3 tests per lane per 1-mi section using Mays Ride Meter)	Gradation (1 test/sublot) P_b (1 test/sublot) VMA (1 test/sublot) VFA (1 test/sublot) V_a (1 test/sublot) Mat Density ($\%G_{mm}$) (1 nuclear density test/sublot)
	AQC Measure Types	P_b: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 0.36\%$) (surface course) ($LSL=JMF_{Targ} - 0.43\%$) (binder course) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + 0.36\%$) (surface course) ($USL=JMF_{Targ} + 0.43\%$) (binder course) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ V_a: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 1.15\%$) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + 1.15\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ VMA: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 1.15\%$) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + 1.15\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Mat Density (%Target): PWL $Q_L = (\bar{X}-LSL)/S$ (LSL=92.2% for high-type, new construction and interstate proj) (LSL=91.2%) (high-type, other proj) $Q_U = (USL-\bar{X})/S$ (USL=96.0%) (high-type, all proj) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Smoothness/MRN: Avg	Gradation: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - z$) (z=2 to 6% depending on sieve size) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + z$) (z=2 to 6% depending on sieve size) Composite PWL_L and PWL_U from statistical table using Q_L, Q_U, and n Comp PWL_T = (Comp PWL_L + Comp PWL_U) − 100 P_b: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 0.5\%$) $Q_U = (5.5\%-\bar{X})/S$ ($USL=JMF_{Targ} + 0.5\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ VMA: PWL $Q_L = (\bar{X}-LSL)/S$ (LSL=10.5 to 13.5%, depending on max agg size of mix) PWL_L from statistical table using Q_L and n $PWL_U = 100\%$ $PWL_T = (PWL_L + PWL_U) - 100$ VFA: PWL $Q_L = (\bar{X}-LSL)/S$ (LSL=65 or 73% for high-traffic mix and depending on max agg size of mix) $Q_U = (USL-\bar{X})/S$ (USL=75 or 76% for high-traffic mix and depending on max agg size of mix) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ V_a: PWL $Q_L = (\bar{X}-2.5\%)/S$ $Q_U = (5.5\%-\bar{X})/S$ PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Mat Density ($\%G_{mm}$): PWL $Q_L = (\bar{X}-91.0\%)/S$ PWL_L from statistical table using Q_L and n $PWL_U = 100\%$ $PWL_T = (PWL_L + PWL_U) - 100$

Table 21. Summary of HMA pavement specifications from South Carolina and Washington (continued).

SPECIFICATION	FEATURE	SC (MARSHALL MIXES) ('00 STD SPECS & '03 SUPP SPECS)	WA (SUPERPAVE MIXES) ('06 SPECS)
Basis for Pay	**Pay Adjustment Procedures**	P_b, V_a, VMA, & Mat Density (%Target) If PWL_T (one AQC)≤20 Reject If PWL_T (two AQCs)≤40 Reject If PWL_T (three AQCs)≤60 Reject If PWL_T (each AQC)>80 Compute pay factor for each AQC using equation: $PF=55 + 0.5\times PWL_T$ Smoothness/MRN (new const), in/mi < 24 PF=105% 25 to 29 103% 30 to 34 101% 35 to 40 100% 41 to 45 95% 46 to 50 90% 51 to 55 80% ≥ 56 −10% for each 5 in/mi Smoothness/MRN (overlays), in/mi over acceptable limit 1 to 5 PF=95% 6 to 10 90% 11 to 15 85% 16 to 20 80% 21 to 25 75% ≥ 26 Replace	Gradation PF_{Grad} from look-up table using PWL_T and n P_b PF_{AC} from look-up table using PWL_T and n VMA PF_{VMA} from look-up table using PWL_T and n VFA PF_{VFA} from look-up table using PWL_T and n V_a PF_{AV} from look-up table using PWL_T and n Mat Density (%G_{mm}) $PF_{\%Gmm}$ from look-up table using PWL_T and n (If $PF_{\%Gmm}$<1.00, then take cores and perform additional density tests)
	Application of Pay Factors	Weighted-Avg Composite Pay Factor for P_b, V_a, VMA, and Mat Density (%Target) $PF_{LOT} = 0.25\times PF_{Pb} + 0.30\times PF_{Va} + 0.10\times PF_{VMA} + 0.35\times PF_{Den}$ Individual for Smoothness/MRN	Avg or Weighted-Avg Composite Pay Factor for Gradation, P_b, VMA, VFA, V_a, and Mat Density (%G_{mm}) $CPF_{LOT} = ([f_1\times PF_1] + [f_2\times PF_2] + \ldots + [f_j\times PF_j]) / \sum f$

Table 22. Summary of HMA pavement specifications from California and Indiana.

SPECIFICATION	FEATURE	CA (HVEEM MIXES) ('06 STD SPECS & SPECIAL PROVISIONS)	IN (SUPERPAVE DENSE-GRADED MIXES) ('06 STD SPECS)
Contractor QC	**QC Quality Characteristics**	Sand Equivalent, Gradation, P_b, V_a, Mat Density (%TMD via nuclear density tests calibrated to lab densities of extracted cores), Hveem Stability	Gradation, P_b, $VMA^{@}N_{Des}$, $V_a{}^{@}N_{Des}$, Dust to Asphalt Ratio, TSR, Mat Density (%G_{mm} via mix and core samples and G_{mm} and G_{mb} determination)
Agency QA	**Type/Nature**	Observation of Contractor QC, Verification Testing	Acceptance Testing
	Sampling & Testing Procedure	Lot=Single mix design placed without suspended production; 1 sublot≤500 tons of mix, with minimum 5 sublots/Lot	Lot (mix properties and density---surface course)=2,400 tons of mix, with 4 sublots/Lot (1 sublot≤600 tons of mix) Lot (mix properties and density---base/binder course)=4,000 tons of mix, with 4 sublots/Lot (1 sublot≤1,000 tons of mix)
Acceptance	**Basis**	Contractor acceptance test results and Agency verification test results	Agency acceptance test results
	Acceptance Quality Characteristics (AQCs)	Gradation (1 test/sublot) P_b (1 test/sublot) Mat Density (%TMD) Smoothness/$PI_{0.2}$ (1 test per wheelpath per 0.1 lane-km using California profilograph, compute average)	P_b (1 test/sublot) $VMA^{@}N_{Des}$ (1 test/sublot) $V_a{}^{@}N_{Des}$ (1 test/sublot) Moisture (surface course) (1 test/sublot) Mat Density (%G_{mm}) (2 cores/sublot) Smoothness/$PI_{0.0}$ (1 test per right wheelpath per 0.1 lane-mi using California profilograph)
	AQC Measure Types	Gradation: PD $Q_L = (\bar{X} - LSL)/S$ ($LSL = JMF_{Targ} - z$) (z=2 to 7% depending on sieve size) $Q_U = (USL - \bar{X})/S$ ($USL = JMF_{Targ} + z$) (z=2 to 7% depending on sieve size) Comp PD_L and PD_U from statistical table using Q_L, Q_U and n Comp PD_T = (Comp PD_L + Comp PD_U) P_b: PD $Q_L = (\bar{X} - LSL)/S$ ($LSL = JMF_{Targ} - 0.45\%$) $Q_U = (USL - \bar{X})/S$ ($USL = JMF_{Targ} + 0.45\%$) PD_L and PD_U from statistical table using Q_L, Q_U and n $PD_T = (PD_L + PD_U)$ Mat Density (%TMD): PD $Q_L = (\bar{X} - LSL)/S$ (LSL=92%) $Q_U = (USL - \bar{X})/S$ (USL=97%) PD_L and PD_U from statistical table using Q_L, Q_U and n $PD_T = (PD_L + PD_U)$ Smoothness/$PI_{0.2}$: Avg If $PI_{0.2}$>8 mm/km, corrective action	P_b: Ind Sublot value within ($JMF_{Targ} \pm 0.5\%$) $\rightarrow$ full acceptance ($JMF_{Targ} - 1.0\%$)>Sublot value>($JMF_{Targ} + 1.0\%$) $\rightarrow$ failed $VMA^{@}N_{Des}$: Ind Sublot value within ($JMF_{Targ} \pm 1.0\%$) $\rightarrow$ full acceptance ($JMF_{Targ} - 2.5\%$)>Sublot value>($JMF_{Targ} + 2.5\%$) $\rightarrow$ failed $V_a{}^{@}N_{Des}$: Ind Sublot value within ($JMF_{Targ} \pm 1.0\%$) $\rightarrow$ full acceptance ($JMF_{Targ} - 2.0\%$)>Sublot value>($JMF_{Targ} + 2.0\%$) $\rightarrow$ failed Mat Density (%G_{mm}): Ind Sublot value within (94.0% ± 2.0%) $\rightarrow$ full acceptance (89.0%)>Sublot value>(97.0%) $\rightarrow$ failed Smoothness/$PI_{0.0}$: Ind $PI_{0.0}$>28.0, corrective action

Table 22. Summary of HMA pavement specifications from California and Indiana (continued).

SPECIFICATION	FEATURE	CA (HVEEM MIXES) ('06 STD SPECS & SPECIAL PROVISIONS)	IN (SUPERPAVE DENSE-GRADED MIXES) ('06 STD SPECS)
Basis for Pay	**Pay Adjustment Procedures**	Gradation, P_b, & Mat Density (%TMD) PF for Gradation, P_b, and Mat Density from statistical table using PD_T and n If $PF_{LOT} \geq 0.90$, Lot is acceptable provided no individual PF<0.75 If $PF_{LOT} < 0.90$, corrective action	P_b, ±% Deviation from JMF_{Targ} ≤0.2 PF_{Sublot}=1.05 0.3 1.04 0.4 1.02 0.5 1.00 0.6 0.90 0.7 0.80 0.8 0.60 0.9 0.30 1.0 0.00 >1.0 Failed $VMA^{@}N_{Des}$, ±% Deviation from JMF_{Targ} ≤0.5 PF_{Sublot}=1.05 0.6 to 1.0 1.00 1.1 to 1.5 0.90 1.6 to 2.0 0.70 2.1 to 2.5 0.30 >2.5 Failed $V_a{}^{@}N_{Des}$, ±% Deviation from JMF_{Targ} ≤0.5 PF_{Sublot}=1.05 0.6 to 1.0 1.00 1.1 0.98 1.2 0.96 1.3 0.94 1.4 0.92 1.5 0.90 1.6 0.84 1.7 0.78 1.8 0.72 1.9 0.66 2.0 0.60 >2.0 Failed Mat Density, $\%G_{mm}$ ≥97.0 Failed 95.6 to 96.9 PF_{Sublot}=1.05−0.01 for each 0.1% above 95.5 94.0 to 95.5 1.05 93.1 to 93.9 1.00+0.005 for each 0.1% above 93.0 92.0 to 93.0 1.00 91.0 to 91.9 1.00−0.005 for each 0.1% below 92.0 90.0 to 90.9 0.95−0.01 for each 0.1% below 91.0 89.0 to 89.9 0.85−0.03 for each 0.1% below 90.0 <89.9 Failed Smoothness/$PI_{0.0}$, in/mi 0.0 to 8.0 PF=1.06 8.1 to 10.0 1.05 10.1 to 12.0 1.04 12.1 to 14.0 1.03 14.1 to 16.0 1.02 16.1 to 20.0 1.01 20.1 to 24.0 1.00 24.1 to 26.0 0.96 26.1 to 28.0 0.92 >28.0 Corrective Action
	Application of Pay Factors	Weighted-Avg Composite Pay Factor for Gradation, P_b, and Mat Density (%TMD) $PF_{LOT} = (0.30 \times PF_{Grad}) + (0.30 \times PF_{Pb}) + (0.40 \times PF_{Den})$	Weighted-Avg Composite Pay Factor for P_b, $V_a{}^{@}N_{Des}$, $VMA^{@}N_{Des}$, and Mat Density ($\%G_{mm}$) $PF_{Sublot} = (0.20 \times PF_{Pb}) + (0.35 \times PF_{Va}) + (0.10 \times PF_{VMA}) + (0.35 \times PF_{Den})$

Table 23. Summary of HMA pavement specifications from New Mexico.

SPECIFICATION	FEATURE	NM (SUPERPAVE MIXES) ('05 INTERIM STD SPECS)	NM (SMA MIXES) ('05 INTERIM STD SPECS)
Contractor QC	**QC Quality Characteristics**	Gradation, Fractured Faces, FAA, Sand Equivalent, Agg Index, V_a, VMA, VFA, Dust to Asphalt Ratio, Temperature, Mat Density (%TMD via mix and core samples and G_{mm} and G_{mb} determination)	Gradation, P_b, V_a, VMA, Stability, Draindown, TSR, Temperature, Mat Density (%TMD via mix and core samples and G_{mm} and G_{mb} determination)
Agency QA	**Type/Nature**	Observation of Contractor QC, Verification Testing	Observation of Contractor QC, Verification Testing
	Sampling & Testing Procedure	Lot (mix properties and density)=Single mix design, with min 3 sublots/Lot (1 sublot=1,500 tons of mix	Lot (mix properties and density)=Single mix design, with min 3 sublots/Lot (1 sublot=1,500 tons of mix
Acceptance	**Basis**	Contractor acceptance test results and Agency verification test results	Contractor acceptance test results and Agency verification test results
	Acceptance Quality Characteristics (AQCs)	Gradation (1 test/sublot) V_a (1 test/sublot) VMA (1 test/sublot) Dust to Asphalt Ratio (1 test/sublot) Mat Density (%TMD) (3 cores/sublot, 2 by Contractor and 1 by Agency) Smoothness/IRI (1 test per lane per 0.1-mi section using both right and left wheelpath profiles, as measured by inertial profiler)	Gradation (1 test/sublot) P_b (1 test/sublot) V_a (1 test/sublot) Mat Density (%TMD) (3 cores/sublot, 2 by Contractor and 1 by Agency) Smoothness/IRI (1 test per lane per 0.1-mi section using both right and left wheelpath profiles, as measured by inertial profiler)
	AQC Measure Types	Gradation: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - z$) (z=1.4 to 5% depending on sieve size) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + z$) (z=1.4 to 5% depending on sieve size) Comp PWL_L and PWL_U from statistical table using Q_L, Q_U and n Comp PWL_T = (Comp PWL_L + Comp PWL_U) − 100 VMA: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 1.3\%$) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + 1.3\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ V_a: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 1.6\%$) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + 1.6\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Dust to Asphalt Ratio: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 0.3$) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + 0.3$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Mat Density: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=94.5\% - 2.5\% = 92\%$) $Q_U = (USL-\bar{X})/S$ ($USL=94.5\% + 2.5\% = 97\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Smoothness/IRI: Avg IRI>67.3 in/mi (Interstate new construction) or IRI>72.8 in/mi (Interstate overlays)→Corrective Action	Gradation: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - z$) (z=2 to 4% depending on sieve size) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + z$) (z=2 to 4% depending on sieve size) Comp PWL_L and PWL_U from statistical table using Q_L, Q_U and n Comp PWL_T = (Comp PWL_L + Comp PWL_U) − 100 P_b: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 0.3\%$) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + 0.3\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ V_a: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=JMF_{Targ} - 1.0\%$) $Q_U = (USL-\bar{X})/S$ ($USL=JMF_{Targ} + 1.0\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Mat Density: PWL $Q_L = (\bar{X}-LSL)/S$ ($LSL=95.0\% - 3.0\% = 92\%$) $Q_U = (USL-\bar{X})/S$ ($USL=95.0\% + 3.0\% = 98\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Smoothness/IRI: Avg IRI>67.3 in/mi (Interstate new construction) or IRI>72.8 in/mi (Interstate overlays)→Corrective Action

Table 23. Summary of HMA pavement specifications from New Mexico (continued).

SPECIFICATION	FEATURE	NM (SUPERPAVE MIXES) ('05 INTERIM STD SPECS)	NM (SMA MIXES) ('05 INTERIM STD SPECS)
Basis for Pay	**Pay Adjustment Procedures**	Gradation, V_a, VMA, Dust to Asphalt Ratio, & Mat Density (%TMD) PF for Gradation, V_a, VMA, Dust to Asphalt Ratio, and Mat Density from statistical table using PWL_T and n If Comp PF≥0.75 and no individual PF<0.75, Lot is acceptable at adjusted price; otherwise remove/replace or accept at reduced price of 50% Smoothness/IRI, in/mi Int New Const — Int Overlays — PF <57.7 — <63.6 — 110% 57.7 to 58.1 — 63.6 to 64.0 — 109% 58.2 to 58.6 — 64.1 to 64.5 — 108% 58.7 to 59.0 — 64.6 to 64.9 — 107% 59.1 to 59.5 — 65.0 to 65.3 — 106% 59.6 to 60.0 — 65.4 to 65.8 — 105% 60.1 to 60.4 — 65.9 to 66.2 — 104% 60.5 to 60.9 — 66.3 to 66.7 — 103% 61.0 to 61.4 — 66.8 to 67.1 — 102% 61.5 to 61.8 — 67.2 to 67.6 — 101% 61.9 to 62.4 — 67.7 to 68.0 — 100% 62.5 to 62.8 — 68.1 to 68.5 — 99% 62.9 to 63.3 — 68.6 to 69.0 — 98% 63.4 to 63.8 — 69.1 to 69.5 — 97% 63.9 to 64.3 — 69.6 to 69.9 — 96% 64.4 to 64.8 — 70.0 to 70.4 — 95% 64.9 to 65.3 — 70.5 to 70.9 — 94% 65.4 to 65.8 — 71.0 to 71.4 — 93% 65.9 to 66.3 — 71.5 to 71.8 — 92% 66.4 to 66.8 — 71.9 to 72.3 — 91% 66.9 to 67.3 — 72.4 to 72.8 — 90% >67.3 — >72.8 — Corrective Action	Gradation, P_b, V_a, & Mat Density (%TMD) PF for Gradation, P_b, V_a, and Mat Density from statistical table using PWL_T and n If Comp PF≥0.75 and no individual PF<0.75, Lot is acceptable at adjusted price; otherwise remove/replace or accept at reduced price of 50% Smoothness/IRI, in/mi Int New Const — Int Overlays — PF <57.7 — <63.6 — 110% 57.7 to 58.1 — 63.6 to 64.0 — 109% 58.2 to 58.6 — 64.1 to 64.5 — 108% 58.7 to 59.0 — 64.6 to 64.9 — 107% 59.1 to 59.5 — 65.0 to 65.3 — 106% 59.6 to 60.0 — 65.4 to 65.8 — 105% 60.1 to 60.4 — 65.9 to 66.2 — 104% 60.5 to 60.9 — 66.3 to 66.7 — 103% 61.0 to 61.4 — 66.8 to 67.1 — 102% 61.5 to 61.8 — 67.2 to 67.6 — 101% 61.9 to 62.4 — 67.7 to 68.0 — 100% 62.5 to 62.8 — 68.1 to 68.5 — 99% 62.9 to 63.3 — 68.6 to 69.0 — 98% 63.4 to 63.8 — 69.1 to 69.5 — 97% 63.9 to 64.3 — 69.6 to 69.9 — 96% 64.4 to 64.8 — 70.0 to 70.4 — 95% 64.9 to 65.3 — 70.5 to 70.9 — 94% 65.4 to 65.8 — 71.0 to 71.4 — 93% 65.9 to 66.3 — 71.5 to 71.8 — 92% 66.4 to 66.8 — 71.9 to 72.3 — 91% 66.9 to 67.3 — 72.4 to 72.8 — 90% >67.3 — >72.8 — Corrective Action
	Application of Pay Factors	Weighted-Avg Composite Pay Factor for Gradation, V_a, VMA, Dust to Asphalt Ratio, and Mat Density (%TMD) $PF_{LOT} = [(50 \times PF_{Grad}) + (50 \times PF_{Va}) + (40 \times PF_{VMA}) + (10 \times PF_{Dust/Asphalt}) + (50 \times PF_{Den})]/(50+50+40+10+50)$ Individual for Smoothness/IRI	Weighted-Avg Composite Pay Factor for Gradation, P_b, V_a, and Mat Density (%TMD) $PF_{LOT} = [(70 \times PF_{Grad}) + (50 \times PF_{Pb}) + (50 \times PF_{Va}) + (50 \times PF_{Den})]/(70+50+50+50)$ Individual for Smoothness/IRI

Table 24. Summary of HMA pavement specifications from Missouri.

SPECIFICATION	FEATURE	MO SMA ('04 STD SPECS)
Contractor QC	**QC Quality Characteristics**	Gradation, Flat and Elongated Particles, Mix Temperature, P_b, $\%G_{mb}{}^{@}N_{des}$, $V_a{}^{@}N_{des}$, $VMA^{@}N_{des}$, $VFA^{@}N_{des}$, Mat Density, TSR
Agency QA	**Type/Nature**	Observation of Contractor QC, Mix Design Verification, QA Testing
	Sampling & Testing Procedure	Lot (mix properties and density)=4 sublots minimum (1 sublot=1000 tons of mix)
Acceptance	**Basis**	Contractor QC test results and Agency QA test results
	Acceptance Quality Characteristics (AQCs)	Gradation (2 tests/sublot) Mix Temperature (1 test/sublot) TSR (1 test/10,000 tons) P_b (1 test/sublot) G_{mm} (1 test/sublot) $VMA^{@}N_{des}$ (1 test/sublot) (test represented by avg of 2 specimens) $V_a{}^{@}N_{des}$ (1 test/sublot) (test represented by avg of 2 specimens) $VFA^{@}N_{des}$ (1 test/sublot) Mat Density (%TMD) (1 core/sublot) Smoothness/$PI_{0.0}$ (1 test per lane per 0.1-mi section using profile of lane center, as measured with California profilograph)
	AQC Measure Types	P_b: PWL $Q_L = (\bar{X} - LSL)/S$ ($LSL = JMF_{Targ} - 0.3\%$) $Q_U = (USL - \bar{X})/S$ ($USL = JMF_{Targ} + 0.3\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ $VMA^{@}N_{des}$: PWL $Q_L = (\bar{X} - LSL)/S$ ($LSL = 17.0\% - 0.5\% = 16.5\%$) $Q_U = (USL - \bar{X})/S$ ($USL = 17.0\% + 2.0\% = 19.0\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U, and n $PWL_T = (PWL_L + PWL_U) - 100$ $V_a{}^{@}N_{des}$: PWL $Q_L = (\bar{X} - LSL)/S$ ($LSL = 4.0\% - 1.0\% = 3.0\%$) $Q_U = (USL - \bar{X})/S$ ($USL = 4.0\% + 1.0\% = 5.0\%$) PWL_L and PWL_U from statistical table using Q_L, Q_U and n $PWL_T = (PWL_L + PWL_U) - 100$ Mat Density ($\%G_{mm}$): PWL $Q_L = (\bar{X} - LSL)/S$ ($LSL = 94.0\%$) PWL_L from statistical table using Q_L and n $PWL_U = 100\%$ $PWL_T = (PWL_L + PWL_U) - 100$ Smoothness/$PI_{0.0}$: Ind
Basis for Pay	**Pay Adjustment Procedures**	P_b (based on minimum 4 tests/Lot) $PF_{AC} = 0.5 \times PWL_T + 55$ (for $PWL_T \geq 70$) $PF_{AC} = 2.0 \times PWL_T - 50$ (for $PWL_T < 70$) $VMA^{@}N_{des}$ (based on minimum 4 tests/Lot) $PF_{VMA} = 0.5 \times PWL_T + 55$ (for $PWL_T \geq 70$) $PF_{VMA} = 2.0 \times PWL_T - 50$ (for $PWL_T < 70$) $V_a{}^{@}N_{des}$ (based on minimum 4 tests/Lot) $PF_{Va} = 0.5 \times PWL_T + 55$ (for $PWL_T \geq 70$) $PF_{Va} = 2.0 \times PWL_T - 50$ (for $PWL_T < 70$) Mat Density (based on minimum 4 tests/Lot) $PF_{Den} = 0.5 \times PWL_T + 55$ (for $PWL_T \geq 70$) $PF_{Den} = 2.0 \times PWL_T - 50$ (for $PWL_T < 70$) Smoothness, in/mi $PI_{0.0} \leq 10.0$ PF=105% $10.0 < PI_{0.0} \leq 15.0$ 103% $15.0 < PI_{0.0} \leq 25.0$ 100% $PI_{0.0} > 25.0$ Must Correct to $PI_{0.0} \leq 25.0$
	Application of Pay Factors	Avg Composite Pay Factor for P_b, VMA, V_a, and Mat Density: $PF_{LOT} = 0.25 \times PF_{Pb} + 0.25 \times PF_{VMA} + 0.25 \times PF_{Va} + 0.25 \times PF_{Den}$ Individual for Smoothness/$PI_{0.0}$

Table 25. Summary of PCC pavement specifications from Kansas, Illinois, and Iowa.

SPECIFICATION	FEATURE	KS ('90 STD SPECS & '06 PROVISIONS)	IL ('07 STD SPECS)	IA ('06 STD SPECS & PROVISIONS)
Contractor QC	**QC Quality Characteristics**	Air Content, Slump, Unit Weight/Yield, Agg Gradation, Comp Strength, Flex Strength, %Pass #200, Agg Moisture, Temperature, Density (fresh PCC)	Air Content, Slump, Unit Weight/Yield, Agg Gradation, Agg Moisture, Comp or Flex Strength, Temperature	Air Content, Slump, Unit Weight, Agg Gradation, Flex Strength, Water-to-cement ratio, Agg Moisture, Coarseness/Workability Factors
Agency QA	**Type/Nature**	Verification testing of above QC quality characteristics	Split-sample testing and, if deemed necessary, independent sample testing	Verification testing of above QC quality characteristics
	Sampling & Testing Procedure	Lot (thickness, strength) = 1 Day's Production, 5 equal sublots per Lot	Lot (thickness) ≈ 5,000 ft, 10 equal sublots per Lot	Lot (thickness) ≈ 2,000 yd^2, 36 equal segments/sublots per Lot
Acceptance	**Basis**	Contractor QC test results (as verified by Agency)	Contractor's compliance with all contract documents for QC Validation of Contractor's QC test results with Agency's QA tests	Contractor QC test results (as verified by Agency test results)
	Acceptance Quality Characteristics (AQCs)	Smoothness/$PI_{0.0}$ (1 test per wheelpath per 0.1 lane-mi, compute average) Comp Strength (28-day) (1 core/sublot) Thickness (1 core/sublot)	Smoothness/$PI_{0.2}$ (1 test per wheelpath per 0.1 lane-mi, compute average) Thickness (1 core/sublot)	Smoothness/$PI_{0.2}$ (1 test per wheelpath per 0.1 lane-mi, compute average) Thickness (1 core/Lot, with min of 10 cores/project)
	AQC Measure Types	Smoothness/$PI_{0.0}$: Avg Thickness: PWL $Q_{Th} = (\bar{X}-LSL)/S$ ($LSL=T_{DES} - 0.2$ in) PWL_{Th} from statistical table using Q_{Th} and n=5 Comp Strength: PWL $Q_{Str} = (\bar{X}-LSL)/S$ (LSL=3,900 lb/in^2) PWL_{Str} from statistical table using Q_S and n	Smoothness/$PI_{0.2}$: Avg Thickness: PWL $Q_L = (\bar{X}-LSL)/S$ (LSL=98% T_{DES}) PWL from statistical table using Q_L Deficient sublots (deficient T>10%) to be removed/replaced	Smoothness/$PI_{0.2}$: Avg Thickness: Avg−StdDev $TI = (\bar{X}-S)-T_{DES}$ Deficient areas (defined by cores > 1 in deficient) to be removed/replaced
Basis for Pay	**Pay Adjustment Procedures**	<u>Smoothness, in/mi</u> $PI_{0.0} \leq 6.0$ +\$2,400 $6.0<PI_{0.0} \leq 10.0$ +\$2,000 $10.0<PI_{0.0} \leq 15.0$ +\$1,500 $15.0<PI_{0.0} \leq 18.0$ +\$740 $18.0<PI_{0.0} \leq 30.0$ +\$0 $30.0<PI_{0.0} \leq 40.0$ +\$0 (correct to 25) $PI_{0.0}>40.0$ −\$1500 (correct to 25) <u>Thickness</u> Based on PWL_{Th} and computed in combination with Comp Strength pay factor (see equation below) <u>Comp Strength</u> Based on PWL_{Str} and computed in combination with Thickness pay factor (see equation below)	<u>Smoothness/$PI_{0.2}$ (in/mi)</u> $PI_{0.2} \leq 10.0$ 100% $10.0 < PI_{0.2} \leq 11.0$ 98% $11.0 < PI_{0.2} \leq 12.0$ 96% $12.0 < PI_{0.2} \leq 13.0$ 94% $13.0 < PI_{0.2} \leq 14.0$ 92% $14.0 < PI_{0.2} \leq 15.0$ 90% $PI_{0.2} > 15.0$ Corrective Work <u>Thickness</u> $PF_{LOT} = 55 + 0.5 \times PWL$ Total PF (TPF) = Avg of all PF_{LOT} (not to exceed 102%) Pay = TPF[CUP×(TotPavt −DefPvt)]	<u>Smoothness/$PI_{0.2}$ (in/mi)</u> 0.0 to 1.0 +\$650 (per segment) 1.1 to 2.0 +\$550 2.1 to 3.0 +\$450 3.1 to 7.0 +\$0 7.1 to 10.0 −\$300 or Grind to 7.0 >10.1 Grind to 7.0 <u>Thickness Index (TI)</u> > 0.00 103% -0.01 to -0.05 102% -0.06 to -0.10 101% -0.11 to -0.15 100% -0.16 to -0.20 99% -0.21 to -0.25 98% -0.26 to -0.30 97% -0.31 to -0.35 96% -0.36 to -0.40 95% -0.41 to -0.45 94% -0.46 to -0.50 93% -0.51 to -0.55 92% -0.56 to -0.60 91% -0.61 to -0.65 90% -0.66 to -0.70 89% -0.71 to -0.75 88% -0.76 to -0.80 87% -0.81 to -0.85 86% -0.86 to -0.90 85% -0.91 to -0.95 84% -0.96 to -1.00 83% -1.01 to -1.05 82% -1.06 to -1.10 81% <-1.10 80%
	Application of Pay Factors	Individual Pay Factor for Smoothness Product Composite for Thickness and Comp Strength: $P_C=\{[(PWL_{Th}+PWL_{Str})\times 0.60]/200\}-0.54$	Individual Pay Factors for Thickness and Smoothness	Individual Pay Factors for Thickness and Smoothness

Table 26. Summary of PCC pavement specifications from New Jersey, North Carolina, and Oregon.

SPECIFICATION	FEATURE	NJ ('01 STD SPECS, '06 PROVISIONS)	NC ('06 STD SPECS & PROVISIONS)	OR ('06 STD SPECS)
Contractor QC	**QC Quality Characteristics**	Air Content, Slump, Comp Strength, Agg Gradation, Temperature	Agg Gradation, Air Content, Slump, Thickness	Agg Gradation, Slump, Air Content, Water-to-Cement Ratio, Unit Weight/Yield, Temperature, Comp Strength
Agency QA	**Type/Nature**	Observation of contractor QC. Acceptance testing	Observation of contractor QC, Acceptance testing	Verification testing, observation of contractor sampling/testing, and additional sampling/testing
	Sampling & Testing Procedure	Lot (strength, smoothness) = 1 Day's Production Lot (thickness) ≈ 14,300 yd^2, 15 equal sublots per Lot Lot (texture) ≈ 2,000 yd^2	Lot (strength, thickness) = 1,333.3 yd^2 of PCC (1,000 ft of 12-ft wide lane)	Lot = Total PCC produced for each mix design. Sublot = 75 m^3 PCC.
Acceptance	**Basis**	Agency acceptance test results	Agency acceptance test results	Contractor QC test results (as verified by Agency test results) and Agency test results
	Acceptance Quality Characteristics (AQCs)	Slump (5 tests/Lot) Air Content (5 tests/Lot) Comp Strength (28-day) (5 cylinders/Lot) Thickness (15 cores/Lot) Smoothness (Rolling Straightedge--1 test per wheelpath over length of Lot) Texture (20 tests/Lot)	Slump (Eng Discretion) Flex Strength (28-day, 3rd Point Loading) (2 beams/Lot) Thickness (1 core/Lot) Smoothness/$PI_{0.0}$ (3 profiles [2 at 3.5 ft inside the outer wheelpath, 1 at longitudinal joint], compute average) Air Content (Eng Discretion)	Smoothness/$PI_{0.2}$ (1 pass per wheelpath per 0.1-mi segment) Thickness (survey method using 200 lane-ft units) Comp Strength (28-day) (3 cylinders/sublot)
	AQC Measure Types	Slump & Air Content: Ind Individual tests must fall within specified ranges for slump (2±1 in) and air (5±1.5%, 6±1.5%, or 7±1.5%, depending on agg gradation). If not, retest and compute average. If still outside range, either reject or allow changes to mix) Comp Strength: PD $Q_{REJECT} = (\bar{X}-3000)/S$ $Q = (\bar{X}-CDS)/S$ (CDS=3,700 lb/in^2 for Class B PCC) PD from statistical table using Q and n Thickness: Avg If $\bar{T} \geq T_{DES}$ and no more than 2 cores (out of 15) deficient by >0.25 in from T_{DES}, then full acceptance. If $\bar{T} < T_{DES}$ by > 0.5 in, remove/replace. Smoothness: PD $PD = L_{DEF}/L_{TOT} \times 100\%$ Texture: PWL $Q = (\bar{X}-L)/S$ (L=0.125 in) Q ≥ 0.15 (acceptable), Q < 0.15 (retest; if deficient again, must groove)	Flex Strength: Ind (Avg 2 beams) Thickness: Ind and Avg If T deficient by ≤0.2 in from T_{DES}, then full acceptance. If 0.2<T≤1.0 deficient, take 2 additional cores and compute $\bar{T}$; if $\bar{T}$ deficient by ≤0.2 in from T_{DES}, then full acceptance, otherwise pay reduction. If any T >1.0 in deficient, then take additional exploratory cores to establish limits for remove/replace. Smoothness/$PI_{0.0}$: Ind (Avg of 3 profiles	Smoothness/$PI_{0.2}$: Ind If each wheelpath $PI_{0.2} \leq 7$ in/mi, then full acceptance If either or both wheelpath $PI_{0.2} > 7$ in/mi, grind or remove/replace Thickness: Ind If T(unit) ≤ 0.2 in deficient from T_{DES}, then full acceptance. If T(unit) > 1 in deficient from T_{DES}, remove/replace unit Comp Strength (f'_c): PWL $\bar{X}$ (sublot) < 85% of specified f'_c (4,000 lb/in^2), remove/replace $Q(lot)=(\bar{X}-LSL)/S$ (LSL=3,700 lb/in^2) PWL from statistical table using Q and n=3 PF from pay factor table using PWL and n=3
Basis for Pay	**Pay Adjustment Procedures**	Comp Strength For PD<50: PPA = 3.0 − (0.3×PD) For PD≥50: PPA = 26.0 − (0.76×PD) Thickness For $\bar{T} < T_{DES}$ (up to 0.5 in deficient): Pay Reduction = $(300 \times T_{DES} - \bar{T})/T_{DES}$ For > 2 cores deficient by >0.25 in: Pay Reduction = 2% Smoothness (PD[Lot]) 0 to 5.0 — 0% reduction 5.1 to 11.0 — 2% 11.1 to 13.9 — 5% > 13.9 — 16% or remove/replace	Flex Strength (FS), lb/in^2 ≥ 650 — PF=100% 600 to 650 — PF = 100.0−(650−FS) <600 — PF=50% or remove/replace Thickness Deficiency, in 0.00 to 0.20 — 100% 0.21 to 0.30 — 80% 0.31 to 0.40 — 72% 0.41 to 0.50 — 68% 0.51 to 0.75 — 57% 0.76 to 1.00 — 50% Smoothness/$PI_{0.0}$ ≤ 25 in/mi — 100% > 25 in/mi — grind	Smoothness/$PI_{0.2}$ When each wheelpath $PI_{0.2} \leq 7$ in/mi and the average of two wheelpath $PI_{0.2} < 5$ in/mi, compute bonus as: $0.006 \times (5.0-PI_{0.2}) \times$(Quantity) ×(Unit Price) Thickness Deficiency, in 0.0 to 0.20 — 100% 0.21 to 0.30 — 83% 0.31 to 0.40 — 76% 0.41 to 0.50 — 73% 0.51 to 0.75 — 63% 0.76 to 1.00 — 59% Comp Strength PF from pay factor table using PWL and n=3 For PF < 1.0: Payment = 0.3×(PF−1)×CUP
	Application of Pay Factors	Individual for Comp Strength, Thickness, and Smoothness	Individual for Smoothness Product Composite for Thickness & Flex Strength	Individual for Smoothness, Thickness, and Comp Strength

Table 27. Summary of PCC pavement specifications from Pennsylvania, Texas, and Wisconsin.

SPECIFICATION	FEATURE	PA ('07 STD SPECS)	TX ('04 STD SPECS & PROVISIONS)	WI ('06 STD SPECS & PROVISIONS)
Contractor QC	**QC Quality Characteristics**	Agg Gradation, Cement Factor, Water-to-Cement Ratio, Air Content, Slump, Temperature, Comp Strength, Smoothness/PI, Thickness/Depth	Agg Gradation, Water-to-Cement Ratio, Slump, Air Content, Temperature, Flex Strength or Comp Strength, Smoothness	Agg Gradation, % Passing #200, Agg Moisture, Air Content, Slump, Temperature, Thickness, Smoothness/$PI_{0.0}$, Comp Strength
Agency QA	**Type/Nature**	Independent sampling/testing	Verification testing	Verification testing
	Sampling & Testing Procedure	Lot (thickness/depth, air, strength) = 5,600 yd^2, 4 equal sublots per Lot	Unit (thickness) = 500 lane-ft	Lot (air, strength) = 1 Day's Production, 5 or more equal sublots per Lot (not to exceed 500 yd^3) Unit (Thickness) = 250 lane-ft
Acceptance	**Basis**	Contractor QC test results and Agency verification test results Acceptance Testing	Contractor QC test results and Agency verification test results	Contractor's QC test results (as verified by Agency)
	Acceptance Quality Characteristics (AQCs)	Air Content (1 test/sublot) Comp Strength (28-day) (2 cylinders/sublot) Thickness/Depth (1 core/sublot) Smoothness/IRI (1 pass per wheelpath per 0.1-mi section, compute average)	Air Content Smoothness/IRI (1 pass per wheelpath per 0.1-mi section, compute average) Thickness (3 probe measures/unit)	Comp Strength (28-day) (2 cylinders/ sublot) Thickness (2 probe measures/unit) Air Content (1 test/sublot) Smoothness/$PI_{0.0}$ (1 pass per wheelpath per 0.1-mi section, compute average)
	AQC Measure Types	Comp Strength (28-day) (F'_c): PWL $Q_L = (\bar{X}-L)/S$ (L=3,000 lb/in^2) PWL from statistical table using Q_L and n=4 Determine Strength Characteristic Percentage (P_s) using PWL and look-up table Air Content: PWL $Q_L = (\bar{X}-L)/S$ (L=4.5%) $Q_U = (U-\bar{X})/S$ (U=7.5%) PWL from statistical table using Q_L and Q_U and n=4 Determine Air Content Characteristic Percentage (P_a) using PWL and look-up table. Thickness/Depth: Avg & Ind If $\bar{D}$ deficient by <0.5 in from D_{DES} and no more than one individual D deficient by ≥0.5 from D_{DES}, then full acceptance. Otherwise, remove/ replace. Determine Thickness/Depth Characteristic Percentage (P_d) using $\bar{D}$ and look-up tables established for different D_{DES} values. Smoothness/IRI: Avg If IRI≤70, full acceptance. Otherwise, corrective action (grind or remove/ replace) required.	Air Content: Ind Air between 2.5% and 5.5%, full acceptance. Air between 5.5 % and 7.0%, acceptance based on strength tests. Air <2.5% or >7.0%, rejected. Smoothness/IRI: Avg If IRI≤65 in/mi, full acceptance. If 66<IRI≤95, price reduction. If IRI>95 in/mi, corrective action to reduce IRI to ≤65 in/mi. Thickness: Avg For thickness deficiency (as determined by probes) >0.2 in, core measurement required. If core thickness deficient between 0.2 and 0.75 in, 2 additional cores required and compute average thickness for pay reduction. If core deficient by >0.75 in, additional exploratory cores to define limits for removal/replacement.	Air Content: Ind Air between 5.5 and 8.5% is conforming. Non-conforming portions of sublots subject to remove/replace Comp Strength (28-day): Avg−StdDev If strength >2,500 lb/in^2, sublot is conforming and subject to pay adjustment. If not, take cores. If each core strength >2,500 lb/in^2, sublot is conforming and subject to pay adjustment. If not, sublot is non-conforming and subject to remove/replace. Thickness: Avg If $\bar{T}$ deficient by ≤0.375 in from T_{DES}, then unit is conforming and given full acceptance. If $\bar{T}$ deficient between 0.375 and 1.0 in, then unit is non-conforming and subject to price reduction. If $\bar{T}$ deficient by >1.0 in, exploratory cores to establish limits of unacceptable thickness, subject to remove/replace or remain-in-place with no pay. Smoothness/$PI_{0.0}$: Avg

Note: TXDOT appears to over-design for strength and place emphasis on QC testing of strength, rather than test strength for acceptance and payment adjustment.

Table 27. Summary of PCC pavement specifications from Pennsylvania, Texas, and Wisconsin (continued).

SPECIFICATION	FEATURE	PA ('07 STD SPECS)	TX ('04 STD SPECS & PROVISIONS)	WI ('06 STD SPECS & PROVISIONS)
Basis for Pay	**Pay Adjustment Procedures**	Comp Strength (28-day) For F'_c and F'_c(QC) $\geq$ 3,500 lb/in^2 (structural design min), pay reduction computed as: [(A/B×0.2)+0.8]×CUP×LOT where: A = F'_c − 3,500 B = F'_c(QC) − 3,500 Thickness Deficiency, in Based on P_d and computed in combination with Air Content and Comp Strength pay factors (see equation below) Smoothness/IRI, in/mi ≤35 +$1,500 ≤50 +$1,000 ≤60 +$500 ≤70 $0 >70 Corrective Action	Smoothness/IRI ≤30 $600 bonus (per 0.1-mi lane) 31 to 60 $bonus = 600 − 20×(IRI−30) 61 to 64 $0 65 to 95 $penalty = 20×(IRI−65) >95 Corrective Action Thickness Deficiency, in 0.00 to 0.20 100% Pay 0.21 to 0.30 80% 0.31 to 0.40 72% 0.41 to 0.50 68% 0.51 to 0.75 57%	Comp Strength, lb/in^2 (Avg−StdDev) ≥ 4650 +$0.276/yd^2 4550 to 4650 +$0.268/yd^2 4450 to 4550 +$0.268/yd^2 4350 to 4450 +$0.259/yd^2 4250 to 4350 +$0.242/yd^2 4150 to 4250 + $0.226/yd^2 4050 to 4150 +$0.201/yd^2 3950 to 4050 +$0.167/yd^2 3850 to 3950 +$0.125/yd^2 3750 to 3850 +$0.067/yd^2 3650 to 3750 $0.000/yd^2 3550 to 3650 −$0.050/yd^2 3450 to 3550 −$0.109/yd^2 3350 to 3450 −$0.167/yd^2 3250 to 3350 −$0.234/yd^2 3150 to 3250 −$0.309/yd^2 3050 to 3150 −$0.385/yd^2 2950 to 3050 −$0.452/yd^2 2850 to 2950 −$0.527/yd^2 < 2850 −$0.552/yd^2 Thickness Avg Deficiency, in 0.000 to 0.375 100% 0.375 to 0.500 80% 0.500 to 0.750 60% 0.750 to 1.000 50% Smoothness/$PI_{0.0}$ (in/mi) < 19.0 $585 (per 0.1-mi) 19.0 to 25.2 $350 25.3 to 44.3 $0 44.4 to 50.6 −$230 ≥ 50.7 −$940
	Application of Pay Factors	Weighted-Avg Composite Pay Factor for Comp Strength, Air Content, and Thickness/Depth $L_p = C_p \times \{[(2P_s+2P_d+P_a)/500]\}$ Individual for Smoothness/IRI	Product Composite Pay Factor CPF = $PF_{str} \times PF_{thk}$	Individual Pay Factors

Note: TXDOT appears to over-design for strength and place emphasis on QC testing of strength, rather than test strength for acceptance and payment adjustment.

Table 28. Summary of PCC pavement specifications from Arizona, Kentucky, and Utah.

SPECIFICATION	FEATURE	AZ ('00 STD SPECS & PROVISIONS)	KY ('04 STD SPECS & PROVISIONS)	UT ('05 STD SPECS & PROVISIONS)
Contractor QC	**QC Quality Characteristics**	Agg Gradation, Slump, Air Content, Temperature	Slump, Air Content, Unit Weight, Temperature, Comp Strength	Slump, Yield, Temperature, Air Content, Water-to-Cement Ratio, Comp Strength
Agency QA	**Type/Nature**	Contractor QC and acceptance testing by Agency	Contractors QC is verified by Agency with random acceptance testing	Contractor QC and acceptance testing by Agency
	Sampling & Testing Procedure	Lot (slump, air content, temperature, comp strength, thickness) = 1 Shift's Production	Lot (thickness) = 6,000 ft paved width, 8 sublots/Lot (i.e., sublot = 750 ft) Lot (air, comp strength) = 4,000 yd^2, 4 equal sublots/Lot (i.e., 1,000 yd^2)	Lot (comp strength) = 2,650 yd^2 Placement Area (thickness)≤12,000 ft^2
Acceptance	**Basis**	Agency acceptance test results and verifications of QC tests	Agency acceptance test results and verifications of QC tests	Agency acceptance test results and verifications of QC tests
	Acceptance Quality Characteristics (AQCs)	Slump (5 tests/Lot) Air Content (5 tests/Lot) Temperature (5 tests/Lot) Comp Strength (28-day) (3 cylinders/Lot) Thickness (10 cores/Lot) Smoothness/$PI_{0.2}$ (1 pass per wheelpath per 0.1-mi section, compute average)	Air Content (1 test/sublot) Comp Strength (28-day) (two 6x12 cylinders/sublot or three 4x8 cylinders/sublot) Thickness (1 core/sublot) Smoothness/($PI_{0.2}$ & IRI) (For $PI_{0.2}$, 1 pass per wheelpath per 1,000-ft section, compute average) (For IRI, 1 pass per wheelpath per 1-mi segment, compute average)	Comp Strength (28-day) (3 cylinders/Lot) Thickness (1 core/placement area) Smoothness/$PI_{0.2}$ (1 pass per wheelpath per 0.1-mi section, compute average)
	AQC Measure Types	Slump: Ind (rejected?? If slump ≤4.5 in, reject prior to placement Air Content: Ind For air-entrained mixes required at elevations ≥3000 ft, if 4.0>%Air>7.0, reject prior to placement For air-entrained or non-air-entrained mixes used below 3000 ft, if %Air>7.0, reject prior to placement Temperature: Ind If PCC temp>90°F, reject prior to placement Comp Strength (28-day): PWL Thickness: PWL $Q_T = (\bar{X}-LL)/S$ ($LL=T_{DES} - 0.2$ in) PWL_T from statistical table using Q_T and n=10 Strength: PWL $Q_S = (\bar{X}-LL)/S$ (LL=4,000 lb/in^2) PWL_S from statistical table using Q_S and n=5 Smoothness/$PI_{0.2}$: Avg	Slump: Ind?? <4.0 in Air Content: PWL $Q_{L1} = (\bar{X}-L1)/S$ ($L1=Air_{target}-1\%$) $Q_{L2} = (\bar{X}-L2)/S$ ($L2=Air_{target}-2\%$) $Q_{U1} = (U1-\bar{X})/S$ ($U1=Air_{target}+1\%$) $Q_{U2} = (U2-\bar{X})/S$ ($U2=Air_{target}+2\%$) PWL_1 and PWL_2 from statistical table using n=4 and Q_{L1} and Q_{U1} and Q_{L2} and Q_{U2}, respectively Comp Strength (28-day): PWL $Q_L = (\bar{X}-L)/S$ (L=3,850 lb/in^2) PWL from statistical table using Q_L and n=4 Thickness: PWL If T deficient by ≥1.0 in, remove/replace sublot, core replaced pavement for PWL determination. Smoothness/$PI_{0.2}$: Avg If $PI_{0.2}$≤6.0 in/mi, full acceptance and further evaluation using IRI to determine incentive payments. If 6.0<$PI_{0.2}$≤10.0, pay reduction. If $PI_{0.2}$>10.0 in/mi, corrective work. Smoothness/IRI: Avg For sections with $PI_{0.2}$<6.0 in/mi, determine average IRI to establish incentive payments.	Comp Strength (28-day): Ind If f'_c ≥ specified min of 4,000 lb/in^2, full acceptance. If f'_c deficient by 1 to 400 lb/in^2 (from 4,000 lb/in^2) pay reduction. If f'_c deficient by >400 lb/in^2 (from 4,000 lb/in^2), remove/replace or 50% price reduction. Thickness: Ind If T deficient by ≤0.125 in, full acceptance. If T deficient between 0.125 and 0.75 in, price reduction. If T>0.75 in, two additional cores to determine limits of pavement subject to remove/replace (or 50% pay reduction per Engineer's discretion). Smoothness/$PI_{0.2}$: Avg
Basis for Pay	**Pay Adjustment Procedures**	Thickness, PWL 100 +\$1.00/yd^2 95 to 99 +\$0.75/yd^2 90 to 94 +\$0.50/yd^2 85 to 89 \$0.00/yd^2 80 to 84 −\$0.25/yd^2 75 to 79 −\$0.75/yd^2 70 to 74 −\$1.75/yd^2 65 to 69 −\$3.25/yd^2 60 to 64 −\$5.00/yd^2 <60 Reject Comp Strength (28-day), PWL Same pay schedule as Thickness (above) Smoothness/$PI_{0.2}$ (in/mi) ≤7.0 +[(\$0.20)×(7.0−$PI_{0.2}$)]/yd^2 7.1 to 8.0 −\$0.50/yd^2 8.1 to 9.0 −\$1.00/yd^2 >9.0 Grind to $PI_{0.2}$≤9.0 or Remove/Replace	Air Content, PWL {[25+(PWL_2×0.25)]+[0.0125×PWL_1]}/100 Thickness Deficiency, in 0.00 to 0.02 100% 0.21 to 0.30 80% 0.31 to 0.40 72% 0.41 to 0.50 68% 0.51 to 0.75 57% 0.76 to 1.00 50% >1.00 Remove/Replace Comp Strength (28-day), PWL [26.25+(0.25×PWL)]/100 Smoothness/$PI_{0.2}$ (in/mi) ≤6.0 0.00 6.1 to 7.0 −0.02 7.1 to 8.0 −0-05 8.1 to 10.0 −0.08 >10.0 Corrective work Smoothness/IRI (in/mi) ≤53 +0.03 54 to 56 +0.02 57 to 60 +0.01	Thickness Deficiency, in 0.0 to 0.125 1.00 (pay factor) 0.125 to 0.25 0.90 0.25 to 0.50 0.75 0.50 to 0.75 0.60 Smoothness/$PI_{0.2}$ (in/mi) Bonus/Penalty Pay = \$200×(5 − $PI_{0.2}$) Comp Strength Deficiency (28-day,lb/in^2) 1 to 100 (<4,000 lb/in^2) 0.95 (pay factor) 101 to 200 0.90 201 to 300 0.85 301 to 400 0.80
	Application of Pay Factors	Individual Pay Factors for Thickness, Comp Strength, and Smoothness	Summation Composite Pay Factor for Air Content and Comp Strength	Individual Pay Factors for Comp Strength, Thickness, and Smoothness

			Individual Pay Factors for Thickness and Smoothness	

Table 29. Summary of PCC pavement specifications from Michigan, Mississippi, and South Dakota.

SPECIFICATION	FEATURE	MI ('04 STD SPECS & PROVISIONS)	MS ('04 STD SPECS & PROVISIONS)	SD ('98 STD SPECS & PROVISIONS)
Contractor QC	**QC Quality Characteristics**	QC Plan, Yield, Air Content, Slump, Temperature, Comp or Flex Strength	None specified.	Prescriptive Specifications
Agency QA	**Type/Nature**	Contractor QC and acceptance testing by Agency	Agency performs QA/QC testing	Agency performs all testing
	Sampling & Testing Procedure	Lot size (temperature, slump, air, strength) is determined at start of project (≤100 yd^3 for small projects, >100 yd^3 for large projects). Unit (thickness) = 500 or 1,000 lane-ft	Section (thickness) = 1,000-ft traffic lane	Unit (thickness)=1,500-ft traffic lane
Acceptance	**Basis**	Agency acceptance test results, and verifications of QC tests	Agency acceptance test results	Agency acceptance test results
	Acceptance Quality Characteristics (AQCs)	Thickness (1 core/unit) Smoothness/RQI/$PI_{0.0}$ (1 pass per wheelpath per 0.1-mi section, compute average, compute weighted average for entire length of each lane) Air Content (large projects) (5 tests/Lot) Temperature (large projects) (5 tests/Lot) Comp Strength (28-day) (large projects) (5 sets of 2 cylinders/Lot)	Thickness (1 core/section) Smoothness/$PI_{0.0}$ (1 pass per wheelpath per 0.1-mi section, compute average)	Thickness (1 core/section, where pavement is believed to be deficient in thickness) Smoothness/$PI_{0.0}$ (1 pass per wheelpath per 0.1-mi section, compute average)
	AQC Measure Types	Thickness: Ind & Avg If initial T≤0.2 in, full acceptance. If 0.2<T≤1.0, two additional cores taken to determine $\overline{T}$ and corresponding pay adjustment. If T>1.0 in, exploratory/ straddler cores taken to determine area to be removed/replaced. Comp Strength: PWL $Q = (\bar{X} - CDS)/S$ (CDS=3,500 lb/in^2 for Class P1 PCC) PWL from statistical table using Q and n=5 (for large projects). Air Content: Avg 6.5±1.5% Slump: Avg ≤3 in Smoothness/RQI/$PI_{0.0}$: Avg & Weighted Avg If RQI (0.1-mi section) ≤ 40 or $PI_{0.0}$ (0.1-mi section) ≤ 30 in/mi, full acceptance; otherwise corrective action. If RQI (entire lane length) ≤ 40 or $PI_{0.0}$ (entire lane length) ≤ 30 in/mi, full acceptance; otherwise corrective action.	Thickness: Ind & Avg If T deficient by ≤0.2 in from T_{DES}, then full acceptance. If 0.2<T≤1.0 deficient, take 2 additional cores and compute $\overline{T}$; if $\overline{T}$ deficient by ≤0.2 in from T_{DES}, then full acceptance, otherwise pay reduction. If any T >1.0 in deficient, then take additional exploratory cores to establish limits for remove/replace. Smoothness/$PI_{0.0}$: Avg	Thickness: Ind & Avg If T deficient by ≤0.2 in from T_{DES}, then full acceptance. If 0.2<T≤1.0 deficient, take 2 additional cores and compute $\overline{T}$; if $\overline{T}$ deficient by ≤0.2 in from T_{DES}, then full acceptance, otherwise pay reduction. If any T >1.0 in deficient, then take additional exploratory cores to establish limits for remove/replace Smoothness/$PI_{0.0}$: Avg
Basis for Pay	**Pay Adjustment Procedures**	<u>Thickness Deficiency, in</u> ≤0.2 0% 0.3 −5% 0.4 −15% 0.5 −25% 0.6 to 1.0 −50% ≥1.1 −100% <u>Comp Strength (28-day)</u> Not specified	<u>Thickness Deficiency, in</u> 0.00 to 0.20 100% 0.21 to 0.30 80% 0.31 to 0.40 72% 0.41 to 0.50 68% 0.51 to 0.75 57% 0.76 to 1.00 50% <u>Smoothness/$PI_{0.0}$ (in/mi)</u> ≤10 +$0.26/$yd^2$ 10.1 to 14 +$0.20/$yd^2$ 14.1 to 18 +$0.13/$yd^2$ 18.1 to 22 +$0.07/$yd^2$ 22.1 to 30 $0.00/$yd^2$ >30 Correct to $PI_{0.0}$≤30	<u>Thickness Deficiency, in</u> 0.0 to 0.2 100% 0.21 to 0.30 80 % 0.31 to 0.40 72% 0.41 to 0.50 68% 0.51 to 0.70 57% 0.71 to 1.00 50% <u>Smoothness/$PI_{0.0}$ (in/mi)</u> ≤10 104.7% 10.1 to 15.0 103.5% 15.1 to 20.0 102.4% 20.1 to 25.0 101.2% 25.1 to 35.0 100.0% 35.1 to 40.0 97.7% ≥40.1 Grind to $PI_{0.0}$≤35 or Remove/Replace
	Application of Pay Factors	Individual Pay Factors for Comp Strength and Thickness Summation Composite Pay Factor when specified.	Individual Pay Factors for Thickness and Smoothness	Individual Pay Factors for Thickness and Smoothness

Note: Michigan DOT also has an acceptance requirement for depth of steel in jointed reinforced concrete (JRC) pavements.

APPENDIX C. PROB.O.PROF 2.0 USER'S MANUAL

OVERVIEW

Prob.O.Prof 2.0 is an Excel® spreadsheet-based software program that uses Visual Basic® macros. A probabilistic simulation of various AQC target quality levels is performed; pay factors and profitability levels are computed based on user-entered AQC target values, user-entered costs, and selected agency specifications. The most profitable quality levels based on composite pay equations and caps are identified.

The program also generates pay factor and profitability estimated for different levels of reliability (i.e., risk percentiles), as chosen by the user. This allows a PCC or HMA contractor (software user) to evaluate various options with respect to target quality levels and to select optimum quality levels that will result in the greatest expected profit at a specified reliability level. The user can enter up to four reliability values at which the pay and profit will be computed for each combination of target quality levels. The default levels of reliability are 50, 75, 90, and 95 percent.

The mean and median (expected) pay and profit also are computed. For example, the contractor who selects a lower reliability level is said to be optimistic and "risk-prone." Such a contractor is willing to take risks with respect to probability that quality measurements of samples from a Lot are better than or equal to the true quality of the Lot. However, a contractor who selects a higher reliability level is said to be "risk-averse." By choosing a higher reliability level (such as 95 percent), the contractor is identifying the acceptable risk (5 percent) that he/she is willing to take in achieving the pay factor for the specified combination of AQCs.

The Prob.O.Prof program allows the user to select a specific State or construction type (in the "Input" sheet) and enter necessary information such as design values, target values, specification limits, costs, standard deviations, cost increments, AQCs, reliability levels, project information, and samples per Lot. The program uses a Monte Carlo simulation method to simulate the AQC samples per Lot, as if their samples were taken from the field.

For each combination of target AQCs, a Lot is simulated hundreds or thousands of times (the actual number of simulations is a user-defined input). Each simulation consists of generating sample values for each target AQC based on the user-entered samples per Lot for that AQC, calculating the Lot statistics (mean, standard deviation, etc.), and computing the Lot pay based on the chosen State specifications. The Lot pay amounts for the various AQCs are combined using the agency pay equation/method. This sampling process is repeated to generate a probability distribution, which is used to obtain the mean net gain, median net gain, and net gains at the chosen reliability levels, for that combination of target AQCs, for the Lot. This information can then be used to choose an appropriate target AQC combination for the Lot based on the contractor's risk tolerance.

For multiple-Lot construction, the probability distribution of the net gains obtained in the single-Lot simulation is used to simulate projects (as compared to simulating Lots). This sampling process is repeated hundreds or thousands of times to generate a probability distribution, which is used to obtain the mean net gain, median net gain, and net gains at the chosen reliability levels, for that combination of target AQCs, for the project. This information can then be used to choose an appropriate target AQC combination for the project based on the contractor's risk tolerance.

The results of the simulation are displayed in four Excel worksheets:

- Results
- GraphicalResults
- MultiLotResults
- MultiLotGraphicalResults

STEP-BY-STEP GUIDE

Step 1: Opening the Program File

Prob.O.Prof 2.0 can be opened using MS Excel® (Clicking on … *File* … *Open* in the Menu Bar, navigating to the appropriate file location, selecting the file, clicking the *Open* button) or by navigating to the appropriate file location in Windows Explorer and double-clicking on the file name. A licensed copy of MS Excel® is required to run the program.

MS Excel displays a security warning regarding the embedded macros in the program file (figure 9). For Prob.O.Prof 2.0 to be functional, the macros have to be enabled by clicking on the *Enable Macros* button. This step enables the macros embedded only in Prob.O.Prof 2.0 and not in any other program.

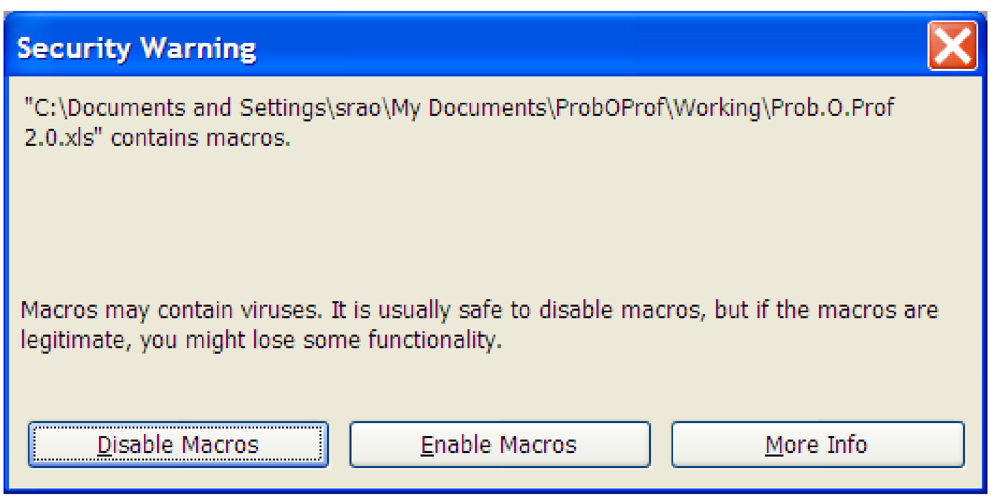

Figure 9. Security warning displayed by MS Excel regarding embedded macros in Prob.O.Prof 2.0, which need to be enabled for proper functioning of the program.

The display of the flash screen (figure 10) indicates that the macros in the program are functioning properly.

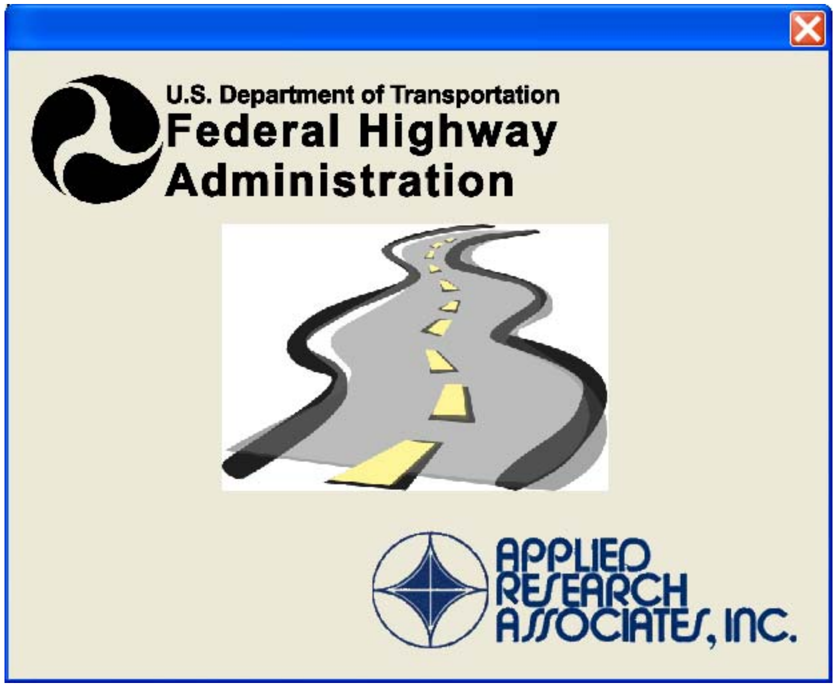

Figure 10. Initial flash screen displayed before the first Prob.O.Prof 2.0 input screen.

Step 2: Entering General Information

This step requires the user to enter general information regarding the analysis (figure 11). Select the pavement type—PCC or AC—by clicking on the appropriate button. Select the specification/State from the drop down list. Prob.O.Prof 2.0 includes the following specifications:

- Portland Cement Concrete – AASHTO, Arizona, Iowa, Wisconsin
- Asphalt Concrete – Alabama Superpave, South Carolina Marshall Surface, South Carolina Marshall Binder, Missouri SMA

Selecting the Specification/State enables the corresponding AQCs for that Specification/State. Choose the AQCs that are being considered for evaluation by checking the appropriate check boxes. For a comprehensive "true" evaluation of a Specification/State, keep all the enabled check boxes checked. Unchecking (i.e., not selecting) an AQC for evaluation effectively results in that AQC being pay neutral with 100 percent pay and no incentive or disincentive tied in to that AQC. All other AQCs will be evaluated appropriately based on the Specification/State information. At least one AQC should be selected for evaluation—if all AQCs are unchecked, a *Please Select One or More AQCs* message box is displayed and the user cannot proceed to the next step (figure 12).

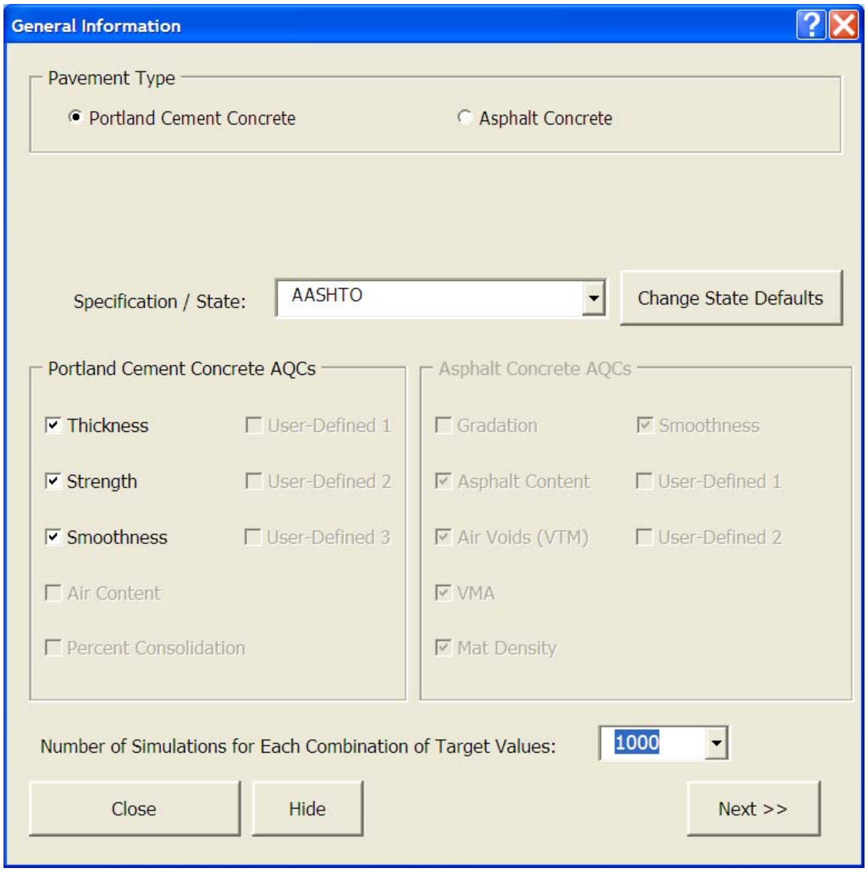

Figure 11. General information screen where the user selects the pavement type, the specification/State, the AQCs that need to be evaluated, and the number of simulations.

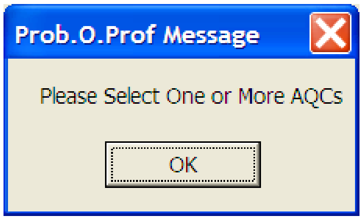

Figure 12. Message box requesting user to select one or more AQCs.

Click on the *Change State Defaults* button to access the Excel® sheet where the specifications are stored. Most users (particularly contractors) will not need to edit these specifications because they represent the up-to-date current specifications. However, an agency may wish to access this sheet to change values (such as ranges, pays, or pay coefficients) to analyze the effect of changing the specifications on contractor pay. More details are covered later in this manual.

Select the number of simulations to be performed for each combination of target values. Choose a smaller number (such as 200 or 500) for an initial evaluation and a larger number (such as 1,000 or 2,000) for the final evaluation. The number of simulations chosen substantially affects run time and the stability of the program. Because of the limitation of MS Excel®, choosing a large number of simulations along with a large number of target AQC combinations can result in instability, program termination, and corresponding error messages during run time.

Clicking on the *Close* button to close the program prompts the user, *Do you want to save the current file?* (figure 13). Select *Yes* to save the file and close the program, *No* to close the program without saving the file, and *Cancel* to go back to the program. Clicking on the *Hide* button hides the input form to access the Excel® sheets in the background.

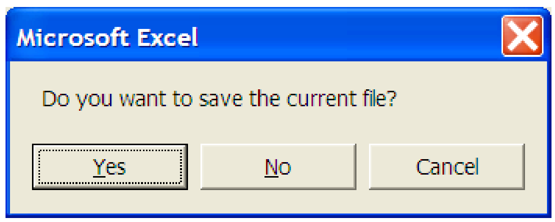

Figure 13. Message box prompting the user if they want to save the current file before closing the program.

Click on *Next* >> to navigate to the next input screen.

Step 3. Entering AQC Inputs

Depending on the information provided in the *General Information*, input forms for the appropriate PCC or AC inputs will be displayed (figures 14 and 15). For each AQC chosen, the user must enter the following information.

<u>Agency Design/Specified Value</u>: For most AQCs, this is the agency design value (design thickness, job mix formula target, etc.) and is the value that typically corresponds to 100 percent pay and no incentives/disincentives. This is also the value that is cost neutral and corresponds to zero relative cost. Generally, a target value better (for the agency) than the specified value has a higher (positive) relative cost, and a target value worse (for the agency) than the specified value has a lower (negative) relative cost. This value is used in the program to:

- Automatically generate the target values (changing this value in the input form automatically generates the target values, which can then be edited manually).
- Calculate pay for some AQCs where pay is relative to the agency design value.

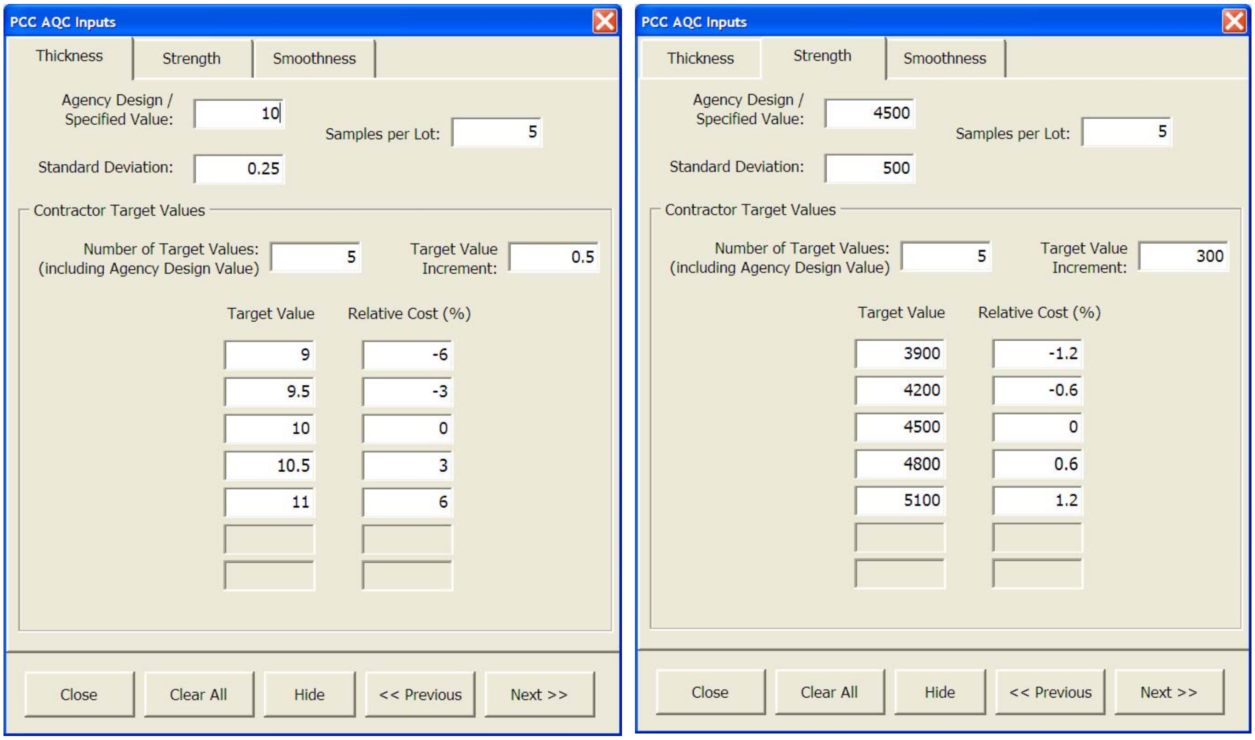

Figure 14. PCC input screens for two AQC inputs: thickness and strength.

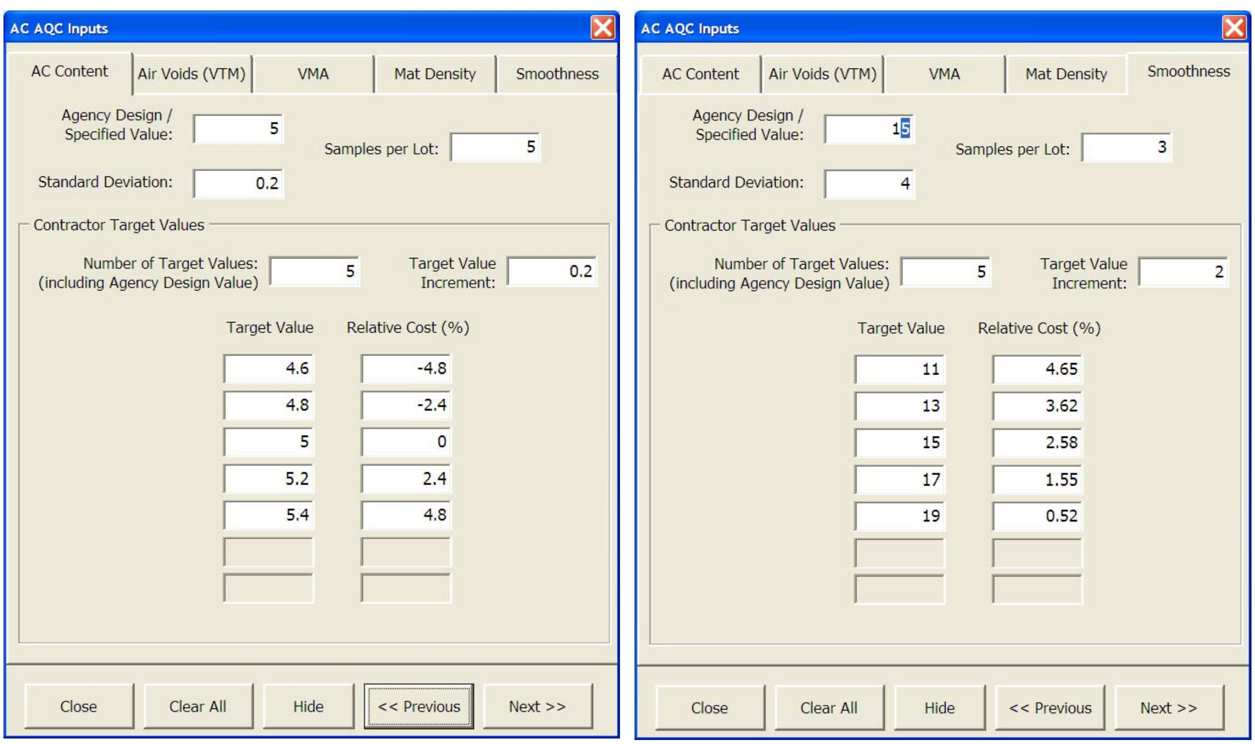

Figure 15. AC input screens for two AQC inputs: AC content and smoothness.

For smoothness and, in some cases, for compressive strength, this input is used only to generate the target values and is not used to compute pay.

The agency design/specified value should have the same units as those of the corresponding AQC for the State/Specification. If a State/Specification specifies thickness in inches, then the value entered should be in inches. If a State/Specification uses IRI in in/mi for smoothness, then the value entered should also correspond to IRI in in/mi. If a State/Specification uses $PI_{0.2}$ in in/mi for smoothness, then the value entered should also correspond to $PI_{0.2}$ in in/mi. Click on the *Change State Defaults* button on the *General Information* form to see these units. Do not use default values for this input.

Sample Size, n: For each AQC, the user enters the sample size or number of sublots per Lot (3 to 50). In most cases, the sample size (number of sublots per Lot) is included in the agency specifications. It is critical that the user-entered sample size be representative of the chosen Specification/State for that AQC. The default values should not be used. Because composite pay combines various AQCs, and the probability of profit is computed for a given Lot, the overall Lot size should be consistent between the various AQCs, and the Lot sizes for all AQCs should be normalized to have the same sizes. This is especially true when considering smoothness as an AQC and when the payment is based on individual profile measurements over a fixed distance (e.g., 0.1 lane-mi).

Standard Deviation: The standard deviation entered is the population standard deviation and corresponds to one sample unit per sublot. This value can be obtained through historical data collected by the contractor or agency. Only one value is simulated per sublot, irrespective of the number of individual specimens per sublot. Thus, if the mean values of two or more replicate specimen are used to represent an AQC for an individual sublot, the standard deviation entered is that of these mean values and not of the specimen values. For example, if Agency A requires the mean value of two samples to be the representative value for a sublot (e.g., mean value of inner and outer wheelpath smoothness measurements, replicate strength or thickness measurements within a sublot, replicate asphalt content or density measurements within a sublot), then the standard deviation used is that of the historical mean values and not the historical individual values. Do not use default values for this input.

> *Example Application: Wisconsin defines a Lot for compressive strength payment as 1 day's production, five or more sublots per Lot, and the sublot should not exceed 500 yd^3 of concrete. The average of two compressive strength tests is used as the representative value for the sublot. The Lot mean and standard deviation are used to compute the compressive strength incentive/disincentive pay for the Lot. Wisconsin includes disincentives per 250-lane-ft unit in their specifications for thickness deficiency. Two probe measurements per unit are conducted to evaluate the thickness, and the average of the two measurements is used to compute the disincentive for that unit depending on the thickness deficiency. Smoothness incentives and disincentives are paid for each 0.1 lane-mi. The average of the inside and outside wheelpath IRI is used to compute the smoothness incentives/disincentives.*

If evaluating the specifications for a 2-lane (12 ft/lane) 10-in PCC pavement and assuming 2,500 yd^3 of concrete is produced in a day:

- *1 Lot = 2,500 yd^3 = 5 compressive strength sublots (each sublot = 500 yd^3 concrete). Average of two compressive strength tests (specimens) per sublot represents an individual unit in a sample. Compressive strength means and standard deviations entered should be of these individual sample units and not of the individual specimen tests.*
- *2,500 yd^3 corresponds to 6,750 lane-ft (12-ft lane, 10-in slab) = 27 250-ft-lane units. This corresponds to 27 thickness sublots per Lot (each sublot Lot = 250 ft-lane). Average of two thickness measurements (specimens) per sublot represents an individual unit in a sample. Compressive strength means and standard deviations entered should be of these individual sample units and not of the actual thickness measurements.*
- *2,500 yd^3 corresponds to 1.28 lane-mi (12-ft lane, 10-in slab) = 13 0.1-lane-mi units. This corresponds to 13 smoothness sublots per Lot (each sublot Lot = 0.1 lane-mi). Average of two smoothness measurements (specimens) per sublot represents an individual unit in a sample. Smoothness means and standard deviations entered should be of these individual sample units and not of the actual individual smoothness measurements.*

Number of Target Values: The number of target values for evaluation is a user input for each AQC. Prob.O.Prof 2.0 simulates the Lot at each target value for each unique combination of AQC. The maximum number of allowable target values for an AQC is seven.

For example, if five target values are chosen for PCC thickness, four target values for PCC compressive strength, and six target values for PCC smoothness, then $5 \times 4 \times 6 = 120$ unique combinations of target values are evaluated. If five target values are chosen for AC content, five target values for air voids, five target values are chosen for VMA, five target values are chosen for mat density, and five target values are chosen for AC smoothness, then $5 \times 5 \times 5 \times 5 \times 5 =$ 3,125 unique combinations of target values are evaluated. The user-entered number of target values also is used to generate the default target values in the input boxes provided. These can then be edited by the user.

As in the case of number of simulations, the total number of target value combinations significantly affects run time and program stability.

Target Value Increment: The user-entered target value increment is used only to generate the default target values in the input boxes provided. These can then be edited by the user.

Target Value: The default target values are generated automatically using the agency design/specified value, number of target values, and target value increment. These can then be edited or changed by the user. The target values should have the same units as those of the corresponding AQC for the State/Specification. Click on the *Change State Defaults* button on the *General Information* form to see these units.

Relative Cost (%): Prob.O.Prof 2.0 automatically generates default relative costs for the default target values. For most AQCs (except smoothness), these costs are relative to the agency design/specified value which is considered cost neutral (0 percent relative cost). These can then be edited by the user.

Clicking on the *Close* button to close the program prompts the user, *Do you want to save the current file?* Select *Yes* to save the file and close the program, *No* to close the program without saving the file, and *Cancel* to go back to the program. Clicking on the *Hide* button hides the input form to access the Excel® sheets in the background. Clicking on the *Clear All* button clears all the information on the input forms for all AQCs.

Click on *Next* >> to navigate to the next input screen or the <<*Previous* button to navigate to the previous input screen.

Step 4. Entering Project Information

In this step, the following project information needs to be entered (figure 16).

Project ID: This is used for agency/contractor reference purposes only. It is not used in the program.

Number of Lanes, Project Length, Project Area, Estimated Average Bid Cost: These are used to convert pay amounts in specifications provided in $/unit area, $/unit length, or $/unit lane-length, such as those in Wisconsin PCC specifications, into percentages. For specifications/States where all incentives/disincentives are specified in percentages (e.g., South Carolina), the entries in these text boxes do not affect the results. Note that all costs, pays, and net gains are calculated as percentages relative to the cost-neutral alternative.

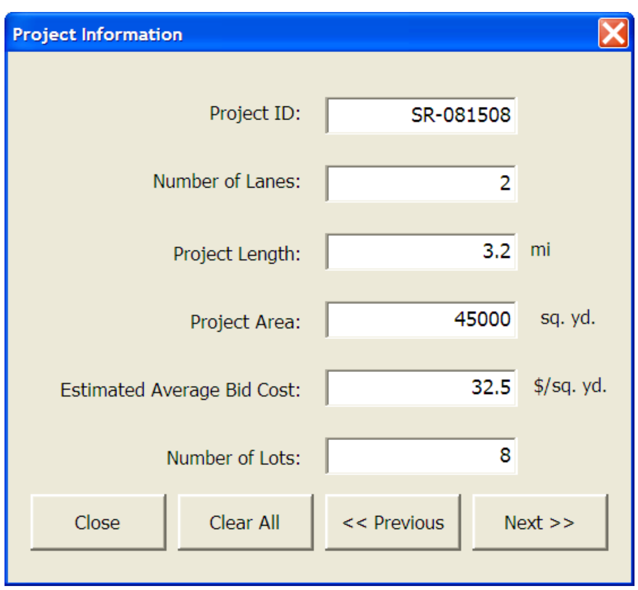

Figure 16. Project information input screen.

Number of Lots: The number of Lots entered is used to perform multiple-Lot (project) analysis. The probability distribution resulting from the single-Lot simulation is used to perform the multiple-Lot simulation. The result of the multiple-Lot simulation is a smoothening and narrowing (smaller probability of extreme values) of the single-Lot distribution.

Clicking on the *Close* button to close the program prompts the user, *Do you want to save the current file?* Select *Yes* to save the file and close the program, *No* to close the program without saving the file, and *Cancel* to go back to the program. Clicking on the *Hide* button hides the input form to access the Excel® sheets in the background. Clicking on the *Clear All* button clears all the information on the input forms for all AQCs.

Click on *Next >>* to navigate to the next input screen or the <<*Previous* button to navigate to the previous input screen.

Step 5. Entering Output Information

In this step, the user must enter the following output information (figure 17):

Number of Top AQC Combinations to be Listed: While the results of all AQC combinations will be displayed in the output sheet, the user can enter the number of top (highest net gain) AQC combinations to be highlighted (in green) at the mean, median, and four user-entered confidence levels. This is particularly useful when a large number of target level combinations is chosen. Note that because of the statistical distribution of the results, the top AQC combinations will be different at the mean, the median, and at the various confidence levels.

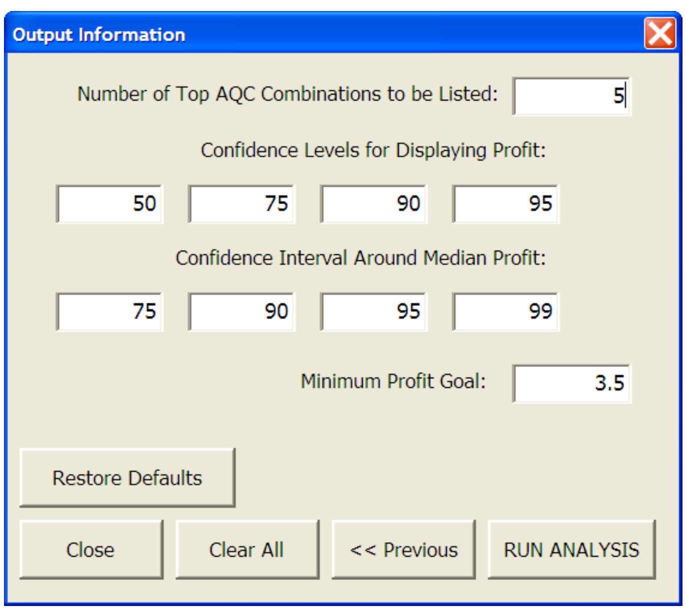

Figure 17. Input screen where user can enter four confidence levels for displaying profit and four confidence interval around median profit.

Confidence Levels for Displaying Profit (1-α): The user can enter four confidence levels for displaying net gain. These levels indicate the percentage of Lots (for single-Lot analysis) and percentage of projects (for multiple-Lot analysis) that will have a higher net gain than the output (displayed) value. Alternatively, the probability of net gain less than the output (displayed) value is (α).

Confidence Interval around Median Profit (CI): The user can enter four confidence intervals around the median profit. This represents the percentage of Lots (for single-Lot analysis) and percentage of projects (for multiple-Lot analysis) that will have a net gain between the two (lower limit and upper limit) output (displayed) values. In other words, the probability of attaining net gain between the displayed lower limit and upper limit = CI.

Minimum Profit Goal: All output values at the mean, median, and the four user-entered confidence levels will be displayed in boldface if the value exceeds the entered minimum profit goal.

Clicking on the *Close* button to close the program prompts the user, *Do you want to save the current file?* Select *Yes* to save the file and close the program, *No* to close the program without saving the file, and *Cancel* to go back to the program. Clicking on the *Hide* button hides the input form to access the Excel® sheets in the background. Clicking on the *Clear All* button clears all the information on the input forms for all AQCs. Clicking on the *Restore Defaults* button restores the default values for this form.

Click on the *Run Analysis* button to navigate to the next screen or the *<<Previous* button to navigate to the previous input screen.

Step 6. Running the Analysis

Click on the *Click to Start Analysis* button to start the analysis (figure 18). Once the analysis has started, it cannot be stopped until the analysis has been completed. The run time can vary from a few minutes to an hour or more, depending on the computer and various user inputs such as number of target value combinations, selected specification/State, and number of simulations. Please make sure to close all other programs before running this analysis (particularly email, VPN, web browsers, and wireless communications), as they may affect the stability of this program. For additional stability, open a new version of the Prob.O.Prof 2.0 file for each run.

Click on the *<<Previous* button to navigate to the previous input screen. The *Run Status* form displays the status of the analysis and the percent complete for each step of the analysis.

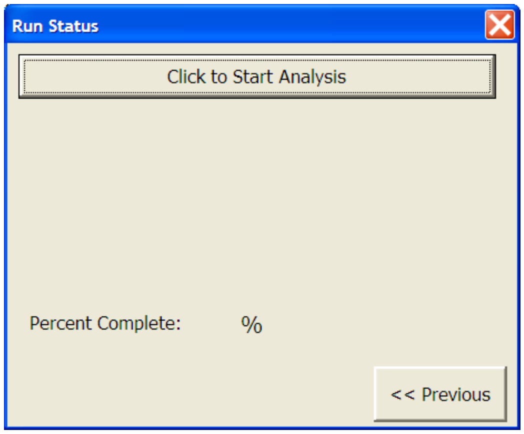

Figure 18. Start analysis and run status screen.

Step 7. Reading Output Results

The "Results" and the "MultiLotResults" sheets display, in a tabular format, the pay factors for various combinations of AQCs for single-Lot analysis and multiple-Lot (project) analysis (tables 30 and 31). The top five combinations resulting in maximum profit are highlighted (in green). These sheets include the following.

<u>AQC Combination Number:</u> This is an identification number ranging from 1 to the total number of unique target value combinations.

<u>Target Values Corresponding to the AQC Combination Number:</u> For each AQC combination number, the target values for each AQC analyzed are displayed.

<u>Relative Cost:</u> The relative cost for a target value combination is the sum of the relative costs for each AQC for the corresponding target values.

<u>Mean Pay, Median Pay, Minimum Pay, Maximum Pay:</u> The mean, median, minimum, and maximum pays are computed from the single-Lot/multiple-Lot simulations (user-entered number of simulations) for each unique combination of target values.

<u>Mean Net Gain/Loss, Median Net Gain/Loss, Minimum Net Gain/Loss, Maximum Net Gain/Loss:</u> The mean, median, minimum, and maximum net gains/losses are the differences between the mean, median, minimum, and maximum pays and the relative costs for each unique combination of target values. These are the values that are most useful to a contractor in evaluating agency specifications, and a contractor would want to maximize the mean and median net gains.

Table 30. Single-Lot results sheet showing the relative costs, pays, and net gains/losses for various AQC combinations at the mean, median, and four confidence levels and four confidence intervals around the median.

AQC Combination Number	Thickness	Strength	Smoothness	Relative Cost (%)	Mean Pay (%)	Median Pay (%)	Mean Net Gain/Loss (%)	Median Net Gain/Loss (%)	Pay @ Conf Level 1 = 50	Pay @ Conf Level 2 = 75	Pay @ Conf Level 3 = 90	Pay @ Conf Level 4 = 95	Net Gain/Loss @ Conf Level 1 = 50	Net Gain/Loss @ Conf Level 2 = 75	Net Gain/Loss @ Conf Level 3 = 90	Net Gain/Loss @ Conf Level 4 = 95
1	9.50	5000.00	4.00	-4.54	-55.82	-56.26	-51.28	-51.72	-56.26	-59.59	-62.10	-64.88	-51.72	-55.05	-57.56	-60.34
2	9.50	5000.00	5.00	-5.09	-56.04	-56.69	-50.95	-51.60	-56.69	-59.64	-62.34	-64.88	-51.60	-54.55	-57.25	-59.79
3	9.50	5000.00	6.00	-5.64	-56.05	-56.69	-50.41	-51.05	-56.69	-59.64	-62.34	-64.88	-51.05	-54.00	-56.70	-59.24
20	10.50	5000.00	5.00	0.91	1.00	3.17	0.09	2.26	3.17	-3.09	-8.05	-33.09	2.26	-4.00	-8.96	-34.00
21	10.50	5000.00	6.00	0.36	0.97	3.10	0.61	2.74	3.03	-3.26	-8.05	-33.09	2.67	-3.62	-8.41	-33.45
22	10.50	5500.00	4.00	2.46	8.91	10.00	**6.45**	**7.54**	10.00	9.44	5.37	3.14	**7.54**	**6.98**	2.91	0.68
23	10.50	5500.00	5.00	1.91	8.76	10.00	**6.85**	**8.09**	10.00	8.84	4.74	2.73	**8.09**	**6.93**	2.83	0.82
24	10.50	5500.00	6.00	1.36	8.73	10.00	**7.37**	**8.64**	10.00	8.67	4.74	2.57	**8.64**	**7.31**	3.38	1.21
25	10.50	6000.00	4.00	3.46	9.89	10.00	**6.43**	**6.54**	10.00	10.00	10.00	9.43	**6.54**	**6.54**	**6.54**	**5.97**
26	10.50	6000.00	5.00	2.91	9.86	10.00	**6.95**	**7.09**	10.00	10.00	10.00	9.10	**7.09**	**7.09**	**7.09**	**6.19**
27	10.50	6000.00	6.00	2.36	9.84	10.00	**7.48**	**7.64**	10.00	10.00	10.00	8.65	**7.64**	**7.64**	**7.64**	**6.29**

AQC Combination Number	Thickness	Strength	Smoothness	Relative Cost (%)	Pay @ Conf Int 1 = 75 LL	Pay @ Conf Int 1 = 75 UL	Pay @ Conf Int 3 = 95 LL	Pay @ Conf Int 3 = 95 UL	Net Gain/Loss @ Conf Int 1 = 75 LL	Net Gain/Loss @ Conf Int 1 = 75 UL	Net Gain/Loss @ Conf Int 2 = 90 LL	Net Gain/Loss @ Conf Int 2 = 90 UL	Net Gain/Loss @ Conf Int 3 = 95 LL	Net Gain/Loss @ Conf Int 3 = 95 UL	Net Gain/Loss @ Conf Int 4 = 99 LL	Net Gain/Loss @ Conf Int 4 = 99 UL
1	9.50	5000.00	4.00	-4.54	-61.57	-48.58	-72.87	-43.64	-57.03	-44.04	-60.34	-41.20	-68.33	-39.10	-70.18	-35.51
2	9.50	5000.00	5.00	-5.09	-61.86	-48.81	-72.87	-43.92	-56.77	-43.72	-59.79	-40.98	-67.78	-38.83	-69.88	-35.30
3	9.50	5000.00	6.00	-5.64	-61.89	-48.81	-72.87	-43.92	-56.25	-43.17	-59.24	-40.43	-67.23	-38.28	-69.33	-34.75
20	10.50	5000.00	5.00	0.91	-6.96	10.00	-34.76	10.00	-7.87	9.09	-34.00	9.09	-35.67	9.09	-40.85	9.09
21	10.50	5000.00	6.00	0.36	-6.96	10.00	-34.84	10.00	-7.32	9.64	-33.45	9.64	-35.20	9.64	-40.30	9.64
22	10.50	5500.00	4.00	2.46	6.32	10.00	1.08	10.00	3.86	7.54	0.68	7.54	-1.38	7.54	-4.36	7.54
23	10.50	5500.00	5.00	1.91	5.94	10.00	0.70	10.00	4.03	8.09	0.82	8.09	-1.21	8.09	-4.37	8.09
24	10.50	5500.00	6.00	1.36	5.94	10.00	0.70	10.00	4.58	8.64	1.21	8.64	-0.66	8.64	-3.82	8.64
25	10.50	6000.00	4.00	3.46	10.00	10.00	8.16	10.00	6.54	6.54	5.97	6.54	4.70	6.54	2.19	6.54
26	10.50	6000.00	5.00	2.91	10.00	10.00	7.72	10.00	7.09	7.09	6.19	7.09	4.81	7.09	2.24	7.09
27	10.50	6000.00	6.00	2.36	10.00	10.00	7.72	10.00	7.64	7.64	6.29	7.64	5.36	7.64	2.79	7.64

Table 31. Multiple-Lot (Project) results sheet showing the relative costs, pays, and net gains/losses for various AQC combinations at the mean, median, and four confidence levels and four confidence intervals around the median.

AQC Combination Number	Thickness	Strength	Smoothness	Relative Cost (%)	Mean Pay (%)	Median Pay (%)	Mean Net Gain/Loss (%)	Median Net Gain/Loss (%)	Pay @ Conf Level 1 = 50	Pay @ Conf Level 2 = 75	Pay @ Conf Level 3 = 90	Pay @ Conf Level 4 = 95	Net Gain/Loss @ Conf Level 1 = 50	Net Gain/Loss @ Conf Level 2 = 75	Net Gain/Loss @ Conf Level 3 = 90	Net Gain/Loss @ Conf Level 4 = 95
1	9.50	5000.00	4.00	-4.54	-55.88	-55.75	-51.34	-51.21	-55.75	-57.32	-58.83	-59.68	-51.21	-52.78	-54.29	-55.14
2	9.50	5000.00	5.00	-5.09	-56.00	-55.96	-50.91	-50.87	-55.96	-57.43	-58.85	-59.77	-50.87	-52.34	-53.76	-54.68
3	9.50	5000.00	6.00	-5.64	-56.06	-56.05	-50.42	-50.41	-56.05	-57.51	-58.76	-59.52	-50.41	-51.87	-53.12	-53.88
20	10.50	5000.00	5.00	0.91	1.15	1.67	0.24	0.76	1.67	-0.85	-3.46	-5.30	0.76	-1.76	-4.37	-6.21
21	10.50	5000.00	6.00	0.36	0.95	1.27	0.59	0.91	1.26	-1.34	-3.98	-5.48	0.90	-1.70	-4.34	-5.84
22	10.50	5500.00	4.00	2.46	8.94	9.09	**6.48**	**6.63**	9.09	8.46	7.80	7.23	**6.63**	**6.00**	**5.34**	**4.77**
23	10.50	5500.00	5.00	1.91	8.77	8.93	**6.86**	**7.02**	8.93	8.24	7.49	7.00	**7.02**	**6.33**	**5.58**	**5.09**
24	10.50	5500.00	6.00	1.36	8.75	8.87	**7.39**	**7.51**	8.87	8.21	7.50	7.06	**7.51**	**6.85**	**6.14**	**5.70**
25	10.50	6000.00	4.00	3.46	9.90	10.00	**6.44**	**6.54**	10.00	9.86	9.66	9.52	**6.54**	**6.40**	**6.20**	**6.06**
26	10.50	6000.00	5.00	2.91	9.86	10.00	**6.95**	**7.09**	10.00	9.77	9.56	9.33	**7.09**	**6.86**	**6.65**	**6.42**
27	10.50	6000.00	6.00	2.36	9.83	9.97	**7.47**	**7.61**	9.97	9.73	9.48	9.32	**7.61**	**7.37**	**7.12**	**6.96**

AQC Combination Number	Thickness	Strength	Smoothness	Relative Cost (%)	Pay @ Conf Int 1 = 75 LL	Pay @ Conf Int 1 = 75 UL	Pay @ Conf Int 3 = 95 LL	Pay @ Conf Int 3 = 95 UL	Net Gain/Loss @ Conf Int 1 = 75 LL	Net Gain/Loss @ Conf Int 1 = 75 UL	Net Gain/Loss @ Conf Int 2 = 90 LL	Net Gain/Loss @ Conf Int 2 = 90 UL	Net Gain/Loss @ Conf Int 3 = 95 LL	Net Gain/Loss @ Conf Int 3 = 95 UL	Net Gain/Loss @ Conf Int 4 = 99 LL	Net Gain/Loss @ Conf Int 4 = 99 UL
1	9.50	5000.00	4.00	-4.54	-58.51	-53.44	-60.46	-51.63	-53.97	-48.90	-55.14	-47.90	-55.92	-47.09	-57.07	-45.59
2	9.50	5000.00	5.00	-5.09	-58.57	-53.58	-60.31	-51.75	-53.48	-48.49	-54.68	-47.37	-55.22	-46.66	-57.02	-44.86
3	9.50	5000.00	6.00	-5.64	-58.50	-53.58	-60.36	-51.82	-52.86	-47.94	-53.88	-46.85	-54.72	-46.18	-56.41	-44.77
20	10.50	5000.00	5.00	0.91	-2.90	4.80	-7.29	6.67	-3.81	3.89	-6.21	5.21	-8.20	5.76	-12.06	6.87
21	10.50	5000.00	6.00	0.36	-3.39	4.74	-7.07	6.73	-3.75	4.38	-5.84	5.43	-7.43	6.37	-9.01	7.66
22	10.50	5500.00	4.00	2.46	7.95	9.86	6.87	10.00	5.49	7.40	4.77	7.54	4.41	7.54	3.27	7.54
23	10.50	5500.00	5.00	1.91	7.72	9.81	6.69	10.00	5.81	7.90	5.09	8.07	4.78	8.09	3.89	8.09
24	10.50	5500.00	6.00	1.36	7.65	9.74	6.63	10.00	6.29	8.38	5.70	8.62	5.27	8.64	4.60	8.64
25	10.50	6000.00	4.00	3.46	9.69	10.00	9.32	10.00	6.23	6.54	6.06	6.54	5.86	6.54	5.48	6.54
26	10.50	6000.00	5.00	2.91	9.62	10.00	9.24	10.00	6.71	7.09	6.42	7.09	6.33	7.09	5.98	7.09
27	10.50	6000.00	6.00	2.36	9.55	10.00	9.06	10.00	7.19	7.64	6.96	7.64	6.70	7.64	6.35	7.64

Pay at Four User-Entered Confidence Levels: These pays are computed from the single-Lot/multiple-Lot simulations (user-entered number of simulations) for each unique combination of target values and represent the lower limit pay for the confidence level percentage of sections. For example for AQC Combination Number 22, the pay at confidence level 90 percent is 5.81 for a single Lot. Thus, 90 percent of the Lots can be expected to have a composite pay greater than 105.81.

Net Gain/Loss at Four User-Entered Confidence Levels: The net gains/losses are the differences between the pays and the relative costs for each unique combination of target values at each of the four user-entered confidence levels. These are the values that are most useful to a contractor in evaluating agency specifications, and a contractor would want to maximize the net gains. A "risk averse" contractor would want to maximize net gains at a higher confidence level, while a "risk prone" contractor would want to maximize net gains at a lower confidence level. For example, for AQC Combination Number 22, the net gain at confidence level 90 percent is 3.35 for a single Lot. Thus, 90 percent of the Lots can be expected to have a net gain greater than 3.35 percent relative to the cost neutral alternative. In other words, the probability of attaining net gain greater than 3.35 percent is 90 percent if the contractor chooses AQC Combination Number 22. Based on the single-Lot results shown above:

- An extremely risk-prone contractor might choose the highest net gain at the 50 percent confidence level and may want to construct the lot at target value combination #24 (10.5-in PCC thickness, 5,500 lb/in^2 compressive strength, and 6.0 in/mi smoothness [$PI_{0.2}$]).
- A moderately risk-prone contractor might choose the highest net gain at the 75 percent confidence level and may want to construct the lot at target value combination #27 (10.5-in PCC thickness, 6,000 lb/in^2 compressive strength, and 6.0 in/mi smoothness [$PI_{0.2}$]).
- A risk neutral contractor might be guided by the average net gain and may want to construct the lot at target value combination #27 (10.5-in PCC thickness, 6,000 lb/in^2 compressive strength, and 6.0 in/mi smoothness [$PI_{0.2}$]).
- A moderately risk-averse contractor might choose the highest net gain at the 90 percent confidence level and may want to construct the lot at target value combination #27 (10.5-in PCC thickness, 6,000 lb/in^2 compressive strength, and 6.0 in/mi smoothness [$PI_{0.2}$]).
- A extremely risk-averse contractor might choose the highest net gain at the 95 percent confidence level and may want to construct the lot at target value combination #27 (10.5-in PCC thickness, 6,000 lb/in^2 compressive strength, and 6.0 in/mi smoothness [$PI_{0.2}$]).

Based on the multiple-Lot results shown above, all contractors, irrespective of their risk tolerance, may want to construct the project at target value combination #27 (10.5-in PCC thickness, 6,000 lb/in^2 compressive strength, and 6.0 in/mi smoothness [$PI_{0.2}$]).

These descriptions are used only as an example, and results and corresponding rankings of combinations at various levels of risk may differ substantially based on individual user inputs and chosen State/specification.

Pay and Net Gain/Loss at Four Confidence Intervals around Median Profit: The "Results" and "MultiLotResults" sheets also include the lower and upper limit pays and net gains/losses at four user-entered confidence intervals around the median profit. For example, for AQC Combination Number 22, the net gain at confidence interval 90 percent around median profit has a lower limit of 1.15 and an upper limit of 7.54 for a single Lot. Thus, 90 percent of the Lots can be expected to have a net gain between 1.15 and 7.54 percent relative to the cost-neutral alternative. For AQC Combination Number 22, the net gain at confidence interval 90 percent around median profit has a lower limit of 4.73 and an upper limit of 7.54 for a single project (with eight Lots). Thus, 90 percent of the eight-Lot projects can be expected to have a net gain between 4.73 and 7.54 percent. In other words, for a given eight-Lot project, the probability of attaining a net gain between 4.73 and 7.54 percent—if a contractor chooses AQC Combination Number 22—is 90 percent.

Step 8. Reading Graphical Results

The results summarized in tabular format in the "Results" and "MultiLotResults" sheets are also displayed in graphical format in the "GraphicalResults" and "MultiLotGraphicalResults" sheets, respectively. The graphical results sheets include the following:

- Tabular display of AQC combination number and corresponding AQC target values.
- Graphical representation of the simulation distribution for three user-entered AQC combination numbers. Following the Prob.O.Prof 2.0 simulation run, the results of the simulation are stored in two text files, POPOutput.txt and POPOutputML.txt, which are located in the same folder as the corresponding MS Excel file. When a specific AQC combination number is entered for graphical display, the data from the text file is read and the appropriate distribution is plotted in the simulation distribution chart (figure 19). This functionality will not work if these text files are deleted or moved. The simulation distribution chart shows the probability of obtaining a net gain (Y-axis) greater than the corresponding net gain/loss (X-axis), for the selected AQCs. For example, in the figure shown below, the probability of obtaining a net gain/loss greater than 5 percent is 30 percent, 85 percent, and 97 percent for AQC combination numbers 18, 22, and 27, respectively. The probability of obtaining a net gain/loss better than −5 percent is 70 percent, 99 percent, and 100 percent for AQC combination numbers 18, 22, and 27, respectively. A contractor needs to consider both the probability and the actual net gains/losses when comparing various AQC combinations.
- The simulation distribution is also displayed in a bar chart format for each of the selected AQCs (figures 20 through 22).

In all the output sheets, the user can click on the <<*Previous* button to return to the input screens.

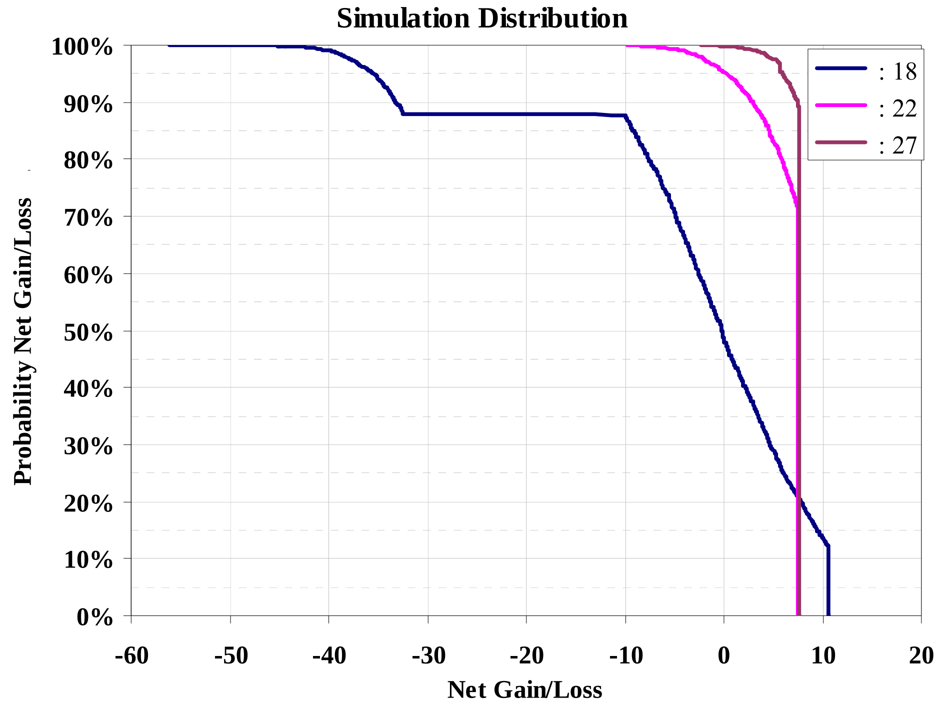

Figure 19. Simulation distribution chart showing the probability of obtaining a net gain (Y-axis) greater than the corresponding net gain/loss (X-axis), for three user-selected AQCs.

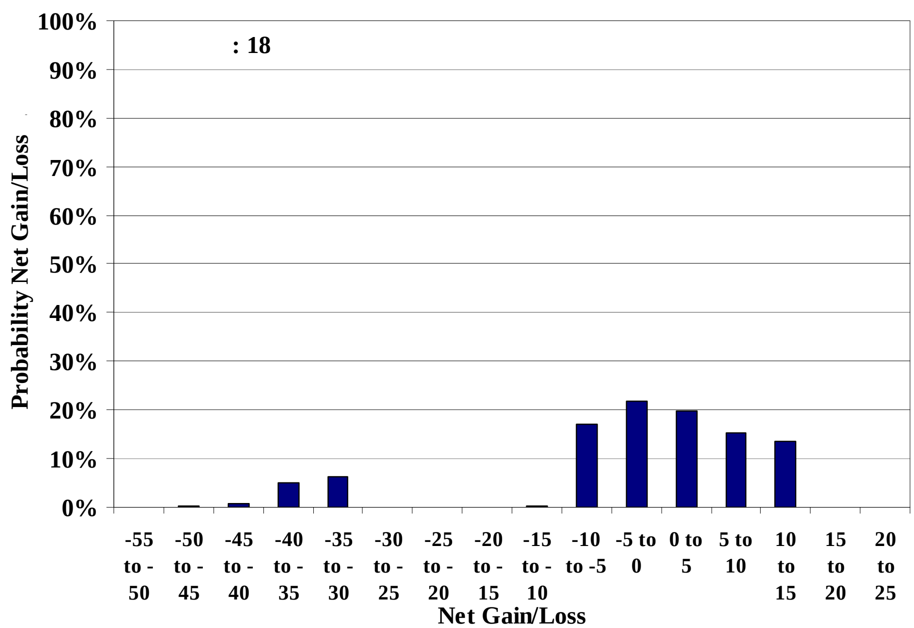

Figure 20. Simulation distribution bar chart showing the probability of obtaining a net gain (Y-axis) and the corresponding range of net gain/loss (X-axis), for AQC combination #18.

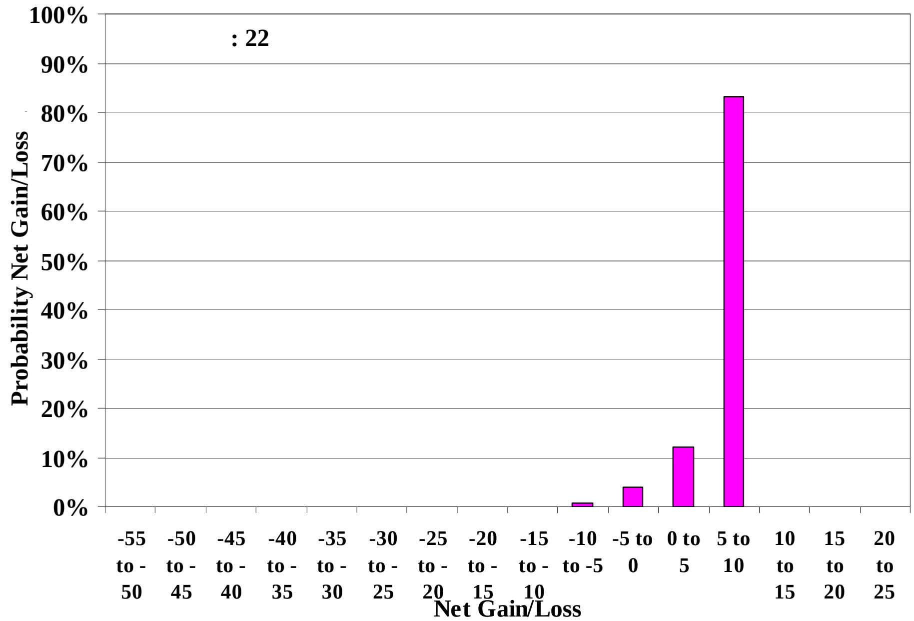

Figure 21. Simulation distribution bar chart showing the probability of obtaining a net gain (Y-axis) and the corresponding range of net gain/loss (X-axis), for AQC combination #22.

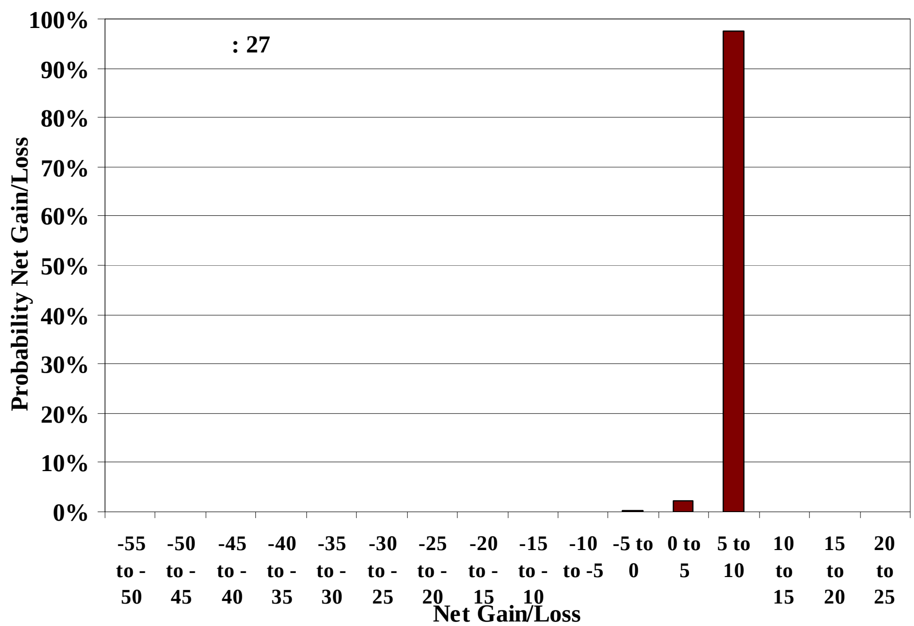

Figure 22. Simulation distribution bar chart showing the probability of obtaining a net gain (Y-axis) and the corresponding range of net gain/loss (X-axis), for AQC combination #27.

SENSITIVITY ANALYSIS

Number of Simulations

Reproducibility of results is a critical issue when performing a Monte Carlo simulation, and a key factor that affects reproducibility is the number of simulations. The greater the number of simulations, the higher the reproducibility of the results. However, reproducibility also is affected by inputs such as sample size, specifications, and target levels. Figures 23 through 27 show the single and multiple-Lot distributions for Prob.O.Prof 2.0 runs (target combination number 1, 15, and 27) with number of simulations ranging from 200 to 5,000, for the PCC AASHTO specification.

To evaluate the reproducibility, for 200 to 5,000 simulations for single and multiple Lots, the simulations were performed 10 times each. The results are summarized in table 32 for three AQC target combinations (1, 15, and 27). The table shows the range (maximum–minimum) of the net gain/loss for the 10 simulation repetitions, and it shows that the results of the simulation are more consistent for higher numbers of simulations (greater than 1,000) and for AQC Combination Number 27 (which had high probability of incentives and very small probability of rejectable material). The table also shows that the 95 percent confidence level interval decreases with higher number of simulations. The detailed results of the 10 simulation repetitions for the three AQC target combinations are shown in table 33.

The inputs for the above analyses were:

- Number of simulations: 200 to 5,000
- Composite Pay Method: Product
- Sample Size: 5 (equal sample size for all AQCs)
- Agency Design/Specified Value: Thickness – 10 in (SD = 0.25 in), Strength – 5,500 lb/in^2 (SD = 500 lb/in^2), Smoothness – 4 in/mi (SD = 1 in/mi)
- Target Value Combination 1: Thickness – 9.75 in, Strength – 5,000 lb/in^2, Smoothness – 3 in/mi
- Target Value Combination 15: Thickness – 10.00 in, Strength – 5,500 lb/in^2, Smoothness – 5 in/mi
- Target Value Combination 27: Thickness – 10.25 in, Strength – 6,000 lb/in^2, Smoothness – 5 in/mi

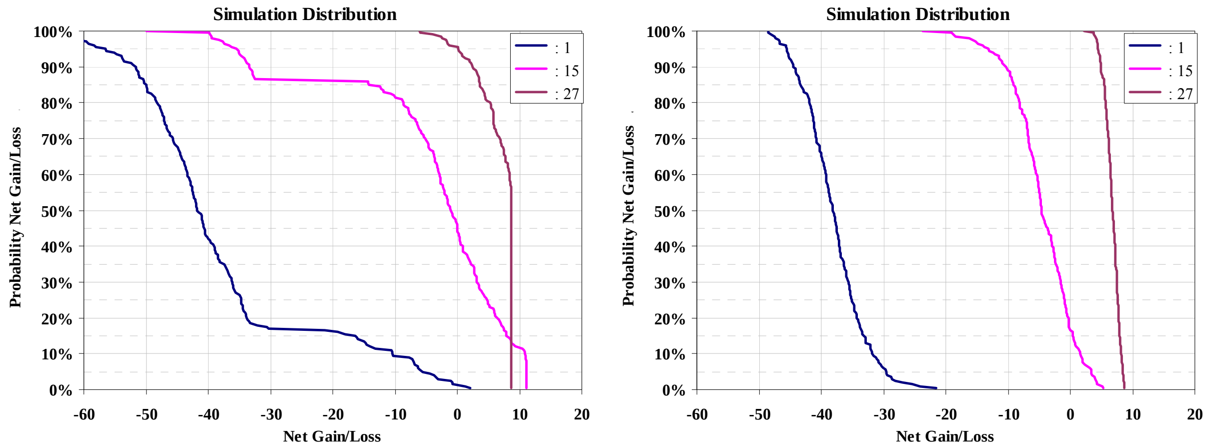

Figure 23. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs with number of simulations = 200.

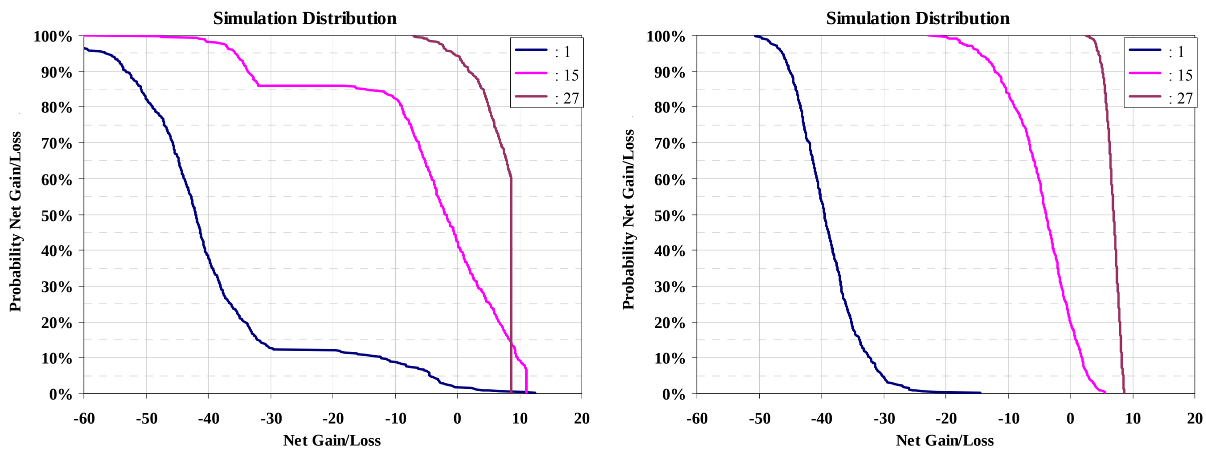

Figure 24. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs with number of simulations = 500.

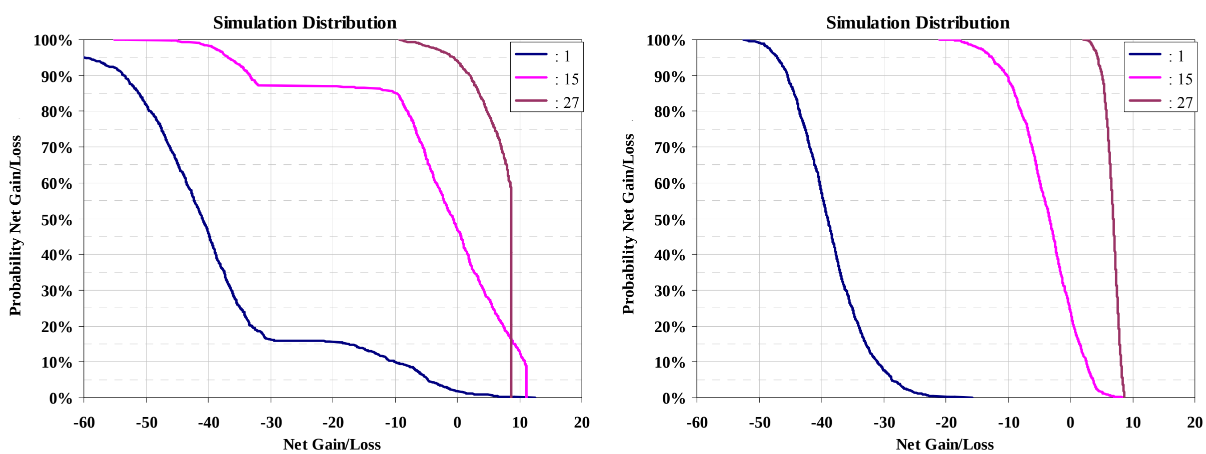

Figure 25. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs with number of simulations = 1,000.

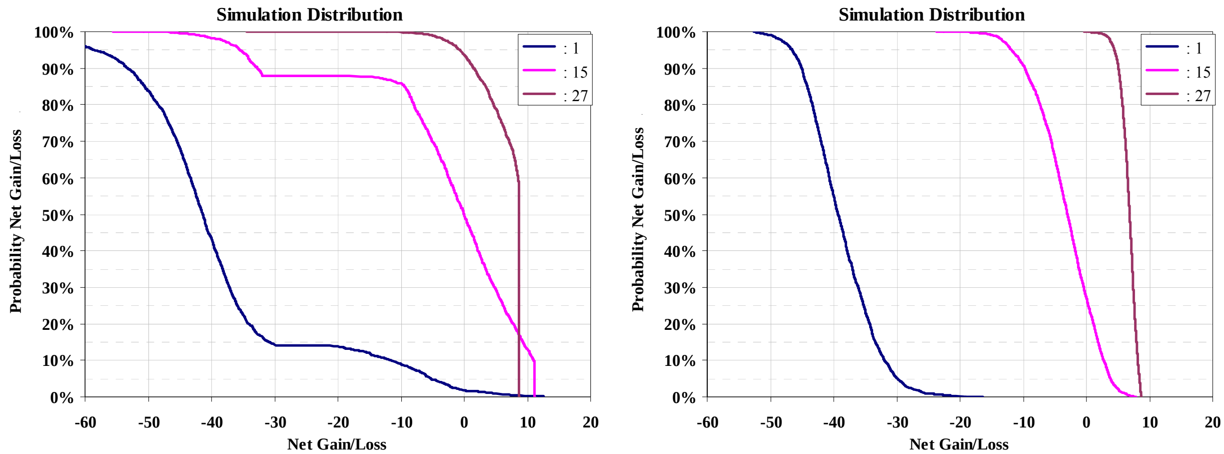

Figure 26. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs with number of simulations = 2,000.

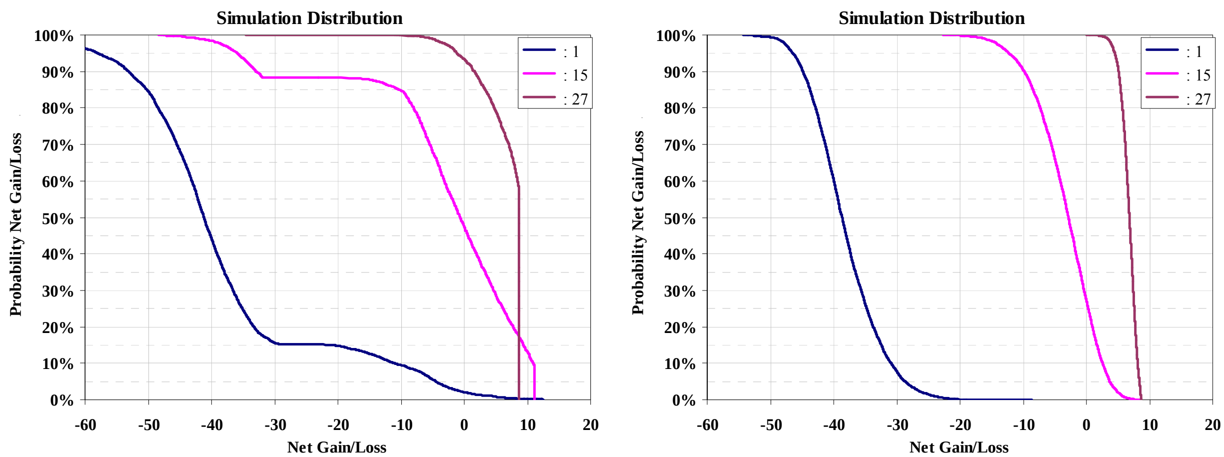

Figure 27. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs with number of simulations = 5,000.

Table 32. Summary results of single-Lot and multiple-Lot sensitivity analysis showing range of net gain/loss (maximum – minimum) for 10 repetitions of simulations for three AQC target combinations.

			NUMBER OF SIMULATIONS				
			200	500	1,000	2,000	5,000
Single Lot Analysis	AQC Combo 1	Mean	2.86	2.00	1.51	0.71	1.00
		Median	1.86	1.17	1.01	0.59	0.47
		CL = 95%	4.87	5.60	2.22	1.69	1.44
	AQC Combo 15	Mean	2.50	2.48	1.20	0.62	0.79
		Median	2.67	1.66	1.33	0.50	0.48
		CL = 95%	2.94	2.33	1.82	1.26	0.97
	AQC Combo 27	Mean	0.87	0.56	0.35	0.14	0.13
		Median	0.00	0.00	0.00	0.00	0.00
		CL = 95%	3.07	1.76	0.80	0.96	0.64
Multiple Lot Analysis	AQC Combo 1	Mean	2.81	2.23	1.53	0.80	1.00
		Median	3.04	1.68	1.54	0.73	0.89
		CL = 95%	2.05	2.18	1.08	0.59	0.80
	AQC Combo 15	Mean	2.79	2.53	1.28	0.73	0.96
		Median	2.83	2.31	1.30	0.85	0.96
		CL = 95%	2.87	3.67	2.20	1.21	0.92
	AQC Combo 27	Mean	0.93	0.58	0.38	0.19	0.16
		Median	0.85	0.61	0.34	0.17	0.14
		CL = 95%	2.90	0.76	0.86	0.43	0.26

Table 33. Detailed results of single-Lot and multiple-Lot sensitivity analysis showing net gain/loss for 10 repetitions of simulations for three AQC target combinations.

			NUMBER OF SIMULATIONS = 200									
Single Lot Analysis	AQC Combo 1	Mean	-38.95	-37.43	-36.96	-39.51	-37.87	-38.68	-39.82	-38.07	-39.16	-37.64
		Median	-41.92	-40.90	-40.40	-41.61	-40.56	-41.24	-41.50	-40.61	-42.27	-40.57
		CL = 95%	-57.29	-59.76	-56.54	-60.30	-57.47	-59.39	-61.41	-59.52	-60.09	-59.17
	AQC Combo 15	Mean	-1.82	-4.22	-2.29	-2.29	-2.41	-4.32	-2.82	-2.05	-2.74	-3.60
		Median	1.17	-1.32	-0.48	-1.05	-0.11	-1.51	-0.98	-0.14	-0.04	-0.14
		CL = 95%	-35.29	-37.03	-34.09	-34.42	-35.07	-36.98	-35.63	-35.56	-35.31	-36.19
	AQC Combo 27	Mean	6.42	6.30	6.92	6.78	6.97	6.73	6.15	6.52	7.02	6.76
		Median	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59
		CL = 95%	-1.50	-1.99	-0.54	-0.69	-0.54	-0.37	-2.98	-0.85	0.09	-1.17
Multiple Lot Analysis	AQC Combo 1	Mean	-39.19	-37.98	-36.62	-38.96	-37.82	-38.80	-39.43	-38.13	-38.94	-37.79
		Median	-40.01	-38.31	-36.96	-39.31	-38.18	-39.51	-39.60	-38.77	-39.57	-38.02
		CL = 95%	-46.68	-45.46	-45.63	-46.20	-45.50	-46.17	-47.52	-45.87	-47.08	-46.33
	AQC Combo 15	Mean	-1.67	-4.03	-2.41	-2.33	-1.98	-4.46	-3.37	-2.02	-3.06	-3.38
		Median	-1.29	-4.12	-1.94	-1.86	-1.31	-3.93	-3.04	-1.90	-2.47	-2.62
		CL = 95%	-10.46	-12.29	-10.38	-10.15	-9.95	-12.82	-10.73	-10.78	-11.10	-12.79
	AQC Combo 27	Mean	6.32	6.30	6.86	6.69	7.12	6.86	6.19	6.63	7.02	6.79
		Median	6.48	6.38	7.04	7.16	7.20	7.22	6.48	6.88	7.23	6.98
		CL = 95%	3.89	4.03	4.71	2.25	5.15	4.10	3.38	4.01	4.76	4.29
			NUMBER OF SIMULATIONS = 500									
Single Lot Analysis	AQC Combo 1	Mean	-38.68	-38.69	-38.80	-39.32	-37.33	-39.03	-38.81	-38.83	-38.39	-38.31
		Median	-41.17	-41.23	-41.78	-41.89	-40.72	-41.81	-41.49	-40.95	-40.87	-40.78
		CL = 95%	-57.51	-57.12	-55.38	-59.96	-58.99	-59.51	-58.27	-59.26	-60.99	-57.54
	AQC Combo 15	Mean	-2.88	-3.72	-4.93	-2.45	-3.64	-2.93	-2.97	-4.12	-2.57	-3.49
		Median	-0.19	-0.31	-1.32	-0.23	-0.14	-0.65	0.10	-1.38	0.28	-0.51
		CL = 95%	-34.84	-36.05	-36.89	-34.96	-36.11	-35.63	-36.15	-37.17	-36.05	-36.61
	AQC Combo 27	Mean	6.87	6.92	6.43	6.55	6.99	6.76	6.80	6.70	6.90	6.91
		Median	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59
		CL = 95%	-0.06	-0.06	-1.17	-1.82	-0.37	-1.17	-1.50	-1.17	-0.22	-1.50
Multiple Lot Analysis	AQC Combo 1	Mean	-38.40	-38.58	-38.96	-39.90	-37.67	-39.20	-38.41	-38.85	-38.37	-38.32
		Median	-38.45	-38.90	-39.42	-39.98	-38.30	-39.58	-38.44	-38.78	-38.78	-38.86
		CL = 95%	-46.87	-47.13	-46.46	-48.07	-46.24	-47.28	-47.29	-46.69	-46.65	-45.89
	AQC Combo 15	Mean	-3.07	-3.27	-4.93	-2.60	-3.71	-3.14	-3.02	-4.06	-2.40	-3.56
		Median	-2.72	-2.74	-4.37	-2.23	-3.33	-2.81	-2.64	-3.75	-2.07	-2.92
		CL = 95%	-11.61	-12.28	-13.92	-11.23	-13.10	-11.90	-12.44	-13.18	-10.25	-11.68
	AQC Combo 27	Mean	6.88	6.87	6.37	6.67	6.95	6.73	6.75	6.64	6.94	6.80
		Median	7.05	7.06	6.52	6.75	7.14	7.00	6.94	6.71	7.12	6.99
		CL = 95%	4.92	4.75	4.16	4.48	4.73	4.40	4.46	4.49	4.85	4.30
			NUMBER OF SIMULATIONS = 1,000									
Single Lot Analysis	AQC Combo 1	Mean	-38.38	-39.05	-38.71	-38.57	-39.51	-38.43	-38.12	-38.00	-38.62	-38.66
		Median	-41.30	-41.36	-41.34	-41.09	-41.88	-40.93	-41.12	-40.87	-41.14	-41.53
		CL = 95%	-59.23	-57.69	-59.82	-58.08	-58.61	-57.80	-58.16	-57.60	-58.52	-59.49
	AQC Combo 15	Mean	-3.32	-3.76	-3.71	-2.93	-2.58	-3.78	-3.40	-3.76	-3.17	-3.44
		Median	-0.43	-0.31	-0.65	-0.63	0.17	-0.81	-0.48	-1.16	-0.14	-0.76
		CL = 95%	-35.63	-36.19	-36.47	-35.35	-35.07	-35.69	-35.77	-35.07	-36.27	-36.89
	AQC Combo 27	Mean	6.51	6.82	6.77	6.73	6.86	6.81	6.69	6.82	6.80	6.74
		Median	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59
		CL = 95%	-1.17	-0.37	-0.69	-1.01	-0.37	-1.17	-0.54	-0.85	-0.54	-0.85
Multiple Lot Analysis	AQC Combo 1	Mean	-38.50	-38.84	-38.69	-38.54	-39.39	-38.28	-37.86	-37.99	-38.60	-38.73
		Median	-38.79	-39.27	-39.28	-38.96	-39.68	-38.65	-38.14	-38.42	-38.67	-39.08
		CL = 95%	-46.76	-46.45	-46.82	-46.22	-47.07	-46.10	-46.69	-45.99	-46.90	-46.82
	AQC Combo 15	Mean	-3.38	-3.56	-3.93	-3.08	-2.65	-3.59	-3.58	-3.64	-3.45	-3.11
		Median	-3.08	-3.08	-3.55	-2.64	-2.24	-3.46	-3.21	-3.35	-3.05	-2.52
		CL = 95%	-12.01	-12.12	-13.19	-10.99	-11.21	-11.74	-12.79	-12.28	-11.92	-11.45
	AQC Combo 27	Mean	6.45	6.78	6.83	6.59	6.82	6.80	6.63	6.72	6.81	6.74
		Median	6.68	6.94	7.02	6.73	6.95	7.02	6.76	6.90	6.95	6.92
		CL = 95%	4.02	4.76	4.75	4.41	4.88	4.53	4.37	4.30	4.73	4.48

Table 33. Detailed results of single-Lot and multiple-Lot sensitivity analysis showing net gain/loss for 10 repetitions of simulations for three AQC target combinations (cont).

			NUMBER OF SIMULATIONS = 2,000									
Single Lot Analysis	AQC Combo 1	Mean	-38.55	-38.81	-38.84	-38.66	-39.26	-38.76	-38.59	-38.69	-38.89	-38.86
		Median	-41.15	-41.28	-41.41	-41.21	-41.74	-41.65	-41.67	-41.29	-41.52	-41.63
		CL = 95%	-59.47	-59.06	-59.07	-58.72	-59.19	-58.95	-59.82	-58.13	-58.73	-58.89
	AQC Combo 15	Mean	-3.46	-3.39	-3.95	-3.79	-3.36	-3.59	-3.47	-3.38	-3.83	-3.33
		Median	-0.49	-0.48	-0.61	-0.98	-0.63	-0.65	-0.48	-0.98	-0.90	-0.48
		CL = 95%	-35.91	-35.13	-35.81	-35.91	-36.11	-36.19	-36.33	-35.07	-35.77	-35.63
	AQC Combo 27	Mean	6.74	6.64	6.61	6.74	6.74	6.75	6.64	6.73	6.61	6.75
		Median	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59
		CL = 95%	-0.54	-0.54	-1.01	-0.85	-1.01	-0.37	-0.69	-0.85	-1.33	-0.85
Multiple Lot Analysis	AQC Combo 1	Mean	-38.65	-38.60	-38.86	-38.73	-39.32	-39.04	-38.51	-38.76	-38.78	-38.82
		Median	-39.18	-39.04	-39.26	-39.00	-39.64	-39.44	-38.91	-39.12	-39.29	-39.11
		CL = 95%	-46.40	-46.81	-46.45	-46.38	-46.85	-46.79	-46.94	-46.46	-46.73	-46.98
	AQC Combo 15	Mean	-3.41	-3.39	-4.01	-3.90	-3.66	-3.58	-3.45	-3.48	-3.85	-3.28
		Median	-3.01	-3.10	-3.59	-3.54	-3.28	-3.12	-3.04	-3.11	-3.43	-2.74
		CL = 95%	-11.86	-11.77	-12.98	-12.86	-12.62	-12.69	-11.92	-11.95	-12.66	-12.01
	AQC Combo 27	Mean	6.70	6.64	6.62	6.69	6.74	6.76	6.59	6.73	6.58	6.77
		Median	6.85	6.82	6.80	6.93	6.90	6.93	6.77	6.92	6.77	6.93
		CL = 95%	4.50	4.44	4.19	4.32	4.52	4.63	4.33	4.46	4.20	4.59
			NUMBER OF SIMULATIONS = 5,000									
Single Lot Analysis	AQC Combo 1	Mean	-39.31	-38.61	-38.66	-38.62	-38.62	-38.31	-38.57	-38.43	-38.65	-38.89
		Median	-41.43	-41.28	-41.46	-41.25	-41.29	-40.99	-41.30	-41.32	-41.33	-41.40
		CL = 95%	-59.63	-59.23	-58.47	-59.13	-58.49	-58.45	-58.19	-58.69	-58.92	-59.18
	AQC Combo 15	Mean	-3.85	-3.74	-3.54	-3.40	-3.29	-3.33	-3.35	-3.43	-3.38	-3.06
		Median	-0.74	-0.68	-0.63	-0.48	-0.65	-0.31	-0.48	-0.65	-0.31	-0.26
		CL = 95%	-36.32	-35.88	-35.49	-35.86	-35.85	-35.35	-35.63	-36.24	-35.91	-35.49
	AQC Combo 27	Mean	6.76	6.63	6.74	6.69	6.73	6.69	6.76	6.70	6.69	6.69
		Median	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59	8.59
		CL = 95%	-0.69	-1.17	-0.69	-0.85	-0.69	-1.33	-0.69	-1.33	-1.17	-0.85
Multiple Lot Analysis	AQC Combo 1	Mean	-39.27	-38.58	-38.51	-38.61	-38.59	-38.27	-38.59	-38.43	-38.69	-38.91
		Median	-39.59	-38.95	-38.86	-39.00	-38.99	-38.69	-38.86	-38.80	-39.07	-39.29
		CL = 95%	-47.14	-46.80	-46.53	-46.54	-46.35	-46.33	-46.39	-46.35	-46.81	-46.63
	AQC Combo 15	Mean	-3.95	-3.75	-3.49	-3.41	-3.26	-3.34	-3.34	-3.39	-3.37	-2.99
		Median	-3.55	-3.32	-3.05	-2.94	-2.79	-3.02	-3.03	-3.03	-3.02	-2.59
		CL = 95%	-12.70	-12.51	-12.23	-12.02	-11.82	-12.01	-11.91	-11.89	-12.03	-11.78
	AQC Combo 27	Mean	6.77	6.60	6.74	6.68	6.75	6.71	6.75	6.69	6.69	6.73
		Median	6.88	6.79	6.91	6.84	6.93	6.88	6.92	6.89	6.88	6.87
		CL = 95%	4.56	4.30	4.55	4.50	4.57	4.43	4.53	4.37	4.52	4.56

Sample Size (AASHTO PCC Specification)

Table 34 shows the effect of sample size on the AASHTO PCC specification for 3 target value combinations (2,000 simulations) for single-Lot and multiple-Lot analysis for a given set of inputs. The table shows the actual net gains and not the range of net gains as in table 32. Three AQCs (thickness, strength, and smoothness) were selected at three target values, resulting in 27 target value combinations. The same sample size was chosen for all three AQCs. The results show that the median is not very sensitive to sample size. However, the mean and the 95 percent confidence value are sensitive to the sample size because they are more affected by extreme values. As in the case of number of simulations, AQC Combination Number 27 is the least sensitive to sample size, while AQC Combination Number 1 is the most sensitive because of the high probability of rejectable material.

Table 34. Effect of sample size on the AASHTO PCC specification showing net gain/loss (mean, median, and at confidence level = 95%) for 3 target value combinations (2,000 simulations) for single-Lot and multiple-Lot analysis.

			SAMPLE SIZE									
			3	4	5	6	8	10	12	15	20	25
Single Lot Analysis	AQC Combo 1	Mean	-39.53	-38.65	-38.59	-39.09	-39.18	-39.55	-39.99	-40.53	-40.99	-41.05
		Median	-41.60	-41.66	-41.09	-41.26	-41.28	-41.32	-41.29	-41.28	-41.51	-41.18
		CL = 95%	-64.59	-60.95	-58.54	-55.44	-52.08	-50.72	-49.38	-48.75	-47.58	-46.93
	AQC Combo 15	Mean	-5.47	-4.54	-3.45	-2.88	-2.30	-1.86	-1.50	-1.23	-1.04	-0.90
		Median	-1.30	-0.67	-0.14	-0.27	-0.63	-0.64	-0.86	-0.73	-0.67	-0.82
		CL = 95%	-38.78	-37.75	-35.91	-35.13	-33.24	-11.80	-9.65	-8.76	-7.82	-6.81
	AQC Combo 27	Mean	6.62	6.64	6.73	6.73	6.74	6.82	6.87	6.96	6.86	6.92
		Median	8.59	8.59	8.59	8.59	7.97	7.70	7.57	7.42	7.24	7.18
		CL = 95%	-5.21	-2.54	-0.54	-0.26	1.10	2.24	2.69	3.51	3.86	4.36
Multiple Lot Analysis	AQC Combo 1	Mean	-39.29	-39.01	-38.80	-39.24	-39.28	-39.44	-40.17	-40.47	-41.04	-41.09
		Median	-39.59	-39.41	-39.11	-39.52	-39.63	-39.90	-40.75	-40.93	-41.37	-41.22
		CL = 95%	-49.68	-48.05	-46.19	-46.05	-45.07	-44.75	-44.18	-44.00	-43.69	-43.34
	AQC Combo 15	Mean	-5.32	-4.59	-3.61	-2.92	-2.36	-1.81	-1.44	-1.22	-1.05	-0.90
		Median	-5.02	-4.17	-3.18	-2.61	-1.93	-1.34	-1.12	-0.94	-0.85	-0.82
		CL = 95%	-16.31	-14.07	-12.82	-10.78	-8.87	-7.45	-6.15	-5.53	-4.67	-3.15
	AQC Combo 27	Mean	6.61	6.67	6.71	6.76	6.74	6.82	6.89	6.94	6.84	6.90
		Median	6.98	6.83	6.89	6.89	6.82	6.89	6.97	7.01	6.89	6.94
		CL = 95%	3.07	4.06	4.64	4.66	5.08	5.42	5.58	5.82	5.82	6.04

The inputs for the above analyses were:

- Number of simulations: 2,000
- Composite Pay Method: Product
- Sample Size: 3 to 25 (equal sample size for all AQCs)
- Agency Design/Specified Value: Thickness – 10 in (SD = 0.25 in), Strength – 5,500 lb/in^2 (SD = 500 lb/in^2), Smoothness (0.2 in blanking band) – 4 in/mi (SD = 1 in/mi)
- Target Value Combination 1: Thickness – 9.75 in, Strength – 5,000 lb/in^2, Smoothness – 3 in/mi
- Target Value Combination 15: Thickness – 10.00 in, Strength – 5,500 lb/in^2, Smoothness – 5 in/mi
- Target Value Combination 27: Thickness – 10.25 in, Strength – 6,000 lb/in^2, Smoothness – 5 in/mi

Sample Size (Alabama AC Specification)

Table 35 shows the effect of sample size on the Alabama AC Specification for 3 target value combinations (2,000 simulations) for single-Lot and multiple-Lot analysis for a given set of inputs. The table shows the actual net gains and not the range of net gains as in table 32. Four AQCs were selected at 4 target values, resulting in 81 target value combinations. The same sample size was chosen for all four AQCs. The results show that the median is not very sensitive to sample size. However, the mean and the 95 percent confidence value are sensitive to the sample size because they are more affected by extreme values.

Table 35. Effect of sample size on the Alabama AC specification showing net gain/loss (mean, median, and at confidence level = 95%) for 3 target value combinations (2,000 simulations) for single-Lot and multiple-Lot analysis.

			SAMPLE SIZE									
			3	4	5	6	8	10	12	15	20	25
Single Lot Analysis	AQC Combo 3	Mean	4.60	5.12	5.52	5.61	5.82	5.90	6.00	6.04	6.04	6.07
		Median	5.90	5.94	6.05	6.05	6.11	6.05	6.05	6.04	6.01	6.01
		CL = 95%	-4.02	-1.25	1.08	1.62	2.88	3.55	4.26	4.52	4.87	5.05
	AQC Combo 46	Mean	-0.53	-0.39	-0.29	-0.25	-0.12	-0.08	0.00	0.11	0.21	0.28
		Median	-1.28	-1.28	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
		CL = 95%	-1.28	-1.28	-1.28	-1.28	-1.28	-1.28	-1.28	-1.28	-1.28	-1.28
	AQC Combo 81	Mean	-7.47	-7.03	-6.72	-6.56	-6.32	-6.27	-6.25	-6.12	-6.14	-6.14
		Median	-6.36	-6.27	-6.12	-6.13	-6.09	-6.12	-6.18	-6.10	-6.19	-6.19
		CL = 95%	-15.58	-12.48	-11.62	-10.58	-8.84	-8.50	-8.06	-7.58	-7.31	-7.17
Multiple Lot Analysis	AQC Combo 3	Mean	4.61	5.14	5.53	5.62	5.82	5.89	5.99	6.04	6.04	6.06
		Median	4.95	5.35	5.69	5.75	5.90	5.95	6.02	6.06	6.04	6.05
		CL = 95%	1.71	2.90	3.74	4.09	4.62	4.89	5.18	5.40	5.55	5.65
	AQC Combo 46	Mean	-0.52	-0.40	-0.30	-0.25	-0.13	-0.08	-0.01	0.12	0.22	0.27
		Median	-0.53	-0.28	-0.28	-0.28	-0.03	-0.03	-0.03	0.22	0.22	0.22
		CL = 95%	-1.33	-1.15	-0.92	-0.78	-0.78	-0.53	-0.53	-0.53	-0.28	-0.28
	AQC Combo 81	Mean	-7.45	-7.06	-6.72	-6.57	-6.32	-6.26	-6.24	-6.11	-6.15	-6.15
		Median	-7.14	-6.82	-6.55	-6.46	-6.24	-6.22	-6.22	-6.11	-6.15	-6.16
		CL = 95%	-10.12	-9.24	-8.57	-7.99	-7.46	-7.16	-7.03	-6.71	-6.62	-6.58

The inputs for the above analyses were:

- Number of simulations: 2,000
- Composite Pay Method: Sum
- Sample Size: 3 to 25 (equal sample size for all AQCs)
- Agency Design/Specified Value: AC Content – 5% (SD = 0.2%), Air Voids – 4% (SD = 0.2%), Mat Density – 96% (SD = 0.5%), Smoothness (0.0 in blanking band) – 18 in/mi (SD = 4 in/mi).
- Target Value Combination #3: AC Content – 4.8%, Air Voids – 3.8%, Mat Density – 95%, Smoothness (0.0 in blanking band) – 21 in/mi.
- Target Value Combination #46: AC Content – 5.0%, Air Voids – 4.2%, Mat Density – 97%, Smoothness (0.0 in blanking band) – 15 in/mi.
- Target Value Combination #81: AC Content – 5.2%, Air Voids – 4.2%, Mat Density – 97%, Smoothness (0.0 in blanking band) – 21 in/mi.

Composite Pay Method (AASHTO PCC Specification)

Using the AASHTO PCC specifications, the above PCC inputs were evaluated with respect to various composite pay methods (sum, product, average, minimum, and weighted average). Again, the result of the sensitivity analysis depends on the exact inputs, particularly the chosen target values and the combination of target values. The graphical results for single Lots and multiple Lots for target Combination Numbers 1, 16, and 27 are shown in figures 28 through 32. The figures show that for the chosen combinations and input values, the product and sum pay methods had greater gains and greater losses as compared to the average and weighted average methods. The minimum pay method showed greater losses and also smaller gains as compared to the average and weighted average methods.

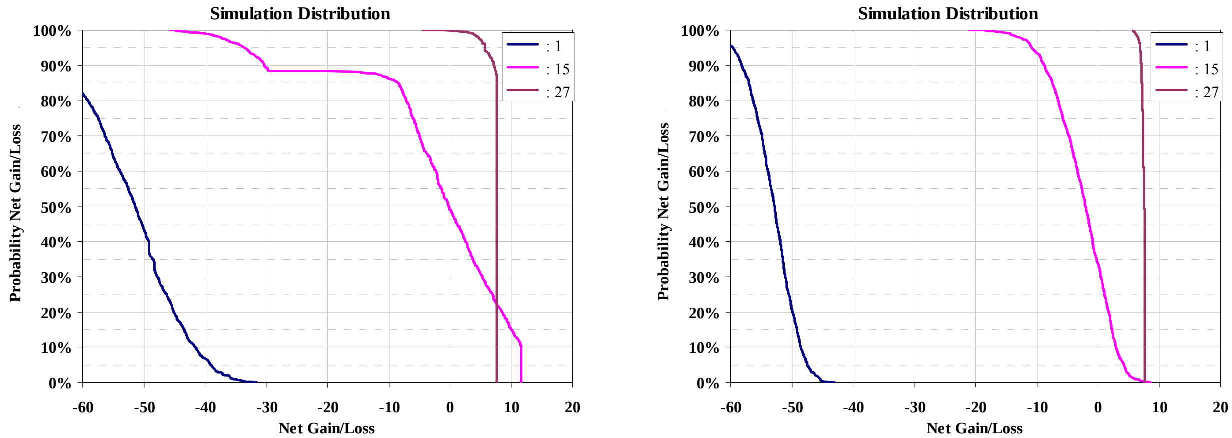

Figure 28. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs using "sum" composite pay method.

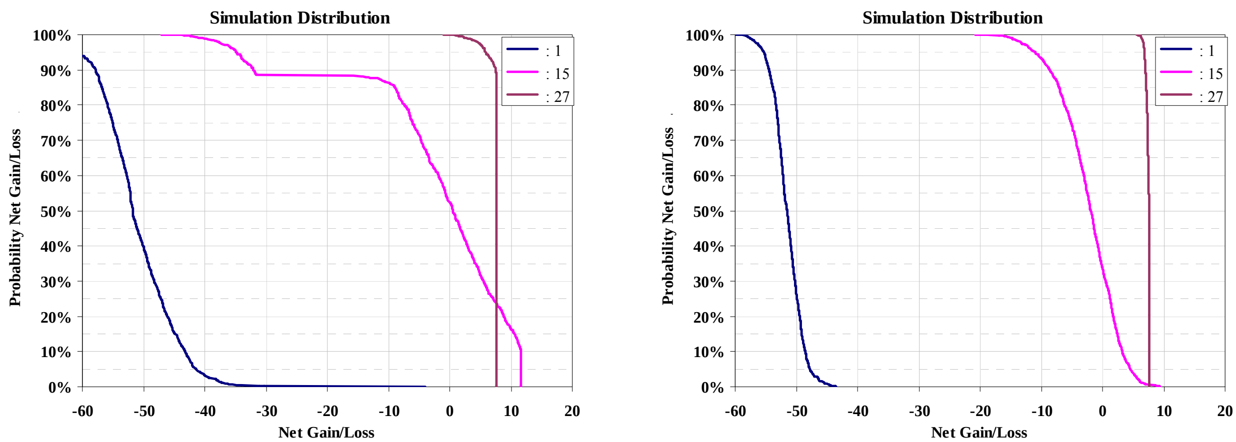

Figure 29. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs using "product" composite pay method.

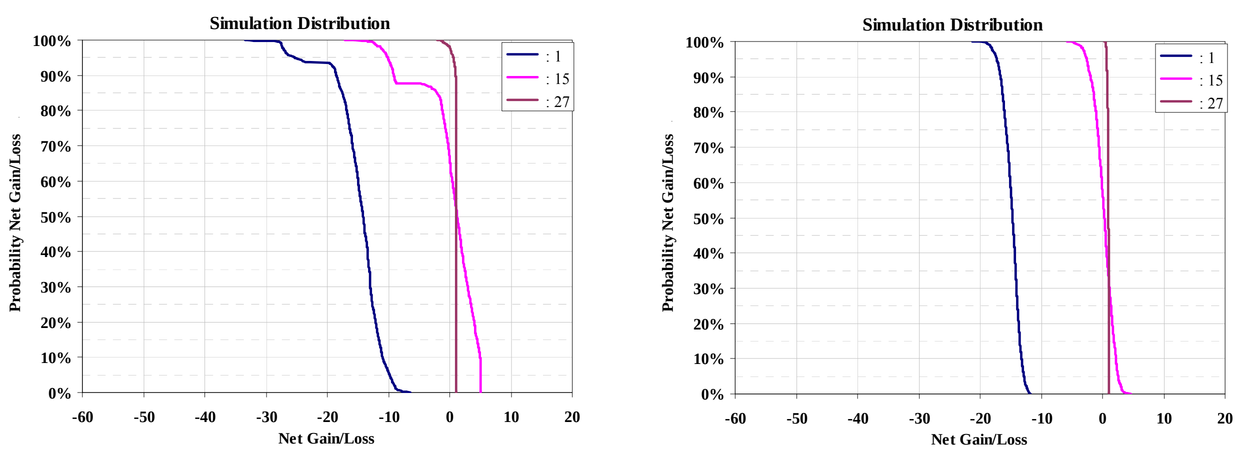

Figure 30. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs using "average" composite pay method.

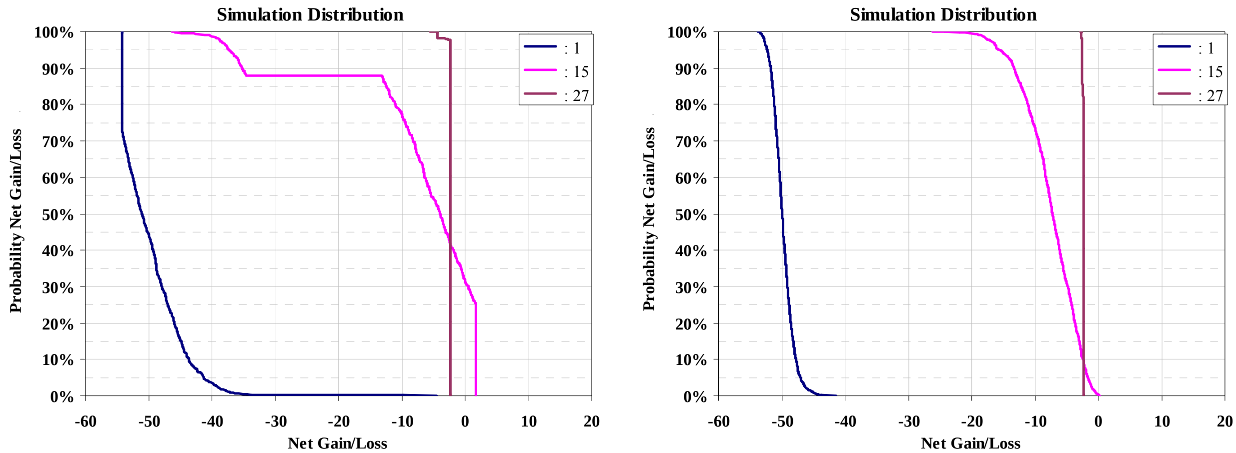

Figure 31. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs using “minimum” composite pay method.

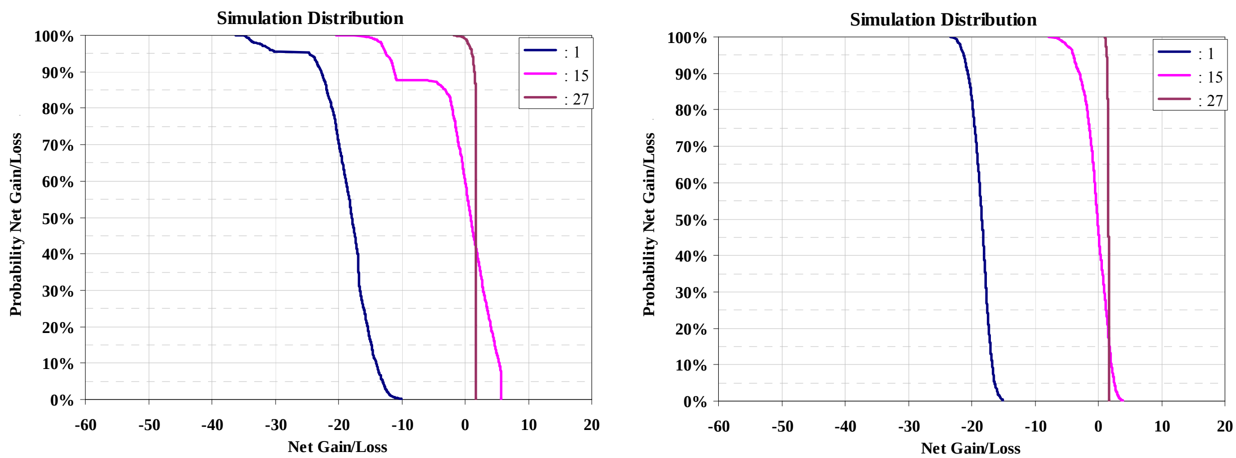

Figure 32. Sensitivity analysis: single-Lot and multiple-Lot simulation distribution charts for three user-selected AQCs using “weighted average” composite pay method (weights: 0.4, 0.4, 0.2).

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REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). 1996. *Quality Assurance Guide Specifications*, AASHTO Highway Subcommittee on Construction, Washington, D.C.

American Association of State Highway and Transportation Officials (AASHTO). 1993. *Guide Specifications for Highway Construction*, AASHTO, Washington, D.C.

Burati, J.L., R.M. Weed, C.S. Hughes, and H.S. Hill. 2003. *Optimal Procedures for Quality Assurance Specifications*, Report No. FHWA-RD-02-095, Federal Highway Administration (FHWA), McLean, Virginia.

Burati, J.L., R.M. Weed, C.S. Hughes, and H.S. Hill. 2004. *Evaluation of Procedures for Quality Assurance Specifications*, Report No. FHWA-HRT-04-046, Federal Highway Administration (FHWA), McLean, Virginia.

Engineering News Record (ENR). 2005. Volume 255, Number 18, ENR, New York, New York.

Federal Highway Administration (FHWA). 1995. "Title 23, Code of Federal Regulation (CFR) Part 637, Subpart B Quality Assurance Procedures for Construction," *Federal Register*, FHWA, Washington, D.C.

Hoerner, T.E., K.D. Smith, and J.E. Bruinsma. 2004. *Incremental Costs and Performance Benefits of Various Features of Concrete Pavements*, Report No. FHWA-HRT-04-044, Federal Highway Administration (FHWA), McLean, Virginia.

Hughes, C.S. 2005. "State Construction Quality Assurance Programs," *NCHRP Synthesis 346*, National Cooperative Highway Research Program (NCHRP), Washington, D.C.

Smith, K.L., L. Titus-Glover, and L.D. Evans. 2002. Pavement Smoothness Index Relationships, Report No. FHWA-RD-02-057, Federal Highway Administration, Washington, D.C.

Transportation Research Board (TRB). 2005. "Glossary of Highway Quality Assurance Terms," *Transportation Research Circular Number E-C074*, TRB, Washington, D.C.

Vidalis, S. 2005. "Relation Between Cost, Quality, and Risk in Portland Cement Concrete Pavement Construction," Ph.D. Thesis Dissertation, University of Florida, Gainesville, Florida.

Walls, J., and M. Smith. 1998. *Life-Cycle Cost Analysis in Pavement Design—In Search of Better Investment Decisions, Interim Technical Bulletin*, Publication No. FHWA-SA-98-079, FHWA, Washington, DC.