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COMMITTEE ON MANAGEMENT OF QUALITY ASSURANCE (A2F03)

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Introduction

Highway quality assurance (QA), like many other specialized subject areas, has its own unique language containing numerous technical terms or expressions having very specific meanings. Some of these terms are not well understood, and their use is subject to a variety of different interpretations. The highway QA language, moreover, is continually changing to keep pace with advances in QA. As new terms come into general use, older terms must often be perceived in a new light. The terminology has grown and evolved steadily since the mid-60s, when much of it was first introduced to the highway community; however, its growth and evolution have been to a large degree uncontrolled.

This document contains terms of common usage and accepted practice. The Circular was generated by a subcommittee, chaired by Peter Kopac, of the Transportation Research Board (TRB) Committee on Management of Quality Assurance (A2F03).

PURPOSE

The purpose of this publication is to provide a reference document containing a recommended standard for usage of highway QA terminology. In developing this publication, the committee reviewed the evolution of the highway QA language, assessed its current condition, and attempted to define not what it is today but *what it should be*.

ORGANIZATION

This publication is divided into four parts: an index, a glossary of highway QA terms, a list of recommended abbreviations and symbols, and a list of references. The major part is the glossary. The terms selected for definition include many terms that are frequently misinterpreted, misunderstood, or generally confusing. The definitions provided are often more than dictionary definitions; they attempt to clarify the sources of confusion. This was done by examining specific topics within highway QA (for example, process control) and focusing on groups of related terms within a topic in order to develop a better understanding of the uniqueness of each individual term. Thus, the glossary terms do not appear alphabetically but are grouped by topic; and within each topic, terms that need to be compared to point out their distinctions are located next to one another. Within some definitions, brackets are used to isolate editorial comments not actually needed as part of a definition but helpful in establishing a better understanding of the term and/or the topic. Also several key figures are provided to illustrate important concepts and strengthen the understanding of relationships among terms.

Because terms are not alphabetical in the glossary, the index can be used to assist the user in more quickly locating a term. The index shows the topic under which a term may be found. It also identifies the reference(s) that were used to develop a definition. The subcommittee, in forming definitions, examined many glossaries and publications containing definitions. It then took, from these existing definitions, what it believed to be the best thoughts and wording and most necessary features, making only minor changes, to create appropriate definitions for use today. Some judgment was used in determining which references should be cited. Because definitions found in the examined publications were seldom referenced, it was decided to cite publications of major standards-producing organizations [such as American Society for Testing and Materials (ASTM), American Association of State and Highway Transportation Officials (AASHTO), American National Standards Institute (ANSI), and American Society for Quality (ASQ)] in all cases where there was agreement with the glossary definition, and to cite only the earliest (i.e., oldest) other publications that may have provided some element to, or was the sole source of, a glossary definition.

NEED FOR UPDATES AND COMMENTS

This publication is an update of the 1996 *Transportation Research Circular Number 457* and the 1999 *Transportation Research Circular E-C010*. The Committee intends to continue to provide updates when necessary. One aspect of the updating is simply to improve the quality of the definitions. Such improvements are certainly anticipated once the definitions are put to use and specific problems or shortcomings are identified by the user. Another aspect of updating includes the addition of new terms that may come into use, along with the review and possible modification of existing definitions to accommodate new understanding resulting from the new term. This latter aspect attempts to account for the dynamic nature of the highway QA language. Still another aspect of updating is the addition of new terms within topics not addressed in this publication. Many additional topics are possible for inclusion in future revisions of the glossary; some topics may require coordination with other TRB committees to best establish suitable definitions.

Closely related to update of glossary definitions is improvement of the overall publication. For example, the referenced sources in this publication may not be entirely accurate, primarily due to the difficulties in identifying the earliest document responsible for creating a definition; therefore, some of the references may need to be corrected. The Committee welcomes any comments or suggestions on how either the definitions themselves or any other parts of this publication can be improved to meet the users' needs and to better provide a reference document that fosters uniformity and understanding. Comments or suggestions should be directed to Peter Kopac, telephone 202-493-3151; fax: 202-493-3161; e-mail: peter.kopac@fhwa.dot.gov.

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Glossary

QUALITY ASSURANCE ELEMENTS

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

Quality control (QC). Also called **process control**. Those QA actions and considerations necessary to assess and adjust production and construction processes so as to control the level of quality being produced in the end product.

Acceptance. Sampling and testing, or inspection, to determine the degree of compliance with contract requirements.

Independent assurance. A management tool that requires a third party, not directly responsible for process control or acceptance, to provide an independent assessment of the product and/or the reliability of test results obtained from process control and acceptance testing. [The results of independent assurance tests are not to be used as a basis of product acceptance.]

Verification. The process of determining or testing the truth or accuracy of test results by examining the data and/or providing objective evidence. [Verification sampling and testing may be part of an independent assurance program (to verify contractor QC testing or agency acceptance) or part of an acceptance program (to verify contractor testing used in the agency's acceptance decision).]

TABLE 1 QA Versus QC

Quality Assurance	Quality Control
Making sure the quality of a product is what it should be (*8, 22*).	Making the quality of a product what it should be (*8, 22*).
A highway agency responsibility.	A producer/contractor responsibility.
Includes QC.	A part of QA.
Doing the right things.	Doing things right.
Motivates good QC practices.	Motivated by QA and acceptance procedures.

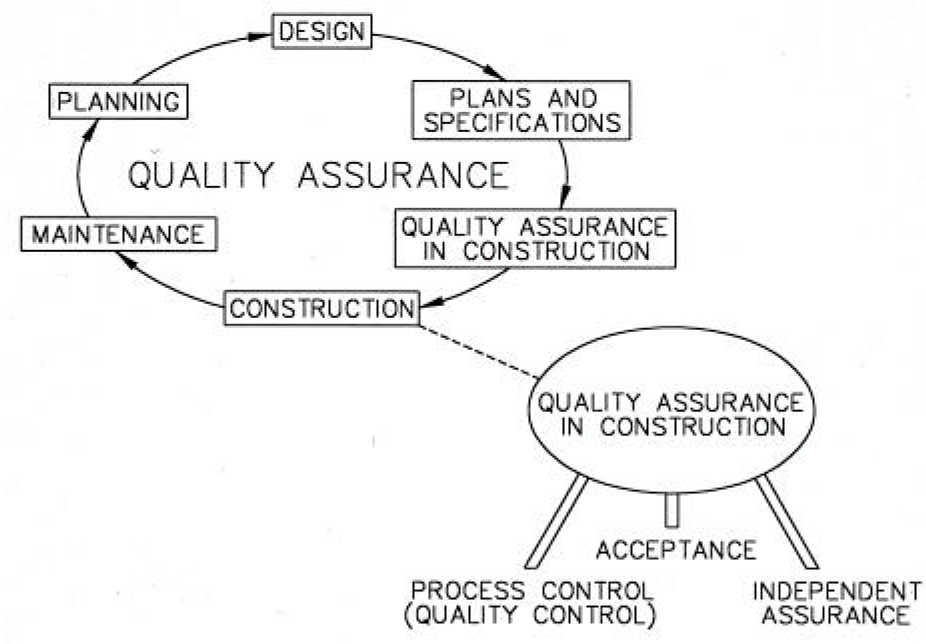

FIGURE 1 QA system elements (*24*, *39*).

Validation. The process of verifying the soundness or effectiveness of a product (such as a model, a program, or specifications) thereby indicating official sanction.

Dispute resolution. Also called **conflict resolution**. For QA programs permitting contractor acceptance testing, procedure to resolve conflicts resulting from discrepancies between the agency's and contractor's results of sufficient magnitude to have an impact on payment. [The procedure may, as an initial step, include the testing of independent samples and, as a final step, third-party arbitration.]

Mixture design. (1) The process of determining and quantifying the required performance characteristics of a mixture, including developing, evaluating, and testing trial mixtures to verify that the required characteristics can be met. For portland cement concrete (PCC) mixtures, some examples of required characteristics are workability, durability, and strength; and for asphalt concrete (AC) mixtures, examples are rutting resistance and fatigue cracking resistance. [The mixture design process leads to the development of a mixture specification.] (2) A quantified description (resulting from the mixture design process) of a mixture developed, evaluated, and tested to meet the specifications.

Mixture proportioning. The identification of mixture ingredients and the selection of appropriate quantities of these ingredients to fulfill the mixture design. [The mixture proportioning process results in a quantification of the mixture ingredients by weight or by volume.]

TYPES OF SPECIFICATIONS

Materials and methods specifications. Also called **method specifications**, **recipe specifications**, or **prescriptive specifications**. Specifications that direct the contractor to use specified materials in definite proportions and specific types of equipment and methods to place the material. Each step is directed by a representative of the highway agency. [Experience has shown this tends to obligate the agency to accept the completed work regardless of quality.]

End result specifications. Specifications that require the contractor to take the entire responsibility for supplying a product or an item of construction. The highway agency's responsibility is to either accept or reject the final product or to apply a price adjustment commensurate with the degree of compliance with the specifications. [End result specifications have the advantage of affording the contractor flexibility in exercising options for new materials, techniques, and procedures to improve the quality and/or economy of the end product.]

Quality assurance specifications. Also called **QA/QC specifications** or **QC/QA specifications**. A combination of end result specifications and materials and methods specifications. The contractor is responsible for QC (process control), and the highway agency is responsible for acceptance of the product. [QA specifications typically are statistically based specifications that use methods such as random sampling and lot-by-lot testing, which let the contractor know if the operations are producing an acceptable product.]

Statistically based specifications. Also called **statistical specifications** or **statistically oriented specifications**. Specifications based on random sampling, and in which properties of the desired product or construction are described by appropriate statistical parameters.

Performance specifications. Specifications that describe how the finished product should perform over time. [For highways, performance is typically described in terms of changes in physical condition of the surface and its response to load, or in terms of the cumulative traffic required to bring the pavement to a condition defined as "failure." Specifications containing warranty/guarantee clauses are a form of performance specifications. Other than the warranty/guarantee type, performance specifications have not been used for major highway pavement components (subgrades, bases, riding surfaces) because there have not been appropriate nondestructive tests to measure long-term performance immediately after construction. They have been used for some products (e.g., highway lighting, electrical components, and joint sealant materials) for which there are tests of performance that can be conducted rapidly.]

Performance-based specifications. QA specifications that describe the desired levels of fundamental engineering properties (e.g., resilient modulus, creep properties, and fatigue properties) that are predictors of performance and appear in primary prediction relationships (i.e., models that can be used to predict pavement stress, distress, or performance from combinations of predictors that represent traffic, environmental, roadbed, and structural conditions.) [Because most fundamental engineering properties associated with pavements are currently not amenable to timely acceptance testing, performance-based specifications have not found application in highway construction.]

Performance-related specifications. QA 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 AC and compressive strength of PCC) 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.]

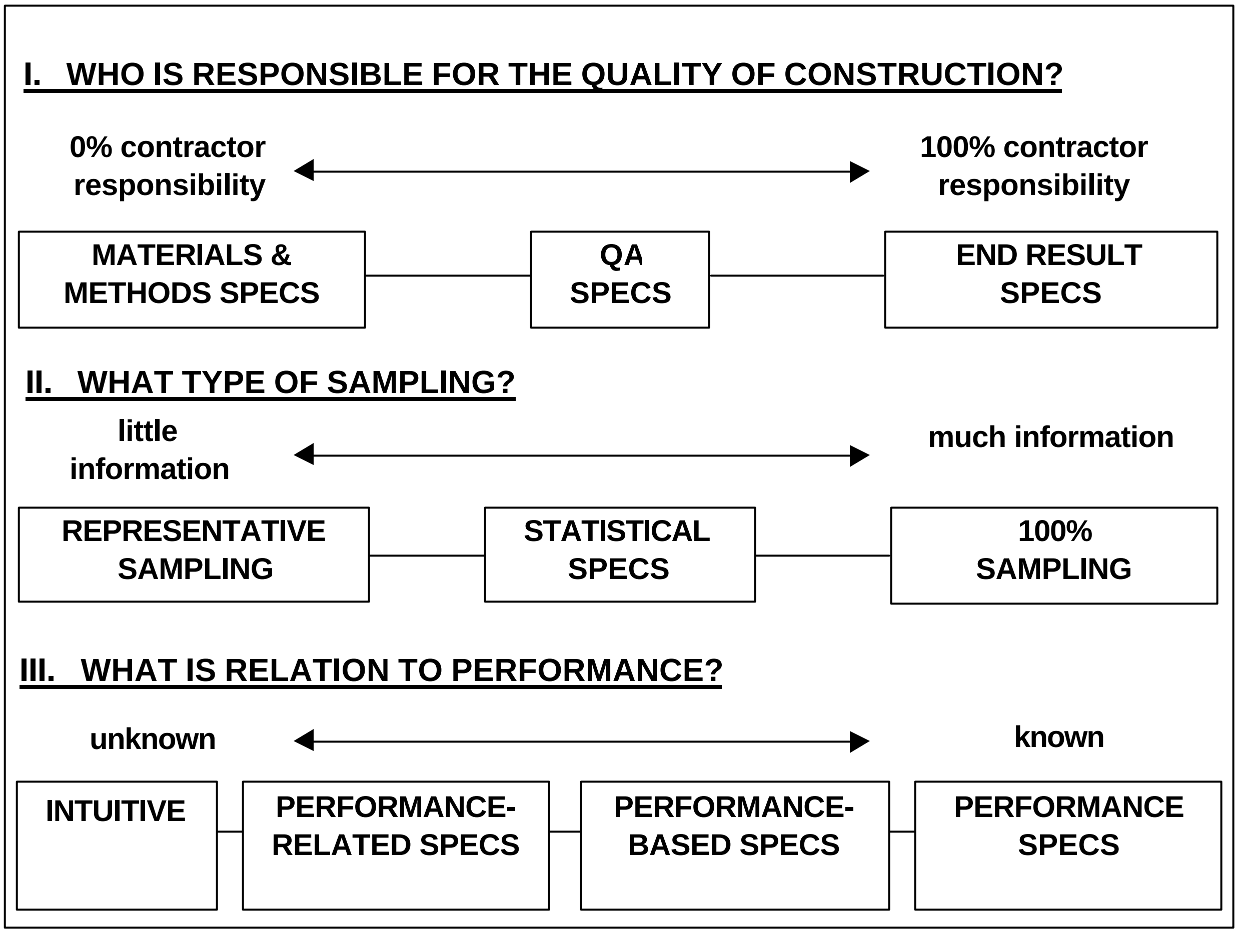

FIGURE 2 Classifying highway construction specifications (*38*). Highway construction specifications may be classified according to (I) who is responsible for the quality of construction, (II) the type of sampling employed, and (III) the relationship between quality criteria and constructed product performance. Thus, a QA specification according to classification I, for example, might be a statistical specification for classification II, and contain intuitive specification limits and pay adjustments for classification II. A specification might also, and usually does, contain one or more features within the same classification. For example, a specification that is primarily performance-related might contain some performance-based acceptance criteria and some intuitively developed acceptance criteria.

ACCEPTANCE PLANS

Acceptance plan. An agreed-upon method of taking samples and making measurements or observations on these samples for the purpose of evaluating the acceptability of a lot of material or construction.

Attributes acceptance plan. A statistical acceptance procedure where the acceptability of a lot of material or construction is evaluated by noting (1) the presence or absence of some characteristic or attribute in each of the units or samples in the group under consideration and (2) counting how many units do or do not possess this characteristic.

Variables acceptance plan. A statistical acceptance procedure where quality is evaluated by (1) measuring the numerical magnitude of a quality characteristic for each of the units or samples in the group under consideration and (2) computing statistics such as the average and the standard deviation of the group.

Lot. Also called **population**. A specific quantity of similar material, construction, or units of product, subjected to either an acceptance or process control decision. [A lot, as a whole, is assumed to be produced by the same process.]

Split sample. A sample that has been divided into two or more portions representing the same material. [Split samples are sometimes taken to verify the acceptability of an operator's test equipment and procedure. This is possible because the variability calculated from differences in split test results is comprised solely of testing variability.]

Independent sample. A sample taken without regard to any other sample that may also have been taken to represent the material in question. [An independent sample is sometimes taken to verify an acceptance decision. This is possible because the data sets from independent samples, unlike those from split samples, each contain independent information reflecting all sources of variability, i.e., materials, sampling, and testing.]

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 quality characteristic. The pay factors are usually expressed as percentages of the contractor's bid price per unit of work.

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 some incentive/disincentive for high/low quality.]

TABLE 2 Understanding Pay Adjustment Schedule and Related Terms

- A pay adjustment schedule typically refers to only one quality characteristic. A pay adjustment system refers to more than one schedule or to a schedule which considers several quality characteristics.
- Pay adjustment schedules may be categorized as
  - Graduated (stepped) schedules versus continuous schedules.
  - Tabular schedules versus schedules in equation form.
  - Schedules that provide pay factors versus schedules that provide pay adjustment dollar amounts.
- Pay adjustment schedules, including those that allow pay increases, do not necessarily function as incentive/disincentive provisions.
- Pay adjustment schedules may or may not be based on liquidated damages.

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 which 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.]

Liquidated damages provision (for quality). A pay adjustment schedule whose primary function is to recover costs associated with the contractor's failure to provide the desired level of quality.

Pay factor. A multiplication factor, often expressed as a percentage, used to adjust the contractor's bid price per unit of work, based on the estimated quality of work. [Typically, the term "pay factor" applies to only one quality characteristic.]

Pay adjustment. The actual amount, either in dollars or in dollars per area/weight/volume, that is to be added or subtracted to the contractor's bid price or unit bid price.

Composite pay factor. 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.

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 (for accept/reject acceptance plans) or (2) the probability of its acceptance at various payment levels (for acceptance plans that include pay adjustment provisions).

Expected pay (EP) curve. A graphic representation of an acceptance plan that shows the relation between the actual quality of a lot and its EP (i.e., mathematical pay expectation, or the average pay the contractor can expect to receive over the long run for submitted lots of a given quality). [Both OC and EP curves should be used to evaluate how well an acceptance plan is theoretically expected to work.]

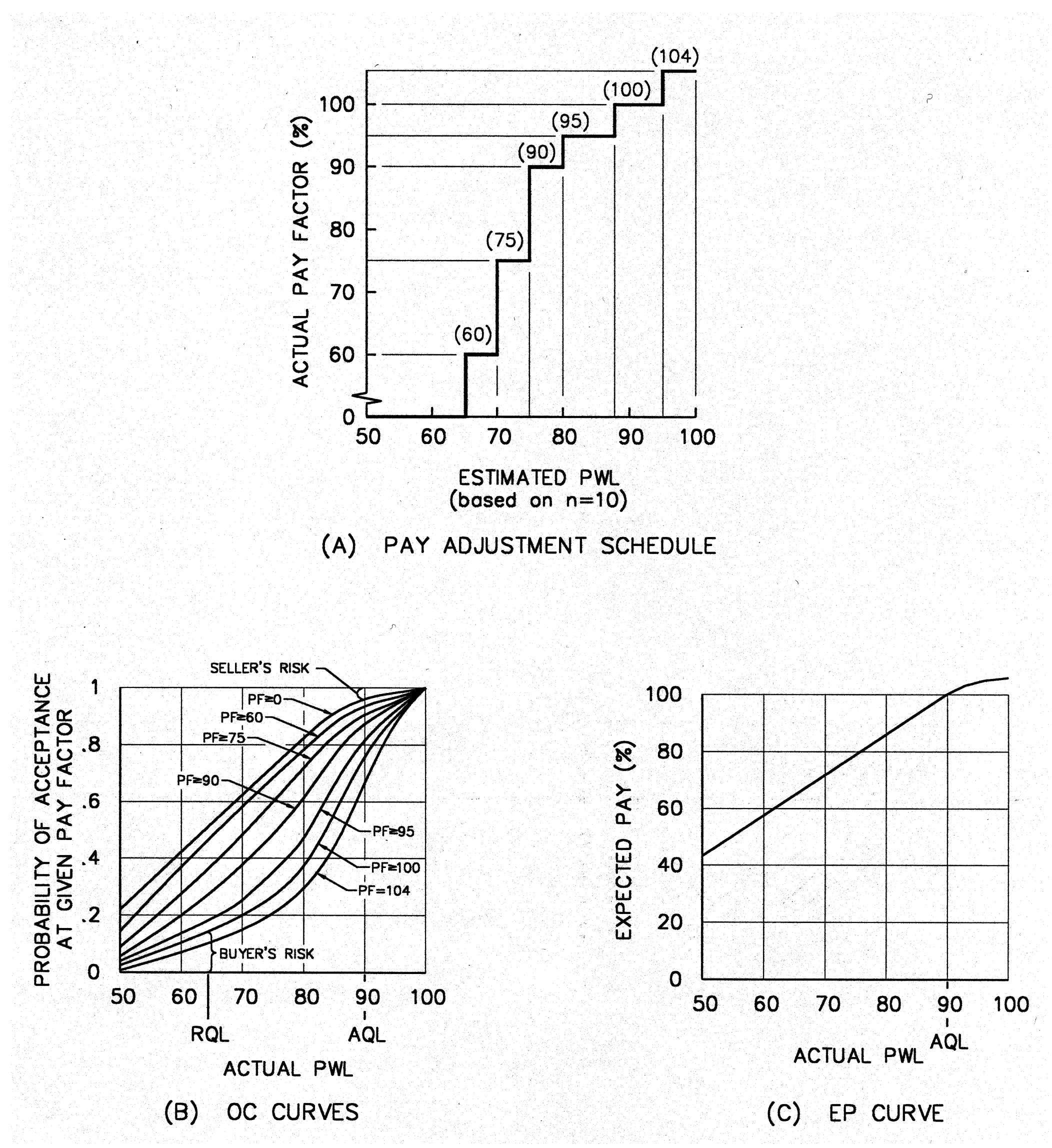

FIGURE 3 Graphic summaries of an acceptance plan (*25*). Shown above are three types of graphs used to summarize a typical acceptance plan containing a pay adjustment schedule. Figure 3a describes the pay adjustment schedule. Figures 3b and 3c present the corresponding set of OC curves and the corresponding EP curve for the acceptance plan. The OC curves show the probability that a contractor working under the acceptance plan will receive a given payment for various levels of actual (not estimated) submitted lot quality. The EP curve, on the other hand, shows the contractor's average payment in the long run for various levels of actual (not estimated) submitted lot quality. Note that information regarding the buyer's and seller's risks is found in the OC curves, and information regarding average payment in the long run is found in the EP curve. Since both types of information are needed to assess how an acceptance plan is (or will be) working, both the OC curves and the EP curve should be developed and evaluated. For instance, the EP curve may seem satisfactory for an acceptance plan; however, this same plan could have OC curves which show the buyer's and/or seller's risk too high.

Seller's risk (α) **.** Also called **risk of a Type I error**. The probability that an acceptance plan will erroneously reject acceptable quality level (AQL) material or construction with respect to a single acceptance quality characteristic. It is the risk the contractor or producer takes in having AQL material or construction rejected.

Buyer's risk (ß). Also called **risk of a Type II error**. The probability that an acceptance plan will erroneously fully accept (100% or greater) rejectable quality level (RQL) material or construction with respect to a single acceptance quality characteristic. It is the risk the highway agency takes in having RQL material or construction fully accepted. [The probability of having RQL material or construction accepted (at any pay) may be considerably greater than the buyer's risk.]

MEASURING QUALITY

Quality. (1) The degree of excellence of a product or service; (2) the degree to which a product or service satisfies the needs of a specific customer; or (3) the degree to which a product or service conforms with a given requirement.

Quality characteristic. That characteristic of a unit or product that is actually measured to determine conformance with a given requirement. When the quality characteristic is measured for acceptance purposes, it is an ***acceptance quality characteristic*** (AQC).

Quality measure. Any one of several means that have been established to quantify quality. Some examples of quality measures are the mean, the standard deviation, the percent within limits, the average absolute deviation, and the quality index.

Quality index (*Q*). A statistic that provides an estimate of either PD or PWL of a lot, when used with appropriate tables. It is typically computed from the mean and standard deviation of a set of test results, as follows:

$$Q_L = (\overline{X} - \text{LSL})/s$$

where

Q_L = quality index relative to lower specification limit
$\overline{X}$ = sample mean
s = sample standard deviation
LSL = lower specification limit

$$Q_U = (\text{USL} - \overline{X})/s$$

where Q_U is the quality index relative to upper specification limit, and USL is the upper specification limit.

Percent defective (PD). Also called **percent nonconforming**. The percentage of the lot falling outside specification limits. [PD may refer to either the population value or the sample estimate of the population value.]

Percent within limits (PWL). Also called **percent conforming**. The percentage of the lot falling above the LSL, beneath the USL, or between the USL and the LSL. [PWL may refer to either the population value or the sample estimate of the population value. PWL = 100 – PD.]

Quality level analysis (QLA). A statistical procedure that provides a method for estimating the PWL, or the PD, of a lot.

Specification limit(s). The limiting value(s) placed on a quality characteristic, established preferably by statistical analysis, for evaluating material or construction within the specification requirements. The term can refer to either an individual upper or lower specification limit, USL or LSL, called a single specification limit; or to USL and LSL together, called double specification limits.

Acceptance limit. In variables acceptance plans, the limiting upper or lower value, placed on a quality measure, that will permit acceptance of a lot. [Unlike specification limits placed on a quality characteristic, an acceptance limit is placed on a quality measure. For example, in PWL acceptance plans, PWL refers to specification limits placed on the quality characteristic, and the minimum allowable PWL identifies the acceptance limit for the PWL quality measure.]

Acceptable quality level (AQL). That minimum level of actual quality at which the material or construction can be considered fully acceptable (for that quality characteristic). For example, when quality is based on PWL, the AQL is that actual (not estimated) PWL at which the quality characteristic can just be considered fully acceptable. [Acceptance plans should be designed so that AQL material will receive an EP of 100%.]

Rejectable quality level (RQL). That maximum level of actual quality at which the material or construction can be considered unacceptable (rejectable). For example, when quality is based on PD, the RQL is that actual (not estimated) PD at which the quality characteristic can just be considered fully rejectable. [It is desired to require removal and replacement, corrective action, or the assignment of a relatively low pay factor when RQL work is detected.]

Acceptance number (*c*). In attributes acceptance plans, the maximum number of defective or nonconforming units in the sample that will permit acceptance of the inspected lot or batch.

Acceptance constant (*k*). The minimum allowable quality index. [The acceptance constant *k* is the acceptance limit associated with the quality index quality measure.]

Sample standard deviation (*s*). A measure of the dispersion of a series of results around their average, expressed as the square root of the quantity obtained by summing the squares of the deviations from the average of the results and dividing by the number of observations minus one.

$$s = \sqrt{\sum (X_i - \overline{X})^2 / (n - 1)}$$

Root-mean-square deviation (RMS). A measure of the dispersion of a series of results around their average, expressed as the square root of the quantity obtained by summing the squares of the deviations from the average of the results and dividing by the number of observations.

$$\text{RMS} = \sqrt{\sum (X_i - \overline{X})^2 / n}$$

[Both *s* and RMS give biased estimates of the population standard deviation (s). However, the sample variance (s^2) provides an unbiased estimate of the population variance (s^2).]

Standard error (of statistic). The standard deviation (*s*) of the sampling distribution of a statistic. For example, the standard error of the mean ($\overline{X}$) is the standard deviation of the sampling distribution of $\overline{X}$ (i.e., $s/\sqrt{n}$).

Standard error of estimate (SEE). In regression analysis, the standard deviation of the errors of estimate in dependent (response) variable *Y.*

$$\text{SEE} = \sqrt{\sum (Y_i - Y_x)^2 / (n - 2)}$$

Conformal index (CI). A measure of the dispersion of a series of results around a target or specified value, expressed as the square root of the quantity obtained by summing the squares of the deviations from the target value and dividing by the number of observations.

$$\text{CI} = \sqrt{\sum (X_i - T)^2 / n}$$

The standard deviation is a measure of precision, but the CI is a measure of exactness (accuracy) or degree of conformance with the target.

Average absolute deviation (AAD). For a series of test results, the mean of absolute deviations from a target or specified value. [A low AAD implies both good accuracy and good precision; a high AAD, however, does not necessarily imply both poor accuracy and poor precision (i.e., accuracy or precision, but not both, might be quite good).]

Skewness. A measure of the symmetry of a distribution. When the distribution has a greater tendency to tail to the right, it is said to have positive skewness. When the distribution has a greater tendency to tail to the left, it is said to have negative skewness. For the normal distribution (as well as for any other symmetrical distribution), the skewness coefficient equals 0.

Population skewness coefficient: $\gamma_1 = \Sigma(X_i - \mu)^3 / 2n\sigma^3$

Sample skewness coefficient: $g_1 = n\Sigma(X_i - \overline{X})^3 / [s^3(n-1)(n-2)]$

Kurtosis. A measure of the shape of a distribution. For the normal distribution, the kurtosis coefficient equals 0. A positive kurtosis coefficient indicates that the distribution has longer tails than the normal distribution, while a negative coefficient indicates that the distribution has shorter tails.

Population kurtosis coefficient:

$$\gamma_2 = [\Sigma(X_i - \mu)^4 / n\sigma^4] - 3$$

Sample kurtosis coefficient:

$$g_2 = [n(n+1)\Sigma(X_i - \overline{X})^4 / s^4(n-1)(n-2)(n-3)] - 3(n-1)^2 / (n-2)(n-3)]$$

PROCESS CONTROL

Control chart. Also called **statistical control chart**. A graphical method of process control that detects when assignable causes are acting on a continuous production line process and when normal, expected variation is occurring.

Assignable cause. A relatively large source of variation, usually due to error or process change, which can be detected by statistical methods and corrected within economic limits. [When assignable causes are identified and removed, the production process is “under control.”]

Chance cause. A source of variation that is inherent in any production process and cannot be eliminated as it is due to random, expected causes.

Controlled process. Also called **process under statistical control**. A production process in which the mean and variability of a series of tests on the product remain stable, with the variability due to chance only. [A process might be “under control” but produce out-of-specification material if the specification limits are tight. Similarly, a process might be “out of control” in that the mean or variability is outside of control limits, yet the specification limits might be wide enough that the material produced is within specifications.]

Tolerance limit(s) (upper, lower). Also called **tolerances**. The limiting value(s) placed on a quality characteristic to define its absolute conformance boundaries such that nothing is permitted outside the boundaries. [A distinction between tolerance limits and specification limits is that tolerance limits apply to process control and specification limits to statistical acceptance.]

Control limit(s) (upper, lower). Also called **action limits**. Boundaries established by statistical analysis for material production control using the control chart technique. When values of the material characteristic fall within these limits, the process is “under control.” When values fall outside the limits, this indicates that there is some assignable cause for the process going “out of control.”

Warning limit(s) (upper, lower). Boundaries established on process control charts within the upper and lower control limits, to warn the producer of possible problems in the production process that may lead to the process going out of control.

STATISTICS

Estimation

Parameter. A constant or coefficient that describes some characteristic of a population. Some examples of parameters are the population standard deviation, the population mean, and the population regression coefficients. [In most highway QA applications, the true population parameter value is unknown. The parameter value can be estimated by calculating a statistic from sample data.]

Statistic. A summary value calculated from a sample of observations. Some examples are the sample standard deviation, the sample mean, and the regression coefficients estimated from the sample.

Estimator. A statistic used to estimate a parameter to help describe the population. [The estimate may be given as a point estimate or as an interval estimate.]

Unbiased estimator. A statistic whose mathematical expected value (i.e., average value over the long run) is equal to the value of the population parameter being estimated. For example, the sample mean is an unbiased estimator of the population mean. On the other hand, the sample range is a biased estimator of the population range.

Consistent estimator. A statistic whose standard error becomes smaller as the sample size increases. [An unbiased estimator is not necessarily a consistent estimator, and a consistent estimator is not necessarily an unbiased estimator. For example, the sample root-mean-square variance (RMS^2) is a consistent estimator of the population variance, but it is not an unbiased estimator.]

Efficient estimator. A statistic having a small standard error. If one considers all possible estimators of a given parameter, the one with the smallest standard error for the same sample size is called the **most efficient estimator** of the parameter. [An efficient estimator is a consistent estimator. Efficient estimators may, or may not, be unbiased for finite samples. As an example, the sample mean and the sample median are consistent and unbiased estimators of the population mean when the population is normally distributed. However, the distribution of the sample mean has a smaller standard error than that of the sample median and is thus the more efficient estimator of the population mean.]

Sufficient estimator. A statistic that contains all the information that can be obtained from the sample regarding the population parameter. Sufficient estimators occur only in special distributions. An example of a sufficient estimator is the sample mean to estimate the population mean from a population having a Poisson distribution (since the Poisson distribution depends only on the mean).

Maximum likelihood estimator. A statistic that is more likely to result in an estimate equal to the population parameter than in any other estimate. As an example, the sample proportion of successes is the maximum likelihood estimator of the proportion of successes from a binomial distribution.

Confidence interval. An estimate of an interval in which the estimated parameter will lie with prechosen probability (called the confidence level). The end points of a confidence interval are called **confidence limits**.

Confidence level. If a large number of confidence intervals are constructed, the proportion of time that the estimated parameter will lie within the interval. [A confidence level is usually expressed as a percentage, typically ranging from 90 to 99%. Confidence level = $1-\alpha$.]

Hypothesis Testing

Significance level. The probability of rejecting a null hypothesis when it is in fact true. [This probability, often denoted by α, is generally specified before any samples are drawn, so that results will not influence the level selected.]

Hypothesis. A statement concerning the value of parameters or form of a probability distribution for a designated population or populations.

Null hypothesis. The hypothesis being tested. [Contrary to intuition, the null hypothesis is often a research hypothesis that the analyst would prefer to reject in favor of the alternative hypothesis. The null hypothesis can never be proved true. It can, however, be shown, with specified risks of error, to be untrue. If it is not disproved (i.e., not rejected), one usually acts on the assumption that there is no reason to doubt that it is true.]

Alternative hypothesis. The hypothesis which one accepts when the null hypothesis is disproved (i.e., rejected).

Type I error. Erroneous rejection of the null hypothesis.

Type II error. Erroneous acceptance of the null hypothesis.

Power curve. A curve, used in hypothesis testing, to indicate the probability of rejecting a hypothesis. The curve shows the relation between the probability $(1-\beta)$ of rejecting the hypothesis that a sample belongs to a given population with a given characteristic and the actual population value of that characteristic. [If β is plotted instead of $(1-\beta)$, the curve is analogous to the OC curve used in accept/reject acceptance plans.]

Regression

Simple linear regression. A means of fitting a straight line to data so that one can predict a dependent (response) random variable Y, using a known independent variable X. $Y = aX + b$ is an example of a simple linear regression equation.

Multiple linear regression. A means of predicting a dependent (response) random variable *Y*, using more than one known independent variable X_i. [The so-called independent variables are independent of *Y* but not necessarily independent among themselves. $Y = a + bX_1 + cX_2$, where $X_2 = \sin X_1^2$, is an example of a multiple linear regression equation. Note that in all cases X_i may be any function, not necessarily of the first degree. The concept of linear is that used in linear algebra—namely the parameters occur linearly.]

Nonlinear regression. A means of predicting a dependent (response) random variable *Y*, using an equation in which the parameters do not occur linearly. The exponential equation, $Y = ae^{bx+c}$, is an example of a nonlinear regression equation. [However, by taking the logarithm to the base e, the equation can be transformed into the form $\log_e Y = \log_e a + bX + c$. Such a model is called intrinsically linear. On the other hand, $Y = e^{-ax} - e^{-bx}$ cannot be transformed; such a model is called intrinsically nonlinear.]

Polynomial regression. A means of predicting a dependent (response) random variable *Y*, using a known independent variable *X*, through a polynomial equation. $Y = aX^2 + bX + c$ is an example of a linear, polynomial regression equation.

Correlation coefficient (*r*). A measure of the linear relationship between a single dependent (response) random variable *Y* and a known independent variable *X*. [The correlation coefficient ranges in value from –1 to +1, indicating a perfect negative linear relationship at –1, absence of linear relationship at 0, and perfect positive linear relationship at +1. Thus, when *Y* varies directly with *X*, the correlation coefficient is positive; when *Y* bears an inverse relationship to *X*, the correlation coefficient is negative.]

Coefficient of determination (r^2). A measure of the linear relationship between a single dependent random variable or response *Y* and a known independent variable *X*. It represents the proportion of the total variation of *Y* due to *X*. For instance, if $r^2 = 0.81$ ($r = 0.9$), then 81% of the variation in the values of *Y* may be accounted for by the linear relationship with the variable *X*. [The value of r^2 from a regression model cannot be evaluated as "good" or "bad" in singularity; it can only be judged relative to other models that have been estimated on similar phenomena. Thus, an r^2 of 0.30 for one phenomenon might be extremely informative, while for another phenomenon it might be uninformative.]

PAVEMENT PERFORMANCE MODELING

Pavement performance. The history of pavement condition indicators over time or with increasing axle load applications.

Pavement condition indicator. Also called **pavement distress indicator**. A measure of the condition of an existing pavement section at a particular point in time, such as cracking measured in feet per mile (or in miles per kilometer), or faulting measured in inches of wheelpath faulting per mile (or in millimeters per kilometer). [When considered collectively, pavement condition indicators provide an estimate of the overall adequacy of a particular roadway.]

Empirical model. A model developed from performance histories of pavements. [An empirical model is usually accurate only for the exact conditions and ranges of independent variables under which it was developed.]

Mechanistic model. A model developed from the laws of mechanics, where the prescribed action of forces on bodies of material elements are related to the resulting stress, strain, deformation, and failure of the pavement.

Deterministic model. A model that does not consider chance or probability. In a deterministic model, each independent variable is treated as a single value.

Stochastic model. Also called **probabilistic model**. A model containing one or more independent variables that are treated as having a range of possible values. [A useful technique for computing the output from a stochastic model is Monte Carlo simulation.]

Primary prediction relationship. An equation that can be used to predict pavement stress, distress, or performance from particular combinations of predictor variables that represent traffic, environmental, roadbed, and structural conditions. Some examples of predictor variables are annual rate of equivalent single axle load accumulation, annual precipitation, roadbed soil modulus, and concrete flexural strength.

Secondary prediction relationship. An equation that shows how one or more materials and construction variables are related to at least one predictor variable. The equation

$$S_f = 9.5\sqrt{S_c}$$

(where S_f is concrete flexural strength, a predictor variable, and S_c is concrete compressive strength) is an example of a secondary relationship.

Materials and construction (M&C) variable. A characteristic of materials and/or construction that can be directly or indirectly controlled. Thickness is an example of an M&C variable that is controlled directly; compressive strength is an example of one controlled indirectly.

Performance-related M&C variable. A characteristic of materials and/or construction that has an influence on pavement performance, either by itself or interactively when in combination with other M&C variables. [Any M&C variable that is a primary or secondary predictor is a performance-related M&C variable.]

Process control M&C variable. A characteristic of materials and/or construction, whose specification enhances the control of another M&C variable. An example of a process control M&C variable is soil moisture content to control density and compaction.

Surrogate M&C variable. A characteristic of materials and/or construction that can be used to substitute for a performance-related M&C variable. For example, concrete compressive strength can be a surrogate for concrete flexural strength.

TEST/MEASUREMENT EXACTNESS

Accuracy. The degree to which a measurement, or the mean of a distribution of measurements, tends to coincide with the true population mean. [When the true population mean is not known, the degree of agreement between the observed measurements and an accepted reference standard may be used to quantify the accuracy of the measurements.]

Bias. An error, constant in direction, that causes a measurement, or the mean of a distribution of measurements, to be offset from the true population mean.

Precision. (1) The degree of agreement among a randomly selected series of measurements or (2) the degree to which tests or measurements on identical samples tend to produce the same results.

Reliability. The degree to which a test produces consistent or dependable results. [Test reliability is increased as both precision and accuracy are improved.] Reliability can also refer to **product reliability**, defined as (1) the degree of conformance or failure of the specific product to meet the consumer's quality needs and (2) the probability of a product performing without failure a specified function under given conditions for a specified period of time. In (1) and (2), reliability is that aspect of QA which is concerned with the quality of product function over time.

Reproducibility. Degree of variation among the results obtained by different operators doing the same test on the same material. In other words, it measures the human influence or human error in the execution of a test. The term reproducibility may be used to designate interlaboratory test precision.

Repeatability. Degree of variation among the results obtained by the same operator repeating a test on the same material. The term repeatability is therefore used to designate test precision under a single operator.

Robustness. Insensitivity of a statistical test to departures from underlying assumptions. [If departures from underlying assumptions do not materially affect the decisions which would be based on the statistical test involved, the test is considered robust. For example, tests based on an assumption of normality that compare averages generally are robust even though the underlying distribution of individual items in the population is not normal.]

Ruggedness. Insensitivity of a test method to departures from specified test or environmental conditions.

SIMULATION

Computer simulation. Use of a computer to generate conditions approximating actual or operational conditions. [Computer simulation is a powerful and convenient tool to solve certain problems that are intractable by other methods.]

Monte Carlo simulation. A simulation technique (particularly useful for QA applications) that uses random numbers to sample from probability distributions to produce hundreds or thousands of

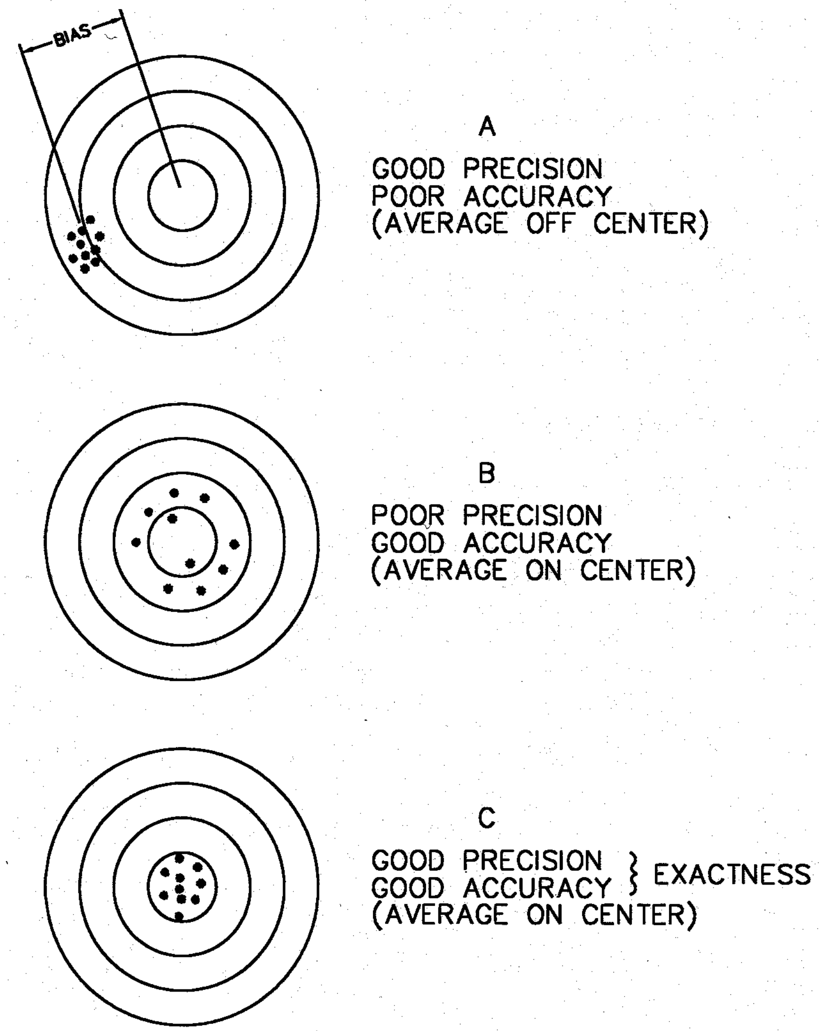

FIGURE 4 Exactness of measurement (*15*)

scenarios (called iterations, trials, or runs). [A complete Monte Carlo simulation thus uses each result from each individual iteration.]

Iteration. (1) The act or process of repeating something; a replication. [Iteration, as opposed to replication, is the preferred term for use with respect to Monte Carlo simulations.] (2) The method of successive trials, each trial producing a result that successively better approximates the desired result.

Replication. (1) The act or process of duplicating or repeating something; an iteration. [Replication, as opposed to iteration, is the preferred term for use with respect to experimental design.] (2) The execution of an experiment more than once to increase precision and to obtain a better estimate of the residual variation (i.e., the remaining variation in a set of data after the variation due to certain effects, factors, and interactions has been removed).

Recommended Abbreviations and Symbols

AAD	average absolute deviation
AQC	acceptance quality characteristic
AQL	acceptable quality level
α	significance level; probability type I hypothesis testing error; confidence coefficient; seller's risk
$1-\alpha$	confidence level
β	probability of type II hypothesis testing error; buyer's risk
$1-\beta$	power
c	acceptance number
CI	conformal index
EP	expected pay
g_1	skewness coefficient, for samples
g_2	kurtosis coefficient, for samples
γ_1	skewness coefficient, for population
γ_2	kurtosis coefficient, for population
k	acceptance constant
LSL	lower specification limit
μ	population mean
M&C	materials and construction
n	number of samples
OC	operating characteristic
PD	percent defective
PF	pay factor
PWL	percent within limits
QA	quality assurance
QC	quality control
QLA	quality level analysis
Q	quality index
Q_L	lower quality index
Q_U	upper quality index
r	correlation coefficient
r^2	coefficient of determination
RMS	root-mean-square deviation
RMS^2	root-mean-square variance
RQL	rejectable quality level
s	sample standard deviation
s^2	sample variance
σ	population standard deviation
σ^2	population variance
SEE	standard error of estimate
T	target or design value
USL	upper specification limit
$\overline{X}$	sample mean
Y_x	linear regression estimate

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