DEVELOPMENT OF A PROTOTYPE PERFORMANCE-RELATED SPECIFICATION FOR CONCRETE PAVEMENTS

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ABSTRACT

This paper summarizes the development and sensitivity of a Level 1 prototype performance-related specification (PRS) for concrete pavement construction. The prototype PRS requires that a pavement lot be divided into consistent sublots for the measurement of quality characteristics (QACs), which are then used to estimate future performance and life cycle costs (LCCs). The difference between the LCCs of the target (as-designed) pavement lot and the actual (as-constructed) pavement lot is used to determine a rational pay adjustment. Both means and variations of all QACs are directly considered in the pay factor determination. A Level 1 prototype is offered as a first step in the implementation of a truly practical PRS. It is designed to be flexible by using an agency's current sampling and testing procedures. Independent pay factor curves are developed for each included QAC. The overall lot pay factor is calculated as the product of the independent pay factors. A Microsoft Windows-based computer program, PaveSpec, was developed to demonstrate the specification (simulating pavement performance and generating pay adjustments).

Key Words: Performance-related specifications, portland cement concrete, pavement performance, pavement construction, life cycle costs, pay adjustment.

INTRODUCTION

Performance-related specifications (PRS) have capabilities beyond traditional quality assurance (QA) specifications. These capabilities include clearly defining lots and sublots, the subsequent sampling and testing of key quality characteristics (QACs) that relate directly to the future performance of the constructed pavement, and the prediction of future life cycle costs (LCCs) used to compute contractor pay adjustments (incentives and disincentives). Thus, the level of quality (mean and deviation) achieved for each of the key QACs can be related directly to rationally computed pay adjustments based on sound economic principles.

The associated risks to the agency and contractor can be assessed for any given sampling and testing plan. This makes it possible for the agency to determine a sampling plan that meets its needs; at the same time, the contractor can utilize this information to prepare the bid by having increased knowledge about the impact of each QAC mean and standard deviation on pay adjustments. Therefore, pay adjustments are much more rational and defensible using a PRS.

Another interesting aspect is that a comprehensive PRS allows the identification and specification of the optimum level of quality that provides the best balance between costs and performance for a given project. It has

been estimated that such improvements in quality assurance procedures could produce long-term benefits to agencies and users measured in billions of dollars (*1*). However, yet to be determined during full-scale usage is the ability of a comprehensive PRS to lead to improved constructed quality, lower QAC variability, and lower overall LCCs.

The initial ground breaking work on PRS was done by Weed for the New Jersey Department of Transportation (*2*). A prototype PRS was developed under a previous Federal Highway Administration (FHWA) research study (*3-6*). The prototype used an innovative approach that considered the estimated future LCC of the pavement as the overall measure of quality. Key QACs (concrete strength, slab thickness, air content, and initial smoothness) are measured at the time of construction on the in situ pavement and then used in established relationships to predict key distress indicators (transverse joint faulting, transverse cracking, transverse joint spalling, and present serviceability rating) in the pavement. The amount of the pay adjustment is based on the increase or decrease in future costs that will be incurred by the agency over the life of the project, assuming a given rehabilitation policy. A computer software program, PaveSpec, was developed to demonstrate the prototype specification.

Although the prototype PRS is based on rational concepts, it is realized that an attempt to implement such a specification at this point would be met with much resistance. This resistance would primarily be due to the general lack of knowledge of the current PRS concepts, the additional costs associated with strongly emphasized in situ testing, and the reliance on *simulated* distresses and associated costs. In an attempt to facilitate the acceptance of PRS concepts, a strategy has been developed that identifies three different implementation levels of PRS. The concepts behind each of the levels are discussed briefly in the following section. This paper focuses on the most practical method at this time (Level 1) by discussing its concepts, demonstrating its procedure, and showing examples of its sensitivity using an actual pavement design.

THREE LEVELS OF PRS IMPLEMENTATION

The overall goal of current research into PRS is to develop an *ideal* PRS that incorporates *all* important QACs of PCC pavements that not only affect pavement performance, but are also under the control of the contractor. As a means of achieving this goal, future research should continue to attempt to:

- Identify distress indicators that significantly affect pavement performance (these drive the PRS).
- Identify the QACs and other variables that directly affect each identified distress indicator.
- Develop early age, rapid, reliable, easy, and cost-effective field tests that measure the in situ quality level of each identified QAC.
- Develop accurate distress indicator prediction models that are dependent on the measured quality level mean and variability of each identified QAC (none of the current models are directly dependent upon variability).
- Develop a practical, yet comprehensive, method for the calculation of overall lot pay adjustments using sound economic principles.

Obviously, there is much research needed to develop and implement an *ideal* PRS that incorporates *all* important elements of concrete pavements that not only affect pavement performance, but are also under the control of the contractor. Such an effort would take much more research effort and funding. Therefore, as a means of organizing the envisioned work needed to develop this *ideal* PRS, three different levels (chronological steps) of PRS implementation are being proposed. These three levels are defined as the following:

- Level 1 – Implementation of a relatively simple PRS that uses current agency tests (even though they may not be optimum).
- Level 2 – Implementation of a comprehensive PRS that will use the results of current research.
- Level 3 – Implementation of a more comprehensive PRS incorporating results from future research (including mostly NDT sampling and testing).

Each level differs by the number of QACs included, the sampling and testing methods required for each QAC, the distress indicator prediction models used to predict pavement performance, and the computation

method for payment adjustments. Level 3 represents the ideal specification that will be achieved only with much future research. Level 2 represents the dynamic transition from the prototype specification presented in the final report of a previous FHWA research project (*3*) to the ultimate goal of Level 3. Level 1 represents a simplified version of the prototype Level 2 PRS that would be immediately implementable so that some progress in full-scale usage could result. The details of the three proposed PRS levels of implementation are summarized in table 1.

EXPLANATION OF THE LEVEL 1 PRS METHODOLOGY

The proposed Level 1 PRS is based on the prototype specification previously developed for the FHWA (*3-5*). It includes a maximum of four QACs: concrete strength, slab thickness, air content, and initial smoothness. The proposed Level 1 PRS uses *currently practiced* field sampling and laboratory testing procedures (see table 1). Because these procedures are currently practiced, it is believed that the Level 1 PRS would be immediately implementable in any highway agency with some adaptation of agency procedures. Under the proposed Level 1 PRS, QAC sample values from a lot are statistically summarized into means and standard deviations.

In the Level 1 PRS, pavement performance is defined by four distress indicators: transverse cracking (fatigue), transverse joint faulting, transverse joint spalling, and pavement smoothness (as indicated by the present serviceability rating [PSR]). Performance models for each of the distress indicators are based on the quality level of one or more of the included QACs. Calculated LCCs (for both the as-designed and as-constructed pavements) are based on a chosen rehabilitation policy and cost models. All of this simulation is conducted using the PaveSpec software, which was developed under the previous PRS project for the FHWA (*3-5*).

The pay factor computation method used in the Level 1 PRS is based on calculating independent pay factors for each individual QAC (all other QACs are assumed to be equal to the target values). Each of these pay factors is determined from a family of simulated pay factor vs. QAC mean curves. Each family of curves is made up of individual curves, each specific to a different as-constructed QAC standard deviation. The curves are created by simulating lot pay factors over a chosen range of QAC means. Each calculated pay factor is therefore a function of the measured as-constructed mean and standard deviation, target mean and standard deviation, and the sample size. One drawback to this approach is that these curves are dependent on the inputs used in simulating the pavement's performance. However, it is possible to develop a series of curves that are specific to particular project designs and site conditions (climate, traffic, subgrade). Minimum and maximum limits must be set for each individual QAC pay factor to ensure the practicality of pay adjustments. No pay factor should be allowed to become too high or too low from a practical point of view.

Final payment for the lot is based on a mathematical manipulation of the individual QAC pay factors. This method may be as simple as the multiplication of individual QAC pay factors, i.e.,

$$PF_{LOT} = PF_{STRENGTH} * PF_{THICKNESS} * PF_{AIR\ CONTENT} * PF_{SMOOTHNESS}.$$

This procedure has been found to provide a reasonable estimate of the overall pay factor determined using the Level 2 PRS method. However, a maximum must be placed on the overall lot pay factor (PF_{LOT}). Since this approach uses current sampling and testing practices, it is not a major leap for most agencies; it does, however, introduce the PRS concept. Its major deficiency is that the QAC tests are not all in situ tests (which provide a better estimate of the actual quality level constructed). Several aspects of a Level 1 PRS remain to be resolved and **are being addressed under ongoing research.**

EXAMPLE OF LEVEL 1 SPECIFICATION DEVELOPMENT

One important aspect of the PRS approach is that the developed specifications are project specific. Therefore, a Level 1 specification would need to be developed prior to going to the field by tailoring the PRS methodology to the specific project. The development of such a specification involves a number of steps, including identifying the project specific constant variables, selecting the included QACs, identifying QAC target

values, selecting lot and sublot lengths, and preparing for the pay-factor calculations. The example below demonstrates these Level 1 specification development steps by using an actual pavement design.

Constant Values

The example project is a doweled jointed plain concrete pavement that is located on a rural four-lane divided freeway and is subjected to heavy truck traffic. Constant input variables, common to both the as-designed and as-constructed pavements, are included in table 2. This pavement was designed for 30 years of traffic (about 12.7 million equivalent single-axle load [ESAL] applications) using the 1993 AASHTO Design Guide and a 95-percent design reliability level. Note that any design procedure or design standard could have been used to develop the target pavement design, but all of the inputs specified in table 2 would still need to be provided to define the as-designed pavement. Future LCCs were calculated over a 60-year design analysis period (two times the design life) to observe the effects of more than one asphalt overlay. Each agency should determine the analysis period that best fits its needs.

The lot consists of two lanes (each 3.7 m [12 ft] wide) of a concrete pavement of uniform thickness constructed over a length of 1.61 km (1.0 mi) in a given day. The unit bid price of the jointed plain concrete pavement is \$24.10/m^2 (\$20.15/yd^2). The total lot bid price is calculated as the following:

Bid Price = Contractor's bid price for the lot (computed using the contractor's unit bid price [\$/m^2] times the m^2 of the lot).

= \$24.10/m^2 * 7,305 m^2/km = \$176,295/km (\$283,712/mi).

Selection of Quality Characteristics

For this example, the following four QACs (and associated measurement methods) were selected for inclusion in the specification.

- Concrete strength—measured as the 28-day modulus of rupture (third-point loading) from beams. Alternatively, compressive strength could be measured from cylinders and converted to a 28-day modulus of rupture using an appropriate conversion equation.

- Slab thickness—measured from in situ cores.
- Air content—measured with a pressure meter.
- Initial smoothness—measured with a California profilograph.

Definition of Lots and Sublots

The example draft specification included the following definitions of lots and sublots:

- Lot—A discrete quantity of constructed pavement to which an acceptance procedure is applied. A lot shall be equal to one day's production or less. The lot shall consist of a pavement one or more traffic lanes wide (but shall not include a shoulder). Payments to the contractor will be made on a lot basis.

- Sublot—A portion of a lot. The lot is divided into sublots of approximately equal surface area. This specification requires that sublots are uniquely defined for all sampling in that one or more samples of all QACs are taken from each defined sublot. The minimum length of a sublot shall be approximately 0.16 km (0.1 mi) to accommodate the measurement of longitudinal initial smoothness.

This example analyzes a 1.61 kilometer long (1.0 mi) lot divided into four equal length sublots.

Identification of As-Designed Target Values

One very important responsibility that falls on the agency is identifying the as-designed target means and standard deviations of the chosen QACs. It is important because the contractor pay will be linked to how well the

contractor matches these chosen values. The as-designed means and standard deviations define the quality levels for which the agency is willing to pay 100 percent (on average) of the bid price. The chosen target as-designed pavement QAC values are discussed below and summarized in table 3:

The target as-designed mean strength (defined as the 28-day, standard laboratory-cured flexural strength tested under third-point loading) is 4,479 kPa (650 psi). The target as-designed standard deviation for the strength is set at 448 kPa (65 psi). This includes point-to-point materials strength variation and also variation due to testing error.

The target as-designed mean slab thickness is 28.32 cm (11.15 in). The target as-designed standard deviation of the thickness is set at 0.64 cm (0.25 in). This value includes point-to-point thickness variation and also variation due to testing error.

The target as-designed entrained air content is 7.0 percent. The target as-designed standard deviation for air content is set at 0.5 percent. This value includes point-to-point air content variation, as well as variation due to testing error.

The target as-designed mean initial smoothness (as measured by a profilograph) is 7.9 cm/km (5.0 in/mi). According to the relationship shown below, this initial smoothness is equivalent to an initial PSR of 4.6.

$$\text{Initial PSR} = 5.0 - 0.0453 * PI$$

where:

PI = Initial profile index measured by a California-type profilograph, cm/km.

The target as-designed standard deviation for initial smoothness is set at 1.6 cm/km (1.0 in/mi). This value includes longitudinal profile variation from profile-to-profile and also variation due to testing error.

Pay-Factor Calculation Preparation

The final step in the specification development process involves determining the expected costs associated with the target as-designed pavement. For the Level 1 specification, this involves constructing individual pay factor curves for the four QACs. Individual QAC pay factors may be interpolated from these charts by knowing the as-constructed QAC lot means and standard deviations.

A number of steps are used to develop the Level 1 pay factor curves. Each is explained below.

1. *Define lots and sublots.* As discussed before, the lot size was 1 day of mainline paving (1.61 km [1.0 mi]). The lot was divided into four sublots of equal length.

2. *Define the number of samples per sublot.* A sample size of two per sublot was selected. Since we assume that a simulated lot is represented by the same statistical population, for QACs such as strength, air, and thickness, the total sample size N may be represented by the number of sublots n times the number of samples per sublot. Therefore, for the case of four sublots per lot, the total sample size N would equal eight.

3. *Define the QAC target means and standard deviations.* The target as-designed QAC means and standard deviations for this project are defined in table 3.

4. *Choose a range of as-constructed means for each QAC.* Reasonable ranges of QAC means are selected that will define the values used for the PaveSpec simulations. For this example, QAC simulation mean ranges included the following:

28-day modulus of rupture:	3,790 to 5,168 kPa (550 to 750 psi)
Slab thickness:	27.56 to 29.08 cm (10.85 to 11.45 in)
Air content:	1.0 to 13.0 %
Initial smoothness:	0.0 to 15.8 cm/km (0.0 to 10.0 in/mi)

5. *Choose a range of as-constructed standard deviation levels for each QAC.* The pay factor curves not only depend on the as-constructed QAC mean, but the as-constructed QAC standard deviation as well. Therefore, it is important to choose a range of as-constructed standard deviation levels that will show the influence of the QAC variability. For this example, QAC standard deviation simulation values included the following:

28-day modulus of rupture:	0, 448, 896 kPa (0, 65, 130 psi)
Slab thickness:	0.00, 0.64, 1.27 cm (0.00, 0.25, 0.50 in)
Air content:	0.00, 0.50, 1.00 %
Initial smoothness:	0.0, 1.6, 4.7 cm/km (0.0, 1.0, 3.0 in/mi)

6. *Simulate the target as-designed life cycle costs.* To calculate pay factors for different hypothetical levels of as-constructed QAC quality, the target as-designed LCCs must first be simulated. The PaveSpec specification simulation software was used to estimate target as-designed LCC means ($AD\text{-}LCC_{MEAN}$) from 500 simulation lots for the case of four sublots per lot (with two QAC samples per sublot). It is also to be noted that the simulations were conducted using a 60-year analysis life (twice the design life) and include 5 percent of the calculated user costs. The resulting simulated as-designed LCC value was the following:

$AD\text{-}LCC_{MEAN}$ (4 sublots) = $ 492,126 /km ($791,831/mi)

7. *Simulate as-constructed LCCs and calculate an independent QAC pay-factor for each hypothetical as-constructed mean / as-constructed standard deviation pair.* The hypothetical as-constructed mean/as-constructed standard deviation pair values (coming from combinations of means and standard deviations defined in steps 5 and 6, respectively) were used to define individual sessions in PaveSpec. Each QAC is investigated independently for each session. For example, if strength is being investigated, all of the other QAC as-constructed means and standard deviations are set equal to the target values.

   Each pair is used in PaveSpec to simulate a corresponding as-constructed LCC mean ($AC\text{-}LCC_{MEAN}$). A pay factor is calculated for each pair using the following equation:

$$PF = [\text{Bid Price} + (AD\text{-}LCC_{MEAN} - AC\text{-}LCC_{MEAN})] / \text{Bid Price}$$

   where:

PF	=	Pay factor for the given as-constructed lot.
Bid Price	=	Contractor's bid price for the lot (computed using the contractor's unit bid price [$/m²] times the m² of the lot).
	=	$176,295/km ($ 283,712/mi) for this project.
$AD\text{-}LCC_{MEAN}$	=	Target as-designed LCC mean simulated in step 6 above.
$AC\text{-}LCC_{MEAN}$	=	Simulated as-constructed LCC mean.

   These simulated pay-factors (from PaveSpec) are summarized below. A more detailed description of the simulation procedures is contained in a previous report describing the development of the original prototype PRS (*6*).

8. *Plot charts of pay-factor vs. QAC mean.* The simulated pay factors determined in step 7 can be graphed as a function of the QAC mean. Each QAC pay factor chart contains three curves corresponding to the three standard deviation levels chosen in step 5. The individual QAC pay factor charts for the case of four sublots (or, N=8) are contained in figures 1 through 4.

   Table 4 summarizes the best-fit pay factor regression equations that represent each of the curves presented in the QAC pay factor charts. Pay factors are determined for as-constructed lots by using the measured QAC means in these regression equations. Since the individual pay factor curves are *only constructed for three different QAC standard deviations, and the measured QAC standard* deviations are not likely to be one of these three, the pay factor most likely must be interpolated (using an assumed linear relationship) using the regression equations. This procedure is discussed in more detail in the following section.

   All individual QAC pay factors, as well as the overall pay factor, were subjected to a maximum pay factor of 105 percent in this example. Each SHA would determine its own appropriate pay factor limits to ensure practicality of pay adjustments.

SENSITIVITY ANALYSIS

This section examines the sensitivity of the Level 1 prototype PRS as it is applied to the actual real life pavement design presented in the previous section. Different hypothetical settings of the as-constructed QAC means and standard deviations are selected to demonstrate the defined specification. The acceptance is assumed to be based on sampling and testing (four sublots per lot, two samples per sublot) of the concrete slab after placement. All pay factors are calculated using the equations presented in table 4.

Different Scenarios Used to Investigate the Sensitivity of the PRS Prototype

A total of six different scenarios are presented to demonstrate the prototype PRS and its sensitivity to changes in some of the chosen QACs. The means and standard deviations of the as-constructed QACs presented in each scenario represent the *measured* means and standard deviations provided by the contractor in the field.

Scenario 1: Contractor matches the target means and standard deviations of all QACs exactly.

The first scenario is the one that provides the basis for all of the others. This scenario assumes the contractor has exactly matched all of the target as-designed QAC means and standard deviations. Since the measured as-constructed standard deviations each match one of the standard deviations used to simulate values for the pay factor charts, the individual QAC pay factors can be calculated *directly* from the equations presented in table 4.

Measured As-Constructed Strength:

Mean = 4,479 kPa (650 psi), Std Dev = 448 kPa (65 psi)

At a mean of 4,479 kPa (650 psi), $PF_{S-(4,479,\ 448)} = -(1.675E\text{-}5)x^2 + 0.20581x - 485.81 = 100.0$ %

Measured As-Constructed Slab Thickness:

Mean = 28.32 cm (11.15 in), Std Dev = 0.64 cm (0.25 in)

At a mean of 28.32 cm (11.15 in), $PF_{T-(28.32,\ 0.64)} = 17.478(28.32) - 394.98 = 100.0$ %

Measured As-Constructed Air Content:

Mean = 7.0 %, Std Dev = 0.5 %

At a mean of 7.0 %, $PF_{A-(7.0,0.5)} = 1.6857(7.0) + 88.2 = 100.0$ %

Measured As-Constructed Initial Smoothness:
Mean = 7.9 cm/km (5.0 in/mi), Std Dev = 1.6 cm/km (1.0 in/mi)
At a mean of 7.9 cm/km (5.0 in/mi), $PF_{SM-(7.9,1.6)}$
$= (2.801E\text{-}4)(7.9)^3 - 0.0604(7.9)^2 + 0.1796(7.9)x + 102.2 = 100.0\ \%$

The overall lot pay factor is calculated using the following equation:
$PF_{LOT(1)} = PF_{STRENGTH} * PF_{THICKNESS} * PF_{AIR\ CONTENT} * PF_{SMOOTHNESS}$
$= (1.000) * (1.000) * (1.000) * (1.000) = 1.000$ which translates to 100.0%.

As expected, this scenario results in exactly 100 percent pay for the contractor. The total payment to the contractor for the 1.61 km (1.0 mi) lot is calculated using the following equation:

Adjusted Bid Price = Bid Price * $PF_{LOT(1)}$
= \$176,295/km * 1.000
= \$176,295/km lot (\$283,712/mi lot)

Scenario 2: Contractor gives greater strength mean and matches the target strength standard deviation.
The second scenario assumes the contractor has exactly matched all of the target as-designed QAC means and standard deviations except for the strength mean. It is assumed that the contractor has provided slightly greater quality for strength with an as-constructed mean value of 4,616 kPa (670 psi), compared to the target as-designed strength mean of 4,479 kPa (650 psi). Again, since all of the measured as-constructed QAC standard deviations match one of the standard deviations used to simulate values for the pay factor charts, the individual QAC pay factors can be calculated *directly* from the equations presented in table 4:

Measured As-Constructed Strength:
Mean = 4,616 kPa (670 psi), Std Dev = 448 kPa (65 psi)
At a mean of 4,616 kPa (670 psi),
$PF_{S-(4,616,448)} = -(1.675E\text{-}5)(4,616)^2 + 0.20581(4,616) - 485.81 = 107.4\ \%$
$= 105.0\ \%$ (after subjection to the chosen PF limit of 105.0%).

Since it is assumed that all of the remaining QAC as-constructed means and standard deviations are exactly equal to the target values, the individual pay factors for slab thickness, air content, and initial smoothness are equal to 100 percent (calculated the same as shown in scenario 1). The overall lot pay factor is calculated using the following equation:

$PF_{LOT(2)} = PF_{STRENGTH} * PF_{THICKNESS} * PF_{AIR\ CONTENT} * PF_{SMOOTHNESS}$
$= (1.050) * (1.000) * (1.000) * (1.000) = 1.050$ which translates to 105.0%.

The total payment to the contractor for the 1.61 km (1.0 mi) lot is calculated using the following equation:

Adjusted Bid Price = Bid Price * $PF_{LOT(2)}$ = \$185,110/km lot (\$297,898/mi lot)

Scenario 3: Contractor gives greater strength mean, but also has a strength standard deviation greater than the target.
The third scenario assumes the contractor has exactly matched all of the target as-designed QAC means and standard deviations except for the strength mean and standard deviation. Scenario 3 differs from scenario 2 in that the contractor has provided a higher strength standard deviation (689 kPa [100 psi] compared to the target of 448 kPa [65 psi]). Note that the strength mean (4,616 kPa [670 psi]) is still higher than the target value of 4,479 kPa (650 psi). For this case, table 4 does not contain a pay factor equation for strength that is specific to the case where the standard deviation is equal to 689 kPa (100 psi). Therefore, the individual pay factor must be interpolated from the results of the equations specific to standard deviations of 448 and 896 kPa (65 and 130 psi). This interpolation process is demonstrated below.

Measured As-Constructed Strength:
Mean = 4,616 kPa (670 psi), Std Dev = 689 kPa (100 psi)

At a mean of 4,616 kPa (670 psi), and standard deviation of 448 kPa (65 psi):

$PF_{S-(4,616\ ,448)} = -(1.675E\text{-}5)(4,616)^2 + 0.20581(4,616) - 485.81 = 107.4\ \%$

At a mean of 4,616 kPa (670 psi), and standard deviation of 896 kPa (130 psi):

$PF_{S-(4,616\ ,896)} = -(6.951E\text{-}6)(4,616)^2 + 0.11611(4,616) - 292.78 = 95.1\ \%$

The pay factor for the case with strength mean and standard deviation equal to 4,616 and 689 kPa (670 and 100 psi) ,respectively, is interpolated (using an assumed linear relationship) by the following equation:

$$PF_{S-(4,616,\ 689)} = PF_{S-(4,616,\ 896)} + (PF_{S-(4,616\ ,448)} - PF_{S-(4,616,\ 896)}) * [(896\ kPa - 689\ kPa)/(896\ kPa - 448\ kPa)]$$
$$= 95.1\ \% + (107.4\ \% - 95.1\ \\%) * [(207\ kPa)/(448\ kPa)]$$
$$= 100.8\ \%$$

Since it is assumed that all of the remaining QAC as-constructed means and standard deviations are exactly equal to the target values, the individual pay factors for slab thickness, air content, and initial smoothness are equal to 100 percent (calculated the same as shown in scenario 1). The overall lot pay factor is calculated using the following equation:

$$PF_{LOT(3)} = PF_{STRENGTH} * PF_{THICKNESS} * PF_{AIR\ CONTENT} * PF_{SMOOTHNESS}$$
$$= (1.008) * (1.000) * (1.000) * (1.000) = 1.008 \text{ which translates to } 100.8\%.$$

The total payment to the contractor for the 1.61 km (1.0 mi) lot is calculated using the following equation:

$$\text{Adjusted Bid Price} = \text{Bid Price} * PF_{LOT(3)} = \$177{,}665/\text{km lot}\ (\$285{,}916/\text{mi lot})$$

Scenario 4: Contractor gives slightly deficient slab thickness mean and matches the target thickness standard deviation.

The fourth scenario assumes the contractor has exactly matched all of the target as-designed QAC means and standard deviations except for the slab thickness mean. It is assumed that the contractor has provided slightly deficient quality for thickness with an as-constructed mean value of 27.94 cm (11.00 in), compared to the target as-designed thickness mean of 28.32 cm (11.15 in). Since all of the measured as-constructed QAC standard deviations match one of the standard deviations used to simulate values for the pay factor charts, the individual QAC pay factors can be calculated *directly* from the equations presented in table 4:

Measured As-Constructed Slab Thickness:

Mean = 27.94 cm (11.00 in), Std Dev = 0.64 cm (0.25 in)

At a mean of 27.94 cm (11.00 in),

$PF_{T-(27.94,\ 0.64)} = 17.478(27.94) - 394.98 = 93.3\ \%$

Since it is assumed that all of the remaining QAC as-constructed means and standard deviations are exactly equal to the target values, the individual pay factors for strength, air content, and initial smoothness are equal to 100 percent (calculated the same as shown in scenario 1). The overall lot pay factor is calculated using the following equation:

$$PF_{LOT(4)} = PF_{STRENGTH} * PF_{THICKNESS} * PF_{AIR\ CONTENT} * PF_{SMOOTHNESS}$$
$$= (1.000) * (0.933) * (1.000) * (1.000) = 0.933 \text{ which translates to } 93.3\%.$$

The total payment to the contractor for the 1.61 km (1.0 mi) lot is calculated using the following equation:

$$\text{Adjusted Bid Price} = \text{Bid Price} * PF_{LOT(4)} = \$164{,}483/\text{km lot}\ (\$264{,}703/\text{mi lot})$$

Scenario 5: Contractor gives slightly deficient slab thickness mean, but has a thickness standard deviation smaller than the target.

The fifth scenario assumes the contractor has exactly matched all of the target as-designed QAC means and standard deviations except for slab thickness. Scenario 5 differs from scenario 4 in that the contractor has

provided a smaller thickness standard deviation (0.25 cm [0.10 in] compared to the target of 0.64 cm [0.25 in]). Note that the thickness mean (27.94 cm [11.00 in]) is still less than the target value of 28.32 cm [11.15 in]. For this case, table 4 does not contain a pay factor equation for strength that is specific to the case where the standard deviation is equal to 0.25 cm [0.10 in]. Therefore, the individual pay factor must be interpolated from the results of the equations specific to standard deviations of 0.00 and 0.64 cm (0.00 and 0.25 in). This interpolation process is demonstrated below.

Measured As-Constructed Thickness:
Mean = 27.94 cm (11.00 in), Std Dev = 0.25 cm (0.10 in)
At a mean of 27.94 cm (11.00 in), and standard deviation of 0.00 cm (0.00 in):
$PF_{T-(27.94,\ 0.00)}$ = 16.971(27.94) - 379.84 = 94.3 %
At a mean of 27.94 cm (11.00 in), and standard deviation of 0.64 cm (0.25 in):
$PF_{T-(27.94,\ 0.64)}$ = 17.478(27.94) - 394.98 = 93.4 %

The pay factor for the case with strength mean and standard deviation equal to 27.94 and 0.25 cm (11.00 and 0.10 in), respectively, is interpolated (using an assumed linear relationship) by the following equation:

$$PF_{T-(27.94,\ 0.25)} = PF_{T-(27.94,\ 0.64)} + (PF_{T-(27.94,\ 0.00)} - PF_{T-(27.94,\ 0.64)}) * [(0.64\text{ cm} - 0.25\text{ cm})/(0.64\text{ cm} - 0.00\text{ cm})]$$
$$= 93.4\ \% + (94.3\ \% - 93.4\ \%) * [(0.15\text{ in})/(0.25\text{ in})]$$
$$= 93.9\ \%$$

Since it is assumed that all of the remaining QAC as-constructed means and standard deviations are exactly equal to the target values, the individual pay factors for strength, air content, and initial smoothness are equal to 100 percent (calculated the same as shown in scenario 1). The overall lot pay factor is calculated using the following equation:

$$PF_{LOT(5)} = PF_{STRENGTH} * PF_{THICKNESS} * PF_{AIR\ CONTENT} * PF_{SMOOTHNESS}$$
$$= (1.000) * (0.939) * (1.000) * (1.000) = 0.939 \text{ which translates to } 93.9\%.$$

The total payment to the contractor for the 1.61 km (1.0 mi) lot is calculated using the following equation:

$$\text{Adjusted Bid Price} = \text{Bid Price} * PF_{LOT(5)} = \$165{,}612/\text{km lot}\ (\$266{,}519/\text{mi lot})$$

Scenario 6: Contractor gives a slightly deficient slab thickness mean, but achieves a slightly better strength mean than required by the target values.

The sixth scenario combines scenarios 2 and 4. All of the QAC as-constructed standard deviations are assumed to be equal to the specified target values. The QAC as-constructed means for air content and initial smoothness are also assumed to be equal to the target values. The strength mean is assumed to be slightly higher than the target mean (4,616 kPa [670 psi] compared to 4,479 kPa [650 psi]), and the thickness mean is assumed to be slightly lower than the target mean (27.94 cm [11.00 in] compared to 28.32 cm [11.15 in]).

The individual strength pay factor for the case where the mean and standard deviation equaled 4,616 and 448 kPa (670 and 65 psi), respectively, was calculated to be 107.4 percent (limited to 105.0 percent) under scenario 2. The individual thickness pay factor for the case where the mean and standard deviation equaled 27.94 and 0.64 cm (11.00 and 0.25 in), respectively, was calculated to be 93.3 percent under scenario 4. The QAC as-constructed means and standard deviations are assumed to be exactly equal to the target values for air content and initial smoothness; therefore, the individual pay factors for these QACs are equal to 100 percent (as calculated in scenario 1).

The overall lot pay factor is calculated using the following equation:

$$PF_{LOT(6)} = PF_{STRENGTH} * PF_{THICKNESS} * PF_{AIR\ CONTENT} * PF_{SMOOTHNESS}$$
$$= (1.050) * (0.933) * (1.000) * (1.000) = 0.980 \text{ which translates to } 98.0\%.$$

The total payment to the contractor for the 1.61 km (1.0 mi) lot is calculated using the following equation:

Adjusted Bid Price = Bid Price * $PF_{LOT(6)}$ = $172,707/km lot ($277,938/mi lot)

SUMMARY

An overview of the approach used in the development of a Level 1 prototype PRS is provided. A general discussion of the three proposed levels of PRS implementation is presented. A Level 1 PRS is believed to be a first step in the successful implementation of a practical PRS. The underlying theory of the Level 1 approach is outlined, and the overall methodology for acceptance testing and pay adjustment calculations is presented. The proposed Level 1 approach was noted to have the following features:

- Mathematical relationships between QACs of the pavement and future distress indicators.
- Inclusion of a rational procedure for computing pay adjustments based on the relationships between QACs, rehabilitation policy, and economic principles.
- Consideration of up to four QACs (concrete strength, slab thickness, air content, and initial smoothness) in the development of a rational overall pay adjustment.
- Consideration of within-lot variability and its effect on the pay factor.
- Provision of incentive to the contractor to provide high-quality work by allowing positive as well as negative pay adjustments for all QACs.
- Flexibility in the methodology that allows agencies to use current sampling and testing procedures.

The described level 1 PRS is a simplified version of the prototype PRS presented in previous research work (*3–6*). An ideal PRS (level 3) is a specification that would include all material- and construction-related QACs identified as having a significant effect on pavement performance, being under the control of the contractor, and having reliable distress indicator prediction models. All of these QACs would be measured in situ and by non destructive methods. Obviously, much research is required to develop such a specification. The Level 1 PRS methodology presented in this paper is offered as a first step in the successful implementation of a practical PRS. It is believed that any agency could implement the Level 1 PRS concepts with little adaptation of current agency procedures. The proposed Level 1 approach is offered as a means of introducing PRS concepts and facilitating the transition from current specifications to PRS. A fully practical and comprehensive PRS will only come from the completion of future research.

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TABLE 1 Details of the three proposed PRS implementation levels.

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TABLE 1 Details of the Three Proposed PRS Implementation Levels

PRS Level	PRS Level Description	QACs Included in the PRS	Method of Testing	Pay Factor Computation Method
Level 1—*Simplified PRS*	Uses the underlying concepts of the Level 2 PRS (limited use of PaveSpec software).	• Concrete Strength • Slab Thickness • Air Content • Initial Smoothness	Based on current SHA lot and sublot definitions and sampling and testing procedures. Modifications will be made to current procedures where necessary.	Independent lot pay factors are calculated for each included QAC, then combined into an overall lot pay factor based on LCC (liquidated damages).
Level 2—*Transitional PRS*	The definition of a Level 2 PRS will change to incorporate the results of new research, until the Level 3 PRS is achieved.	• Concrete Strength • Slab Thickness • Initial Smoothness • Air Content • Consolidation Level at Doweled Joints • Tie Bar Depth • Sawcut Depth (These QACs are defined by the field work being conducted in current research).	Focus on in-situ sampling procedures and rapid testing methods.	An overall pay factor is calculated for each lot (based on the premise of liquidated damages) using the PaveSpec software. Measured QAC values, the defined rehabilitation plan, and the developed distress indicator models all influence LCCs.
Level 3—*Ideal PRS*	The Level 3 PRS represents the goal of all Level 2 PRS research. The achievement of the *true* Level 3 PRS requires much research effort and funding.	All QACs that affect PCC pavement performance and are under the control of the contractor.	Focus on nondestructive sampling procedures allowing more sampling, and the near elimination of required testing methods.	Same as Level 2.

TABLE 2 Constant Input Values

Project Information	
Pavement Type	Plain, doweled
Road Location	Rural, 4 or more lanes, divided
Design Life	30 years
Project Length	9.31 kilometers (5.78 miles)
Number of Lanes in One Direction	2
Lane Width	3.7 meters (12 feet)
Joint Spacing	6.1 meters (20 feet)
Traffic Information	
Total Design ESALs	12.7 million
1996 AADT	4,600 vehicles per day
2016 AADT	5,725 vehicles per day
Percent Trucks	28 percent
Design ESALs Per Day	1158
Materials and Climatic Information	
Annual Temperature Range	48.9 °C (120 F°)
Freezing Index	300 degree days
Average Annual Precipitation	88.9 centimeters (35 inches)
Annual Freeze-Thaw Cycles	15
Joint Sealant Type	Liquid
Slab Support Information	
Base Type	Granular
Modulus of Subgrade Reaction	2,188 kPa/cm (125 psi/in)
Subgrade Soil Type	Fine Grained (A-4 to A-7)
Presence of Longitudinal Subdrains	Yes
Load Transfer Information	
Dowel Bar Diameter	3.8 centimeters (1.5 inches)
Presence of Tied PCC Shoulder	No
Cost Information	
Construction Bid	$24.10/m^2 ($ 20.15 /sy)
Cost of Overlay	$10.77/m^2 ($ 9.00 /sy)
Cost of Joint Patching	$95.69/m^2 ($ 80.00 /sy)
Cost of Slab Replacement	$83.73/m^2 ($ 70.00 /sy)
Annual Interest Rate	6 percent
Annual Inflation Rate	3 percent

TABLE 3 Chosen QAC Target Means and Standard Deviations

Quality Characteristic	Target Mean	Target Standard Deviation
28-Day Modulus of Rupture (third-point loading)	4,479 kPa (650 psi)	448 (65 psi)
Slab Thickness	28.32 cm (11.15 in)	0.64 cm (0.25 in)
Air-Content	7.0 %	0.5 %
Initial Smoothness	7.9 cm/km (5.0 in/mi)	1.6 cm/km (1.0 in/mi)

TABLE 4 QAC Best Fit Pay Factor Regression Equations (4 sublots, lot sample size N=8).

Quality Characteristic	As-Constructed Standard Deviation	Pay-Factor Regression Equation, x = mean value in SI units
28-day Modulus of Rupture	0 kPa (0 psi)	$PF_{S-(x,0)} = -(2.844E-5)x^2 + 0.30624x - 690.33$
(third-point loading)	448 kPa (65 psi)	$PF_{S-(x,448)} = -(1.675E-5)x^2 + 0.20581x - 485.81$
	896 kPa (130 psi)	$PF_{S-(x,896)} = -(6.951E-6)x^2 + 0.11611x - 292.78$
Slab Thickness	0.00 cm (0.00 in)	$PF_{T-(x,0.00)} = 16.971x - 379.84$
	0.64 cm (0.25 in)	$PF_{T-(x,0.64)} = 17.478x - 394.98$
	1.27 cm (0.50 in)	$PF_{T-(x,1.27)} = 17.421x - 397.27$
Plastic Air-Content	0.00 %	$PF_{A-(x,0.00)} = 1.6857x + 88.2$
	0.50 %	$PF_{A-(x,0.50)} = 1.6857x + 88.2$
	1.00 %	$PF_{A-(x,1.00)} = 1.9x + 86.7$
Initial Smoothness	0.0 cm/km (0.0 in/mi)	$PF_{SM-(x,0.0)} = (2.801E-4)x^3 - 0.0604x^2 + 0.1796x + 102.72$
	1.6 cm/km (1.0 in/mi)	$PF_{SM-(x,1.6)} = (2.801E-4)x^3 - 0.0604x^2 + 0.1796x + 102.2$
	4.7 cm/km (3.0 in/mi)	$PF_{SM-(x,4.7)} = (2.801E-4)x^3 - 0.0604x^2 + 0.1796x + 100.05$

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FIGURE 1 Pay factor vs. mean flexural strength for different flexural strength standard deviations (5% user costs, 4 sublots).

FIGURE 2 Pay factor vs. mean slab thickness for different slab thickness standard deviations (5% user costs, 4 sublots).

FIGURE 3 Pay factor vs. mean air content for different air content standard deviations (5% user costs, 4 sublots).

FIGURE 4 Pay factor vs. mean initial smoothness for different initial smoothness standard deviations (5% user costs, 4 sublots)

FIGURE 1 Pay factor vs. mean flexural strength for different flexural strength standard deviations (5% User Costs, 4 Sublots)

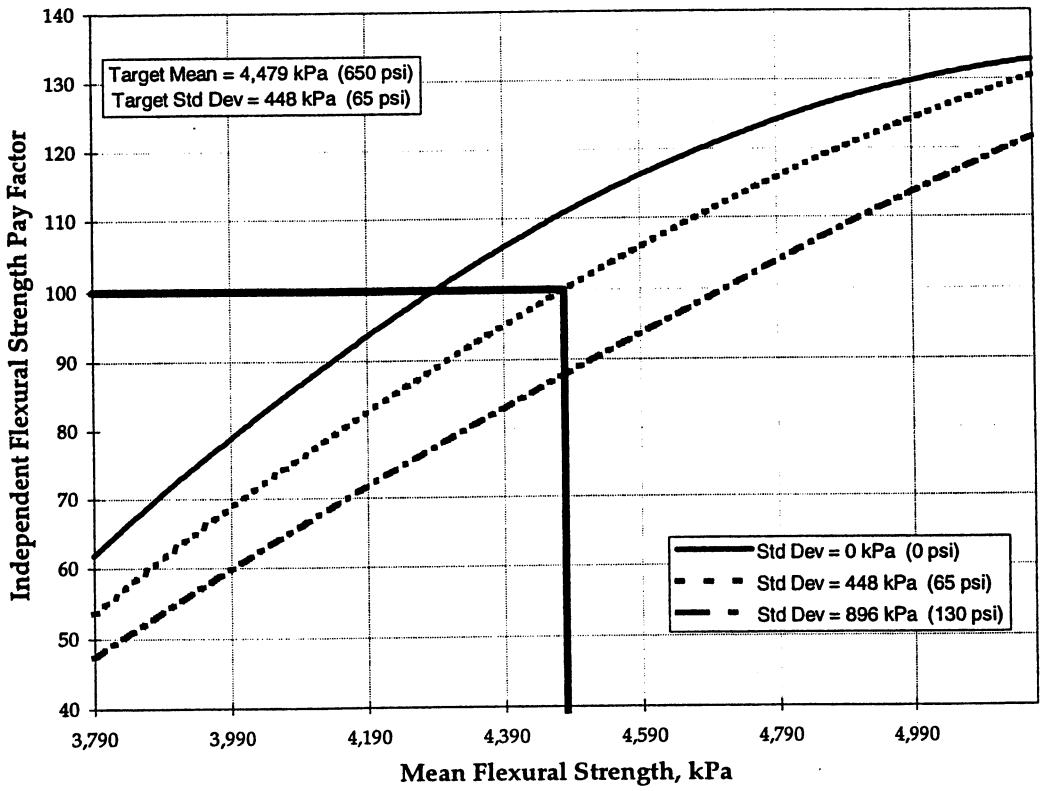


FIGURE 2 Pay factor vs. mean slab thickness for different slab thickness standard deviations (5% User Costs, 4 Sublots)

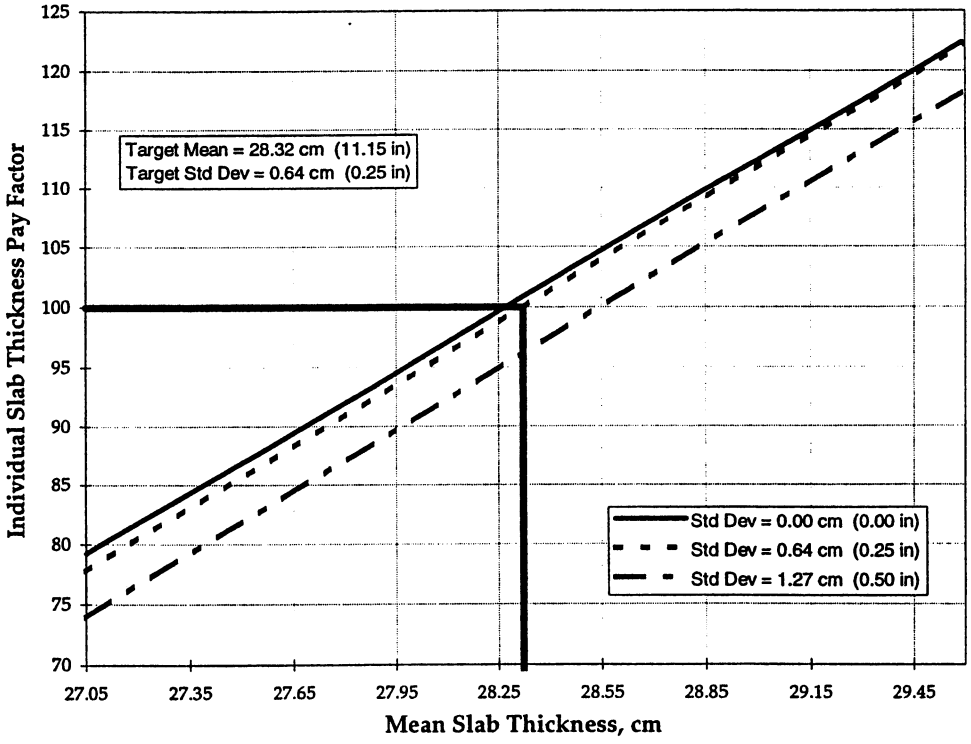


FIGURE 3 Pay factor vs. mean air content for different air content standard deviations (5% User Costs, 4 Sublots)

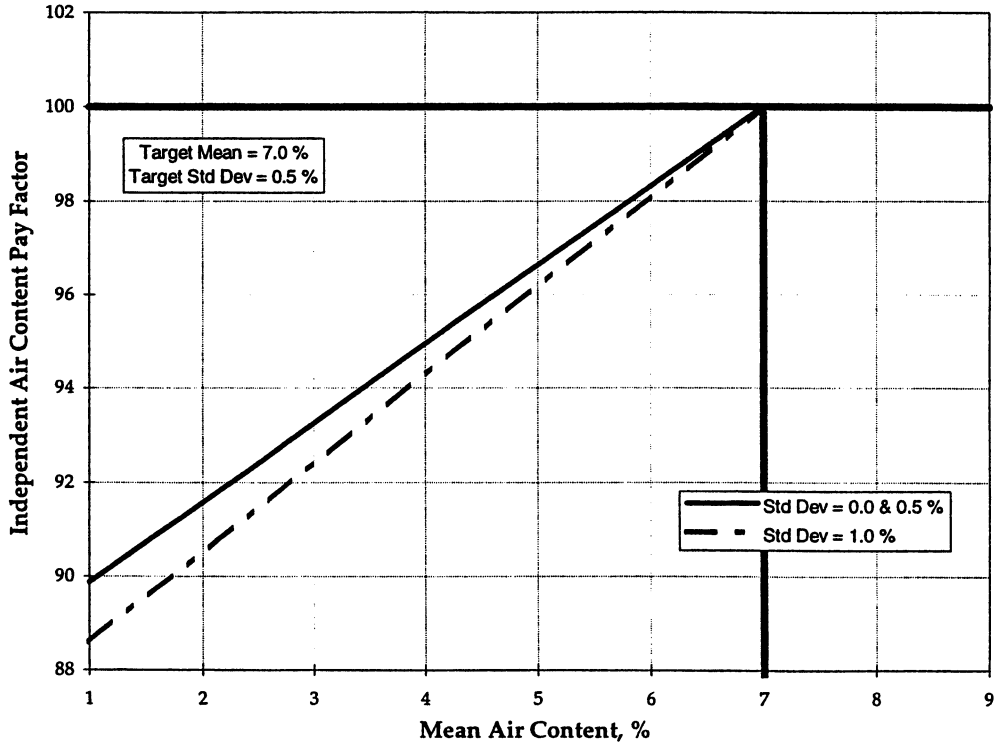
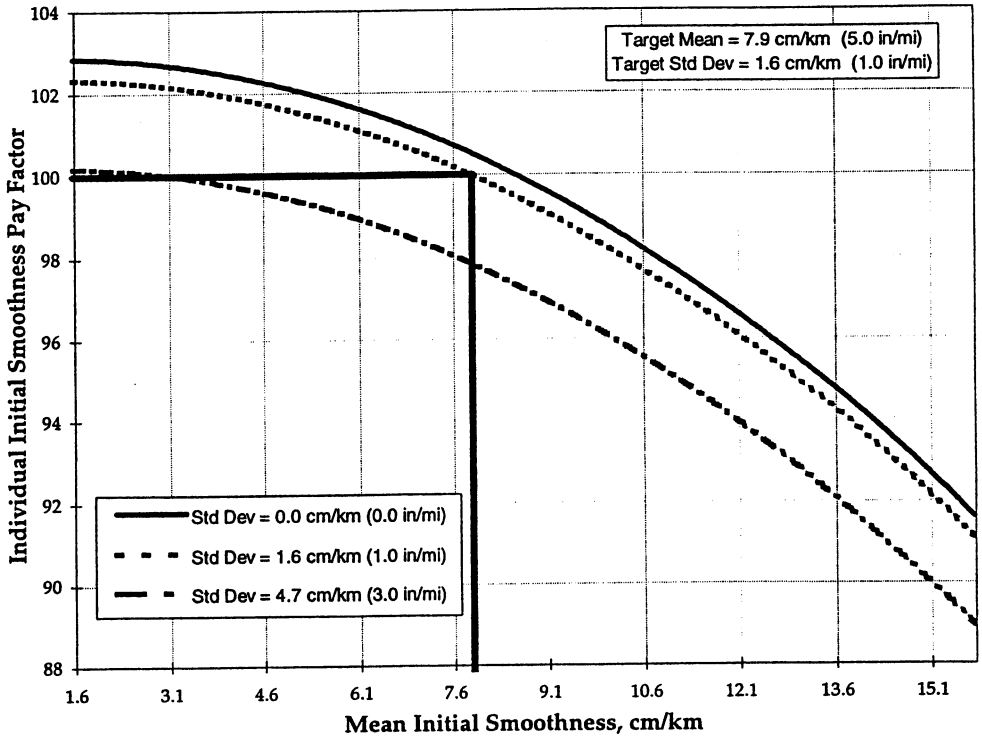


FIGURE 4 Pay factor vs. mean initial smoothness for different initial smoothness standard deviations (5% User Costs, 4 Sublots)



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