Risk Analysis of ODOT's HMA Percent Within Limits (PWL) Specification

Final Report
ODOT Item Number 2182

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Supplementary Notes

15. Abstract

The Oklahoma Department of Transportation (ODOT) is considering switching its method of payment for hot mix asphalt (HMA) construction from their current procedure to a Percent Within Limits (PWL) specification. Quality characteristics are percent asphalt content (%AC), percent laboratory compacted air voids (%AV) and percent roadway density (%RD). As the PWL methodology is new to both ODOT and its contractors, there is concern that differences between the methodologies could result in significant differences in the payments awarded for contracted HMA work.

A risk based simulation approach, using Monte Carlo simulation, was structured to evaluate the probabilities that PWL's generated randomly from a representative data base structured from ODOT paving projects would be within "acceptable" limits. In this way ODOT would be able to assess the expected performance and pay structure resulting from adoption of the PWL methodology against a set of previously collected data.

The data set provided by ODOT showed that contractors are, on average, hitting the target value for asphalt content but running 0.37 and 0.9 percent below the target value for %AV and %RD, respectively. Comparisons of the ODOT generated data to data sets found in the literature indicate that the ODOT data set contains a high measure of control, while the simulation efforts showed that average performance for both %AC and %RD would earn bonuses but less than full pay for %AV, and less than full pay for the lot.

The draft PWL specification as currently written appears to not fairly reward a contractor for a high level of quality control. Recommendations for adjustments in the target limits and specification limits were made. It is recommended that ODOT proceed slowly with the implementation of PWL specifications until a sufficiently large data base can be obtained and the analysis repeated to verify any changes to specification and target limits.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units					Approximate Conversions from SI Units				
Symbol	When you know	Multiply by	To Find	Symbol	Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.40	millimeters	mm	mm	millimeters	0.0394	inches	in
ft	feet	0.3048	meters	m	m	meters	3.281	feet	ft
yd	yards	0.9144	meters	m	m	meters	1.094	yards	yds
mi	miles	1.609	kilometers	km	km	kilometers	0.6214	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.00155	square inches	in^2
ft^2	square feet	0.0929	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.8361	square meters	m^2	m^2	square meters	1.196	square yards	yd^2
ac	acres	0.4047	hectacres	ha	ha	hectacres	2.471	acres	ac
mi^2	square miles	2.590	square kilometers	km^2	km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.0338	fluid ounces	fl oz
gal	gallon	3.785	liters	L	L	liters	0.2642	gallon	gal
ft^3	cubic feet	0.0283	cubic meters	m^3	m^3	cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.7645	cubic meters	m^3	m^3	cubic meters	1.308	cubic yards	yd^3
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.0353	ounces	oz
lb	pounds	0.4536	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C	°C	degrees Fahrenheit	9/5(°C)+32	degrees Celsius	°F
		FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**		
lbf	poundforce	4.448	Newtons	N	N	Newtons	0.2248	poundforce	lbf
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa	kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

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RISK ANALYSIS OF OKLAHOMA'S HMA PERCENT WITHIN LIMITS (PWL) SPECIFICATION

PROBLEM STATEMENT

The Oklahoma Department of Transportation (ODOT) is currently considering switching its method of payment for hot mix asphalt (HMA) from their current QC procedures to one reliant upon compliance within statistical tolerance limits. This latter method, called Percent Within Limits (PWL), reimburses contractors as a function of how closely the mean and standard deviation of five (5) sublot samples collected from a lot of HMA conform to previously established standards and limits for percent asphalt content (%AC), percent laboratory compacted air voids (%AV) and percent roadway density (%RD).

As the PWL methodology is new to both ODOT and its contractors, there is concern that differences between the methodologies could result in significant differences in the payments awarded for contracted HMA work. Contractors have expressed concerns that equivalent performance under the PWL system will result in less payment, while correspondingly ODOT has concerns that additional payments beyond those which would have been awarded under existing QC methods could result from the proposed system.

RESEARCH APPROACH

A risk based simulation approach, selected to address this problem, was structured to evaluate the probabilities that PWLs generated randomly from a data base structured from representative paving projects would be within "acceptable" limits. In this way ODOT would be able to assess the expected performance and pay structure resulting from adoption of the PWL methodology against a set of previously collected data.

The modeling technique chosen for this effort, called Monte Carlo simulation, is based upon:

- the construction of statistical distributions of critical input variables
- random accessing of these statistical distributions
- inputting these randomly accessed values into an appropriate equation or model
- determining a single output
- repeating the process numerous times
- pooling the collected outputs into their own statistical distributions
- determining probabilities of occurrence for desired events.

Figure 1 presents this sequence for a hypothetical model with 'n' input variables. Each is randomly and repeatedly accessed and input into the model which sequentially produces outputs. The collection of outputs is then pooled into a statistical distribution which can be utilized to assess the probability of the individual events.

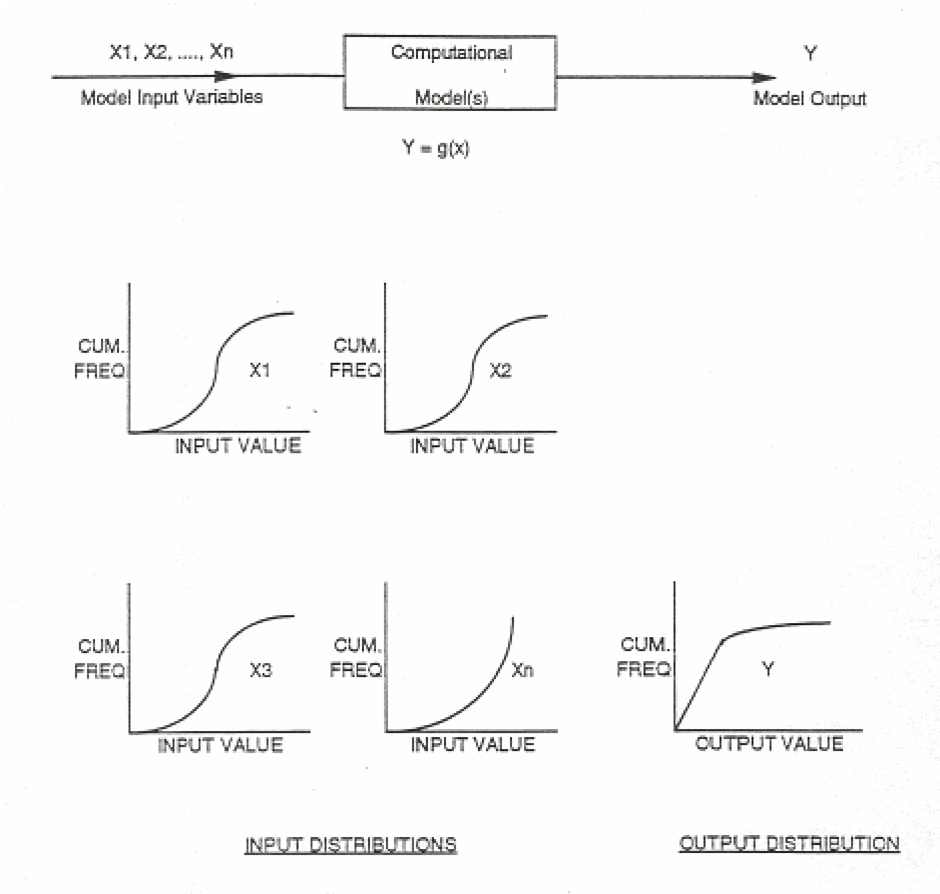

Figure 1 Schematic description of the Monte Carlo method for uncertainty analysis (*American Petroleum Institute, 1994*).

METHODOLOGY

PWL Overview

The proposed ODOT PWL specification uses three quality characteristics, percent asphalt content (%AC), percent laboratory compacted air voids (%AV) and percent roadway density or percent compaction (%RD). The specification consists of upper and lower specification limits and upper and lower target limits. The target limits are within the specification limits and apply a penalty for a target miss. The specification and target limits evaluated are shown in Table 1. The specification and target limits evaluated are the same as used in the original two pilot PWL projects with the exception of the lower specification limit for roadway density. After the pilot projects, ODOT lowered the lower specification limit from 92% to 91%.

Table 1. Trial PWL Specification and Target Limits

Quality Characteristic	Specification Limit		Target Limit	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit
%AC	JMF – 0.4%	JMF + 0.4%	JMF – 0.16%	JMF + 0.16%
%AV	- 1.25%	+1.25%	-0.50%	+0.50%
%RD	91.0%	97.0%	93.0%	96.0%

Table 2 includes examples of the input data set as well as intermediate calculations using PWL equations supplied by ODOT. The means listed for the three variables of concern, %AC, %AV and %RD would result from the five sublot samples taken from each lot in the field. The Final S" in column 2 results from a manipulation of the corresponding standard deviation (s') completed for the five collected sublot samples to address compliance with a target range for each of the three variables. That is, the standard deviation calculated from the field data is "target adjusted."

Table 2. Example PWL Calculation Configuration

Quality Char.	Mean	S'	USL	LSL	UTL	LTL	Closest Target	S"	
%AC	5.14	0.130	5.40	4.60	5.16	4.84	5.16	0.132	
%AV	3.40	0.480	5.25	2.75	4.50	3.50	3.50	0.520	
%RD	92.5	1.025	97.0	91.0	96.0	93.0	93.0	1.140	
	Final S"	Qu	Ql	PDu	PDl	PD	PWL	PF	CPF
%AC	0.130	2.000	4.154	0.00	0.00	0.00	100.00	1.020	
%AV	0.520	3.750	1.058	0.00	14.68	14.68	85.32	0.980	
%RD	1.025	4.390	1.463	0.00	6.72	6.72	93.28	1.010	1.003
							Pay Adjustment		$585.87

Target adjustments are made by the following:

If the absolute value of the collected mean value minus the lower target limit (LTL) established by ODOT is less than the absolute value of the collected mean minus the upper target limit (UTL) then the LTL is used. If the absolute value of the collected mean value minus the lower target limit (LTL) established by ODOT is greater than the absolute value of the collected mean minus the upper target limit (UTL) then the UTL is used. In a more typical equation format this relationship is equal to:

IF (ABS(Mean-LTL)<ABS(Mean-UTL)

$$\text{Target} = \text{LTL} \qquad [1]$$

IF (not true)

Target = UTL [1a]

The target value is used to calculate a modified standard deviation or "target-adjusted" standard deviation, S":

S"= SQRT((original sample standard deviation)^2 + (target value- mean)^2) [2]

The target adjusted standard deviation is compared to the original sample standard deviation and to an upper and lower specification limit (USL and LSL) to generate a Final S" which is used for subsequent calculations:

IF (original sample mean > LSL and < LTL)

Final S" = target-adjusted standard deviation (S") [3]

and/or

IF (original sample mean > UTL and < USL)

Final S" = original sample standard deviation (S') [3a]

Some intermediate calculations are performed to find the upper and lower quality index, Q_U and Q_L, as well as the upper and lower percent defectives (PD_U and PD_L). Q_U and Q_L are calculated:

Q_U = (USL-original sample mean) / Final S" [4]

Q_L = (original sample mean-LSL) / Final S" [4a]

The upper and lower percent defective (PD_U and PD_L) are accessed by standard percent defective tables using Q_U and Q_L. For ODOT and this effort the table has been reduced to equation form.

The upper and lower percent defectives (PD_U and PD_L) are converted to an overall percent defective (PD) by:

$PD = PD_U + PD_L$ [5]

and the percent within limits (PWL) follows:

PWL = 100 – PD [6]

Additional calculations include a payfactor (PF) for each of the three input variables (%AC, %AV and %RD) and a composite pay factor (CPF) for the entire lot. Respectively, these are:

IF (PWL<50)

$$PF = 0 \text{ (No pay is awarded)} \quad [7]$$

IF PWL ≥ 50

$$PF = 0.0324(PWL) - 0.00016(PWL)^2 - 0.62 \quad [7a]$$

and

$$CPF = (2^* \text{ PF for \%AC} + 3^* \text{ PF for \%AV} + 5^* \text{ PF for \%RD})/10 \quad [8]$$

Briefly, equation 7 introduces an ODOT constraint where no pay will be awarded for a compliance rate of less than 50 percent within limits for any of the three variables. Equation 8 presents the overall composite formula for payment; where the PWLs for %AC, %AV and %RD have weightings of 2, 3 and 5, respectively. This means that ODOT places 2.5 times as much emphasis on compliance with roadway density as they do asphalt content. Equation 8 will generate a maximum value of 1.02, indicating a possible 2% bonus payment for outstanding compliance to the new standards.

The pay adjustment for the lot (PA_{Lot}) can be determined by multiplying the composite pay factor (CPF) by the product of the contract unit price (CUP) per ton for the HMA and the quantity of HMA in the lot (Q_{Lot}). For this effort Q_{Lot} and CUP were assumed as 5,000 tons and $40.00 per ton, respectively. Equation 9 presents this relationship:

$$PA_{Lot} = (CPF - 1)^*\$40/\text{ton}^*5000 \text{ tons per lot} \quad [9]$$

Random inputs of means and Final S" for each input variable were repeatedly and randomly accessed and employed within these equations in a Monte Carlo format to produce a series of outcomes with some probability of occurrence. The next section of this report details this effort.

Monte Carlo Structure

For this project, a representative data base generated from previous QC paving projects was secured from ODOT. This data base consisted of the means and standard deviations of %AC, %AV and %RD calculated from sample lots collected from projects considered by ODOT to be appropriate for this evaluation. One hundred and four (104) means and ninety-three (93) standard deviations (s') were included in the data set. Sample standard deviations were modified in accordance with equations [3] and [3a] and statistical distributions for the sample means and Final S" values for %AC, %AV and %RD were determined using the software package @Risk (Palisades, 2004).

The statistical distributions for these input data were then randomly accessed repeatedly to eventually define the statistical distributions for PWL and other output variables of interest. A two stage process was established:

- Phase 1 sampling: 1,000 random samples were taken from the input distributions, each individually input into the pertinent PWL equations. Comparisons were made between these simulations to identify stability of outputs across iterations. Comparisons were also made between Monte Carlo and Latin Hypercube sampling techniques,

- Phase 2 sampling: complete 1,000 random samples for each of 10 iterations. Pool data at the completion of each iteration. Compare results.

RESULTS

Input Statistical Distributions

Statistical distributions were developed for the collected means and Final S" for %AC, %AV and %RD, respectively, using the BestFit subprogram available in the professional version of @Risk (Palisades Corp., 2005). Figures 2 through 7 present these data. The histograms included in each of these figures represent the actual data while the curve is the fitted distribution. The @Risk software compares three methods for determining the most appropriate statistical distribution, the Chi Square, the Anderson Darling and the Kolmogorov-Smirnov. For this effort, the default distributions reported by the software were used for subsequent simulations. Each figure also delineates the central 90% of the distributions. For example, in Figure 2, the normalized means of the sampled %AC values, 90% of the data are between -0.2156 and 0.1971.

Examination of these figures shows that the Final S" distributions for all three variables, as well as the distribution of the %RD means, were discontinuous across the distributions. Three of the variables exhibited this in the right tail while the %RD means displayed this pattern in both tails. Frequently, these types of discontinuities can be attributable to data outside the general range of collection. For additional analyses, these four distributions were truncated to reflect these discontinuities and similar Monte Carlo simulations were completed. The results generated with the truncated data sets exhibited marginally higher PWL compliance probabilities than did the unmodified inputs, but these differences were not considered significant and they are not included in this report. They are available; however, to ODOT should it be so desired.

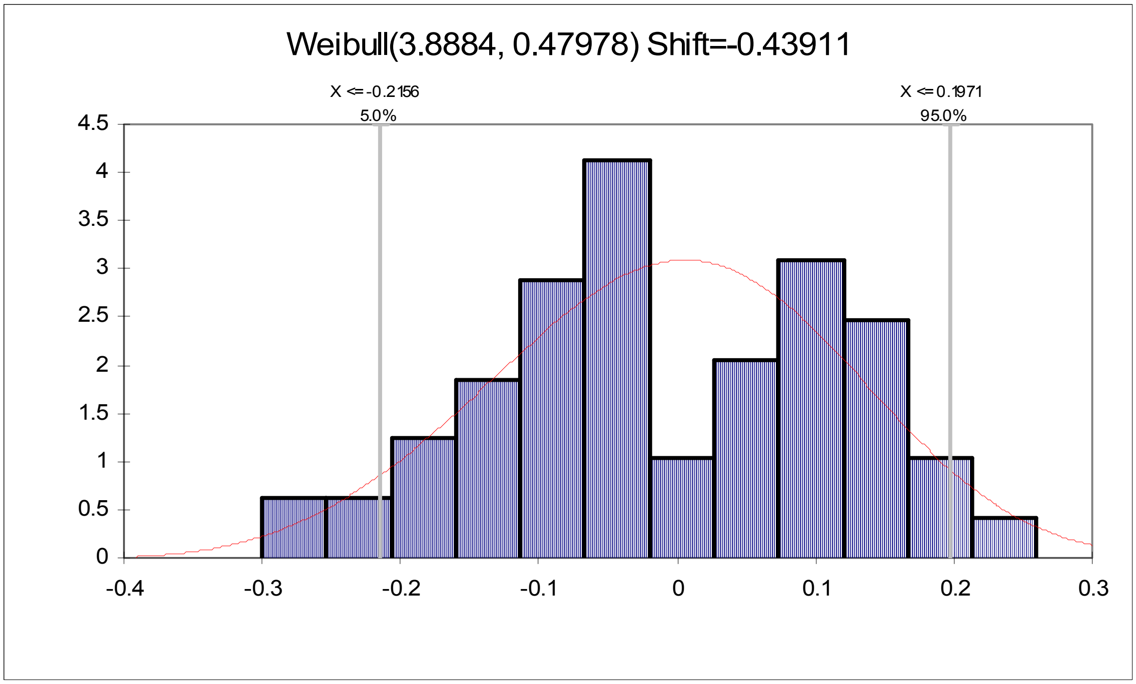

Figure 2 Input data and statistical distribution for %AC means.

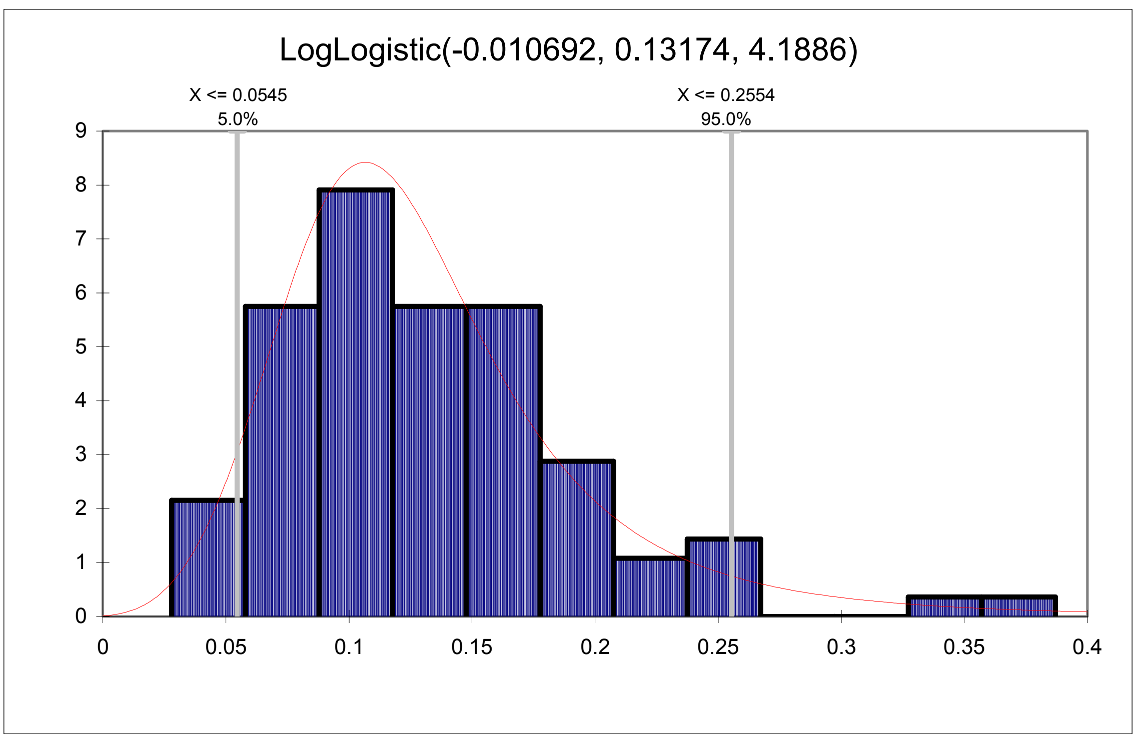

Figure 3 Input data and statistical distribution for %AC Final S".

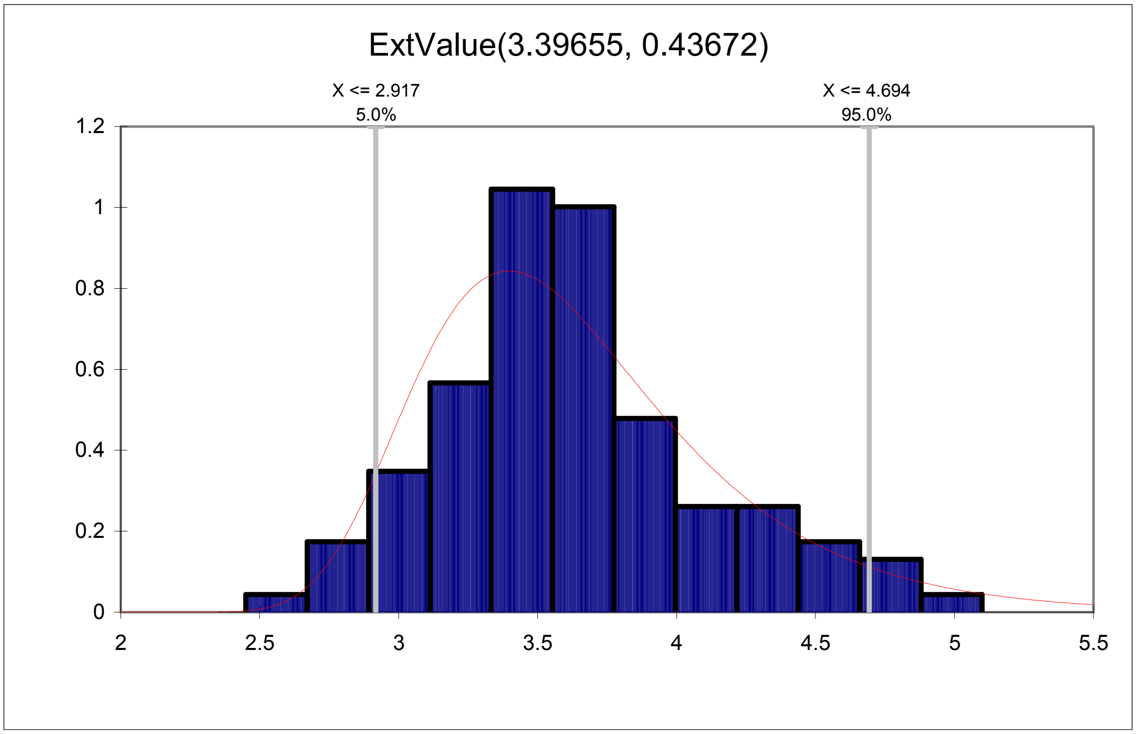

Figure 4 Input data and statistical distribution for %AV means.

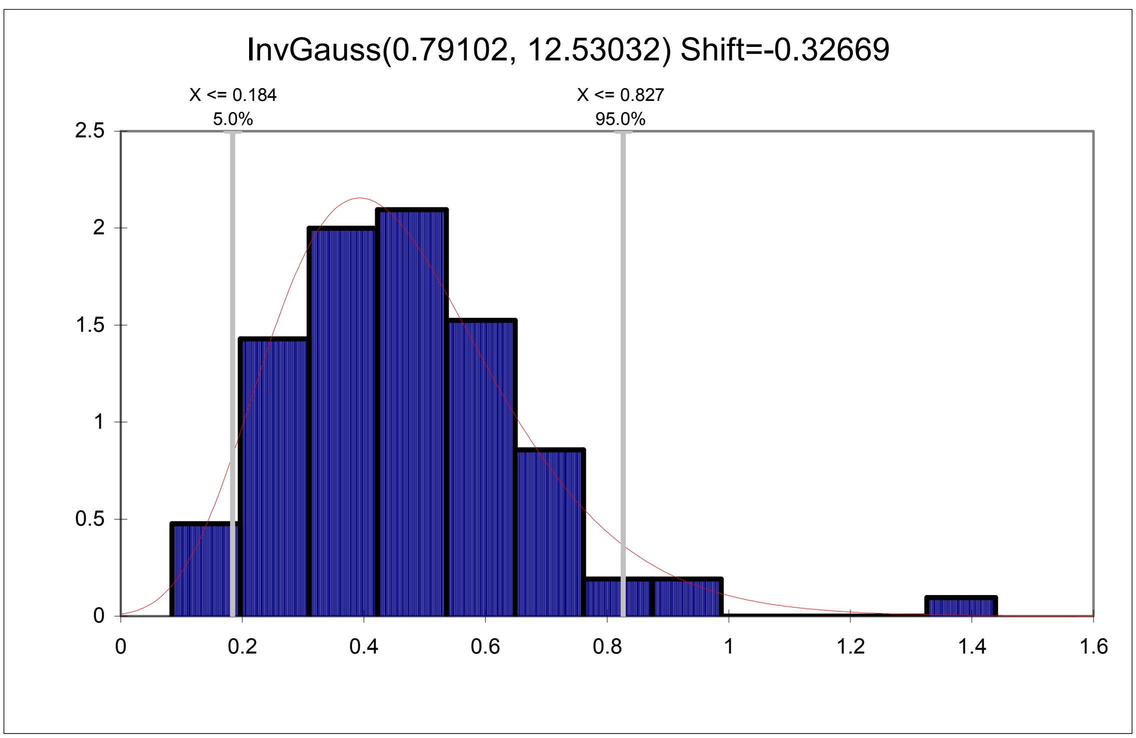

Figure 5 Input data and statistical distribution for %AV Final S".

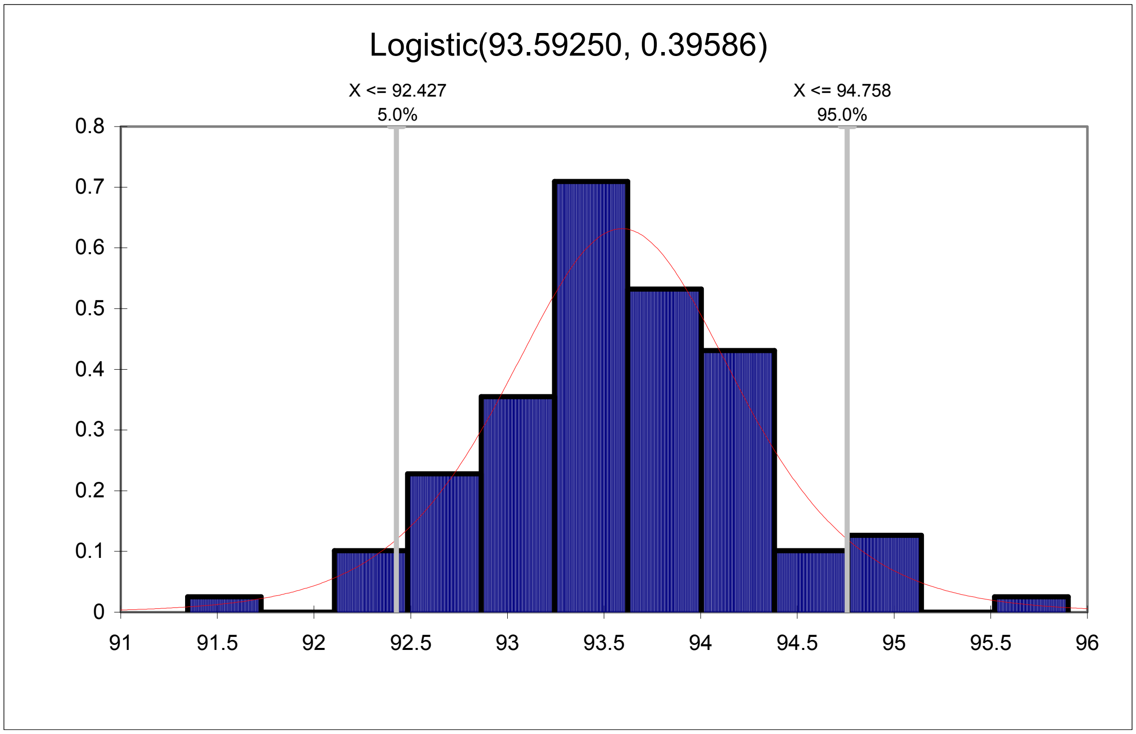

Figure 6 Input data and statistical distribution for %RD means.

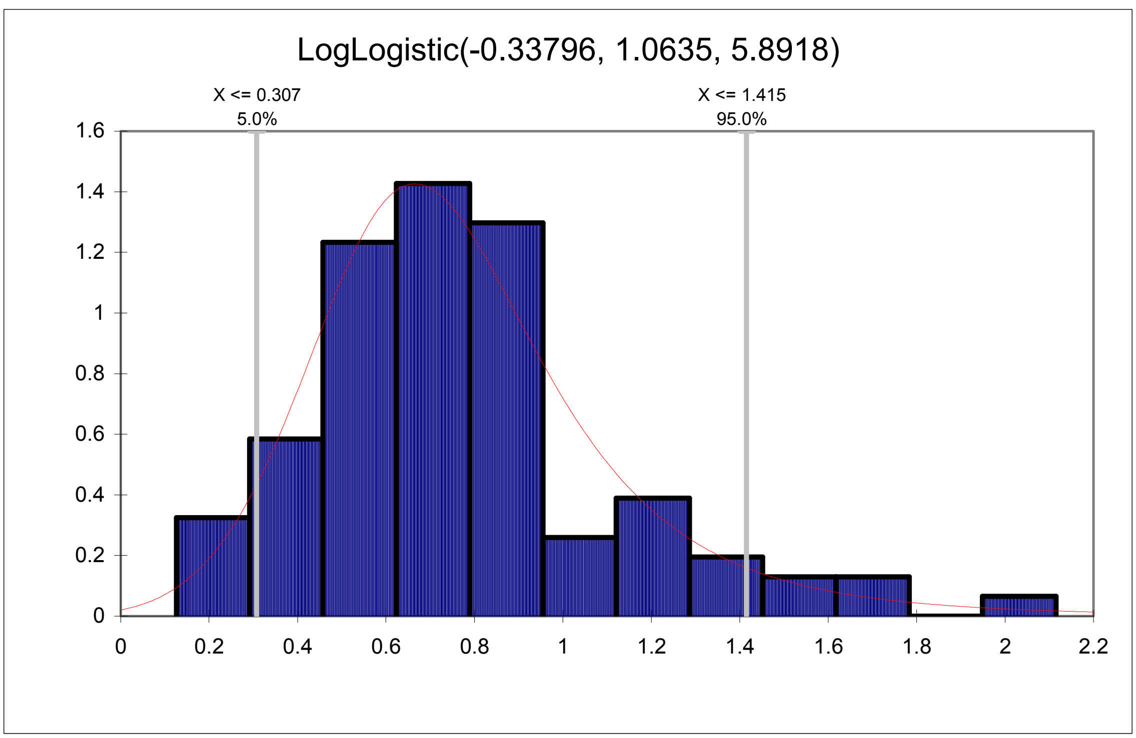

Figure 7 Input data and statistical distribution for %RD Final S".

Comparisons to Published Data

In order to fully interpret the results of the Monte Carlo simulations, an indication of the quality of the data is necessary. That is, does the data set represent the best effort, average effort or below average effort of Oklahoma contractors. This determination is by nature subjective; however, the data can be compared to published data to assist in this ranking.

Three reports were found in the literature with published means and standard deviations for HMA construction QC/QA results. The reports are Cominsky, et al., NCHRP Report 409, 1998; Parker and Hossain, TRR 1813, 2002; and Hall and Williams, TRR 1813, 2002. Their results are shown in Table 3. The standard deviations were calculated assuming that the data was normally distributed, a common assumption with construction data. In order to compare the ODOT data to the published data, the means and standard deviations for the ODOT data were calculated assuming a normal distribution as well. The results are shown in Table 3.

Table 3. Comparison of ODOT Data with Published Data

		ODOT Data	Hall & Williams Arkansas DOT			Parker Alabama DOT	Cominsky NCHRP 409
			High	Medium	Poor		
%AC							
	Mean	-0.01	0.06	0.21	0.33	0.004	*
	s	0.128	0.184	0.251	0.413	0.248	0.24
%AV							
	Mean	3.63	3.58	3.09	5.02	3.60	*
	s	0.48	0.649	0.768	2.097	0.903	0.9
%RD							
	Mean	93.6	92.57	91.82	90.43	93.22	*
	s	0.72	0.790	0.959	1.313	1.132	*

*Data not reported.

Hall and Williams separated their project data into three categories of process control, high, medium and poor control. The other cited reports are averages for all project data. The Oklahoma data appears similar to the high control data for Arkansas and shows similar means and lower standard deviations than the NCHRP data or the Alabama data. The Oklahoma data used in the Monte Carlo simulations appears to have a high level of control.

Simulation Results

PWL Determinations

Figures 8, 9 and 10 are presented here to illustrate the overall trends that were evident in all of the simulations. The output data generated for all simulations is available from the authors but is not included in the report due to the large size of the data sets. Figures 8, 9 and 10 are one of ten iterations, each with 1,000 simulations, which were completed to determine the percent within limits (PWL) for %AC, % AV and %RD, respectively. Figure 8 shows that for % AC, 0.2% of the time a PWL less than 50% would result and that 12% of the time a PWL from 50 to 90% would be expected. (Please note that the 12.2% attributed in Figure 8 inclusively is the less than 90% PWL for %AC: this includes the 0.2% associated with the less than 50% compliance interval.) PWL's greater than 90% were projected 87.8% of the time, with a mean or expected value of 96.72%.

Figures 9 and 10 illustrate the projected PWL's for %AV and %RD, respectively. As with Figure 8, these figures are representative of those generated for the entire set of simulations. These figures also highlight the probabilities in the less than 50%, from 50% to 90% and greater than 90% ranges. In summary, for %AV, 2.6% of the lots would be expected to produce a PWL less than 50% and 32.2 percent of the time ODOT could expect a PWL between 50% and 90%. This means that 65.2% of the time %AV would have a PWL greater than 90%. Similarly for %RD, these representative simulations show that a PWL ≤ 50% would be earned only 0.1% of the time, while a PWL greater than 90% would be expected to occur 97.7% of the time.

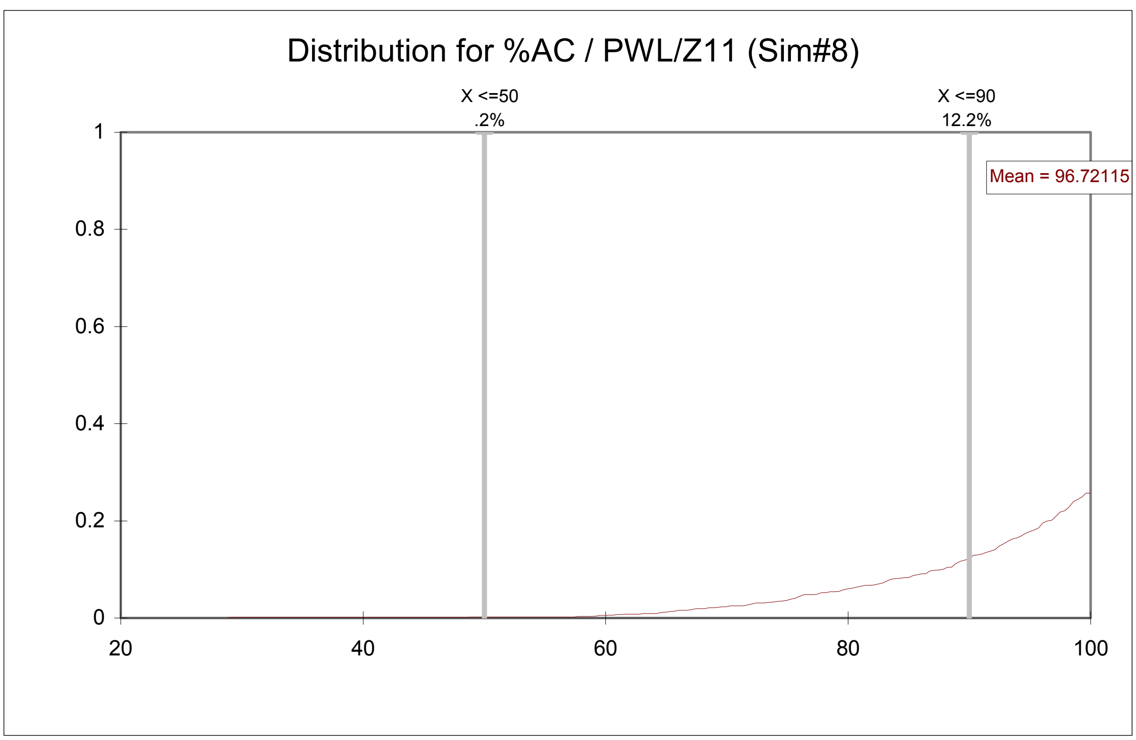

Figure 8 Representative PWL curve for %AC: target adjustment, no truncation.

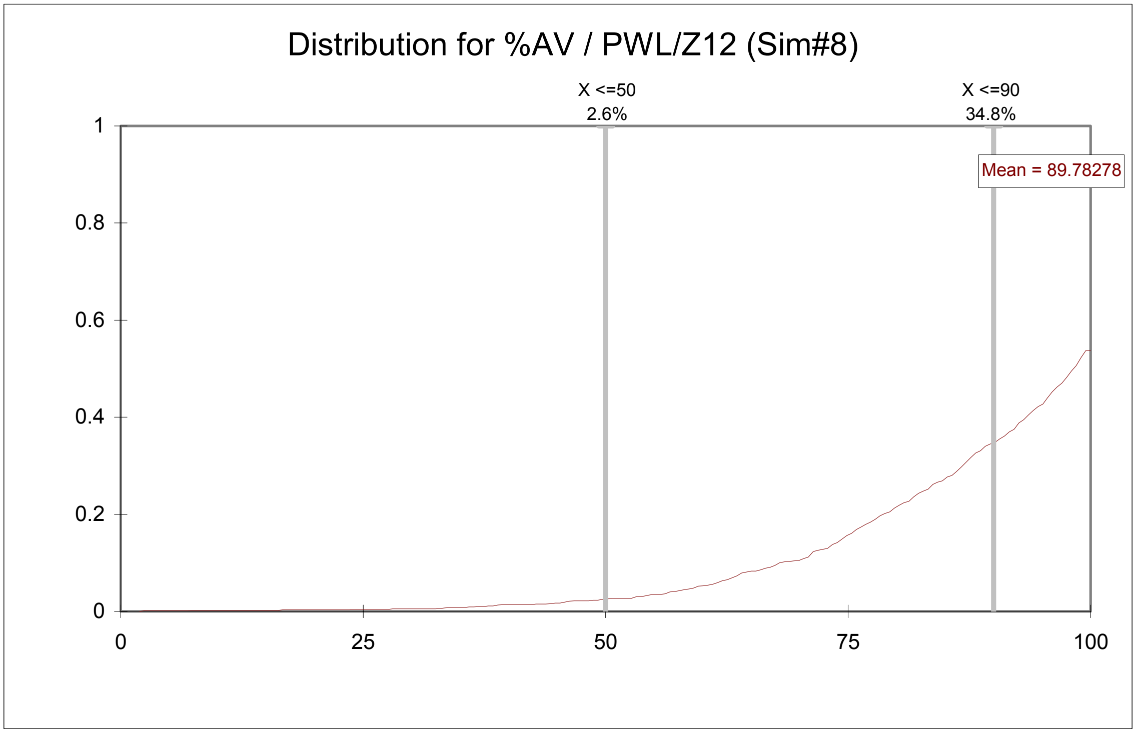

Figure 9 Representative PWL curve for %AV: target adjustment, no truncation.

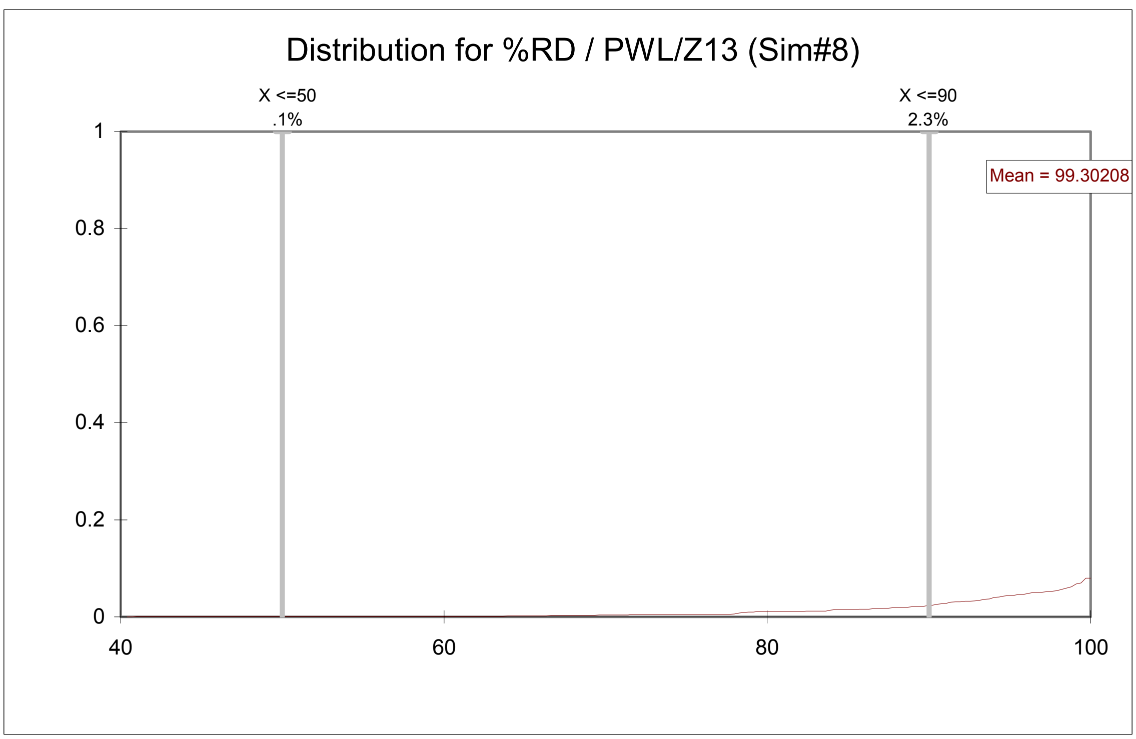

Figure 10 Representative PWL curve for %RD: target adjustment, no truncation.

Table 4 summarizes these graphed simulations as well as the other nine completed for this effort while Table 5 presents additional results for these same simulations. Table 4 shows that the average of all 10 simulations for %RD is that 96.71% of the time a PWL greater than 90% is expected, with corresponding probabilities for %AC and %AV equaling 87.99% and 62.13%, respectively. Obviously, %AV is the least responsive of the three variables tested for the data set provided by ODOT having the lowest percent compliance for the greater than 90% interval while also having 2.5% of the individual simulations occurring in the less than 50% compliance interval. The data in Table 4 exhibit good consistency across the simulations. This is an additional measure of the overall quality of the simulation which supports Phase 1 efforts briefly discussed earlier in this report.

Table 5 presents an alternative analysis of the full data base. The minimum, maximum and mean for each of the 10 simulations is presented. Unlike Table 4, these have no probabilities associated with them. Rather, these data are included to highlight the range of individual Percent Within Limits (PWL) that could be expected from collected data similar to those provided by ODOT.

The data confirm the previously presented probability values in that for all three variables the mean percent within limits were exceptionally high; generating mean scores of 96.8, 88 and 99% compliance respectively. Of the three quality characteristics, air voids (%AV) had the lowest mean and minimum PWL.

Table 4. Percent Within Limits (PWL) for %AC, %AV and %RD

%AC										
Iteration:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
50-90%	12.2	13.4	11.4	9.7	9.3	14.3	12.4	12.0	10.9	11.6	11.72
>90%	87.6	86.3	88.3	90.2	90.1	85.4	87.3	87.8	88.8	88.1	87.99
<50%	0.2	0.3	0.3	0.1	0.6	0.3	0.3	0.2	0.3	0.3	0.29
%AV											
50-90%	35.7	34.1	38.1	36.6	38.4	34.1	33.7	32.2	35.0	35.7	35.36
>90%	62.2	63.1	59.9	60.3	59.3	63.4	63.3	65.2	62.3	62.3	62.13
<50%	2.1	2.8	2.0	3.1	2.3	2.5	3.0	2.6	2.7	2.0	2.51
%RD											
50-90%	3.5	4.1	2.9	2.7	3.5	2.6	3.4	2.2	3.7	3.2	3.18
>90%	96.4	95.9	96.9	97.1	96.4	97.4	96.4	97.7	96.2	96.7	96.71
<50%	0.1	0.0	0.2	0.2	0.1	0.0	0.2	0.1	0.1	0.1	0.11

Table 5. Data Summary for Simulated PWL Values by Variable and Iteration

%AC											
Iteration:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
Minimum	28.25	41.34	31.16	44.95	42.00	40.04	38.14	28.41	34.10	42.88	37.12
Mean	96.70	96.64	96.90	97.28	91.19	96.44	96.66	96.72	96.89	96.78	96.82
Maximum	100	100	100	100	100	100	100	100	100	100	100
%AV											
Minimum	6.90	6.05	2.80	7.88	2.97	2.74	2.02	1.41	0.91	18.45	5.21
Mean	89.13	89.55	88.76	88.12	88.26	89.59	88.69	89.78	88.84	89.21	88.99
Maximum	100	100	100	100	100	100	100	100	100	100	100
%RD											
Minimum	49.34	51.50	47.80	21.84	46.87	55.39	40.38	40.40	28.44	37.34	41.93
Mean	98.97	98.98	99.11	98.94	99.07	99.32	98.87	99.30	98.90	98.83	99.03
Maximum	100	100	100	100	100	100	100	100	100	100	100

Pay Factors (PF)

Figures 11, 12 and 13 present the probability plots for pay factors (PF) for %AC, %AV and %RD, respectively. These figures show the percent payment, as a decimal, that the contractor would expect from the simulated efforts for each of the three variables of concern. Reflective of the previously presented PWL analyses, the highest percentage for payment would be in the %RD category followed by %AC and %AV. Roadway density (%RD) had a mean pay factor of 1.017025 from a maximum achievable of 1.02, while the mean pay factor for %AC and %AV were 1.006094 and 0.9547253, respectively. These results show that a mean response for road bed density and asphalt content would earn the contractor bonus pay and that this performance for %AV would earn less than full pay.

Table 6, which presents other relationships from this single set of simulations, reinforces the observation originally made with the PWL data that %AV, as defined by the data base supplied by ODOT, limits the overall potential performance of the contractors operating under the proposed system, generating a full pay to bonus payment condition only 65.2 % of the time. A penalty would be expected the other 34.8% of the time. Approximately two-thirds of this penalty would be in the 10% or less range, with the other one-third being greater than 10%. The corresponding penalty values for %AC and %RD would be 3.3 and 0.5% of the time, respectively.

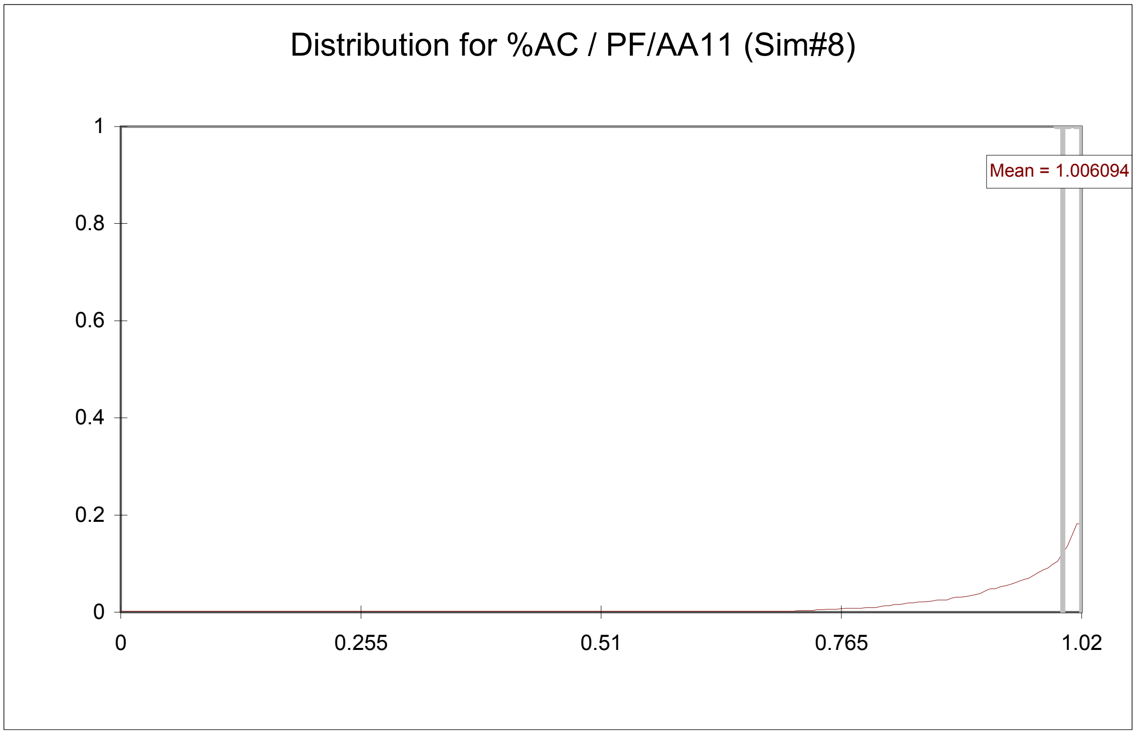

Figure 11 Pay Factor (PF) for %AC.

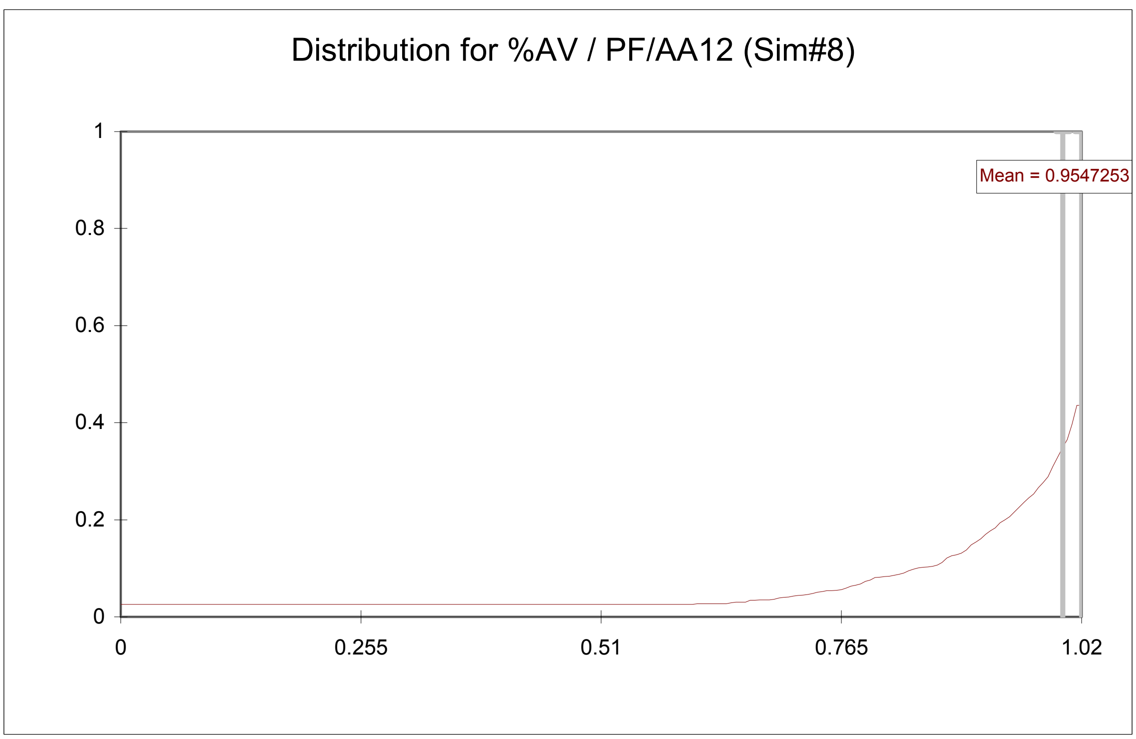

Figure 12 Pay Factor (PF) for %AV.

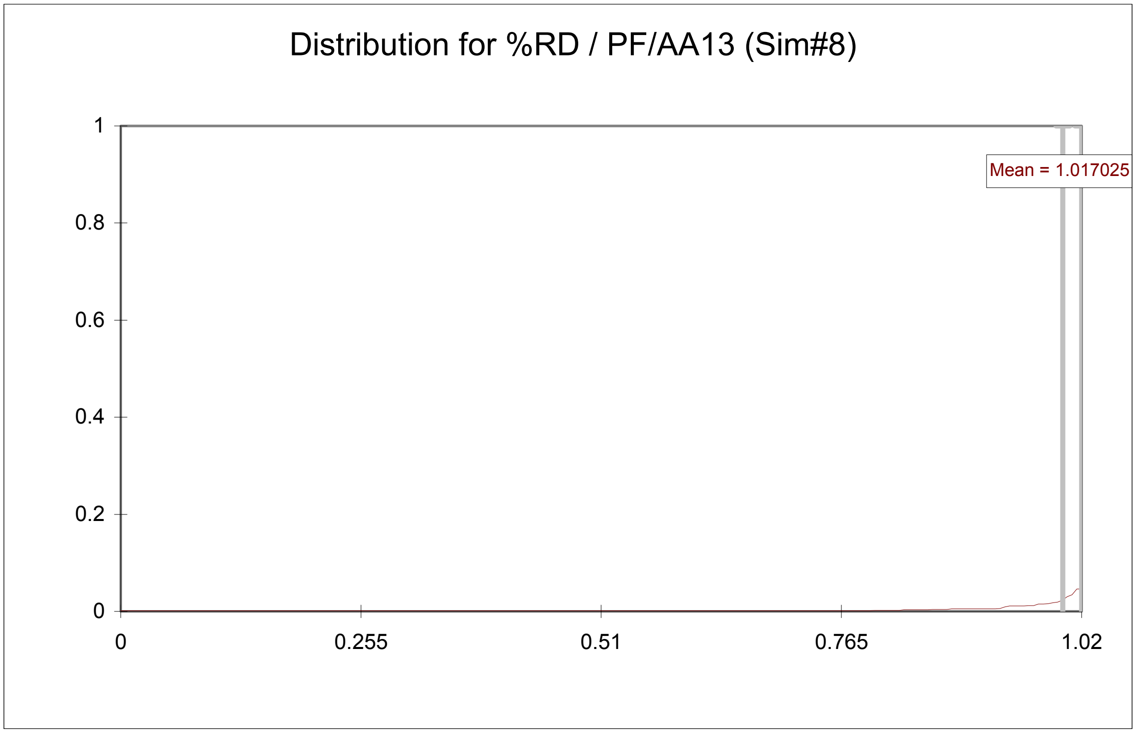

Figure 13 Pay Factor (PF) for %RD.

Table 6. Summary Probabilities for Pay Factor (PF) for %AC, %AV and %RD from Same Iteration as Depicted in Figures 11, 12 and 13

Variable	Mean Value	Probability that Pf is from 1.0 to 1.02	Probability Pf < 1.0	Probability Pf 0.9 to 1.0	Probability Pf < 0.9
%AC	1.0061	87.8%	12.2%	8.9%	3.3%
%AV	0.9547	65.2%	34.8%	20.6%	14.2%
%RD	1.0170	97.7%	2.3%	1.8%	0.5%

Note: for convenience and consistency, the authors have decided to report PF and CPF to four decimal places. This results however, in some potential discrepancies if ODOT or other readers should use these values to calculate Pay Adjustments, as they are reported in this text using the full expressions for PF and CPF.

Table 7 summarizes this same type of information for all ten (10) iterations. Each iteration is an individual simulation of 1000 Monte Carlo runs. These data reinforce the conclusions drawn from the single simulation probabilities presented in Figures 11, 12 and 13 as well as in Table 6. That is, %AC and %RD in this data base generated pay factors far more favorable to contractors across all of the iterations than did the %AV.

Table 7. Pay Factors (PF) for %AC, %AV and %RD

Pay Factors (PF)											
Iteration:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
%AC											
1.0 to 1.02	87.6	86.3	88.3	90.2	90.1	85.4	87.3	87.8	88.8	88.1	87.99
< 1.0	12.4	13.7	11.7	9.8	9.9	14.6	12.7	12.2	11.2	11.9	12.01
0.9 to 1.0	9.7	10.6	8.0	6.6	7.1	11.8	9.4	8.9	8.6	8.4	8.91
< 0.9	2.7	3.1	3.7	3.2	2.8	2.8	3.3	3.3	2.6	3.5	3.10
Mean pay factor	1.0062	1.0051	1.0053	1.0089	1.0045	1.0053	1.0047	1.0061	1.0062	1.0055	1.0056
%AV											
1.0 to 1.02	62.2	63.1	59.9	60.3	59.3	63.4	63.3	65.2	62.3	62.3	62.13
< 1.0	37.8	36.9	40.1	39.7	40.7	36.6	36.7	34.8	37.7	37.7	37.87
0.9 to 1.0	21.7	22.4	24.5	21.6	23.0	22.8	19.6	20.6	21.6	20.9	21.87
< 0.9	16.1	14.5	15.6	18.1	17.7	13.8	17.1	14.2	16.1	16.8	16.00
Mean pay factor	0.9550	0.9533	0.9544	0.9409	0.9478	0.9543	0.9462	0.9547	0.9494	0.9540	0.9510
%RD											
1.0 to 1.02	96.4	95.9	96.9	97.1	96.4	97.4	96.4	97.7	96.2	96.7	96.71
< 1.0	3.6	4.1	3.1	2.9	3.6	2.6	3.6	2.3	3.8	3.3	3.29
0.9 to 1.0	2.6	3.5	2.1	1.6	3.1	2.2	2.7	1.8	2.9	1.7	2.42
< 0.9	1.0	0.6	1.0	1.3	0.5	0.4	0.9	0.5	0.9	1.6	0.87
Mean pay factor	1.0156	1.0165	1.0152	1.0147	1.0166	1.0178	1.0145	1.0170	1.0151	1.0141	1.0157

On average, a contractor could be expected to receive from a full pay level through the maximum bonus about 88% of the time for %AC and almost 97% of the time for %RD. Correspondingly, similar pay levels would be achieved for %AV only slightly more than 62% of the time. Pay factors (PF) for %AC and %RD averaged 1.00558 and 1.0157, respectively, when the pay factor for full pay is 1.0 and the maximum bonus level is described by a pay factor equal to 1.02. On average, contractors with performance similar to that exhibited in the underlying data base could expect full payment to bonus pay for %AV only 62.13% of the time.

Table 8 presents additional data from these simulations where the maximum, mean and minimum for each variable are presented for each of the 10 iterations completed. These data, as with those presented in Table 5, do not have associated probabilities. Rather, they are included to allow ODOT review of the worst and best case conditions generated during the Monte Carlo simulations.

Table 8. Data Summary for Simulated Pay Factor (PF) Values by Variable and Iteration

	Pay Factors (PF)										
Iteration:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
	%AC										
Minimum	0	0	0	0	0	0	0	0	0	0	0
Mean	1.0062	1.0051	1.0052	1.0090	1.0045	1.0053	1.0047	1.0061	1.0062	1.0055	1.0058
Maximum	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
	%AV										
Minimum	0	0	0	0	0	0	0	0	0	0	0
Mean	0.9550	0.9533	0.9544	0.9409	0.9478	0.9543	0.9462	0.9547	0.9493	0.9543	0.9510
Maximum	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
	%RD										
Minimum	0	0.6242	0	0	0	0.6838	0	0	0	0	0.1308
Mean	1.0156	1.0165	1.0153	1.0147	1.0166	1.0178	1.0144	1.0170	1.0151	1.0141	1.0157
Maximum	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02

Composite Pay Factors (CPF) and Pay Adjustments (PA_{Lot})

Figures 14 and 15 present a representative example of the composite pay factor (CPF) and pay adjustment (PA_{Lot}) analyses, respectively. The CPF is generated by weighting the respective pay factors (PF) according to equation 8, where 20% is attributable to %AC, 30% to %AV and 50% to %RD.

Corresponding probabilities for CPF to those presented in Table 6 include a mean of 0.9961488, a 71.9% probability that CPF will be between 1.0 and 1.02, a 28.1% probability that it will be less than 1.0, 25% that it will be between 0.9 and 1.0 and a 3.1% chance that it will be less than 0.9. Full pay is achieved when the CPF equals 1.0. Bonus pay can be earned up to 2%, corresponding to a CPF of 1.02.

Taken with the representative adjusted pay levels generated from a single iteration of 1,000 model cycles presented in Figure 15, these results begin to define the financial reimbursements projected for participating contractors whose work can be approximated by the input data base.

Figure 15 requires additional introduction as it has a different scale than the other probability plots previously presented, as it deals in dollars rather than compliance values. The value ‘4’ on the extreme right hand side of the bottom horizontal axis is \$4,000.00 and represents the bonus paid for exceptional performance. Zero, identified on the upper horizontal axis, is “full pay” and the mean -\$770.24 is the deduction from full pay expected as the mean response. That is, full pay in this hypothetical example is

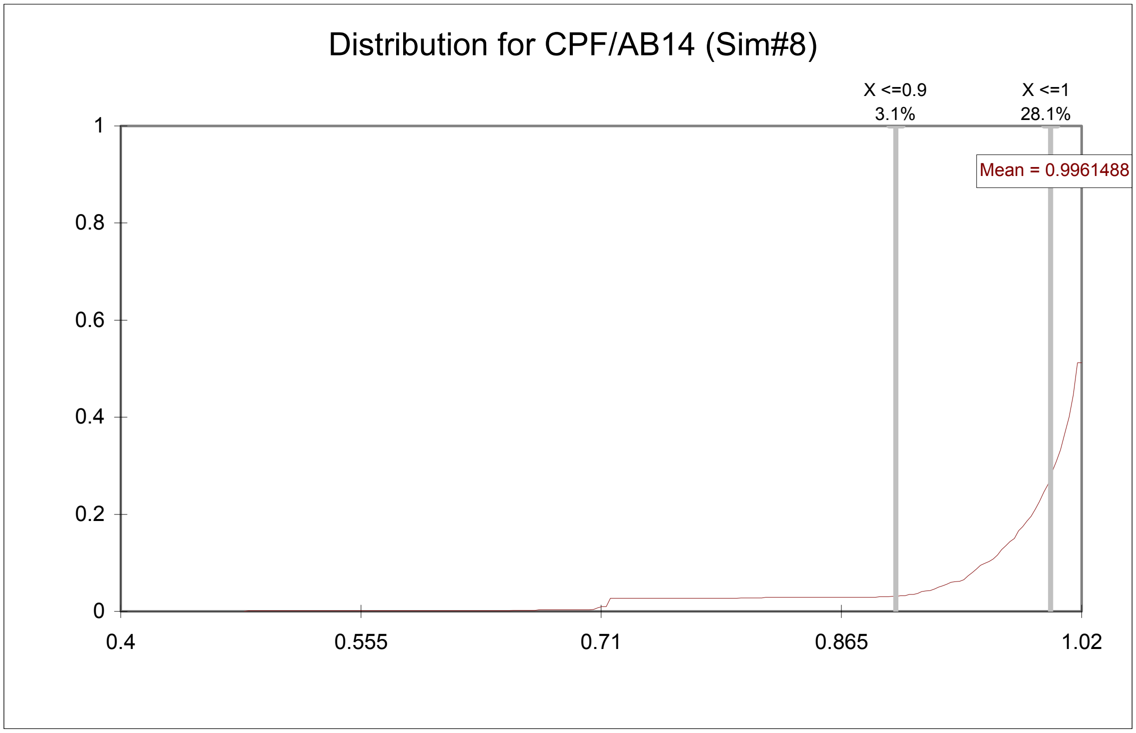

Figure 14 Expected probabilities for Composite Pay Factor (CPF).

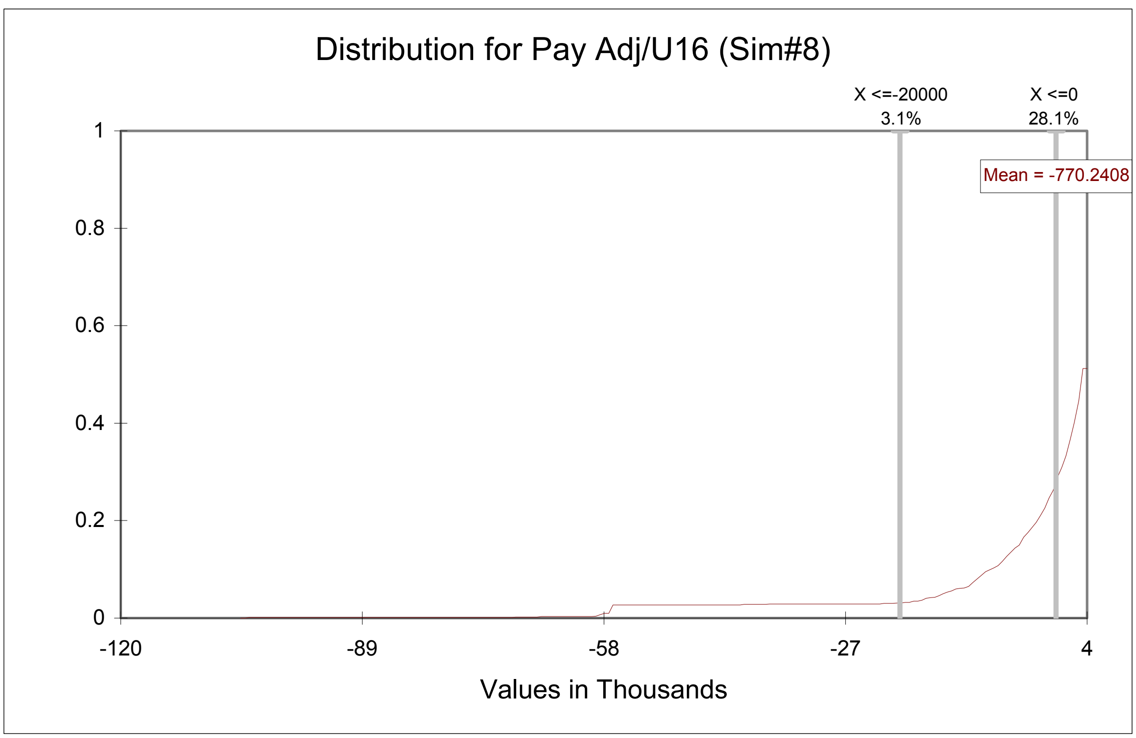

Figure 15 Expected probabilities for pay adjustment.

$40.00 per ton times 5,000 tons = $200,000.00. The $4,000.00 bonus would be in addition to this "full pay" level and the -$770.24 mean equates to payment of $200,000 – 770.24 = $199, 229.76. The corresponding probabilities to those previously presented going from full pay (i.e. '0') to full bonus ($4,000.00) equals 71.9%, with a 28.1% probability of getting less than full pay (<"0" in Figure 15). The probability of seeing a $20,000.00 deduction to full pay range is 25% while the probability of getting greater than a $20,000.00 deduction being 3.1%. These last two probabilities are equivalent to the 0.9 to 1.0 and to the <0.9 CPF levels, respectively.

This last analysis shows that the PWL approach, as configured and tested with the trial data set, produces a mean pay adjustment of $199, 229.76 compared to a neutral "full pay" level of $200,000.00. Additionally, there is only a 3.1% projected probability that the contractor would be paid less than $180,000.00 for this same HMA lot. Not shown on Figure 15, but available to ODOT at their request, is the projected probability of 1% that the contractor will be paid $ 42,000.00 for this same lot. As before, the results of all 10 of the iterations are compiled in tabular form in Table 9.

Table 9. Probabilities of Occurrence for Composite Pay Factor and Pay Adjustment Results

Composite Pay Factors (PF)										
Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Value	Probability of Occurrence									
1.0 to 1.02	69.5	71.7	69.3	67.7	67.7	72.1	68.4	71.9	68.8	69.9
< 1.0	30.5	28.3	30.7	32.3	32.3	27.9	31.6	28.1	31.2	30.1
0.9 to 1.0	27.2	24.9	27.9	27.9	28.6	24.2	27.7	25.0	27.2	26.6
< 0.9	3.3	3.4	2.8	4.4	3.7	3.7	3.9	3.1	4.0	3.5
Mean CPF	0.9955	0.9953	0.9950	0.9914	0.9936	0.9963	0.9920	0.9961	0.9936	0.9945
Pay Adjustment										
Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Value	Probability of Occurrence									
$200K to $204K	69.5	71.7	69.3	67.7	67.7	72.1	68.4	71.9	68.8	69.9
< $200K	30.5	28.3	30.7	32.3	32.3	27.9	31.6	28.1	31.2	30.1
$180K to $200K	27.2	24.9	27.9	27.9	28.6	24.2	27.7	25.0	27.2	26.6
<$180K	3.3	3.4	2.8	4.4	3.7	3.7	3.9	3.1	4.0	3.5
Mean pay adjustment ($)	-886	-948	-995	-1719	-1295	-748	-1592	-770	-1278	-1107
Mean Pay per lot ($)	$199.11K	$199.05K	$199K	$198.28K	$198.71K	$199.25K	$198.41K	$199.23K	$198.72K	$198.89K

Table 9 contains these results for composite pay factor (CPF) and similar analyses for the pay adjustment (PA_{Lot}) simulations. The probabilities of occurrence for CPF and PA_{Lot} are the same, as pay adjustment converts the composite pay factor into dollars. A CPF equal to 1.0 for the hypothetical example used in these analyses translates to $200,000.00 for a 5,000 ton lot at $40.00 per ton. Bonus pay from a CPF of 1.02 would mean that ODOT would be responsible for $204,000.00 for the same 5,000 ton lot.

Table 10 presents the various mean responses for the probabilities as well as the means and pay adjustment data included in Table 9. Contractors with equivalent data sets to that used in this analysis should receive full pay to full bonus almost 70% of the time. ODOT should expect to pay less than full pay under this PWL system, with collected values similar to the underlying data base, about 30% of the time. Further, these analyses suggested that a 10% deduction or more should be expected for about 3.5% of the HMA lots tested. For the hypothetical $200,000.00 per lot example, this means that contractors should see an average reimbursement of $198,865.00.

Table 10. Summary Data for Composite Pay Factor and Pay Adjustments for 10 Monte Carlo Iterations

Composite Pay Factor Mean Values	Probability of Occurrence mean of 10 iterations	Pay Adjustment Mean Value
1.0 to 1.02	69.62	$200K to $204K per lot
<1.0	30.30	<$200K per lot
0.9 to 1.0	26.72	$180K to $200K per lot
<0.9	3.58	<$180K per lot
Mean = 0.9943		Mean Pay Adj.= -$1138.80
		Mean Pay = $198.865K

Additional Analyses

As shown in Table 3, the ODOT data set indicated that there was a substantial "target miss" for laboratory compacted air voids (%AV). The mean for %AV was 3.63% and the target value was 4.0%. This target miss resulted in a PF for %AV of 0.951 and 37.87% of the simulated lots had a PWL of < 90%.

Under the current specification, contractors do not have a strong incentive to correct a target miss if the test result is still within the specification limits. In an attempt to better quantify the impact of the %AV inputs on its PWL and PF as well as on the overall CPF and Pay Adjustments, an additional Monte Carlo simulation was undertaken. In this effort, the %AV data were adjusted so that the mean would hit the %AV target. This was accomplished by changing the target level of 4.0% to 3.5% and adjusting the specification limits accordingly, for comparison.

The revised statistical distributions were developed and 1000 simulations completed. Table 11 compares these data to those previously developed and introduced throughout this report. It should be noted that the data found in the literature and reported in Table 3 indicated that contractors typically run 0.4 to 0.5% below the target value of 4.0% AV.

Table 11. Comparison of Monte Carlo Simulation Results for %AV = 4.0* and 3.5*

	PWL		PF	CPF		Pay Adjustment
Target Adjusted to = 3.5% AV						
50-90%	16.7%	**1.0-1.02**	79.8%	81.5%	**$200K to $204**	81.5%
>90%	79.8%	**<1.0**	20.2%	18.5%	**<$200K**	18.5%
<50%	3.5%					
Mean	92.91%		0.9652	0.9984		-$327.24
Target = 4.0 % AV						
50-90%	35.4%	**1.0-1.02**	62.1%	69.6%	**$200K to $204**	69.6%
>90%	62.1%	**<1.0**	37.9%	30.4%	**<$200K**	30.3%
<50%	2.5%					
Mean	88.99%		0.9510	0.9943		-$198.865

*the 3.5% AV data are from 1000 simulations while the 4.0% data are the averages of 10 iterations of 1000 simulations each.

The data in Table 11 shows that while the hypothetical correction for the target miss resulted in an increase in the average PWL of almost 4%, it also generated a 17+% increase in the number of lots receiving full pay (i.e. from 62.13 to 79.8% above 90% PWL). When factored into the corresponding outputs for %AC and %RD an increase in the composite pay factor (CPF) and pay adjustments for full to bonus pay levels of almost 12% resulted. Correspondingly, a decrease in the estimated number of lots receiving less than full pay was also almost 12% with a decrease in the average penalty from $327.24 to $198.87 per lot.

It should be noted however, that even with this modification, the average contractor generating data equivalent to the ODOT provided data set should expect a slight penalty. This penalty results from %AV compliance and offsets bonus pay expected for both %AC and %RD.

INITIAL CONCLUSIONS

ODOT Data Set

The data set provided by ODOT shows that the contractors are, on average, hitting the target value for asphalt content but running 0.37 and 0.9 percent below the target value for %AV and %RD, respectively. The ODOT data set shows lower variability, as measured by standard deviation, and less target miss, than the data reported in the literature from Arkansas, Alabama or the NCHRP 409 study. The ODOT data set shows lower standard deviations and less target miss than the data from Arkansas labeled as high control.

Monte Carlo Simulations

The Monte Carlo simulations indicated that contractors generating data similar to that simulated could expect a pay factor of 1.006 for %AC, 0.951 for %AV and 1.016 for %RD. These pay factors result in a CPF for a lot of 0.994 and a pay adjustment of - $1,138.80 (on a $200,000.00 per lot basis). If the contractors could adjust their %AV to closer match the target value of 4.0%, a pay factor of 1.006 for %AC, 0.965 for %AV and 1.016 for %RD is projected. These pay factors result in a CPF for a lot of 0.998 and a pay adjustment of - $327.24 (again on a $200,000.00 per lot basis).

INITIAL RECOMMENDATIONS

The results of the Monte Carlo simulations are only as applicable as the ODOT data set is to contractor quality in Oklahoma. Comparisons of the ODOT generated data to data sets found in the literature indicate that the average values from the ODOT data set compared to a high measure of control in the literature. The simulation efforts showed that average performance from the Oklahoma data set (an overall high level of control) for %AC would earn full pay and average performance for %RD would earn a bonus. Average performance for %AV however, resulted in less than full pay. Additionally, this AV consideration manifested itself in the overall composite pay factor (CPF) of slightly less than 1.00 and a Pay Adjustment of - $1,138.90 on a $200,000 per lot basis. Even with this high level of control in the Oklahoma data set, a contractor would not be able to consistently generate a bonus for asphalt content, full pay for laboratory compacted air voids or a positive pay adjustment.

It is the author's view that a contractor exhibiting a consistently high level of control should be able to expect to earn bonus pay. However, the Monte Carlo simulations indicate that an ODOT contractor exhibiting a high level of control can expect, on average, a slight penalty.

The draft PWL specification as currently written appears to not fairly reward a contractor for high quality control. The specification limits and or target limits for %AC and %AV appear too restrictive. The specification limits for %AC, %AV and %RD appear similar to those found in the literature. However, ODOT is the only agency found that is applying a target miss or target limit to their PWL specifications.

Based on the above discussions and the analysis contained in this report, the following recommendations are made.

1. The analysis was performed on a limited data set. It is recommended that the DOT proceed slowly with the implementation of PWL specifications until a sufficiently large data base could be obtained and the analysis repeated to verify any changes to specification and target limits. A procedure similar to that followed by the Alabama DOT where the specification was incrementally implemented over a three year period with no pay adjustments in the first year followed by half pay adjustments in the second year and full pay adjustments in the third year could serve as a guide.
2. Should ODOT desire, additional Monte Carlo simulations can be completed to evaluate the effects of adjusting the target and specification limits on PF and CPF. At the conclusion of the simulations, recommendations for any adjustments to specification and target limits would be made.

FINAL ANALYSIS

Based on the initial conclusions and recommendations, ODOT requested two additional sets of simulations on the data sets to more fully explain expected compliance with the proposed PWL specification. As before, the conclusions and recommendations from these additional analyses are dependent upon the assumptions underlying the ODOT supplied data sets. These evaluations were:

- A comparison of results if the RD LSL was raised from 91.0% to 91.5%.
- A sequential comparison of results when the %AV specification limits as well as target limits were incrementally changed from their original levels. These expansions investigated the possible outcomes that a change in the specification and target limits would generate.

Increasing RD LSL

This set of simulations compared output variations when the RD LSL was increased from its original 91.0% level to 91.5%. All other variables were held constant at their original levels. These simulations employed the original data bases; not those normalized in the previous effort for %AV. Table 12 presents these comparisons. Both data sets resulted from 1,000 simulations.

Table 12. Comparisons for RD PWL for LSL = 91.0% and 91.5%

RD LSL = 91.0%											
Iteration:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
50-90%	3.28	3.20	3.12	3.04	3.32	3.44	3.54	3.36	3.28	3.62	3.32
>90%	96.56	96.72	96.68	96.76	96.60	96.38	96.30	96.48	96.56	96.20	96.52
<50%	0.16	0.08	0.20	0.20	0.08	0.18	0.16	0.16	0.16	0.18	0.16
Mean	98.98	99.09	99.03	99.01	99.03	98.97	98.93	98.93	98.98	98.88	98.98
RD LSL = 91.5%											
50-90%	8.22	8.08	8.12	7.62	7.06	7.86	7.34	8.70	7.64	8.96	7.96
>90%	91.30	91.32	91.26	91.92	92.58	91.60	92.20	90.72	91.92	90.46	91.53
<50%	0.48	0.60	0.62	0.46	0.36	0.54	0.46	0.58	0.44	0.58	0.51
Mean	97.50	97.49	97.41	97.58	97.81	97.57	97.68	97.31	97.61	97.21	97.52

These simulations show that raising the LSL from 91.0% to 91.5% for RD resulted in about a 5% reduction in the number of times a bonus condition would result even though an average reduction in the overall PWL for RD of only 1.46% was noted.

The average results of the simulations for pay factor (PF), composite pay factor (CPF) and pay adjustments further illustrate the potential impact of raising the LSL for RD from 91.0% to 91.5%. Table 13 presents the pay factors (PF), composite pay factor (CPF) and pay adjustments for these simulations. Table 14 is a summary of the results.

The percent of the lots earning full or bonus pay for RD decreased from 96.52% to 91.53% and the percent of lots receiving less than full pay increased from 3.48% to 8.47%. For these simulations the effect on CPF is a function of RD only, as the other pay factors (AV and AC) were not changed. The percent of the lots receiving full or bonus pay for the CPF decreased from 70.2% to 67.5% and the percent of lots receiving less than full pay for the CPF increased from 19.8% to 32.47%. The mean CPF decreased from 0.9944 to 0.9907. Changing the LSL from 91.0% to 91.5% results in an average reduction in payment to the contractor of $740.00 per lot on a $200,000 full pay lot.

Sequential Modifications to %AV Limits

In the original simulations %AV were the most problematic in terms of generating PWL that would insure a full pay condition. This work addresses the changes needed to move the %AV levels to points where full or bonus pay could occur. The simulations focused initially upon identifying the impacts to the PWL and PF for %AV as the specification and target limits were sequentially widened. These results were utilized to calculate overall composite pay factors and pay adjustments. Based on the previous work detailing the differences between RD LSL of 91.0% and 91.5%, these simulations were repeated with each of these base conditions.

Table 13. Comparison of %RD Pay Factors (PF), Composite Pay Factor and Pay Adjustments for RD LSL = 91% and 91.5%

Pay Factors (PF)											
Iteration:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
RD LSL = 91.0%											
1.0 to 1.02	96.56	96.72	96.68	96.76	96.60	96.38	96.30	96.48	96.56	96.2	96.52
< 1.0	3.44	3.28	3.32	3.24	3.40	3.62	3.70	3.52	3.44	3.80	3.48
Mean pay factor	1.015	1.016	1.015	1.015	1.016	1.011	1.015	1.015	1.015	1.015	1.015
RD LSL = 91.5%											
1.0 to 1.02	91.30	91.32	91.26	91.92	92.58	91.60	92.20	90.72	91.92	90.46	91.53
< 1.0	8.70	8.68	8.74	8.08	7.42	8.40	7.80	9.28	8.08	9.54	8.47
Mean pay factor	1.007	1.006	1.005	1.007	1.009	1.007	1.008	1.005	1.008	1.005	1.011
Composite Pay Factor when RD LSL = 91.0%											
1.0 to 1.02	70.60	70.00	71.20	70.40	70.72	70.14	69.26	69.82	70.32	69.34	70.20
< 1.0	29.40	30.00	28.80	29.60	29.28	29.86	30.74	30.18	29.68	30.66	29.80
Mean pay factor	0.995	0.994	0.994	0.995	0.996	0.994	0.994	0.994	0.995	0.993	0.994
Composite Pay Factor when RD LSL = 91.5%											
1.0 to 1.02	66.50	67.82	67.80	67.92	68.32	68.82	67.34	67.86	66.36	66.58	67.50
< 1.0	33.50	32.18	32.20	32.08	31.68	31.18	32.66	32.14	33.64	33.42	32.47
Mean pay factor	0.990	0.991	0.991	0.991	0.992	0.991	0.991	0.991	0.990	0.989	0.991
Pay Adjustment when RD LSL = 91.0%											
\$200K to \$204K	70.60	70.00	71.20	70.40	70.72	70.14	69.26	69.82	70.32	69.34	70.20
< \$200K	29.40	30.00	28.80	29.60	29.28	29.86	30.74	30.18	29.68	30.66	29.80
Mean pay adjustment(\$)	-1051	-1195	-1027	-751	-1224	-1261	-1106	-970	-1374	-1374	-1133
Pay Adjustment when RD LSL = 91.5%											
\$200K to \$204K	66.50	67.82	67.80	67.92	68.32	68.82	67.34	67.86	66.36	66.58	67.50
< \$200K	33.50	32.18	32.20	32.08	31.68	31.18	32.66	32.14	33.64	33.42	32.50
Mean pay adjustment(\$)	-2046	-1828	-1886	-1742	-1670	-1817	-1727	-1870	-1949	-2192	-1873

Table 14. Summary of Simulation Results for RD LSL = 91% and 91.5%

	PWL		PF	CPF		Pay Adjustment
RD LSL = 91.0%						
50-90%	3.32%	**1.0-1.02**	96.52%	70.20%	**$200K to $204**	70.20%
>90%	96.52%	**<1.0**	3.48%	29.80%	**<$200K**	29.80%
<50%	0.16%					
Mean	98.98%		1.015	0.994		-$1133
RD LSL = 91.5%						
50-90%	7.96%	**1.0-1.02**	91.53%	67.50%	**$200K to $204**	67.50%
>90%	91.53%	**<1.0**	8.47%	32.50%	**<$200K**	32.50%
<50%	0.51%					
Mean	97.52%		1.011	0.991		-$1873

Table 15 presents the overall simulation approach. The last column on the right presents the data employed in the original efforts. Tables 16 and 17 present summaries of each of the 10 iterations (of 5,000 simulations each in these cases) for each of the six sets of overall simulations detailed in Table 15.

Table 15. Simulation Approach for Comparisons of Variation in %AV Specification and Target Limits

Simulation Set	RD LSL	Input Variables for %AV		Original Input Variables
1	91.0%	**LSL = 2.60**	LTL = 3.20	LSL = 2.75
4	91.5%	USL = 5.40	UTL = 4.80	USL = 5.25
2	91.0%	**LSL = 2.65**	LTL = 3.25	LTL = 3.50
5	91.5%	USL = 5.35	UTL = 4.75	UTL= 4.50
3	91.0%	**LSL = 2.70**	LTL = 3.30	
6	91.5%	USL = 5.30	UTL = 4.70	

Tables 16 and 17 illustrate the increased projected PWL and pay factors (PF) for %AV with increased width of both the specification and target limits. There is an overall increase of about 3% in PWL from Simulation Sets 5 and 6 to those of Sets 1 and 2. A generally lessened response is noted in the expected pay factors together across the same simulation sets. Similarly, it is noted that a 90% average PWL does not earn an average PF = 1.0 in these %AV outputs. The same reasoning explains both of these observations. That is, the PWL and PF data bases are not exactly equivalent. The PWL data base includes all of the projected results while the PF outputs are modified by the internal

Table 16. PWL for Alternative Conditions for %AV

RD LSL = 91.0%, AV LSL = 2.60% PWL Simulation Set 1										
Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
50-90%	21.70	22.52	21.76	21.68	22.42	22.88	20.56	21.42	22.58	21.76	21.93
>90%	77.18	76.34	77.18	77.4	76.58	75.88	78.08	77.38	76.14	77.10	76.93
<50%	1.12	1.14	1.06	0.92	1.00	1.24	1.36	1.20	1.28	1.14	1.15
mean	93.70	93.37	93.63	93.62	93.60	93.27	93.59	93.62	93.23	93.64	93.53
RD LSL = 91.0%, AV LSL = 2.65% PWL Simulation Set 2											
Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
50-90%	25.80	25.58	26.42	26.24	26.40	26.46	26.34	25.26	25.06	25.44	25.90
>90%	72.70	73.20	72.28	72.50	72.50	72.36	72.44	73.32	73.70	73.14	72.81
<50%	1.50	1.22	1.30	1.26	1.10	1.18	1.22	1.42	1.24	1.42	1.29
mean	92.09	92.59	92.37	92.35	92.29	92.30	92.23	92.34	92.56	92.38	92.35
RD LSL = 91.0%, AV LSL = 2.70% PWL Simulation Set 3											
Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
50-90%	29.26	30.00	28.46	30.78	28.58	28.8	29.8	27.62	29.76	28.7	29.18
>90%	69.02	68.48	69.88	67.32	69.62	69.32	68.64	70.12	68.50	69.56	69.05
<50%	1.72	1.52	1.66	1.90	1.80	1.88	1.56	2.26	1.74	1.74	1.78
mean	90.96	91.12	91.20	90.51	91.15	91.02	91.05	90.94	90.97	91.26	91.02
RD LSL = 91.5%, AV LSL = 2.60% PWL Simulation Set 4											
Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
50-90%	21.98	21.48	21.22	21.22	22.10	22.38	21.16	21.34	21.96	21.54	21.64
>90%	77.04	77.42	77.82	77.98	77.08	76.48	77.88	77.68	77.20	77.60	77.42
<50%	0.98	1.10	0.96	0.80	0.82	1.16	0.96	0.98	0.84	0.86	0.942
mean	93.72	93.29	93.78	94.07	93.68	93.50	93.73	93.85	93.70	93.92	93.72
RD LSL = 91.5%, AV LSL = 2.65% PWL Simulation Set 5											
Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
50-90%	25.62	24.58	26.42	27.00	25.34	26.08	25.40	25.39	25.78	25.06	25.67
>90%	73.22	73.94	72.18	71.34	73.34	72.20	73.44	72.86	72.76	73.62	72.89
<50%	1.16	1.48	1.40	1.66	1.32	1.72	1.16	1.24	1.46	1.32	1.39
mean	92.50	92.44	92.`14	91.92	92.46	91.96	92.51	92.33	92.39	92.44	92.33
RD LSL = 91.5%, AV LSL = 2.70% PWL Simulation Set 6											
Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
50-90%	32.40	30.40	29.00	27.40	30.30	28.50	30.00	28.10	30.10	27.60	29.38
>90%	66.10	68.10	69.30	70.90	68.50	70.00	67.90	69.60	67.80	71.10	68.93
<50%	1.50	1.50	1.70	1.70	1.20	1.50	2.10	2.30	2.10	1.30	1.69
mean	90.07	90.69	91.12	91.25	91.18	91.50	90.66	90.72	90.45	91.44	90.91

Table 17. PF for Alternative Conditions for AV

RD LSL = 91.0%, AV LSL = 2.60% PF Simulation Set 1

Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
1.0-1.02	77.18	76.34	77.18	77.40	76.58	75.88	78.08	77.38	76.14	77.10	76.93
<1.0	22.82	23.66	22.82	22.60	23.42	24.12	21.92	22.62	23.86	22.90	23.07
mean	0.986	0.983	0.985	0.986	0.996	0.982	0.983	0.985	0.981	0.985	0.985

RD LSL = 91.0%, AV LSL = 2.65% PF Simulation Set 2

Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
1.0-1.02	72.70	73.20	72.28	72.50	72.50	72.36	72.44	73.32	73.70	73.14	72.81
<1.0	27.30	26.80	27.72	27.50	27.50	27.64	27.56	26.68	26.30	28.86	27.39
mean	0.975	0.980	0.978	0.978	0.979	0.978	0.978	0.977	0.979	0.977	0.978

RD LSL = 91.0%, AV LSL = 2.70% PF Simulation Set 3

Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
1.0-1.02	69.02	68.48	69.88	67.32	69.62	69.32	68.64	70.12	68.50	69.56	69.00
<1.0	30.98	32.52	30.12	32.68	30.38	30.68	31.36	29.88	31.50	30.44	31.00
mean	0.966	0.968	0.969	0.963	0.967	0.965	0.968	0.962	0.967	0.968	0.967

RD LSL = 91.5%, AV LSL =2.60% PF Simulation Set 4

Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
1.0-1.02	77.04	77.42	77.82	77.98	77.08	76.48	77.88	77.68	77.20	77.60	77.42
<1.0	22.96	22.58	22.18	22.02	22.92	23.54	22.12	22.32	22.80	22.40	22.58
mean	0.987	0.983	0.987	0.990	0.987	0.984	0.986	0.987	0.987	0.989	0.987

RD LSL = 91.5%, AV LSL = 2.65% PF Simulation Set 5

Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
1.0-1.02	73.22	73.94	72.18	71.34	73.34	72.20	73.44	72.86	72.76	73.62	72.89
<1.0	26.78	26.06	27.82	28.66	26.66	27.80	26.56	27.14	27.24	26.38	27.11
mean	0.980	0.977	0.976	0.973	0.978	0.973	0.979	0.978	0.977	0.978	0.977

RD LSL = 91.5%, AV LSL = 2.70% PF Simulation Set 6

Iteration	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	AVE
1.0-1.02	66.10	68.10	69.30	70.90	68.50	70.00	67.90	69.60	67.80	71.10	68.93
<1.0	33.90	31.90	30.70	29.10	31.50	30.00	32.10	30.40	32.20	28.90	31.07
mean	0.963	0.966	0.967	0.968	0.972	0.971	0.964	0.962	0.961	0.971	0.966

constraint employed when a projected PWL is less than 50%. Instead of using this PWL value to calculate a PF with equations 7 and 7a, a PF = 0 is assigned. This internal constraint results in a modified PF data base when compared to that developed for PWL determinations and results in a condition where an average PWL does not generate an expected average PF in these simulations.

The averages of the 10 iterations itemized in Tables 16 and 17 are presented in Table 18. The last two columns on the right of Table 18 contain the %AV PWL and PF values from the original simulations described by a specification limit equal to ± 1.25% and a target limit of ± 0.5% (coded as LSL = 2.75%).

Table 18. Comparison of Specification and Target Level Modifications for %AV on PWL, and PF

Simulation Set	%RD	Input Variable Marker	Average %AV PWL	Average %AV PF	Original Ave %AV PWL	Original Ave %AV PF
1	91.0	LSL = 2.60	93.53	0.984		
2	91.0	LSL = 2.65	92.35	0.978	89.11	0.952
3	91.0	LSL = 2.70	91.02	0.966		
4	91.5	LSL = 2.60	93.72	0.987		
5	91.5	LSL = 2.65	92.31	0.973	89.15	0.953
6	91.5	LSL = 2.70	90.91	0.966		

These data further support the observation that there are generally only minor differences between the 2.65 LSL input simulation sets and those on either side. Larger differences exist however, between the 2.60 and the 2.70 data sets as well as between these simulations and the values developed from the original data sets (i.e. LSL = 2.75%). Widening the specification window from its original 2.75 to 5.25 width, together with a commensurate increase in the target window results in about a 4% increase in PWL percentages and about a 3% increase in Pay Factors. Similar data describing the average composite pay factor as well as an overall pay adjustment for a hypothetical $40 per ton, 5000 ton lot are presented in Table 19.

The data in Table 19 shows that, as expected, widening of the Specification and Target limits from their original values (± 1.25% and ± 0.5%, respectively) results in increases in the composite pay factor as well as the Pay Adjustment. A gain of over $2,000 or approximately 1% of a $200,000 lot is projected. These results are fully dependent upon the underlying data set. Other data sets would produce different results. If this data set can be considered typical of a "good" contractor, these projections highlight how modifications to the Specification and Target limits can move expected payments from a slight penalty condition to one where a bonus would be secured for the same quality of overall effort.

Table 19. Comparison of Projected Composite Pay Factor and Pay Adjustment when %AV Target and Specification Limits are Modified

Simulation Set	%RD	Input %AV Variable Marker	Average Projected CPF	Average Projected Pay Adj.	Original CPF LSL = 2.75	Original Pay Adj. LSL = 2.75
1	91.0	LSL = 2.60	1.004	$858	0.994	-$1133
2	91.0	LSL = 2.65	1.002	$456		
3	91.0	LSL = 2.70	0.999	-$236		
4	91.5	LSL = 2.60	1.001	$125	0.991	-$1873
5	91.5	LSL = 2.65	0.998	-$460		
6	91.5	LSL = 2.70	0.993	-$1299		

CONCLUSIONS

ODOT Data Set

The data set provided by ODOT shows that the contractors are, on average, hitting the target value for asphalt content but running 0.37 and 0.9 percent below the target value for %AV and %RD, respectively. The ODOT data set shows lower variability, as measured by standard deviation, and less target miss, than the data reported in the literature from Arkansas, Alabama or the NCHRP 409 study. The ODOT data set shows lower standard deviations and less target miss than the data from Arkansas labeled as high control. Based on the data in the literature, the data set evaluated appears to indicate better than average control.

Monte Carlo Simulations

1. The Monte Carlo simulations indicated that contractors generating data similar to that simulated could expect a pay factor of 1.006 for %AC, 0.951 for %AV and 1.016 for %RD. These pay factors result in a CPF for a lot of 0.994 and a pay adjustment of - $1,138.80 (on a $200,000.00 per lot basis).
2. If the contractors could adjust their %AV to closer match the target value of 4.0%, a pay factor of 1.006 for %AC, 0.965 for %AV and 1.016 for %RD is projected. These pay factors result in a CPF for a lot of 0.998 and a pay adjustment of - $327.24 (again on a $200,000.00 per lot basis).
3. Adjusting the lower specification limit from 91.0% to 91.5% resulted in a change in pay factor for RD from 1.015 to 1.011. This change in pay factor for %RD resulted in

a change in CPF for a lot from 0.9944 to 0.9907and a change in pay adjustment from -$1,133 to -$1,873 (again on a $200,000.00 per lot basis).

4. If the LSL for RD is raised from 91.0% to 91.5%, the specification limits and target limits for %AV would need to be raised to ±1.40% and ±0.80%, respectively, to average above full pay for the data set evaluated.
5. If the LSL for RD is maintained at 91.0%, the specification limits and target limits for %AV would need to be raised to ±1.35% and ±0.75%, respectively, to average above full pay for the data set evaluated.

RECOMMENDATIONS

The results of the Monte Carlo simulations are only as applicable as the ODOT data set is to contractor quality in Oklahoma. Comparisons of the ODOT generated data to data sets found in the literature indicate that the average values from the ODOT data set compared to a high measure of control in the literature. The simulation efforts showed that average performance from the Oklahoma data set (an overall high level of control) for %AC would earn full pay and average performance for %RD would earn a bonus. Average performance for %AV however, resulted in less than full pay. Additionally, this AV consideration manifested itself in the overall composite pay factor (CPF) of slightly less than 1.00 and a Pay Adjustment of - $1,138.90 on a $200,000 per lot basis. Even with this high level of control in the Oklahoma data set, a contractor would not be able to consistently generate a bonus for asphalt content, full pay for laboratory compacted air voids or a positive pay adjustment.

It is the author's view that a contractor exhibiting a consistently high level of control should be able to expect to earn bonus pay. However, the Monte Carlo simulations indicate that an ODOT contractor exhibiting a high level of control can expect, on average, a slight penalty.

The draft PWL specification as currently written appears to not fairly reward a contractor for high quality control. The specification limits and or target limits for %AC and %AV appear too restrictive. The specification limits for %AC, %AV and %RD appear similar to those found in the literature. However, ODOT is the only agency found that is applying a target miss or target limit to their PWL specifications.

Based on the above discussions and the analysis contained in this report, the following recommendations are made.

1. The analysis was performed on a limited data set. It is recommended that ODOT proceed slowly with the implementation of PWL specifications until a sufficiently large data base can be obtained and the analysis repeated to verify any changes to specification and target limits. A procedure similar to that followed by the Alabama DOT where the specification was incrementally implemented over a three year period with no pay adjustments in the first year followed by half pay adjustments in the second year and full pay adjustments in the third year could serve as a guide.

2. Consider removing the target limits from the PWL specifications. ODOT was the only state found in the literature that is applying a target adjusted standard deviation for a target miss.
3. During the initial implementation it is recommended that the specification and target limits be set to values shown in Table 20.

Table 20. Recommended Trial Adjustments to PWL Limits

Quality Characteristic	Specification Limit		Target Limit	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit
%AC	JMF – 0.4%	JMF + 0.4%	JMF – 0.16%	JMF + 0.16%
%AV	- 1.35%	+1.35%	-0.75%	+0.75%
%RD	91.0%	97.0%	93.0%	96.0%

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