

# Implementing Percent within Limits for Hot Mix Asphalt

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## ABSTRACT

The implementation of percent within limit (PWL) specifications for hot mix asphalt is being advocated by the Federal Highway Administration as an improved method for assessing quality over other more traditional methods utilizing mean values. A synthesis published by the National Cooperative Highway Research Program in 2005 shows that 27 out of 45 state agencies surveyed now utilize a form of PWL specifications. The purpose of this paper is to introduce PWL and some of the related aspects, including how to address risk in transitioning from more traditional construction specifications to ones utilizing PWL.

PWL specifications date back to the 1950s, when they were used by the military, and they were first applied by the New Jersey Department of Transportation in the 1970s. The main steps of application are introduced in this paper, together with linking PWL to the common statistical concept of the normal distribution. The PWL methodology has several advantages for both owner/agencies and contractors. There are also several disadvantages to PWL; one notable disadvantage is an incomplete understanding of the PWL concept. Field data are used to evaluate the implications of implementing PWL through simulations and evaluating how to balance the risk between PWL and other traditional specifications.

**Key words:** hot mix asphalt—pay factor—percent within limits

## INTRODUCTION

One of the main issues in any construction project is the evaluation of the project. This includes acceptance or rejection of the final product or applying a factor to the project payment. Pavement is one of the aspects of construction for which these issues are applicable. As with any other project, specifications are set and contractors place their bids based on those specifications. After the project or a project stage is complete, the owner/agency evaluates the product, and based on this evaluation the contractor gets paid. The question at this point is whether the contractor will be paid in full, penalized, or rewarded. This depends on the performance and the quality of the product.

Many different types of pay factor systems exist for highway agencies. A pay factor can be defined as a multiplication factor that is often expressed as a percentage and is used to determine a contractor's payment for a unit of work, based on the estimated quality of work. This term is usually applied to quality characteristics (TRB 2005). The pay factors are calculated based on relations to the main volumetric characteristics specified in a quality control/quality assurance system for hot mix asphalt. Pay factors are determined using three main systems: "percent within limits (PWL), difference between average sample quality characteristics and target job mix formula (JMF), and probability based. All three methods use sample mean values, but only the percent within limits and probability based specifications use the sample standard deviation or variance, which takes into account material variability" (Bausano et al. 2006). In a synthesis published in 2005 by the National Highway Research Program (NCHRP), the most commonly used method is PWL or its complement, percent defective (Hughes 2005). Figure 1 shows that 27 out of the 45 agencies surveyed apply PWL. This paper will focus on the PWL specifications due to the importance of this methodology.

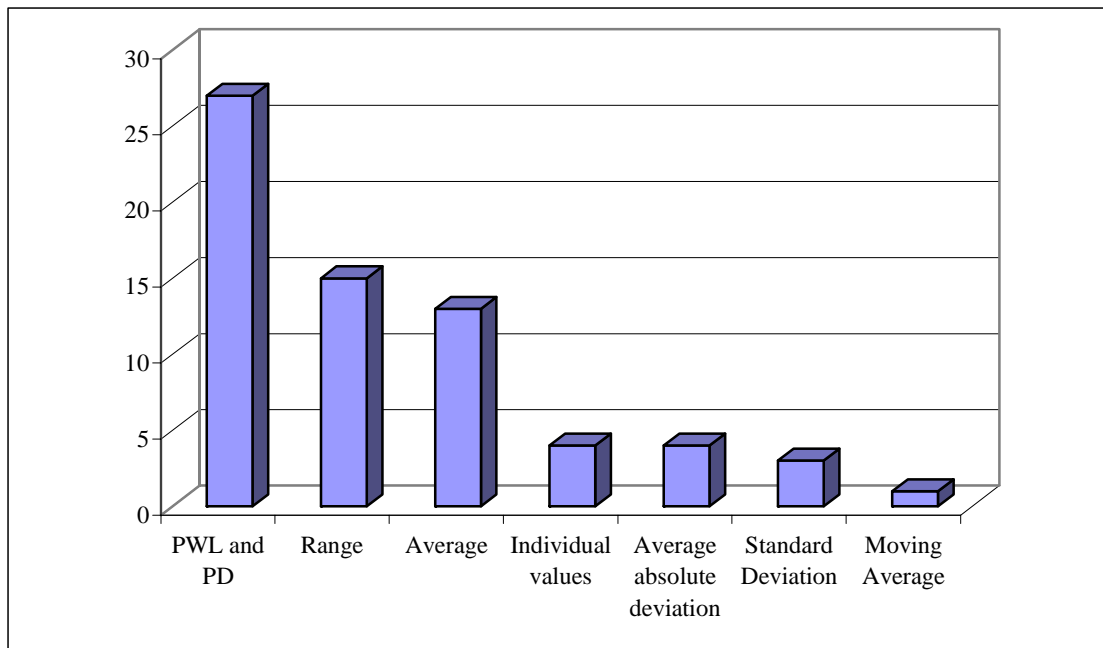


Figure 1. Results from NCHRP Synthesis 346 (Hughes 2005)

## BACKGROUND INFORMATION

PWL is defined as the percentage of the lot falling above the lower specification limit (LSL), beneath the upper specification limit (USL), or between the LSL and the USL. PWL may refer to either the

population value or the sample estimate of the population value. The following formula describes PWL:  $PWL = 100 - PD$ , where PD is the percentage defective (TRB 2005). The history of PWL dates back to the 1950s, when the military started a percent defective method (Newcomb and Epps 2001). The New Jersey Department of Transportation was the first to implement a PWL methodology in the 1970s; however, at that time the name “percent defective” was utilized (Hughes 2006). Later, partially for psychological reasons, the phrase “percent within limits” was implemented in the highway industry (Newcomb and Epps 2001). The other primary reason for the switch to the PWL methodology is that the rejected portion is not defective as the name implies, but it is just of lower quality than the specification limits (Hughes 2006). The PWL, or its complement, the PD, is the recommended statistical measure for material and construction quality in many places. In many cases, the acceptable quality level is 90% within limits, which means 10% is defective or of lesser quality. The advantage of this method is that it combines both the mean and the standard deviation into a single quality measure. For most acceptance quality characteristics, PWL provides a better measure of specified quality than other single statistical measures, such as the average, moving average, average absolute deviation, conformance index, or various other quality indexes (Kopac 2005).

## METHODOLOGY

The concept of applying the PWL procedure is simple and based on the concept of the normal distribution. In a normal distribution curve, the percentage of the population within certain limits can be calculated by knowing the area under the curve. The same concept is applied to specify the percentage within limits for a certain lot. There is in this case the quality index,  $Q$ , that is used to estimate the PWL; it is equivalent to the  $z$ -value for the normal distribution curve. The  $Q$  value is used with a PWL table to determine the estimated PWL for the lot (Burati et al. 2003). The distance of offset of the sample mean from the specification limits in sample standard deviation units is represented by the  $Q$  value. The number of standard deviation units that a sample mean falls inside the specification limits is represented by a positive  $Q$  value. On the other hand, the number of standard deviation units that a sample mean falls outside the specification limits is represented by a negative  $Q$  value (Hughes 2006). In theory, the use of the PWL method assumes that the population being sampled is normally distributed. In practice, it has been found that statistical estimates of quality are reasonably accurate, provided the sampled population is at least approximately normal, i.e., reasonably bell shaped and not bimodal or highly skewed (Burati et al. 2003).

To understand the parameters of the PWL and the main concerns when this method is applied, the calculation procedure is presented. To calculate the PWL, the following procedure is used, as outlined in NCHRP report 451 (Anderson and Russell 2001):

1. The approved JMF and the upper and lower tolerances should be known.
2. Calculate the LSL and the USL using the following equations:

$$LSL = JMF - \text{Lower Tolerance} \quad (1)$$

$$USL = JMF + \text{Upper Tolerance} \quad (2)$$

3. The lower and upper quality indices  $Q_l$  and  $Q_u$  are calculated using the following equations:

$$Q_l = \frac{\bar{x} - LSL}{s} \quad (3)$$

$$Q_u = \frac{USL - \bar{x}}{s} \quad (4)$$

where

- Q<sub>l</sub> = Lower quality index
- Q<sub>u</sub> = Upper quality index
- $\bar{x}$  = Lot average
- s = Lot standard deviation

4. The lower percent within limits (LPWL) and the upper percent within limits (UPWL) are then determined from a PWL table using Q<sub>l</sub> for LPWL and Q<sub>u</sub> for UPWL together with the n value, which represents the sample size.
5. For each quality parameter, the total percent within limits (TPWL) is calculated using the following equation:

$$TPWL = (LPWL + UPWL) - 100 \quad (5)$$

6. TPWL is calculated for each parameter and each lot to obtain the value for a parameter; the average of the TPWL is taken.
7. To determine the PWL for the whole project, a weighted average is taken for the TPWL of each quality parameter according to the weight given to this parameter.

## ADVANTAGES AND DISADVANTAGES OF PERCENT WITHIN LIMITS

The reason that many agencies use PWL specifications can be related to the associated advantages that were presented by Hughes (2006):

- The best combined estimate for the population parameters is provided by PWL.
- PWL as a quality measure is sensitive to variability. This sensitivity gives an advantage to contractors with lower variability in their production.
- The method offers control over production for the contractor. A contractor with low variability can work near the specification limits. A contractor with high variability has to work near the job mix formula to avoid producing materials with quality characteristics outside the limit.
- When PWL is applied, a varying sample size is accounted for in the estimate of quality, which is not the case in the average method.
- Both a contractor and an agency can calculate their risks using PWL.
- Use of PWL is compatible with the American Association of State Highway and Transportation Officials (AASHTO) because it is presented as the “featured method” in R9.
- FHWA technical advisory T6120.3 presents PWL as the “used quality measure.”

With an understanding of the main steps in calculating PWL and knowing the advantages of the method, the following material introduces some of the challenges that may be faced when applying PWL analysis. For example, when the samples are analyzed, the results depend on the mean and standard deviation of the samples. As a result of this, a test may be performed in which all the samples satisfy the requirements, but the statistical analysis may show the percent within limits to be less than 100%. In this case, AASHTO R9 recommends reevaluating the results before applying penalties (AASHTO 2005). The pay factor is applied when the PWL is between two specified levels. If the PWL is below the lower level, the contractor is required to remove and replace the subject lot. The dependence or independence of the selected evaluation items affects the results tremendously. That is, if the factors are dependent, the

probability of their compliance or noncompliance moves together. Alternatively, if the factors are independent, the probability of having one of them not complying is high (Newcomb and Epps 2001).

In an ideal world, the results achieved through testing samples with the same properties should be equal, but in practice they are not. This can be shown clearly in the multilaboratory and multiuser variability, even if the samples are split between the parties. This variation causes uncertainty in the results and causes a risk of rejection when PWL is applied (Manik 2006). The use of PWL imposes uncertainties on all project parties that would not have occurred had the project been evaluated for compliance (e.g., average quality characteristics) without using the PWL approach.

PWL can be misleading because it rewards uniformity. The method does not distinguish between uniformity around a desirable target and uniformity around the threshold of unacceptable properties. This leads to the presence of two types of PWL procedure application. These two types were presented by Mahboub and Hancher (2002), who identified these two types as “blind PWL” and “smart PWL.” Blind PWL is when the PWL procedure is applied without judgment; in this case, the application of PWL procedures may be much too penalty-oriented. Smart PWL is when judgment is involved; this method should replace the blind PWL. Smart PWL is the method that provides for moving the process toward desirable targets. Mahboub and Hancher (2002) presented a two-step process to avoid the problems of PWL:

1. A subplot that does not conform to the specification should be rejected. If this subplot has a high PWL and is not rejected based on this, a second-order adjustment is needed. The severity of the specifications’ violation must be accounted for in this second-order adjustment.
2. A second adjustment should be applied to the results achieved from applying PWL to provide an incentive to the contractors to perform close to the target, not to the specification limits. This adjustment should be applied in case all subplot values are within the specification limits. The adjustment should be made to account for the closeness of the subplot values to a desirable target within the specification limits. This will facilitate contractors making changes in their processes to move away from a uniform but marginally acceptable material to a more desirable material.

One of the problems of PWL is that the number of samples can be infinite, which will lead to a value for the percentage within limits and consequently the percent defective. In this case, it is not clear what is the defect and what are the consequences from this defect. For example, in the case of asphalt content, the percent defective does not show whether it is higher or lower asphalt content, although each case will result in a different pavement performance because too much asphalt content leads to bleeding and loss of skid resistance and too little asphalt content leads to early deterioration (Kopac 2005). It can be concluded that the use of PWL is good as a statistical method, but it does not correlate strongly with performance. This causes problems for highway agencies that seek to have a pay factor related to quality represented in the expected pavement performance (Kopac 2005).

One of the main factors that affects the results from PWL analysis is the calculation and rounding procedure used. When the pay factor is calculated based on PWL, this issue can be a point of conflict. This is because the values from the tables can be rounded up, rounded down, or interpolated. A contractor usually prefers the rounding up because it increases the PWL achieved. The method of rounding must be specified prior to implementation to ensure that there are no conflicts regarding this issue. As a result, it is important for an agency to stipulate the calculation process, including number of decimal places to be carried in the calculations, as well as the exact manner in which the PWL table is to be used (Burati et al. 2003).

There are three cases that can occur when a PWL is applied. The first case is when the percent within limits is very high; in this case, the contractor is rewarded. The second case is when the percentage within limits is low, but higher than a certain value; in this case, the contractor is penalized. The last case is when the percentage within limits falls below the lower specified limit; in this case, the contractor has to repeat the work (Pavement Digest 2006).

## CASE STUDY

Percent within limits simulation was conducted on data provided by Iowa contractors to examine the implications of its implementation. It is important to understand that these simulations represent project data that includes multiple lots, because multiple test values of certain quality characteristics were not measured for each lot, as this is not required for the existing specification. The quality characteristics examined were laboratory voids based on field mix compacted in the laboratory (laboratory voids), binder content ( $P_{be}$ ), percent passing the 0.075mm sieve, and the field voids based on field cores. The following criteria for the quality characteristics were used in conducting the percent within limit simulation utilizing Iowa contractor data:

- Laboratory voids: Design +/- 1% (3%–5%),
- Effective binder content ( $P_{be}$ ): Design +/- 0.3%,
- Percent passing the 0.075 sieve (P200): Design +/- 2%, and
- Field voids: 4%–8%.

The calculation of the lower and upper quality indices was done according to the Oregon Department of Transportation (ODOT) specification, which follows the NCHRB 451 methodology presented earlier. Tables presented by ODOT (2006) were used to calculate the PWL and pay factors from the quality indices. The project pay factor was calculated to be the average of the pay factors of lab voids, binder content, percentage passing sieve number 200 (P200), and field voids, as is done in Oregon. Other PWL specifications have various weightings of the quality characteristic pay factors, i.e., they are not necessarily equal. Table 1 summarizes the outcomes of the PWL simulations.

**Table 1. PWL Calculation for Iowa projects using ODOT specifications**

| Project | Characteristic | Mean | St. dev | n  | $Q_L$ | $P_L$ | $Q_U$ | $P_U$ | $P_T$ | PF    | Average PF |
|---------|----------------|------|---------|----|-------|-------|-------|-------|-------|-------|------------|
| 1       | Lab Voids      | 3.30 | 0.58    | 10 | 2.93  | 100   | 0.52  | 69    | 69    | 0.91  | 1.0000     |
|         | Binder Content | 5.11 | 0.10    | 10 | 4.40  | 100   | 1.60  | 95    | 95    | 1.04  |            |
|         | P200           | 3.66 | 0.21    | 10 | 8.28  | 100   | 10.76 | 100   | 100   | 1.05  |            |
|         | Field Voids    | 6.81 | 1.13    | 9  | 1.05  | 85    | 2.49  | 100   | 85    | 1.01  |            |
| 2       | Lab Voids      | 3.86 | 0.40    | 24 | 2.85  | 100   | 2.15  | 99    | 99    | 1.05  | 0.9700     |
|         | Binder Content | 4.82 | 0.10    | 24 | 5.70  | 100   | 0.30  | 62    | 62    | 0.81  |            |
|         | P200           | 3.52 | 0.31    | 24 | 5.10  | 100   | 7.81  | 100   | 100   | 1.05  |            |
|         | Field Voids    | 5.93 | 0.36    | 24 | 5.75  | 100   | 5.36  | 100   | 100   | 1.05  |            |
| 3       | Lab Voids      | 4.18 | 0.32    | 20 | 2.56  | 99    | 3.69  | 100   | 99    | 1.05  | 1.0417     |
|         | Binder Content | 4.93 | 0.10    | 20 | 4.60  | 100   | 1.40  | 92    | 92    | 1.025 |            |
|         | P200           | 4.75 | 0.15    | 20 | 9.67  | 100   | 17.00 | 100   | 100   | 1.05  |            |
|         | Field Voids    | 6.90 | 0.64    | 20 | 1.72  | 96    | 4.53  | 100   | 96    | 1.04  |            |
| 4       | Lab Voids      | 3.10 | 0.40    | 11 | 4.75  | 100   | 0.25  | 59    | 59    | 0.83  | 0.9767     |
|         | Binder Content | 5.48 | 0.07    | 11 | 3.57  | 100   | 5.00  | 100   | 100   | 1.05  |            |
|         | P200           | 4.60 | 0.12    | 5  | 14.17 | 100   | 19.17 | 100   | 100   | 1.05  |            |
|         | Field Voids    | 5.95 | 0.35    | 10 | 5.86  | 100   | 5.57  | 100   | 100   | 1.05  |            |

**Table 1. Continued**

| Project | Characteristic | Mean | St. dev | n  | QL    | PL  | QU    | PU  | PT  | PF            | Average PF |
|---------|----------------|------|---------|----|-------|-----|-------|-----|-----|---------------|------------|
| 5       | Lab Voids      | 4.25 | 0.52    | 17 | 1.44  | 93  | 2.40  | 99  | 92  | 1.03          | 1.0433     |
|         | Binder Content | 5.65 | 0.13    | 5  | 1.77  | 100 | 2.85  | 100 | 100 | 1.05          |            |
|         | P200           | 4.87 | 0.08    | 5  | 11.62 | 100 | 38.38 | 100 | 100 | 1.05          |            |
|         | Field Voids    | 6.82 | 0.47    | 5  | 2.51  | 100 | 6.00  | 100 | 100 | 1.05          |            |
| 6       | Lab Voids      | 3.90 | 0.45    | 45 | 2.44  | 99  | 2.00  | 98  | 97  | 1.04          | 1.0200     |
|         | Binder Content | 5.58 | 0.23    | 14 | 1.04  | 85  | 1.56  | 95  | 80  | 0.97          |            |
|         | P200           | 5.66 | 0.30    | 14 | 2.47  | 99  | 10.87 | 100 | 99  | 1.05          |            |
|         | Field Voids    | 7.57 | 0.34    | 7  | 1.26  | 90  | 10.50 | 100 | 90  | 1.03          |            |
| 7       | Lab Voids      | 4.18 | 0.38    | 39 | 2.16  | 99  | 3.10  | 100 | 99  | 1.05          | 1.0100     |
|         | Binder Content | 4.68 | 0.11    | 13 | 4.08  | 100 | 0.64  | 74  | 74  | 0.93          |            |
|         | P200           | 5.15 | 0.42    | 13 | 2.74  | 100 | 6.78  | 100 | 100 | 1.05          |            |
|         | Field Voids    | 7.02 | 0.91    | 13 | 1.08  | 86  | 3.32  | 100 | 86  | 1.005         |            |
| 8       | Lab Voids      | 3.89 | 0.52    | 40 | 2.13  | 98  | 1.71  | 96  | 94  | 1.025         | Reject     |
|         | Binder Content | 4.54 | 0.13    | 14 | 6.23  | 100 | -1.62 | 50  | 50  | <b>Reject</b> |            |
|         | P200           | 5.02 | 0.34    | 21 | 4.06  | 100 | 7.70  | 100 | 100 | 1.05          |            |
|         | Field Voids    | 7.36 | 1.02    | 14 | 0.63  | 73  | 3.29  | 100 | 73  | 0.925         |            |
| 9       | Lab Voids      | 4.04 | 0.75    | 20 | 1.28  | 90  | 1.39  | 92  | 82  | 0.965         | 1.0100     |
|         | Binder Content | 4.47 | 0.20    | 8  | 1.15  | 88  | 1.85  | 98  | 86  | 1.015         |            |
|         | P200           | 4.66 | 0.63    | 10 | 2.76  | 100 | 3.59  | 100 | 100 | 1.05          |            |
|         | Field Voids    | 6.74 | 0.90    | 8  | 1.40  | 93  | 3.04  | 100 | 93  | 1.04          |            |
| 10      | Lab Voids      | 3.50 | 0.50    | 52 | 1.00  | 85  | 3.00  | 100 | 85  | 0.97          | 1.0100     |
|         | Binder Content | 5.04 | 0.09    | 19 | 5.44  | 100 | 1.22  | 89  | 89  | 1.01          |            |
|         | P200           | 3.64 | 0.35    | 22 | 7.26  | 100 | 4.17  | 100 | 100 | 1.05          |            |
|         | Field Voids    | -    | -       | -  | -     | -   | -     | -   | -   | -             |            |
| 11      | Lab Voids      | 3.56 | 0.57    | 42 | 0.98  | 84  | 2.53  | 100 | 84  | 0.96          | 0.9900     |
|         | Binder Content | 4.99 | 0.13    | 14 | 3.54  | 100 | 1.08  | 86  | 86  | 1             |            |
|         | P200           | 4.88 | 0.38    | 17 | 7.58  | 100 | 2.95  | 100 | 100 | 1.05          |            |
|         | Field Voids    | 6.54 | 1.29    | 91 | 1.97  | 98  | 1.13  | 87  | 85  | 0.95          |            |
| 12      | Lab Voids      | 4.07 | 0.50    | 16 | 0.36  | 64  | 0.84  | 80  | 44  | <b>Reject</b> | Reject     |
|         | Binder Content | 3.93 | 0.12    | 5  | 7.75  | 100 | 8.92  | 100 | 100 | 1.05          |            |
|         | P200           | 3.57 | 0.39    | 7  | 6.33  | 100 | 3.92  | 100 | 100 | 1.05          |            |
|         | Field Voids    | 6.73 | 0.79    | 28 | 3.46  | 100 | 1.61  | 95  | 95  | 1.03          |            |

The data were also analyzed using the methodology utilizing quality characteristics and their acceptable ranges currently implemented by the Iowa Department of Transportation (Iowa DOT) to calculate the pay factor (Iowa DOT 2006). In this methodology, the quality index was calculated for the density using equation 6, and the pay factor for density, gradation, P200, binder content, and film thickness was determined from tables in the Iowa DOT specifications. The results of the analysis are presented in Table 2.

$$QI_{Density} = \frac{(Average - G_{mb})_{FieldLot} - ((\% Density)_{specified} \times (Average - G_{mb})_{LabLot})}{(Standard - Deviation - G_{mb})_{Field - Lot}} \quad (6)$$

**Table 2. Pay factor calculations using Iowa DOT methodology**

|    | QI<br>(Density) | Deductions |                   |                             |        |                    | Total | Pay Factor |
|----|-----------------|------------|-------------------|-----------------------------|--------|--------------------|-------|------------|
|    |                 | Density    | Film<br>Thickness | Gradation<br>(without P200) | P(200) | Asphalt<br>Content |       |            |
| 1  | 0.0727          | 15         | 0                 | 0                           | 2      | 0                  | 17    | 0.83       |
| 2  | 0.3152          | 15         | 0                 | 0                           | 2      | 0                  | 17    | 0.83       |
| 3  | 0.1509          | 15         | 0                 | 0                           | 2      | 0                  | 17    | 0.83       |
| 4  | 0.2750          | 15         | 0                 | 0                           | 2      | 0                  | 17    | 0.83       |
| 5  | 0.4914          | 5          | 0                 | 0                           | 6      | 0                  | 11    | 0.89       |
| 6  | 0.3799          | 15         | 0                 | 0                           | 6      | 0                  | 21    | 0.79       |
| 7  | 0.1553          | 15         | 0                 | 8                           | 2      | 0                  | 25    | 0.75       |
| 8  | 0.0814          | 15         | 0                 | 8                           | 6      | 12                 | 41    | 0.59       |
| 9  | 0.1145          | 15         | 0                 | 8                           | 6      | 0                  | 29    | 0.71       |
| 10 | -               | -          | 0                 | 0                           | 2      | 0                  | 2     | 0.98       |
| 11 | 0.0670          | 15         | 0                 | 0                           | 4      | 0                  | 19    | 0.81       |
| 12 | 0.1264          | 15         | 0                 | 4                           | 2      | 0                  | 21    | 0.79       |

It is important to understand that the pay factors developed here are based upon project-level data and not based upon lot data, as the comparison for project-level comparisons can be made, e.g., multiple test results for all the quality characteristics do not exist in the current specifications for use in PWL specifications. The results from both analysis methods can now be compared, since the same projects were used for both of them. The following can be concluded from the comparison:

- Iowa DOT specifications do not include a bonus opportunity, which is available in the ODOT specifications.
- Pay factors calculated using the Iowa DOT specifications are lower than those calculated using ODOT specifications, and the difference cannot be attributed to the bonus opportunity, as this is more than the 5% bonus opportunity.
- PWL methodology identified two projects that should be rejected, while in the Iowa DOT methodology the pay factor was reduced from full pay.
- If the Iowa DOT implemented the PWL methodology, a set of equations or tables needs to be developed to calculate the pay factor based on the PWL.

## CONCLUSIONS

The advantage of the use of the PWL is that it combines two important statistical measures, mean and standard deviation, in one parameter (Burati et al. 2003). Combining these two parameters can lead to some ambiguity in the results. Some highway agencies use the mean and standard deviation directly to calculate the pay factor. These agencies have charts relating the mean and standard deviation values to contractor payment. The use of this method eliminates the ambiguity caused by using PWL, which hides some of the population properties when the results are blended together (Kopac 2005). It is important when applying PWL to understand the statistical background behind the method and to apply judgment to the results to be able to obtain the optimum results. It is also important that the specifications be clear and that every issue is addressed in detail, e.g., rounding. Adding incentives to having results towards the desired value, not just within the required range, is important because PWL, as previously mentioned, rewards uniformity within any point of the specified range.

The methodology used by the Iowa DOT to calculate pay factor leads to lower pay factors than the methodology implemented by ODOT. It is important to note that, although two projects were acceptable

using the Iowa DOT methodology, these projects were rejected using the ODOT methodology. For Iowa to implement the PWL methodology, a new calculation method for the pay factor should be adopted, and a decision should be made whether to incorporate an incentive or not.

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