

NCHRP Project No. 10-79

GUIDELINES FOR QUALITY-RELATED PAY ADJUSTMENT FACTORS FOR PAVEMENTS

Final Report

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Recommended Guidelines For Quality-Related Pay Adjustment Factors For Pavements

These proposed guidelines, prepared as part of NCHRP Project 10-79 Guidelines for Quality-Related Pay Adjustment Factors for Pavements, is a recommendation by NCHRP Project 10-79 staff at Fugro Consultants, Inc. and the consultant authors. These guidelines have not been approved by NCHRP or any AASHTO committee or formally accepted for adoption by AASHTO.

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1 Scope

- 1.1 Definition of Quality-Related Pay Adjustment Factors – Appropriate and defensible pay factors, pay adjustment schedules, and pay adjustment systems that relate payment to a function of quality received for flexible and rigid pavements.
- 1.2 Purpose of Quality-Related Pay Adjustment Factors – This recommended practice provides guidelines for the development of pay factors, pay adjustment schedules, and pay adjustment systems that relate payment to a function of quality received. These guidelines must be realistic, fair to both the contractor and agency, and must be statistically accurate. This recommended practice includes the basic criteria for the most common AASHTO flexible and rigid pavement applications.
- 1.3 Target Audience – It is assumed that the user is a mid-level materials or construction engineer and has an understanding of statistics, including the calculation of the mean and standard deviation. It is helpful if the user has at least a rudimentary knowledge of the SpecRisk software (SpecRisk User's Manual 2008).
- 1.4 Background Sources – Preparatory knowledge of quality-related payment factors is included in Section 2 AASHTO REFERENCED DOCUMENTS.

2 AASHTO Referenced Documents

- 2.1 AASHTO R-10 Standard Recommended Practice Definition of Terms Related to Quality and Statistics As Used in Highway Construction
- 2.2 AASHTO R-9 Standard Recommended Practice for Acceptance Sampling Plans for Highway Construction
- 2.3 AASHTO R-42 Standard Recommended Practice for Development of a Quality Assurance (QA) Plan for Hot Mix Asphalt
- 2.4 AASHTO R-54 Standard Recommended Practice for Accepting Pavement Ride Quality When Measured Using Inertial Profiling Systems

3 Definitions

The following definitions are those contained in AASHTO R-10-06 unless otherwise noted.

- 3.1 *acceptance* — The process whereby all factors used by the agency (i.e. sampling, testing, and inspection) are evaluated to determine the degree of compliance with contract requirements and to determine the corresponding value for a given product.
- 3.2 *acceptance plan* - Also called acceptance sampling plan or statistical acceptance plan. An agreed upon process for evaluating the acceptability of a lot of material. It includes lot size and sample size (i.e. number of samples), quality measure, acceptance limit(s), evaluation of risks, and pay adjustment provisions.
- 3.3 *acceptance quality characteristic (AQC)* - A quality characteristic that is measured and used to determine acceptability
- 3.4 *acceptable quality level (AQL)* - The level of established actual quality for a quality characteristic that is fully acceptable. [For example, when the quality

measure used is percent within limits (PWL), the AQL is the established (not estimated) PWL at which the quality characteristic is fully acceptable. Acceptance plans should be designed so that AQL material will receive an expected pay (EP) of 100%.]

- 3.5 *average absolute deviation (AAD)* - For a series of test results, the mean of absolute deviations from a target or specified value. [Its use as an acceptance measure is not recommended.]
- 3.6 *buyer's risk (β)* - Also called *agency's risk*, or *risk of a Type II* or *beta (β) error*. It is the risk to the agency of accepting rejectable quality level (RQL) material or workmanship. [For an accept/reject acceptance plan, it is the probability that an acceptance plan will erroneously accept RQL material or workmanship with respect to a single acceptance quality characteristic. For variables acceptance plans using adjusted pay schedules, it is equivalent to β_{PF} , where PF = 100. It is the probability that a variable payment acceptance plan will erroneously fully accept RQL material or workmanship at 100 percent pay or greater with respect to a single acceptance quality characteristic.]
- 3.7 *composite pay factor (CPF)* - Also called *combined pay factor* or *overall pay factor*. A multiplication factor, often expressed as a percentage that considers two or more quality characteristics and is used to determine the contractor's final payment for a unit of work. [It may be established using a performance model and life-cycle cost analysis.]
- 3.8 *expected pay (EP) curve* - A graphical representation of an acceptance plan that shows the relationship between the established actual quality of a lot and its expected pay. [The EP is the mathematical pay expectation, or average pay the contractor can expect to receive over the long run for submitted lots of a given quality. The EP should be 100 percent pay for AQL material. Both OC and EP curves should be used to evaluate how well an acceptance plan is theoretically expected to work.]
- 3.9 *incentive/disincentive provision (for quality)* - A pay adjustment schedule which functions to motivate the contractor to provide a high level of quality. [A pay

adjustment schedule, even one that provides for pay increases, is not necessarily an incentive/disincentive provision, as individual pay increases/decreases may not be of sufficient magnitude to motivate the contractor toward high quality.]

- 3.10 *operating characteristic (OC) curve* - A graphic representation of an acceptance plan that shows the relationship between the actual quality of a lot and either (1) the probability of its acceptance or (2) the probability of its acceptance at various payment levels.
- 3.11 *pay adjustment* - The actual amount, either in dollars or in dollars per area/weight/volume, which is to be added or subtracted to the contractor's bid price or unit bid price.
- 3.12 *pay adjustment schedule (for quality)* - Also called *price adjustment schedule* or *adjusted pay schedule*. A pre-established schedule, in either tabular or equation form, for assigning pay factors associated with estimated quality levels of a given characteristic. The pay factors are usually expressed as percentages of the contractor's bid price per unit of work but may also be given as direct dollar amounts.
- 3.13 *pay adjustment system (for quality)* - Also called price adjustment system or adjusted pay system. All pay adjustment schedules along with the equation or algorithm that is used to determine the overall pay factor for a submitted lot of material or construction. [A pay adjustment system, and each pay adjustment schedule, should yield sufficiently large pay increases/decreases to provide the contractor sufficient incentive/disincentive for high/low quality.]
- 3.14 *pay factor (PF)* - A multiplication factor, often expressed as a percentage that considers a single quality characteristic and is used to determine the contractor's payment for a unit of work.
- 3.15 *percent within limits (PWL)* - The percentage of the lot falling above a lower specification limit, beneath an upper specification limit, or between upper and lower specification limits. $PWL = 100 - PD$. [PWL may refer to either the

population value or the sample estimate of the population value. The term percent conforming should not be used as a synonym for PWL.]

- 3.16 *percent defective (PD)* - The percentage of the lot falling outside specification limits. $PD = 100 - PWL$. [PD may refer to either the population value or the sample estimate of the population value. The term percent nonconforming should not be used as a synonym for PD.]
- 3.17 *performance-related specifications (PRS)* - Quality assurance specifications that describe the desired levels of key materials and construction quality characteristics that have been found to correlate with fundamental engineering properties that predict performance. These characteristics (for example, air voids in asphalt concrete pavements and compressive strength of portland cement concrete) are amenable to acceptance testing at the time of construction. [True performance-related specifications not only describe the desired levels of these quality characteristics, but also employ the quantified relationships containing the characteristics to predict as-constructed pavement performance. They thus provide the basis for rational acceptance/pay adjustment decisions.]
- 3.18 *population (lot)* - A specific quantity of similar material, construction, or units of product, subject to either an acceptance or process control decision. This can range from all of the history of a material to a single lot (*Transportation Research Circular Number E-C137, 2009*).
- 3.19 *quality measure* - Any one of several mathematical tools that are used to quantify the level of quality of an individual quality characteristic. [Typical quality measures used in quality assurance are selected because they quantify the average quality, the variability, or both. Examples of quality measures that may be used include; mean, standard deviation, percent defective (PD), percent within limits (PWL), average absolute deviation (AAD), moving average, and conformal index (CI). PWL or PD are the quality measures that are recommended for use in quality assurance specifications.]
- 3.20 *rejectable quality level (RQL)* - The level of established actual quality for a quality characteristic that is rejectable when using a particular quality measure.

[For example, when the quality measure used is percent within limits (PWL), the RQL is the established (not estimated) PWL at which the quality characteristic is rejected. It is desired to require remove - and - replace, corrective action, or the assignment of a relatively low pay factor when RQL work is detected.]

- 3.21 *sample* - A small part of a population (lot) that represents the whole. This implies a statistical sample. Thus, the use of the term sample size, n , denotes the number of test values used to make a decision. (This should not be confused with size of sample that indicates a quantity of material).
- 3.22 *sampling and testing* - Sampling, testing, and the assessment of test results done to determine whether or not the quality of produced material or construction is acceptable in terms of the specifications (*AASHTO Designation: R 10*). The results are best used to estimate a population. This is true for both QC and acceptance functions. To estimate a population, two measures are needed, one is the center of the estimated population, and the other is a measure of its variability.
- 3.23 *seller's risk (α)* - Also called *contractor's risk*, or *risk of a type 1* or *alpha (α) error*. The risk to the contractor of having acceptable quality level (AQL) material or workmanship rejected. [For an accept/reject acceptance plan, it is the probability that an acceptance plan will erroneously reject AQL material or workmanship with respect to a single acceptance quality characteristic. For variables acceptance plans using adjusted pay schedules, it is equivalent to α_{PF} , where $PF = 100$. It is the probability that a variable payment acceptance plan will erroneously accept AQL material or workmanship at less than 100 percent pay with respect to a single acceptance quality characteristic.]
- 3.24 *types of acceptance plans* - A statistical acceptance plan is one based on either an analysis of variables or attributes. This recommended practice focuses on analysis of variables for acceptance. Analysis by attributes is based on noting the presence or absence of some characteristic or attribute. Attribute analysis is most often used in visual inspections, or when an item can only be classified as either acceptable or not acceptable, or pass/fail. Attribute plans are sometimes used with "screening tests" in which the material is tested before it is incorporated in the construction. Variables analysis is applicable to materials and construction in which quality is evaluated by measuring the numerical magnitude of a quality

characteristic. A quality characteristic is a characteristic of a unit or product that is actually measured for acceptance purposes (*Transportation Research Circular Number E-C137, 2009*).

- 3.24.1 *variability known acceptance plans* - Acceptance plans that assume a known and constant variability. [These types of acceptance plans measure only the average and are not appropriate for highway materials and construction and are not covered in this recommended practice.]
- 3.24.2 *variability unknown acceptance plans* - Acceptance plans that measure both the product average and variability as estimates of a population. [This is the type of acceptance plan used in this recommended practice.]

4 Development of Quality-Related Pay Adjustment Factors

- 4.1 Background – Quality measures are generally used by highway agencies for the acceptance of pavement construction. Material properties, smoothness, and other characteristics of the constructed pavement will generally vary somewhat from the specified design values because construction operations are influenced by many factors. Such variance will affect pavement quality and performance and, therefore, will affect both the highway agency and road users. Consequently, many highway agencies incorporate pay–adjustment clauses in their construction contracts to encourage excellent quality pavement and, failing that, to assess increasing amounts of pay reduction for increasing departures from the desired level of quality. Many such clauses are of the incentive/disincentive (I/D) type that also award incentive payments above and beyond the contract price for superior quality.

These guidelines for quality-related pay adjustment factors present a process that should continuously be updated as new processes, test methods, etc. are found. The use of the factors listed below provides the basis for a rational procedure for estimating quality-related pay factors.

- Acceptance Quality Characteristics (AQC)s
- Quality Measures (QM)
- Individual Pay Factors and Pay Schedules
- Composite Pay Factors (CPF)
- Risks Associated with Composite Pay Factors
- Operating Characteristic (OC) and Expected Pay (EP) Curve Analyses

In addition to general guidelines related to both flexible pavements and rigid pavements, examples are provided to illustrate the application of guidelines for (1) Ride Quality, (2) flexible pavements, and (3) rigid pavements. In addition, an example is included to illustrate the use of the Empirical PRS Method for flexible pavements.

4.2 Procedures for Flexible and Rigid Pavements

4.2.1 Description of Procedure – The description of the procedures applies to both flexible and rigid pavements because the basic concepts apply equally well to both. The procedure uses a composite pay factor procedure that is adapted from those workable and applicable procedures that are presently in use by several SHAs. The basis of the procedure was developed based on work reported in NCHRP Synthesis 346 “State Quality Assurance Programs” (Hughes 2005) and procedures used in AASHTO R-9 “Acceptance Sampling Plans for Highway Construction” and AASHTO R-42 “Development of a Quality Assurance (QA) Plan for Hot Mix Asphalt”. A recent survey conducted in support of these guidelines also verified the extensive use of this form of pay factor. The procedure provides a thorough analysis of the relevant factors. The procedure provided uses statistically valid methods and provides sufficient flexibility to allow individual SHAs to modify the suggested AQC)s and weights to meet their needs and experience using a composite pay factor.

The procedure, adapted from AASHTO R-9 and AASHTO R-42, is based on experience and generally does not include a bona fide model, or pay schedules based on any specific economic analysis.

Composite Pay Factors – The recent survey found that several agencies use a weighting system to combine individual pay factors based on the concept that some AQC's are more important than others are. The form of the weighted composite pay factor (AASHTO R-9) is expressed by the following Equation 1:

$$\text{CPF} = W_1(\text{PF}_1) + W_2(\text{PF}_2) + \dots + W_k(\text{PF}_k) \quad (1)$$

Where

CPF = Composite pay factor,

W_i = Weighting factor for AQC "i",

PF_i = Pay Factor for AQC "i",

I = Subscript to denote specific AQC's, and

K = Number of AQC's.

4.2.2 Evaluative Work and Guidelines – In general, these procedures are evaluated by comparison against recognized practices that are presently being used and that have evolved over several decades of highway QA experience. The factors included in the guidelines are the selection of the:

- AQC's,
- statistical QM,
- individual pay factors and pay schedules,
- CPF equations, and
- determination of the risks, by development of OC and EP curves.

4.2.3 Overview of General Guidelines and Inputs – This general overview of the guidelines applies equally well to both flexible and rigid pavements. However, there are individual issues that differ for some inputs for each pavement type. The general overview includes the following inputs for this procedure:

4.2.3.1 Acceptance Quality Characteristics – AASHTO R-10 defines an AQC as "A quality characteristic that is measured and used to determine acceptability." For these guidelines, the definition of AQC is modified to include only those

characteristics related to pay factors. For example, the use of AQC's as screening tests that can be quickly determined and prevent "non-conforming" material from being incorporated in the project, are not included.

The AQC's that are used for pay factor adjustment are those considered by the engineering community to be those most related to quality and ultimately to performance. AQC's that are correlated, (i.e., not independent) should be avoided (Burati et al 2003) because of the greater likelihood that the pay factor will be compromised by the correlation, [i.e., a reduction (or increase) by one would affect the same response in the other].

Several AQC's, particularly for flexible pavements, are correlated to some extent but many highway acceptance procedures include AQC's that have appreciable correlation. As an example for flexible pavements, if the asphalt content is increased, it is expected that the air voids will decrease. However, both of these AQC's are considered important characteristics and both are often measured for use as pay factors. Furthermore, it is conceivable that there may be additional cases in which SHAs would prefer to use correlated characteristics as a conservative "belt-and-suspenders" approach to QA. Therefore, these guidelines use AQC's that have been shown to be correlated to some degree.

A variety of AQC's are used by the various SHAs. AQC's supported by engineering experience and used by the majority of SHAs are presented and discussed in the sections for each pavement type.

In current practice, the choice of whether to apply quality-related pay adjustment factors to functional classes of roadways is generally handled in one of two ways. One is the choice of the AQC's to use. On relatively low trafficked roadways, (secondary roads for example) density or thickness may not be used as an AQC whereas on higher trafficked roadways it would be used. The second way is to relate the use of pay adjustment factors to the size of the project in terms of material quantities or project geometrics. For example, some SHAs predicate the choice of whether to use of pay adjustment factors or methods specifications (which generally are unsuited to using quality-related pay adjustment factors) based on project size or geometrics.

If SHAs choose to use functional class as the determinate of whether to use quality-related pay adjustment factors, quality-related pay adjustment factors may be used on Interstate, principal urban and rural arterials, and major collectors; whereas method specifications may be used on rural secondary, ramps, and facilities with geometric issues that may place a burden on contractors.

4.2.3.2 Quality Measures – The QM used in these guidelines is the one that is best suited to provide a measure of population parameters related to quality, since the purpose of a QM is to estimate basic population parameters, i.e., mean and standard deviation; a measure of these is essential. This is especially true of AQC's with both upper and lower specification limits. For these AQC's, using only the average as a QM has proven to be less effective than also measuring the variability (Burati and Hughes, 2003). The reason for this is that the former encourages the contractor to balance low test values with high values (or vice versa) by changing the process to meet the specification. This may result in creating a bimodal population, i.e., one with two modes or peaks with an increase in the variability. Using only the average also presents a problem when trying to quantify risks as the population variability is an important factor when calculating risks. Therefore using only the average as a QM is not used in these guidelines.

4.2.3.2.1 Percent Within Limits (PWL) or percent defective (PD) – are used in the guidelines as the preferred QM because they have been recognized as being the most effective measures to control both central tendency and variability (as evidenced by their inclusion in AASHTO R-9 and R-42) and they are often used QMs by SHAs, Federal Aviation Administration (FAA), and the Federal Highway Administration (FHWA) (Rafalowski 2010).

The PWL is estimated by using the quality index, Q . The Q -statistic is used with a PWL table to determine the estimated PWL. PWL is used throughout these guidelines, except for the empirical PRS for flexible pavements in which PD is used to simplify the calculations.

Conceptually, the PWL procedure is similar to determining areas under the normal curve that can be calculated to determine the percentage of the population that is within certain limits by using the standard normal variant, Z . Instead of using the Z -value (from the normal distribution) and the standard normal curve, a

similar statistic, Q , is used to estimate PWL by the use of a PWL table. The Q -statistic is calculated in Equations 2 and 3.

$$Q_L = \frac{\bar{x} - LSL}{s} \quad (2)$$

and

$$Q_U = \frac{USL - \bar{x}}{s} \quad (3)$$

Where

Q_L = quality index for the lower specification limit.

Q_U = quality index for the upper specification limit.

LSL = lower specification limit.

USL = upper specification limit.

\bar{x} = the sample mean for the lot.

s = the sample standard deviation for the lot.

Q_L is used when there is a one-sided lower specification limit, and Q_U is used when there is a one-sided upper specification limit. For two-sided specification limits, the PWL value is estimated in Equation 4:

$$PWL_T = PWL_U + PWL_L - 100 \quad (4)$$

Where

PWL_U = percent below the upper specification limit (based on Q_U).

PWL_L = percent above the lower specification limit (based on Q_L).

PWL_T = percent within the upper and lower specification limits.

4.2.3.2.2 Other QMs – The guidelines considered using other QMs such as average absolute deviation (AAD), and a combination of average and standard deviation.

AASHTO R-10 does not recommend the use of AAD. It is not included in these guidelines for the following reasons:

- deviations measured from a target value often do not exist for AQC's with single lower or upper limits (e.g., thickness or rigid pavement compressive strength),
- because neither an estimate of the mean nor the variability of the population (lot) is provided or measured, the same AAD value can be calculated from populations with much different means and standard deviations, and possibly very different quality potential,
- in order to analyze the risks, either the population mean or the population standard deviation must be held constant, not a realistic situation.

Besides the average, PWL and PD, and AAD, some SHAs use the average and standard deviation separately, but determining risks for myriad possible combinations is difficult and requires the assumption of holding one parameter constant while varying the other.

4.2.3.3 Individual Pay Factors, Pay Adjustment Schedule, and Pay Adjustment System – There are several forms of pay factors, pay adjustment schedules, and pay adjustment systems that can be used. In keeping with the AASHTO definitions, there are three steps in determining the pay adjustment system: (1) establishing the payment for a single AQC, (2) pre-establishing a schedule in either tabular (stepped) or equation (continuous) form, and (3) determining how the pay adjustment schedule will be applied.

The form of pay factor for the chosen individual AQC's should include an incentive so that the desired level of pay at the acceptable quality level (AQL) is met (i.e., is 100%) in the long term.

AASHTO R-9 presents two conditions that apply to any pay adjustment schedule. They are:

- The pay should be 1.00 (100 percent) when the PWL is at the AQL.

- For the average pay to be 1.00 at the AQL there must be an incentive that allows pay above 1.00 to compensate for lower pay factors from estimated quality levels below the AQL. Due to the random nature of the sampling process, occasionally a sample of the material at the AQL would indicate that a reduced pay factor should be applied. However, if there is no incentive provision, when the sample indicates quality in excess of the AQL the pay factor would be 1.0. Since in this scenario the maximum pay is 1.0, it is not possible for material at the AQL to receive an average pay factor of 1.0.

Continuous (equation-type) pay schedules are used more often than stepped (tabular) pay schedules. They are straightforward and concise, and avoid disputes that may arise when the estimated quality level falls just on one side or the other of a large step in a stepped pay schedule. However, these guidelines consider tables with small steps in the quality measure and pay factors.

A commonly used continuous pay schedule is expressed by Equation (5):

$$PF = 55 + 0.5 \text{ PWL} \quad (5)$$

Where

PF = payment factor as a percent of contract price.

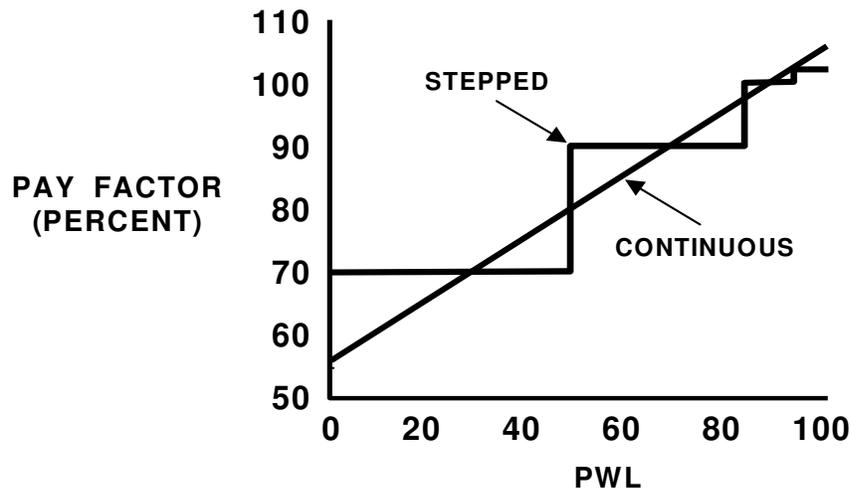
PWL = estimated percent within limits.

Some state laws apparently disallow the payment of incentives. To accommodate this restriction, a few SHAs use incentives only to offset disincentives. Because this practice is not used widely and does not present an equitable risk consideration, the guidelines do not consider this application. However, a SHA may incorporate this provision by having positive and negative pay adjustments offset each other, preferably accompanied by a risk analysis.

In 1976, it was reported that payment schedules were often tabular or stepped schedules, such as that shown in Table 1 and plotted in Figure 1 (Bowery and Hudson 1976). Information from a recent survey indicates that these types' schedules are still often used.

Table 1. Typical Stepped Payment Schedule Based on PWL

Estimated PWL	Payment Factor, %
95.0 - 100.0	102
85.0 - 94.9	100
50.0 - 84.9	90
0.0 - 49.9	70

**Figure 1: Example of Stepped and Continuous Payment Schedules**

This example points out a weakness that should be avoided, such that a small change in quality (as measured in this example by PWL) can make a large difference in payment. For example, if the PWL estimate is 84.9, the payment is 90% but the payment would be 100% for a one-tenth percentage increase in quality to a PWL of 85.0.

Although risk analysis would show continuous and stepped payment schedules have nearly the same long-term performance, there is a distinct advantage associated with the continuous form. When the true quality level of the work lies

close to a boundary in a stepped payment schedule, the quality estimate obtained from the sample may fall on either side of the boundary due primarily to chance resulting in a substantial difference in payment level. This may lead to disputes over measurement precision, round-off rules, and so forth. Continuous payment schedules that provide a smooth progression of payment as the quality measure varies would eliminate such situations.

In addition to the AQL, the rejectable quality level (RQL) is another definition to measure risks and analyze the efficacy of a pay adjustment schedule. While there is, a requirement that product quality at the AQL receives 100% pay, there is no requirement for a minimum pay factor at the RQL. The general practice is to either have a minimum pay factor or require the contractor to remove - and - replace (R&R) the material. The R&R may warrant a retesting of the product before enforcing the R&R.

4.2.3.3.1 AASHTO Pay Equation – Many SHAs use the AASHTO Pay Equation (Equation 5).

A recent survey conducted as part of NCHRP 10-79 showed that of 31 SHAs (out of 37 responding) use incentives which range from one (1) percent to 15 percent; 18 of which use a 5 percent maximum. Typically, the 15 percent incentives are restricted to Ride Quality. This value reflects the importance of this Ride Quality as reported in the survey on customer satisfaction (AASHTO Journal 1996).

The AASHTO R-9 pay equation (Equation 5) results in a straight-line relationship with 105% pay at 100 PWL and 100% pay at 90 PWL.

Florida DOT has used the equation and has reported satisfactory results (Scholar 2006). However, other SHAs have developed their individual equations that follow the AASHTO form, but establish different incentive values. The AASHTO Pay Equation has been questioned as to its applicability for all AQC's, but no research has been done to prove or disprove it. Willenbrock and Kopac suggest that the price adjustment system must be consistent with the highway agency's philosophy regarding the level of quality desired in future construction (Willenbrock et al 1977).

These guidelines consider the continuous equation to be consistent with the tabular form by having the RQL of 50 PWL assess a pay factor of 70 percent for both procedures. However, this is not straightforward for the tabular form because of the range of PWL values that exist at each pay factor.

4.2.3.3.2 Other forms of Pay Equations – Two other forms of pay equations are sometimes used. One is a series of straight-line pay equations that have different slopes to accentuate the incentive or the disincentive as indicated in equations 6a through 6d. An example of such a pay equation series is shown below and in Figure 2.

$$\text{From PWL} = 90 \text{ to } 100; \text{PF} = 55 + 0.5(\text{PWL}) \quad (6a)$$

$$\text{From PWL} = 70 \text{ to } 89.9; \text{PF} = 10 + 1.0(\text{PWL}) \quad (6b)$$

$$\text{From PWL} = 50 \text{ to } 69.9; \text{PF} = -25 + 1.5(\text{PWL}) \quad (6c)$$

$$\text{For PWL} = <50; \text{PF} = 50\% \text{ or remove - and - replace} \quad (6d)$$

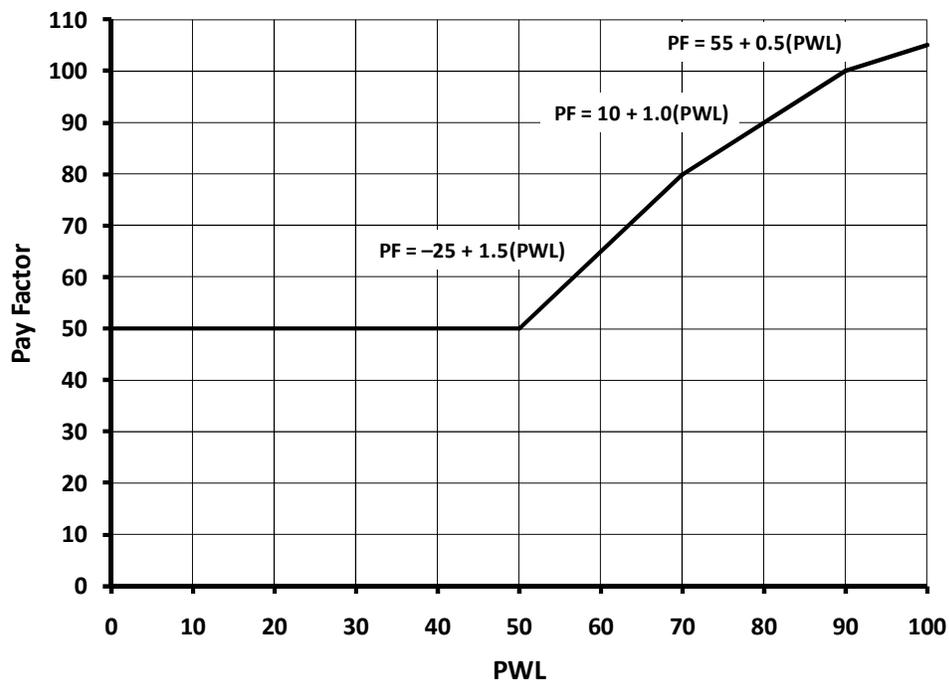


Figure 2. Example of Multiple Straight-line Pay Equations

This series of pay equations makes the disincentive more severe as the quality level decreases. A risk analysis should be done before deciding on this or any other pay equation series.

Very few curvilinear relationships between quality and pay factors have been developed. One example is a pilot specification developed for the Virginia Department of Transportation (VDOT) for HMA (Hughes 1995). The pay equation, Equation 7 was:

$$PF = -0.01166(PWL)^2 + 2.2039(PWL) - 3.716 \quad (7)$$

Where

PF = pay factor

PWL = percent within limits

In this equation a PWL=90 and a PWL=40 were established for the AQL and RQL, respectively. Thus, if the PWL was 100, the maximum pay factor attainable was 107.5%. At the AQL, the Pay Factor was 100.2% (slightly higher than the 100% required by the AQL definition). At the RQL of 40, the minimum pay factor was 37.4% (Hughes 1995).

4.2.3.3.3 RQL Provisions - Most often, more attention has been given to establishing an equitable pay factor at the AQL than at the RQL. While it is important to assure that the contractor can expect 100% pay in the long run when producing AQL product, it is also important that the disincentive at the RQL be equitable to both the contractor and the SHA. For the contractor, it must not be overly punitive. In addition, it is appropriate that the pay reduction for RQL work be large enough to compensate the SHA for the extra expense from additional maintenance costs and/or premature failure. Although many current highway construction specifications do not define an RQL this level of quality should be included. In a well designed and effective acceptance procedure, analysis of the risks at both the AQL and RQL is important.

4.2.3.4 Composite Pay Factors – The method for combining individual pay factors should be decided upon when developing the pay schedule. Weighted pay factors is the primary recommended procedure, following the recommended practice in AASHTO R-9. Life-cycle-cost (LCC) analysis, a technique often used and well understood by the engineering profession, is a useful procedure to establish and justify pay adjustment schedules.

There are several ways of developing composite pay factors; the most often used include using the minimum, average, multiplication, or weighted. The first three methods all give equal weight to all the AQCs. Examples of these three methods are given in Table 2 (Burati and Hughes 2003).

Table 2. Composite Pay Factors Using Various Approaches

Individual Pay Factor for each AQC			Composite Pay Factor		
AC%	AV%	Density	Minimum	Average	Multiply
1.00	1.00	1.00	1.00	1.00	1.00
1.05	1.05	1.05	1.05	1.05	1.16
0.80	0.80	0.80	0.80	0.80	0.51
1.00	0.80	1.05	0.80	0.95	0.84

In this example, when all the pay factors are 1.00 (100%) they all result in a composite pay factor of 1.00 (100%), which is not a typical occurrence. When different pay factors occur and the minimum pay factor is used, the AQC that produces the lowest pay factor determines the composite pay factor and this AQC is assumed to be the most likely to cause an early failure. The use of the average approach produces the least variable pay factor of the three methods. The use of the multiplication approach produces the most variable in that it creates the lowest pay factor for inferior product and the highest pay factor for superior product.

It has been questioned if an incentive should be paid if one or more AQCs produce a disincentive. This could occur (see Table 2) if the incentives of two of the three AQCs were sufficiently high. Such an occurrence could be avoided by stating to the effect that “no composite incentive will be paid if any AQC produces an individual disincentive.”

The recommended weights in these guidelines consider the weights found in the recent survey and in AASHTO R-42; however SHAs may use other weights according to their experience.

For flexible pavements, material AQC's are often determined at the asphalt plant and paid for separately from those associated with roadway construction. Thus, a method for determining the pay factors for material AQC's prior to testing for construction must be considered. Nevertheless, for some SHAs, the materials and construction AQC's are determined at the construction site. Thus, a procedure for determining pay factors that addresses the separate as well as combined use of mixture and construction AQC's are included in the guidelines for flexible pavements.

Since the AQC of Ride Quality is often used as a separate pay factor and less often as a component in a composite pay factor, both procedures are addressed in the guidelines.

The level of construction quality (e.g., superior, good, adequate, and poor) is considered by selecting the QM and the individual and combined pay factors determined to be the most appropriate by the SHA.

- 4.2.3.4.1 Risks Associated with Composite Pay Factors – Using more AQC's than needed to define product quality is unnecessary. The risks discussed below apply to each pay factor. The calculation of risks is complicated when using composite pay factors. It is desirable that the AQC's not be highly correlated because this can result in an inefficient use of sampling resources. If the AQC's are correlated to a substantial degree, it is possible to use only one AQC, or else mitigate the effect by using smaller weights on the individual pay factors. While there is no specific number of AQC's that should be used, only those AQC's that are predictors of quality (and thus of performance) of the constructed product should be used.
- 4.2.3.5 Risks, Operating Characteristic (OC) and Expected Pay (EP) Curve Analysis – All acceptance plans contain risks, (i.e., probability of making a wrong decision.) Risks also apply to the probability of assigning the wrong pay adjustment.

Two risks exist; the seller's risk (α) and the buyer's risk (β). Risks cannot be eliminated but they can be minimized and balanced which is the goal of a well-written acceptance plan and pay adjustment schedule.

4.2.3.5.1 OC and EP Curves – Because OC and EP Curves are invaluable tools for assessing risks; the guidelines describe methods for conducting an OC and EP Curve analysis on the proposed procedures to assure they are working properly.

The AASHTO R-10 defines the OC curve as “A graphical representation of an acceptance plan that shows the relationship between the actual quality of a lot and either (1) the probability of its acceptance or (2) the probability of its acceptance at various payment levels.” The second part of the definition is used in these guidelines.

AASHTO R-10 also defines an EP curve and states “Both OC and EP curves should be used to evaluate how well an acceptance plan is theoretically expected to work.”

These analyses provide an assessment of the SHA and Contractor risks that are expected to be reasonably balanced at low values. Such analyses are necessary to ensure the procedure's effectiveness.

One important aspect of risks that applies equally to OC and EP curves is the effect of sample size that is a key component for any procedure used. Regardless of the sophistication or accuracy of the models, the effectiveness of the procedure is limited by the sample size. The sample size will always be the primary factor influencing the risk of making proper payment decisions!

Too large a risk for either party undermines credibility. Thus, the risks should be balanced and should be reasonably small. For most highway products, if this is not possible because of the sample size selected, it is generally agreed that the risks to the contractor should be less than that to the agency except for potential catastrophic failures (Burati and Hughes 2003). AASHTO R-9 notes that for pavements, the seller's (Contractor's) risk should be lower than the buyer's (Agency's) risk.

4.2.3.5.2 Risks Concepts – The concept of α and β risks derives from statistical hypothesis testing that results in either a right or wrong decision. As such, when α and β risks are applied to highway pavements they are only truly appropriate for the case of a pass/fail or accept/reject decision and, therefore, may lead to considerable confusion if an attempt is made to apply them to the pay adjustment case. When materials not only can be accepted or rejected, but can also be accepted at an adjusted pay, then additional interpretations or clarifications must be applied to the definitions of risks.

For example, in the definition for buyer's risk, β is the probability that RQL material will be accepted at 100 percent pay or greater. The definition also points out that there may be a much greater probability that the RQL material will receive some reduced pay. While it is not stated as directly, the same reasoning is true for the seller's risk. The definition indicates that α is the probability that AQL material will be rejected. Although not stated in the definition, there may be a much greater probability that the AQL material will be accepted at a reduced pay.

OC Curves – α and β are very narrowly defined to occur at only two specific quality levels. β is the probability of accepting, at full pay or more, material that is exactly at the RQL, while α is the probability of rejecting material that is exactly at the AQL. These definitions do not provide an indication of the risks over a wide range of possible quality levels. To evaluate how the acceptance plan will actually perform in practice, it is necessary to construct an OC curve.

An example of an OC curve for a pass/fail or accept/reject acceptance plan is shown in Figure 3. Probability of acceptance is shown on the vertical axis for the range of quality levels indicated on the horizontal axis. An example of an OC curve for an acceptance plan with pay adjustment provisions is shown in Figure 4. The figure shows curves for different pay levels.

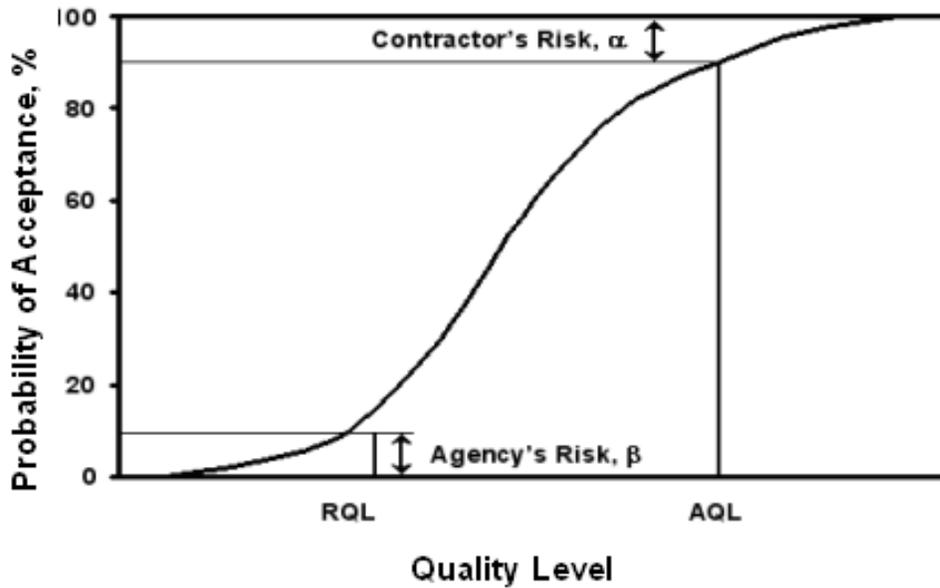


Figure 3. Typical OC Curve for an Accept/Reject Acceptance Plan

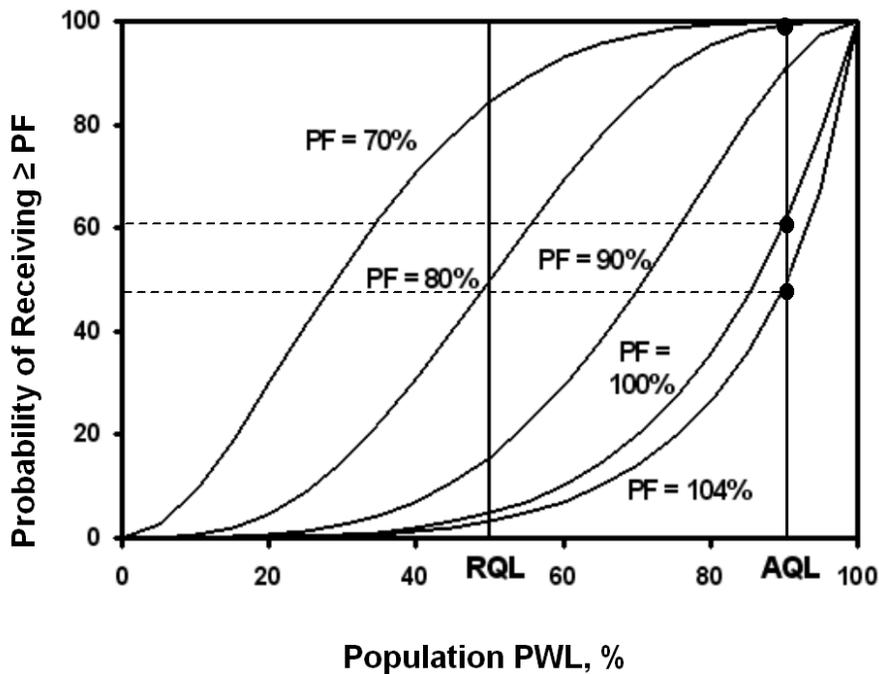


Figure 4. Typical OC Curves for an Acceptance Plan with Pay Adjustments

Each curve in Figure 4 represents the probability of receiving a pay factor equal to or greater than that indicated for the line. For example, material that is of exactly

AQL quality has approximately a 45 percent chance of receiving a pay factor of 1.04 (104 percent) or greater, has approximately a 60 percent chance of receiving full pay (100 percent) or greater, (i.e., approximately a 40 percent chance of receiving less than 100 percent pay). This material has also a 100 percent chance of receiving a pay factor of 0.80 (80 percent) or greater.

On the other hand, material that is of exactly RQL quality has approximately a 50 percent chance of receiving a pay factor of 0.80 (80 percent) or greater, and better than an 80 percent chance of receiving a pay factor of 0.70 (70 percent) or greater. Similar pay probabilities can be determined for any level of quality, and additional curves could be developed for any specific pay factor.

4.2.3.5.3 Pay Adjustment System Plans – As discussed in Section 4.2.3.5.2 and shown in Figure 3, because α and β risks occur only at two points on the curve and determine the probability of acceptance, this does not assess the risks when pay adjustments are used. From Figure 4, it can be seen that using multiple OC curves can be a confusing way to evaluate an acceptance plan.

EP Curves – An EP curve provides another way to present the pay performance for an acceptance plan that may be easier to understand. An example of an EP curve is shown in Figure 5. Quality levels are indicated on the horizontal axis and the vertical axis gives the expected (long-term average) pay factor as a percent of the contract price.

Although the risks have a different interpretation when associated with EP curves than with OC curves, they provide the same type of information. It is a generally accepted tenet that the average pay for material that is just fully acceptable should be close to 100 percent of the contract price. For the example in Figure 5, AQL work would be expected to receive a pay of 100 percent, while superior work (better than the AQL) would receive an expected pay up to a maximum of 102 percent. At the other extreme, RQL work would expect to receive a pay of 70 percent. For lower levels of quality, the curve levels off at an expected minimum pay of 50 percent.

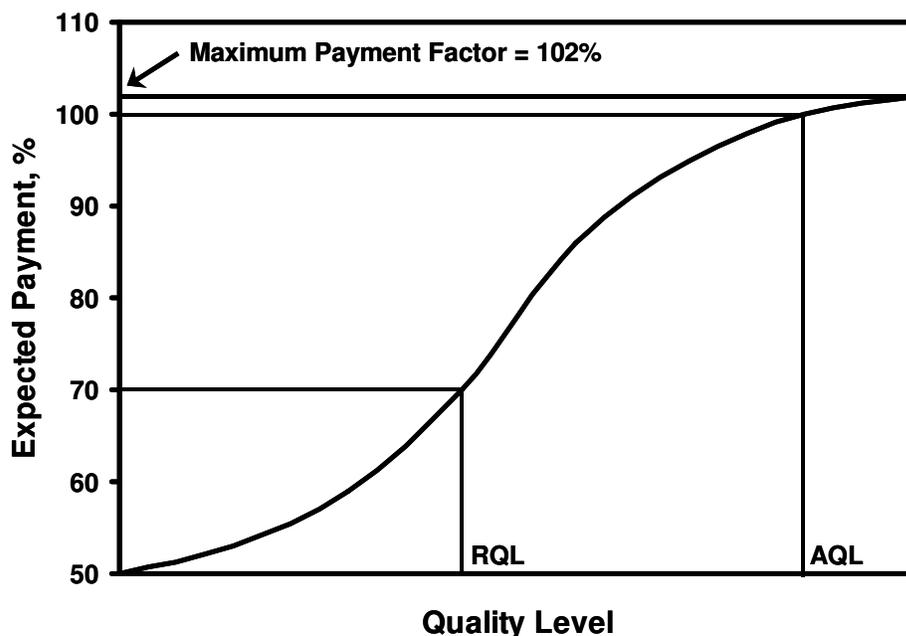


Figure 5. Typical EP Curve

- 4.3 Guidelines for Ride Quality – Ride Quality is an AQC that applies equally well to flexible and rigid pavements and is adopted as an AASHTO Recommended Standard Practice R-54-10 using the International Roughness Index (IRI) as the QM (rather than PWL).
- 4.3.1 Use of Ride Quality – The use of Ride Quality has become a very important AQC. The recent survey conducted for NCHRP Project 10-79 showed that 26 SHAs (out of 37 responses) use Ride Quality as an AQC. The move toward using Ride Quality as an AQC is attributed, at least in part, to a FHWA survey of the traveling public that reported that the pavement Ride Quality was the most important factor (of seven analyzed) and the one most in need of improvement (AASHTO Journal 1996). Thus, to increase customer satisfaction an increased use of monetary incentives was initiated for Ride Quality to provide the contractor an incentive to not only meet the specifications but to exceed them for smoothness.

However, currently there is a wide discrepancy among SHAs on the pavement roughness measurement (IRI) or profile Index (PI), measurement interval, limit of

the IRI range, and related pay factors. The incentives used by some SHAs are larger than those used for other AQC's (e.g., as high as 15 percent in some SHAs) and are often paid separately from the other AQC's.

The recent review of different existing roughness measurement systems across the country indicated that IRI is the most often accepted type of pavement roughness measurement (Wilde 2007). In addition, Ride Quality has recently been adopted as AASHTO Standard Recommended Practice R54-10 "Accepting Pavement Ride Quality When Measured Using Inertial Profiling Systems". This practice recommends using IRI measurements to compute the final pay adjustment for roughness.

A typical system of pay adjustment is established for a project length of roadway with measurement intervals of 0.1 mile of the roadway. AASHTO R-54 provides an unpopulated Pay Adjustment table (Table 3) that allows a SHA to decide a pay adjustment schedule to determine the Final Pay Factor.

Table 3. Pay Adjustment Factors and Computation of Final Pay Factor (AASHTO R-54 Method)

IRI range, in./mi	Pay Adjustment Factors(decimal)	Percent of Pavement within IRI Range	Pay Adjustment
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—
—	—	—	—

^Taken from Approval's Smoothness Assurance Module (SAM)

The first column of Table 3 is the range of IRI and the second column is the percent of incentive or disincentive that the SHA consider for each of these IRI ranges. Since the limits of IRI are based on the initial serviceability of the pavement, it varies with the functional class of roadway. Highways are expected to be smoother than local roads and hence a comparably higher initial serviceability index or a lower IRI range for the maximum limit without corrective action (RQL) for highways is used. A maximum allowable IRI of 95 in./mile (corresponding to a present serviceability index of 3.35) is typically used for a highway (Wilde 2007). There are other factors that influence the pavement roughness including the pavement type (flexible or rigid), lift thickness of AC layer (flexible pavement), number of resurfacing layers (i.e., single-lift or multiple-lift construction), presence of inlets and gutters, intersections, and posted speed limit. The SHAs define the pay schedule deemed suitable for their specific set of field conditions.

The review indicated that the acceptable range of IRI is generally from 95 in./mile to 65 in./mile, with an IRI below 65 in./mile considered to provide superior Ride Quality that should receive an incentive. An IRI range of 65 to 75 in./mile is reported to be an acceptable range where the pay factor should be 1.0 or 100 percent and IRI values above 75 in./mile should receive proportional degrees of disincentive. The review showed wide variation in the upper limit of IRI (from 75 to 120 in./mile), at which corrective action is recommended. The corrective actions typically undertaken to improve smoothness are grinding, remove - and - replace of the pavement section, or requirement of an additional resurfacing layer. Disincentives apply to IRI values above 75 in./mile up to the maximum permissible IRI of 95 in./mile and corrective action is recommended for Iris above this maximum value (Wilde 2007).

The percent of IRI measurements that fall within a specific IRI range is obtained from Provably (software used for processing IRI data from a profiler) and entered in Table 3. The pay adjustment determined is the product of the pay adjustment factor and percent of pavement within the specified IRI range. The pay adjustments are then summed and divided by 100 to obtain the Final Pay Factor (incentive or disincentive) for that project length. Since the lot size is 2 miles and $n = 10$ has been chosen as the sample size for the construction AQC's (density and thickness), the interval does not match that of the IRI measurement interval (0.1 mile) and continuous sampling, making it difficult to directly compare the statistics. A feasible alternative is to make the corrective actions as required based

on the 0.1 mile IRI measurement, and then obtain representative IRI values for the sample interval selected for other AQC's ($n = 10$ for the 2 miles of roadway) to combine them with other AQC's. SHAs may use or modify this system.

Table 4 shows an example of IRI data for a two-mile roadway (divided into the 0.2 mi. sections) after corrective action. These data are used to complete the AASHTO R-54 table (Table 5).

Table 4. Representative IRI Data after Corrective Action

IRI Measurements¹	IRI, (in/mile)
#1	56.46
#2	51.56
#3	49.68
#4	52.04
#5	38.31
#6	41.80
#7	50.07
#8	51.14
#9	64.21
#10	77.00

¹For 0.2 mile segments

Table 5. Example of Pay Adjustment Factors

IRI Range, in/mi	Pay Adjustment Factors	Percent within IRI Range¹	Pay Adjustment
<45.0	1.05	20	21.00
45.1 – 50.0	1.04	10	10.40
50.1 – 55.0	1.03	40	41.20
55.1 – 60.0	1.02	10	10.20
60.1 – 65.0	1.01	10	10.10
65.1 – 75.0 (AQL)	1.00	0	0.00
75.1 – 80.0	0.95	10	9.50
80.1 – 85.0	0.90	0	0.00
85.1 – 90.0	0.85	0	0.00
90.1 – 95.0 (RQL)	0.80	0	0.00
> 95	0.80	0	0.00
Total		100	PF = 102.40

¹Using example IRI data in Table 4

4.3.2

AQL and RQL for AASHTO R-54 – The AQL (70 in./mile) and RQL (92.5 in./mile) values are close to those suggested in the MnDOT study. As discussed in the Guidelines for flexible pavements, determining the AQL and RQL values using a stepped procedure is not straightforward. These values and the limits of IRI range noted in these examples may need to be adjusted to suit the requirements of the roadway considered and the SHAs' experience.

It is also possible to use the data in Table 4 to calculate a PWL value for IRI as is done for other AQC's and use that value (McGhee 1998). This calculation requires the average and standard deviation of the data, estimated to be 53.23 and 10.96, respectively.

These data can then be used to estimate the PWL. The next step would be to enter the PWL into Equation 5 to determine the final pay factor. For this example, the following equation is needed.

With an Upper Specification Limit (USL) = 95, the Q_U value for the upper limit from Equation 3 is:

$$Q_U = \frac{USL - \bar{x}}{s} = \frac{95 - 53.23}{10.96} = 3.81$$

For a $Q_U = 3.81$ and a sample size $n = 10$, the PWL_U value is 100. PWL_L is assumed to be 100 because there is no lower specification limit. Therefore, the total PWL for this data set is computed with Equation 4 to be $PWL_T = 100 + 100 - 100 = 100$.

Thus the pay factor estimated from Equation 5 is $PF = 55 + 0.5 PWL_T = 55 + 0.5(100) = 105$.

Because of the AQL and RQL values that were used in this application, the continuous method always produces a slightly higher pay factor value than the stepped method.

However, other factors need to be considered when combining the IRI data with other AQC's including the measurement/sampling interval and the percent of incentive and disincentive of each AQC.

Different systems are used to consider corrective actions in computing the final pay adjustment. AASHTO R-54 recommends either applying disincentives to sections identified as having localized roughness (based on a separate pay adjustment schedule considering each 25 feet section) or taking corrective action. If corrective action is applied to reduce the roughness within the specified range, the re-profiled values are used to compute the overall pay adjustment of the project. Alternatively, R-54 recommends applying the disincentives for localized roughness in addition to the pay factor determined for the project. Some SHAs prohibit paying an incentive and allow a maximum 1.0 pay factor for those sections where corrective action was required to reduce the roughness to the lower IRI range where incentives are applicable. This practice recognizes the contractor's failure to meet the specification such that a correction was necessary.

Another issue pertains to the maximum individual pay factor for Ride Quality that should be considered before combining Ride Quality with other AQC's to determine a composite pay factor. Some SHAs use a maximum pay factor of 1.15 or higher although the AASHTO Pay Equation and the stepped pay factor restrict the maximum pay factor to 1.05. The influence of an individual AQC can be increased by making the individual maximum pay factor larger than others or by making the coefficient in the composite pay factor equation larger. Making an individual pay factor for one AQC higher than the others could possibly cause one AQC to be stressed to the detriment of other AQC's. For example if the maximum pay factor for Ride Quality was 1.15 and the maximum factor for thickness was 1.05, it is conceivable that Ride Quality would be emphasized and thickness deemphasized. Thus, a maximum pay factor for Ride Quality that is equal to that for other AQC's is necessary. The factor should be consistent with that of the AASHTO pay equation of 1.05. In addition, it would be appropriate to use both the stepped table and AASHTO pay equation and to emphasize Ride Quality with an increased coefficient in the composite pay factor equation. This approach is demonstrated in the examples (Appendix A.).

4.4 Procedures for Flexible Pavements – The procedures for flexible pavements contain specific quality-related factors for these pavements. These are:

- Acceptance Quality Characteristics
- Quality Measures
- Individual Pay Factors and Pay Schedules
- Composite Pay Factors
- Risks Associated with Composite Pay Factors
- Operating Characteristic and Expected Pay Curve Analyses

4.4.1 Flexible Pavement AQC's – The AQC's that are used for pay factor adjustment should be those most related to quality and performance.

AASHTO R-42 “Development of a Quality Assurance (QA) Plan for Hot Mix Asphalt” states that, “hot mix asphalt (HMA) properties used for acceptance

typically include the asphalt content (AC); air voids (AV), and voids in the mineral aggregate (VMA) and other requirements of the agency. Target values for these HMA properties should be those from the JMF and acceptance testing should also include density on the roadway.”

The “other requirements” often include one or more gradation sieves. However, including too many sieves could bias the payment provisions (depending on the weighting factors chosen) towards gradation and away from other material properties. Trends show that if one sieve is on one side of the target value, other adjacent sieves also tend to be on that same side [i.e., the gradation tends to run on the coarse (or fine) side of the JMF]. For low volume roads, it is suggested that emphasis placed on material AQC's and construction AQC's be minimized. Thickness and Ride Quality are suggested construction AQC's to be applied to moderate and high traffic categories, in addition to density. There has been a recent increase in the use of joint density in addition to lane density as construction AQC's. These are not included in the procedure but may be added by SHAs.

The AQC's are separated into Materials and Construction categories. Acceptance of materials is normally based on plant-tested samples and acceptance of construction is based on field-tested samples. They may be used in a pay adjustment system separately or combined.

- 4.4.1.1 Materials AQC's – The most appropriate AQC's for flexible pavement materials are asphalt content (AC), lab compacted air voids (AV), voids in the mineral aggregate (VMA), and “other requirements” (AASHTO R-42). (Gradation was selected as the other requirement).
- 4.4.1.1.1 AC – AC was one of the first AQC's used in pay adjustments (McCloud 1956, Roberts et al, 1996); the relationship between AC and pavement performance has been recognized for many years. Too much asphalt can result in permanent deformation and too little asphalt can result in early fatigue cracking and raveling. Acceptance based on asphalt content has been reported by a large number of SHAs.

- 4.4.1.1.2 Air Voids (AV) – Laboratory AV has been recognized since the use of the Marshall mix design procedure as an important predictor of asphalt mix performance (McCloud, 1956). AV is instrumental in predicting the ability of the mix to be compacted in the field that is a strong indication of performance. Acceptance based on AV has been reported to be used by a large number of SHAs.
- 4.4.1.1.3 VMA – VMA is the volume of the compacted mix that is not occupied by asphalt (Hinrichsen, 1996). It indicates the ability of the total gradation to accommodate the asphalt. It is used as an AQC by several SHAs.
- 4.4.1.1.4 Gradation – Gradation has been used as an AQC since the 1940s (Hveem 1940). However, the number of sieves used for acceptance has changed over the years. Initially a full suite of sieves was used, from the top size sieve down to the #200 (0.075-mm). More recently, it has been recognized that an acceptable testing AQC can be obtained from using fewer sieves; that also enhances the ability of a contractor to control the gradation. Several SHAs reported the use one or more sieves as an AQC. Often, one sieve is chosen for acceptance of the coarse portion of the gradation, [percent passing the ½” (12.5-mm) sieve], one for the fine portion, [percent passing the #4 (4.75-mm) or #8 (2.36-mm) sieve], and one for the fines [the percent passing the #200 (0.075-mm) sieve].
- 4.4.1.2 Construction AQC’s – The most often used AQC’s for construction are density, thickness, and Ride Quality.
- 4.4.1.2.1 Density –Density has been used as a primary AQC for many years. It has been suggested that if only one AQC could be specified for acceptance of asphalt concrete, it would be density. This is because it directly relates to the performance of the material (Brown 1990) and helps ensure the asphalt content and air voids are within a reasonably acceptable range.
- 4.4.1.2.2 Joint Density – Joint density has recently become a useful AQC (Sebaaly et al 2005, Zinke et al 2008) because the first pavement failure sometimes points to the longitudinal joint. Joint density is used as an AQC by some SHAs. However, joint density as an AQC has not been included in the composite pay factors.

- 4.4.1.2.3 Thickness – Thickness is often used as an AQC because it is related to pavement performance and is defined as part of the pavement design (Deacon 1997).
- 4.4.2 Quality Measures – QM are intended to provide a measure of the population parameters of mean and standard deviation. PWL/PD is recognized as the most effective measure of quality and is used in these guidelines because it incorporates both the mean and the variability. A recent survey indicated that 28 SHAs use PWL/PD for flexible pavements (Rafalowski, 2010).
- 4.4.3 Individual Pay Factors – Individual pay factors should pay 1.00 (100%) when the QM is at the AQL and should also average 1.00 (100%) in the long run when the QM is at the AQL. For this to occur, an incentive must be provided in the pay schedule. This is because the quality level is estimated from the samples that are taken. Due to the random nature of the sampling process, when the quality is at the AQL the estimates will fall both above and below the AQL. If there is no positive incentive provision, those that fall below the AQL will receive pay factors below 100%, while those that fall above the AQL will be limited at the maximum pay factor of 100%. Therefore, unless there is a provision that allows the tests that fall above the AQL to receive pay factors in excess of 100% to offset those that fall below, the acceptance procedure cannot pay 100% on the average for work that is at the level stated to be acceptable.
- 4.4.3.1 Tabular or stepped pay schedules – The concept of incentives applies to both tabular (stepped) as well as continuous (equations) schedules. Stepped pay schedules are used by several SHAs for asphalt content, density, and for Ride Quality. One of the reasons for the use of stepped pay schedules is that they are easy to implement. Once the QM is determined, the pay factor can be read from a table. Also, a non-linear relationship between quality level and pay factor can be easily established.

However, when developing this type pay schedule, it is important to avoid small changes in quality level that cause large changes in pay. Table 6 presents an example of a pay schedule with small pay steps is suitable for either flexible or rigid pavements. The pay steps are all less than or equal to 2 percent until the RQL of PWL = 50 is reached.

The AASHTO equation (Equation 5) was chosen to have an AQL of $PWL = 90$ and to pay 100 percent at that quality level in the long run. These guidelines are developed to make the continuous and stepped pay forms agree as closely as possible. To create a stepped pay schedule with essentially the same performance as the AASHTO equation, it is necessary to use a series of many relatively small steps. In Table 6 the AQL is 90 PWL and the RQL is 50 PWL to match those values chosen for the AASHTO equation. A comparison of the two procedures is shown in Figure 6.

This table of stepped pay factors is used in an example (provided in Appendix A) that illustrates the associated risks.

In this table, the PWL at the minimum pay factor of 70 percent is applied at the RQL (to agree with the assumption used in the AASHTO pay equation). When the PWL is at 50, the estimated PWLs form a distribution that ranges from zero to 100. The estimates lower than 50 all receive the minimum pay factor = 70, but those estimates higher than 50 can receive pay factors up to the maximum of 105, depending on the sample size. As a result, the average pay factor will always be greater than 70, and were found to be as high as 81 in the examples (in Appendix A). This result occurs with both the continuous and the stepped form of the pay schedule, and stresses the importance of conducting the EP analysis.

Table 6. Stepped Pay Schedule for Flexible and Rigid Pavements

Estimated PWL	Payment Factor, %
98.0-100	105
94.0-97.9	103
92.0-93.9	101
88.0-91.9 (AQL)	100
84.0-87.9	98
82.0-83.9	96
78.0-81.9	94
74.0-77.9	92
70.0-73.9	90
66.0-69.9	88
62.0-65.9	86
58.0-61.9	84
54.0-57.9	82
50.0-53.9	80
(RQL) <50.0	70

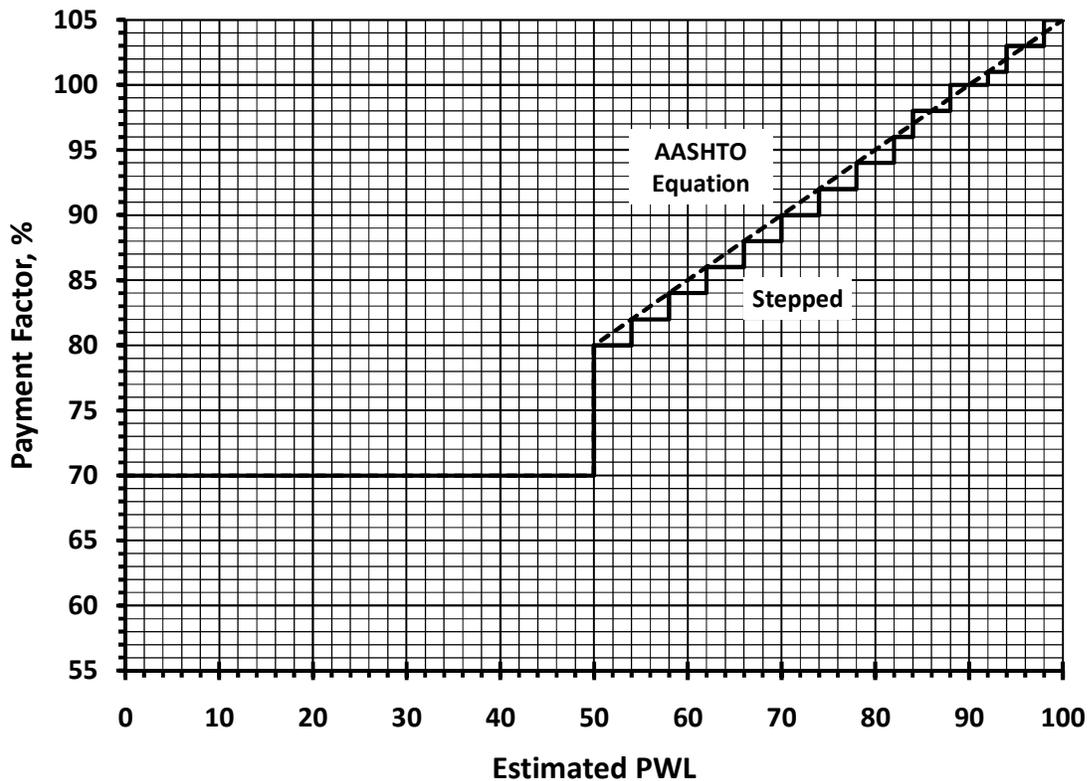


Figure 6. A Comparison of the Continuous (AASHTO Equation) and Stepped Pay Forms

There are ways of treating product at the RQL other than applying the minimum PF. Sometimes a mandatory or optional remove - and - replace clause is used in an acceptance plan at the RQL. However, if a mandatory clause is used, a retest of the product to confirm that it is truly RQL material is advisable. The efficacy of the retest provision can be checked with the OC and EP analyses.

Continuous pay schedules are used more often than stepped pay schedules for asphalt content, air voids, density, and Ride Quality.

4.4.4

Composite Pay Factors – A few SHAs use the average, minimum, or multiplication to develop composite pay factors in which they give equal weight to the individual AQC's. However, many SHAs do not believe that all AQC's affect quality equally, and use different “experience-based” weights for those AQC's that have a larger effect on quality and lesser weight for the others. While many SHAs reported the use of weighted composite pay factors, one SHA used

different weights for interstate, multi-layer new construction and thick (>2 in) and thin overlays, and one SHA used one pay equation for surface and another for base and binder. While these procedures work well for the SHAs that use them, they are considered too cumbersome for a generalized procedure.

- 4.4.4.1 AQC's for CPFs – While several SHAs have included density among the AQC's for the composite pay equation, most limit them to asphalt content, air voids, VMA, gradation of at least one sieve, and Ride Quality.

For flexible pavements, material AQC's are often evaluated at the asphalt plant and the pay factors handled separately from those for construction AQC's that are evaluated in the field.

Other SHAs determine the material AQC's along with the construction AQC's in the field and combine them into a single composite pay schedule. Most agencies use the AQC of Ride Quality as a separate pay factor. The guidelines include a procedure that allows combining Ride Quality with other material and construction AQC's. The level of construction quality (e.g., superior, good, adequate, and poor) is considered in the individual pay factor as well as the combined ones. The procedure guards against unbalanced bids by applying reasonably weighted individual pay factors for the different AQC's. (For composite pay schedules that combine several AQC's, the use of default values that, when exceeded, might require retesting, remove - and - replace, or the negation of a positive incentive for the lot as a whole may be used.)

- 4.4.4.2 Materials CPFs – When accepting asphalt concrete mixture separately from construction, the pay factor Equation 8 is suggested. The coefficients in this equation are chosen considering the importance of each AQC using AASHTO R-42 and other practices:

$$\text{CPF} = 0.40(\text{PF}_{AC}) + 0.40(\text{PF}_{AV}) + 0.10(\text{PF}_{VMA}) + 0.03(\text{PF}_{\#4 \text{ or } 8 \text{ SIEVE}}) + 0.07(\text{PF}_{\#200 \text{ SIEVE}})(8)$$

This equation is used in an example presented in the appendix to analyze the associated risks.

- 4.4.4.3 Construction CPFs - When accepting asphalt concrete construction separately from the mixture, the composite pay factor given in Equation 9 is provided. The weights (coefficients) in this equation are chosen based on the considered importance of each AQC:

$$\text{CPF} = 0.4(\text{PF}_{DEN}) + 0.2(\text{PF}_{THICK}) + 0.4(\text{PF}_{RQ}) \quad (9)$$

This equation is used in an example presented in the appendix to analyze the associated risks.

- 4.4.4.4 Materials and Construction CPFs – Equations 10 and 11 are provided for the acceptance of materials and construction with and without the AQC of Ride Quality. Equation 10 is taken from AASHTO R-42 and Equation 11 adjusts the individual pay factors to include the AQC of Ride Quality. The coefficients in Equation 11 approximate values used by most SHAs for CPFs.

$$\text{CPF} = 0.35(\text{PF}_{DEN}) + 0.2(\text{PF}_{AC}) + 0.35(\text{PF}_{AV}) + 0.1(\text{PF}_{VMA}) \quad (10)$$

$$\text{CPF} = 0.3(\text{PF}_{DEN}) + 0.15(\text{PF}_{AC}) + 0.15(\text{PF}_{AV}) + 0.1(\text{PF}_{THICK}) + 0.3(\text{PF}_{RQ}) \quad (11)$$

These CPF equations are used in the examples presented in the appendix to analyze the associated risks.

- 4.4.5 EP and OC Curve Analysis – Because risks cannot be eliminated, the goal of a well-written acceptance plan and pay adjustment schedule is to minimize and balance these risks. OC and EP curves are invaluable tools in assessing risks. While the EP curve shows the long-term average payment for any given quality level, it does not provide information regarding the variability, or the likelihood of receiving any specific payment factor. This information can be obtained with the use of OC curves show the probabilities of receiving various payment factors (or higher) which help evaluate the risks. These curves are “acceptance plan specific” and require the definition of AQL, RQL, sample size, and the form of pay

schedule. Both EP and OC curves that show the risk were developed for the examples presented in Appendix A.

4.5 Procedure for Rigid Pavements – The procedure for rigid pavements contains the following specific quality-related factors for these pavements. These are:

- Acceptance Quality Characteristics
- Quality Measures
- Individual Pay Factors and Pay Schedules
- Composite Pay Factors
- Risks Associated with Composite Pay Factors
- Operating Characteristic and Expected Pay Curve Analyses

4.5.1 AQC's – Compressive strength, thickness, and Ride Quality are the three most often used AQC's for rigid pavements. Many studies have shown the influence of both strength and thickness on the performance of rigid pavements. Compressive strength is used more often than beam strength because of the lower variability. Flexural strength, air content, and gradation are less often used as AQC's. Air content is most often used by the northern SHAs (for freeze-thaw resistance) as a screening test for concrete acceptance for placement but not as a pay adjustment factor.

4.5.2 Quality Measures – A few SHAs use only the range of the AQC as a QM. This is a measure of the variability but does not measure the central tendency. Several SHAs use only the average as a QM for rigid pavements. However, neither the range, standard deviation, nor the average by itself is a very strong indicator of quality or expected performance. It has been recognized that a measure that combines the central tendency (average) and dispersion (variability, standard deviation, etc.) is a better predictor of performance than either by itself, and that PWL/PD are extremely well suited statistical quality measures for this purpose. The PWL/PD QM uses both the mean and variability as input variables, and it is used in these guidelines.

4.5.3 Individual Pay Factors – Individual pay factors should pay 1.00 (100%) when the QM is at the AQL and should also average 1.00 (100%) in the long run when the QM is at the AQL. For this to occur, an incentive must be provided in the pay schedule. This is because the quality level is estimated from the samples that are taken. Due to the random nature of the sampling process, when the quality is at the AQL the estimates will fall both above and below the AQL. If there is no positive incentive provision, those that fall below the AQL will receive pay factors below 100%, while those that fall above the AQL will be limited at the maximum pay factor of 100%. Therefore, unless there is a provision that allows the tests that fall above the AQL to receive pay factors in excess of 100% to offset those that fall below, the acceptance procedure cannot pay 100% on the average for work that is at the level stated to be acceptable

4.5.3.1 Tabular or stepped pay schedules – The concept of incentives applies to both tabular (stepped) as well as continuous (equations) schedules. Stepped pay schedules are used by several SHAs for compressive strength, thickness, and Ride Quality. One of the reasons for the use of stepped pay schedules is that they are easy to implement. Once the QM is determined, the pay factor can be read from a table. Also, a non-linear relationship between quality level and pay factor can be easily established.

However, when developing this type pay schedule, it is important to avoid small changes in quality level that cause large changes in pay. Table 6 (Section 4.4.3.1) presents an example of a pay schedule with small pay steps is suitable for either flexible or rigid pavements. The pay steps are all less than or equal to 2 percent until the RQL of $PWL = 50$ is reached.

The AASHTO equation (Equation 5) was chosen to have an AQL of $PWL = 90$ and to pay 100 percent at that quality level in the long run. These guidelines are developed to make the continuous and stepped pay forms agree as closely as possible. To create a stepped pay schedule with essentially the same performance as the AASHTO equation, it is necessary to use a series of many relatively small steps. In Table 6 the AQL is 90 PWL and the RQL is 50 PWL to match those values chosen for the AASHTO equation. A comparison of the two procedures is shown in Figure 6.

Table 6 is used in the examples (provided in Appendix A) that illustrates the associated risks. In this table the PWL at the minimum pay factor of 70 percent is applied at the RQL (to agree with the assumption used in the AASHTO pay equation). When the PWL is at 50, the estimated PWLs form a distribution that ranges from zero to 100. The estimates lower than 50 all receive the minimum pay factor = 70. But those estimates higher than 50 can receive pay factors up to the maximum of 105. As a result, the average pay factor will be greater than 75, and they are about 77 to 81 in the examples (in Appendix A). This compromise is necessary to match the two forms of pay equations. However, because it is unlikely that a SHA would use both forms such situations should not arise.

4.5.3.2 Continuous Pay Schedules – Continuous pay schedules are used less for rigid pavements than for flexible pavements.

4.5.4 Composite Pay Factors – There is no agreement on the method or weights to use to combine pay factors for rigid pavements, and no single method appears to be clearly favored. Only one SHA reported the use of a composite pay factor; strength, thickness, gradation, and air content were used as the AQC's. However only five SHAs use gradation and seven SHAs use air content as AQC's. Predominately, strength, thickness, and ride quality are the three AQC's used by SHAs. Based on this usage, typical “experience-based” weights are included in Equation 12.

$$CPF = 0.25(PF_{STRENGTH}) + 0.35(PF_{THICK}) + 0.40(PF_{RQ}) \quad (12)$$

4.5.5 EP and OC Curve Analysis – Because risks cannot be eliminated, the goal of a well-written acceptance plan and pay adjustment schedule is to minimize and balance these risks. OC and EP curves are invaluable tools in assessing risks. The EP curve shows the long-term average payment for any given quality level, but does not provide information regarding the variability, or the likelihood of receiving any specific payment factor. OC curves show the probabilities of receiving various payment factors (or higher) and help evaluate the risks. These curves are “acceptance plan specific” and require the definition of AQL, RQL, sample size, and the form of pay schedule. Both EP and OC curves that show the risk were developed for the examples presented in Appendix A.

4.6 Empirical PRS Method for Flexible Pavements

An Empirical PRS method for flexible pavements has been developed based on sound mathematical and economic principles. The method is intended to provide a rational basis for a pay adjustment system that fairly represents the interests of both highway agencies and the construction industry.

4.6.1 Description of Procedure-This method, which has been referred to as the “Expected-Life” method in the SpecRisk User’s Manual describing the specification analysis software, bases payment on the expected performance (service life) of the as-constructed pavement (SpecRisk User’s Manual 2008). On the premise that intrinsic load-bearing capacity is strongly tied to expected service life and resultant economic value, this method is believed to provide justification for effective and defensible adjusted-payment schedules. It is further described as follows:

The procedure develops performance-related highway construction specifications (PRS) by first developing mathematical models based on empirical performance data, and then applies life-cycle-cost analysis to establish pay adjustment provisions related to predicted performance. (*Transportation Research Circular Number E-C137, 2009*)

The Empirical PRS Method is based on derived mathematical models and is an outgrowth of several approaches used successfully by the New Jersey Department of Transportation (Weed, 2001 and 2006). The procedure includes two basic mathematical models - a performance model expressing expected life as a function of quality received, and an economic model expressing value as a function of expected life.

The performance model serves two purposes. It helps to better understand the consequences of either exceeding or falling short of the desired quality levels, and provides a quantitative measure upon which a pay adjustment system can be based. The economic model provides a rational basis for the magnitude of the adjusted payment schedules that are an integral part of the Empirical PRS Method.

4.6.2 Development of the Performance Model-The following basic steps are used to develop the performance model:

- An appropriate mathematical form is chosen for the performance model.
- A statistical quality measure is selected (PWL or PD).
- Appropriate field data are obtained (or estimated by an expert panel).
- The data are used to construct a general performance matrix.
- A set of simultaneous equations is developed from the performance matrix.
- Solution of the equation set completes the performance model (equation).

To apply this model (equation), acceptance tests from a construction site are used to calculate the level of quality received (PWL or PD) and this is entered into the performance equation to obtain an estimate of expected service life (EXPLIF). This result is then entered into a life-cycle-cost model (the development of which is described below) to determine the monetary gain or loss to the highway agency, thus justifying both aspects of incentive/disincentive clauses. Figure 7 illustrates the modeling procedure.

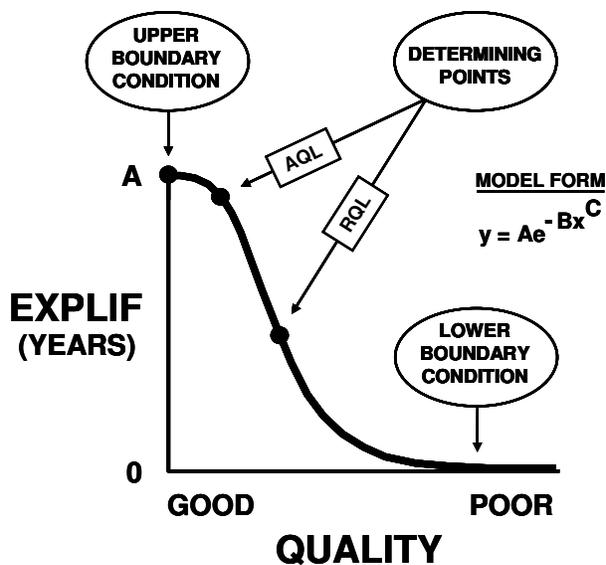


Figure 7: Illustration of Performance-Modeling Procedure.

The upper and lower boundary conditions in Figure 7 indicate that a reverse S-shape is suited for this application, thus suggesting the exponential model shown in this figure. The acceptable quality level (AQL) and the rejectable quality level (RQL)-two critical quality levels when analyzing the risks associated with statistical acceptance procedures for highway construction-provide convenient determining points to specify the model more precisely. The general exponential relationship shown in this figure is appropriate for a single quality characteristic, but similar multidimensional models can be developed for any reasonable number of quality characteristics (as illustrated below).

- 4.6.2.1 Standard Equation for Performance Model-Based on considerable research done over a period of time (Weed 2006), it was determined that the model given by Equation 13 is especially effective for this application. This equation is patterned after the form shown in Figure 7, except that it has been expanded to account for multiple quality characteristics.

$$\text{EXPLIF} = e^{(B_0 + B_1 \text{PD}_1^C + B_2 \text{PD}_2^C + \dots + B_k \text{PD}_k^C)} \quad (13)$$

Where

EXPLIF = expected life (years),

B_i = equation coefficients (constants to be derived),

PD = statistical quality measure (individual percent defective values),

C = shape factor, a common exponent for all PD terms,

i = identifier of individual quality characteristics,

k = number of acceptance quality characteristics, and

e = base of natural logarithms.

Equation 13 is written in terms of PD as the statistical quality measure because this is a simpler mathematical form for the derivation process. After the final expression for EXPLIF has been derived, the equation can be expressed in terms of PWL by substituting the term $(100 - \text{PWL})$ for each PD term.

- 4.6.2.2 Performance Matrix – To set up and solve a simultaneous equation set to obtain the coefficients for the multi-characteristic performance model given by Equation

13 above, it is first necessary to complete a performance matrix (such as that shown in Table 7.)

Table 7. Typical Performance Matrix

PD_{VOIDS}	PD_{THICK}	PD_{SMOOTH}	EXPLIF (Years)
10 (AQL)	10 (AQL)	10 (AQL)	10 (Design Life)
65 (RQL)	10	10	Life (Poor Voids)
10	75 (RQL)	10	Life (Poor Thickness)
10	10	85 (RQL)	Life (Poor Smoothness)

The values in Columns 1, 2, and 3 in Table 7 represent combinations of AQL and RQL values for which it is often possible to obtain reasonably accurate estimates of expected life (entered in the last column). It has been found that it is effective to set all quality characteristics in the first row at their respective AQL values. In the remaining rows, each characteristic is set at its respective RQL value, while the remaining characteristics are maintained at their AQL values. The expected-life values in the last column may be obtained either from actual data or a consensus panel of knowledgeable engineers. The complete application of this procedure is illustrated in the example (Appendix A.)

4.6.2.3 Creating and Solving the Simultaneous Equations Set – To use the performance matrix to create the set of simultaneous equations, natural logarithms are taken of both sides of Equation 13 to produce Equation 14.

$$\ln(\text{EXPLIF}) = B_0 + B_1 \text{PD}_1^C + B_2 \text{PD}_2^C + \dots + B_k \text{PD}_k^C \quad (14)$$

The PD and EXPLIF values from each row of Table 7 are then substituted into Equation 14 to produce the following set of simultaneous equations (in which DESLIF = design life).

$$\ln(\text{DESLIF}) = B_0 + 10^C B_1 + 10^C B_2 + 10^C B_3 \quad (15a)$$

$$\ln(\text{EXPLIF}_1) = B_0 + 65^C B_1 + 10^C B_2 + 10^C B_3 \quad (15b)$$

$$\ln(\text{EXPLIF}_2) = B_0 + 10^C B_1 + 75^C B_2 + 10^C B_3 \quad (15c)$$

$$\ln(\text{EXPLIF}_3) = B_0 + 10^C B_1 + 10^C B_2 + 85^C B_3 \quad (15d)$$

Since there are a total of 5 unknowns (4 “B” coefficients plus the unknown shape factor “C”), it is necessary to assume a trial value for C in order to solve the equation set. Experience has shown that this value will usually fall between 1.0 and 2.0, and that 1.5 is an effective starting value. For each trial, all numerical coefficients in Equation Set 15 are raised to the power of C, and the resulting simultaneous equation set is then solved to obtain the B coefficients in the performance model given by Equation 13. This process is demonstrated in the example (Appendix A.)

This expression can also be developed in terms of PWL as the statistical quality measure. However, because the general form of the model shown in Figure 7 has a fixed Y-intercept (a boundary condition) and comes in asymptotically to the X-axis (another boundary condition), it is not possible to write this same form of expression in terms of PWL in the simple form given by Equation 13. To produce a model in terms of PWL, the derivation should be done in units of PD, and then the term (100 – PWL) is substituted in place of PD in the final result in the form of Equation 13.

- 4.6.2.4 Validation Testing of the Performance Model – A critical part of empirical model development is validation testing. Once the performance model has been obtained, it must be thoroughly tested to make sure the model produces realistic results under all conditions that may be encountered in actual practice. An extensive series of tests is included in the example (Appendix A) as part of the evaluation procedure for this method.
- 4.6.3 Development of Life-Cycle-Cost Model – Once the performance model has been obtained and validated, the remaining task is to develop the cost model. Life-Cycle-Cost (LCC) analysis, a mathematical tool widely used in the engineering profession to evaluate costs that are spread over various intervals of time, provides a very effective way to estimate the present value of future economic losses resulting from deficient construction (or gains resulting from superior construction).

To derive a valid cost model, it is essential that the LCC analysis account precisely for the construction and maintenance practices of the highway agency. Toward this end, it should be considered that minor-to-moderate deficiencies are not repaired at the time of construction but, instead, lead to premature failure and an earlier scheduling of future overlays. Similarly, superior quality extends the performance life of the pavement, thus delaying the expense of future overlays.

This is shown conceptually in Figure 8 for initial pavement construction that is expected to last 20 years, after which routine overlays are expected to be required at 10-year intervals. (Only the first two overlays are shown in this figure, but the analysis method mathematically accounts for all future overlays.) In this figure, the initial construction was deficient in some way, causing it to fail about 4 years prematurely. Consequently, all future overlays are expected to be moved about 4 years earlier in time, resulting in considerable added expense to the highway agency.

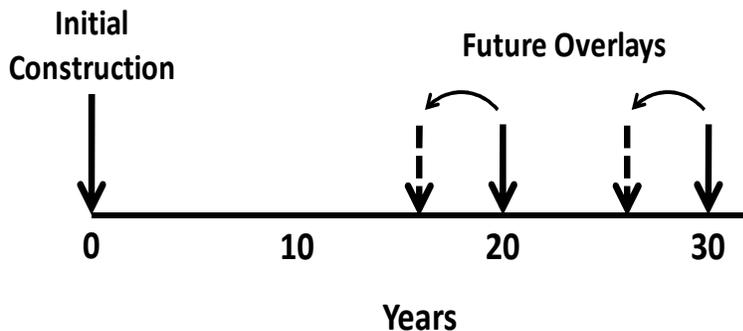


Figure 8. Illustration of Consequences of Premature Failure.

The development of the economic model is based on the fact that there is an inherent cost associated with the need to schedule any major expenses sooner than intended; this includes the higher costs to make corrections. Similarly, there is also a corresponding benefit associated with delaying future expenses. This development justifies both aspects of incentive/disincentive pay clauses.

Since the consequences of defective work (as well as the benefits of superior work) will occur long after the contractor has completed the project, the most practical way to recoup the losses (or reward the benefits) is to make suitable

adjustments to the contract payments at the time of construction. Life-cycle-cost analysis provides an extremely effective way to determine the appropriate magnitude of these adjustments.

The basic economic model has previously been derived and is presented here as Equation 16.

$$\text{PAYADJ} = C (R^{\text{DESLIF}} - R^{\text{EXPLIF}}) / (1 - R^{\text{OVLIF}}) \quad (16)$$

Where

PAYADJ = appropriate pay adjustment for pavement or overlay (same units as C)

C = present total cost of resurfacing (this might be as much as \$350,000 per lane mile at the time of this writing)

DESLIF = design life of pavement or overlay (typically 20 years for new pavement, 10 years for overlay)

EXPLIF = predicted expected life of pavement (years) obtained from a performance model

OVLIF = expected life of successive overlays (typically 10-years)

R = $(1 + \text{INF}) / (1 + \text{INT})$ in which INF is the long-term annual inflation rate and INT is the long-term annual interest rate, both in decimal form. (Values of 0.04 and 0.08 have been used in the past for INF and INT, but smaller values may be appropriate today. Since INF and INT tend to track in parallel, the ratio R tends to remain stable over time.)

Equations 13 and 16 provide the two key relationships needed to develop a technically sound pay schedule. Equation 13 provides an empirical link between quality and performance, and Equation 16 links performance to economic gain or loss. It then becomes a simple matter to combine these two equations to link quality received to economic effect, thus providing a rational basis for payment schedules. This method is fully developed in Appendix A.

This approach is readily understandable and easily implementable. After a single-characteristic or a multiple-characteristic performance model has been developed to predict expected life from the quality received, the next step is to translate that level of expected life into an appropriate amount of pay adjustment. This can have far-reaching financial and legal consequences for both the transportation agency

and the construction industry; therefore, this step must be valid, accurate, and defensible.

4.6.4 Validation Testing – A critical part of model development is validation testing. Once the performance model has been obtained it must be thoroughly tested to make sure the model produces realistic results under all conditions that may be encountered in actual practice. An extensive series of tests is included in the example in the appendix as part of the evaluation procedure for this method.

4.6.5 Legal Aspects – Most SHAs have dispute-resolution procedures to resolve disagreements and other conflicts that may arise during the construction process. A pay adjustment schedule that may withhold substantial payment from the contractor for defective work could potentially lead to serious disputes that may not be resolvable by this method. Therefore, it is important that the pay schedule be based on sound rationale that can be demonstrated to be fair and defensible.

In essence, an adjusted-payment schedule serves the same purpose as a liquidated-damages clause because its function is to state an agreed-upon monetary remedy for a breach of contract (i.e., the failure to provide the level of quality specified) for a situation in which the monetary damages are not known precisely and can only be estimated. The magnitude of the payment reduction must be at least reasonably appropriate for the amount of damages actually suffered. This highlights the importance of developing the necessary quality-performance relationships that make it possible to estimate the effects of poor quality. However, this need not be interpreted to mean that the amount of damages must be estimated with absolute precision.

Although the liquidated-damages concept has traditionally been applied to losses related to delay of completion, there is no apparent reason why this same rationale should not also apply to losses resulting from failure to provide the specified level of quality. A logical extension of that argument is that it should also apply to monetary incentives awarded for superior quality. The acknowledgement that extra quality translates into additional value lends credibility to the pay-adjustment concept as a whole.

References:

Analysis of Risks in Percent Within Limits and Percent Defective Acceptance Plans and Specifications, SpecRisks User's Manual Version 2.4, Office of Infrastructure Research and Development, Federal Highway Administration, 6300 Georgetown Pike, McLean, Virginia, 22102-2296, July 2008.

Bowery, Frank J., Jr., and S. B. Hudson, "Statistically Oriented End-Result Specifications" NCHRP Synthesis 38, Transportation Research Board, Washington, DC, 1976, 40pp

Brown, E., Ray, "Density of Asphalt Concrete-How Much is Needed" NCAT Report No. 90-3, National Center for Asphalt Technology, 1990.

Burati, J.L., Weed, R.M., Hughes, C.S., and Hill, H.S., *Optimal Procedures for Quality Assurance Specifications*, Office of Research, Development, and Technology, Report FHWA-RD-02-095, FHWA McLean VA, June 2003, 347pp.

Burati, James L. Jr., and Charles S. Hughes, "Materials Control and Acceptance- Quality Assurance", Highway Materials Engineering, National Highway Institute Course No. 131023, Publication Number FHWA NHI-04-005, Federal Highway Administration, October, 2003.

Deacon, J. A., C. L. Monismith, and J. T. Harvey "Pay Factors for Asphalt-Concrete Construction: Effect of Construction Quality on Agency Costs" Technical Memorandum, TMUCB-CAL/APT-97-1, April 1997.

Glossary of Highway Quality Assurance Terms, *Transportation Research Circular Number E-C137*, 2009.

Hinrichsen, John A., and John Heggen, "Minimum Voids in Mineral Aggregate in Hot-Mix Asphalt Based on Gradation and Volumetric Properties", Transportation Research Record 1545, TRB, National Research Council, Washington, D.C.1996.

Hughes, C. S., "Results from VDOT's Pilot Project Using Volumetric Properties and Asphalt Content for Acceptance of Asphalt Concrete", Virginia Transportation Research Council, VTRC 95-TAR9, Charlottesville, VA 1995.

Hughes, C. S., *State Construction Quality Assurance Programs*, NCHRP Synthesis 346, Transportation Research Board, Washington, DC, 2005, 75pp.

Hveem, F. M., "Gradation of Mineral Aggregates for Dense-graded Bituminous Mixtures" Proceedings, Association of Asphalt Pavement Technologists, Vol. 11, 1940.

McGhee, Kevin K., and Charles S. Hughes, *Development of a Smoothness Specification with a Variability Component*, Presented to the 77th Annual Meeting of the Transportation Research Board, January 12, 1998.

McLeod, N.W., “*Relationships Between Density, Bitumen Content and Voids Properties of Compacted Bituminous Paving Mixtures*” Proceedings, Highway Research Board, Vol. 35, 1956.

National Highway User Survey, The AASHTO Journal, FHWA-SA-95-004, June 1996.

Rafalowski, Michael, FHWA Personal communication May 1, 2010.

Roberts, Freddy L., Prithvi S. Kandhal, E. Ray Brown, Dah-Yinn Lee, and Thomas W. Kennedy *Hot Mix Asphalt Materials, Mixture Design and Construction*, Second edition, 1996.

Sebaaly, Peter E., Juan Carlos Barrantes, George Fernandez, “*Development of a Joint Density Specification Phase II Evaluation of Test Sections*” NDOT Research Report No. 13DL-2, Nevada Department of Transportation, January 2005.

Sholar, G.A., J. A. Musselman, G. C. Page, and H. L. Moseley, “*Development and Refinement of the Florida Department of Transportation’s Hot Mix Asphalt Percent Within Limits Specification*”, Journal of the Association of Asphalt Paving Technologists Vol. 75, 2006, pp. 877-891.

Weed, R. M., *Derivation of Equation for Cost of Premature Pavement Failure*, Transportation Research Record 1761, TRB, National Research Council, Washington, DC, 2001, pages 93 – 96 2001.

Weed, R. M., *Mathematical Modeling Procedures for Performance Related Specifications*, Transportation Research Record 1946, TRB, National Research Council, Washington, DC, 2006, pages 63 – 70.

Wilde, W. James, “*Implementation of an IRI for MnDOT Pavement Construction and Rehabilitation*”, Report Number MN-RC 2007-09, Minnesota Department of Transportation Research Services Section, April 2007.

Willenbrock, Jack H. and Peter A. Kopac, *Development of Price-Adjustment Systems for Statistically Based Highway Construction Specifications*, Transportation Research Record 652, Transportation Research Board, Washington, DC, 1977, pg 52-58.

Zinke, Scott, James Mahoney, Eric Jackson, Gregg Shaffer “*Comparison of the Use of Notched Wedge Joints vs. Traditional Butt Joints in Connecticut*” Final Report No. CT-2249-F-08-4, November 7, 2008.

Appendix A. Examples Using The Recommended Guidelines

A.1 Examples for Flexible Pavements

The examples use inputs of QA procedures and data that are typical of what most SHAs use. The examples use various combinations of individual pay and composite pay factors,

A.1.1 Inputs

The AQC's used in the example are:

- Asphalt Content (AC)
- Lab compacted Air Voids (AV)
- Voids in Mineral Aggregate (VMA)
- Gradation of the #8 and #200 sieves
- Density
- Thickness
- Ride Quality

The QM used is PWL

Two individual payment systems are used in the examples:

- The continuous procedure (equation) uses the AASHTO pay equation, Equation 5 with the AQL = 90 PWL and the RQL = 50 PWL (with a minimum pay factor = 70%) for all AQC's.
- The tabular procedure (stepped) uses Table A.1 with the AQL = 90 PWL and the RQL = 50 PWL for all AQC's other than Ride Quality.

For Ride Quality (using the tabular method) the AQL = 70 in./mile and the RQL = 92.5in/mi.

Table A. 1. Stepped Payment Schedule Based on PWL

Estimated PWL	Payment Factor, %
98.0-100	105
94.0-97.9	103
92.0-93.9	101
88.0-91.9 (AQL)	100
84.0-87.9	98
82.0-83.9	96
78.0-81.9	94
74.0-77.9	92
70.0-73.9	90
66.0-69.9	88
62.0-65.9	86
58.0-61.9	84
54.0-57.9	82
50.0-53.9	80
(RQL) <50.0	70

Four composite pay factors are used in the examples:

- Materials Only: Uses Equation 8 from the Guidelines
- Construction Only: Uses Equation 9 from the Guidelines
- Materials and Construction: Without Ride Quality, uses Equation 10 from the Guidelines
- Materials and Construction: With Ride Quality, uses Equation 11 from the Guidelines

Other specification information:

- Spec Limits:
 - AC - JMF ± 0.4
 - AV - 3%-6%
 - VMA - Min. 14%

- Gradation:
 - #8 Sieve - JMF ± 6
 - #200 Sieve - JMF ± 2
- Density - Min. 92% MTD
- Thickness - Plan thickness 2" (PT- 0.2": thus, Lower spec limit = 1.8")
- Ride Quality - Max 95 in/mi

- Lot size, Material Only: 2000 tons.
- Sample size, Material Only: $n = 4$.
- Lot size, Construction Only and Material and Construction: Two lane miles.
- Sample size, Construction Only and Material and Construction:
 - Material $n = 6$ (note this is different from the case for Material Only above)
 - Construction $n = 10$

A.1.2 Example 1: Materials Only

A.1.2.1 Data:

The data used in the examples are included in the tables below.

Table A. 2. Material Properties

Test	AC	AV	VMA	No 8 Sieve	No. 200 Sieve
JMF	5.50	-	-	41.0	5.0
#1	5.66	3.8	15.1	43	4.6
#2	5.52	3.9	15.8	39	4.7
#3	5.35	4.9	13.3	41	4.5
#4	5.47	3.0	14.5	43	5.4
Average	5.50	3.9	14.7	41.5	4.8
Standard Deviation	0.128	0.78	1.06	1.9	0.41

A.1.1.2 PWL Calculations

Note: A partial table of Quality Index Values for Estimating Percent Within Limits (PWL), Table A.26 is at the end of this appendix on page 116

For AC:

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{5.50 - 5.10}{0.128} = 3.33; \text{PWL}_L = 100$$

$$Q_U = \frac{USL - \bar{x}}{s} = \frac{5.90 - 5.50}{0.128} = 3.12; \text{PWL}_U = 100$$

$$\text{PWL}_T = \text{PWL}_L + \text{PWL}_U - 100$$

$$\text{PWL}_T = (100 + 100 - 100) = 100$$

For AV:

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{3.9 - 3.0}{0.78} = 1.15; \text{PWL}_L = 88$$

$$Q_U = \frac{USL - \bar{x}}{s} = \frac{6.0 - 3.9}{0.78} = 2.69; \text{PWL}_U = 100$$

$$\text{PWL}_T = \text{PWL}_L + \text{PWL}_U - 100$$

$$\text{PWL}_T = (88 + 100 - 100) = 88$$

For VMA: (Assume $PWL_U = 100$)

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{14.7 - 14.0}{1.06} = 0.66; PWL_L = 72$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (72 + 100 - 100) = 72$$

For #8 Sieve:

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{41.5 - 35.0}{1.9} = 19.21; PWL_L = 100$$

$$Q_U = \frac{USL - \bar{x}}{s} = \frac{47.0 - 41.5}{01.9} = 2.89; PWL_U = 100$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (100 + 100 - 100) = 100$$

For #200 Sieve

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{4.8 - 3.0}{0.41} = 4.39; PWL_L = 100$$

$$Q_U = \frac{USL - \bar{x}}{s} = \frac{7.0 - 4.8}{0.41} = 5.37; PWL_U = 100$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (100 + 100 - 100) = 100$$

A.1.2.3 Individual Pay Factor Determinations:

Continuous Method

For AC:

$$PF_{AC} = 55 + .5 PWL = 55 + 0.5 (100) = 105$$

For AV:

$$PF_{AV} = 55 + .5 PWL = 55 + 0.5 (88) = 99$$

For VMA:

$$PF_{VMA} = 55 + .5 PWL = 55 + 0.5 (72) = 91$$

For #8 Sieve:

$$PF_{\#8 \text{ sieve}} = 55 + .5 PWL = 55 + 0.5 (100) = 105$$

For #200 Sieve:

$$PF_{\#200 \text{ sieve}} = 55 + .5 PWL = 55 + 0.5 (100) = 105$$

Stepped Method (From Table A.1)

For AC:

$$PWL_{AC} = 100; PF_{AC} = 105$$

For AV:

$$PWL_{AV} = 88; PF_{AV} = 100$$

For VMA:

$$PWL_{VMA} = 72; PF_{VMA} = 90$$

For #8 Sieve:

$$PWL_{\#8 \text{ sieve}} = 100; PF_{\#8 \text{ sieve}} = 105$$

For #200 Sieve:

$$PWL_{\#200 \text{ sieve}} = 100; PF_{\#200 \text{ sieve}} = 105$$

A.1.2.4 Composite Pay Factor Determinations:

Continuous Method

$$CPF = 0.40(PF_{AC}) + 0.40(PF_{AV}) + 0.10(PF_{VMA}) + 0.03(PF_{\#8 \text{ sieve}}) + 0.07(PF_{\#200 \text{ sieve}})$$

$$CPF = 0.40(105) + 0.40(99) + 0.10(91) + 0.03(105) + 0.07(105)$$

$$CPF = 42.00 + 39.60 + 9.10 + 3.15 + 7.35$$

$$CPF = 101.20$$

Stepped Method

$$CPF = 0.40(PF_{AC}) + 0.40(PF_{AV}) + 0.10(PF_{VMA}) + 0.03(PF_{\#8 \text{ sieve}}) + 0.07(PF_{\#200 \text{ sieve}})$$

$$CPF = 0.40(105) + 0.40(100) + 0.10(90) + 0.03(105) + 0.07(105)$$

$$CPF = 42.00 + 40.00 + 9.00 + 3.15 + 7.35$$

$$CPF = 101.50$$

A.1.2.5 Flexible Pavement EP and OC Curve Analysis:

The SpecRisk computer software was used to develop the EP and OC curve analyses. The various screens necessary to reach the EP and OC curve analyses are shown, initially, to clarify the steps necessary to accomplish this.

Continuous Method

Figures A.1 through A.3 show the three sets of SpecRisk computer software screens related to the analyses of the EP and OC curves using Equation 5 (the continuous method) in the Guidelines.

As can be seen from the top screen in Figure A.1, “Quality Characteristics Data Entry”, this shows some of the several input values and the bottom screen, “Analyze Selected”, shows the result of an abbreviated run using this input. The column headed “Average” in the lower table gives the average (i.e., expected) pay factors resulting from the specific combinations of quality levels that were entered in the previous columns for the five quality characteristics. When all AQC’s are at the AQL level of 90 PWL (lower blue highlighted line) the average pay factor is 99.9 percent, close to the desired value of 100 percent. When all AQC’s are at the RQL level of 50 PWL, the average pay factor is 78.4 percent. The result at the AQL is close to the desired value of 100 percent and is judged to be satisfactory.

SpecRisk System							
Setup Analysis							
Profiles Quality Characteristic Data Entry Correlation Data Entry Pay Relationship Data Entry OC Curves Data Entry Simulation Points Data Entry							
Define up to 5 quality characteristics							
1 pages (5 rows)							
#	Quality Characteristic	Pay Equation Designation	Spec Limit	Sample Size (n)	AQL	RQL	Retes
1	AC	PWL(Pay Factor Percent): Proj 10-79 CONTINUOUS METHOD	2 - sided	4	90	50	<input type="checkbox"/>
2	AV	PWL(Pay Factor Percent): Proj 10-79 CONTINUOUS METHOD	2 - sided	4	90	50	<input type="checkbox"/>
3	VMA	PWL(Pay Factor Percent): Proj 10-79 CONTINUOUS METHOD	1 - sided	4	90	50	<input type="checkbox"/>
4	#8 Sieve	PWL(Pay Factor Percent): Proj 10-79 CONTINUOUS METHOD	2 - sided	4	90	50	<input type="checkbox"/>
5	#200 Sieve	PWL(Pay Factor Percent): Proj 10-79 CONTINUOUS METHOD	2 - sided	4	90	50	<input type="checkbox"/>

Analyze Selected EP Data EP Graph RQL Frequency Retest Frequency Multiple OCs Graph PWL/PD Histogram Pay Histogram Random N											
Insert and select individual analysis cases											
1 pages (5 rows)											
Select	AC	AV	VMA	#8 Sieve	#200 Sieve	Average	Standard ...	5 Percentile	50 Percentile	95 Percentile	
<input checked="" type="checkbox"/>	100	100	100	100	100	105	0	105	105	105	
<input checked="" type="checkbox"/>	90	90	90	90	90	99.9357	3.793	92.9208	100.5683	104.7002	
<input checked="" type="checkbox"/>	70	70	70	70	70	89.003	6.4103	78.1402	89.0273	99.2003	
<input checked="" type="checkbox"/>	50	50	50	50	50	78.448	6.1245	70.3145	77.7595	89.386	
<input checked="" type="checkbox"/>	0	0	0	0	0	70	0	70	70	70	

Figure A. 1. Example of input data for SpecRisk Analysis for the EP and OC Curves for composite results using the continuous method.

Figure A.2 shows the “EP: Composite” curve obtained from the input values in Figure A.1 and it shows the expected composite (i.e., overall) pay factor at all possible levels of PWL, along with the 5, 50, and 95 percentile curves.

The Pay Factor Percent at the AQL and RQL are seen to be consistent with the values produced in Figure A.1. From Figure A.1, the 5 and 95 percentiles are within a reasonably narrow range, indicating that when at the AQL for all five AQC's, the contractor can expect to receive a pay factor between 92.9 and 104.7 approximately 90 percent of the time. When all five AQC's are at the RQL, the SHA can expect to pay between 70.3 and 89.4 percent, also about 90 percent of the time.

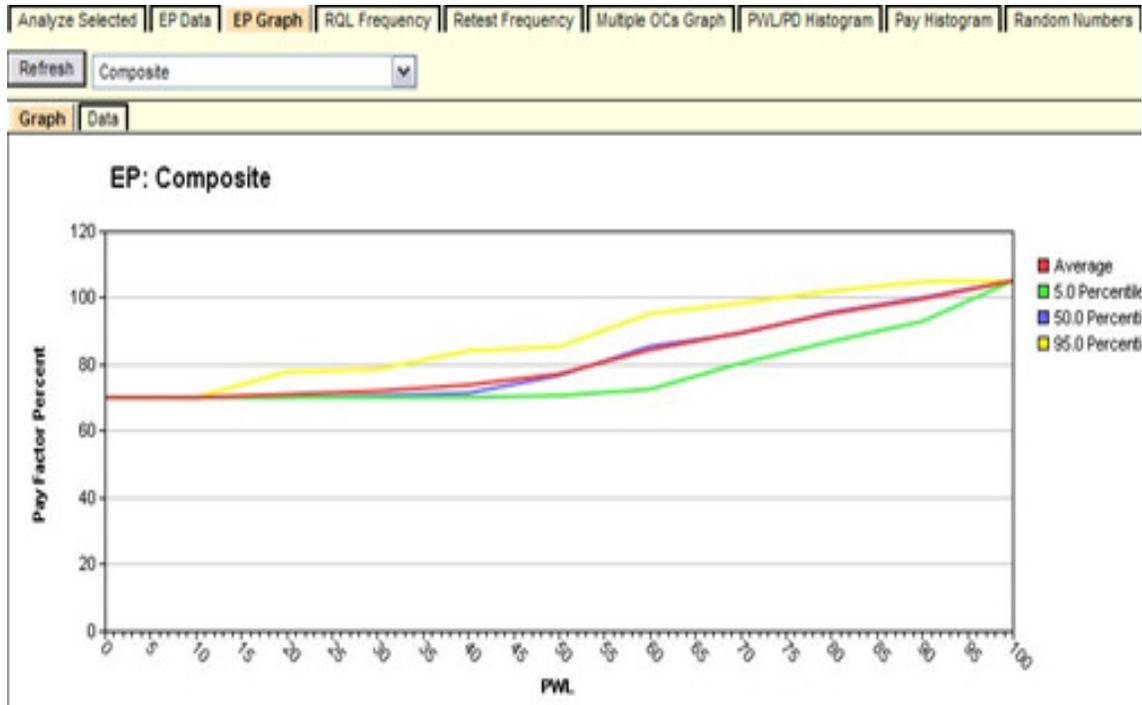


Figure A. 2. Example of EP Curve for composite results using the continuous method

Figure A.3 shows the multiple “OC: Composite” curves with the probability of receiving greater than or equal to the pay factor in the index on the right at all levels of PWL. The likelihood that a contractor will receive a pay factor of 105 percent increases from about 4 percent when all AQC’s are at the AQL (90 PWL) to essentially 100 percent when at a PWL of 100. There is approximately a 50 percent chance that the contractor will receive a pay factor of 100 percent or more when operating at the AQL of 90 PWL. Since the minimum pay factor using Equation 5 in the Guidelines has been established at 70 percent, the SHA will always pay at least 70 percent (unless it chooses to remove and replace or retest product detected to be at the RQL or lower). If a retest provision is part of the acceptance procedure, this would be included as part of the input information into SpecRisk, and a slightly different analysis would be done.

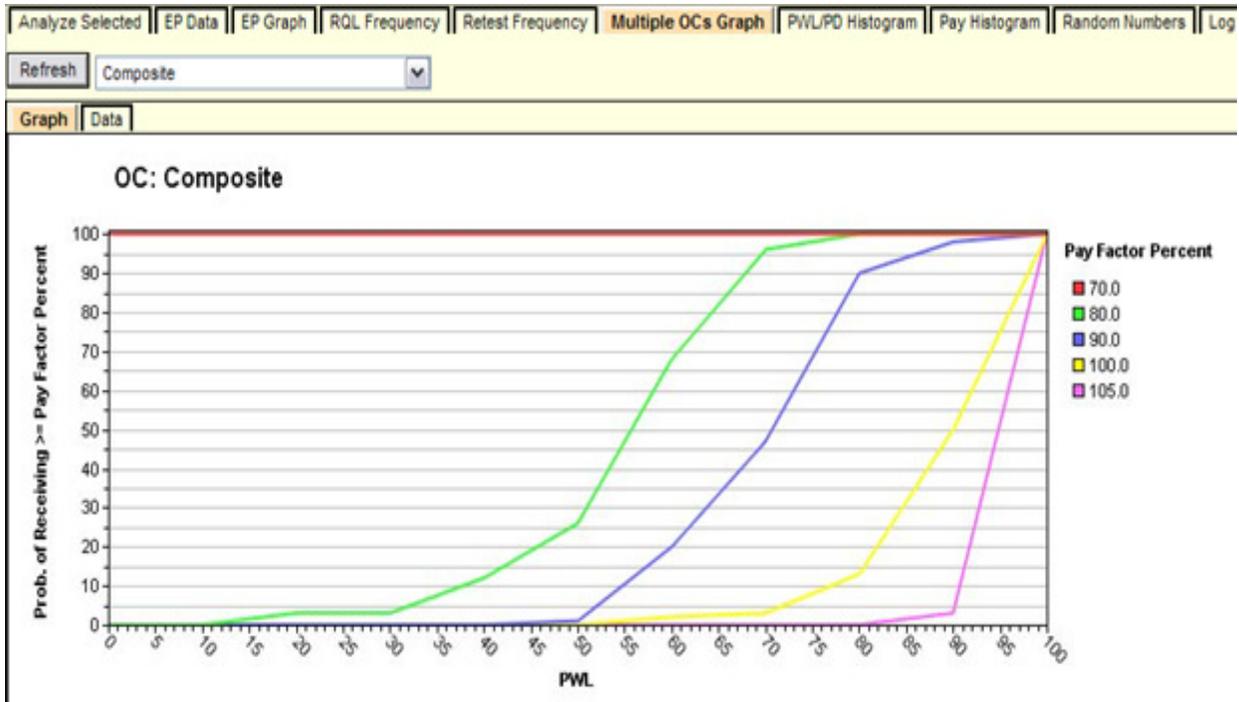


Figure A. 3. Example of Multiple OC Curves for composite results using the continuous method

Stepped Method

Figures A.4 through A.6 show the SpecRisk computer software screens related to the analyses of the EP curves using the stepped method (Table A.1).

The top screen “Quality Characteristics Data Entry” in Figure A.4 shows some of the input values. Using these data, the bottom screen, “Analyze Selected”, shows that the average pay factor when all AQC’s are at the AQL level of 90 PWL is 99.6 percent, again close to the desired and expected value of 100 percent. When all are at the RQL level of 50 PWL, the average pay is 77.9 percent. (These are essentially the same results obtained in Figure A.1 using the continuous method.) The average result at the AQL is close to the desired expected pay factor of 100 percent.

SpecRisk System										
Setup > Analysis >										
Profiles Quality Characteristic Data Entry Correlation Data Entry Pay Relationship Data Entry OC Curves Data Entry Simulation Points Data Entry										
Define up to 5 quality characteristics										
1 pages (5 rows)										
#	Quality Characteristic	Pay Equation Designation	Spec Limit	Sample Size (n)	AQL	RQL	Retes			
1	AC	PWL(Pay Factor Percent): Proj 10-79 STEPPED METHOD	2 - sided	4	90	50	<input type="checkbox"/>			
2	AV	PWL(Pay Factor Percent): Proj 10-79 STEPPED METHOD	2 - sided	4	90	50	<input type="checkbox"/>			
3	VMA	PWL(Pay Factor Percent): Proj 10-79 STEPPED METHOD	1 - sided	4	90	50	<input type="checkbox"/>			
4	#8 Sieve	PWL(Pay Factor Percent): Proj 10-79 STEPPED METHOD	2 - sided	4	90	50	<input type="checkbox"/>			
5	#200 Sieve	PWL(Pay Factor Percent): Proj 10-79 STEPPED METHOD	2 - sided	4	90	50	<input type="checkbox"/>			

Analyze Selected EP Data EP Graph RQL Frequency Retest Frequency Multiple OCs Graph PWL/PD Histogram Pay Histogram Random N										
Insert and select individual analysis cases										
1 pages (5 rows)										
Select	AC	AV	VMA	#8 Sieve	#200 Sieve	Average	Standard ...	5 Percentile	50 Percentile	95 Percentile
<input checked="" type="checkbox"/>	100	100	100	100	100	105	0	105	105	105
<input checked="" type="checkbox"/>	90	90	90	90	90	99.5671	3.9569	92.1095	99.965	104.67
<input checked="" type="checkbox"/>	70	70	70	70	70	88.9498	6.4372	78.049	89.005	99.342
<input checked="" type="checkbox"/>	50	50	50	50	50	77.8666	5.8948	70	77.08	88.536
<input checked="" type="checkbox"/>	0	0	0	0	0	70	0	70	70	70

Figure A. 4. Example of input data for SpecRisk Analysis for the EP and OC curves for composite results using the stepped pay schedule

The EP curves in figure A.5 for the Stepped Method are essentially identical to those in Figure A.2 for the continuous method, indicating that either procedure can be designed to produce similar risks. This same conclusion can be drawn for a comparison of OC curves.

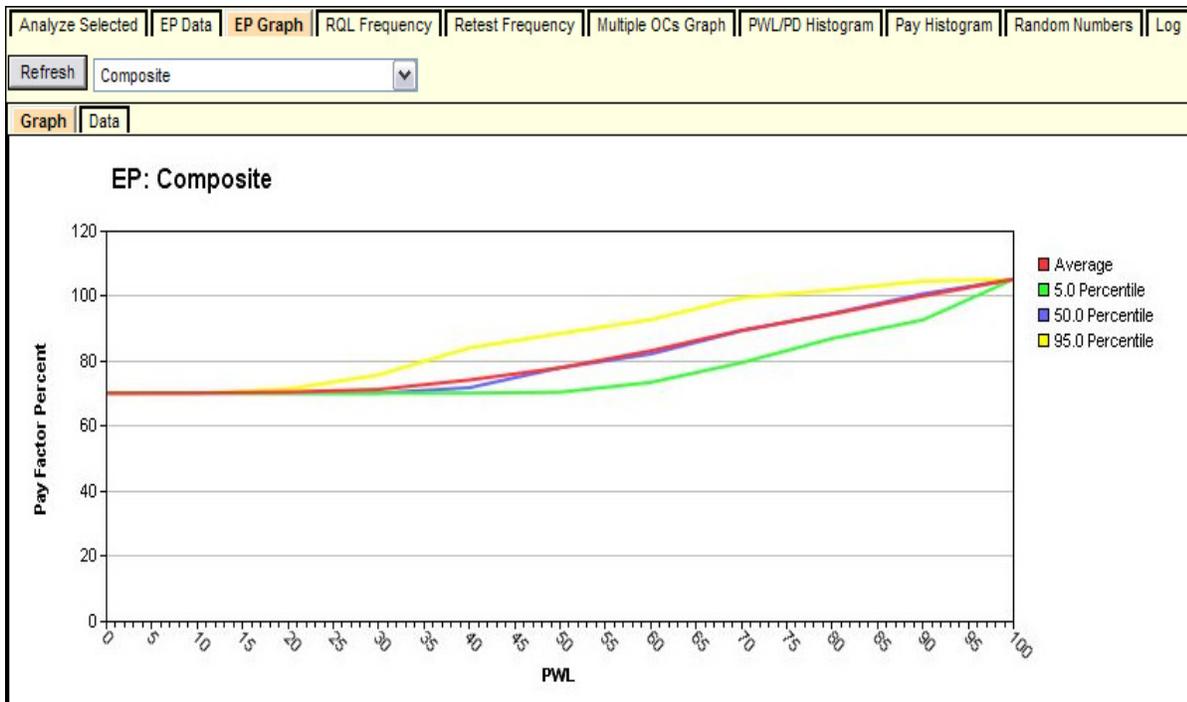


Figure A. 5. Example of EP Curve for Composite Results using the stepped pay schedule

Figure A.6 shows “OC: Composite” curves for this analysis and shows the probability of receiving payment greater than or equal to the pay factors in the index on the right at all levels of PWL. The likelihood that a contractor will receive a pay factor of 105 percent increases from about 2 percent when all AQC’s are at the AQL (90 PWL) to 100 percent when at a PWL of 100. There is approximately a 55 percent chance that the contractor will receive a pay factor of 100 percent or more when operating at the AQL of 90 PWL. Since the minimum pay factor using the continuous method has been established at 70 percent, the SHA will always pay at least 70 percent unless it chooses to remove and replace or retest product detected to be at the RQL or lower.

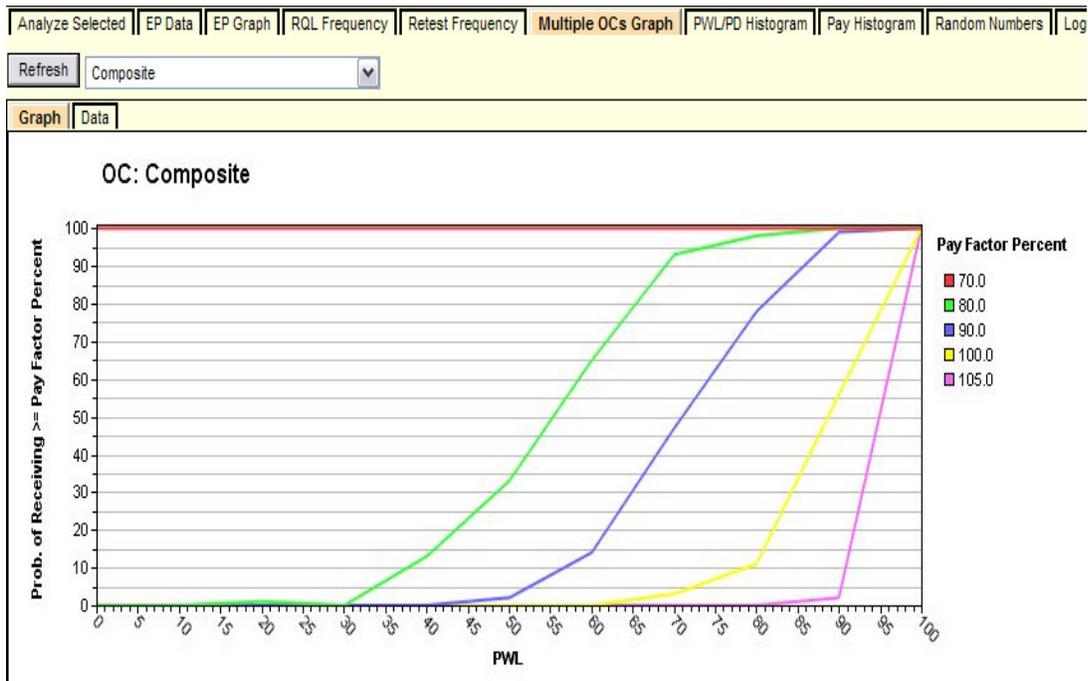


Figure A. 6. Example of Multiple OC Curves for composite results using the stepped pay schedule

A.1.3 Example 2: Construction Only

A.1.3.1 Data:

Tables A.3 through A.5 show the data that are used in this example.

Table A.3. Density and Thickness Data

Test	Density, MTD	Thickness, in
#1	92.5	1.9
#2	93.0	2.1
#3	91.5	2.2
#4	92.9	2.2
#5	92.5	2.3
#6	93.2	2.0
#7	91.1	1.8
#8	94.4	2.1
#9	93.4	2.0
#10	95.0	1.7
Average	93.0	2.0
Standard Deviation	1.18	0.19

Table A. 4. IRI Data (for two miles of roadway) after corrective action

IRI Measurement Number	IRI, (in/mile)¹
#1	56.46
#2	51.56
#3	49.68
#4	52.04
#5	38.31
#6	41.80
#7	50.07
#8	51.14
#9	64.21
#10	77.00
Average	53.23
Standard Deviation	10.96

¹These data are applied to the stepped pay factor table established for Ride Quality and are shown in Table A.5.

Table A. 5. Analysis of IRI Data

IRI Range, in/mi	Pay Adjustment Factors	Percent within IRI Range ¹	Pay Adjustment
<45.0	1.05	20	21.00
45.1 - 50.0	1.04	10	10.40
50.1 - 55.0	1.03	40	41.20
55.1 - 60.0	1.02	10	10.20
60.1 - 65.0	1.01	10	10.10
65.1 - 75.0 (AQL)	1.00	0	0.00
75.1 - 80.0	0.95	10	9.50
80.1 - 85.0	0.90	0	0.00
85.1 - 90.0	0.85	0	0.00
90.1 - 95.0(RQL)	0.80	0	0.00
>95.0	0.80	0	0.00
Total		100	102.40

A.1.3.2 PWL Calculations:

For Density: (Assume $PWL_U = 100$)

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{93.0 - 92.0}{1.18} = 0.85 ; PWL_L = 80$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (80 + 100 - 100) = 80$$

For Thickness: (Assume $PWL_U = 100$)

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{2.0 - 1.8}{0.19} = 1.05 ; PWL_L = 86$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (86 + 100 - 100) = 86$$

For Ride Quality (Assume $PWL_L = 100$)

$$Q_L = \frac{USL - \bar{x}}{s} = \frac{95 - 53.25}{10.96} = 3.81; PWL_U = 100$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (100 + 100 - 100) = 100$$

A.1.3.3 Individual Pay Factor Determinations:

Continuous Method

For Density:

$$PF_{DEN} = 55 + .5 PWL = 55 + 0.5 (80) = 95$$

For Thickness:

$$PF_{THICK} = 55 + 0.5 PWL = 55 + 0.5 (86) = 98$$

For Ride Quality:

$$PF_{RQ} = 55 + 0.5 PWL = 55 + 0.5 (100) = 105$$

Stepped Method

For Density: (Table A.1)

$$PWL = 80, PF = 94$$

For Thickness: (Table A.1)

$$PWL_{THICK} = 86, PF = 98$$

For Ride Quality: (Table A.5)

$$PWL_{IRI} = 100, PF = 102.4$$

A.1.3.4 Composite Pay Factor Determinations:Continuous Method

$$CPF = 0.4(PF_{DEN}) + 0.2(PF_{THICK}) + 0.4(PF_{RQ})$$

$$CPF = 0.4 (95) + 0.2 (98) + 0.4 (105)$$

$$CPF = 38.00 + 19.60 + 42.00$$

$$CPF = 99.60$$

Stepped Method

$$CPF = 0.4(PF_{DEN}) + 0.2(PF_{THICK}) + 0.4(PF_{RQ})$$

$$CPF = 0.4(94) + 0.2(98) + 0.4(102.4)$$

$$CPF = 37.60 + 19.60 + 40.96$$

$$CPF = 98.16$$

A.1.3.5 EP and OC Curve Analysis:

The analyses for this example use the same SpecRisk computer software procedure to obtain the EP and OC curve analyses for the continuous method (Equation 5 in the Guidelines) as the previous example.

Continuous Method

The composite EP analysis results in Figure A.7 show that the expected (average) pay factor is close to the desired value of 100 percent when all AQC's are at the AQL level of 90 PWL. When all AQC's are at the RQL level of 50 PWL, the expected pay factor is almost 80 percent. Also when at the AQL for all three AQC's, the contractor can expect to receive a pay factor between about 95 and 104 percent approximately 90 percent of the time. And when at the RQL for the three AQC's, the SHA can expect to pay between 70 and 86 percent about 95 percent of the time.

Figure A.7 “EP Curves: Composite” shows the expected pay levels for the complete range of PWL from 0 to 100.

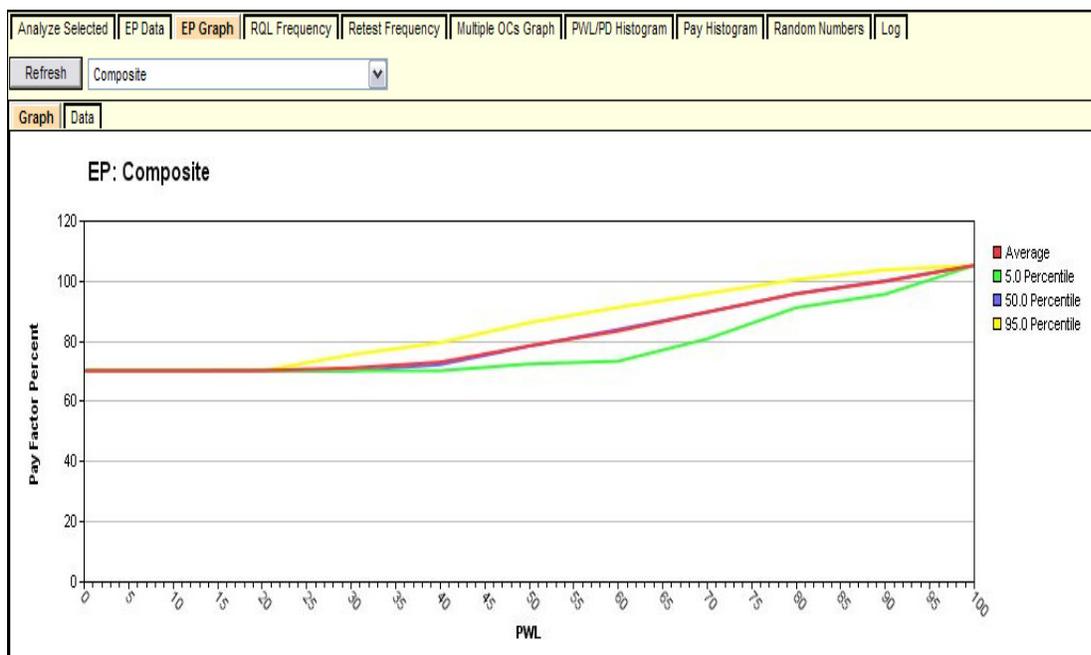


Figure A. 7. Example of the EP Graph for composite results using the continuous method

Figure A.8 shows the multiple OC curves using the continuous method. “OC: Composite” indicates that all AQC’s are simultaneously at the levels displayed on the X-axis, and the Y-axis gives the probability of receiving greater than or equal to the pay factor in the index on the right at all levels of PWL. The likelihood that a contractor will receive a pay factor of 105 percent increases from nearly zero when all AQC’s are at the AQL (90 PWL) to essentially 100 percent when at a PWL of 100. There is approximately a 50 percent chance that the contractor will receive a pay factor of 100 percent or more when operating at the AQL of 90 PWL. Furthermore, since the minimum pay factor in Equation 5 in the Guidelines has been chosen as 70 percent, the SHA will always pay at least 70 percent unless it chooses to remove and replace or retest product detected to be at the RQL or lower.

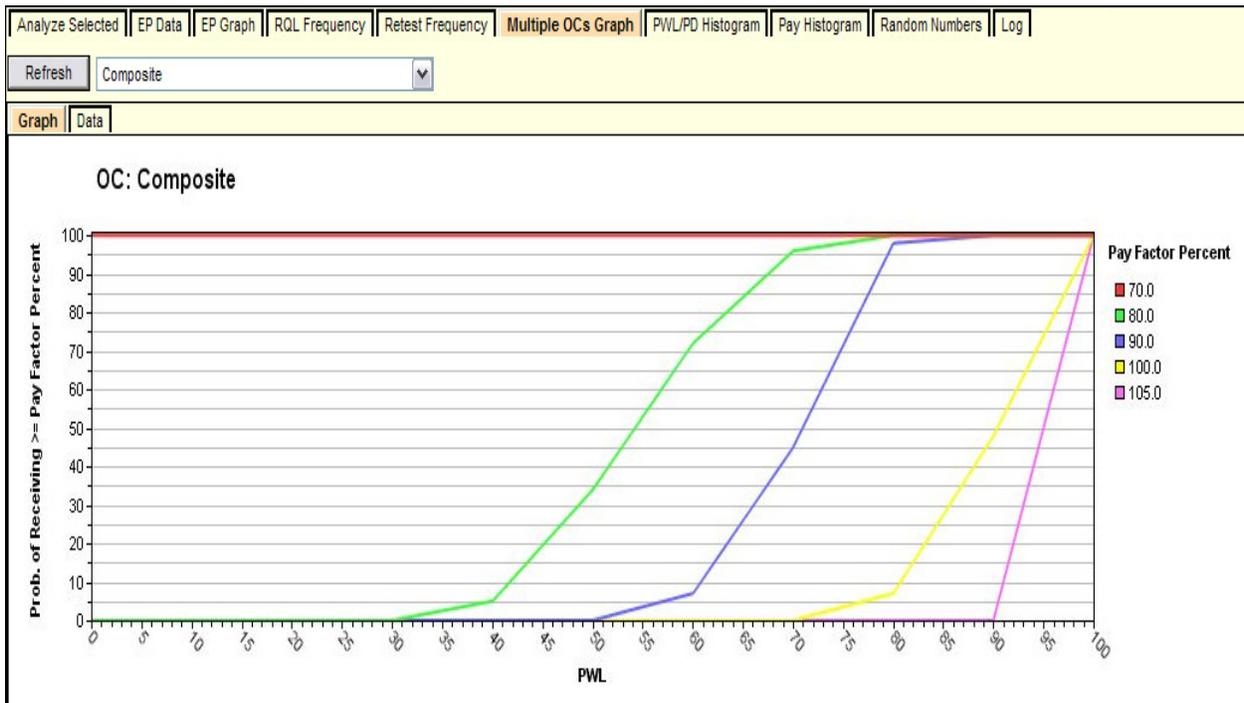


Figure A. 8. Example of the Multiple OC Curves for composite results using the continuous method

Stepped Method

This analysis, shown in Figure A.9, provides the EP and OC curves when the stepped pay schedule is used.

The average pay factor when all AQC's are at the AQL level of 90 PWL is almost exactly 100 percent, and when all AQC's are at the RQL level of 50 PWL, it is about 78 percent. The average result at the AQL is essentially the desired expected pay factor of 100 percent.

The EP analysis in Figure A.9 also shows that the 5 and 95 percentile lines are within a narrow range, indicating that when at the AQL for all three AQC's, the contractor can expect to receive a pay factor between 95 and 103 percent about 90 percent of the time. And when at the RQL for the three AQC's, the SHA can expect to pay between 70 and 85 percent about 95 percent of the time. These results are essentially identical to those using the continuous method.

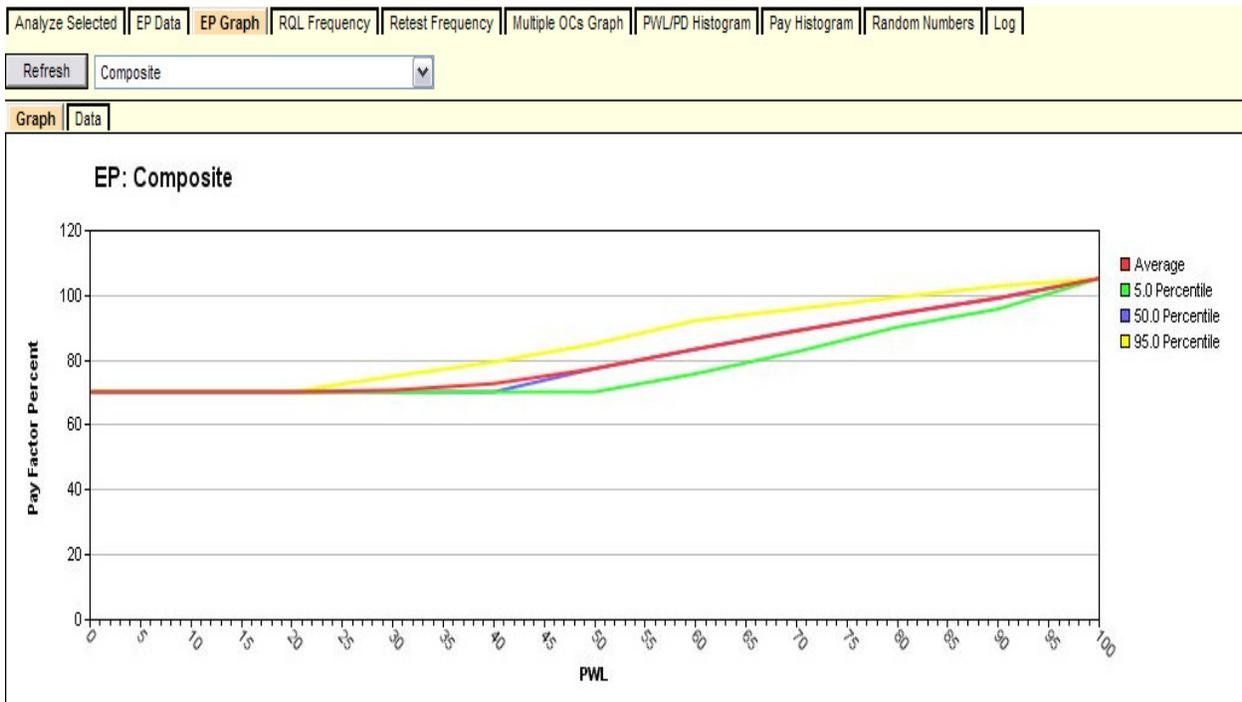


Figure A. 9. Example of the EP Curves for composite results using the stepped pay schedule

Figure A.10 shows the multiple OC Curves for using the stepped pay schedule. The “OC: Composite” shows the probability of receiving greater than or equal to the pay factor in the index on the right when all AQC’s are at the PWL values on the X-axis. The likelihood that a contractor will receive a pay factor of 105 percent increases from nearly zero percent when all AQC’s are at the AQL (90 PWL) to essentially 100 percent when at a PWL of 100. Since the minimum pay factor in the stepped pay schedule is 70 percent, the SHA will always pay at least 70 percent unless it chooses to remove and replace or retest product detected to be at the RQL or lower. These curves are very similar to those developed using the continuous method.

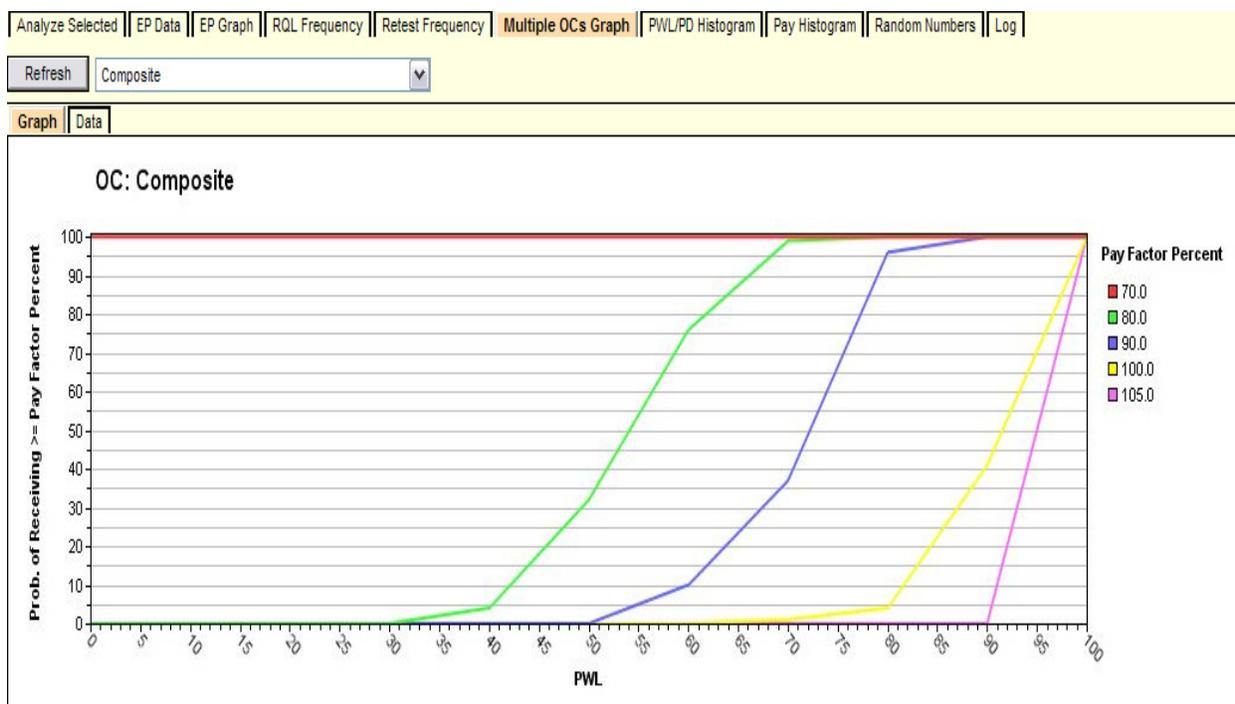


Figure A. 10. Example of the OC Curves for composite results using the stepped pay schedule

A.1.4 Flexible Pavement Example 3: Materials and Construction

A.1.4.1 Data:

The data used in this example are shown in tables A.6 through A.9.

Table A. 6. Material Property Data

	AC	AV	VMA
JMF	5.5	4.0	-
Test #1	5.66	3.8	16.1
Test #2	5.52	3.9	15.8
Test #3	5.35	4.9	16.3
Test #4	5.47	2.5	14.5
Test #5	5.53	3.4	15.4
Test #6	5.43	2.7	14.5
Average	5.49	3.5	15.4
Standard Deviation	0.105	0.88	0.78

Table A. 7. Density and Thickness Data

Test	Density, MTD	Thickness, in
#1	92.5	1.9
#2	93.0	2.1
#3	91.5	2.2
#4	92.9	2.2
#5	92.5	2.3
#6	93.2	2.0
#7	91.1	1.8
#8	94.4	2.1
#9	93.4	2.0
#10	95.0	1.7
Average	93.0	2.0
Standard Deviation	1.18	0.19

Table A. 8. IRI Data

IRI Measurement Number	IRI, (in/mile)
#1	56.46
#2	51.56
#3	49.68
#4	52.04
#5	38.31
#6	41.80
#7	50.07
#8	51.14
#9	64.21
#10	77.00
Average	53.23
Standard Deviation	10.96

These data are applied to the stepped pay factor table established in the Guidelines for Ride Quality and are shown below in Table A.9.

Table A. 9. Analysis of IRI Data

IRI range, in/mi	Pay Adjustment Factors	Percent Within IRI range	Pay Adjustment
<45.0	1.05	20	21.00
45.1 - 50.0	1.04	10	10.4
50.1 - 55.0	1.03	40	41.20
55.1 - 60.0	1.02	10	10.20
60.1 - 65.0	1.01	10	10.10
65.1 - 75.0 (AQL)	1.00	0	0.00
75.1 - 80.0	0.95	10	9.50
80.1 - 85.0	0.90	0	0.00
85.1 - 90.0	0.85	0	0.00
90.1 - 95.0	0.80	0	0.00
> 95 (RQL)	remove and replace or retest	0	0.00
Total		100	PF =102.40

A.1.4.2 PWL Calculations:

Materials

For AC:

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{5.49 - 5.10}{0.105} = 3.71; \text{PWL}_L = 100$$

$$Q_U = \frac{USL - \bar{x}}{s} = \frac{5.90 - 5.49}{0.105} = 3.90; \text{PWL}_U = 100$$

$$\text{PWL}_T = \text{PWL}_L + \text{PWL}_U - 100$$

$$\text{PWL}_T = (100 + 100 - 100) = 100$$

For AV:

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{3.5 - 3.0}{0.88} = 0.57; \text{PWL}_L = 71$$

$$Q_U = \frac{USL - \bar{x}}{s} = \frac{6.0 - 3.5}{0.88} = 2.84; \text{PWL}_U = 100$$

$$\text{PWL}_T = \text{PWL}_L + \text{PWL}_U - 100$$

$$\text{PWL}_T = (71 + 100 - 100) = 71$$

For VMA: (Assume $\text{PWL}_U = 100$)

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{15.4 - 14.0}{0.78} = 1.79; \text{PWL}_L = 100$$

$$\text{PWL}_T = \text{PWL}_L + \text{PWL}_U - 100$$

$$\text{PWL}_T = (100 + 100 - 100) = 100$$

Construction

For Density: (Assume $PWL_U = 100$)

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{93.0 - 92.0}{1.18} = 0.85; PWL_L = 80$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (80 + 100 - 100) = 80$$

For Thickness: (Assume $PWL_U = 100$)

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{2.0 - 1.8}{0.19} = 1.05; PWL_L = 86$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (86 + 100 - 100) = 86$$

For Ride Quality (Assume $PWL_L = 100$)

$$Q_L = \frac{USL - \bar{x}}{s} = \frac{95 - 53.23}{10.96} = 3.81; PWL_U = 100$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (100 + 100 - 100) = 100$$

A.1.4.3 Individual Pay Factor Determinations:

Materials

Continuous Method

For AC:

$$PF_{AC} = 55 + .5 PWL = 55 + 0.5 (100) = 105$$

For AV:

$$PF_{AV} = 55 + .5 PWL = 55 + 0.5 (71) = 90.5$$

For VMA:

$$PF_{VMA} = 55 + .5 PWL = 55 + 0.5 (100) = 105$$

Stepped Method (From Table A.1)

For AC:

$$PWL_{AC} = 100; PF_{AC} = 105$$

For AV:

$$PWL_{AV} = 71; PF_{AV} = 90$$

For VMA:

$$PWL_{VMA} = 100; PF_{VMA} = 105$$

Construction

Continuous Method

For Density:

$$PF_{DEN} = 55 + .5 PWL = 55 + 0.5 (90) = 100$$

For Thickness:

$$PF_{\text{THICK}} = 55 + .5 \text{ PWL} = 55 + 0.5 (100) = 105$$

For Ride Quality:

$$PF_{\text{RQ}} = 55 + 0.5 \text{ PWL} = 55 + 0.5 (100) = 105$$

Stepped Method (From Table A.1)

For Density:

$$PWL_{\text{DEN}} = 90, PF_{\text{DEN}} = 100$$

For Thickness:

$$PWL_{\text{THICK}} = 100, PF_{\text{THICK}} = 105$$

For Ride Quality (From Table A.5)

$$PWL_{\text{RQ}} = 100, PF = 102$$

A.1.4.4 Composite Pay Factor Determinations:

- Materials and Construction (Without Ride Quality)

$$CPF = 0.35(PF_{\text{DEN}}) + 0.2(PF_{\text{AC}}) + 0.35(PF_{\text{AV}}) + 0.1(PF_{\text{VMA}})$$

$$CPF = 0.35(100) + 0.2(105) + 0.35(90.5) + 0.1(105)$$

$$CPF = 35.00 + 21.00 + 31.68 + 10.50$$

$$CPF = 98.18$$

- Materials and Construction (With Ride Quality)

$$CPF = 0.3(PF_{\text{DEN}}) + 0.15(PF_{\text{AC}}) + 0.15(PF_{\text{AV}}) + 0.1(PF_{\text{THICK}}) + 0.3(PF_{\text{RQ}})$$

$$CPF = 0.3(100) + 0.15(105) + 0.15(90.5) + 0.1(105) + 0.3(105)$$

$$CPF = 30.00 + 15.75 + 13.575 + 10.50 + 31.50$$

$$CPF = 101.325$$

Stepped

- Materials and Construction (Without Ride Quality)

$$\text{CPF} = 0.35(\text{PF}_{\text{DEN}}) + 0.2(\text{PF}_{\text{AC}}) + 0.35(\text{PF}_{\text{AV}}) + 0.1(\text{PF}_{\text{VMA}})$$

$$\text{CPF} = 0.35(100) + 0.2(105) + 0.35(90.5) + 0.1(105)$$

$$\text{CPF} = 35.00 + 21.00 + 31.675 + 10.50$$

$$\text{CPF} = 98.175$$

- Materials and Construction (With Ride Quality)

$$\text{CPF} = 0.3(\text{PF}_{\text{DEN}}) + 0.15(\text{PF}_{\text{AC}}) + 0.15(\text{PF}_{\text{AV}}) + 0.1(\text{PF}_{\text{THICK}}) + 0.3(\text{PF}_{\text{RQ}})$$

$$\text{CPF} = 0.3(100) + 0.15(105) + 0.15(90) + 0.1(105) + 0.3(102)$$

$$\text{CPF} = 30.00 + 15.75 + 13.50 + 10.50 + 30.60$$

$$\text{CPF} = 100.35$$

A.1.4.5 Flexible Pavement EP and OC Curve Analysis:

The analyses for this example use the same SpecRisk computer software procedure to obtain the EP and OC curve for the continuous method as the previous example. There are two CPF equations for this method, one without Ride Quality and one with Ride Quality, so there are two sets of EP and OC curves.

Continuous Method (without Ride Quality)

In Figure A.11 it is seen that the average pay factor when all AQC's are at the AQL level of 90 PWL is 99.9 percent, and when all are at the RQL level of 50 PWL, it is just below 80 percent. Therefore, the desired result at the AQL has been achieved and the average result at the RQL (80.1) percent is commensurate with the pay schedule.

The 5 and 95 percentile lines in this figure show that, when at the AQL for all four AQC's, the contractor can expect to receive a pay factor between about 96 and 103 percent roughly 90 percent of the time. And when at the RQL for the four AQC's, the SHA can expect to pay between about 70 and 85 percent about 95 percent of the time.

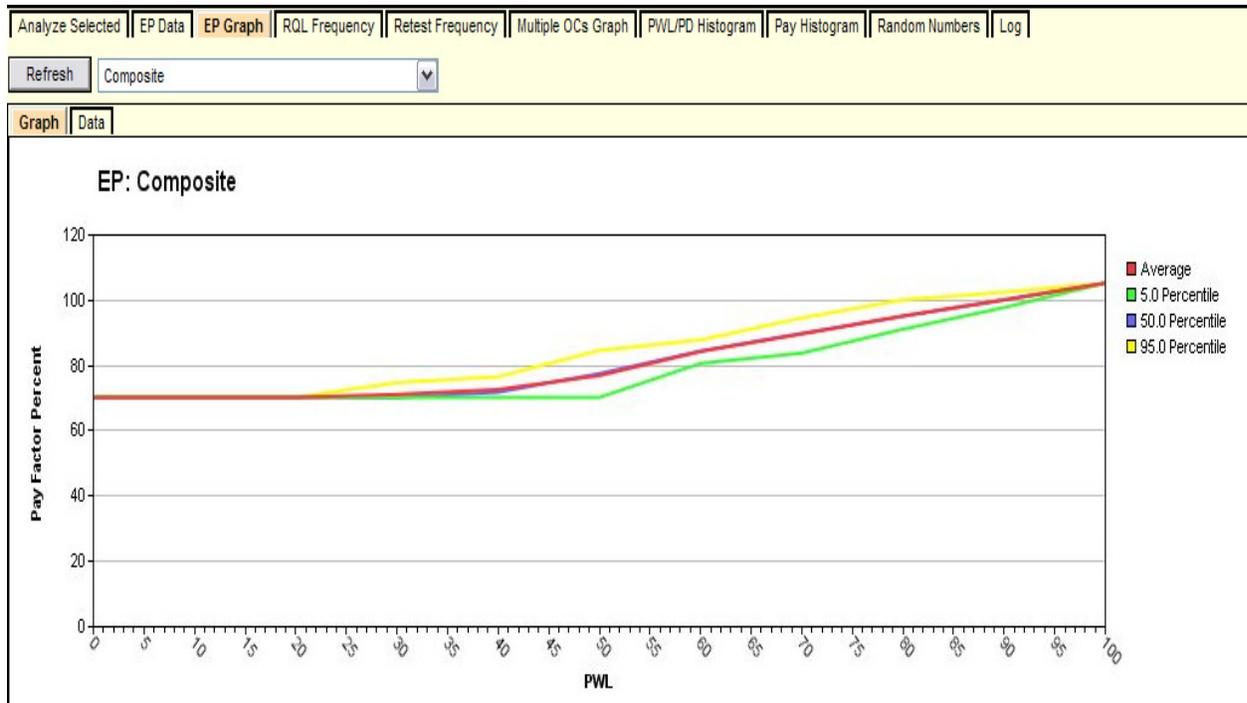


Figure A. 11. Example of SpecRisk Analysis for the EP Curve for composite results using the continuous method (without Ride Quality).

Figure A.12 shows the multiple OC curves using the continuous method (without Ride Quality). This OC: Composite shows the probability of receiving greater than or equal to the pay factor in the legend on the right for all levels of PWL. The likelihood that a contractor will receive a pay factor of 105 percent increases from essentially zero percent when all AQC's are at the AQL (90 PWL) to virtually 100 percent when at a PWL of 100. There is the probability of about 60 percent that the contractor will receive a pay factor of 100 percent or more when operating at the AQL (90 PWL) in all characteristics. Since the minimum pay factor using the continuous method is 70 percent, the SHA will always pay at least 70 percent, unless it chooses to remove and replace or retest product detected to be at the RQL or lower.

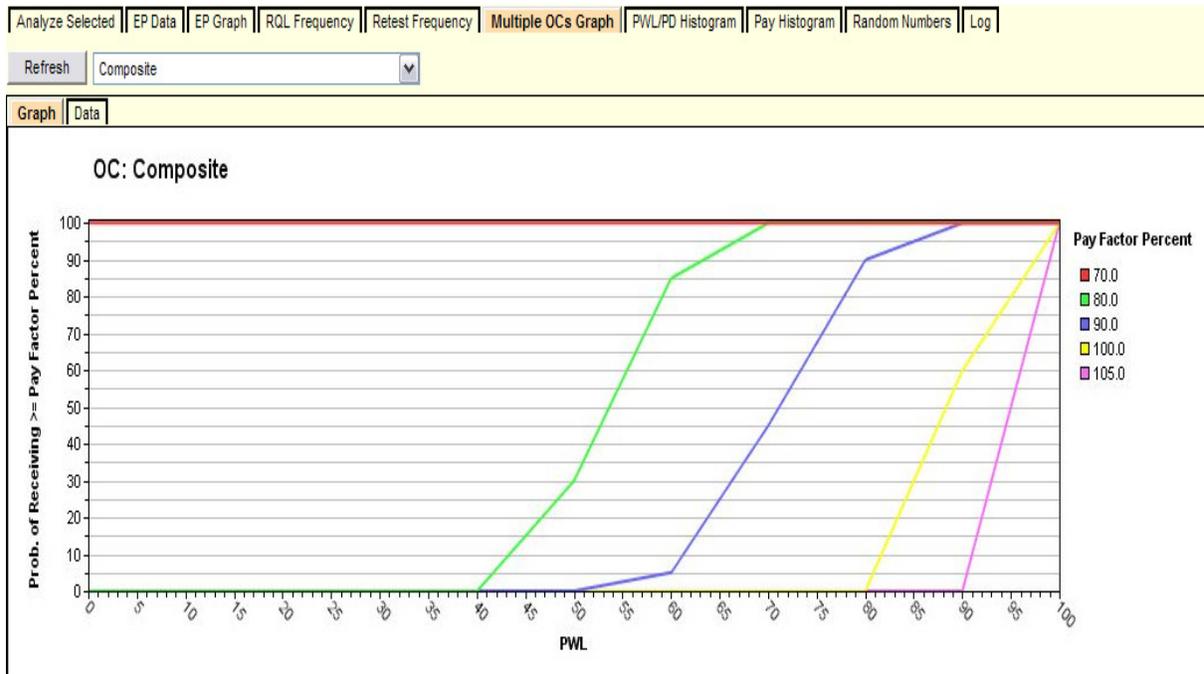


Figure A. 12. Example of SpecRisk Analysis for the OC Curve for composite results using the Continuous method (without Ride Quality).

Figure A.12 shows the multiple OC curves using the composite method (without Ride Quality). The “OC: Composite” curve show the probability of receiving greater than or equal to the pay factor in the legend on the right for all levels of PWL. The likelihood that a contractor will receive a pay factor of 105 percent increases from 0 percent when all AQC’s are at the AQL (90 PWL) to essentially 100 percent when at a PWL of 100. In this case, there is higher than normal probability of about 60 percent that the contractor will receive a pay factor of 100 percent or more when operating at the AQL (90 PWL) in all characteristics. Since the minimum pay factor in the Equation 5 in the Guidelines is 70 percent, the SHA will always pay at least 70 percent, unless it chooses to remove and replace or retest product detected to be at the RQL or lower.

Stepped Method (without Ride Quality)

This analysis presents the EP and OC curves when the stepped pay schedule is used.

It is seen in Figure A.13 that the average pay factor when all AQC's are at the AQL level of 90 PWL is essentially 100 percent, as desired and when all AQC's are at the RQL level of 50 PWL, it is about 76 percent. These results are very similar to the results of the continuous method at the AQL, but the stepped method has a slightly lower average (76 percent versus 80 percent) at the RQL than those for the analysis using the continuous method

Figure A.13 also shows the EP Curves (without Ride Quality) using the stepped pay schedule. The "EP: Composite" selection shows the expected pay factors when all AQC's are at all levels of PWL indicated on the X-axis. The analysis shows that when at the AQL for all four AQC's, the contractor can expect to receive a pay factor between about 96 and 103 percent about 90 percent of the time. And when at the RQL for the four AQC's, the SHA can expect to pay between about 70 and 85 about 95 percent of the time.

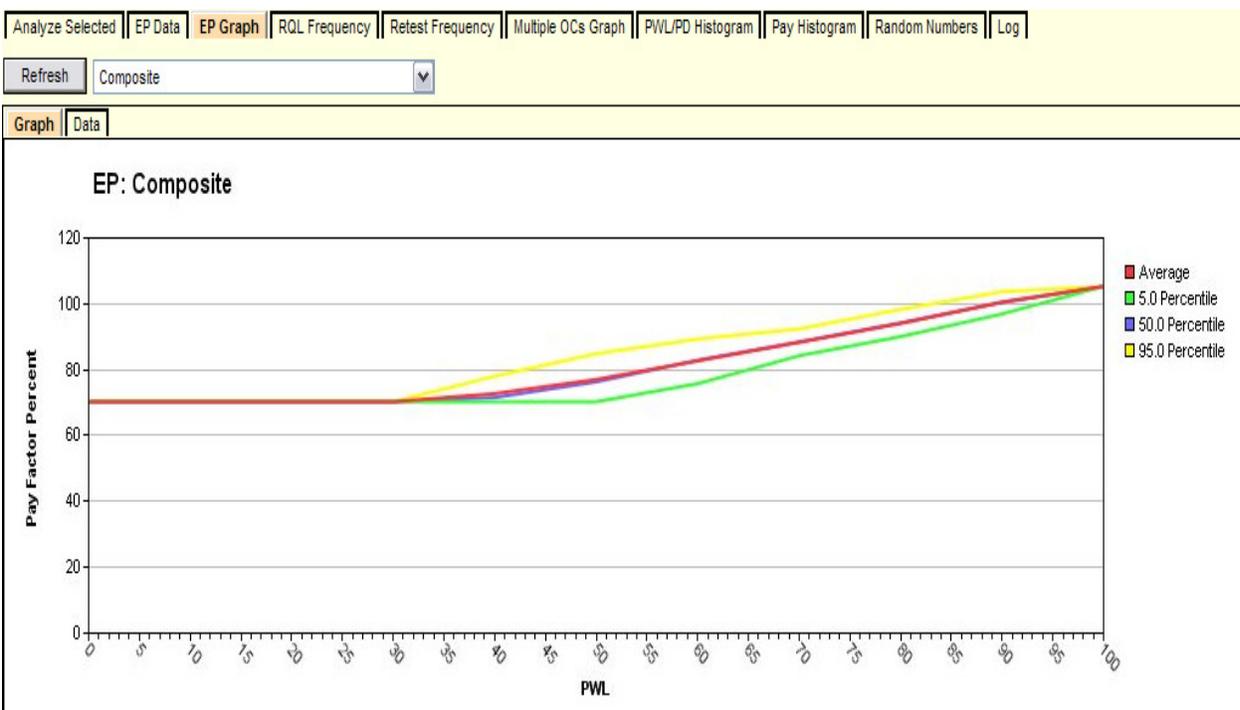


Figure A. 13. Example of SpecRisk Analysis for the EP Curve for composite results using the stepped pay schedule (without Ride Quality).

Figure A.14 shows the multiple OC curves using the stepped pay schedule (without Ride Quality). The OC: Composite figure shows the probability of receiving greater than or equal to the pay factor in the index on the right when all AQC's are at the levels of PWL displayed on the X-axis. The likelihood that a contractor will receive a pay factor of 105 percent increases from essentially zero percent when all AQC's are at the AQL (90 PWL) to virtually 100 percent when at a PWL of 100. There is approximately a 55 percent chance that the contractor will receive a pay factor of 100 percent or more when operating at the AQL (90 PWL) in all characteristics. Since the minimum pay factor in the stepped Pay Schedule is 70 percent, the SHA will always pay at least 70 percent unless it chooses to remove and replace product detected to be at the RQL or lower.

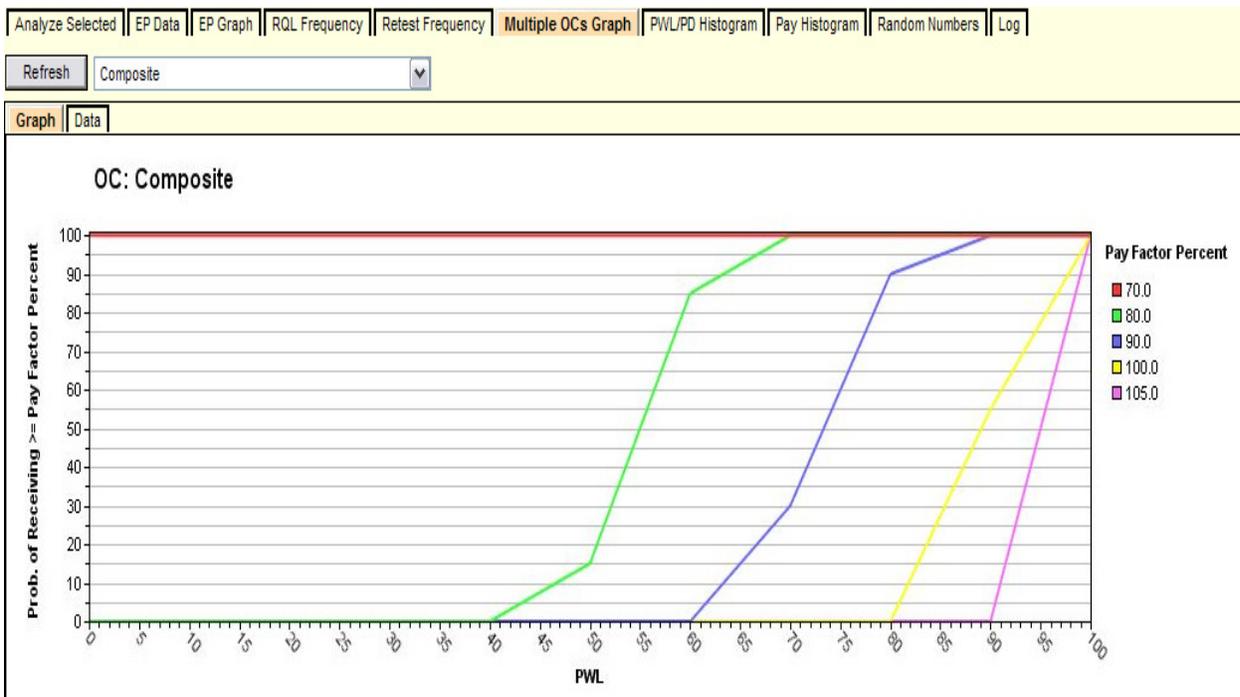


Figure A. 14. Example of the SpecRisk Analysis for the OC Curve for composite results using the stepped pay schedule (without Ride Quality).

Continuous Method (with Ride Quality)

The analysis shown in Figure A.15 indicates that the average pay factor when all AQC's are at the AQL level of 90 PWL will be virtually 100 percent, and when all are at the RQL level of 50 PWL, the average is about 78 percent.

Figure A.15 also shows the EP Curves using the continuous method (with Ride Quality). The “EP: Composite” selection presents the results for all AQC’s taken together and shows the expected pay factor at all levels of PWL. This analysis indicates that when all five AQC’s are at the AQL of 90 PWL, the contractor can expect to receive a pay factor between about 97 and 103 percent about 90 percent of the time. And when all five AQC’s are at the RQL of 50 PWL, the SHA can expect to pay between about 71 and 84 percent roughly 90 percent of the time.

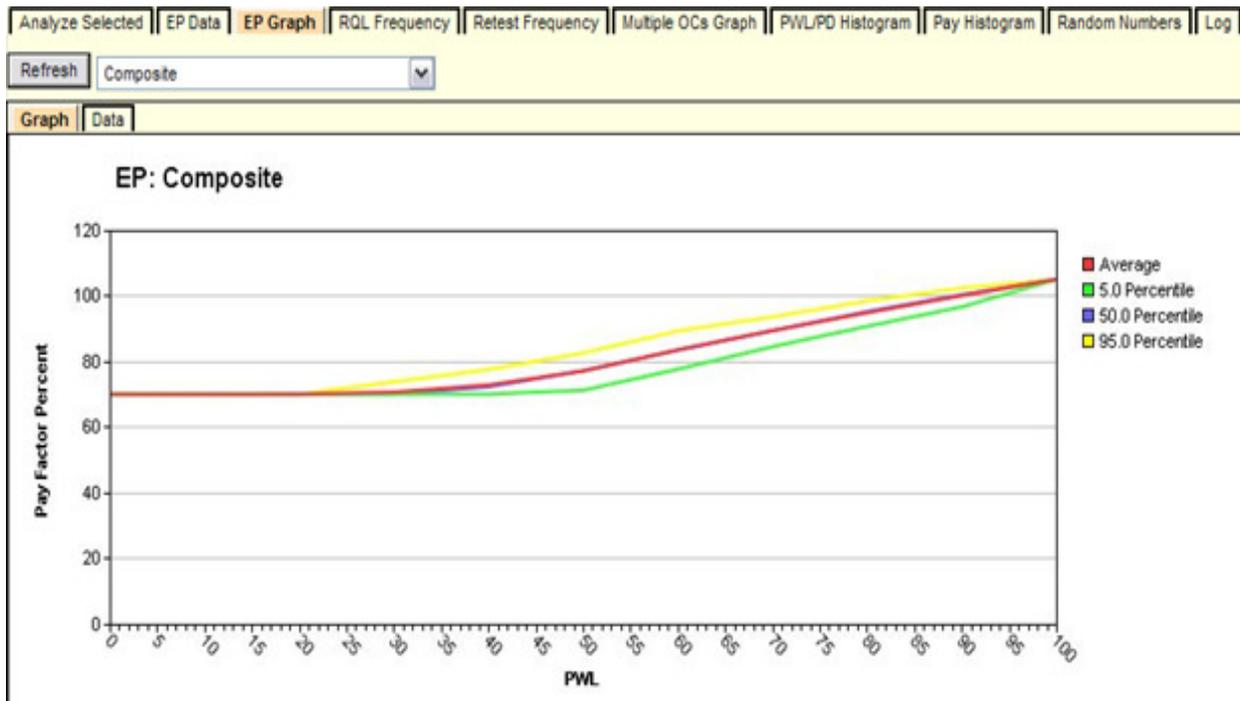


Figure A. 15. Example of SpecRisk Analysis for the EP Curve for composite results using the continuous method (with Ride Quality).

Figure A.16 shows the multiple OC curves for the continuous method (with Ride Quality). The OC: Composite graph produces the probabilities of receiving greater than or equal to the pay factor in the legend on the right at all levels of PWL. The likelihood that a contractor will receive a pay factor of 105 percent increases from essentially zero percent when all AQC’s are at the AQL (90 PWL) to essentially 100 percent when at a PWL of 100. There is about a 60 percent chance that the contractor will receive a pay factor of 100 percent or more when operating at the AQL (90 PWL). Since the minimum pay factor is 70 percent, the

SHA will always pay at least 70 percent unless it chooses to remove and replace or retest product detected to be at the RQL or lower.

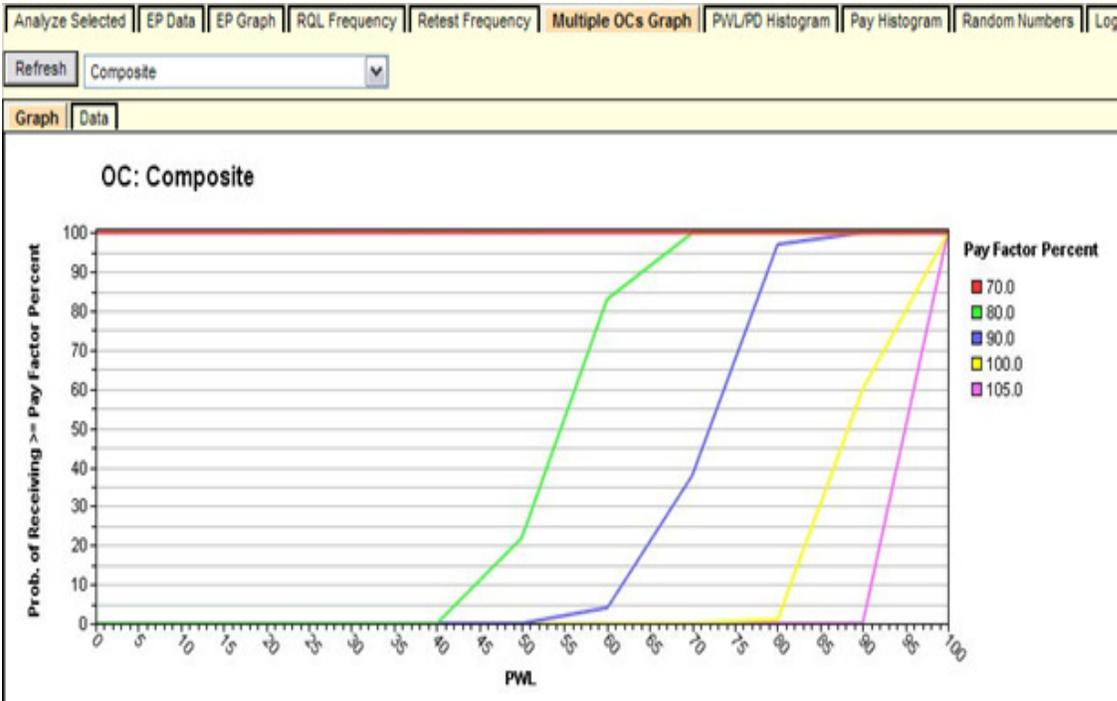


Figure A. 16. Example of SpecRisk Analysis for the OC Curve for composite results using the continuous method (with Ride Quality).

Stepped Method (with Ride Quality)

This analysis presents the EP and OC curves when the stepped pay schedule is used.

Figure A.17 indicates that the average pay factor when all AQC's are at the AQL level of 90 PWL is virtually 100 percent, and when all are at the RQL level of 50 PWL, it is about 77 percent. These results are very similar to the results of the continuous method at the AQL (100 and 78 percent, respectively).

Figure A.17 also shows the EP Curves (with Ride Quality) using the stepped pay schedule. The "EP: Composite" graph shows the expected pay factors at all levels of PWL. When all AQC's are at the AQL of PWL = 90, the contractor can expect

to receive a pay factor between about 96 and 103 percent about 90 percent of the time. And when at the RQL of PWL = 50 for the five AQC's, the SHA can expect to pay between about 71 and 83 percent roughly 90 percent of the time.

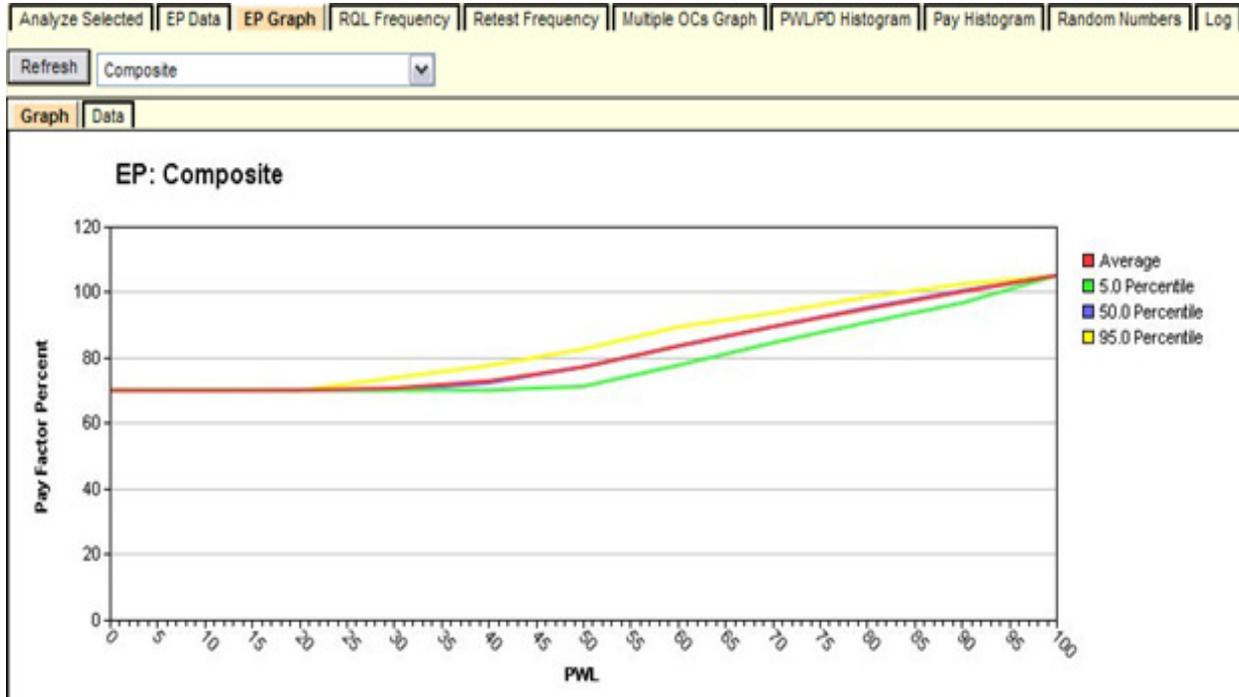


Figure A. 17. Example of SpecRisk Analysis for the EP Curve for composite results using the stepped pay schedule (with Ride Quality).

Figure A.18, with OC: Composite selected, shows the probability of receiving pay factors greater than or equal to those in the legend on the right for all PWL levels. This figure is very similar to previous figures of this type. There is a 50 percent chance that the contractor will receive a pay factor of 100 percent or more when operating at the AQL (90 PWL). Since the minimum pay factor in the pay schedule is 70 percent, the SHA will always pay 70 percent or more unless it chooses to remove and replace or retest product detected to be at the RQL or lower.

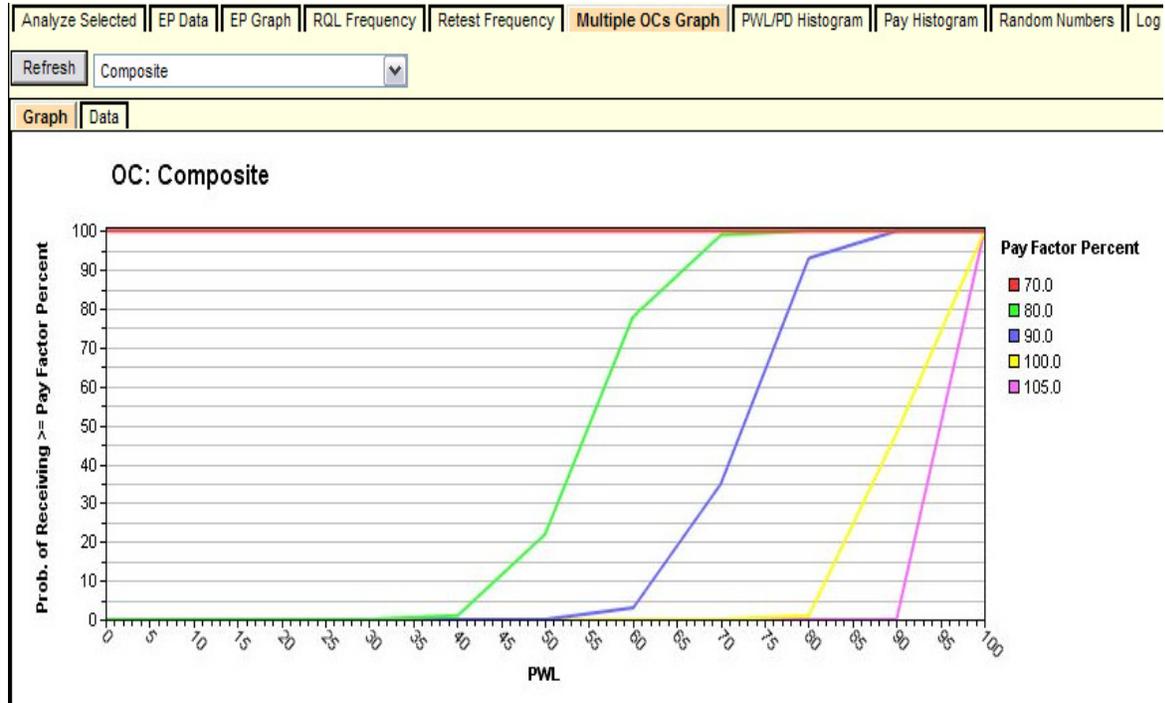


Figure A. 18. Example of SpecRisk Analysis for the OC Curve for composite results using the stepped pay schedule (with Ride Quality).

A.2 Example for Rigid Pavements

The example uses inputs of QA procedures developed in the Guidelines and data that are typical of what most SHAs use.

A.2.1 Inputs

The AQC's used in the examples are:

- Compressive Strength, 28-day (2 cylinders per test result)
- Thickness
- Ride Quality

The QM used is PWL

The individual pay factors used in the examples are:

- The continuous method uses Equation 5 in the Guidelines:
With the AQL = 90PWL and RQL= 50PWL (with a minimum pay factor = 70 percent) for all AQCs.
- The stepped method uses Table A.1.
With the AQL = 90 PWL and the RQL = 50 PWL for all AQCs other than Ride Quality.
- For Ride Quality (using the tabular method) the AQL = 70in./mile and the RQL = 92.5in./mile.

The composite pay factor used in the examples is Equation 12 in the Guidelines.

Other specification information:

- Spec Limits;
 - Compressive strength: - Minimum 3000 psi
 - Thickness - Plan thickness 12" (PT- 0.5": thus, Lower spec limit = 11.5")
 - Ride Quality: Max 95 in/mi
- Lot size: two lane miles
- Sample size: $n=10$.

A.2.2 Data

The data used in the example are found in the tables below.

Table A. 10. Strength and Thickness Data

Test	Strength, (psi)	Thickness, (in)
#1	4691	11.5
#2	5007	12.4
#3	4899	12.8
#4	4590	11.4
#5	3794	12.2
#6	3940	12.6
#7	3772	11.3
#8	4677	11.8
#9	4881	12.3
#10	5111	12.5
Average	4536	12.1
Standard Deviation	509.9	0.54

Table A. 11. IRI Data

IRI Measurements	IRI, (in/mile)
#1	62.13
#2	66.09
#3	75.29
#4	67.87
#5	64.04
#6	55.06
#7	53.01
#8	54.54
#9	48.93
#10	49.94
Average	59.69
Standard Deviation	8.69

Table A. 12. Analysis of IRI Data

IRI range, in/mi	Pay Adjustment Factors	Percent within IRI Range1	Pay Adjustment
<45.0	1.05	0	0.00
45.1 - 50.0	1.04	20	20.80
50.1 - 55.0	1.03	20	20.60
55.1 - 60.0	1.02	20	20.40
60.1 - 65.0	1.01	20	20.20
65.1 - 75.0 (AQL)	1.00	10	10.00
75.1 - 80.0	0.95	10	9.50
80.1 - 85.0	0.90	0	0.00
85.1 - 90.0	0.85	0	0.00
90.1 - 95.0	0.80	0	0.00
> 95.0 (RQL)	0.80	0	0.00
Total		100	PF = 101.50

A.2.2.2**PWL Calculations:**

For Strength: (Assume $PWL_U = 100$)

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{4536 - 3000}{509.9} = 3.01; PWL_L = 100$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (100 + 100 - 100) = 100$$

For Thickness: (Assume $PWL_U = 100$)

$$Q_L = \frac{\bar{x} - LSL}{s} = \frac{12.1 - 11.5}{0.54} = 1.11; PWL_L = 87$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (87 + 100 - 100) = 87$$

For Ride Quality: (Assume $PWL_L = 100$)

$$Q_U = \frac{USL - \bar{x}}{s} = \frac{95 - 59.69}{8.69} = 4.06; PWL_U = 100.$$

$$PWL_T = PWL_L + PWL_U - 100$$

$$PWL_T = (100 + 100 - 100) = 100$$

A.2.2.3 Individual Pay Factor Determinations:

Continuous Method

For Strength:

$$PF_{STREN} = 55 + .5 PWL = 55 + 0.5 (100) = 105$$

For Thickness:

$$PF_{\text{THICK}} = 55 + .5 \text{ PWL} = 55 + 0.5 (87) = 98.5$$

For Ride Quality:

$$PF_{\text{RQ}} = 55 + 0.5 \text{ PWL} = 55 + 0.5 (100) = 105$$

Stepped Method

For Strength: (From Table A.10)

$$\text{PWL} = 100, PF_{\text{STREN}} = 105$$

For Thickness: (From Table A.10)

$$\text{PWL} = 87, PF_{\text{THICK}} = 98$$

For Ride Quality: (From Table A.12)

$$PF_{\text{RQ}} = 101.50$$

A.2.2.4 Composite Pay Factor Determinations:

Continuous Method

$$\text{CPF} = 0.25(PF_{\text{STREN}}) + 0.35(PF_{\text{THICK}}) + 0.40(PF_{\text{RQ}})$$

$$\text{CPF} = 0.25(105) + 0.35 (98) + 0.4(105)$$

$$\text{CPF} = 26.25 + 34.30 + 42.00$$

$$\text{CPF} = 102.55$$

Stepped

$$CPF = 0.25(PF_{STREN}) + 0.35(PF_{THICK}) + 0.40(PF_{RQ})$$

$$CPF = 0.25(105) + 0.35(98) + 0.4(101.5)$$

$$CPF = 26.25 + 34.30 + 40.60$$

$$CPF = 101.15$$

A.2.2.5 EP and OC Curve Analysis

The analyses for this example use the same SpecRisk computer software procedure to obtain the EP and OC curve analysis for the continuous method (Equation 5 in the Guidelines).

Continuous Method

Figure A.19 indicates that average pay factor when all AQC's are at the AQL level of 90 PWL will be essentially 100 percent. and when all AQC's are at the RQL level of 50 PWL, the expected pay factor will be about 78 percent.

The selection "EP: Composite" produces the expected pay factors at all levels of PWL. When at the AQL of 90 PWL for all three AQC's, the contractor can expect to receive a pay factor between about 96 and 103 percent about 90 percent of the time. And when the three AQC's are at the RQL of 50 PWL, the SHA can expect to pay between 70 and about 86 percent about 95 percent of the time.

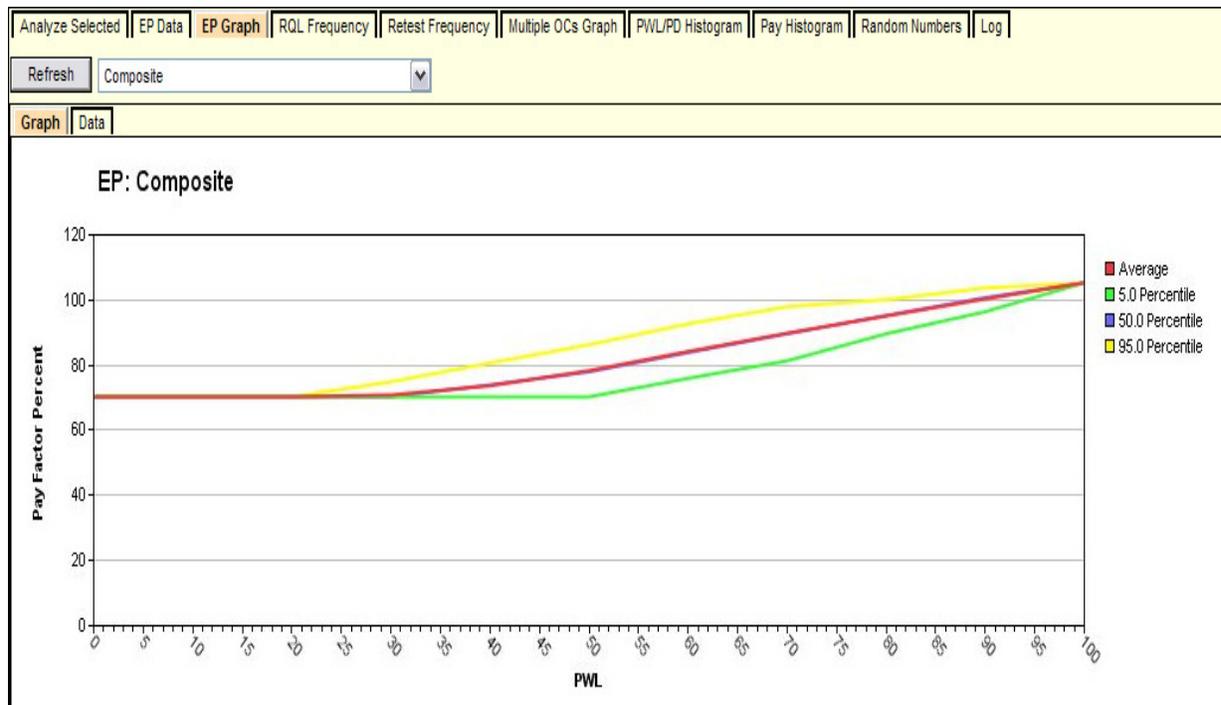


Figure A. 19. Example for SpecRisk Analysis of the EP curve for composite results using the continuous method

Figure A.20, with "OC: Composite" selected, shows the probability at each PWL of receiving greater than or equal to the pay factors in the legend on the right. The likelihood that a contractor will receive a pay factor of 105 percent increases from nearly zero percent when all AQC's are at the AQL (90 PWL) to essentially 100 percent when at a PWL of 100. For these examples, there is about a 55 percent

chance of receiving 100 percent payment (or more) when all AQC's are at the AQL of 90 PWL, as desired and expected. Furthermore, since the minimum pay factor in the Equation 5 in the Guidelines is 70 percent, the SHA will always pay at least 70 percent unless it chooses to remove and replace or retest product detected to be at the RQL or lower.

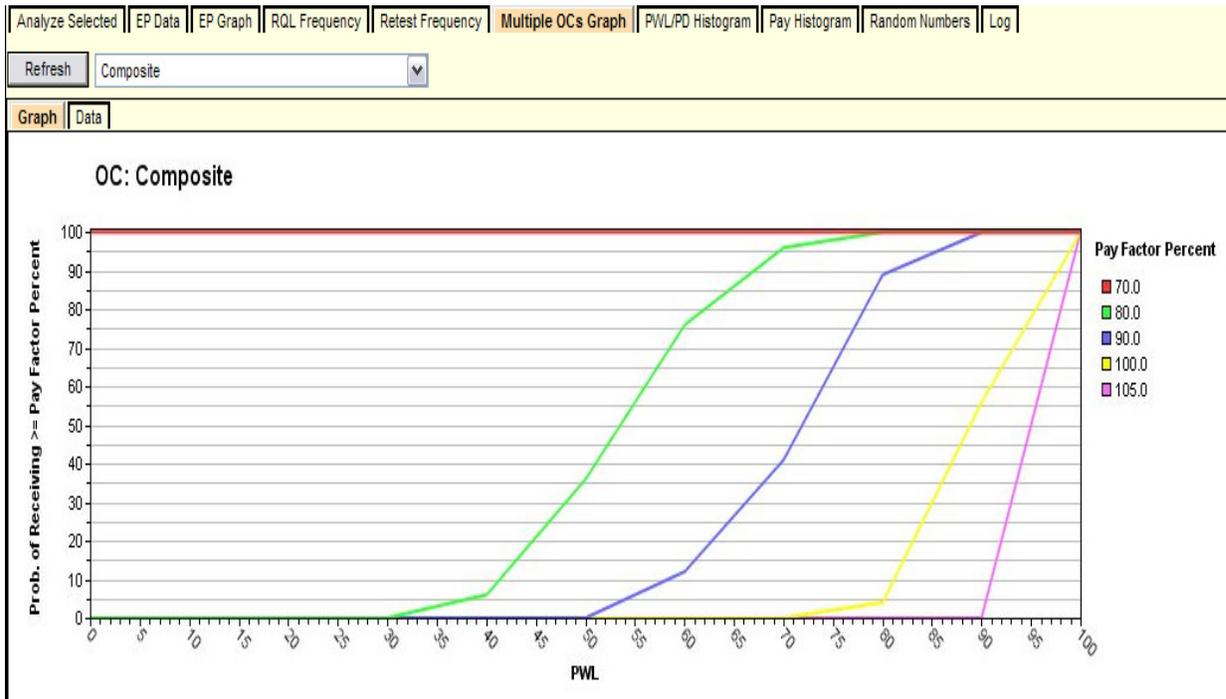


Figure A. 20. Example for SpecRisk Analysis of the OC Curves for composite results using the continuous method.

Stepped Method

The EP Composite curve in Figure A.21 indicates that the average pay factor when all AQC's are at the AQL level of 90 PWL is close to 100 percent, and when all are at the RQL level of 50 PWL, it is just below 80 percent. These results are very similar to those for the analysis using the continuous method.

It can also be seen from Figure A.21 that when at the AQL for all three AQC's, the contractor can expect to receive a pay factor between about 95 and 103 percent approximately 90 percent of the time. And when at the RQL for the three AQC's, the SHA can expect to pay between 70 and about 85 percent about 95 percent of the time. These results are also similar to those using the continuous method.

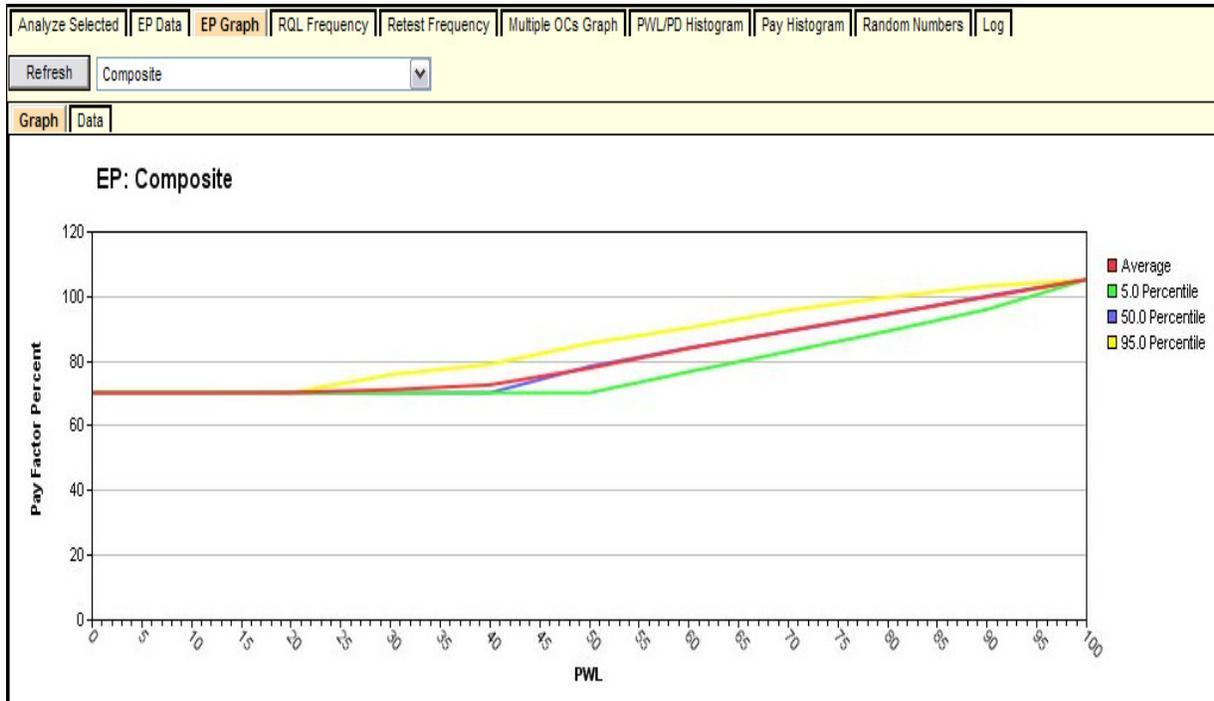


Figure A. 21. Example of Input Data for SpecRisk Analysis for the EP Graph for composite results using the stepped pay schedule

Figure A.22 with “OC: Composite” selected shows the probability at all levels of PWL of receiving greater than or equal to the pay factors in the legend on the right. The likelihood that a contractor will receive a pay factor of 105 percent increases from nearly zero percent when all AQC’s are at the AQL (90 PWL) to essentially 100 percent when at a PWL of 100. There is nearly a 50 percent chance of receiving 100 percent payment (or more) when all AQC’s are at the AQL of 90 PWL. Furthermore, since the minimum pay factor is 70 percent, the SHA will always pay at least 70 percent unless it chooses to remove and replace or retest product detected to be at the RQL or lower.

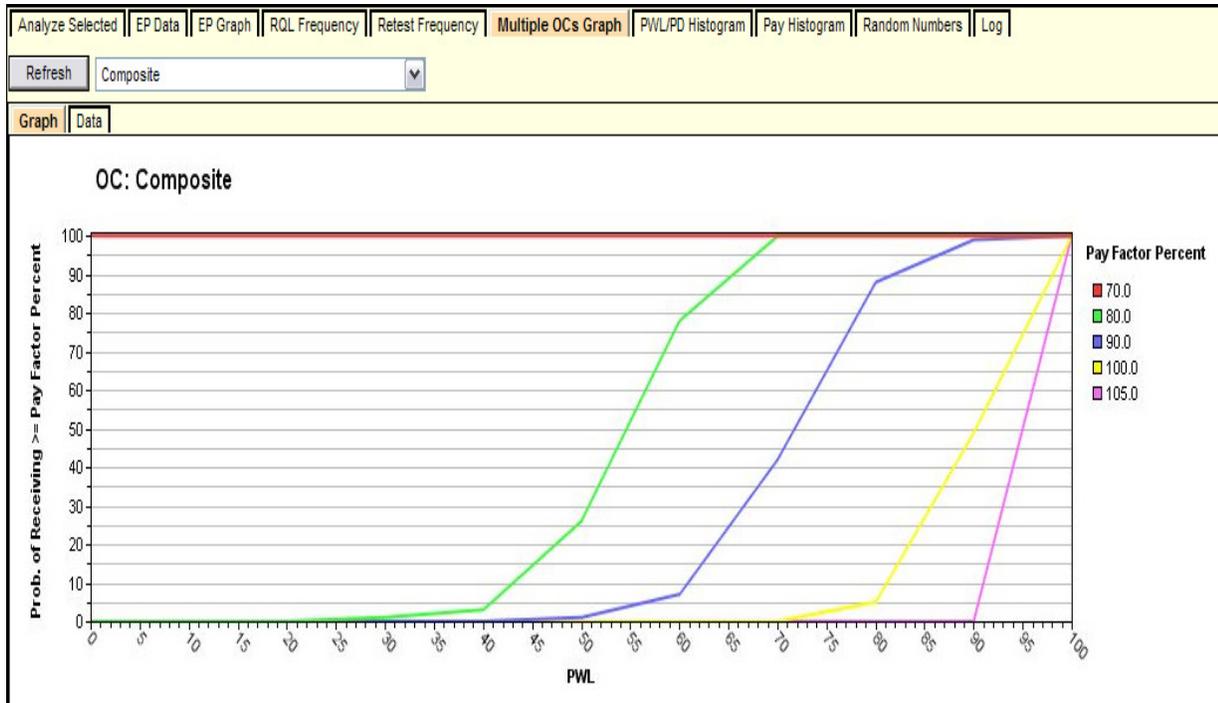


Figure A. 22. Example of the OC curves for composite results using the stepped pay schedule

A.3 Example of Empirical PRS Method for Flexible Pavements

The Empirical PRS Method was developed specifically to provide a method based on sound mathematical, economic, and legal principles. As such, it is intended to provide a rational basis for a pay adjustment system that fairly represents the interests of both highway agencies and the construction industry, and which is believed to be based on defensible principles of contract law.

This example illustrates the specification development process as discussed in the Guidelines based on the following decisions made by SHA:

A.3.1 Initial Specification Parameters and Assumptions

Type of Specification:

- HMA pavement overlay

The AQC's used are:

- AC (2-sided, field test)
- AV (2-sided, field test)
- Density (1-sided, field test)
- Thickness (1-sided, field test)

The QM used is PWL

Correlation of AQC's

Since there is some degree of correlation among some of these AQC's, it is assumed that the correlation levels are as shown in Table A.13 below.

Table A. 13. Correlation Matrix

AQC	AC	AV	Density	Thickness
AC	1.0	-0.25	0.35	0.0
AV	-	1.0	-0.30	0.0
Density	-	-	1.0	0.0
Thickness	-	-	-	0.0

Table A.14 presents the AQL and RQL levels selected. To simplify the mathematics, this procedure uses percent defective (PD) rather than the compliment, PWL. (The final result can be converted back to PWL, if desired.) An AQL of PD = 10 is the value recommended in AASHTO R-9, while the RQL values are left up to the SHA.

Table A. 14. AQL and RQL Levels (PD)

AQC's	AC	AV	Density	Thickness
AQL	10	10	10	10
RQL	65	65	55	55

A.3.2 Completing the Performance Matrix

Complete the performance matrix for the selected combinations of AQL and RQL in Table A.14 and shown in Table A.15.

Table A. 15. Typical Performance Matrix

PD_{AC}^1	PD_{AV}	$PD_{DENSITY}$	$PD_{THICKNESS}$	EXPLIF (Years)
10 (AQL)	10 (AQL)	10 (AQL)	10 (AQL)	10 (Design Life) ²
65 (RQL) ³	10	10	10	5 (Poor AC)
10	65 (RQL) ³	10	10	5 (Poor AV)
10	10	55 (RQL) ³	10	5 (Poor Density)
10	10	10	55 (RQL) ³	5 (Poor Thickness)

¹ AQC quality levels are in terms of PD.

² This application represents overlays with a design life of 10 years.

³ Example assumes RQL values chosen to correspond to EXPLIF = 5 years.

A.3.3 Setting Up and Solving the Simultaneous Equations

The general exponential performance model for this method is given below.

$$EXPLIF = e^{-(B_0 + B_1 PD^C_1 + B_2 PD^C_2 + \dots + B_k PD^C_k)}$$

This equation is used to develop the simultaneous equation set by taking natural logarithms producing the following equation.

$$\ln(\text{EXPLIF}) = B_0 + B_1 \text{PD}_1^C + B_2 \text{PD}_2^C + \dots + B_k \text{PD}_k^C$$

Where

EXPLIF = expected life (years),

B_i = equation coefficients (constants to be derived),

PD_i = statistical quality measure (individual percent defective values),

C = shape factor, a common exponent for all PD terms,

i = identifier of individual quality characteristics,

k = number of acceptance quality characteristics,

e = base of natural logarithms, and

\ln = natural logarithm operator.

To solve for the “B” coefficients, a trial-and-error process is used by choosing a trial C value, setting up the equation set above, and then solving to obtain the performance relationship given below. A series of test calculations can then be made to determine whether the model is satisfactory. If not, it will be necessary to repeat the process with a different C exponent.

The final C value will usually be between 1.0 and 2.0, and very often falls close to $C = 1.5$. Therefore, this value is a practical starting point. Normally, a satisfactory model can be obtained with very few attempts.

The set of simultaneous equations given below represent the third and final trial run to obtain the performance model. These equations were constructed from the information in Table A.15 applied to the performance model. The natural logarithms of the expected-life values in the last column of Table A.15 are shown below:

$$\ln(10) = 2.302585$$

$$\ln(5) = 1.609438$$

The coefficients to the right of the equals signs are the PD values from Table A.15 raised to the power of the final trial value of $C = 1.562$. That is:

$$10^{1.562} = 6.4754$$

$$55^{1.562} = 522.934$$

$$65^{1.562} = 678.845$$

The subscripts in the equations below represent:

$$1 = AC$$

$$2 = AV$$

$$3 = DENSITY$$

$$4 = THICKNESS$$

This results in the following equation set:

$$2.302585 = B_0 + 36.4754 B_1 + 36.4754 B_2 + 36.4754 B_3 + 36.4754 B_4$$

$$1.609438 = B_0 + 678.845 B_1 + 36.4754 B_2 + 36.4754 B_3 + 36.4754 B_4$$

$$1.609438 = B_0 + 36.4754 B_1 + 678.845 B_2 + 36.4754 B_3 + 36.4754 B_4$$

$$1.609438 = B_0 + 36.4754 B_1 + 36.4754 B_2 + 522.934 B_3 + 36.4754 B_4$$

$$1.609438 = B_0 + 36.4754 B_1 + 36.4754 B_2 + 36.4754 B_3 + 522.934 B_4$$

The set of simultaneous equations was solved by a function included in the SpecRisk specification analysis software, yielding the following equation coefficients:

$$B_0 = 2.485249$$

$$B_1 = B_{AC} = -0.001079$$

$$B_2 = B_{AV} = -0.001079$$

$$B_3 = B_{DENSITY} = -0.001425$$

$$B_4 = B_{THICKNESS} = -0.001425$$

AC and AV have the same equation coefficients as do Thickness and Density. This is because they have the same AQL/RQL combinations of 10/65 and 10/55 (in units of PD), respectively. These coefficients, along with the final trial

exponent of $C = 1.562$, are then substituted into the performance model equation to complete the performance model given below.

$$\text{EXPLIF} = e^{(2.49 - 0.0017 \text{PD}_{\text{AC}}^{1.56} - 0.0017 \text{PD}_{\text{AV}}^{1.56} - 0.0014 \text{PD}_{\text{DEN}}^{1.56} - 0.0014 \text{PD}_{\text{THICK}}^{1.56})}$$

The various numerical terms in the equation above have been written with fewer significant figures than those that were derived. For the validation steps that follow, full precision will be used.

A.3.4 Standard Validation Tests

Validation Test #1: Test at Extremes

The first test of the performance model is to check that it returns satisfactory values at the two extremes at which all $\text{PD} = 0$ and all $\text{PD} = 100$, levels at which empirical models sometimes break down. These results are presented in Table A.16.

Table A. 16. Test of Model at Extremes

Values Entered in Model				EXPLIF
PD_{AC}	PD_{AV}	PD_{DEN}	PD_{THICK}	Returned
				(Years)
0	0	0	0	12.004
100	100	100	100	0.015

The first thing to note from Table A.16 is that the predicted expected life at the best quality level possible with all $\text{PD} = 0$ (all $\text{PWL} = 100$) is 12 years when a 10-year-design overlay is constructed with excellent quality. At the other extreme with all $\text{PD} = 100$ (all $\text{PWL} = 0$), the model predicts an expected life of essentially zero. Both results seem reasonable so the model is judged to have satisfied this first test.

Validation Test #2: Test of Quality Levels Used for Derivation

The next test is to check that the multidimensional model passes through all the points used to derive it. Using the performance matrix in Table A.15, when the quality levels from the first four columns are entered into the model, it should return exactly the EXPLIF values shown in the last column of that table. Table A.17 demonstrates that the model satisfies this requirement to at least two decimal places.

Table A. 17. Test of Model at Derivation Values

Values Entered in Model				EXPLIF
PD_{AC}	PD_{AV}	PD_{DEN}	PD_{THICK}	
10 (AQL)	10 (AQL)	10 (AQL)	10 (AQL)	10.00
65 (RQL)	10	10	10	5.00
10	65 (RQL)	10	10	5.00
10	10	55 (RQL)	10	5.00
10	10	10	55 (RQL)	5.00

Validation Test #3: Sensitivity Test of All Characteristics Simultaneously

The next test is examine how the EXPLIF values change as all AQC's decline over the entire range from best possible quality to worst possible quality. These results are shown in Table A.18.

Table A. 18. Results over Range of Quality

Values Entered in Model				EXPLIF Returned (Years)
PD_{AC}	PD_{AV}	PD_{DEN}	PD_{THICK}	
0	0	0	0	12.004
10 (AQL)	10 (AQL)	10 (AQL)	10 (AQL)	10.000
20	20	20	20	7.000
30	30	30	30	4.346
40	40	40	40	2.442
50	50	50	50	1.257
60	60	60	60	0.598
70	70	70	70	0.264
80	80	80	80	0.109
90	90	90	90	0.042
100	100	100	100	0.015

When the four AQC's all decline by PD = 10 in each successive row in Table A.18, this amounts to a substantial decrease in overall quality at each step. Consequently, the predicted value of expected life in the last column similarly declines rather quickly. It can be seen in Table A.18 that if all AQC's were simultaneously at PD = 50 (PWL = 50), which would normally be regarded as an extremely poor combined level of quality, the predicted life of the 10-year-design overlay is only slightly more than a year. Although such an unlikely combination of poor quality in all AQC's should be a rare occurrence, this appears to be a reasonable result. Therefore, this test further supports the validity of this model.

Validation Test #4: All Quality Characteristics at Their Respective RQL Values

The prediction of expected life when all four characteristics are at their respective RQL values simultaneously is checked. This result appears in Table A.19 where it is seen that a low value of EXPLIF = 0.625 years is obtained. This seems appropriate for such extremely poor quality.

Table A. 19. All AQC's at their Respective RQL Values

Values Entered in Model				EXPLIF Returned (Years)
PD _{AC}	PD _{AV}	PD _{DEN}	PD _{THICK}	
65 (RQL)	65 (RQL)	55 (RQL)	55 (RQL)	0.625

Validation Tests #5 – #8: Sensitivity of Model to Individual AQC's

The next series of tests explore the model's sensitivity to each individual AQC as it is varied over the range of excellent to poor quality. Tables A.20 – A.23 show the effects of AC, AV, Density, and Thickness quality, respectively, on EXPLIF with the remaining quality characteristics held constant at the AQL of PD = 10.

Table A. 20. Sensitivity of Model to AC Quality

Values Entered in Model				EXPLIF Returned (Years)
PD _{AC}	PD _{AV}	PD _{DEN}	PD _{THICK}	
0	10	10	10	10.401
10 (AQL)	10 (AQL)	10 (AQL)	10 (AQL)	10.000
20	10	10	10	9.260
30	10	10	10	8.356
40	10	10	10	7.380
50	10	10	10	6.396
60	10	10	10	5.450
70	10	10	10	4.570
80	10	10	10	3.777
90	10	10	10	3.078
100	10	10	10	2.475

NOTE: Other AQC's held constant at AQL of PD = 10.

Table A. 21. Sensitivity of Model to AV Quality

Values Entered in Model				EXPLIF Returned (Years)
PD _{AC}	PD _{AV}	PD _{DEN}	PD _{THICK}	
10	0	10	10	10.401
10 (AQL)	10 (AQL)	10 (AQL)	10 (AQL)	10.000
10	20	10	10	9.260
10	30	10	10	8.356
10	40	10	10	7.380
10	50	10	10	6.396
10	60	10	10	5.450
10	70	10	10	4.570
10	80	10	10	3.777
10	90	10	10	3.078
10	100	10	10	2.475

NOTE: Other AQC's held constant at AQL of PD = 10.

Table A. 22. Sensitivity of Model to Density Quality

Values Entered in Model				EXPLIF Returned (Years)
PD _{AC}	PD _{AV}	PD _{DEN}	PD _{THICK}	
10	10	0	10	10.533
10 (AQL)	10 (AQL)	10 (AQL)	10 (AQL)	10.000
10	10	20	10	9.035
10	10	30	10	7.889
10	10	40	10	6.695
10	10	50	10	5.543
10	10	60	10	4.486
10	10	70	10	3.555
10	10	80	10	2.764
10	10	90	10	2.109
10	10	100	10	1.582

NOTE: Other AQC's held constant at AQL of PD = 10.

Table A. 23. Sensitivity of Model to Thickness Quality

Values Entered in Model				EXPLIF
PD_{AC}	PD_{AV}	PD_{DEN}	PD_{THICK}	Returned (Years)
10	10	0	10	10.533
10 (AQL)	10 (AQL)	10 (AQL)	10 (AQL)	10.000
10	10	10	20	9.035
10	10	10	30	7.889
10	10	10	40	6.695
10	10	10	50	5.543
10	10	10	60	4.486
10	10	10	70	3.555
10	10	10	80	2.764
10	10	10	90	2.109
10	10	10	100	1.582

NOTE: Other AQC's held constant at AQL of PD = 10.

Tables A.20 – A.23 provide additional information on how the performance model will function. In these tables, if any single AQC is found to be increasingly defective, even though the others are at acceptable levels, the expected performance of the pavement as a whole is significantly affected. This is one of the arguments for the use of RQL provisions which allow SHAs the option of requiring remove - and - replace at the contractor's expense when any individual quality characteristic falls below some critical level of poor quality. This model supports the use of such provisions.

Another observation to be made from tables A.20 – A.23 is that both AC and AV by themselves can produce a minimum value of EXPLIF = 2.475 years, while both Density and Thickness can produce a lower minimum value of EXPLIF = 1.582 years. This is because Density and Thickness have the more severe RQL value of PD = 55 while AC and AV have a more lenient RQL of PD = 65, as seen in the performance matrix.

A.3.5 Validation Testing of Equivalent AQL Combinations

One additional validation test is performed to assure that the model is functionally realistic. With any multicharacteristic acceptance procedure, there will be some degree of ambiguity associated with the definition of AQL work. While the definition of AQL can be explicit for individual quality characteristics (e.g., $PWL = 90$ or $PD = 10$), the situation becomes more complex when multiple AQC's are involved. This is so because most quantified procedures will allow excesses in quality in one characteristic to offset deficiencies in another characteristic.

The condition at which all individual AQC's are at their respective AQL values can be regarded as the primary definition of an AQL lot, at which full payment should be awarded. But when analyzing multicharacteristic acceptance procedures, it becomes apparent that there are many other combinations of quality that will produce full payment when some AQC's test out as better than required while others test out as deficient. This will occur whenever the expected life predicted by the performance equation equals the intended design life of the pavement. As long as these individual departures from the design level of quality are relatively small, they may represent little more than sampling error and pavement performance is seldom adversely affected when these terms balance out. What remains to be tested for this particular model is just how large these departures could be and still yield 100 percent payment (i.e., resulting from $EXPLIF = \text{design life}$). Any combination of quality levels characteristics that lead to 100 percent payment is referred to as an "equivalent" AQL.

One way to perform this test is to hold the remaining AQC's at the maximum quality level of $PD = 0$ ($PWL = 100$) while each individual AQC is incrementally decreased to determine the lowest quality level at which the model predicts that the expected life equals the design life. There are four individual quality characteristics to test to determine the lowest level at which the model produces $EXPLIF = 10$ years (intended design life for the overlay). These are presented in separate blocks in Table A.24 to illustrate this trial-and-error process.

Table A. 24. Determination of Equivalent AQL Combinations

Values Entered in Model				EXPLIF
PD _{AC}	PD _{AV}	PD _{DEN}	PD _{THICK}	Returned (Years)
20	0	0	0	10.687
30	0	0	0	9.644
26	0	0	0	10.076
27	0	0	0	9.969
26.7 ¹	0	0	0	10.002
0	26.7 ¹	0	0	10.002
0	0	20	0	10.296
0	0	30	0	8.990
0	0	22	0	10.046
0	0	23	0	9.918
0	0	22.3 ²	0	10.007
0	0	0	22.3 ²	10.002

¹Critical AC and AV Values rounded to 27

²Critical Density and Thickness Values Rounded to 22

It is seen from Table A.24 that the worst case occurs with AQLs AC and AV, either of which could be as poor as PD = 27 (PWL = 73) when the other AQLs are at PD = 0 (PWL = 100), at which the expected life of the pavement would still equal the design life of 10 years, thus resulting in full payment. An agency might consider this to be an acceptable situation, partly because the exceptional quality in the other three characteristics would tend to offset this relatively moderate deficiency in AC or AV, and partly because such an extreme combination of quality levels would be expected to occur only very rarely.

For AQLs of Density and Thickness, the situation may be of less concern because the poorest quality of either characteristic that could lead to full payment for the lot would be about PD = 22 (PWL = 78). Therefore, it is probable a SHA would consider the performance model given above to be practical and effective.

A.3.6 RQL Provisions

There are two alternative solutions if the tests shown in Table A.24 had indicated that the individual AQC's could reach unacceptably low quality levels when the procedure indicated that the expected life was equal to the design life (resulting in full payment). One is to include an RQL provision on any or all AQC's such that, if an unacceptably low quality level were found for any individual characteristic, it would permit the agency to have the option of requiring remove - and - replace of the work at the contractor's expense.

Another alternative that can be used either by itself or in conjunction with the individual RQL provisions is a composite RQL provision based on the expected life value returned by the performance equation. If the design life is 10 years, a composite RQL provision can be written to give the agency the option of requiring remove - and - replace whenever EXPLIF falls below some low level. (In essence, the performance matrix presented in Table A.15 represents an RQL level of 5 years expected life.)

A.3.7 Standard Cost Model

This essentially completes the validation process for the performance model equation.

A.3.8 Application of the Models

Taken together, the performance equation and cost equation are the two key components that underlie the Empirical PRS Method. The performance equation provides a practical and effective empirical link between quality and performance, and the cost equation links performance to economic gain or loss. It then becomes a simple matter to combine these two equations to link quality directly to economic effect, thus providing a solid and defensible analytical basis for the pay schedule.

The performance and cost models can be applied successively, and that may be more practical than attempting to combine them into a single equation that accounts for both. Doing this has the additional advantage of producing an estimate of expected life which can be recorded as part of the project records.

Table A.25 presents typical results of such a two-staged application using the input values presented with the performance and cost equations, except that three different combinations of interest (INT) and inflation (INF) rates have been used.

Table A. 25. Two-Staged Application of Empirical PRS Method

EXPLIF from Performanc e Equation (Years)	Resultant Pay Adjustments from Cost Equation					
	INT = 8 INF = 4		INT = 6 INF = 3		INT = 5 INF = 2	
	(\$/lane mile)	(\$/sy)	(\$/lane mile)	(\$/sy)	(\$/lane mile)	(\$/sy)
12 MAX	+53,500	+7.88	+58,700	+8.34	+58,600	+8.33
11	+28,300	+4.02	+29,800	+4.23	+29,700	+4.22
10 DES	0	0.0	0	0.0	0	0.0
9	-29,400	-4.17	-30,700	-4.35	-30,600	-4.35
8	-59,800	-8.50	-62,200	-8.84	-62,100	-8.82
7	-91,500	-13.00	-94,700	-13.45	-94,600	-13.43
6	-124,400	-17.67	-128,100	-18.19	-128,000	-18.18
5	-158,500	-22.52	-162,500	-23.08	-162,300	-23.06
4	-194,000	-27.56	-197,800	-28.10	-197,700	-28.09
3	-230,800	-32.79	-234,300	-33.28	-234,200	-33.26
2	-269,100	-38.22	-71,700	-38.60	-271,700	-38.59
1	-308,800	-43.86	-310,300	-44.08	-310,300	-44.07
0	-350,000	-49.72	-350,000	-49.72	-350,000	-49.72

Where

INT = long-term interest rate (percent).

INF = long-term inflation rate (percent).

MAX = maximum EXPLIF value from performance equation (years).

DES = design life for overlay used in this example (years).

Table A.25 shows the general magnitude of the pay adjustments in units of both dollars per lane mile and dollars per square yard. It can be seen that these can be substantial for departures from the design life of 10 years for the standard overlay, and that reflects that there were significant departures from the desired levels of AQL quality. The magnitudes of these pay adjustments reflect the fact that it is

the total cost of the pavement (including engineering, mobilization, traffic protection, construction, testing, etc.) that must be moved either earlier or later in time, depending upon whether the quality is substandard or superior. These magnitudes also reflect that whenever a pavement fails prematurely (or conversely, has its life extended), it affects all future overlays.

Table A.25 also shows that the procedure is not sensitive to the actual interest and inflation rates, but is more sensitive to the difference between these two rates. Since long-term interest and inflation rates tend to track approximately in parallel, the process itself tends to be quite stable over time. Long term rates of approximately $INT = 8$ percent and $INF = 4$ percent were used in the example.

This method provides quantitative justification for both payment incentive and disincentive clauses, although it can be seen in Table A.25 that the maximum incentives are much smaller than the maximum disincentives. This is largely because the increases in expected life due to superior quality are substantially smaller than the decreases in life due to poor quality.

Finally, a current total cost of \$350,000 per lane mile was assumed for a typical overly project, as noted in the definition of terms for the cost equation. This method produces a payment reduction of that full amount when the expected life calculated from the performance model happens to be zero. This occurs in all cases, as can be seen in the last row of Table A.25.

A.3.9 Alternate Application Method

Because the mathematical model given by the performance equation has four independent variables (PD_{AC} , PD_{AV} , $PD_{DENSITY}$, and $PD_{THICKNESS}$), there is no way to simplify this model. However, because the life-cycle-cost model has only a single input ($EXPLIF$), this model can be simplified. If the SHA has decided that the appropriate values for long term interest and inflation are $INT = 6$ and $INF = 3$ percent, respectively, values from the appropriate columns in Table A.25 are plotted as shown in Figure A.23 to reveal that this provides a nearly linear relationship for pay adjustment as a function of expected life (dashed line in this figure).

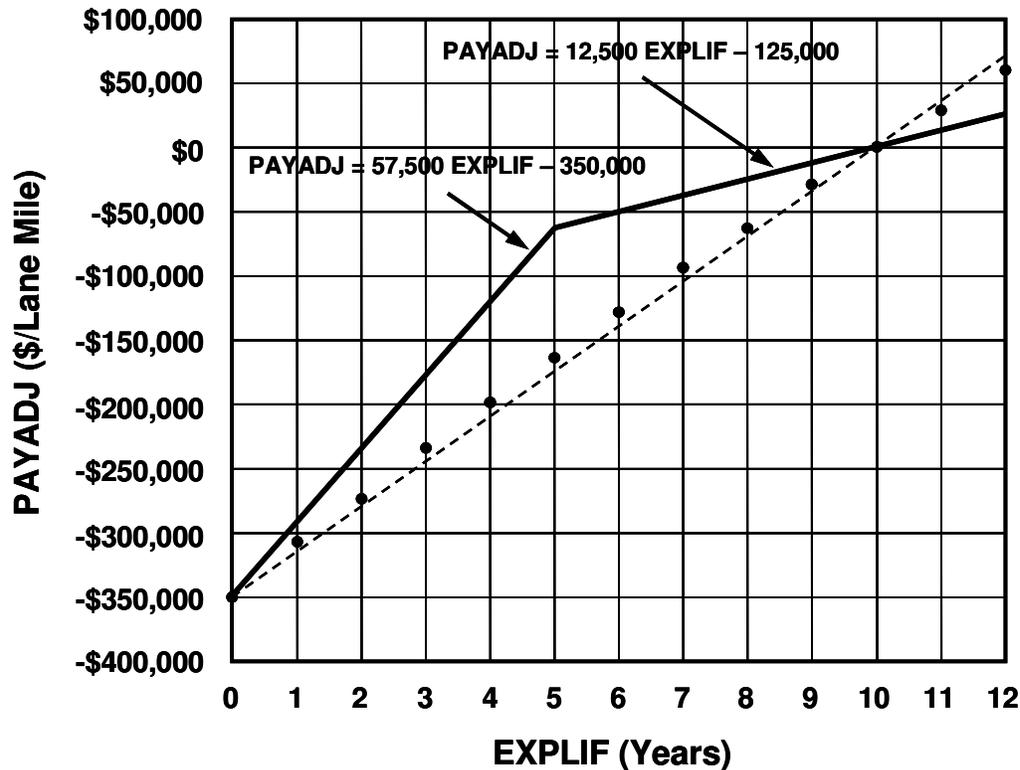


Figure A. 23. Plot of Pay Relationship vs. Pay Schedule

Although a simple linear pay schedule could be developed to match this dashed line, a more practical pay schedule is the compound linear pay schedule plotted as a solid line in Figure A.23 and described by the equations below:

For EXPLIF 5 to EXPLIF = 12:

$$\text{PAYADJ} = 12500 \text{ EXPLIF} - 125000$$

For EXPLIF < 5:

$$\text{PAYADJ} = 57500 \text{ EXPLIF} - 350000$$

Where

PAYADJ = pay adjustment (\$)

EXPLIF = expected life value (years) returned by the performance model.

Many variations of this compound linear pay schedule are considered equally workable. For the SHA, the use of a shallower slope than might be justified by the mathematical models enhances the defensibility of the method while still providing a strong incentive to the contractor to produce good quality work. For the contractor, this approach allows some degree of forgiveness for work that comes close to meeting the desired levels, which comes in exchange for smaller positive incentives for superior quality work.

By developing the approximate pay relationship given by the equations above, the SHA has simplified the acceptance process and has chosen to cap the maximum incentive at \$25,000 per lane mile of pavement. Since this analysis has been based on a total in-place cost of \$350,000 per lane mile, this amounts to a maximum incentive of about 7.1 percent.

The theoretical basis for this method justifies a linear pay relationship up to but not exceeding the slope of the data such as that shown in Figure A.23.

A.3.10 Expected Payment (EP) Curve Analysis

The pay levels indicated by any schedule, whether in equation or tabular form, do not guarantee that these are the average pay levels that will be received in the long term in actual practice. This is due to the normal variability associated with random sampling, and it may reflect an inherent bias in the pay schedule itself. The only way to be certain how a pay schedule will actually perform is to conduct an EP curve analysis, which provides the long-term average pay factor to be expected at any given level of true lot quality.

Table A. 26. Quality Index Values for Estimating Percent Within Limits

PWL	<i>n</i> = 3	<i>n</i> = 4	<i>n</i> = 6	<i>n</i> = 7	<i>n</i> = 10	<i>n</i> = 15
100	1.17	1.50	2.04	2.23	2.65	3.04
99	1.16	1.47	1.80	1.89	2.04	2.14
98	1.15	1.44	1.70	1.77	1.86	1.93
97	1.15	1.41	1.62	1.67	1.74	1.80
96	1.15	1.38	1.55	1.59	1.64	1.69
95	1.14	1.35	1.49	1.52	1.56	1.59
94	1.13	1.32	1.43	1.46	1.49	1.51
93	1.12	1.29	1.38	1.40	1.43	1.44
92	1.11	1.26	1.33	1.35	1.37	1.38
91	1.10	1.23	1.29	1.30	1.32	1.32
90	1.09	1.20	1.24	1.25	1.26	1.27
89	1.08	1.17	1.20	1.21	1.21	1.22
88	1.07	1.14	1.16	1.17	1.17	1.17
87	1.06	1.11	1.12	1.12	1.13	1.13
86	1.05	1.08	1.08	1.08	1.08	1.08
85	1.03	1.05	1.04	1.05	1.04	1.04
84	1.02	1.02	1.01	1.01	1.00	1.00
83	1.00	0.99	0.97	0.97	0.96	0.96
82	0.98	0.96	0.94	0.94	0.93	0.92
81	0.96	0.93	0.90	0.90	0.89	0.89
80	0.94	0.90	0.87	0.87	0.85	0.85
79	0.92	0.87	0.84	0.83	0.82	0.82
78	0.89	0.84	0.81	0.80	0.79	0.78
77	0.87	0.81	0.77	0.77	0.76	0.75
76	0.84	0.78	0.74	0.74	0.72	0.72
75	0.82	0.75	0.71	0.71	0.69	0.69
74	0.79	0.72	0.68	0.67	0.66	0.66
73	0.77	0.69	0.65	0.64	0.63	0.62
72	0.74	0.66	0.62	0.61	0.60	0.59
71	0.71	0.63	0.59	0.58	0.57	0.56
70	0.68	0.60	0.56	0.55	0.54	0.54
69	0.65	0.57	0.53	0.53	0.51	0.51
68	0.62	0.54	0.50	0.50	0.48	0.48
67	0.59	0.51	0.47	0.47	0.46	0.45
66	0.56	0.48	0.44	0.44	0.43	0.42
65	0.53	0.45	0.42	0.41	0.40	0.40
64	0.49	0.42	0.39	0.38	0.37	0.37
63	0.46	0.39	0.36	0.35	0.35	0.34
62	0.43	0.36	0.33	0.33	0.32	0.31
61	0.39	0.33	0.30	0.30	0.30	0.29
60	0.36	0.30	0.27	0.25	0.25	0.25
55	0.18	0.15	0.14	0.13	0.13	0.13
50	0.00	0.00	0.00	0.00	0.00	0.00

ATTACHMENT 1

Summary

1 Background

The acceptance of construction work by pay adjustment is apparently unique to the highway field and is one of its most practical innovations. Highway construction is affected by many factors such as weather, equipment, operator skill, material and construction variability, and local conditions. Because of these many variables rarely does the as-constructed quality precisely equal the level specified. When the quality level is sufficiently deficient that short-term failure or safety issues may be present, then it is clearly appropriate to reject the work outright and require remove - and - replace, or some other suitable remedy. When the quality level is only marginally deficient, such that the expected service life is only slightly diminished, experience has shown that while it is not practical to remove - and - replace the product at the time of construction, neither does such substandard work warrant full payment. Consequently, the practice of accepting marginally deficient pavement at somewhat lower than the contract price has evolved as a practical and effective solution. In more recent years, this process has evolved still further and the majority of highway agencies also offer small incentives (bonus payments) for quality that clearly exceeds the specified level.

A variety of quality characteristics have been used by the highway profession for the acceptance of pavement construction. Material properties, thickness, smoothness, and other characteristics are known to be related to the successful performance of the pavement, and various statistical measures of these items have commonly been used as the basis for pay-adjustment systems. Since variation of these items from their design values will affect pavement performance in the form of longevity and smoothness of ride, many highway agencies incorporate pay-adjustment clauses in their construction contracts to encourage excellent quality pavement and, failing that, to assess increasing amounts of pay reduction for increasing levels of deficiency. Many modern highway acceptance procedures are now of the incentive/disincentive (I/D) type that also award incentive payments above and beyond the contract price for superior quality.

Most of the approaches currently used by highway agencies for the acceptance of materials and construction by assigning pay adjustments have been developed empirically without a thorough understanding of the actual relationships between pay factor adjustments and quality. In addition, these approaches use different procedures for

determining the amount and method of pay adjustment that do not consider some relevant issues, such as highway functional classification, constructability, defining appropriate acceptable quality level (AQL) and rejectable quality level (RQL) values, combining multiple pay factors, impacts on the highway users, contractor/agency risk sharing, contractor motivation, and legal ramifications. Further improvement is needed to develop rational guidelines for determining scientifically sound, quantitative relationships between quality received and expected performance, which will not only be fair and effective for both highway agencies and the construction industry but will also be capable of withstanding legal challenge if it should occur.

There are several important decisions that must be made when developing highway construction payment relationships (Burati et al 2003), including:

- selection by the SHA of those quality characteristics believed most closely associated with the performance of the finished product,
- establishment of the acceptable quality levels (AQLs) of those characteristics that will result in the desired performance, and clearly conveying this in the specifications,
- determination of the capability of the construction industry to meet the desired acceptance requirements without the use of extraordinary quality control procedures,
- availability of valid and reliable sampling and testing methods and procedures to accurately determine the quality received, and
- development of a fair and defensible pay schedule to award incentives and assess disincentives that are reasonably commensurate with the expected gains or losses expected from the quality levels received.

Experience with the development of quality assurance (QA) acceptance plans has shown that payment relationships are one of the most important factors from a contractor's perspective. Thus, it becomes incumbent upon the highway agency to take the necessary steps to assure that the pay relationships are fair and equitable to all parties, and thus will be defensible if challenged.

Methods to develop rational and defensible pay adjustment factors have long been sought, and one of the earliest investigations is detailed in a 1977 report (Willenbrock et al 1977). About 15 years later this work was carried further (Afferton et al 1992).

Considerable additional progress has been made since these earlier efforts, much of it reported through publications of the Transportation Research Board (TRB) and project reports for Federal Highway Administration (FHWA)-sponsored research.

As a general rule, the more rational the pay adjustment procedure, the more the likelihood that it will be accepted by both SHA and contractor agencies and the more legally defensible it will be.

1.1 Objective

The objective of this research is to develop guidelines for determining quality-related pay adjustment factors for flexible and rigid pavements.

1.2 Scope

TASKS: Accomplishment of this objective will require the following tasks.

Phase I

Task 1. Collect and review information relevant to quality-related pay adjustment factors. This information may be obtained from a literature review; a survey of highway agencies, industry, and other organizations; and other sources.

Task 2. Based on the information gathered in Task 1, categorize and evaluate the different processes used for determining quality-related pay adjustment factors. Identify processes that merit further consideration or improvement for use in the guidelines that will be developed in Task 5.

Task 3. Prepare an updated, detailed work plan for Phase II, to develop guidelines for determining quality-related pay adjustment factors for flexible and rigid pavements.

Task 4. Prepare an interim report that documents the research performed in Tasks 1 and 2 and includes the updated work plan for Phase II. Following review of the interim

report by the NCHRP, the research team will be required to make a presentation to the project panel. Work on Phase II of the project will not begin until the interim report is approved and the Phase II work plan is authorized by the NCHRP.

PHASE II (will be considered after completion of Phase I):

Task 5. Execute the Phase II plan approved in Task 4. Based on the results of this work, develop the guidelines for determining quality-related pay adjustment factors for flexible and rigid pavements.

Task 6. Using the guidelines developed in Task 5; prepare examples to illustrate use of the guidelines for different pavement types, highway functional classes, and quality measure types and combinations.

Task 7. Submit a final report that documents the entire research effort. The guidelines shall be prepared as a stand-alone document suitable for consideration and adoption by AASHTO; the examples shall be presented as an appendix.

1.3 Philosophy

The literature review revealed several programs and documents that address quality-related pay adjustment factors.

There are existing programs such as HMASPEC (Epps 2002, Hand 2004), PAVESPEC (Hoerner 2000), and the procedures developed under NCHRP 9-22 “A Performance-Related Specification for Hot-Mixed Asphalt (NCHRP 704, 2011) that contain pay adjustment procedures considered to be embryonic versions of quality/performance related specifications. Others, such as some of the NJDOT developments, are based on mathematical models of expected performance combined with a life-cycle-cost model derived specifically for this purpose (Chamberlain 1995, Weed 2001). However, the current state-of-the-practice covers a broad spectrum of procedures ranging from the use of acceptance quality characteristics (AQC) that are easy to measure but less strongly related to quality, to those that are considered to be more strongly performance related but less easy to implement.

The philosophy adopted in developing the guidelines should be quality-related and have the potential of being immediately implementable as a recommended practice. Furthermore, they should have sufficient flexibility to allow the transition from present consensus practices to those considered to be performance-related. Thus, the individual ingredients in the programs are key components as to their consideration and evaluation and should be related to pay adjustments and not design criteria. The research relied heavily on existing AASHTO Recommended Standards that are related to QA (AASHTO R-9, R-10, and R-42).

1.4 Description of the Work Performed Including Process, Criteria, and Rationale

The project began by conducting an international literature review on the topic of quality-related pay adjustment factors combined with a survey of SHAs, AASHTO, industry, colleagues, and other printed sources of information such as presentations not published in texts, journals, or other sources.

When this information gathering was complete and analyzed, it was obvious that little work had been done in this area and that the guidelines would need to be developed on the basis of current practice and the expertise of the research team. Data used in the guidelines were extracted from several sources. Among these were the survey and references cited in this report and SHA specifications. Also used were personal experiences of the research team in conducting studies including the development of SpecRisk, publishing papers, conducting training with SHAs throughout the country, and interacting with SHAs on a personal level. The use of these sources became the process by which the guidelines were formulated.

The overriding principal involved in developing the criteria and rationale behind the guidelines was that that they were more likely to be accepted for implementation if they were simple to understand, related to performance with the tools currently available, and defensible.

Using all the tools described above, the research team evaluated the state-of-the-practice in this area by categorizing, evaluating, and eliminating, if needed, a host of approaches currently being used. In this respect, the team found the currently used

processes workable and understandable and did not explore any untried or untested procedures.

The study concluded with recommendations to SHAs that when adopting or implementing quality-related pay adjustment factors, they should seriously consider the use of the Percent Within Limits approach, evaluate the risks associated with the selected parameters, and provide an incentive to the contractor for acceptable work and a disincentive when less than acceptable work is provided.

It was never in the scope of this project to actually construct trial projects, apply the guidelines, and modify them if necessary based on the results of the trials. Actually, this has been accomplished by several SHAs in the past.

References:

AASHTO Standard Recommended Practice R-9 *Acceptance Sampling Plans for Highway Construction*, American Association of State Highway and Transportation Officials, Washington, DC, 2005.

AASHTO Standard Recommended Practice R -10 *Definition of Terms Related to Quality and Statistics As Used in Highway Construction*, American Association of State Highway and Transportation Officials, Washington, DC, 2006.

AASHTO Standard Recommended Practice R-42 *Development of a Quality Assurance (QA) Plan for Hot Mix Asphalt*, American Association of State Highway and Transportation Officials, Washington, DC, 2006.

Afferton, Kenneth C., Jack Freidenrich, and Richard M. Weed, *Managing Quality: Time for a National Policy*, Transportation Research Record 1340, Washington D. C., 1995, pp. 3-39.

Burati, J.L., Weed, R.M., Hughes, C.S., and Hill, H.S., *Optimal Procedures for Quality Assurance Specifications*, Office of Research, Development, and Technology, Report FHWA-RD-02-095, FHWA McLean VA, June 2003, 347pp.

Burati, J.L. and Weed, R.M., "Estimating Percent Within Limits for Skewed Populations," Transportation Research Record 1946, Journal of the Transportation Research Board, Washington, D.C., 2006

Chamberlin, William P., *Performance-Related Specifications for Highway Construction and Rehabilitation*, NCHRP Synthesis 212, Transportation Research Board, Washington, DC, 1995, 48 pp.

Epps, J. A., A.J. Hand, S. Seeds, T. Schotz, S. Alavi, C. Ashmore, C. L. Monismith, J. A. Deacon, J.T. Harvey, R. Leahy, *Recommended Performance-Related Specification for Hot-Mix asphalt Construction: Results of WesTrack Project, NCHRP Report No. 455*, Transportation Research Board, 2002.

Hand, A J, Martin A E, Sebaaly, P E, Weitzel, D, *Evaluating Field Performance: Case Study Including Hot Mix Asphalt Performance-Related Specifications*, Journal of Transportation Engineering Vol 130 No. 2, ASCE, April 2004.

Hoerner T E, Darter M I, Khazanovich L, Titus-Glover, Smith K L, *Improved Prediction Models for PCC Pavement Performance-Related Specifications*, Volume II: Pave Spec 3.0 User's Guide, FHWA, September 2000.

Hoerner T E, Darter M I, *Improved Prediction Models for PCC Pavement Performance-Related Specifications*, Volume I: Final Report, FHWA, September 2000

NCHRP Report 704, *A Performance Related Specification for Hot-Mixed Asphalt*, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC 2011.

Willenbrock, Jack H. and Peter A. Kopac, *Development of Price-Adjustment Systems for Statistically Based Highway Construction Specifications*, Transportation Research Record 652, Transportation Research Board, Washington, DC, 1977, pg 52-58.

R. M. Weed, *Derivation of Equation for Cost of Premature Pavement Failure*, Transportation Research Record 1761, TRB, National Research Council, Washington, DC, 2001, pages 93 – 96
2001

Attachment 2

Research Approach

1 Literature Review

1.1 Conduct of Literature Search

The research team completed an extensive national and international literature review that captured and documented both national and international approaches and processes for pay adjustment factors for flexible and rigid pavements. The literature review included a search of the Transportation Research Information Service (TRIS) and many other pertinent sources. Since nearly all work of this nature has been done in the highway field, particular attention was paid to the Transportation Research Record series, NCHRP Syntheses, and FHWA contracts on this subject as well as other reports related to this study. A list of the literature cited and reviewed is included under References. Executive Summaries of the literature most pertinent to this study are detailed in Appendix B.

Contacts were made with highway agencies in Australia, New Zealand, Europe, and South America. Literature reviews of European practices relevant to the use of pay adjustment factors revealed that the subject has been considered but has not been pursued. No European country was found that has implemented pay adjustment factors. Similarly, New Zealand's perspective towards this subject suggests that preliminary work has been conducted but pay adjustment factors have neither been finalized nor implemented. South American contacts also provided information that this practice is not yet used in the region but interest in using it is clearly significant. Contacts found that some Canadian provinces (e.g., Ontario) have pay adjustments systems that are similar to those used in the U.S. The similarity is such that the Canadian concepts are well covered in the responses that the U. S. transportation agencies made to the questionnaire responses.

1.2 Summary of Literature Review

The search identified current procedures some of which were found to be quite complex and typically use sophisticated software to apply what are largely proprietary techniques of analysis. These appear to be scientifically based and are very close to the definition of a true performance related specification (PRS) (AASHTO R-10). However, they do present a challenge to analyze because of the complexity and less-than-transparent nature of the software.

Other procedures were found to be of lesser degrees of complexity and greater degrees of transparency that still appear to satisfy the basic requirements of the PRS definition and warranted further investigation. Finally, there were still other procedures that might be described as “experienced-based practices” that do not satisfy the PRS definition, but which appear to be functioning well and which agencies might wish to modify as a first step toward a true PRS. These latter two categories were those on which this study focused.

2 Survey of Highway Agencies

The survey questionnaire was sent electronically to state highway agencies (SHAs) to elicit information concerning their pay adjustment schedule practices. Responses were received from 37 agencies. An overall summary is included in Appendix C and the highlights are listed below.

2.1 Summary of Survey

A brief highlight of important conclusions of the overall survey summary is presented here:

General

- Pay adjustment factors are further developed and used more often for flexible pavements than for rigid pavements.
- The AQCs used vary appreciably among agencies for flexible pavements and, to a lesser extent, for rigid pavements.
- Many agencies (16 out of 37 responses) use weighted composite pay factor equations. However, the weights and AQCs vary considerably.

2.1.1 Flexible Pavements

- The type of pay adjustment factors are nearly equally divided between stepped (tabular) and equations (continuous). Both of these types vary appreciably among agencies.
- Ride quality is a separate AQC from materials/construction for 27 agencies.
- Percent Within Limits (PWL) is the single most often used quality measure (used by 16 agencies for one or more AQCs), with the exception of Ride Quality where the average is the quality measure used by 13 agencies.

- Most (31) agencies have maximum incentives, ranging from 1% to 15% (15% is used for only Ride Quality).
- The most commonly used maximum incentive is 5%.
- Most (27) agencies have maximum disincentives; 23 use a remove-and-replace provision and five use a shutdown provision. Agencies use several different triggers for applying a combination of a maximum disincentive, a shut down provision, and/or a remove-and-replace clause.
- A clear majority (26) of agencies pay actual incentives for superior quality levels of the various AQC's. A minority (9) uses them only to offset disincentives (i.e., no incentive is paid but it is allowed to offset the disincentive).
- Two agencies use different weights and acceptance quality characteristics depending on highway classification; e.g., lower classification roads may not include a measure of density.

2.1.2 Rigid Pavements

- Strength, thickness, and Ride Quality are the three most often used AQC's. There is little consensus on how these and others are used.
- Stepped pay adjustments are used more often than an equation. For instance, thickness is the most often used AQC (used by 26 agencies) and of these a stepped pay adjustment is used by 18; an equation used by six.
- There is little consensus on how individual pay adjustment factors are combined.
- Only one agency reported on the use of a composite weighted pay adjustment equation.
- Percent Within Limits (PWL) and the average are the most often used quality measures. Again, using thickness as the AQC as an example, 11 agencies use the average and four (4) use PWL.
- A clear majority (21) pay actual incentives for superior quality pavement. Very few (3) use them only to offset disincentives.
- Several (13) agencies have maximum incentives, ranging from 3% to 15% (15% is used for only Ride Quality).
- The most commonly used maximum incentive is 5% for rigid pavements.
- Twenty-one have maximum disincentives. Fifteen use a remove - and - replace provision (remove - and - replace) and two (2) use a shutdown procedure.

3 Categorization and Evaluation of Quality-Related Pay Factors

3.1 Categorization of Quality-Related Pay Factor Methods.

Based on the review of the literature and the questionnaire responses, the potential candidate methods were divided into three logical categories of quality relationships, as follows:

3.1.1 Complex (Engineering-Based) Methods

There were three recently developed methods found in the literature and described below that are complex and use sophisticated software to apply what are largely proprietary techniques of analysis. The approach used in these methods is based on PRS that require AQC's to be identified that can be correlated to fundamental engineering properties that predict pavement performance.

These are methods that have been developed using appropriate engineering and mathematical principles applied to recent, peer-reviewed research. They typically include performance relationships based on mechanistic design (or other suitable pavement design theory), and use valid, established cost-evaluation procedures such as life cycle cost (LCC) analysis. These methods should have the greatest potential for accuracy and precision, but they also tend to be correspondingly complex.

The three methods are:

- For rigid pavements, the PAVE Spec software was developed under the FHWA research study "Validation of Performance Models for Portland Cement Concrete Pavement Construction" to test this concept (Hoerner 2000). Well over 100 user inputs are required to obtain results for this procedure.
- For flexible pavements, the HMA Spec software was developed under Project NCHRP 9-20, "Performance Related Specification for Hot-Mix Asphalt Construction." (Epps 2002, Hand 2004). Similar to PAVE Spec, this software requires approximately 100 user inputs to operate this procedure.
- Also for flexible pavements, the evaluation project for HMA Spec software, "Beta Test and Validation of HMA PRS", has recently been completed. It included the recently released software "Quality Related Specification Software (QRSS)", incorporating the performance prediction models of the new Mechanistic-Empirical Pavement Design Guide (MEPDG) models (Moulthrop and Witzak 2010). These software products are still in the evaluation phase and appear to be scientifically based and closer to the definition of true performance-related specifications.

3.1.2 Empirical-Based Methods

There were two methods, one for flexible pavements (NJDOT HMA Empirical PRS Specification) (Weed 2006) and one for rigid pavements (NJDOT PCC Empirical PRS Specification) (Weed 1999), which generally use the same underlying engineering and mathematical principles as the complex engineering-based methods, but unlike the latter, are based on empirical data obtained from highway agency experience rather than the results of scientific research. They are simpler by nature, and therefore may be less precise, but they offer greater ease of implementation than the complex methods.

3.1.3 Experience-based Methods

There are other methods that might be described as “experienced-based” that appear to be functioning well for highway agencies and contractors. These are compatible with AASHTO R-9 Standard Recommended Practice for *Acceptance Sampling Plans for Highway Construction* and AASHTO R-42 Standard Recommended Practice *Development of a Quality Assurance (QA) Plan for Hot Mix Asphalt*. These methods usually are not formally derived from either engineering or mathematical principles. They do not consider predicting the future pavement performance, but compute pay factors based on a consensus approach to the manner and extent to which AQC's influence pavement performance. This general approach has been in use for several years and appears to be workable and effective.

4 Evaluation of Quality-Related Pay Factors

4.1 Reasons for Eliminating Complex Procedures as Candidate Procedures

In the simplest terms, a procedure or method is judged to be practical if it is focused on ease of accomplishment and the usefulness of the end result. Because of the complexity of the software and the number of inputs necessary to run the “Pave Spec”, “HMA Spec”, and “QRSS” programs, it was considered that the immediate implementation of these programs was improbable. Thus, they did not seem to be ready to be considered for potential adoption as an AASHTO Standard Recommended Practice. Furthermore, to implement complex procedures such as these would almost certainly require additional training of agency staff, or the hiring of outside consultant services, at a time when both budgets and manpower are scarce and likely to remain so for the foreseeable future. In addition, these procedures do not appear to lend themselves to a partial or gradual implementation but, instead, would require a major initial commitment. Another potentially serious question, that apparently has never been definitively answered, is the degree to which error in the many (often over 100) input variables might

affect the error in the output. Thus, verification of the programs would be difficult and time consuming.

The elimination of these programs from additional study in this project is in no way intended to imply that these and other complex procedures should not be considered for further development and verification in the future. However, the research team did not consider them to be easily implemented, meeting the requirement of one task of this study and, thus, to be an efficient use of the resources in the present study.

4.2 Reason for Eliminating Empirical PCC Candidate Procedure

The empirical method described above, an early NJDOT PCC Pavement Specification for PCC pavements (a precursor to the Empirical method for flexible pavements), was noted to have historical interest, but is not sufficiently developed to be included among the final candidates for this study as an Experienced-Based Practice.

4.3 Procedures Evaluated

Eliminating the programs mentioned above left three procedures to be evaluated, “Recommended Practices for Flexible Pavements”, “Recommended Practices for Rigid Pavements”, and the “Empirical PRS Method for Flexible Pavements”.

4.3.1 Recommended Practices for Flexible Pavements

This procedure uses proven statistically valid methods, even though a consensus has not been reached on either the individual AQC's nor the weights assigned to them. The procedure is based on experience and generally does not include a bona fide model, or pay schedules based on any specific economic analysis. The procedure, as adapted here, uses engineering judgment coupled with experience to create the next generation of quality-related pay factor adjustments.

4.3.2 Recommended Practices for Rigid Pavements

This procedure is similar to that for flexible pavements only the details differ. It uses proven statistically valid methods, even though a consensus has not been reached on either the individual AQC's nor the weights assigned to them. The procedure is based on experience and generally does not include a bona fide model, or pay schedules based on any specific economic analysis. The procedure, as adapted here, uses engineering judgment coupled with experience to create the next generation of quality-related pay factor adjustments.

4.3.3 Empirical PRS Method for Flexible Pavements

This method, which has been referred to as the “Expected-Life” method in the User’s Manual for the SpecRisk specification analysis software, bases payment on the expected performance (service life) of the as-constructed pavement (SpecRisk User’s Manual 2008). On the premise that intrinsic load-bearing capacity is strongly tied to expected service life and resultant economic value, this method is believed to provide justification for effective and defensible adjusted-payment schedules. Subsequently, this method was renamed the Empirical PRS Method in the TRB Glossary of Highway Quality Assurance Terms (Glossary of Highway Quality Assurance Terms 2009).

5 Conclusions and Recommendations

5.1 Conclusions

There are several important decisions that must be made concerning quality-related pay adjustment factors. Experience with developing quality assurance (QA) acceptance plans has shown that payment relationships are one of the most important factors from a contractor’s perspective. Thus, it is essential that the relationship be viewed as being fair to both the contractor and the SHA and reasonable and achievable. The following conclusions are drawn from this study.

- Quality-related pay adjustment factors for pavements are used extensively in the United States and Canada. They are not presently being used in Europe, South America, New Zealand, or Australia.
- Where used, these procedures continue to evolve and have gained wide-spread acceptance as some of the most practical procedures for dealing with highway construction.
- The quality-related pay adjustment factors in use vary in the AQC’s that are used and the manner and magnitude in which they are applied.
- Many agencies have not defined either AQL or RQL in their specifications. Of those that have, AQL is used more often than RQL.
- There are several issues related specifically to the AQL:
 - The SHA should give consideration to the level of quality required to achieve the desired performance.
 - The job specifications must describe the level of quality required, and the pay schedule should pay an average of 100 percent in the long term when that level of quality is delivered.

- There are also several issues related specifically to the RQL.
 - RQL provisions can enhance the SHA's protection against accepting deficient quality.
 - The option of requiring remove and replace at the contractor's expense requires care on the part of the SHA to make sure that the level selected as the RQL warrants such consequences.
 - It was found that some agencies use retest provisions to confirm poor results before enforcing a remove and replace provision.
- Because of the economic consequences when deficient work is discovered, the pay schedule should have a sound basis that is defensible.
- PWL is the most used quality measure (QM) in North America.
- Composite pay factors are used by many SHAs.
- Ride Quality is typically included as a separate AQC from other material and construction AQCs in specifications; however it can be incorporated with other AQCs if desired.
- The use of both incentive and disincentive pay adjustment factors are commonplace within SHA acceptance plans.
- There are several levels of sophistication contained in procedures that use quality-related pay adjustment factors.
 - The highest level of sophistication is engineering-based methods which often require specialized and proprietary software. These do not appear to be ready for immediate implementation.
 - The next level of sophistication is empirical-based methods that use the same underlying engineering and mathematical principles but are more tailored to local data and experience.
 - Intuitive methods that are not derived from either engineering or mathematical principles, but which appear to have performed successfully for many years and may be adaptable for the development of quality-related procedures are the least sophisticated but allow the greatest opportunity for immediate implementation. .
- The natural evolution of guidelines for the development of quality-related pay adjustment factors has made considerable progress since the 1980s, with even greater acceleration in recent years.
- While stepped pay schedules can be constructed to perform satisfactorily, continuous (equation-type) pay schedules have certain desirable advantages as explained in the guidelines.

- Very little information was found related to use of quality-related pay adjustment factors in terms of functional classification.

5.2 Recommendations

There are several recommendations that emanate from this study. Depending upon the current level of quality consciousness of the SHA, they may offer the opportunity to realize economic benefits from a general upgrading of methods and procedures. The following steps will help to determine if this is the case:

- SHA's that have not adopted the Percent Within approach should be encouraged to do so.
- Choose the AQCs that are considered to be best related to performance. Use only the number of AQCs considered necessary to define the desired product.
 - For Flexible pavement materials, these are asphalt content, lab compacted air voids, voids in the mineral aggregate, and two sieve sizes. For flexible pavement construction, these are, density, thickness, and Ride Quality.
 - For Rigid pavements, these are compressive strength, thickness, and Ride Quality.
- Establish both AQL and RQL values. It is recommended the AQL be set at PWL= 90 for flexible and rigid pavements (AASHTO R-9 2008). No RQL value is recommended and each SHA should establish its own value after conducting a risk analysis.
- Conduct a risk analysis of the acceptance plan before it is implemented. Recently developed software (*Analysis of Risks in Percent Within Limits and Percent Defective Acceptance Plans and Specifications 2008*) is a useful tool for this analysis.
- To fairly compensate the contractor when producing product at the AQL, specifications must contain an incentive provision.
- If SHAs choose to use functional class as the determinate of whether to use quality-related pay adjustment factors, quality-related pay adjustment factors may be used on Interstate, principal urban and rural arterials, and major collectors; whereas method specifications may be used on rural secondary, ramps, and facilities with geometric issues that may place a burden on contractors.

References

AASHTO Standard Recommended Practice R-9 *Acceptance Sampling Plans for Highway Construction*, American Association of State Highway and Transportation Officials, Washington, DC, 2005.

AASHTO Standard Recommended Practice R -10 *Definition of Terms Related to Quality and Statistics As Used in Highway Construction*, American Association of State Highway and Transportation Officials, Washington, DC, 2006.

AASHTO Standard Recommended Practice R-42 *Development of a Quality Assurance (QA) Plan for Hot Mix Asphalt*, American Association of State Highway and Transportation Officials, Washington, DC, 2006.

Epps, J. A., A.J. Hand, S. Seeds, T. Schotz, S. Alavi, C. Ashmore, C. L. Monismith, J. A. Deacon, J.T. Harvey, R. Leahy, *Recommended Performance-Related Specification for Hot-Mix asphalt Construction: Results of WesTrack Project, NCHRP Report No. 455*, Transportation Research Board, 2002.

Fugro Consultants, Inc., Arizona State University, *A Performance Related Specification for Hot-Mixed Asphalt, NCHRP Report 704*, Transportation Research Board, 2011.

Hand, A J, Martin A E, Sebaaly, P E, Weitzel, D, *Evaluating Field Performance: Case Study Including Hot Mix Asphalt Performance-Related Specifications*, Journal of Transportation Engineering Vol 130 No. 2, ASCE, April 2004.

Hoerner T E, Darter M I, Khazanovich L, Titus-Glover, Smith K L, *Improved Prediction Models for PCC Pavement Performance-Related Specifications*, Volume II: Pave Spec 3.0 User's Guide, FHWA, September 2000.

Hoerner T E, Darter M I, *Improved Prediction Models for PCC Pavement Performance-Related Specifications*, Volume I: Final Report, FHWA, September 2000

Weed, R. M., *Practical Framework for Performance-Related Specifications*, Transportation Research Record 1654, Transportation Research Board, Washington, D.C., 1999.

Transportation Research Record 1712, Transportation Research Board, Washington, D.C., 2000

Weed, R. M., *Mathematical Modeling Procedures for Performance Related Specifications*, Transportation Research Record 1946, TRB, National Research Council, Washington, DC, 2006, pages 63 – 70.

Appendix A

Literature Review - Executive Summaries

I. NCHRP 9-22 Beta Test and Validation of HMA PRS

Executive Summary

The recently completed NCHRP 9-22 research project conducted by Fugro and Arizona State University is considered a true first step to integrate asphalt mix design and pavement structural design in the same methodology. It is based on the integration of the Mechanistic-Empirical Performance Design Guide (MEPDG) (NCHRP 1-37A and NCHRP 1-40) with the Simple Performance Test (NCHRP 9-19) to develop a probabilistic Quality Specification for Quality Assurance of HMA Construction (QRSS).

The methodology is based on relating the HMA dynamic modulus, through a closed form solution (CFS), for the three major pavement distresses of permanent deformation, fatigue cracking and thermal cracking. This CFS, developed based on MEPDG 1.0, predicts the distress at the end of design life. A probabilistic simulation using the dynamic modulus in conjunction with the CFS is done to determine the variability of the distress prediction due to the variability in the material used in the mix design as well as in constructing the pavement sections. A Monte-Carlo simulation is run using the project mix design to predict the as-designed distress and its associated variability. The as-designed distress is then used to predict the remaining service life of the pavement. Similarly, a Monte-Carlo simulation is run on the as-built material to estimate the mean and variance of the predicted distress. The mean and variance of the remaining service life of the pavement are then estimated from the predicted distress. The normal distribution is used for rutting; while, the beta distribution is used for the fatigue cracking because cracking has a minimum of zero and a maximum value of 100%. Similarly, thermal cracking uses a beta distribution as the distress has a minimum of zero and a maximum of 2112 ft / mile.

This approach is considered the first step to relate quality of construction to the performance of pavement over the life of the pavement. A validation study, using actual pavement construction section and QA data, in different states is currently underway to assess the initial validity of the methodology and its suitability for use by different SHAs.

II. HMA Spec – Performance Related Specification- Method of Pay Adjustment

Executive Summary

HMA Spec is a performance related specification (PRS) method of pay adjustment that is based on the difference in the predicted life cycle cost of the as-designed pavement compared to the as-constructed pavement. The means and standard deviations for the HMA acceptance quality characteristics of layer thickness, initial smoothness, asphalt content, air void, and aggregate gradation parameters are used for pay factor relationship development. Pavement performance prediction models are developed for fatigue, rutting and international Roughness Index (IRI). The PRS allows two levels of performance prediction relationships, where the Level 1 pavement performance prediction relationship is empirical in nature based on regression analysis of material, traffic, and performance data from the WesTrack project. The Level 2 pavement performance prediction relationship is mechanistic- empirical based and includes the laboratory tests and layered elastic analysis calibrated to the WesTrack performance data.

Using the HMA spec, the pay factor relationship (PFR), which is a function of the deviation of the actual acceptance quality characteristics (AQC) from its target mean is developed for the selected AQCs, to determine the mean life cycle cost (LCC) of the as-designed pavement. It also estimates the pay adjustments for a simulated distribution of as-constructed pavements. Using HMA Spec software, the Agency is free to develop its own PFR through statistical analysis of the results of the Monte Carlo simulations for an individual distress or for a combination of distress. Based on the predicted distress, a decision tree selects the rehabilitation and the associated cost of the treatment. The cost of treatment is based on the type of treatment, quantity, unit cost of treatment and the year of service. A “z”-value is calculated for each AQC and its combination to determine whether the as-constructed AQC is above or below the as-designed target.

Through multiple regression analysis, a statistically valid relationship for pay factor using the z-terms of each AQC is generated. The methodology employed in HMA spec to perform the analysis involves the use of a general linear model (GLM). Analysis of Variance (ANOVA) is used to identify specific terms in the PF equation that explains the variability observed in the PF-z data combinations. Two approaches of sensitivity analysis discussed were first, to create pay factor tables using the regression coefficients of each AQC term and secondly to prepare charts or nomographs that graphically relate the effect of the AQCs to the estimated pay factor. Using the as-constructed means and standard deviations of each AQC distribution, the mean LCC of the as-constructed pavement is estimated. Pay adjustment and pay factor obtained for the as-constructed pavement is prorated for each lot size.

Confidence level is obtained by comparing the mean LCC of the as-constructed against the as-designed. If there is a significant difference between the two, a pay adjustment is assessed. In this process, significance is established using the z-test. Confidence level determines the upper and lower limits of the mean and standard deviation of the LCC of the as-designed pavement. The agency and the contractor mutually agree the percent of confidence. A “leeway” zone where there is no incentive/ disincentive was considered necessary, as this was required when the mean of the as-constructed LCC deviates significantly from the as-designed. Upper and lower limits of the Pay Factor are defined based on the maximum amount of incentive allowed and the minimum quality that does not require the remove - and - replace of the lot. The final contractor lot payment will be a product of the bid price with the pay factor and corresponding lot size.

III. PAVE Spec – Pavement Performance Related Specification

Executive Summary

PAVE Spec software was developed to determine the pay adjustment in Portland Cement Concrete (PCC) pavement construction based on a pavement performance related specification (PRS). It is based on the concept of comparing the as-designed life cycle cost with the as-constructed life cycle cost to determine the amount of pay adjustment. The key acceptance quality characteristics (AQC) that are found to be sensitive in PCC acceptance testing are air voids, slab thickness, initial smoothness, concrete strength, consolidation near dowel bars, and air voids. In this PRS approach, the predicted pavement performance is a function of both the AQC means and standard deviations, which is an improvement over a traditional QA specification where typically only the mean or a percentage within limits that does not correlate well with performance were specified. Agencies are also required to define their desired quality in terms of AQC means and standard deviations, which should reflect the level of quality for which the agency is willing to pay 100 percent. Performance prediction models were developed for transverse joint faulting, transverse joint spalling, transverse fatigue cracking, and International Roughness Index (IRI). Based on the predicted performance, the maintenance and rehabilitation strategies were selected and the life cycle cost was determined based on the selected treatment.

At different AQC mean values, expected pay curves were developed that illustrates the probability that the computed pay factor will be greater than or equal to a corresponding pay factor acceptance value. The sensitivity analysis to determine the effect of AQC mean and standard deviation changes on pay factors and pay adjustments can be performed. The composite pay adjustment can be obtained using five (5) different ways of simple average, weighted average, product, minimum and maximum. The difference in the life cycle cost of the as-designed and as-constructed values is computed for each lot for pay adjustment.

In the PCC construction projects where this specification was applied, it achieved values higher than the target AQC's. It has proven to be successful when implemented in all the trial PCC construction projects.

IV. NCHRP Synthesis 346- Quality Assurance Programs for Hot-Mix Asphalt

Executive Summary

NCHRP Synthesis 346 summarizes the wide range of methods and procedures that agencies use to ensure construction quality. A higher rate of response to the HMA quality assurance (QA) program questionnaire indicates that the QA program for HMA has been developed and in use for more agencies compared to any other construction materials. Although the QA programs currently being used by the agencies varies greatly, the basis of all the QA programs are the three components of 1) HMA quality attributes, 2) verification process and 3) pay system and the method of combining pay factors associated with each HMA quality attributes.

Compaction, asphalt content, Ride Quality, gradation, voids total mix, voids in mineral aggregate, aggregate fractured faces, thickness, and voids filled with asphalt are the commonly used quality attributes of HMA used in the QA/QC program of state agencies. In this, the quality attribute of compaction and asphalt content is mostly used in the QA program and aggregate gradation and asphalt content dominates in the QC program. The verification process for quality assurance that is mostly used and noted in the survey is one agency test compared to several contractor tests of a lot. Only three (3) agencies were reported to use the complete project comparison. The statistical method mostly applied for verification was the combination of F-test and t-test. Independent and split samples are both used. The quality measure for acceptance that is identified to be common is the percent within limits (PWL), average, and range, with PWL being the one mostly used. The pay systems that are identified to be mostly used by the agencies are pay adjustment system, stepped pay schedule, equations and accept/reject acceptance plan, and less common is the accept/ reject acceptance plan.

V. Weed, R. M. "Equitable Graduated Pay Schedules: An Economic Approach" Transportation Research Record 691, Transportation Research Board, Washington, D.C., 1978.

Executive Summary

The author in this paper introduces an example in which concrete pavement is evaluated in terms of compressive strength. The approach introduced consists of determining the present worth of the extra expense anticipated in the future as a result of work of deficient quality. An appropriate pay schedule is developed on the premise that it would be justifiable to withhold this

amount from the contract price. The method is applicable in the case of construction items for which data are available that relate quality to performance. An example is given in which an AASHTO nomograph is used to determine the ratio of as-built load-carrying capacity to design load capacity, making it possible to estimate expected life. From this, an appropriate level of pay adjustment can be determined. By using such a nomograph, it would also be possible to develop a pay schedule based on pavement thickness and, in fact, these two parameters of quality (strength and thickness) could be used jointly.

VI. Weed, R. M. "Unbiased Graduated Pay Schedules," Transportation Research Record 745, Transportation Research Board, Washington, D.C., 1980.

Executive Summary

Many existing pay schedules do not pay 100 percent when the work is exactly at the acceptable quality level (AQL) and this can impose a severe hardship on contractors. The statistical quality measure on which they are based is an unbiased estimator of the true quality level of the population but, because the highest level in the pay table is 100 percent, the average pay factor will be biased downward, which typically pays the contractor less than 100 percent for truly acceptable quality. This creates problems in many instances but can be overcome by developing unbiased continuous and stepped pay schedules that are linear functions of the estimate of the population quality measure. These pay factors can be used to establish credit that may be applied to offset lower pay factors within specified time intervals throughout a construction project. It is not the same (nor as effective) as an incentive provision because the overall pay factor for each time period is still limited to 100 percent. The author presents tables for estimating PD, and both continuous and stepped pay schedules based on unbiased pay schedules are also described. Operating characteristics curves and optimization curves are also presented to compare these approaches and assess their effect on bidding strategies. A properly designed acceptance procedure will be fair to the construction industry, and will encourage contractors to perform at or just above the AQL.

VII. Weed, R. M. "Method to Establish Pay Schedules for Rigid Pavement," Transportation Research Record 885, Transportation Research Board, Washington, D.C., 1982.

Executive Summary

This paper presents an early prototype of a procedure based on a performance estimate combined with a life-cycle cost analysis to calculate the appropriate pay adjustment as a function of expected life of a pavement. A performance ratio is obtained using both as-built and design values of pavement design parameters with the AASHTO Design Procedure to develop a ratio of as-built load capacity to design loading. This can then be multiplied by design life to estimate the

expected life of the pavement, which is then combined with a life-cycle cost (LCC) analysis to determine a defensible pay adjustment.

VIII. Weed, R. M. "Development of Multi-Characteristic Acceptance Procedures for Rigid Pavement," Transportation Research Record 885, Transportation Research Board, Washington, D.C., 1982.

Executive Summary

This paper is a further development and application of the methodology described in reference VII. A much improved derivation and presentation of the LCC analysis method was published in 2001 and is described in reference XVI below.

IX. Weed, R. M. "Adjusted Pay Schedules: New Concepts and Provisions," Transportation Research Record 986, Transportation Research Board, Washington, D.C., 1984.

Executive Summary

Pay schedules may be of two types, stepped or continuous. Stepped pay defines discrete intervals for the quality characteristic and assigns a specific pay factor for each interval. Continuous pay schedules employ an equation to compute the appropriate pay factor for any given quality level given as:

$$PF = 105 - 0.5 PD$$

Where

PF = Pay Factor in units of percent

PD = Percent Defective

This equation pays a maximum of 105 percent unless an agency wishes to limit the maximum pay factor to some lower level. Although stepped pay schedules are still more prevalent (at the time of this writing), continuous pay schedules are rapidly gaining acceptance. Not only they are concise and easy to apply, they provide a more precise determination of the appropriate pay factor.

Another rational method discussed is combining the legal principle of liquidated damages with the pay schedule to withhold sufficient payment at the time of construction to cover the cost of future repairs made necessary by defective work. The author highlights the two consequences of this approach. The author also calls attention to the disparity that exists between different pay adjustment systems that are followed by highway agencies and the need to establish a uniform

system of pay adjustment that is legally and technically sound. The author also mentions the importance of using pay factors greater than 100 percent. A first option is called “crediting concept” where pay factors greater than 100 are offered only to offset the lower pay factors and the second alternative termed as “positive incentive/ bonus” that allows lots of exceptionally high quality to receive pay factors greater than 100 percent. Per the author, the approach of positive incentive is easy to administer and more effective to achieve the average pay factor of 100 percent at the AQL. Overall, the paper discusses the advancements in pay schedules and analyzes the rationale underlying the advancements and the fairness of the system. Both stepped and continuous pay schedules are in common use and both can be constructed to provide essentially the same long-term performance.

X. Weed, R. M. “Managing Quality: Time for a National Policy,” (Coauthors: K. Afferton and J. Freidenrich), *Transportation Research Record 1340, Transportation Research Board, Washington, D.C., 1995*

Executive Summary

Statistical quality assurance has proven to be a very effective tool to encourage high-quality construction. This paper stresses the need for sweeping reforms and suggests that the time is overdue for the establishment of a uniform and thorough national policy on transportation quality assurance. It also describes a variety of obstacles such as technical, managerial, political, and cultural issues that must be overcome if such a transformation is to be made. In addition, the author outlines an extensive series of fundamental principles that must be understood in order to derive the maximum benefit from a quality assurance program. Finally, the paper presents a plan of action that, if conscientiously followed, will significantly increase the effectiveness of transportation quality assurance practices.

XI. Weed, R.M., “Composite Pay Equations: General Approach,” *Transportation Research Record 1465, Transportation Research Board, Washington, D.C., 1994*

Executive Summary

A method was developed by which several acceptance requirements could be combined into a single, composite pay equation. The New Jersey Department of Transportation (NJDOT) used five measures of quality for Portland cement concrete pavement: slump, air entrainment, thickness, compressive strength, and smoothness. Based on the slump and air entrainment tests, it is possible to accept or reject the concrete before it is placed since these two quality characteristics are measurable at the time of construction. However, the other three cannot be measured until after placement and curing of the concrete. In this case, the acceptance decision

takes the form of a pay adjustment equation that combines these three measures into a single pay equation:

$$PF = 105 - 0.12 PD_{\text{thickness}} - 0.10 PD_{\text{strength}} - 0.11 PD_{\text{smoothness}}$$

Where

PF = Pay Factor in units of percent

PD_{thickness} = Percent defective for concrete pavement thickness

PD_{strength} = Percent defective for concrete pavement strength

PD_{smoothness} = Percent defective for concrete pavement smoothness

This equation represents a practical and straightforward way to translate the measured quality levels into a workable acceptance procedure. In essence, the relatively complex AASHTO design equation was combined with engineering-economic principles and restated in the form of this linear pay equation. In addition, an extensive series of expected payment (EP) curves was developed to verify that the acceptance procedure would function as intended.

XII. Seeds, S.B., R. Basavaraju, J. Epps, and R.M. Weed. "Development of Performance-Related Specifications for HMA Pavements Through WesTrack," Transportation Research Record 1575, Transportation Research Board, Washington, D.C., 1997.

Executive Summary

The FHWA-sponsored Wes Track project was conducted to further the development of performance-related specifications for HMA construction (twenty-six HMA test sections) through the accelerated loading of a full-scale test track facility in Northern Nevada. This was performed to provide performance data to be used to improve existing (or develop new) pavement performance prediction relationships that better account for the effects that "off-target" values of asphalt content, air-void content, and aggregate gradation have on such distress factors as fatigue cracking, permanent deformation, roughness, raveling, and tire-pavement friction. The authors discuss the development of Performance Related Specifications for HMA pavements based on the West Track Project performance data. Several HMA test sections provide performance data to improve pavement performance prediction relationships that better account for the effects of the HMA quality characteristics. As part of this study, a plan for assessing contractor pay adjustments (incentives and disincentives) based on data collected from the as-constructed pavement was developed.

XIII. Weed, R. M., “A Rational Method for Relating As-Built Quality to Pavement Performance and Value,” Transportation Research Record 1632, Transportation Research Board, Washington, D.C., 1998

Executive Summary

The paper presents the basis for pay adjustment on the development of an expected life procedure. The general method discussed in this paper is based on life-cycle-cost procedures that can be structured around any valid fatigue relationship for pavements, such as those found in the AASHTO Guide for Design of Pavement Structures. This method is based on the premise that, when construction quality is deficient, a pavement tends to fail prematurely, and the degree to which its life is shortened can be estimated from the same fatigue relationship that was used to design it. An example is presented based on flexible pavement thickness in which it was assumed that pavement thickness was accepted on the basis of a defined AQL of PD =10. The results suggest that the amount of pay adjustment typically applied in current specifications may be insufficient to fully recoup the real costs incurred because of defective work. Overall, the proposed procedures in this report are generally applicable to all types of construction for which fatigue relationships exist or can be approximated.

XIV. Weed, R. M., “Practical Framework for Performance-Related Specifications,” Transportation Research Record 1654, Transportation Research Board, Washington, D.C., 1999

Executive Summary

The paper discusses the different statistically based quality measures including the sample mean, percent defective (PD), percent within limits (PWL), average absolute deviation (AAD), and conformance index (CI). The study indicated that AAD has mathematical inconsistencies that weaken its usefulness as a statistical quality measure. CI may be somewhat more consistent, but like AAD, populations with markedly different combinations of mean and standard deviation can produce the same CI value, a significant shortcoming. Although both AAD and CI can be made to work for two-sided specifications for which there is a specific target value (often midway between the two limits), neither is well suited for a one-sided specification for which a single, specific target value cannot be defined. PD and PWL are established statistical measures that do work well for either single- or double-sided specifications, with a small weakness that they are not very sensitive for populations close to PD = PWL = 50, a level of quality well below any conventional AQL value. Another alternative is presented by which the mean and standard deviation can be used jointly which may present some advantages.

***XV. Weed, R.M., “Method to Model Performance Relationships and Pay Schedules,”
Transportation Research Record 1712, Transportation Research Board, Washington, D.C.,
2000***

Executive Summary

This paper discusses the use of mathematical models in developing the relationship of construction quality to pavement performance, and explores different ways that pay levels for individual quality characteristics can be combined to arrive at the overall composite payment for the lot. The study also discusses the development of software to explore the distributional aspects of pavement quality. The New Jersey Department of Transportation (NJDOT) also conducted a series of pilot projects using the Superpave design procedure along with a modified statistical acceptance procedure based on air voids, thickness, and Ride Quality as the acceptance characteristics which provided field data that were useful to study these issues.

A survey was also conducted to obtain information to infer how the individual effects of deficiencies in two or more quality measures might be combined to check the results of the other experimental data. The analysis of the survey results suggests that the combined effect is close to the sum of the individual effects, but may be best represented by the product of the ratios of the individual effects.

***XVI. Weed, R. M. “Derivation of Equation for Cost of Premature Pavement Failure,”
Transportation Research Record 1761, Transportation Research Board, Washington, D.C.,
2001***

Executive Summary

This paper details the derivation of a pay adjustment equation based on withholding sufficient payment at the time of construction to cover the extra cost anticipated in the future as the result of deficient work. It is based on life-cycle-cost (LCC) analysis and provides quantification and justification for both aspects of incentive/disincentive pay schedules. The pay equation is presented below, and a series of validation steps are discussed in the paper.

$$\text{PAYADJ} = C(R^D - R^E) / (1 - R^O)$$

Where

PAYADJ = appropriate pay adjustment for pavement or overlay (same units as C)

C = present total cost of resurfacing (this might be as much as \$350,000 per lane mile based on current NJDOT experience)

D = design life of pavement or overlay (typically 10 years for new pavement, 10 years for overlay)

E = predicted expected life of pavement (years) obtained from a performance model

O = expected life of successive overlays (typically 10 years)

R = $(1 + \text{INF}) / (1 + \text{INT})$ in which INF is the long-term annual inflation rate and INT is the long-term annual interest rate, both in decimal form. .

This equation computes the net present value of failure cost (or the monetary benefit of extended service life) based on information readily available to highway agencies, and therefore provides a convenient method to develop defensible pay schedules. A secondary use is that it can be used to perform validation checks for complex procedures already in existence.

XVII. Weed, R.M., “Multicharacteristic Performance-Related Specification for HMA Pavement: A Complete Development Process, “Transportation Research Record 1861, Transportation Research Board, Washington, D.C., 1861, 2003

Executive Summary

This paper discusses the use of empirical construction data to develop realistic performance models for a HMA pavement specification based on multiple quality characteristics, and the use of those models to establish practical, effective, and defensible pay equations for performance-related specifications. Three characteristics of HMA (air voids, thickness, and smoothness) were used to develop a performance model for expected life. This approach has two stages; first estimating expected life and then using a life-cycle cost (LCC) analysis to determine an appropriate pay schedule.

XVIII. Burati, J.L., “Risks with Multiple Pay Factor Acceptance Plans,” Transportation Research Record, 1907, Journal of the Transportation Research Board, Washington, D.C., 2005.

Executive Summary

It is rare that a state highway agency (SHA) uses only a single quality characteristic to determine the pay factor for a lot. This paper deals with two specific types of risk associated with the use of multiple quality characteristics: remove - and - replace provisions, and the effect on pay factor determination if the quality characteristics are correlated. First, computer simulation studies showed that typical acceptance plan provisions that call for lot remove - and - replace at a given quality level, such as 60 PWL or 50 PWL, can place much greater risk on the contractor when they apply to multiple characteristics. An approach to correct this problem was developed. Next, a total of 1,742 sets of asphalt content (AC), air voids (AV), and VMA test results were analyzed for correlations. VMA was shown to be positively correlated with both AV and AC. Additional simulation studies showed that while this correlation does not affect the long-term average pay factor for a lot, it would increase the variability in the individual lot composite pay factors. The positive correlation also has the effect of increasing the weighting of AV and AC in a composite pay equation. The use of multiple quality characteristics for determining the pay factor for a lot introduces sources of risk that are not present when only one characteristic is used. Any SHA that uses multiple pay factors should consider performing the types of remove - and - replace and correlation analyses presented in this paper.

XIX. Burati, J.L., "Evaluating Specification Limits," Transportation Research Record, Journal of the Transportation Research Board, 1946, Washington, D.C., 2006

Executive Summary

The results of a study to evaluate the existing SCDOT hot mix asphalt Quality Assurance specification are presented. When the existing specification was developed, assumed values were used for the standard deviations needed to establish the specification limits. Acceptance test results from 39 different projects were analyzed to determine standard deviation values that were being obtained for asphalt content, air voids, VMA, and density. For each project, standard deviation values were calculated for each lot, and these were then pooled to obtain a typical value for the project. The target miss variability, i.e., the ability of contractors to center their processes on the target, was also determined for each acceptance characteristic. The project and target miss values were then used to establish a typical process standard deviation value for each of the four acceptance characteristics. All of these standard deviation values proved smaller than those initially assumed, and resulted in the SCDOT narrowing the specification limits for each of the acceptance characteristics. The project standard deviation values justified that these changes were made to reflect the actual variability that was present, and not simply to tighten the specifications.

XX. Burati, J.L. and Weed, R.M., "Accuracy and Precision of Typical Quality Measures", Transportation Research Record, 1946, Journal of the Transportation Research Board, Washington, D.C., 2006

Executive Summary

Computer simulation studies were performed to evaluate the accuracy and precision of the estimators for three quality measures: percent within limits (PWL), average absolute deviation (AAD), and conformal index (CI). Sample sizes of 3, 5, and 10 were simulated for various levels of actual population PWL, AAD, or CI. The estimators for all three quality measures exhibited similar trends with respect to the variabilities of their respective individual estimates. For each estimator, the variability decreased as the sample size increased. For PWL, the variabilities increased as the actual population PWL departed from either 0 or 100 PWL, peaking at 50 PWL. For AAD and CI, the variabilities increased as the actual population value, AAD or CI, departed from 0. Both PWL and AAD were unbiased estimators of their respective population parameters. However, the CI appeared to be a biased estimator, consistently underestimating the true population CI. Since the CI offers no benefits compared to AAD, and since it appears to be a biased estimator, the AAD is preferred to the use of CI. In this study, PWL and AAD exhibited similar trends so it is difficult to conclude that either method is preferred based on bias and precision. While there are many other differences between PWL and AAD, since they exhibited similar trends this study shows that the decision to choose PWL or AAD will need to be based on factors other than the bias and precision of their respective estimators.

XXI. Burati, J.L., and Weed, R.M., "Estimating Percent Within Limits for Skewed Populations," Transportation Research Record 1946, Journal of the Transportation Research Board, Washington, D.C., 2006

Executive Summary

Computer simulation, using samples of size 3, 5, and 10, was used to evaluate the PWL estimates for populations with skewness coefficients from 0.0 to ± 3.0 . The average bias and variability were then determined for the 10,000 PWL estimates. The analyses show that even a moderate amount of skewness in the underlying population can affect both the accuracy (bias), and variability of individual lot PWL values. The amount of bias increased as the amount of skewness increased, and the bias also increased as the sample size increased. The results show that with two-sided specifications the bias varies not only in its magnitude but also in its sign, i.e., positive or negative, depending upon the split of defective material outside the lower and upper limits (the PD_L/PD_U split). The amount of variability also increases as a greater percentage of the defective material is on the long tail of the distribution. Increased variability means that errors in individual lot estimates will be larger, thereby creating a greater spread in the pay factors on a project. If skewness is present, the population cannot be identified only by its PWL value. It will also be necessary to consider what percentage of the defective material is outside each of the specification limits. The analyses indicate that erroneous results for a population's

PWL value can be obtained if the population is only moderately skewed. For this reason, it is very important to monitor process data to ensure that they are from an approximately normal population.

Appendix B

Overall Questionnaire Summary

(37 Responses)

Part One: Hot Mix Asphalt

- 1a. Please check all of the following quality characteristics that are accepted by pay adjustment. Also check the method that is used to combine individual pay factors to determine the total pay factor when there is more than one quality characteristic used.

One state did not submit Hot Mix Asphalt Data

Quality Characteristic	Type of Pay Schedule			Method of Combining Pay Factors				
	Stepped	Equation	Other	Min.	Ave.	Multiply	Weighted	Other
Gradation	7	10	3	3	1		11	1
Sieve# 1 1/2"			2				2	
Sieve# 1" or 3/4"	3	3	2	1	1		5	
Sieve# 1/2"	4	5	3	1	1		7	1
Sieve# 3/8"	4	3	2	1	1		4	2
Sieve# 4	5	6	2	2	1		7	1
Sieve# 8	8	7	3	2	1		10	2
Sieve# 30, 40 or 50	5	3		3			2	2
Sieve# 100	1			1				
Sieve# 200	7	8	1	2	1		9	2
Aggregate FF	1		1	1				1
Asphalt Content	10	15	2	2	1		17	4
Air Voids	9	16	2	1	3		13	3
VMA	3	8	1				5	2
VFA		2					1	
Thickness	3	5					2	5
Density	17	19	4	3	3		17	4
Joint Density	3	3	2	1	1		4	
Ride Quality	14	8	6	1	5	1	5	6
Other: G _{mm} for Overlays; D/A; Cross Slope; MC; FT*	1	4					2	

*FT = Film Thickness

2 SHAs are essentially method spec states.

$$\#2 PF_T = (0.25)PF_{Den} + (0.25)PF_{AC} + (0.25)PF_{VMA} + (0.25)PF_{AV}$$

$$\#3 PF_T = (0.35)PF_{Den} + (0.25)PF_{AC} + (0.25)PF_{AV} + (0.10)PF_{\#200} + (0.05)PF_{\#8}$$

$$\#4 PF_T = (0.35)PF_{Den} + (0.20)PF_{AC} + (0.10)PF_{VMA} + (0.35)PF_{AV}$$

$$\#5 PF_T = (0.30)PF_{LaneDen} + (0.15)PF_{JointDen} + (0.05)PF_{AC} + (0.25)PF_{AV} + (0.25)PF_{VMA}$$

$$\#6 PF_T = (1/3)PF_{Den} + (1/3)PF_{AV} + (1/3)PF_{RQ}$$

$$\#7 PF_T = (0.25)PF_{Den} + (0.10)PF_{AC} + (0.25)PF_{AV} + (0.10)PF_{Thick} + (0.30)PF_{RQ}$$

$$\#8 PF_T = (0.40)PF_{Den} + 0.60 + [(0.52)PF_{AC} + (0.48)PF_{Grad}]$$

$$\#9 PF_T = (0.40)PF_{Den} + (0.30)PF_{AC} + (0.30)PF_{Grad}$$

$$\#10 PF_T = (0.35)PF_{Den} + (0.30)PF_{AC} + (0.25)PF_{AV} + (0.10)PF_{VMA}$$

$$\#11 (A) PF_T = (0.45)PF_{Den} + (0.15)PF_{JointDen} + (0.25)PF_{AC} + (0.15)PF_{Grad}$$

$$\#11 (B) PF_T = (0.35)PF_{Den} + (0.15)PF_{JointDen} + (0.10)PF_{AC} + (0.30)PF_{AV} + (0.10)PF_{VMA}$$

$$\#12 (A\&B) PF_T = (0.5)PF_{Den} + (0.10)PF_{AC} + (0.20)PF_{AV} + (0.20)PF_{VMA}$$

$$\#12 (C) PF_T = (0.5)PF_{Den} + (0.25)PF_{AC} + (0.25)PF_{Grad}$$

$$\#13 PF_T = (0.2)PF_{Den} + (0.15)PF_{AC} + (0.15)PF_{Grad} + (0.10)PF_{CS*} + (0.10)PF_{AV} + (0.30)PF_{RQ} \text{ (*CS= Cross Slope)}$$

$$\#14 PF_T = (0.40)PF_{Den} + (0.30)PF_{AC} + (0.30)PF_{AV}$$

$$\#15 PF_T = (0.40)PF_{Den} + (0.30)PF_{AV} + (0.30)PF_{VMA}$$

$$\#16 PF_T = (0.4)PF_{Den} + (0.26)PF_{AC} + (0.26)PF_{Grad} + (0.08)PF_{MC}$$

1b. Is Ride Quality a separate pay item from materials/construction?

Yes 27; No 8

2. Please check the statistical quality measure(s) you use for acceptance of the following quality characteristics.

Quality Characteristic	Statistical Quality Measure(s)								
	PWL	PD	\bar{x}	SD	R	\bar{x} & SD	\bar{x} & R	\bar{x} & x_i^*	AAD
Gradation	11	1	1		3	1			2
Aggregate FF			1						
AC%	15	1	1		2	2		1	3
Air Voids	15		3		2	1	2	1	2
VMA	7		1		3		1		
VFA	1		1		1		1		
Thickness	3	1	4		1				
Density	16	2	7		1	1	1	2	3
Joint Density	3		4					1	
Ride Quality	2	1	13		7	1		2	

* Average and individual

3. a. Do you use incentives only to offset disincentives?

Yes 9; No 26

b. Do you have a maximum incentive?

Yes 31; No 3

If yes, how much

1-(1%), 1-(2%), 4-(3%), 1-(3-5%), 18-(5%), 2-(6%), 1-(5-7.5%), 1-(5-12%), 1-(15%), 1-(\$1.50/ton)

c. Do you have a maximum disincentive?

Yes 27; No 6

d. If yes for 3 b. what action is imposed at the maximum? Remove and replace 23, [Comments:-(Density below RQL = Remove and replace. Smoothness below RQL = R&R. Binder content, voids or VMA below RQL: Composite pay factor for ALL volumetric tests = 55%. Other criteria below RQL = shutdown); (80% or R&R); (R&R, Mixture: 60%, lesser quality R&R. Ride: 77%, lesser quality requires corrective action); (By specification minimum payment can be 0%, but if allowed to remain in place there is value therefore some price should be paid); (75%); Shutdown 5.]

4. Pay adjustment units:
- Pay factor (percent) 8
 - Pay factor (decimal) 11
 - Pay adjustment (percent) 5
 - Pay adjustment (decimal) 3
 - Pay adjustment (direct dollar amount) 9

Part Two Paving PCC

1a. Please check all of the following quality characteristics that are accepted by pay adjustment. Also check the method that is used to combine individual pay factors to determine the total pay factor when there is more than one quality characteristic used.

Four (4) states do not use PCC.

One state did not submit PCCP data.

Quality Characteristic	Type of Pay Schedule			Method of Combining Pay Factors				
	Stepped	Equation	Other	Min.	Ave.	Multiply	Weighted	Other
Gradation	1	2	2	1			2	1
Sieve 4 #		1					1	
Sieve 8 #		1					1	
Sieve 200#		1						
Sieve ___ #								
Aggregate F F		1						
Cylinder strength	8	6	3		2	1	2	7
Core strength		1					1	
Beam strength	2		1		1			1
Water/Cement Ratio		1	1					
Air content	4	2	1		1		2	1
Permeability	1							1
COET ¹								
Thickness	18	6	2		5	1	2	5
Ride Quality	15	5	3		2	1		6
Other ²	1	2	1					2

¹COTE – Coefficient of Thermal Expansion

²Other – Dowel Bar alignment, Finess Modulus, Sand Equivalent

2. SHAs are essentially method spec states.

$$\#1 PF_T = (0.40)PF_{Strength} + (0.40)PF_{Thick} + (0.10)PF_{Grad} + (0.10)PF_{Air}$$

1b. Is Ride Quality a separate pay item from materials/construction?

Yes 20, (Ride quality is a separate pay *incentive* from the combined compressive strength / thickness pay incentive.) No. 7

2. Please check the statistical quality measure(s) you use for acceptance of the following quality characteristics.

Quality Characteristic	Statistical Quality Measure(s)								
	PWL	PD	\bar{x}	SD	R	\bar{x} & SD	\bar{x} & R	\bar{x} & x_i^*	AAD
Gradation		1	1		2	1	1		1
Aggregate FF			1				1		
Cylinder strength	6		5		1		1	2	1
Core strength	1								
Beam strength	1		2				1		
W/C			1		2				
Air content	1		1		4	1			1
Slump		1	1		2				
Permeability					1		1		
Coefficient of Thermal Expansion			1						
Thickness	4		11		2	1	1	1	1
Ride quality			9		7		8	11	

* Average and individual SHA#8 W/C; max. value

3.a. Do you use incentives only to offset disincentives?

Yes 3; No 21 No Incentive 7

b. Do you have a maximum incentive?

Yes 13; No 8

If so, how much? 1-3%; 1-(3-6%); 6-(5%); 2-(6%); 1-(15% Ride Quality only)

c. Do you have a maximum disincentive?

Yes 21; No 9

d. If yes for 3 b. what action is imposed at the maximum? Remove and Replace: 15

Minimum payment: 10 if so, how much: [Comments; (0%); (0%, although the pay factor scale does extend down to 0%; minimum acceptable limits for strength (3500 psi) and thickness (10 % less than plan) preclude agency from allowing the contractor to take such a reduction. Rather, the pavement would probably be removed and replaced); (Eng. Decision); (50% or R&R); (0% or R&R); (76-88%); (When the average thickness is > 1 inch, the Engineer decides whether to R&R or leave the concrete in place.); (R&R if PI > 50 in, or Thickness Deficiency >0.75, or Compressive Strength < 85% specified, or product of PA for thickness and strength < 50%); (Mixture: 65%, lesser quality R&R. Ride: 77%, lesser quality requires corrective action); (Min payment theoretically 0%);

Shut down 2 ; Other

4. Pay adjustment units:

- Pay factor (percent) 6
- Pay factor (decimal) 3
- Pay adjustment (percent) 8
- Pay adjustment (decimal) 4
- Pay adjustment (direct dollar amount) 7

Part Three Future of QA Program

1. Do you anticipate significant changes in your pay adjustment procedures for HMA or PCC paving in the near future?

Yes 10 No 21 Maybe 4

1a. If Yes or maybe, for HMA 9; for PCC Paving 6 ? Briefly list the changes and reason for them:

- The State has been performing preliminary statistical work and is moving toward implementation by using statistically valid tests for comparison of QA test results with the contractor's test results used for acceptance.
- Possibly add test for Freeze-thaw.
- Anticipate improvements in the specification to be completed between 11/09 and 3/10; likely focused on streamlining mix approval/verification; revising pay factors including reassessment of plant air voids.
- HMA Considering sampling from roadway instead of plant; considering contractor acceptance with verification; PCCP Expect to implement IRI specification.
- Pilot HMA for 2009, Addition of Pay Disincentives: Use more contractor test results for acceptance; initiate a Quality System Manual for each entity of a HMA project, i.e., a QSM for manufacturer, one for paving co., one for contractor.
- Going to the new FHWA tables with stepped maximum pay factor for small frequency of tests; and to a maximum lot size of 15 so that the DOT and contractors risk is about the same; for HMA, using the differences between test data and the job mix formula.
- Add Gradation pay adjustment and de-emphasize Strength.
- Used PWL for thickness, strength, and ride on a trial basis, but have not fully implemented.
- Change from current tables to equations for pay adjustments.
- HMA pay adjustment under study.
- Trying to improve quality of materials.
- PWL spec under development.
- Working toward Pay For Performance using PWL and $PF = 53 + 0.3PWL$.
- Add Gradation pay adjustment and de-emphasize Strength.
- Used PWL for thickness, strength, and ride on a trial basis, but have not fully implemented.

- Change from current tables to equations for pay adjustments.
- HMA pay adjustment under study.
- Trying to improve quality of materials.
- PWL spec under development.
- We review the HMA QA program on a yearly basis with industry. For PCCP, we are going to address the QA since there are some PCCP projects coming out.