For convenience, the values of interest are reproduced in the following table:

Population Mean	Lower Bounds for Probability of Acceptance			
	N = 1	N = 2	N = 5	N = 10
4500	0.82	0.89	0.93	0.88
4600	0.87	0.94	0.96	0.93
4700	0.91	0.96	0.98	0.96
4800	0.94	0.98	0.99	0.98
4900	0.96	0.99	0.99	0.99

If, for example, the number of samples is specified to be N = 5 and the producer desires a probability of acceptance of at least 99 percent, these data indicate that a population mean of 4800 must be achieved.

Another interesting observation to be made from the values noted above concerns the effect of increasing the sample size. Ordinarily, increasing the number of samples would be expected to reduce both the producer's and the consumer's risks. However, with dual acceptance procedures of the type used in this example, this is not necessarily the case for producer's risk. For the larger values of the population mean representing higher levels of quality, the probability of acceptance increases up to N = 5 and then begins to decrease as N becomes larger. This is the result of the increased opportunity to fail the requirement on individual test values.

CONCLUSION

Because the probabilities of passing the requirements of a multiple acceptance procedure are correlated, the compound probability of passing all requirements cannot readily be determined. As an alternate approach, upper and lower bounds for the desired probability can be calculated. The theoretical basis for this approach was developed, and the results were tested by computer simulation.

An example was presented that demonstrated that these bounds provide a reasonably precise interval estimate of the true probability of acceptance. The calculations were performed by an interactive computer program that can be a valuable aid, both to the specification writer in developing the acceptance procedure and to the producer in determining the target value necessary to meet it.

The purpose of this paper is to provide guidance in the analysis of multiple acceptance criteria, not to advocate the use of acceptance procedures of this type. Depending on the measure of quality that is used and the manner in which it is related to performance, other acceptance procedures may be preferable. For example, the concept of percent defective (i.e., percentage of a lot falling outside specification limits) is often preferred by both designers and specification writers. For this approach, the methods of Military Standard 414 (3) may be applied.

Looking ahead, the bounds given by Equations 14 and 15 may prove to be useful in other situations in which correlation exists. Successive moving averages, for example, are correlated and may be analyzed in this manner. Also, certain sequential sampling plans, in which a failure results in the taking of a second sample and combining it with the first, produce correlated probabilities that can be analyzed effectively by the boundary approach. In general, any application that involves positively correlated probabilities is a potential candidate for this method.

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Unbiased Graduated Pay Schedules

Richard M. Weed

Conventional graduated pay schedules are biased in the sense that, on the average, they provide less than 100 percent payment for a product that is exactly at the acceptable quality level. The quality index on which they are based is an essentially unbiased indicator of the percent defective of the population but, because the highest level in the pay table is 100 percent, the average pay factor will usually be somewhat less. This may create serious problems in certain instances but can be overcome by developing unbiased pay schedules that are linear functions of the estimate of the population percent defective. This approach can be applied to both continuous and stepped pay schedules and, in both cases, pay factors greater than 100 percent are permitted. These are used to establish credit that may be applied to offset lower pay factors within specified time intervals throughout a construction project. This method is mathematically sound and produces the desired average pay factor at all quality levels. It is not the same as a bonus provision because the overall pay factor for each time period is still limited at 100 percent. The preparation of tables for estimating percent defective is reviewed, and both continuous and stepped pay schedules based on this measure are developed. Operating characteristics curves and optimization curves are presented to compare these approaches and assess their effect on bidding strategies.

Statistical construction specifications are based on a desired end result and usually employ graduated pay schedules to award payment in proportion to the extent that the end result is achieved. An acceptable quality level (AQL) is defined as that level of some quality measure of a product considered necessary for satisfactory performance. When the acceptance procedure indicates that the quality level is greater than or equal to the AQL, the lot is eligible for 100 percent payment. If the tests indicate that the lot quality level is less than the AQL, a graduated pay schedule is used to determine the appropriate reduced pay factor. In addition to the AQL, it is customary to define a rejectable quality level (RQL) below which the buyer reserves the option to require removal and replacement of the defective product. This approach is described in several recent publications (1-3) and has gained favor with many specifying agencies because it provides a practical and equitable way to accept work that is only slightly deficient.

Although this concept has worked reasonably well in practice, conventional pay schedules are biased in that they award less than 100 percent payment, on the average, when the product is exactly at the AQL. Because the highest pay factor in a conventional pay schedule is 100 percent and AQL lots will occasionally receive lower pay factors, the expected average pay factor for AQL product will always be somewhat less than 100 percent. Typical AQL pay factors are often about 98 percent.

In many cases, contractors can compensate for this bias by making small adjustments in their bid prices or by producing at slightly higher quality levels. In some cases, however, this bias can have serious consequences. For example, consider the independent concrete producer who supplies AQL concrete at $39.24/m^3$ ($30/yd^3$) to a general contractor who places it in a structure valued at $392.39/m^3$ ($300/yd^3$). In this case, an average pay factor of 98 percent corresponds to a pay reduction of $0.02 \times \$392.39 = \$7.85/m^3$ ($0.02 \times \$300 = \$6/yd^3$) that, in all likelihood, would be passed back to the producer.

To offset this expected pay reduction, the producer must either raise the bid price for AQL concrete by $7.85/m^3$ ($6/yd^3$) or else plan to produce concrete at a considerably higher quality level, neither of which is completely satisfactory. The first approach involves an uncertain game of numbers in which the bid price will not realistically reflect the value of the concrete. The second alternative, discussed in a paper on optimum strategy (4), can produce an equitable result for all parties but leads to the extra expense of an average quality level substantially above that which the specifying agency has defined as acceptable. However, countermeasures such as these will not be necessary if unbiased pay schedules that award an average pay factor of 100 percent for AQL product can be developed.

ESTIMATING PERCENT DEFECTIVE

Before proceeding with the development of unbiased pay schedules, it is first necessary to define the measure of quality on which these pay schedules will be based. Of the various ways that an acceptable or unacceptable product might be defined, the concept of percent defective (i.e., percentage of the total population outside specification limits) seems to have considerable appeal to specification writers. The overall proportion within specification limits is felt to be strongly related to a product's performance or service life, or both. This general philosophy is promulgated in Standard 214-77 (5) of the American Concrete Institute (ACI), although the ACI acceptance criteria do not use a pure percent-defective approach.

In order to develop a specification based on percent defective, it is necessary to have an accurate method for estimating the percent defective of a population. Military Standard 414 (6) provides a method that involves the calculation of a quality index from the mean and standard deviation (or range) of a random sample. Once the quality index has been calculated, a table is consulted to obtain the estimate of the percent defective of the lot from which the sample was drawn. This method assumes random sampling from a normal universe, conditions that can be sufficiently met for most construction quality characteristics.

For the standard-deviation method, variability assumed unknown and a lower limit only, the quality index is calculated as

$$Q_L = (\bar{X} - L)/S \qquad (1)$$

where

Q_L = quality index (lower limit),
$\bar{X}$ = sample mean,
L = lower limit, and
S = sample standard deviation.

In addition to the standard-deviation method, Military Standard 414 provides a similar approach that uses the sample range as the measure of variability. Although the two methods are essentially equivalent for small sample sizes, the standard-deviation method provides a more precise estimate of the population percent defective as the sample size increases. Also, Willenbrock and Kopac (7) have pointed out that, although the range method is quite accurate, only the standard-deviation method furnishes a true minimum variance unbiased estimate.

Willenbrock and Kopac (7) illustrate how Pearson's Tables of the Incomplete Beta Function (8) can be used to develop the Military Standard 414 tables that relate the quality index to the estimate of percent defective. By using Pearson's tables, it is possible to obtain both a greater number of significant figures and a greater selection of sample sizes than are presented in Military Standard 414. Although it is possible to work directly from Pearson's tables, it is far more efficient to perform this entire operation by computer. A typical table developed in this manner is shown in Figure 1.

DEVELOPING THE PAY SCHEDULE

Before developing the mechanics of the pay schedule, it is first necessary to determine the amount of payment appropriate for various quality levels of work. Several methods have already been proposed (1,2). When information is available that relates a product's quality to its performance, as is the case with the American Association of State Highway Officials' nomographs for pavement design (9), I favor an economic approach (3) in which the pay reduction is the present value of the extra future cost anticipated as the result of deficient-quality construction. Because this method takes into account the salvage value of pavement that has reached the terminal serviceability index, it tends to award higher pay factors than some of the other methods and, because it relates payment directly to value received, this approach is believed to be both equitable and legally defensible.

When applied to concrete pavement, the economic approach produces a nearly linear relation between percent defective and the appropriate pay factor as shown in Figure 2. Although a pay schedule could be developed that follows the curved relation, a straight-line approximation is felt to be adequate for practical purposes. Since the primary points of interest are at the AQL and RQL, the linear approximation will be made to pass through these two points. Because the curve is concave upward, the linear approach will produce slightly inflated pay factors between the AQL and RQL.

By means of the economic approach, or one of the other methods, suppose that the desired pay factors at the AQL and RQL are determined to be as follows:

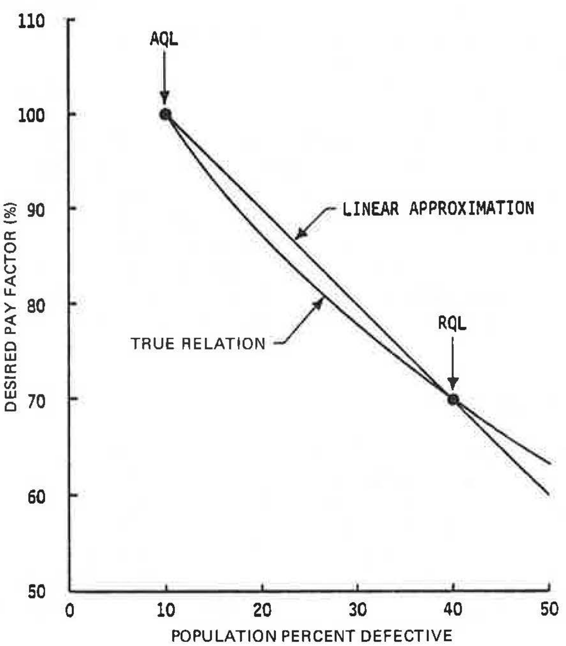
Quality Level	Percent Defective	Pay Factor (%)
AQL	10	100
RQL	40	70

Figure 1. Typical table used to estimate the percent defective of a normal population (standard-deviation method).

N = 7

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.63	49.25	48.88	48.50	48.13	47.75	47.38	47.01	46.63
0.1	46.26	45.89	45.51	45.14	44.77	44.40	44.03	43.65	43.28	42.91
0.2	42.54	42.17	41.80	41.44	41.07	40.70	40.33	39.97	39.60	39.23
0.3	38.87	38.50	38.14	37.78	37.42	37.06	36.69	36.33	35.98	35.62
0.4	35.26	34.90	34.55	34.19	33.84	33.49	33.13	32.78	32.43	32.08
0.5	31.74	31.39	31.04	30.70	30.36	30.01	29.67	29.33	28.99	28.66
0.6	28.32	27.98	27.65	27.32	26.99	26.66	26.33	26.00	25.68	25.35
0.7	25.03	24.71	24.39	24.07	23.75	23.44	23.12	22.81	22.50	22.19
0.8	21.88	21.58	21.27	20.97	20.67	20.37	20.07	19.78	19.48	19.19
0.9	18.90	18.61	18.33	18.04	17.76	17.48	17.20	16.92	16.65	16.37
1.0	16.10	15.83	15.56	15.30	15.03	14.77	14.51	14.26	14.00	13.75
1.1	13.49	13.25	13.00	12.75	12.51	12.27	12.03	11.80	11.56	11.33
1.2	11.10	10.87	10.65	10.42	10.20	9.98	9.77	9.55	9.34	9.13
1.3	8.93	8.72	8.52	8.32	8.12	7.93	7.73	7.54	7.35	7.17
1.4	6.98	6.80	6.62	6.45	6.27	6.10	5.93	5.77	5.60	5.44
1.5	5.28	5.13	4.97	4.82	4.67	4.52	4.38	4.24	4.10	3.96
1.6	3.83	3.70	3.57	3.44	3.31	3.19	3.07	2.96	2.84	2.73
1.7	2.62	2.51	2.41	2.30	2.20	2.11	2.01	1.92	1.83	1.74
1.8	1.66	1.57	1.49	1.41	1.34	1.26	1.19	1.12	1.06	0.99
1.9	0.93	0.87	0.81	0.76	0.70	0.65	0.61	0.56	0.51	0.47
2.0	0.43	0.39	0.36	0.32	0.29	0.26	0.23	0.21	0.18	0.16
2.1	0.14	0.12	0.10	0.08	0.07	0.06	0.05	0.04	0.03	0.02
2.2	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.0	0.0	0.0

Figure 2. Typical relation between percent defective and desired pay factor.



This leads to two equations in two unknowns that can be solved to give the slope and intercept of the linear function passing through these two points. This yields

$$PF = 110 - PD \quad (2)$$

where PF = pay factor and PD = percent defective.

Equation 2 can be regarded as a continuous pay schedule that awards payment as a linear function of the estimate of the population percent defective. As this estimate approaches zero, the pay factor approaches a maximum of 110 percent. The possibility of obtaining pay factors greater than 100 percent could be interpreted as a bonus provision if the specifying agency wished to treat it as such. However, for purposes of this paper, it will not be considered as a bonus because it is proposed that pay factors above 100 percent be used only to establish credit to offset pay factors less than 100 percent. Under this provision, the total payment for any billing period cannot exceed 100 percent.

A stepped pay schedule (equivalent to Equation 2) can be constructed, as shown below, in which discrete pay levels are associated with specific ranges of percent defective:

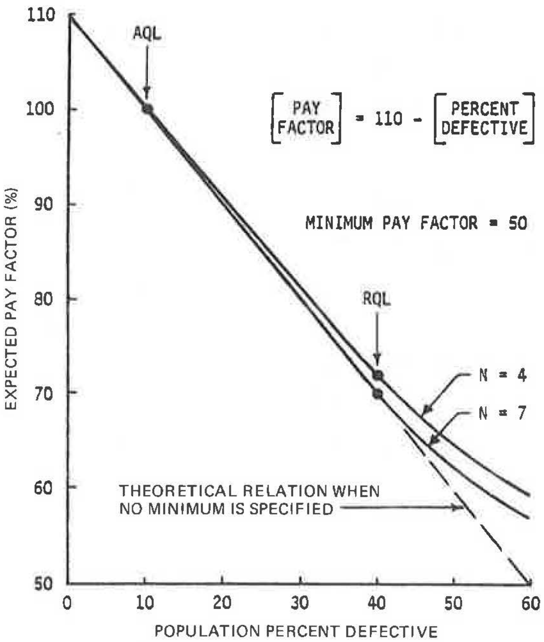
Percent Defective	Pay Factor (%)
<5	110
5-14.99	100
15-24.99	90
25-34.99	80
35-44.99	70
45-54.99	60
≥55	50

Frequently, stepped schedules are based directly on the quality index (for specific sample sizes) and do not include an estimate of the population percent defective. This eliminates the need for special tables to convert the quality index to percent defective but may be less meaningful to those who lack an understanding of the theoretical basis for this approach.

The minimum pay factor in the stepped pay schedule shown is 50 percent. If this same limitation is imposed on the continuous pay schedule given by Equation 2, it can be demonstrated by computer simulation that the two pay schedules have essentially the same operating characteristics curves as shown in Figure 3. Although the existence of a minimum pay factor is a biasing influence, both pay schedules remain unbiased at the AQL because they both provide expected pay factors of 100 percent at that point. At the RQL, the expected pay factor is very close to the desired value of 70 percent for a sample size of N = 7 but, for a sample size of N = 4, it is biased upward by about 2 percent. This slight amount of bias at the RQL can probably be tolerated but, if not, it can be removed by increasing the sample size or by lowering the minimum pay factor.

If no minimum pay factor is specified, both pay schedules have exactly the same operating characteristics curve for all sample sizes, which continues in a straight line down to a pay factor of 10 percent at 100 percent

Figure 3. Typical operating characteristics curves produced by unbiased pay schedules.



defective. This relation results from the fact that the pay factor serves as a linear function of the percent-defective estimate that, in turn, is an unbiased estimate of the population percent defective. When a minimum pay factor is specified, the operating characteristics curve becomes asymptotic to that value as the percent defective increases.

Although either type of pay schedule, continuous or stepped, will produce the same result in the long run, the continuous type may produce more satisfactory short-term results. With the stepped schedule, the difference in pay between two successive steps may be fairly substantial. Whenever the true population percent defective happens to fall close to one of the boundaries in a stepped schedule, it is largely a matter of chance whether the higher or lower pay factor will be received. Although this tends to balance out in the long run, it could work to the disadvantage of either party on a project that has a small number of lots. The continuous pay schedule, on the other hand, avoids this problem and is limited only by the precision of the estimate of the population percent defective.

REFINEMENTS OF THE UNBIASED APPROACH

One refinement, the setting of a minimum pay factor, has already been shown to have very little effect on the operating characteristics curves down to the RQL, provided that the minimum pay factor is set at a level somewhat below that associated with the RQL. The purpose for such a provision is to establish a minimum payment level for rejectable work that, for practical reasons, the specifying agency has allowed to remain in place. For example, if either unbiased pay schedule is used and the acceptance procedure has indicated a lot percent defective of 65 percent, the lot is considered to be rejectable and the specifying agency has the option to require that it be removed and replaced at the contractor's expense. However, in certain noncritical situations, the specifying agency may not wish to exercise this option. The continuous pay schedule of Equation 2 would award a pay factor of PF = 110 - 65 = 45 percent that, in this case, would be raised to the minimum level of 50 percent. If the acceptance procedure had indicated a percent defective of 50 percent, this would still be considered to be of RQL quality but would receive a pay factor of PF = 110 - 50 = 60 percent if allowed to remain in place.

Another refinement that may be desirable is a limit on the length of time or number of lots over which the contractor is allowed to apply credit obtained from pay factors in excess of 100 percent. The concern here is that a large accumulation of credit during the early stages of a project could diminish the incentive to maintain high quality standards later on and, possibly, the reverse situation might also occur. Because accounting procedures are frequently based on one-month billing periods, this may be a practical time interval within which to permit crediting. An alternate approach would be to establish a fixed number of lots in lieu of a specific time interval. In either case, however, it is desirable that the total number of lots within the credit interval be reasonably large to permit the averaging process to operate effectively.

Still another refinement that specification writers may wish to make is the setting of a lower limit below which a pay factor would not be eligible to receive credit. This must be pursued with caution, however, because it lowers the operating characteristics curve and may affect the pay factor at the AQL. It is recommended that this limiting pay factor be set no higher than that associated with the RQL.

A final refinement concerns the situation in which there are items of different unit value. If lots of substantially different value are allowed to be averaged together by the crediting process, the degree of incentive to produce good quality will be roughly proportional to the in-place cost of the lot. This may or may not be desirable from the specifying agency's standpoint and must be taken into consideration in deciding how the procedure is to be administered. If this approach were incorporated into a concrete specification, for example, it might be advisable to treat pavement and structural items separately because of the considerable difference in unit price.

IMPLEMENTATION

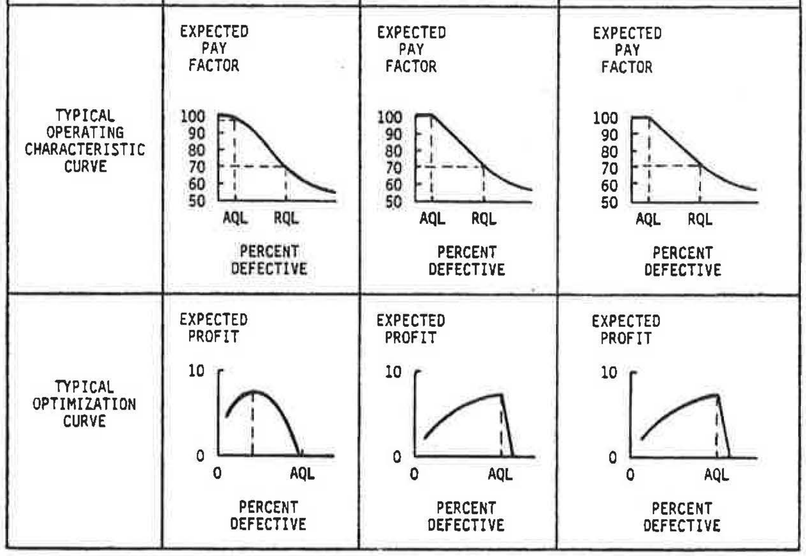
The implementation of this procedure lends itself to a computerized approach, although a similar format can be prepared quite readily by hand. Either way, the basic input information for each lot would include the date, job and section number, contracting firm, item code, lot size, unit price, design value, sample size, and the individual test values. The itemized format would include all this information plus the calculation of the quality index, percent defective, pay factor, contract value, and the credit or reduction in payment for each lot included within the pay period. The net payment for the period would then be computed in a brief summary as shown below:

SUMMARY FOR PAY PERIOD 07/01/79 THROUGH 07/31/79

TOTAL NUMBER OF LOTS INCLUDED IN THIS PAY PERIOD 30
NUMBER OF LOTS ACCEPTED AT FULL PAYMENT OR EXTRA CREDIT 25
NUMBER OF LOTS ACCEPTED AT REDUCED PAYMENT 5
NUMBER OF LOTS JUDGED UNACCEPTABLE 0

Figure 4. Comparison of three types of pay schedules.

	TYPE OF PAY SCHEDULE		
	CONVENTIONAL STEPPED	UNBIASED STEPPED	UNBIASED CONTINUOUS
TYPICAL EXAMPLE	PERCENT DEFECTIVE / PAY FACTOR ≤10.00 / 100 10.01-20.00 / 90 20.01-30.00 / 80 30.01-40.00 / 70 40.01-50.00 / 60 >50.00 / 50	PERCENT DEFECTIVE / PAY FACTOR <5.00 / 110 5.00-14.99 / 100 15.00-24.99 / 90 25.00-34.99 / 80 35.00-44.99 / 70 45.00-54.99 / 60 ≥55.00 / 50 MAXIMUM OVERALL PAY FACTOR IS LIMITED AT 100 PERCENT.	[PAY FACTOR] = 110 - [PERCENT DEFECTIVE] MAXIMUM OVERALL PAY FACTOR IS LIMITED AT 100 PERCENT. MINIMUM PAY FACTOR FOR INDIVIDUAL LOTS IS 50 PERCENT.



TOTAL CONTRACT AMOUNT FOR THIS PAY PERIOD	$827 300.00
TOTAL CREDIT	$ 17 983.16
TOTAL REDUCTION	$ 16 856.23
NET REDUCTION	$ 0.00
TOTAL PAYMENT DUE FOR THIS PAY PERIOD	$827 300.00

In this particular example, since the total credits exceeded the sum of the pay reductions, the contractor would have been entitled to a small bonus if such a provision were in effect. Because this is not the case, the contractor receives the maximum of 100 percent payment for this period.

EFFECT ON BIDDING STRATEGIES

It has been shown that conventional pay schedules may create problems for both the contractor and the specifying agency (4). The contractor who bids on and produces exactly at the AQL will fail to achieve the desired profit margin and may even suffer a loss. In order to maximize profits, it is often necessary to bid and produce at levels substantially above the AQL. As a result, both the quality and the price will be higher than the specifying agency anticipated and, in fact, may not be economically justifiable from a cost-benefit standpoint. However, these problems can be avoided with the use of unbiased pay schedules that produce an average pay factor of 100 percent at the AQL.

Typical operating characteristics curves and optimization curves for three types of pay schedules—conventional stepped, unbiased stepped, and unbiased continuous—are compared in Figure 4. The optimization curves shown in this figure represent the expected outcome for a concrete producer supplying structural grade concrete under a statistical specification. With the conventional stepped pay schedule, the producer must set the target strength well above the AQL in order to achieve the maximum profit margin. In contrast to this, the optimum point falls exactly at the AQL for the two unbiased pay schedules. As a result, unbiased pay schedules will tend to cause producers to control their production close to the AQL level.

When making the optimization calculations, the operating characteristics curves for the unbiased pay schedules are modified slightly to reflect the provision that the total payment for any pay period cannot exceed 100 percent. The curves in Figure 4 are identical to those shown in Figure 3 except that they plateau at a pay factor of 100 percent. It is this discontinuity combined with the 100 percent limit that produces the rather sharp peak in the optimization curves. Because of the very steep decline of the optimization curves as the percent defective increases above the AQL, the prudent producer may still wish to set the target strength above the AQL value by a small amount.

CONCLUSION

Conventional pay schedules are biased in that they award less than 100 percent payment, on the average, for product that is exactly at the AQL. Besides being basically undesirable, this bias can create difficulties for both contractors and specifying agencies in many instances. Bidding strategies may be adversely affected and the average quality level produced may be quite different from what specification writers expect.

Unbiased pay schedules can be developed by permitting pay factors in excess of 100 percent to offset lower pay factors with the provision that total payment for any billing period cannot exceed 100 percent. Pay schedules of this type award payment in direct proportion to the quality of the product up to an expected pay factor of 100 percent at the AQL. This overcomes a basic deficiency of conventional pay schedules and tends to encourage contractors to perform at or just above the AQL.

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Information Systems in Highway Construction: The State of the Art

Errol C. Noel

This paper is the result of an in-depth analysis of automated data-processing techniques used in managing information that is normally generated during highway construction. Such information includes material availability, results of material testing, and quality-control decisions. Information systems used by New York, Colorado, Pennsylvania, Louisiana, Illinois, West Virginia, Georgia, and Minnesota are briefly reviewed. Three categories of material and test data information (MATTI) systems are discussed: batch information systems, on-line interactive information systems, and on-line interactive laboratory information systems. These systems represent the state of the art. Research indicates that there is currently insufficient coordination among the states in sharing experience in the development and use of MATTI systems. Because MATTI systems compete with other large users of computer resources, the need for careful planning is emphasized so that too-sophisticated systems are not developed where less-sophisticated systems are more than adequate. The need for multidisciplinary involvement throughout systems development requires greater emphasis.

This paper is the result of an in-depth analysis of automated data-processing techniques used in managing information that is normally generated during highway construction. This information includes material availability, results of material testing, and quality-control decisions.

Information systems used in New York, Colorado, Pennsylvania, Louisiana, Illinois, West Virginia, Georgia, and Minnesota are briefly examined. Detailed descriptions of systems structure, use, and capabilities can be found elsewhere (1).

Three categories of material and test data information (MATTI) systems are analyzed: batch information systems, on-line interactive information systems, and on-line interactive laboratory information systems. These systems represent the state of the art.

BACKGROUND

The increasing need for improved quality of highway materials has led to a search for new and more effective quality-control methods (2,3). This search began in the early 1960s with the application of statistical analysis techniques to material performance data and culminated in the implementation of statistically derived specifications for highway construction materials and procedures. Applying statistical quality-control methods to specification writing has now become standard practice. However, there is a continued need for the periodic updating of specifications and for more efficient methods of providing basic data for justifying adjustments to existing specifications. Manual methods for satisfying this need have been less than satisfactory (4). Efficient manual processing and monitoring of material information are practically impossible for large highway projects because of the difficulty in retrieving historical data and managing the more current accumulation. This management problem is not only due to tedious data-gathering procedures but also to inconsistencies in test-result recording procedures and filing methods used by various administrative districts within each state.

Recent efforts to improve the materials management process have focused on the adoption of the systems engineering concept. With this adoption, it became apparent that high-speed data processing is necessary for improving the standard written specification and test-reporting methods (5). Thus, the trend in the 1970s has been the use of high-speed electronic computers for providing continuous feedback related to material use, test performance, availability, specifications, and any