TRANSPORTATION RESEARCH RECORD 1056

Statistically Based Acceptance Procedures, Quality Assurance, and Construction Management

TRB
TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1986

Transportation Research Record 1056
Price $12.20
Editor: Elizabeth W. Kaplan
Compositor: Lucinda Reeder
Layout: Betty L. Hawkins

modes
1 highway transportation
2 public transit
3 rail transportation
4 air transportation
5 other

subject area
33 construction

Transportation Research Board publications are available by ordering directly from TRB. They may also be obtained on a regular basis through organizational or individual affiliation with TRB; affiliates or library subscribers are eligible for substantial discounts. For further information, write to the Transportation Research Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data
National Research Council. Transportation Research Board.

Statistically based acceptance procedures, quality assurance, and construction management.

(Transportation research record, ISSN 0361-1981 ; 1056)
1. Pavements—Design and construction. 2. Road materials. 3. Road construction industry—Management. I. National Research Council (U.S.). Transportation Research Board. II. Series.
TE7.H5 no. 1056 380.5 s 86-16412
[TE250] [625.8]
ISBN 0-309-03974-6

Sponsorship of Transportation Research Record 1056

GROUP 2—DESIGN AND CONSTRUCTION OF TRANSPORTATION FACILITIES
David S. Gedney, Harland Bartholomew & Associates, chairman

Construction Section
Garland W. Steele, West Virginia Department of Highways, chairman

Committee on Quality Assurance and Acceptance Procedures
E. J. Breckwoldt, Louisiana State Department of Transportation and Development, chairman
S. C. Shah, Louisiana Department of Transportation and Development, secretary
Paul E. Benson, James L. Burati, Jr., Ronald J. Cominsky, James Daves, Richard L. Davis, Ervin L. Dukatz, Jr., Robert P. Elliott, Claude Gentry, Robert K. H. Ho, Charles S. Hughes, Roy D. McQueen, Terry M. Mitchell, John T. Molnar, James S. Moulthrop, Roger P. Northwood, Orrin Riley, Randell C. Riley, Byron E. Ruth, Garland W. Steele, Carl J. Steinhauer, Richard M. Weed

Committee on Construction Management
Donn E. Hancher, Purdue University, chairman
William G. Bowers, E. J. Breckwoldt, William E. Brewer, Richard N. Cochrane, Warren B. Diederich, Edward J. Kehl, James E. Kelly, Robert B. Newman, M. Lee Powell III, Orrin Riley, James E. Rowings, Jr., Earl R. Scyoc, William H. Shaw, Arunprakash M. Shirole, Richard R. Stander, Jr., H. Randolph Thomas, Jr., Charles H. Van Deusen

Evaluations, Systems and Procedures Section
Terry M. Mitchell, Federal Highway Administration, chairman

Committee on Mineral Aggregates
Richard C. Ingberg, Minnesota Department of Transportation, chairman
David A. Anderson, Gordon W. Beecroft, Robert J. Collins, Sabir H. M. Dahir, James R. Dunn, Stephen W. Forster, Richard D. Gaynor, Erling K. Hansen, Robert F. Hinshaw, Eugene Y. Huang, Mark D. Johnson, Donald W. Lewis, Charles R. Marek, Vernon J. Marks, Michael F. McCormick, Frank P. Nichols, Jr., John T. Paxton, Richard W. Petrarca, T. Paul Teng, Lennard J. Wylde

William G. Gunderman and Neil F. Hawks, Transportation Research Board

Sponsorship is indicated by a footnote at the end or each paper. The organizational units, officers, and members are as of December 31, 1985.

Contents

Development of a Statistically Based Specification for Unbound Aggregates

ZAHUR SIDDIQUI, DAVID A. ANDERSON, and CHARLES E. ANTLE

ABSTRACT

The research conducted for developing a statistically based specification for the gradation of unbound aggregates is described. Statistical parameters that describe within-batch, between-batch, and sampling variances for three aggregates, Pennsylvania Department of Transportation (PennDOT) 2A (dense-graded subbase), PennDOT 1B (AASHTO B), and PennDOT 2 (AASHTO 67), were estimated from data that were collected according to a statistically designed sampling plan. This information was then used in a computer simulation program to generate a distribution of the estimated percentage of material within limits ($\hat{PWL}$). Operating characteristic curves and expected payment curves were developed based on the $\hat{PWL}$ and a discrete price adjustment schedule. The specification includes a statistically based acceptance plan and a system for assigning payment when multiple price adjustments are involved.

Aggregates are manufactured products and represent the bulk of the materials used in portland cement concrete, bituminous concrete, base courses, and subbases. The performance of highways and structures is affected by the quality and uniformity of the aggregate used in their construction. For this reason it is important that aggregates meet certain acceptance criteria and fall within specification limits.

Many state highway agencies, including the Pennsylvania Department of Transportation (PennDOT), currently use statistically based specifications for the acceptance of bituminous concrete mixtures and construction (1). In Pennsylvania, this type of specification is referred to as a restricted performance specification (RPS). The purpose of this paper is to consider the research that was done to extend restricted performance specifications to the gradation of unbound aggregates. As a result of the research, an acceptance plan was formulated for the gradation of three Pennsylvania aggregates: 2A, 1B, and 2. PennDOT 2A aggregate is a dense-graded aggregate that is commonly used as a subbase. PennDOT 1B and the aggregates are one-sized, similar to AASHTO gradations 8 and 67, respectively. However, for the purpose of this paper, the development of a statistically based acceptance plan will be discussed only with reference to the PennDOT 2A aggregate.

The distinguishing elements of a statistically oriented specification are

1. Performance-oriented acceptance criteria.
2. Use of statistical techniques for the purpose of
    - Ensuring unbiased, accurate information;
    - Effective and timely process control;
    - Objective evaluation of quality characteristics in terms of both central tendency and dispersion; and
    - Making acceptance decisions on a rational basis.
3. Clear delineation of responsibilities with respect to
    - Process control by the contractor or the agency, or both, in the case of maintenance force work; and
    - Acceptance sampling, testing, and inspection by the highway agency.
4. An equitable price adjustment schedule for materials and construction that are not fully in compliance with requirements.

To develop such a specification, it was necessary to estimate the statistical parameters of the existing process capabilities of aggregate producers.

DEVELOPMENT OF STATISTICAL MODEL

Statistical parameters can be estimated by performing statistical analysis on historical data or by collecting data according to a statistically based sampling plan. Appropriate historical data were not available, and therefore a sampling plan was developed to establish the various components of variance necessary to develop the specifications.

Although specification limits are based on the overall variance of a material, it is necessary to analyze this variance and quantify its relative components. Of interest are the between-batch variance, the within-batch variance, and the variance due to testing error. For the purpose of this paper, a batch is defined as a mini-stockpile formed by dumping a randomly chosen loader bucket of aggregate on the ground. Other work done as part of this research has shown that the mini-stockpile is the preferred sampling location, and this procedure has subsequently been adopted by PennDOT for use in the interim maintenance specification.

The between-batch (or batch-to-batch) variance is an important component of variance because it may result in differences in the performance of different batches within a lot. The magnitude of this variance is a function of the efficiency of the method of handling, transporting, and storing aggregates and the resulting degree of segregation.

The within-batch variance is a measure of the homogeneity within a given batch. It is found by

---

The Pennsylvania Transportation Institute, Pennsylvania State University, University Park, Pa. 16802.

collecting and testing two test portions from suitably separated points within the same batch. This variance represents the nonuniformity of aggregate gradation within a batch.

Variance due to testing error occurs because of the lack of repeatability of the test procedure. This error is due to random variations associated with the testing technique. A large variance due to testing error would require a review of the testing procedure with the objective of reducing this variance. A statistical model was developed to define the hierarchical nature of the components of variance:

$$Y_{ijklm} = \mu + P_i + V_{j(i)} + B_{k(i,j)} + S_{l(i,j,k)} + E_{m(i,j,k,l)}$$

and

$$\mathrm{Var}\,(Y_{ijklm}) = \sigma^2{}_p + \sigma^2{}_v + \sigma^2{}_b + \sigma^2{}_s + \sigma^2$$

where

Y_{ijklm} = percentage passing a given sieve on a single test;
μ = true population mean of the percentage passing a given sieve for all aggregates in Pennsylvania;
P_i = effect of the ith plant; P_i is assumed to be distributed normally with mean = 0 and variance = $\sigma^2{}_p$;
$V_{j(i)}$ = effect of the jth visit within the ith plant; $V_{j(i)}$ is assumed to be distributed normally with mean = 0 and variance = $\sigma^2{}_v$;
$B_{k(i,j)}$ = between batch with mean = 0 and variance = $\sigma^2{}_p$; $B_{k(i,j)}$ is assumed to be distributed normally with mean = 0 and variance = $\sigma^2{}_b$;
$S_{l(i,j,k)}$ = effect due to taking the lth sample within the kth batch within the jth visit within the ith plant; $S_{l(i,j,k)}$ is assumed to be distributed normally with mean = 0 and variance = $\sigma^2{}_s$; and
$E_{m(i,j,k,l)}$ = testing error on the lth sample within the kth batch within the jth visit within the ith plant; $E_{m(i,j,k,l)}$ is assumed to be distributed normally with mean = 0 and variance = σ^2.

This model is a random effects model based on the assumption that each source of variation (effect) is random; that is, that each plant, visit, batch, and sample is selected at random. Testing error is assumed to be a random error not an error due to an assignable cause such as a weighing error. In addition, it is assumed that the effects are independent of each other. The model has a nested or hierarchical structure. That is, the testing effect (error) is nested within the sampling effect, the sampling effect is nested within the batch effect, and so forth.

DEVELOPMENT OF SAMPLING PLAN

PennDOT has developed an interim statistically based specification for unbound aggregates used in maintenance work (2). During the 1983 construction season, aggregate producers from nine of the eleven engineering districts supplied material under this interim specification. For the development of the sampling plan used in this study, plants were selected to represent those nine engineering districts. These plants use either gravel or limestone as the source material for manufacturing aggregate. To meet the Environmental Protection Agency (EPA) requirements or to control the minus No. 200 sieve material, or both, some limestone plants employ a washing process to remove excess fines. However, due to the long-graded nature of the 2A aggregate, limestone plants do not use the washing process for manufacturing this material. In this paper 2A aggregate produced without washing is referred to as a "2A dry."

Sampling location is an important element of any acceptance plan. In its current acceptance plan, PennDOT collects samples from trucks. This is an unacceptable location because of safety problems and the difficulty of obtaining a representative sample. Mini-stockpiles are formed by dumping a randomly selected bucket load of aggregate on the ground while the trucks are being loaded for shipment. Details of this sampling procedure, which was used in this study, can be found elsewhere (3).

The design selected for the sampling plan was a compromise between budgetary limitations and statistical requirements. It was decided that

1. Four plants would be sampled for each combination of aggregate type and manufacturing process,
2. One visit would be made to each plant for the collection of samples, and
3. Samples would be collected to provide 16 degrees of freedom (df) for estimating the sampling (within-batch) variance and 12 df for estimating the between-batch variance.

Several combinations of sublot size (number of sublots) and number of samples per sublot would provide at least the necessary degrees of freedom. However, it was concluded that using four sublots and two samples per sublot provided an acceptable compromise among the statistical requirements of the project, the logistics of obtaining field samples, and the limitations of the laboratory. Figure 1 shows a graphic illustration of the sampling plan. Samples were properly identified and transported to the laboratory, where a sieve analysis was conducted in accordance with the appropriate testing methods.

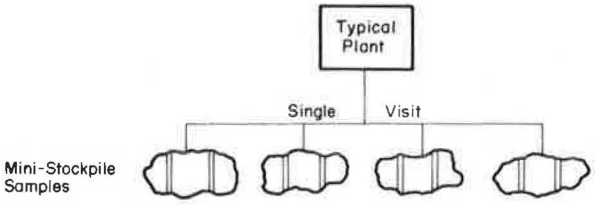


FIGURE 1 Illustration of components-of-variance sampling.

ANALYSIS OF VARIANCE

The gradation test results were used with the "nested" procedure of the Statistical Analysis System (SAS) to conduct an analysis of variance (ANOVA) (4). The results of this ANOVA are summarized in Tables 1-5. Because of the loss of two samples, the total number of degrees of freedom for the 2A-gravel combination was reduced from 31 to 29. In the case of 2A-dry, process samples collected for the sampling location study were also included in the ANOVA. This resulted in additional degrees of freedom. Because lot acceptance is affected by the between-batch ($\sigma^2{}_b$), sampling ($\sigma^2{}_s$), and testing ($\sigma^2{}_t$) variance, overall variance ($\sigma^2{}_o$) was determined by using the equation:

$$\sigma^2_o = \sigma^2_b + \sigma^2_s + \sigma^2_t$$

As indicated earlier, testing variance is a measure of the repeatability of the testing procedure. Because of budgetary considerations and time constraints, testing variance was estimated only for 2A-dry plants. It was assumed that this component of variance did not change with the process.

TABLE 1 Components of Variance for 2A Aggregate, 3/4-in. Sieve

	Degrees of Freedom		Variance Component (%)	
Variance Source	Gravel	Dry	Gravel	Dry
Total	29	88	73.357	64.276
Plant	3	3	26.669	23.405
Visit	0	2		28.510
Between-batch	12	21	23.861	1.264
Within-batch	14	40	22.827	7.956
Error (testing)	0	22		3.141
Mean percentage passing (spec. 52-100)			77.27	82.90
Standard deviation (σ_o)			6.83	3.52
$(\sigma_b^2/\sigma_o^2) \times 100$			50	10

TABLE 2 Components of Variance for 2A aggregate, 3/8-in. Sieve

	Degrees of Freedom		Variance Component (%)	
Variance Source	Gravel	Dry	Gravel	Dry
Total	29	88	69.484	124.110
Plant	3	3	-1.830	50.354
Visit	0	2		42.092
Between-batch	12	21	36.041	8.428
Within-batch	14	40	33.443	19.234
Error (testing)	0	22		4.001
Mean percentage passing (spec. 36-70)			52.59	49.60
Standard deviation (σ_o)			8.34	5.63
$(\sigma_b^2/\sigma_o^2) \times 100$			52	27

TABLE 3 Components of Variance for 2A Aggregate, No. 4 Sieve

	Degrees of Freedom		Variance Component (%)	
Variance Source	Gravel	Dry	Gravel	Dry
Total	29	88	62.056	93.251
Plant	3	3	23.027	55.040
Visit	0	2		10.690
Between-batch	12	21	17.542	10.692
Within-batch	14	40	21.486	13.375
Error (testing)	0	22		3.454
Mean percentage passing (spec. 24-50)			37.66	30.85
Standard deviation, (σ_o)			6.25	5.25
$(\sigma_b^2/\sigma_o^2) \times 100$			45	39

TABLE 4 Components of Variance for 2A Aggregate, No. 16 Sieve

	Degrees of Freedom		Variance Component (%)	
Variance Source	Gravel	Dry	Gravel	Dry
Total	29	88	19.151	54.732
Plant	3	3	6.558	43.451
Visit	0	2		-0.174
Between-batch	12	21	5.974	6.195
Within-batch	14	40	6.619	3.582
Error (testing)	0	22		1.505
Mean percentage passing (spec. 10-30)			21.77	15.37
Standard deviation (σ_o)			3.55	3.36
$(\sigma_b^2/\sigma_o^2) \times 100$			47	55

TABLE 5 Components of Variance for 2A Aggregate, No. 200 Sieve

	Degrees of Freedom		Variance Component (%)	
Variance Source	Gravel	Dry	Gravel	Dry
Total	29	88	5.119	4.747
Plant	3	3	3.671	2.217
Visit	0	2		0.425
Between-batch	12	21	1.142	1.109
Within-batch	14	40	0.306	0.208
Error (testing)	0	22		0.788
Mean percentage passing (spec. 0-10)			6.90	7.04
Standard deviation (σ_o)			1.20	1.45
$(\sigma_b^2/\sigma_o^2) \times 100$			79	53

PRICE ADJUSTMENT SCHEDULE

So that the tentative acceptance plan would be similar to PennDOT's statistically based specification for bituminous concrete, it was decided that lot acceptance should be based on an estimate of the percentage of material that falls within specification limits. This estimate, commonly referred to as $\widehat{PWL}$, can be thought of as an index of the quality of a lot submitted by the producer for acceptance. A trial price adjustment schedule was developed (Table 6), which established a relationship between the $\widehat{PWL}$ (i.e., material quality) and payment. In developing this schedule, the authors kept in mind the relative criticality of the sieve sizes in the gradation of the aggregate. For example, because of the importance of the minus No. 200 sieve fraction, the tentative schedule for the No. 200 sieve is relatively more stringent than the payment schedules for the other sieves.

TABLE 6 Price Adjustment Schedule 1 for Tentative Acceptance Plan for 2A Aggregate (percentage of contract price to be paid)

	Sieve Size				
Estimated PWL	3/4 in.	3/8 in.	No. 4	No. 16	No. 200
91-100	100	100	100	100	100
86-90	95	95	95	95	90
81-85	90	90	85	90	80
76-80	80	80	75	80	70
71-75	70	70	65	70	60
65-70	60	60	–[a]	60	–[a]
<65	–[a]	–[a]		–[a]	

[a] The contractor shall remove and replace the lot to meet specification requirements, or the engineer and the contractor may agree in writing that, for practical purposes, the lot shall not be removed and will be paid for at 50 percent of the contract price.

OPERATING CHARACTERISTIC CURVES

A sample size of N = 5, PennDOT's gradation limits for 2A aggregate, and the estimated standard deviation computed (Tables 1-5) were then used in a computer simulation program to generate the distribution of the $\hat{PWL}$ of a lot (5). For each sieve in the gradation, six lots with various true means (μ) were studied. The μ-values were selected so as to range between the specification mean and a specification limit. For the No. 200 sieve, the lot true means studied were 5.0, 6.0, 7.0, 8.0, 9.0, and 10.0. The computer program then generated values of $\hat{PWL}$ by simulating the selection of 10,000 independent random samples of size N = 5 from each of the lots described.

The values of $\hat{PWL}$ thus obtained were then employed with the payment schedule to develop the operating characteristic (OC) curves for the acceptance plan. OC curves were developed for each sieve and each aggregate-process combination. Appendix A gives a part of the computer output obtained for the No. 200 sieve of the 2A-dry process limestone. The OC curves shown in Figure 2 were based on the computer output and the payment schedule of Table 6. These curves provide a graphic illustration of the consequences of the acceptance plan.

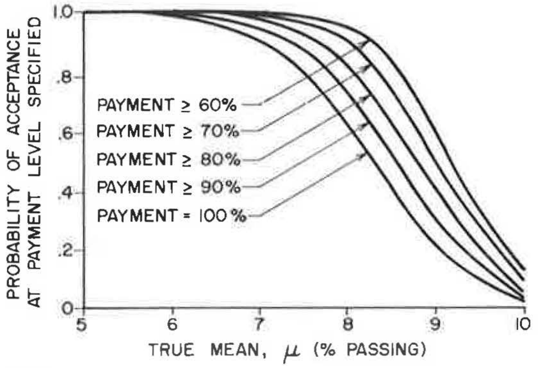


FIGURE 2 OC curves for No. 200 sieve of 2A-dry process aggregate.

EXPECTED PAYMENT CURVE

The expected payment curve indicates the average payment (over the long run) that a contractor will receive if he continues to supply material of a given conformity. Thus the curve illustrates the relationship between the conformity of the contractor's product and his expected payment.

The development of the expected payment curve for the No. 200 sieve is explained here with reference to the output (Appendix A) from the computer simulation program described earlier. According to the computer output, the probability that a lot with a true mean of μ = 8.00 will be assigned 100 percent payment is 1 - (3,740/10,000) = 0.626. The probability that this lot will be received at 90 percent payment is (3,740 - 2,662/10,000 = 0.1118. Similarly, the probability that this lot will be received at 80, 70, and 60 percent payment is 0.0874, 0.0758, and 0.0505, respectively. Now let us assume that when the $\hat{PWL}$ is less than 71 percent the material will be accepted at 50 percent payment (in lieu of removal) in R(1 - L) percent cases, where

L = Offset of true mean from specification mean ÷ (Specification upper limit - Specification lower limit)^2

and R = probability that the $\hat{PWL}$ is rejectable. For the lot under consideration,

L = (8.00 - 5.00)/5.00 = 3/5 or 0.6

and the probability that the $\hat{PWL}$ will be less than 71 percent (rejectable quality) is 0.0485. Thus the probability that 50 percent payment will be made is 0.0485 x (1 - 0.6) or 0.0194. Finally, the difference between the probability that $\hat{PWL}$ is of rejectable quality and the probability that the lot will be accepted at 50 percent payment gives the probability of 0 percent payment. For the lot under discussion, the probability that no payment will be made is given by 0.0485 - 0.0194 = 0.0291. Expected payment is then determined by the relationship:

Expected payment = Σ [(Payment) x (Probability of receiving payment)]

Thus for a lot with μ = 8.00

Expected payment = [(100)(0.0626) + (90)(0.1118) + (80)(0.0874) + (70)(0.0758) + (60)(0.0505) + (50)(0.0194) + (0)(0.0291)] = 88.96%

This indicates that, under the tentative acceptance plan, a producer who supplies 2A aggregate such that its true mean on the No. 200 sieve is 8.00 will receive an average payment (over the long run) of 88.96 percent. The expected payment determined and the expected payments calculated for lots of other quality have been summarized in Table 7. This infor-

TABLE 7 Expected Payment Curve for No. 200 Sieve of 2A (dry process) Aggregate Based on Schedule 1, σ_o = 1.45, N = 5, and Acceptance Limits of 0 to 10 Percent

True (lot) Mean, μ	Probability of Receiving Indicated Payment (%) 100	90	80	70	60	50[a]	0	Expected[b] Payment (%)
5.00	0.9993	0.0005	0.0002					99.91
6.00	0.9913	0.0065	0.0016	0.0006				99.89
7.00	0.9118	0.0508	0.0229	0.0093	0.0034	0.0011	0.0007	98.49
8.00	0.6260	0.1118	0.0874	0.0758	0.0505	0.0194	0.0291	88.96
9.00	0.2122	0.0833	0.0920	0.1107	0.1100	0.0784	0.3134	54.35
10.00	0.0247	0.0133	0.0173	0.0292	0.0438	0.0000	0.8717	9.72

[a] Assumptions for 50% payment: percentage of cases in which 50% payment will be made in lieu of removal:

R (1 - L) x 100

where

L = offset of true mean from specification mean/(Specification mean - Specification lower limit) and
R = probability that PWL is rejectable.

[b] Expected payment = Σ [(Payment) x (Probability of receiving payment)].

mation was then used to plot the expected payment curve shown in Figure 3. It can be seen from this curve that the contractor's expected payment is 9.72 percent when his process is centered at the specification upper limit, but that the expected payment rises sharply as he moves the process toward the mean of the acceptance limits. Because the lower limit on this sieve is zero, his expected payment will be 100 percent for any true mean less than 5.00.

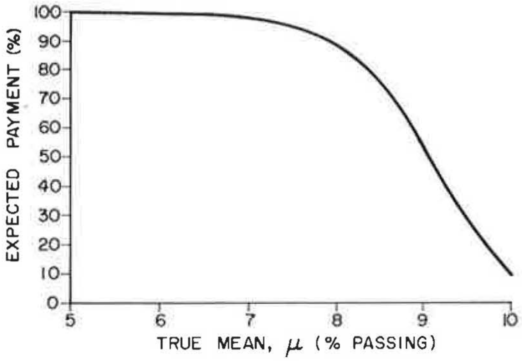


FIGURE 3 **Expected pavement curve for No. 200 sieve of 2A-dry process aggregate, where $\sigma = 1.45$.**

REVIEW OF ACCEPTANCE LIMITS

The objective of assigning numerical limits for a measurable characteristic such as aggregate gradation is to ensure uniformity or to ensure that some critical value that would affect performance is not exceeded, or both (6). The acceptance plan discussed previously was developed with the department's current specification limits given in Table 8 (7). Whether acceptance limits can be modified in accordance with the objectives for assigning numerical limits but without causing undue hardship to most aggregate producers and without incurring additional cost to the state will be assessed next.

TABLE 8 **Gradation Limits for PennDOT's 2A Aggregate** *(7)*

Sieve Size	Percentage Passing
3/4 in.	52-100
3/8 in.	36-70
No. 4	24-50
No. 16	10-30
No. 200	0-10

Consider the No. 200 sieve for the 2A aggregate with specification limits of 0 to 10 percent. This is a single-limit specification because one limit is zero. Therefore the limit of concern is 10. The data in Table 5 indicate that the dry process plants have an overall standard deviation of 1.45 percent and a mean percentage passing that is equal to 7.04 percent. The offset between the upper limit and the process mean is 10 - 7.04 = 2.96, which is equal to two standard deviations. Also, for the gravel producers, the between-plant component of variance is 79 percent of the total variance. This indicates that some of the plants sampled would be unable to produce aggregate within the limit. However, because of the critical nature of the material finer than the No. 200 sieve, it is not considered advisable to raise the upper limit of the specification.

A rationale similar to that used in reviewing acceptance limits for the No. 200 sieve was applied to the other sieves in the 2A gradation. Except for the 3/4-in. sieve, it was found that, with the producers' existing (1983) capabilities, the offset between the specification mean and a limit was less than three standard deviation units. In addition, for two of the four sieves (No. 4 and No. 16), the means for the two processes (gravel and dry) were located on opposite sides of the specification mean. If the acceptance limits are to be modified, fairness will require that the lower limit be lowered and that the upper limit be raised to accommodate both processes. This would, however, widen the specification band, which in turn could play havoc with the uniformity of the material and have an adverse effect on its performance. Consequently, acceptance limits were not changed for these sieves. For the same reason, the acceptance band for the 3/8-in. sieve also was not widened.

On the 3/8-in. sieve, the gravel process has the larger standard deviation (6.83). However, the existing limits on this sieve are such that the specification mean is more than three standard deviation units from a specification limit. Therefore these limits do not require any modification.

It should be mentioned here that an additional reason for not changing the acceptance limits for the 3/8-in. sieve and sieve Nos. 4, 16, and 200 is the belief that enforcement of a statistically oriented acceptance plan would provide the aggregate producers with the incentive to meet the specification limits.

MULTIPLE PRICE ADJUSTMENTS

The price adjustment schedule described earlier, which was incorporated into the tentative acceptance plan, was designed for individual sieves. However, it is possible for an aggregate gradation to be such that payment reductions must be applied to two or more sieves. A system had to be devised to determine the total payment in such cases. In general, three methods are possible:

1. Add price reductions,
2. Multiply payment percentages, and
3. Use smallest payment percentage.

Consider a 2A aggregate lot that has been tested for acceptance. Suppose the payment schedule indicates that the lot should be assigned 90, 90, and 70 percent payment for the 3/4-in., 3/8-in., and No. 4 sieves, respectively. If the first method is followed, the payment factor is 1.00 - (1 - 0.90) - (1 - 0.90) - (1 - 0.70) = 0.50 or 50 percent. The second method will result in 57 percent payment, and the third will accept the lot at 70 percent payment. Now consider a 2A aggregate lot for which the individual schedules for the same three sieves would allocate 80, 75, and 70 percent, respectively. In this case the lot would be accepted at 25, 47, and 70 percent payment by Methods 1, 2, and 3, respectively. It can be seen from this example that Methods 1 and 2 are excessively harsh. The third method, on the other hand, using the smallest payment percentage, encourages the producer to supply quality materials. Therefore this method was adopted as part of the tentative acceptance plan. The recommended tentative acceptance plan is given in Appendix B.

SUMMARY AND CONCLUSIONS

The primary objective of the research project was to develop a statistically based specification for the gradation of unbound aggregates. The development of an acceptance plan for a dense-graded base course aggregate (PennDOT 2A) has been described. The acceptance plan was based on statistical parameters estimated with the help of a statistically designed sampling plan. The procedure can be adopted as a model for formulating a statistically based specification for any unbound aggregate used in highway construction or maintenance.

The acceptance plan developed here incorporates a trial price adjustment schedule based mainly on judgment. It should, therefore, be treated as a preliminary or tentative acceptance plan. It is important that a field simulation plan be designed, executed, and properly conducted to verify that the plan is implementable and fair both to the state and to industry. If the parties concerned, the state highway department and the aggregate producers, find that the acceptance plan is not reasonable, it may have to be modified in one or more of the following ways:

1. Loosen or tighten the acceptance limits,
2. Change the sample size (N),
3. Increase or decrease payment for a given PWL, and
4. Reduce or increase the number of payment levels in the schedule.

On the basis of the extensive field sampling and data analysis conducted as part of the research project, a number of conclusions and findings are relevant:

1. For a given sieve size, the statistical parameters (mean and standard deviation for percentage passing) varied significantly between dry process limestone and gravel aggregate.

2. Many of the plants sampled would not have any difficulty in meeting the specification limits. However, the magnitude of the between-plant component of variance indicated that there were several plants that were producing aggregate that would not meet this specification (2). It is expected that the adoption of the proposed acceptance plan will provide aggregate producers with an incentive for improved process control.

RECOMMENDATIONS

The acceptance plan described here should be considered tentative, especially because it is based on a trial price adjustment schedule. It is recommended that a continuous payment schedule be developed for the acceptance plan. The acceptance plan should then be evaluated and verified with an appropriately designed field simulation study. The simulation study should include sampling of both new construction and maintenance projects. A sample size of five was recommended in the tentative specification to allow for a comparative analysis of sample sizes ranging from three to five. Finally, the results obtained from the field simulation study should be used to modify the acceptance plan before it can be incorporated in a quality assurance program.

REFERENCES

1. Statistically Oriented End-Result Specifications. NCHRP Synthesis of Highway Practice 38. TRB, National Research Council, Washington, D.C., 1976.
2. A Guide to Maintenance Materials Acceptance. Maintenance Materials Task Force, Pennsylvania Department of Transportation, Harrisburg, 1983.
3. D.A. Anderson et al. Acceptance Criteria for Aggregates. Final Report, PennDOT Research Project 81-6. Pennsylvania Transportation Institute, Pennsylvania State University, University Park, 1985.
4. SAS User's Guide. SAS Institute, Inc., Cary, N.C., 1979.
5. J.H. Willenbrock and P.A. Kopac. The Development of Operating Characteristic Curves for PennDOT's Restricted Performance Bituminous Concrete Specifications. Research Project 74-27. Pennsylvania Transportation Institute, Pennsylvania State University, University Park, 1976.
6. Miller-Warden Associates. Development of Guidelines for Practical and Realistic Construction Specifications. NCHRP Report 17. TRB, National Research Council, Washington, D.C., 1965.
7. Specifications. Publication 408. Pennsylvania Department of Transportation, Harrisburg, 1983.

APPENDIX A
COMPUTER OUTPUT FROM SIMULATION PROGRAM

```
THIS PROGRAM IN FILE PWL18W200COR MARCH 31,1985
   N  NM  NIT   MEANS                                        LIMITS
  5    610000  5.00   6.00   7.00   8.00   9.00  10.00   0.00  10.00



DIST OF CONTENT FOR MEAN=    8.00     OFFSET OF POP. MEAN=   -3.00
           0.0     0.1     0.2     0.3     0.4     0.5     0.6     0.7     0.8     0.9
    50      10      10      11      11      12      14      14      16      17      18
    51      18      20      21      21      21      21      21      21      21      21
    52      23      23      23      23      23      23      23      24      24      24
    53      24      24      25      25      26      26      26      26      26      26
    54      26      26      26      26      26      27      28      28      31      31
    55      31      33      33      34      34      34      35      36      39      39
    56      39      39      39      39      39      39      40      40      40      41
    57      41      43      44      46      47      50      50      51      52      53
    58      54      56      57      58      59      60      61      61      63      63
    59      63      64      67      68      68      69      70      74      76      79
    60      80      82      83      86      89      90      90      91      92      94
    61      96      99     101     102     103     106     106     106     108     112
    62     115     116     116     117     119     120     121     121     123     125
    63     128     133     138     139     143     147     150     152     159     160
    64     163     169     174     175     180     187     190     194     196     196
    65     201     203     205     208     213     215     217     221     222     225
    66     226     229     233     235     239     242     248     252     256     263
    67     268     271     273     274     284     288     291     299     304     309
    68     313     321     328     333     340     344     353     355     360     366
    69     375     380     387     393     401     405     412     420     422     427
    70     431     438     448     453     459     463     467     472     481     485
    71     494     503     511     521     527     537     544     557     566     575
    72     585     599     607     615     622     631     638     650     663     674
    73     684     695     709     720     730     740     755     763     774     783
    74     788     799     804     807     815     830     842     852     861     868
    75     881     894     911     919     930     938     951     969     979     990
    76    1003    1022    1036    1050    1062    1081    1092    1109    1122    1132
    77    1144    1165    1179    1196    1213    1228    1244    1264    1279    1301
    78    1317    1325    1342    1358    1369    1387    1399    1410    1433    1451
    79    1469    1476    1487    1503    1519    1532    1549    1567    1575    1591
    80    1607    1619    1631    1648    1667    1681    1699    1710    1729    1748
    81    1771    1789    1808    1821    1839    1863    1881    1894    1917    1938
    82    1956    1965    1983    1994    2006    2022    2043    2059    2070    2086
    83    2104    2120    2141    2162    2177    2189    2209    2223    2243    2258
    84    2272    2290    2309    2327    2353    2371    2399    2415    2433    2452
    85    2484    2500    2512    2528    2541    2559    2569    2579    2599    2622
    86    2632    2662    2684    2706    2725    2748    2768    2786    2810    2838
```

APPENDIX B
RECOMMENDED ACCEPTANCE PLAN

Acceptance Sampling

Sampling Location

Aggregate will be sampled from mini-stockpiles at the source of supply (quarry) or the processing plant as it is loaded on trucks for shipment.

Lot Size

Each 1,000 tons of material shipped from a plant will be treated as a lot for acceptance purposes. However, if the purchase order quantity is less than 1,000 tons, the quantity on the purchase order will constitute the lot size.

Sample Size

Each lot will be divided into five equal sublots, and replicate samples will be obtained from each sublot.

Sampling Procedure

A stratified random sampling procedure will be used to collect a pair (replicate) of sample increments from each sublot (2). The 10 sample increments so collected will be separated into two sample sets designated sample set 1 and sample set 2. Each sample set will include one increment from each sublot.

Referee Sample

Sample set 2 will constitute the referee sample. This sample will be tested for gradation analysis, and the results will be employed for acceptance purposes in the event that gradation results from sample set 1 are questioned.

Evaluating Material Acceptability

Testing Procedure

Sample set 1 will be tested for gradation in accordance with the appropriate Pennsylvania test methods.

The test results thus obtained for each lot will be used to compute the sample mean (x_1) and sample standard deviations (s_1) for each sieve. The subscript 1 indicates that the statistics are associated with sample set 1. These results will be used in the acceptance procedure unless the statistics for one or more sieves are questioned. In that event the contractor or the department may request that gradation results for the entire sample set 1 be disregarded and that acceptance be based on the mean (x_2) and the standard deviation (s_2) computed from the gradation analysis of the referee sample. If the request for testing the referee sample is made by the contractor, he should pay for the additional testing of the lot at a previously determined rate. However, the department has the option to waive the charge for the additional testing. The contractor will have the option of monitoring all acceptance sampling and testing.

Acceptance Procedure

Acceptance for aggregate gradation will be based on the estimated percentage of the material that is within the specification limits (PWL). The specification limits for the sieves used to control the gradation of the aggregate are given in Table 8. The standard deviation method will be used for estimating the PWL. For each sieve the PWL will be estimated with the help of two quality indices, Q_U and Q_L:

$$Q_U = (U - x_i)/s_i$$

TABLE B-1 Table for Estimating Percentage of Lot Within Limits (PWL) (standard deviation method)

Percent Within Limits	Negative Values of Q_U or Q_L					Percent Within Limits	Positive Values of Q_U or Q_L				
	n=3	n=4	n=5	n=6	n=7		n=3	n=4	n=5	n=6	n=7
50	.0000	.0000	.0000	.0000	.0000	99	1.1510	1.4700	1.6719	1.8016	1.8893
45	.1806	.1500	.1406	.1364	.1338	98	1.1476	1.4400	1.6018	1.6990	1.7615
						97	1.1439	1.4100	1.5428	1.6190	1.6662
40	.3568	.3000	.2823	.2740	.2689	96	1.1402	1.3800	1.4898	1.5500	1.5868
39	.3912	.3300	.3106	.3018	.2966	95	1.1367	1.3500	1.4408	1.4892	1.5184
38	.4252	.3600	.3392	.3295	.3238						
37	.4587	.3900	.3678	.3577	.3515	94	1.1330	1.3200	1.3946	1.4332	1.4562
36	.4917	.4200	.3968	.3859	.3791	93	1.1263	1.2900	1.3510	1.3813	1.3990
						92	1.1170	1.2600	1.3091	1.3328	1.3465
35	.5242	.4500	.4254	.4140	.4073	91	1.1087	1.2300	1.2683	1.2866	1.2966
34	.5564	.4800	.4544	.4426	.4354	90	1.0977	1.2000	1.2293	1.2421	1.2494
33	.5878	.5100	.4837	.4712	.4639						
32	.6187	.5400	.5131	.5002	.4925	89	1.0864	1.1700	1.1911	1.2001	1.2045
31	.6490	.5700	.5424	.5292	.5211	88	1.0732	1.1400	1.1538	1.1592	1.1615
						87	1.0596	1.1100	1.1174	1.1196	1.1202
30	.6788	.6000	.5717	.5586	.5506	86	1.0446	1.0800	1.0819	1.0813	1.0798
29	.7076	.6300	.6018	.5880	.5846	85	1.0286	1.0500	1.0469	1.0437	1.0413
28	.7360	.6600	.6315	.6178	.6095						
27	.7635	.6900	.6619	.6480	.6395	84	1.0118	1.0200	1.0125	1.0073	1.0032
26	.7905	.7200	.6919	.6782	.6703	83	.9940	.9900	.9782	.9718	.9673
						82	.9748	.9600	.9453	.9367	.9315
25	.8164	.7500	.7227	.7093	.7011	81	.9555	.9300	.9123	.9028	.8966
24	.8416	.7800	.7535	.7403	.7320	80	.9342	.9000	.8798	.8693	.8626
23	.8661	.8100	.7846	.7717	.7642						
	.8896	.8400	.8161	.8040	.7964	79	.9122	.8700	.8479	.8363	.8290
21	.9122	.8700	.8479	.8363	.8290	78	.8896	.8400	.8161	.8040	.7964
						77	.8661	.8100	.7846	.7717	.7642
						76	.8416	.7800	.7535	.7403	.7320
						75	.8164	.7500	.7227	.7093	.7011
20	.9342	.9000	.8798	.8693	.8626	74	.7905	.7200	.6919	.6782	.6703
19	.9555	.9300	.9123	.9028	.8966	73	.7635	.6900	.6619	.6480	.6395
18	.9748	.9600	.9453	.9367	.9315	72	.7360	.6600	.6315	.6178	.6095
17	.9940	.9900	.9782	.9718	.9673	71	.7076	.6300	.6018	.5880	.5846
16	1.0118	1.0200	1.0125	1.0073	1.0032	70	.6788	.6000	.5717	.5586	.5506
15	1.0286	1.0500	1.0469	1.0437	1.0413	69	.6490	.5700	.5424	.5292	.5211
14	1.0446	1.0800	1.0819	1.0813	1.0798	68	.6187	.5400	.5131	.5002	.4925
13	1.0597	1.1100	1.1174	1.1196	1.1202	67	.5878	.5100	.4837	.4712	.4639
12	1.0732	1.1400	1.1538	1.1592	1.1615	66	.5564	.4800	.4544	.4426	.4354
11	1.0864	1.1700	1.1911	1.2001	1.2045	65	.5242	.4500	.4254	.4140	.4073
10	1.0977	1.2000	1.2293	1.2421	1.2494	64	.4917	.4200	.3968	.3859	.3791
9	1.1087	1.2300	1.2683	1.2866	1.2966	63	.4587	.3900	.3678	.3577	.3515
8	1.1170	1.2600	1.3091	1.3328	1.3465	62	.4252	.3600	.3392	.3295	.3238
7	1.1263	1.2900	1.3510	1.3813	1.3990	61	.3912	.3300	.3106	.3018	.2966
6	1.1330	1.3200	1.3946	1.4332	1.4562	60	.3568	.3000	.2823	.2740	.2689
5	1.1367	1.3500	1.4408	1.4892	1.5184	55	.1806	.1500	.1406	.1364	.1338
4	1.1402	1.3800	1.4898	1.5500	1.5868	50	.0000	.0000	.0000	.0000	.0000
3	1.1439	1.4100	1.5428	1.6190	1.6662						
2	1.1476	1.4400	1.6018	1.6990	1.7615						
1	1.1510	1.4700	1.6719	1.8016	1.8893						

and

$Q_L = (x_i - L)/s_i$

where

x_i = mean of the measurements on the lot;
U = specification upper limit;
L = specification lower limit;
s_i = standard deviation of the measurements on the lot; and
i = 1 or 2, depending on whether gradation results for sample set 1 or 2 were used for determining acceptance.

The value of Q_U thus obtained will be used with Table B-1 to determine the estimated percentage of the material below the upper limit (PWL_U) for the sieve. Similarly, the value of Q_L, used in conjunction with Table B-1, will provide the estimated percentage of the material above the lower limit (PWL_L). In the case of a given sieve, the PWL estimate for the lot will then be calculated as

$PWL = (PWL_U + PWL_L) - 100$

Price Adjustment

The price adjustment for a given sieve size based on the estimated PWL will be determined by reference to the appropriate price adjustment schedule (Table 8).

Multiple Price Adjustments

If the estimated PWL values for a particular lot of material indicate price adjustments for more than one sieve, the total pay factor for the lot will be determined by the smallest individual pay factor (in decimal form). For example, if the estimated PWL values for a lot of aggregate indicated pay factors of 90, 90, and 80 percent for the 3/8-in., No. 4, and No. 8 sieve, respectively, the total pay factor for the lot would be 0.80 (or 80 percent of the unit bid price).

This work was sponsored by the Pennsylvania Department of Transportation and the FHWA, U.S. Department of Transportation. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the FHWA, U.S. Department of Transportation, or the Commonwealth of Pennsylvania. This paper does not constitute a standard, specification, or regulation.

Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.

Development of an Asphalt Construction Pay Schedule Based on the Value Concept

ROBERT P. ELLIOTT and MORELAND HERRIN

ABSTRACT

Pavement construction pay adjustment schedules have generally been based on a somewhat arbitrary selection of "acceptability limits" with the adjusted pay based on a concept of the percentage of construction within these limits. In this paper an alternate approach applied to asphalt paving is presented and demonstrated. Acceptability limits are selected to represent the capabilities of normal, good contractors. To assure this, the limits are established through an analysis of actual construction test data. For this study, these data include more than 2,300 field density and 2,300 field extraction tests conducted on random samples from past construction projects. The pay adjustments for work outside the identified acceptability limits are then set on the basis of the anticipated relative effect of such deviations on pavement service life. This relative life effect was determined by a quasi-theoretical analysis of laboratory data in which the effects of variations in mixture composition and density were studied. The framework around which the schedule is developed is called the value concept. This concept serves as a rational basis for the establishment of pavement construction pay schedules. As such, it provides a means for considering both the average and the variability (standard deviation or range) of construction test results and provides a mechanism for setting pay adjustments that reflect the impact of construction variability on expected pavement life.

Construction pay adjustment schedules are used by many highway agencies. Although primarily thought of in connection with the quality assurance (QA) type of construction contracts, they are also used by many agencies with the more traditional method-oriented specifications to establish payment when it becomes necessary (or at least prudent) to accept construction that does not fully comply with the specifications. Of the 47 highway agencies that responded to an Oregon survey (1), 43 indicated that "out-of-specification" construction is sometimes accepted, and 39 of these indicated that they have a formal method for establishing pay adjustments for such work.

There is, however, no generally accepted method for establishing such schedules, and there appears to be a general consensus that most of the schedules in current use are not fully rational or equitable. For example, of the 39 agencies cited, only 12 indicated a belief that their pay adjustments were equivalent to the value of the reduced pavement serviceability.

Because of a similar concern, the Illinois Department of Transportation sponsored a research study at the University of Illinois (2) for the development of an asphalt construction QA specification pay adjustment schedule that would be fair to both the contractor and the highway agency. The object of the study was to establish a pay schedule that would help assure that the highway user receives a fair value for his tax dollar without unduly penalizing the contractor.

To meet this objective, four basic criteria were adopted to govern the development of the pay schedules:

1. All work should be judged on the basis of the quality that can normally be produced by good contractors using normal care and effort,
2. "Good" or "acceptable" work should always receive full or 100 percent pay,
3. "Superior" work should be rewarded, and
4. "Inferior" work should be penalized.

Two diverse approaches were employed in the development of the payment schedule: (a) an analysis of past construction data to determine typical ranges of variability and (b) a quasi-theoretical analysis of "value" based on the effects of construction variability on pavement life. The first of these assured that the limits adopted for acceptable and superior construction would reflect the construction quality that can be achieved routinely by typical contractors. The second was used to establish penalties for unacceptable construction that reflects the detrimental effect of the degree of unacceptability on the pavement.

Data from 279 lots of binder mix and 189 lots of surface mix from 23 Illinois QA projects were analyzed. From this analysis, limits were established for acceptable work that is to receive full (100 percent) pay and for superior work that is to receive bonus (>100 percent) pay. For the inferior work falling outside these limits, pay adjustments were established on the basis of a concept of construction value measured in terms of the expected relative effect on pavement life.

PAY SCHEDULE FORMAT

Mix Parameters

Before the pay schedule was developed, a general format and the construction parameters to be used for pay determination were selected. Only those items

---

R.P. Elliott, Department of Civil Engineering, University of Arkansas, Fayetteville, Ark. 72701. M. Herrin, Department of Civil Engineering, University of Illinois, Urbana, Ill. 61801.

over which the contractor has direct and immediate control were considered. These included aggregate gradation, asphalt content, density, thickness, and smoothness.

Of these, thickness and smoothness were not considered to be appropriate because most Illinois QA projects involve resurfacing. Because of the surface irregularities in the existing pavement, the contractor's control over these two parameters is limited. Consequently, only gradation, asphalt content, and density were selected to be included as pay schedule parameters.

Illinois' old QA specification was based on these same parameters. Payment levels were determined for four gradation size fractions (e.g., 1 to 1/2 in. and No. 4 to No. 10), asphalt content, and density. Asphalt content and gradation were considered together to establish a mix pay level. The mix pay level was the lowest of these five individual values. The lot pay was then established as the average of the density and mix pay levels.

In the development of the new pay schedule, the four gradation size fractions from the old specification were retained. However, lot pay would be based on the average of three values: (a) the lowest of the four gradation pay values, (b) the asphalt pay value, and (c) the density pay value.

Inclusion of Standard Deviation

With the exception of bonus pay determination, payment under the old QA specification was based on the average of several (generally five) tests. Quite obviously, any construction feature can be acceptable "on the average" and still be quite unacceptable because of extreme variability. In recognition of this, it was considered imperative that the new pay schedule take into account both the average and the variability of test results. To accomplish this, a value concept (3) was developed that serves as the rational basis for the pay schedule. The value concept provides a rational means for including both the average and the standard deviation of test values in the pay determination and a means for basing the pay on the relative effect of construction variability on the life expectancy of the pavement surface.

VALUE CONCEPT

Development of the value concept has been presented in detail previously (3). The concept recognizes that the overall performance of the pavement is a function not of just the average value of material properties but of the entire distribution. It further recognizes that, at the time a pavement is considered to have failed, the area of actual failure is but a small percentage of the pavement surface. This suggests that the life of a pavement surface is controlled by some lower percentile of the material property distribution consistent with this small percentage of surface failure.

The value concept calls this lower percentile the controlling property level. As illustrated in Figure 1d, the controlling property level (assuming a normal distribution) is defined by the equation:

$$Cb = Pb - Z*Sb \qquad (1)$$

where

Cb = controlling property level,
Pb = average value of the material property,
Z = number of standard deviations consistent with the percentage of surface area failed when a pavement is considered unacceptable, and
Sb = standard deviation of the material property distribution.

The controlling property level can be used to establish a general value relationship between an acceptable distribution of construction variability and any other distribution. It is assumed that some relationship exists between the material property and its life expectancy and, initially for simplicity, that that relationship is linear (Figure 1a). A value relationship based on ratios of expected life can be identified. For example, if the controlling property level of an acceptable or "base" distribution (Cb) has a life expectancy of Nb and another distribution (Ca) has a life expectancy of Na, the value of the other distribution is defined as Na/Nb (Figure 1e). This relationship is expressed in terms of controlling property levels by the equation:

$$V = 100 - dV * (Cb - Ca) \qquad (2)$$

where

V = value of the other distribution as a percentage of the value of the acceptable distribution;
dV = slope of the value relationship; and
Cb and Ca = controlling property levels for the acceptable and other distributions, respectively (Figure 1f).

To use the value concept in developing a pay schedule, it was necessary (a) to identify acceptable controlling property levels (Cb) for each of the pay control factors (i.e., gradation size fractions, asphalt content, and density) and (b) to establish relationships between the variation of these factors and expected surface life.

SELECTION OF A Z-VALUE

A step that preceded the identification of acceptable controlling property levels and the application of the value concept was the selection of an appropriate value for Z (number of standard deviations). According to the value concept, Z should be based on the percentage of surface area failed when a typical pavement is considered unacceptable. The exact value of this percentage is quite questionable because no consensus has been reached by engineers who have studied it. Nevertheless, many engineers believe that the percentage should be around 10 percent (Z = 1.28). This suggests that a Z-value somewhat greater than 1 would be appropriate.

However, due to the manner in which the acceptable controlling property levels were to be selected and due to the way they would later be used to establish contractor pay, the specific value of Z was found to not be significant as long as it was reasonable. This was examined by analyzing QA test data from 15 previous construction projects. Pay schedules were developed with Z-values ranging from 0.5 to 3.0 (4). These were applied to the project test data to determine the average pay percentage for each project. The results of this analysis are given in Table 1.

The "correct" value for Z is believed to be between 1.0 and 2.0. The data in Table 1 demonstrate that, within this practical range of values, the precise value selected has only a minor impact on the average project pay, generally less than 1 percent. Because of this and for lack of any strong indication of a more appropriate value, 1.0 was selected as the value for Z. This simplified the controlling property level equation to

$$Cb = Pa - Sb \qquad (3)$$

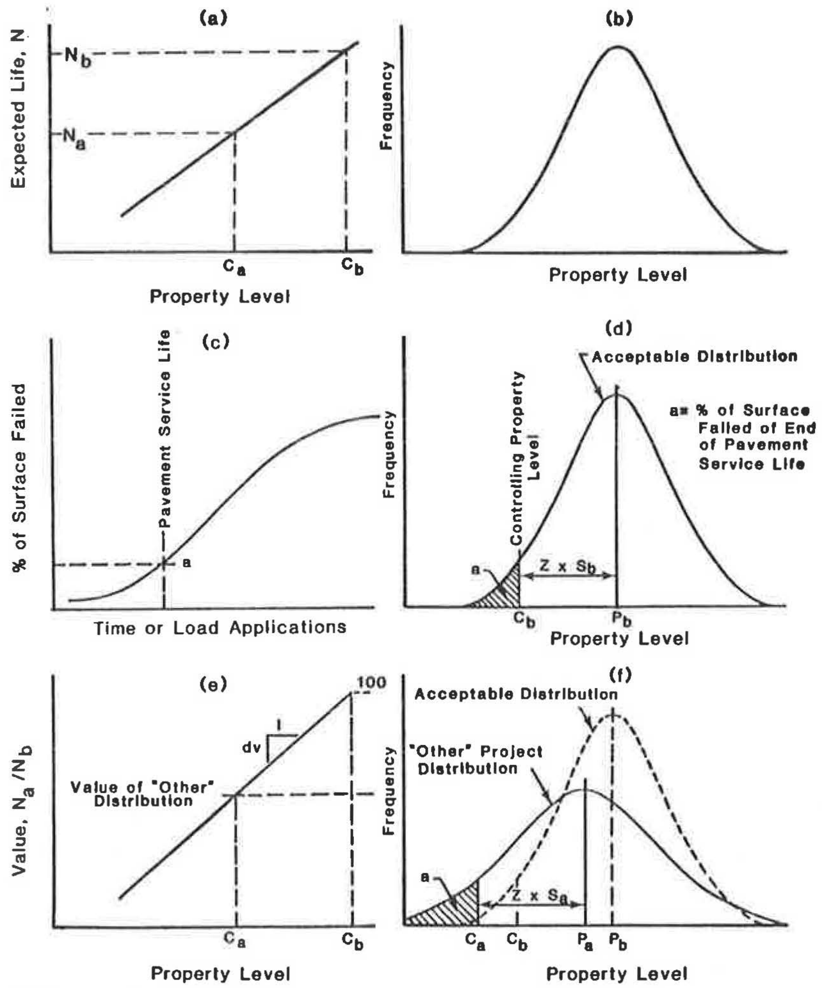


FIGURE 1 Development of the value concept.

USE OF RANGE IN THE VALUE CONCEPT

As a further simplification for practical application, the range of QA test results was substituted into the controlling property level equation as an estimate of the standard deviation (Sb). In actual practice, the true mean and standard deviation of the lot are never known but must be estimated from the results from a small number of test samples. For the mean, the average of the test results is easily calculated and routinely used by field personnel. However, the calculation of standard deviation was considered more complex than what is normally desired for routine field calculation. For small samples, the true population standard deviation can be estimated from the range of test values (difference between high and low) with almost as much efficiency as it can from the more complex calculation (5). The estimate is made by multiplying the range by an appropriate factor that depends on the size of the sample. Table 2 lists the range factors for sample sizes of three through seven.

TABLE 1 Results of Applying Pay Schedules Based on Various Z-Values to Past QA Surface Mix Data

	Average Project Pay Percentage for Z-Value					
Project	0.5	1.0	1.5	2.0	2.5	3.0
A	94.6	95.1	94.6	95.1	95.0	95.0
B	98.6	98.6	98.4	98.8	99.0	99.1
C	100.5	100.7	100.7	101.0	100.2	100.2
D	97.4	96.8	94.8	94.8	94.5	93.8
E	102.5	102.5	102.7	102.7	101.9	100.8
F	100.4	100.4	100.1	99.3	98.7	97.8
G	100.7	101.7	100.9	100.9	100.9	100.2
H	88.8	84.8	84.8	83.1	81.5	81.5
I	99.3	98.8	96.4	94.8	93.1	92.4
J	98.8	98.8	98.5	98.0	98.0	97.6
K	95.7	96.8	96.7	97.1	97.6	97.8
L	98.8	99.6	99.6	99.6	100.0	100.0
M	100.2	100.0	100.2	100.2	100.4	100.4
N	96.3	96.0	94.6	94.4	94.5	93.8
O	96.7	98.3	98.8	99.0	99.0	99.0
Average, all lots	97.9	98.1	97.6	97.5	97.3	97.0
Best job	102.5	102.5	102.7	102.7	101.9	100.8
Worst job	88.8	84.8	84.8	83.1	81.5	81.5

Substituting the range estimate for the standard deviation in the controlling property level equation, the equation becomes

$$Cb = Pb - f*R \tag{4}$$

where f is the range factor from Table 2 for the number of samples tested in a lot and R is the difference between the high and the low test value.

IDENTIFICATION OF PAY DETERMINATION FACTORS

To avoid confusion between the actual pay schedule usage and the value concept as a general basis for pay schedule development, the controlling property

TABLE 2 Factors for Estimating the Standard Deviation from the Range of Test Results *(5)*

Sample Size	Range Factor
3	0.591
4	0.486
5	0.430
6	0.395
7	0.370

level equation was redefined as a pay determination factor (PDF) and modified somewhat to account for the direction of slope of the material property-to-service life (or value) relationship. In developing the value concept, the expected life and value relationships were depicted as increasing with increasing property levels (Figure 1a). With this depiction, the controlling property level was identified as being below the mean resulting in the negative sign in Equation 4. However, for many material properties a reverse trend of decreasing life with increasing property levels exists. For this situation the controlling property level would be greater than the average and the sign would become positive.

Asphalt and Gradation PDFs

For asphalt content and gradation, the deviation from the project's job mix formula was selected as the pay determination parameter. Higher deviations are considered to be associated with shorter life expectancy. Consequently, the PDF equation for asphalt content and the gradation size fractions was defined as

$$PDF = dJMF + f*R \qquad (5)$$

where

PDF = pay determination factor,
dJMF = absolute value of the deviation of the lot average from the job mix formula,
f = range factor from Table 2, and
R = range of test results for the lot.

Density PDFs

For density, however, lower values are associated with shorter life expectancies. Therefore the negative sign is retained in the density PDF equation.

The density parameter selected for the pay schedule was the density quality level determined by Illinois' test strip density control method. In this procedure, Illinois uses the nuclear density device correlated to density cores taken from a test strip. The density quality level is defined by the equation:

$$QL = (MLD/TD) * (MCD/0.95D) * 100 \qquad (6)$$

where

QL = quality level,
MLD = average of nuclear density tests taken at a site at five specified locations across the paved area,
TD = target nuclear density established as the average nuclear density from the project's compaction calibration test strip,
MCD = average density of cores taken from the calibration strip, and
D = theoretical maximum (zero air voids) mix density.

Using this quality level definition, the density PDF equation was defined as

$$PDF = QL - f*R \qquad (7)$$

where QL is the lot average quality level and R is the range of quality level values.

SELECTION OF BONUS AND PENALTY PDFs

Test data representing 279 lots of binder and 189 lots of surface from past QA projects were analyzed to identify PDF values for each of the pay parameters that would represent the limits of acceptable and superior work. The objective of the analysis was to select penalty PDFs that would assure that the bulk of normal construction would be paid for at 100 percent (or greater) of the contract price. A secondary objective was to select bonus PDFs that could be used to identify a smaller percentage of lots for bonus pay.

Penalty and Bonus Frequencies

To make these selections, judgment had to be exercised relative to the number of lots, as represented by the historical QA data, that should be penalized and the number that deserves bonus pay. These numbers must be sufficiently high to encourage quality construction and assure normal acceptable construction but not so high as to affect the cost of construction.

Statistically, deviations from the mean of up to plus or minus one standard deviation are often considered normal and are routinely acceptable in highway construction. Assuming a normal distribution, this would suggest that about 70 percent of all lots might be considered to represent normal, acceptable construction. In this instance, about 15 percent of the lots would be considered at least marginally unacceptable and 15 percent would be superior. This distribution was selected for use in developing the pay schedules--15 percent unacceptable (penalty), 15 percent superior (bonus pay), and 70 percent normally acceptable (100 percent pay).

Actually, of course, any distribution of percentages could be selected. Therefore, to provide complete flexibility to highway administrators who would be responsible for adopting the developed pay schedule, bonus and penalty PDFs were selected based on percentages of 5, 10, 15, 20, and 25. Although the pay schedule developed and presented herein is based on the 15-70-15 distribution, schedules based on other distributions can be established by following the steps used in this paper and using the appropriate bonus and penalty PDFs given in Tables 3 and 4.

Asphalt Content PDFs

In establishing the penalty and bonus levels, the PDF of each lot of past QA data was calculated using either Equation 5 for asphalt content and each gradation sieve size or Equation 7 for density. As an example, for one surface lot, the JMF for asphalt content was 5.5 percent. The average of five samples taken from the lot was 5.74 percent, and the range of test values was 0.26 percent. Using the range factor (f) of 0.43 from Table 2, the PDF for the asphalt content of this lot was

$$(5.74 - 5.50) + 0.43*0.26 = 0.35$$

TABLE 3 Bonus and Penalty Pay Determination Factors for Binder Mixes

	Pay Determination Factors for Percentage of Lots Expected to Receive Penalties or Bonuses				
Mix Parameter	5	10	15[a]	20	25
100% Pay					
Density	97.0	97.3	97.5	97.7	97.9
Asphalt content	0.88	0.70	0.60	0.56	0.48
Size fraction					
1-1/2 in.	11.4	11.1	10.0	9.5	8.7
No. 4-No. 10	5.5	5.3	5.0	4.4	4.05
No. 40-No. 80	4.0	3.3	3.2	3.1	3.0
Minus No. 200	2.7	2.6	2.3	2.1	2.0
Bonus Pay					
Density	100.6	100.3	100.0	99.8	99.6
Asphalt content	0.13	0.19	0.21	0.23	0.25
Size fraction					
1-1/2 in.	4.3	4.6	5.0	5.5	5.9
No. 4-No. 10	1.7	2.0	2.2	2.3	2.5
No. 40-No. 80	1.2	1.4	1.5	1.6	1.8
Minus No. 200	0.8	0.9	1.0	1.05	1.1

[a] 15% was selected for use in developing the pay schedule presented in this paper.

TABLE 4 Bonus and Penalty Pay Determination Factors for Surface Mixes

	Pay Determination Factors for Percentage of Lots Expected to Receive Penalties or Bonuses				
Mix Parameter	5	10	15[a]	20	25
100% Pay					
Density	95.9	96.1	96.6	97.1	97.4
Asphalt content	0.60	0.47	0.43	0.39	0.36
Size fraction					
1/2 in.-No. 4	9.0	7.5	7.2	7.0	6.7
No. 4-No. 10	6.0	5.8	5.3	5.2	4.9
No. 40-No. 80	4.0	3.3	3.0	2.8	2.7
Minus No. 200	2.3	2.2	2.05	1.95	1.8
Bonus Pay					
Density	100.3	99.9	99.5	99.3	99.0
Asphalt content	0.12	0.17	0.18	0.19	0.21
Size fraction					
1/2 in.-No. 4	3.2	3.6	3.7	4.0	4.5
No. 4-No. 10	1.8	2.0	2.2	2.5	2.7
No. 40-No. 80	1.2	1.3	1.5	1.7	1.8
Minus No. 200	0.75	0.9	0.95	1.05	1.15

[a] 15% was selected for use in developing the pay schedule presented in this paper.

The PDFs were determined for all controls (sieve sizes, asphalt content, and density quality level) for each of the 279 binder lots and the 189 surface lots. As one example, the distribution of the various lot PDFs for asphalt content of binder mixes is shown in Figure 2.

The bonus and penalty PDFs for asphalt content were finally selected by examining the lot PDFs and selecting the values that would cause penalties to be assessed to 15 percent of the lots from past QA projects and that would provide bonus payment to another 15 percent. The remaining 70 percent of the lots would receive payment at the full contract price (100 percent pay). As an example, 15 percent of the 279 binder lots is (0.15*279) 42 lots. The PDF for asphalt content of binder mixes was found to be 0.21 or less for 42 of 279 lots and 0.60 or greater for another 42 of 279 lots (see Figure 2). Therefore these values (0.21 and 0.60) were selected as the binder bonus and penalty PDFs, respectively. The PDFs for surface mix lots were selected by the same procedure using (0.15*189) 28 lots as the divider.

Density PDFs

The PDFs for density were selected in a similar fashion. However, the selection process was modified slightly to accommodate the decision to retain the old specification's limits that are intended to prevent excessive density, which can contribute to bleeding and rut development. These limits prohibit bonus pay for any lot that has a sublot quality level of 103 or greater (average air voids of about 2 percent or less) or a lot quality level of 102 or greater (average air voids of about 3 percent or less). To account for this, any lot of previous QA data having a sublot quality level of 103 or greater or an average lot quality level of 102 or greater was deleted from the analysis. This reduced the number of binder lots from 279 to 241 and the number of surface lots from 189 to 176. The bonus and penalty PDFs for density were determined from these reduced numbers of lots.

Gradation PDFs

For gradation, the selection process was complicated because payment is controlled by four values. For example, if the pay percentages for the four different size fractions were 100, 95, 100, and 90, the gradation pay would be the minimum value of 90. Similarly, all four pay percentages must be in the bonus category for bonus pay to be received. With this situation, the PDFs for gradation were selected so that each of the four size fractions has equal likelihood of causing a penalty or permitting bonus payment.

Various combinations of gradation PDF values were applied to the data. The objective in applying these values was to identify those values that would result in the desired number of lots being penalized (or receiving bonuses) with the cause of the penalties evenly distributed among the four size fractions. For example, at the binder mix PDFs for the 15 percent penalty level (42 of 279 lots being penalized), 13 lots fell into the penalty category for each of the four size fractions. (Some of the lots fell into the penalty category on more than one of the size fractions.)

The PDF values selected from the analysis are given in Tables 3 and 4 for binder and surface mixes, respectively.

VALUE RELATIONSHIP SLOPES

The PDFs for 100 percent pay provided the Cb terms to be applied to the basic value concept equation (Equation 2). Completion of the development of the payment schedule required the determination of value relationship slopes (dV in Equation 2) and the computation of PDFs (Ca in Equation 2) for the pay percentages less than 100 percent.

Value relationship slopes were adopted for asphalt content, density, and gradation on the basis of analysis of data in the laboratory phase of the project. This phase was conducted to identify the relative life effects of variations in asphalt content, density, and gradation in terms of the load-associated modes of failure of fatigue cracking and rut development. Details of this work have been reported elsewhere (6).

Figures 3 and 4 show the relationships found for asphalt content and density variation. The fatigue relationships were developed for two extreme strain conditions that were believed to bracket the probable range of effects. As shown in Figures 3 and 4, the rutting relationships were found to fall between the fatigue extremes. Value relationship slopes for

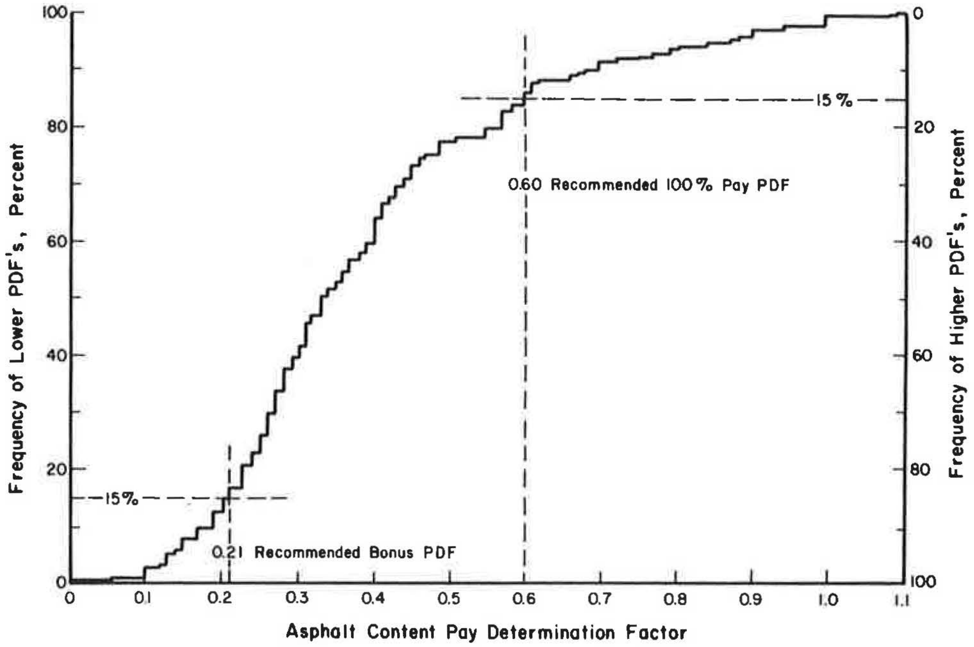


FIGURE 2 Frequency plot of asphalt PDFs for binder mix from previous QA projects.

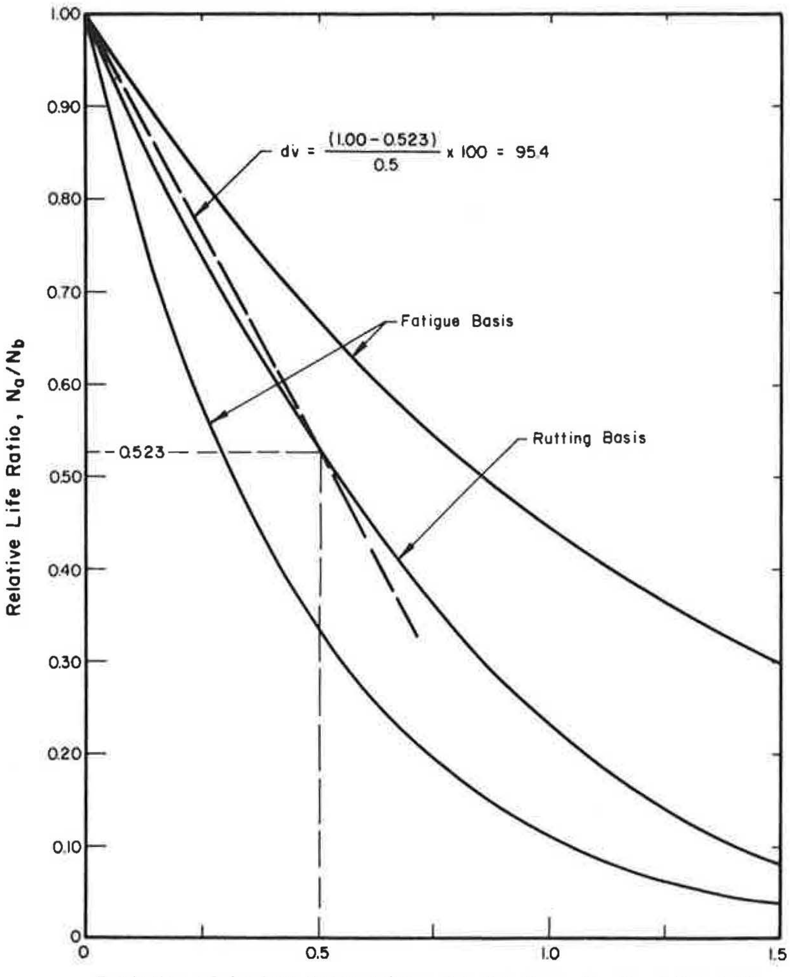


FIGURE 3 Selection of the value relationship slope (dV) for asphalt content.

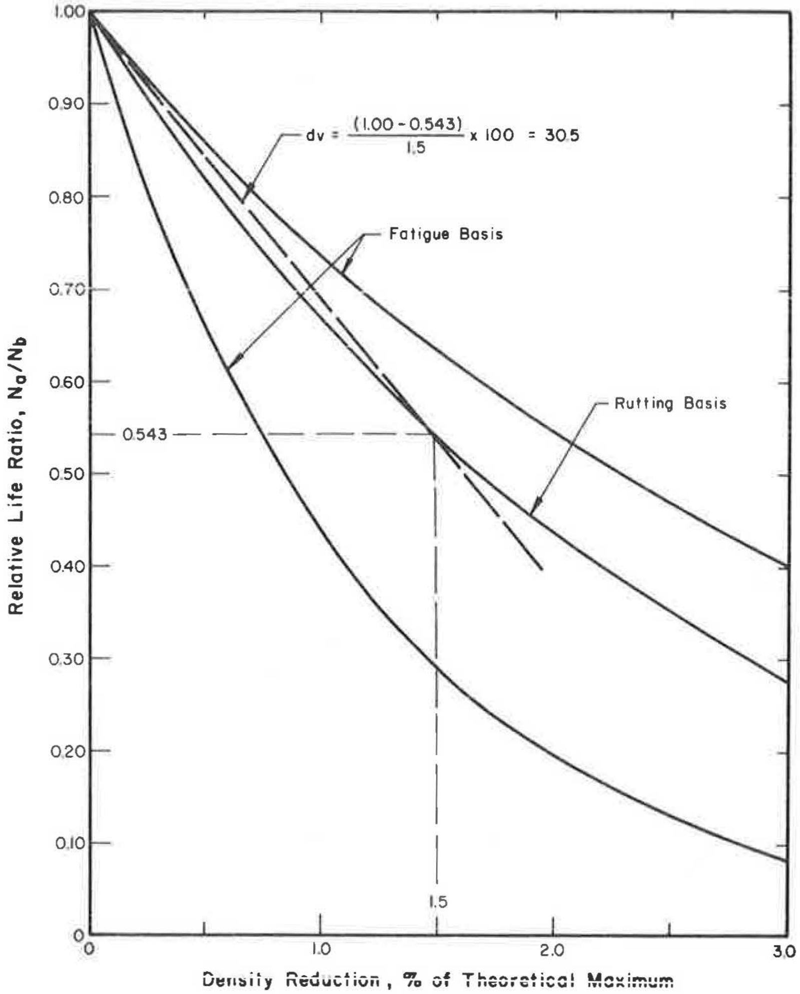


FIGURE 4 Selection of the value relationship slope (dV) for density.

asphalt content and density were selected on the basis of the rut development relationships. Consequently these slopes are considered representative of both fatigue and rutting effects. As shown in these figures, the value relationship slopes were selected as straight line approximations of the initial portion of the rut development curves. These were

$dV = [(1.00 - 0.523)/0.5]*100 = 95.4$
for asphalt content

and

$dV = [(1.00 - 0.543)/1.5]*100 = 30.5$ for density

The value relationship slope for gradation variation was selected on the basis of the finding that the fine and coarse gradation specimens exhibited a relative fatigue life ratio of between 0.33 and 0.60 compared with job mix formula specimens. The middle of this range (0.50) was selected and used to select value relationship slopes for the various gradation size fractions.

The gradation variations used in the testing (difference between the job mix formula percentage and either the coarse or the fine gradation) were 5.7 percent for the 1/2-in. to No. 4 material, 3.8 percent for the No. 4 to No. 10 material, 3.2 percent for the No. 40 to No. 80 material, and 1.9 percent for the material finer than the No. 200 sieve. With these percentages the value relationship slopes were found to be

$dV = [(1.00 - 0.50)/5.7]*100 = 8.8$
for 1/2-in. to No. 4 material,

$dV = [(1.00 - 0.50)/3.8]*100 = 13.2$
for No. 4 to No. 10 material,

$dV = [(1.00 - 0.50)/3.2]*100 = 15.6$
for No. 40 to No. 80 material, and

$dV = [(1.00 - 0.50)/1.9]*100 = 26.3$
for minus No. 200 material.

These slopes were considered characteristic of surface mixes because only surface mixes were tested with gradation variations. However, it would appear that these values can also be applied to binder mixes. The effects of variations in the other mix parameters (asphalt content and density) were not found to be significantly different for binder and surface. Thus the same slopes for gradation were used for both surface and binder mixes with one exception, the 1- to 1/2-in. binder material. Because that material size is not used in surface mixes, its value slope was not established by the testing. To select a value, a plot of the value slopes versus sieve size was developed. A smooth curve was passed between the points and a value

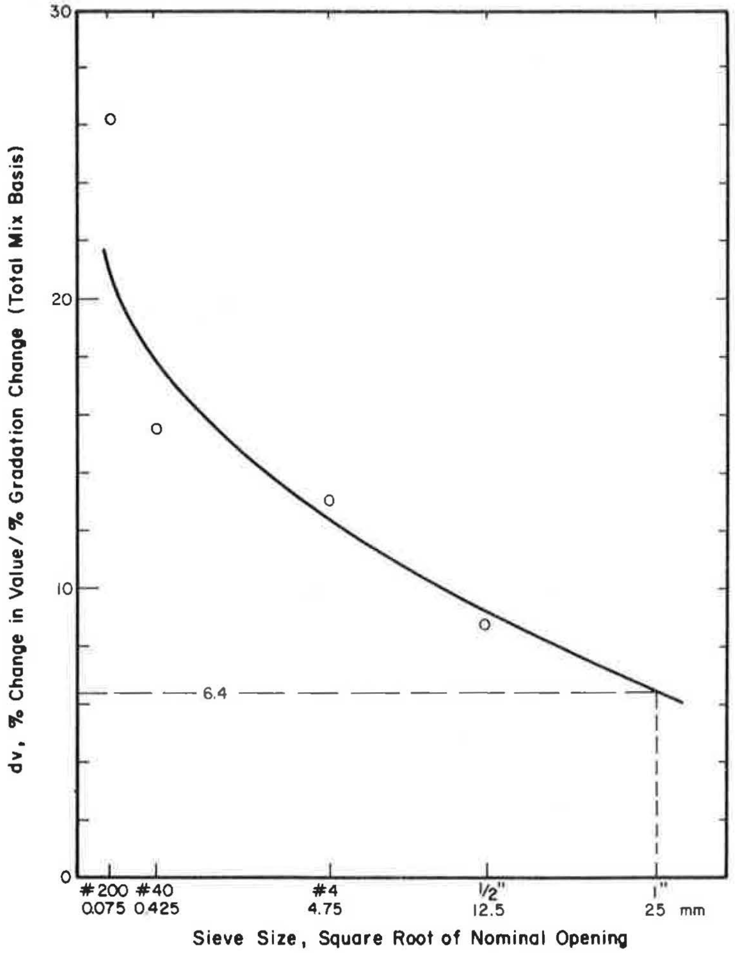


FIGURE 5 Selection of the value relationship slope (dV) for 1- to 1/2-in. material.

relationship slope of 6.4 was selected for the 1- to 1/2-in. material. This plot is shown in Figure 5.

PAY ADJUSTMENT INTERVALS

With bonus and penalty PDFs identified and with value relationship slopes selected, PDFs for pay levels other than 100 percent and bonus could be determined. However, instead of directly computing PDF values, pay adjustment intervals were determined based on the (Cb - Ca) portion of the value equation (Equation 2). These, coupled with the bonus and penalty PDF values identified for various percentages of lots to receive penalties (or bonuses), provide the flexibility needed to permit officials of any highway agency to apply their engineering judgment in accepting or modifying the recommended pay schedule. This flexibility is demonstrated in the next section.

Pay adjustment intervals were established for payment at 95, 90, 85, 80, 75, and 70 percent of the contract price. Based on the value concept, the pay adjustment intervals were determined from the equation:

$$(Cb - Ca) = (100 - P)/dV \quad (8)$$

where (Cb - Ca) is the pay adjustment interval for the payment percentage P.

Pay adjustment intervals were subsequently determined by applying the value relationship slopes to Equation 8. For example, the asphalt content pay adjustment interval for 95 percent pay (P = 95, dV = 95.4) was found by

$$(Cb - Ca) = (100 - 95)/95.4 = 0.05$$

The pay adjustment intervals found are given in Table 5.

PAY SCHEDULE

The recommended payment schedule was developed as a combination of the pay adjustment intervals (Table 5) and the PDFs for 100 percent and bonus pay (Tables

TABLE 5 Pay Adjustment Intervals

	Payment According to Percentage of Contract Price					
Mix Parameter	95	90	85	80	75	70
Density	0.16	0.33	0.49	0.66	0.82	0.98
Asphalt content	0.05	0.11	0.16	0.21	0.26	0.31
Size fraction						
1-1/2 in. (binder)	0.78	1.56	2.34	3.13	3.91	4.69
1/2 in.-No. 4 (surface)	0.57	1.14	1.70	2.27	2.84	3.41
No. 4-No. 10	0.38	0.76	1.14	1.52	1.89	2.27
No. 40-No. 80	0.32	0.64	0.96	1.28	1.60	1.92
Minus No. 200	0.19	0.38	0.57	0.76	0.95	1.14

3 and 4). For example, for asphalt content of binder mixes the 100 percent PDF was found to be 0.60 and the 95 percent pay adjustment interval was found to be 0.05. The PDF for 95 percent pay therefore is

0.60 + 0.05 = 0.65

Thus 95 percent pay would be given if the PDF value for a binder lot were between 0.61 and 0.65. For bonus pay, the PDF is simply the value for bonus pay listed in Table 3 (binder) or 4 (surface). As an example, bonus pay would be given for asphalt content of a binder mix if the lot PDF were 0.21 or less.

The complete pay schedule developed for binder mix is given in Table 6. Table 7 gives the pay schedule for surface mix.

The reader will recall that the payment schedules given in Tables 6 and 7 are based on 15 percent of all lots being penalized and 15 percent receiving bonus pay. In developing the schedule, it was recognized that other percentages of bonus or penalty (including no provision for bonus) may be deemed more appropriate. Therefore the pay schedule data were developed and presented in a manner that would permit the highway administrator to easily modify the schedule for other percentages.

Pay schedules based on other percentages can easily be developed by combining the pay adjustment intervals (Table 5) with the appropriate 100 percent and bonus PDF values from Tables 3 and 4. For example, the 100 percent pay PDF for asphalt content in binder mixes at 10 percent penalized is 0.70 (Table 3). Combining this with the 95 percent pay adjustment interval (0.05), the 95 percent pay PDF for 10 percent penalized is found to be 0.75. The bonus pay PDF for this case would be 0.19 (Table 3).

EFFECT OF SCHEDULE ON PROJECT PAY

A natural question to be asked is, "How will this payment schedule affect the average pay of the typical construction project?" To answer this, the schedule was applied to the 279 lots of binder data and 189 lots of surface data from the previous QA projects. For comparison, the previous Illinois QA payment schedule was also applied to these data. For both schedules, 50 percent pay was assigned for any item (density, gradation, or asphalt content) found to not qualify for at least 70 percent pay. According to Illinois' specification, this is the pay percentage used if the test results are beyond the schedule pay limits but the material is not removed and replaced. Also in accordance with the Illinois specification, bonus pay was awarded at 105 percent of the contract price.

The results of the analyses are summarized in Table 8. The upper portion of the table gives the average pay percentages for all lots based on (a) the current Illinois specification pay schedule; (b) the developed pay schedule that follows a 15-70-15 distribution of penalty, 100 percent, and bonus pay; and (c) a similar pay schedule based on a 10-80-10 pay distribution. Comparison of the old and newly developed schedules shows that the average pay for all projects would be slightly lower (98.1 versus 99.4 for surface and 98.1 versus 100.7 for binder) under the new payment schedule. The lower portion of Table 8 gives the percentage distribution of penalty, 100 percent, and bonus pay for each of the three pay schedules.

Examination of the results indicates that the primary reason for the lower average pay under the new schedule would be a reduction in the number of bonus payments. This is particularly true with regard to density. Actual payment data for QA jobs completed in 1979-1980 show that bonus payment was awarded for 38 percent of all surface lots and for 44 percent of all binder lots. Only 12 percent of surface lots and 9 percent of binder lots were penalized because of density. Similarly, the same data show that 20 percent of all surface lots and 42 percent of all binder lots received a bonus based on gradation and asphalt content. The penalty percentages were 23 and 7, respectively. In contrast the new pay schedule was formulated so that 15 percent of all lots would be

TABLE 6 Pay Adjustment Schedule for Binder

	Pay Determination Factors for Pay Percentage							
Mix Parameter	105	100	95	90	85	80	75	70
Density[a]	100.0	97.5	97.34	97.17	97.01	96.84	96.68	96.52
Asphalt content	0.21	0.60	0.65	0.71	0.76	0.81	0.86	0.91
Size fraction								
1-1/2 in.	5.0	10.0	10.78	11.56	12.34	13.13	13.91	14.69
No. 4-No. 10	2.2	5.0	5.38	5.76	6.14	6.52	6.89	7.27
No. 40-No. 80	1.5	3.2	3.52	3.84	4.16	4.48	4.80	5.12
Minus No. 200	1.0	2.3	2.49	2.68	2.87	3.06	3.25	3.44

[a] For lots having a sublot quality level of 103 or greater or an average lot quality level of 102 or greater, the pay percentage will be reduced to the next lower pay percentage.

TABLE 7 Pay Adjustment Schedule for Surface

	Pay Determination Factors for Pay Percentage							
Mix Parameter	105	100	95	90	85	80	75	70
Density[a]	99.5	96.6	96.44	96.27	96.11	95.94	95.78	95.62
Asphalt content	0.18	0.43	0.48	0.54	0.59	0.64	0.69	0.74
Size fraction								
1/2 in.-No. 4	3.7	7.2	7.77	8.34	8.90	9.47	10.04	10.61
No. 4-No. 10	2.2	5.3	5.68	6.06	6.44	6.82	7.19	7.57
No. 40-No. 80	1.5	3.0	3.32	3.64	3.96	4.28	4.60	4.92
Minus No. 200	0.95	2.05	2.24	2.43	2.62	2.81	3.00	3.19

[a] For lots having a sublot quality level of 103 or greater or an average lot quality level of 102 or greater, the pay percentage will be reduced to the next lower pay percentage.

TABLE 8 Results of Applying the Current and Recommended Payment Schedules to Data from 189 Surface Lots and 279 Binder Lots

	Pay Schedule					
	Surface Mix			Binder Mix		
	Current Specification	Recommended 15% P&B	10% P&B[a]	Current Specification	Recommended 15% P&B	10% P&B[a]
Average Pay Percentages						
All lots	99.4	98.1	98.6	100.7	98.1	98.9
Best job	103.2	102.5	102.5	103.1	101.9	101.0
Worst job	92.5	84.8	86.5	86.1	87.5	92.9
Percentage of All Lots						
Pay > 100%	51	28	24	60	27	22
Pay = 100%	24	38	51	25	44	59
Pay < 100%	25	34	25	15	29	19

Note: P&B = penalty and bonus and current specification is the pay schedule in Illinois' current QA specification.

[a] Effect of using a schedule based on a 10-80-10 percentage distribution of penalty, 100% pay and bonus.

penalized and 15 percent would receive a bonus in each of the pay determination categories (density, asphalt content, and gradation).

To compensate for this and to perhaps enhance the incentive capability of the bonus provision, an increase in the bonus pay to 110 percent of contract price was recommended. An alternative or possible additional method for compensating for the lower pay would be to adopt a schedule that would award bonus pay more frequently than it would penalize (e.g., 10 percent penalty and 15 percent bonus). As demonstrated, the schedule was developed in a manner that would easily facilitate adjustment to implement such an administrative decision.

In examining the lower portion of Table 8, the reader may question why the penalty and bonus percentages under the developed schedule were found to differ from 15 percent. Recall that in developing the pay schedule the 15 percent was applied to each of the three pay determination categories. Therefore 15 percent of all lots are penalized (or receive bonus) for density, 15 percent for asphalt content, and 15 percent for gradation. Lot pay, however, is the average of the pay for the three categories. A penalty (or bonus) in any one category could cause the average to be less than (or more than) 100 percent.

EXAMPLE USE OF THE PAY SCHEDULE

Table 9 gives an example use of the pay schedule. The upper portion of the table lists the target job mix formula followed by test results from five sublot

TABLE 9 Example Application of the Payment Schedule

	Job Mix Formula	Binder Mix Sublot Test Results					Avg	dJMF	Range
		1	2	3	4	5			
Size fraction									
1-1/2 in.	28.6	24.2	26.8	23.4	30.8	24.7	26.0	2.6	7.4
1/2 in.-No. 4	25.7	26.3	24.6	27.3	24.2	28.4			
No. 4-No. 10	6.5	9.0	7.3	6.3	8.8	7.1	7.7	1.2	2.7
No. 10-No. 40	13.9	12.8	14.4	16.7	11.7	13.0			
No. 40-No. 80	10.9	12.1	11.1	10.2	11.7	10.4	11.1	0.2	1.9
No. 80-No. 200	5.3	5.6	6.5	7.5	3.6	6.0			
Minus No. 200	4.3	5.0	4.0	3.9	4.7	4.9	4.5	0.2	1.1
Asphalt content	4.8	5.0	5.3	4.7	4.5	5.5	5.0	0.2	1.0
Density quality level		99.0	101.8	98.6	99.3	100.8	99.9		3.2

Note: Gradation and asphalt content

PDF = dJMF + f*R

Density

PDF = QLavg - f*R

where

dJMF = absolute difference (always positive) between the job mix formula and the average of the test values;
QLavg = lot or average density quality level;
f = range factor from Table 2, 0.43 for five samples; and
R = range, difference between the high and low test values.

PDF(1-1/2 in.) = (2.6) + 0.43(7.4) = 5.78 Pay = 100%[a]
PDF(#4-#10) = (1.2) + 0.43(2.7) = 2.36 Pay = 100%[a]
PDF(#40-#80) = (0.2) + 0.43(1.9) = 1.02 Pay = 105%[a]
PDF(< #200) = (0.2) + 0.43(1.1) = 0.67 Pay = 105%[a]
Gradation pay = 100%[b]
PDF(asphalt) = (0.2) + 0.43(1.0) = 0.63 Asphalt pay = 95%[a]
PDF(density) = 99.9 - 0.43(3.2) = 98.52 Density pay = 100%[a]
Lot pay = (100 + 95 + 100)/3 = 98.3%

[a] From Table 6.

[b] Lowest pay of the four gradation size fractions.

samples. The last three columns display the average, the deviation of the average from the job mix formula (dJMF), and the range of these test results for asphalt content, density quality level, and each of the gradation size fractions that are considered relative to pay determination. The PDF equations and definition of the terms included in the equations are shown below the test result listing. This is followed by the application of the test results in determining the PDFs and the resulting payment percentage for the lot.

It will be noted that the PDFs are determined for each of the four gradation sizes using the deviation of the average test value from the job mix formula and the range of the test values. The pay percentage for each size is determined from Table 6 with the lowest percentage being used as the gradation pay. The pay percentages for asphalt content and density are determined similarly except that for density the average quality level is used and the range has a negative impact on the PDF value. The lot payment is the average of the pay percentages determined for gradation, asphalt content, and density.

SUMMARY AND CONCLUSIONS

The developed pay schedule is based on the value concept (3), which provides a rational means for combining "real world" variability with laboratory and theoretical pavement life relationships in order to establish the value of any construction project. With this concept, both the average and the variability of the construction are taken into account.

To assure that the resulting schedule would not result either in requiring an unwarranted costly improvement in quality or in permitting a reduction in quality from current levels, data from previous QA projects were analyzed to identify the limits of acceptable and superior construction. For inferior work falling outside these limits, pay adjustments were established by using the concept of construction value as measured in terms of the expected relative effect on pavement life. The relative life effect was identified through analysis of laboratory test data and pavement behavior theory (6).

The payment schedule given in Tables 6 and 7 was developed so that 15 percent of the lots from the previous projects would have been penalized and another 15 percent would have received bonus pay. However, the schedule was developed in such a fashion that it can be easily modified to accommodate other percentages of bonus and penalty that may be considered more appropriate.

Application of the schedule to past QA project data (Table 9) indicated that, on the average, contractors would receive slightly less pay with this schedule than they would have with the QA pay schedule previously used in Illinois. To compensate for this and to provide added incentive for quality construction, it was recommended that bonus pay be increased from 105 to 110 percent of the contract bid price. At the same time, however, it is possible to use the contents and data presented to establish a pay schedule that would include no provision for bonus pay.

Based on this work, it was concluded that the value concept provides a rational, practical means for establishing pavement construction pay adjustment schedules that are fair to both the contractor and the contracting agency.

ACKNOWLEDGMENTS

This paper is based on the results of Project IHR-411, Quality Assurance Specifications.

IHR-411 was sponsored by the Illinois Department of Transportation as a cooperative study between the department and the University of Illinois. Planning of the project was a joint effort. Field data and the materials used in the testing phase were provided by the department. The laboratory testing and data analyses were performed by the university.

REFERENCES

1. R.M. Moore. Evaluation of Questionnaire on Pay Adjustment Factors for Asphalt Concrete Mixtures. Oregon Institute of Technology, Klamath Falls, 1980.
2. R.P. Elliott and M. Herrin. Asphalt Q.A. Specifications--Influence of Significant Material Factors and Development of a Rational Payment Schedule. Transportation Engineering Series 39. University of Illinois at Urbana-Champaign, 1983.
3. R.P. Elliott. A Value Concept for Pavement Construction Pay Adjustment Schedules. In Transportation Research Record 1040, TRB, National Research Council, Washington, D.C., 1985, pp. 45-48.
4. R.P. Elliott. Value Concept for Developing Construction Pay Schedules with Application to Asphalt Paving. Ph.D. dissertation. University of Illinois at Urbana-Champaign, 1984.
5. W.J. Dixon and F.J. Massey. Introduction to Statistical Analysis. McGraw-Hill Book Company, Inc., New York, 1951.
6. R.P. Elliott and M. Herrin. Relative Life Effects of Mix Composition and Density Variation. Presented at the 1985 Meeting of the Association of Asphalt Paving Technologists, San Antonio, Tex., forthcoming.

The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Illinois Department of Transportation. This paper does not constitute a standard, specification, or regulation.

Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.

Revision of a Flawed Acceptance Standard

RICHARD M. WEED

ABSTRACT

A major revision of AASHTO Standard R9-84, Acceptance Sampling Plans for Highway Construction, has just been completed. The primary goals were to correct a major conceptual error and to reduce the level of complexity. In this paper the flaws in the original version are discussed, the basic changes that were made are described, and a significant addition to the new standard is presented. This addition is operating characteristic tables that enable the user to quickly and easily select acceptance plans that will provide the desired degree of quality assurance. Computer simulation is used to demonstrate that single-limit variables operating characteristic curves are sufficiently accurate for most double-limit applications. Two examples are included to illustrate the use of the revised standard.

In the early 1960s, the AASHO Road Test produced a wealth of statistical data that could be used to relate pavement quality to performance. Highway engineers began to recognize that various desirable quality characteristics could be described statistically, and, toward the end of that decade, several highway agencies had begun to develop acceptance procedures based on statistical concepts. Today, many highway agencies routinely use statistical acceptance procedures in one form or another.

The first statistical acceptance procedures were often far from optimal. Highway engineers were relatively unfamiliar with statistical terms and procedures, especially in regard to the construction of operating characteristic curves and the analysis of risks. Consequently, the early development of statistical specifications consisted largely of a trial-and-error process and several revisions were often required to obtain a workable specification.

More recently, there has been a significant improvement in the manner in which these specifications are developed. Highway engineers have acquired a better understanding of statistical methods (1-3) and the computer has emerged as a valuable aid (4,5) in performing much of the development and analysis work. The state of the art has now progressed to the extent that statistical specification writing must be regarded as a thoroughly scientific activity.

AASHTO Standard R9-84, Acceptance Sampling Plans for Highway Construction (6), was adopted in 1984 to document and standardize practices that had evolved over the previous two decades. It covers both attributes sampling for defects that are counted and variables sampling for characteristics that are measured on a continuous scale. Primary source documents for these two approaches are Military Standard 105 for attributes sampling (7) and Military Standard 414 for variables sampling (8), both published by the U.S. Department of Defense. The theory underlying attributes sampling is relatively simple and is covered in connection with the hypergeometric distribution in many texts on statistics and quality assurance (9-11). The theoretical basis for variables sampling is considerably more complex, involving both the beta and the noncentral t distributions, and is not as well known (11-13).

Unfortunately, the current version of Standard R9 is seriously flawed, both by what it includes and by what it omits. It is based on an early method that contains both technical and conceptual errors and it fails to cover the analysis of operating characteristic curves, one of the most important steps in the development of any acceptance procedure. A higher level of technical competence must be demanded of a work that is to serve as a procedural guide for the highway quality assurance profession.

BASIC PROBLEMS AND CORRECTIVE MEASURES

The original developers of the methodology used in AASHTO Standard R9 undoubtedly had nothing but the best of intentions. At a time when statistical procedures were new and unfamiliar, and considerable resistance to the new methods was often encountered, it was understandably tempting to make various seemingly harmless modifications to make these procedures more palatable. Obviously, the arbitrary modification of any highly technical procedure by practitioners unfamiliar with the underlying theory is a dangerous business and, not surprisingly, the validity of some of these methods was seriously compromised. This is essentially what happened in the development of the procedures used in Standard R9. Specific shortcomings and the necessary corrective measures are as follows:

1. Both the attributes and variables plans described in Standard R9 are designed to control percent defective, the percentage of the lot falling outside a lower or upper specification limit, or outside both lower and upper specification limits, as illustrated in Figure 1. As presently written, however, Standard R9 is oriented partly toward percent defective and partly toward population means, which leads to considerable confusion. For example, it is stated in the current standard that, for a variables plan with the standard deviation unknown, only one risk (buyer's or seller's) can be controlled. Indeed, when quality is measured in terms of percent defective, both the buyer's risk and the seller's risk can be controlled by either variables or attributes plans. This basic contradiction has been corrected by basing the revised standard entirely on the percent defective parameter.
2. A major omission in the current standard is a convenient method of constructing the operating characteristic (OC) curves for the acceptance plans that are developed. OC curves give the probability

---

New Jersey Department of Transportation, 1035 Parkway Avenue, CN 600, Trenton, N.J. 08625.

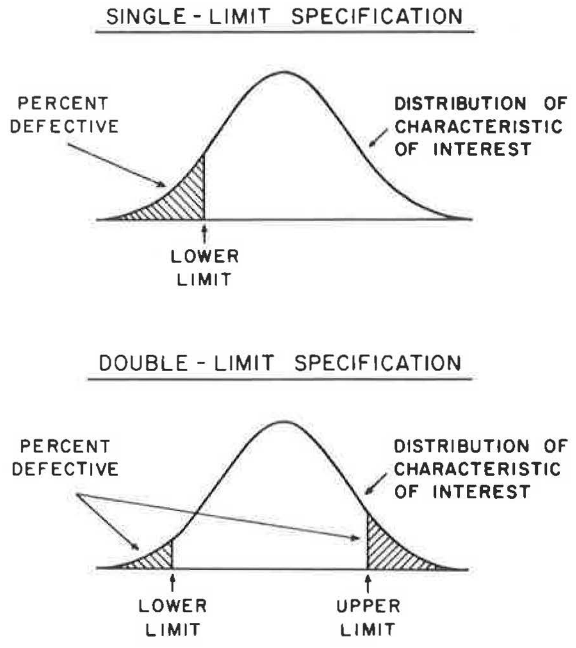


FIGURE 1 Illustration of the concept of percent defective.

of acceptance associated with various levels of submitted quality and provide a graphic representation of an acceptance plan's ability to discriminate between acceptable and unacceptable work. A typical example is shown in Figure 2. The importance of examining OC curves cannot be overemphasized. In this manner, the risks to both the specifying agency and the contractor can be determined in advance and modifications to the acceptance plan can be made, if necessary, before embarrassing and troublesome situations arise in the field. This shortcoming of the current standard has been corrected by the development of several new operating characteristic tables for both attributes and variables plans.

3. When constructing an OC curve for a variables plan, the problem cited in Item 1 becomes much more apparent. Because the variables approach was derived to control percent defective, there is a unique probability of acceptance associated with any particular level of lot percent defective, as can be seen in Figure 2. (This is precisely correct for single-limit plans and is approximately correct for double-limit plans.) However, if the acceptance procedure were oriented around population means, as it is in the current version of Standard R9, there would no longer be a unique OC curve because each level of population mean could correspond to a wide range of percent defective, depending on the value of the population standard deviation. Rewriting the standard entirely around the percent defective parameter has corrected this problem.

4. The table for the estimation of percent defective in the current version of the standard is not in the most logical or useful form and it omits several potentially useful sample sizes. The new table includes several additional sample sizes, it is accurate to a greater number of decimal places, and two revised formats are provided.

5. The current table for attributes sampling was taken from Military Standard 105 (7). It gives the recommended sample size and acceptance number (maximum allowable number of defective items in a sample) based on lot size and the user's definition of acceptable quality level (AQL). In its present form, it does not allow the user to know or control the risks that are involved and, as in the percent de-

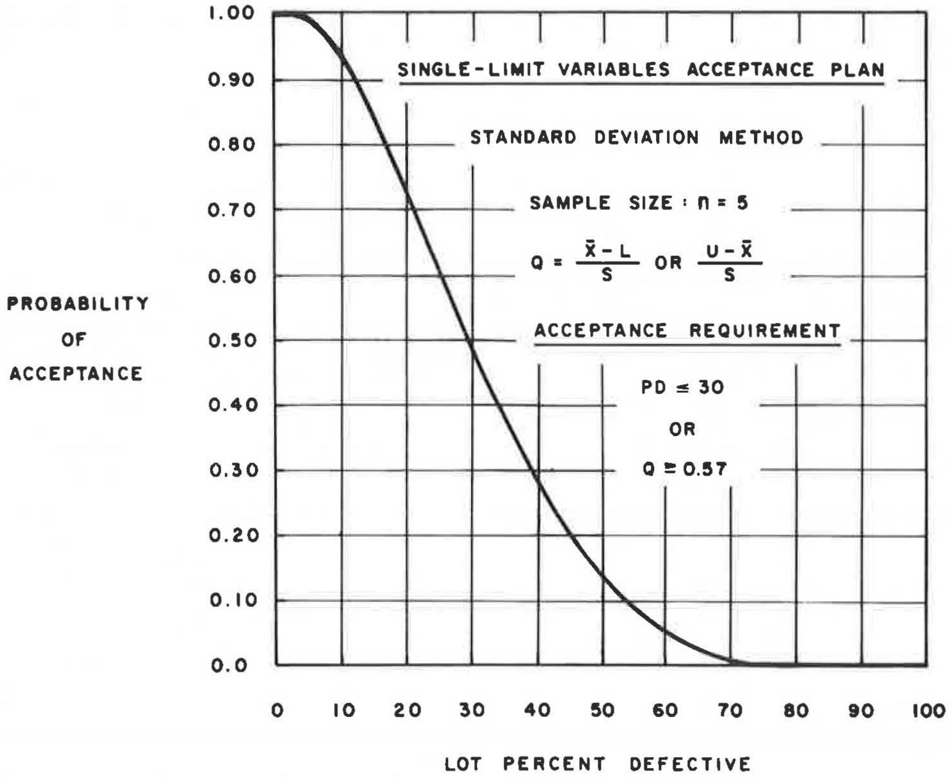


FIGURE 2 Typical operating characteristic curve for a variables acceptance plan.

fective estimation table, several useful sample sizes have been omitted. This table has been completely revised to be more suitable for highway construction applications.

6. The current version of the standard emphasizes the range method for variables acceptance plans. The standard deviation method is included, but the user is required to estimate the standard deviation from the range. For this reason, the current version fails to capitalize on the standard deviation's superior mathematical efficiency. To realize the cost savings associated with the smaller sample sizes required with the standard deviation method, this is made the primary procedure in the revised version of the standard. The range method has been retained and some new tables have been provided, but this procedure has now been relegated to an appendix.

7. If an acceptance specification developed by the method outlined in the current version of Standard R9 were to be challenged in court, it is possible that the weaknesses in the standard could be used to attack the validity of the specification. Although it is true that the acceptance plan could be perfectly satisfactory even though the methodology used to develop it was flawed, the highway agency might still be cast in an unfavorable light. This potential vulnerability can be avoided by using valid statistical procedures in a rigorous fashion. It is believed that the revised version of Standard R9 will encourage the proper use of these methods.

8. Finally, a major drawback of the present version of Standard R9 is its technical complexity. At best, it will fail to promote a wider use and acceptance of statistical quality assurance and, at worst, it could even be a deterrent. A primary goal in rewriting the standard was to make it considerably easier to understand and use.

DEVELOPMENT OF NEW TABLES

To correct the deficiencies of the current standard, it was first necessary to develop several new tables. These form the core around which the rest of the standard has been constructed and are discussed in the order in which they appear in the appendices of the revised standard.

In Appendix A of the new standard, the previous table for attributes sampling has been replaced with operating characteristic tables that give probability of acceptance for selected levels of population (lot) percent defective for many different combinations of sample size and acceptance number. Those plans that have relatively undesirable OC curves have been omitted, and not all plans in these tables will be suitable for all situations. The primary benefit of the new tables is that it is possible to tell at a glance how different plans will perform over a wide range of submitted quality.

The new attributes tables appear in four sections, one each for lot sizes of 20, 100, 500, and infinity. Two of these tables, for lot sizes of 100 and infinity, are shown in Figures 3 and 4. The tables are constructed so that it will never be necessary to interpolate between acceptance numbers or between sample sizes up to a sample size of n = 10. Some interpolation may be necessary for larger sample sizes or for specific lot sizes, although the OC curves are relatively insensitive to lot size. For plans with variable lot sizes, it will be necessary to plot bounding OC curves.

Appendix B of the new standard contains the corresponding operating characteristic tables for variables acceptance plans (standard deviation method), one of which is shown in Figure 5. The acceptance plans in these tables are specified by sample size and either the maximum allowable estimated percent defective (M) or the minimum allowable value (k) of the quality index (Q). The quality index is computed by Equation 1 or 2, as appropriate.

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

$$Q_U = (U - \bar{X})/S \qquad (2)$$

where

Q = quality index,
$\bar{X}$ = sample mean,
S = sample standard deviation, and
L, U = lower and upper specification limits outside of which the material or work is defined as defective.

Because variables plans deal with continuous data, there are an infinite number of plans that might be used and it will occasionally be necessary to interpolate between the acceptance parameters shown in Figure 5. The operating characteristic tables for variables plans include a wide range of acceptance plans and, like the attributes tables, not all plans will be suitable for all situations.

Appendix C of the new standard provides a more complete table for the estimation of lot percent defective (standard deviation method). This table is the equivalent of Table B5 in Military Standard 414 on variables sampling (8) except that it includes several useful sample sizes that were omitted in both Military Standard 414 and AASHTO Standard R9. The new table consists of five sections, one of which is shown in Figure 6.

The percent defective estimation tables in Appendix C of the new standard cover a wide range of sample sizes, considerably more than would ever be used in a single acceptance procedure. For acceptance procedures that make use of only one or two sample sizes, it is possible to construct much more compact tables such as the one shown in Figure 7. With this format, there is a separate short table for each sample size.

Appendix D of the new standard contains two tables that have been developed for use with variables procedures based on the range as the measure of variability. The first, shown in Figure 8, gives the operating characteristics for a wide selection of range plans. The largest sample size included in this table is n = 15 because, above that sample size, range plans are considerably less efficient than standard deviation plans. The second, shown in Figure 9, gives the estimate of lot percent defective associated with the quality index (Q) computed by the range method in accordance with Equations 3 and 4. Because the range tends to be larger than the standard deviation, the Q-values tend to be smaller, and the table is more compact than its counterpart for the standard deviation method. Also, because it is believed that some precision is lost in adapting the standard deviation algorithms to construct the range table, the percent defective estimates in the body of the table have been printed to only a single decimal place.

$$Q_L = (\bar{X} - L)/R \qquad (3)$$

$$Q_U = (U - \bar{X})/R \qquad (4)$$

where

Q = quality index;

$\overline{X}$ = sample mean;
R = sample range, difference between largest and smallest values in the sample; and
L, U = lower and upper specification limits outside of which the material or work is defined as defective.

Still another useful format for operating characteristic tables is shown in Figure 10, although this particular version has not been included in the new standard. Whereas the more customary format lists lot percent defective in the heading of the table and probability of acceptance in the body of the table, this version does just the opposite. The advantage of this format is that it always provides an ample number of plotting points spaced conveniently throughout the length of each OC curve, a refinement that is especially useful when a wide range of sample sizes is included in a single table. This approach is appropriate primarily for variables plans, but it is also suitable for attributes plans when the lot size is divisible by 100.

ATTRIBUTES ACCEPTANCE PLANS LOT SIZE = 100

SAMPLE SIZE (n)	ACCEPTANCE NUMBER (c)	PROBABILITY OF ACCEPTANCE FOR SELECTED LEVELS OF LOT PERCENT DEFECTIVE													
		5	10	15	20	25	30	35	40	45	50	55	60	65	70
1	0	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30
2	0	0.90	0.81	0.72	0.64	0.56	0.49	0.42	0.36	0.30	0.25	0.20	0.16	0.12	0.09
3	0	0.86	0.73	0.61	0.51	0.42	0.34	0.27	0.21	0.16	0.12	0.09	0.06	0.04	0.03
3	1	0.99	0.97	0.94	0.90	0.85	0.79	0.72	0.65	0.58	0.50	0.42	0.35	0.28	0.21
4	0	0.81	0.65	0.52	0.40	0.31	0.23	0.17	0.12	0.09	0.06	0.04	0.02	0.01	0.01
4	1	0.99	0.95	0.89	0.82	0.74	0.65	0.56	0.47	0.39	0.31	0.24	0.17	0.12	0.08
5	1	0.98	0.92	0.84	0.74	0.63	0.53	0.42	0.33	0.25	0.18	0.13	0.08	0.05	0.03
5	2	1.00	0.99	0.98	0.95	0.90	0.84	0.77	0.69	0.60	0.50	0.40	0.31	0.23	0.16
6	1	0.97	0.89	0.78	0.66	0.53	0.41	0.31	0.23	0.16	0.10	0.06	0.04	0.02	0.01
6	2	1.00	0.99	0.96	0.91	0.84	0.75	0.65	0.54	0.44	0.34	0.25	0.17	0.11	0.06
7	1	0.96	0.86	0.72	0.57	0.44	0.32	0.22	0.15	0.09	0.06	0.03	0.02	0.01	0.00
7	2	1.00	0.98	0.93	0.86	0.76	0.65	0.53	0.42	0.31	0.22	0.14	0.09	0.05	0.02
8	1	0.95	0.82	0.66	0.50	0.36	0.24	0.16	0.10	0.06	0.03	0.01	0.01	0.00	0.00
8	2	1.00	0.97	0.90	0.80	0.68	0.55	0.42	0.31	0.21	0.13	0.08	0.04	0.02	0.01
8	3	1.00	1.00	0.98	0.95	0.90	0.81	0.71	0.60	0.48	0.36	0.25	0.16	0.10	0.05
9	1	0.94	0.78	0.60	0.43	0.29	0.18	0.11	0.06	0.03	0.02	0.01	0.00	0.00	0.00
9	2	1.00	0.96	0.87	0.74	0.60	0.46	0.33	0.22	0.14	0.08	0.04	0.02	0.01	0.00
9	3	1.00	0.99	0.97	0.92	0.84	0.74	0.61	0.48	0.35	0.24	0.15	0.09	0.05	0.02
10	1	0.92	0.74	0.54	0.36	0.23	0.14	0.07	0.04	0.02	0.01	0.00	0.00	0.00	0.00
10	2	0.99	0.94	0.83	0.68	0.52	0.37	0.25	0.15	0.09	0.05	0.02	0.01	0.00	0.00
10	3	1.00	0.99	0.96	0.89	0.79	0.65	0.51	0.37	0.25	0.16	0.09	0.05	0.02	0.01
15	2	0.98	0.83	0.60	0.38	0.21	0.11	0.05	0.02	0.01	0.00	0.00	0.00	0.00	0.00
15	3	1.00	0.96	0.84	0.65	0.45	0.28	0.15	0.07	0.03	0.01	0.00	0.00	0.00	0.00
15	4	1.00	0.99	0.95	0.85	0.70	0.51	0.34	0.20	0.10	0.05	0.02	0.01	0.00	0.00
15	5	1.00	1.00	0.99	0.95	0.87	0.73	0.57	0.39	0.24	0.13	0.06	0.02	0.01	0.00
20	2	0.95	0.68	0.38	0.18	0.07	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	3	0.99	0.89	0.65	0.39	0.20	0.08	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00
20	4	1.00	0.97	0.85	0.64	0.40	0.21	0.09	0.03	0.01	0.00	0.00	0.00	0.00	0.00
20	5	1.00	1.00	0.95	0.83	0.62	0.40	0.22	0.10	0.04	0.01	0.00	0.00	0.00	0.00
20	6	1.00	1.00	0.99	0.94	0.81	0.62	0.40	0.22	0.10	0.04	0.01	0.00	0.00	0.00
30	3	0.97	0.65	0.28	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	4	1.00	0.86	0.51	0.21	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	5	1.00	0.96	0.73	0.40	0.16	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	6	1.00	0.99	0.89	0.62	0.31	0.12	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00
30	7	1.00	1.00	0.96	0.80	0.51	0.24	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.00
30	8	1.00	1.00	0.99	0.91	0.70	0.41	0.18	0.06	0.01	0.00	0.00	0.00	0.00	0.00
50	5	1.00	0.63	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	6	1.00	0.84	0.29	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	7	1.00	0.95	0.50	0.11	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	8	1.00	0.99	0.71	0.23	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	9	1.00	1.00	0.87	0.40	0.08	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	10	1.00	1.00	0.95	0.60	0.18	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	11	1.00	1.00	0.99	0.77	0.32	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	8	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	9	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	10	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	11	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	12	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	13	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	14	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	15	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	16	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	17	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	18	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PROBABILITY OF ACCEPTANCE IS UNINFLUENCED BY THE DISTRIBUTIONAL FORM OF THE POPULATION BUT IS DEPENDENT UPON LOT SIZE FOR ATTRIBUTES PLANS. FOR VARIABLE LOT SIZES, IT WILL BE NECESSARY TO CONSTRUCT BOUNDING OPERATING CHARACTERISTIC CURVES.

FIGURE 3 Operating characteristics of attributes acceptance plans with a lot size of n = 100.

OPERATING CHARACTERISTICS OF DOUBLE-LIMIT PLANS

Acceptance plans that have both lower and upper limits are referred to as double-limit plans. The operating characteristics for attributes plans shown in Figures 3 and 4 are correct for both single-limit and double-limit plans. For double-limit variables plans, there is no unique operating characteristic curve because probability of acceptance is influenced in part by the manner in which the percent defective is distributed between the two tails of the population. There exists, instead, a band of OC curves for each double-limit variables plan. It has been found (11,p.246), however, that this band is quite narrow and that the single-limit OC curves are sufficiently accurate for most double-limit applications. The table, generated by computer simulation, that is shown in Figure 11 provides a convincing demonstration of this fortunate property.

ATTRIBUTES ACCEPTANCE PLANS LOT SIZE = INFINITE

SAMPLE SIZE (n)	ACCEPTANCE NUMBER (c)	PROBABILITY OF ACCEPTANCE FOR SELECTED LEVELS OF LOT PERCENT DEFECTIVE													
		5	10	15	20	25	30	35	40	45	50	55	60	65	70
1	0	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30
2	0	0.90	0.81	0.72	0.64	0.56	0.49	0.42	0.36	0.30	0.25	0.20	0.16	0.12	0.09
3	0	0.86	0.73	0.61	0.51	0.42	0.34	0.27	0.22	0.17	0.13	0.09	0.06	0.04	0.03
3	1	0.99	0.97	0.94	0.90	0.84	0.78	0.72	0.65	0.57	0.50	0.43	0.35	0.28	0.22
4	0	0.81	0.66	0.52	0.41	0.32	0.24	0.18	0.13	0.09	0.06	0.04	0.03	0.02	0.01
4	1	0.99	0.95	0.89	0.82	0.74	0.65	0.56	0.48	0.39	0.31	0.24	0.18	0.13	0.08
5	1	0.98	0.92	0.84	0.74	0.63	0.53	0.43	0.34	0.26	0.19	0.13	0.09	0.05	0.03
5	2	1.00	0.99	0.97	0.94	0.90	0.84	0.76	0.68	0.59	0.50	0.41	0.32	0.24	0.16
6	1	0.97	0.89	0.78	0.66	0.53	0.42	0.32	0.23	0.16	0.11	0.07	0.04	0.02	0.01
6	2	1.00	0.98	0.95	0.90	0.83	0.74	0.65	0.54	0.44	0.34	0.26	0.18	0.12	0.07
7	1	0.96	0.85	0.72	0.58	0.44	0.33	0.23	0.16	0.10	0.06	0.04	0.02	0.01	0.00
7	2	1.00	0.97	0.93	0.85	0.76	0.65	0.53	0.42	0.32	0.23	0.15	0.10	0.06	0.03
8	1	0.94	0.81	0.66	0.50	0.37	0.26	0.17	0.11	0.06	0.04	0.02	0.01	0.00	0.00
8	2	0.99	0.96	0.89	0.80	0.68	0.55	0.43	0.32	0.22	0.14	0.09	0.05	0.03	0.01
8	3	1.00	0.99	0.98	0.94	0.89	0.81	0.71	0.59	0.48	0.36	0.26	0.17	0.11	0.06
9	1	0.93	0.77	0.60	0.44	0.30	0.20	0.12	0.07	0.04	0.02	0.01	0.00	0.00	0.00
9	2	0.99	0.95	0.86	0.74	0.60	0.46	0.34	0.23	0.15	0.09	0.05	0.03	0.01	0.00
9	3	1.00	0.99	0.97	0.91	0.83	0.73	0.61	0.48	0.36	0.25	0.17	0.10	0.05	0.03
10	1	0.91	0.74	0.54	0.38	0.24	0.15	0.09	0.05	0.02	0.01	0.00	0.00	0.00	0.00
10	2	0.99	0.93	0.82	0.68	0.53	0.38	0.26	0.17	0.10	0.05	0.03	0.01	0.00	0.00
10	3	1.00	0.99	0.95	0.88	0.78	0.65	0.51	0.38	0.27	0.17	0.10	0.05	0.03	0.01
15	2	0.96	0.82	0.60	0.40	0.24	0.13	0.06	0.03	0.01	0.00	0.00	0.00	0.00	0.00
15	3	0.99	0.94	0.82	0.65	0.46	0.30	0.17	0.09	0.04	0.02	0.01	0.00	0.00	0.00
15	4	1.00	0.99	0.94	0.84	0.69	0.52	0.35	0.22	0.12	0.06	0.03	0.01	0.00	0.00
15	5	1.00	1.00	0.98	0.94	0.85	0.72	0.56	0.40	0.26	0.15	0.08	0.03	0.01	0.00
20	2	0.92	0.68	0.40	0.21	0.09	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	3	0.98	0.87	0.65	0.41	0.23	0.11	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00
20	4	1.00	0.96	0.83	0.63	0.41	0.24	0.12	0.05	0.02	0.01	0.00	0.00	0.00	0.00
20	5	1.00	0.99	0.93	0.80	0.62	0.42	0.25	0.13	0.06	0.02	0.01	0.00	0.00	0.00
20	6	1.00	1.00	0.98	0.91	0.79	0.61	0.42	0.25	0.13	0.06	0.02	0.01	0.00	0.00
30	3	0.94	0.65	0.32	0.12	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	4	0.98	0.82	0.52	0.26	0.10	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	5	1.00	0.93	0.71	0.43	0.20	0.08	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
30	6	1.00	0.97	0.85	0.61	0.35	0.16	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00
30	7	1.00	0.99	0.93	0.76	0.51	0.28	0.12	0.04	0.01	0.00	0.00	0.00	0.00	0.00
30	8	1.00	1.00	0.97	0.87	0.67	0.43	0.22	0.09	0.03	0.01	0.00	0.00	0.00	0.00
50	5	0.96	0.62	0.22	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	6	0.99	0.77	0.36	0.10	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	7	1.00	0.88	0.52	0.19	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	8	1.00	0.94	0.67	0.31	0.09	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	9	1.00	0.98	0.79	0.44	0.16	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	10	1.00	0.99	0.88	0.58	0.26	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	11	1.00	1.00	0.94	0.71	0.38	0.14	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00
100	8	0.94	0.32	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	9	0.97	0.45	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	10	0.99	0.58	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	11	1.00	0.70	0.16	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	12	1.00	0.80	0.25	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	13	1.00	0.88	0.35	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	14	1.00	0.93	0.46	0.08	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	15	1.00	0.96	0.57	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	16	1.00	0.98	0.67	0.19	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	17	1.00	0.99	0.76	0.27	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	18	1.00	1.00	0.84	0.36	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PROBABILITY OF ACCEPTANCE IS UNINFLUENCED BY THE DISTRIBUTIONAL FORM OF THE POPULATION BUT IS DEPENDENT UPON LOT SIZE FOR ATTRIBUTES PLANS. FOR VARIABLE LOT SIZES, IT WILL BE NECESSARY TO CONSTRUCT BOUNDING OPERATING CHARACTERISTIC CURVES.

FIGURE 4 Operating characteristics of attributes acceptance plans with an infinite lot size.

VARIABLES ACCEPTANCE PLANS *** VARIABILITY-UNKNOWN PROCEDURE *** STANDARD DEVIATION METHOD

SAMPLE SIZE (n)	MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE (M)	MINIMUM ALLOWABLE QUALITY INDEX (k)	PROBABILITY OF ACCEPTANCE FOR SELECTED LEVELS OF LOT PERCENT DEFECTIVE						
			10	20	30	40	50	60	70
3	34	0.556	0.89	0.71	0.52	0.35	0.22	0.12	0.05
3	36	0.492	0.91	0.74	0.56	0.39	0.24	0.13	0.06
3	38	0.425	0.93	0.78	0.60	0.42	0.27	0.15	0.07
3	40	0.357	0.95	0.81	0.64	0.46	0.30	0.17	0.08
3	42	0.287	0.96	0.84	0.68	0.50	0.33	0.20	0.09
3	44	0.216	0.97	0.87	0.71	0.54	0.37	0.22	0.11
3	46	0.145	0.98	0.89	0.75	0.58	0.41	0.26	0.13
3	48	0.073	0.98	0.91	0.79	0.63	0.46	0.29	0.15
4	28	0.660	0.88	0.66	0.44	0.27	0.14	0.06	0.02
4	30	0.600	0.91	0.70	0.48	0.29	0.16	0.07	0.02
4	32	0.540	0.93	0.74	0.52	0.33	0.18	0.08	0.03
4	34	0.480	0.94	0.77	0.56	0.36	0.20	0.10	0.03
4	36	0.420	0.96	0.81	0.60	0.40	0.23	0.11	0.04
4	38	0.360	0.97	0.84	0.64	0.44	0.26	0.13	0.05
4	40	0.300	0.97	0.86	0.69	0.48	0.30	0.15	0.06
4	42	0.240	0.98	0.89	0.72	0.53	0.33	0.18	0.07
4	44	0.180	0.99	0.91	0.76	0.57	0.37	0.20	0.09
4	46	0.120	0.99	0.93	0.79	0.61	0.41	0.23	0.10
5	26	0.692	0.89	0.65	0.40	0.22	0.10	0.04	0.01
5	28	0.632	0.92	0.69	0.45	0.25	0.12	0.04	0.01
5	30	0.572	0.94	0.73	0.49	0.28	0.14	0.05	0.01
5	32	0.513	0.95	0.77	0.54	0.32	0.16	0.06	0.02
5	34	0.455	0.96	0.81	0.58	0.36	0.18	0.07	0.02
5	36	0.397	0.97	0.84	0.63	0.40	0.21	0.09	0.03
5	38	0.339	0.98	0.87	0.67	0.44	0.25	0.11	0.03
5	40	0.282	0.99	0.90	0.71	0.49	0.28	0.13	0.04
5	42	0.225	0.99	0.92	0.75	0.54	0.32	0.15	0.05
5	44	0.169	0.99	0.93	0.79	0.58	0.36	0.18	0.06
6	24	0.740	0.89	0.62	0.35	0.17	0.06	0.02	0.00
6	26	0.678	0.92	0.67	0.40	0.20	0.08	0.02	0.00
6	28	0.618	0.94	0.71	0.45	0.23	0.10	0.03	0.01
6	30	0.558	0.95	0.76	0.49	0.27	0.11	0.04	0.01
6	32	0.500	0.97	0.80	0.55	0.31	0.14	0.05	0.01
6	34	0.442	0.98	0.84	0.60	0.35	0.16	0.06	0.01
6	36	0.386	0.98	0.87	0.64	0.39	0.19	0.07	0.02
6	38	0.329	0.99	0.90	0.69	0.44	0.23	0.09	0.02
6	40	0.274	0.99	0.92	0.74	0.49	0.27	0.11	0.03
6	42	0.219	1.00	0.94	0.78	0.54	0.31	0.13	0.04
7	22	0.796	0.88	0.57	0.29	0.12	0.04	0.01	0.00
7	24	0.732	0.91	0.63	0.34	0.15	0.05	0.01	0.00
7	26	0.670	0.93	0.68	0.39	0.18	0.06	0.02	0.00
7	28	0.610	0.95	0.73	0.44	0.21	0.08	0.02	0.00
7	30	0.550	0.97	0.78	0.50	0.25	0.10	0.03	0.00
7	32	0.492	0.98	0.82	0.55	0.29	0.12	0.04	0.01
7	34	0.435	0.98	0.86	0.61	0.34	0.15	0.05	0.01
7	36	0.379	0.99	0.89	0.66	0.39	0.18	0.06	0.01
7	38	0.324	0.99	0.91	0.71	0.44	0.21	0.07	0.02
7	40	0.269	1.00	0.93	0.75	0.49	0.25	0.09	0.02
8	22	0.792	0.90	0.58	0.28	0.11	0.03	0.01	0.00
8	24	0.727	0.92	0.64	0.33	0.13	0.04	0.01	0.00
8	26	0.665	0.95	0.70	0.38	0.16	0.05	0.01	0.00
8	28	0.604	0.96	0.75	0.44	0.20	0.07	0.01	0.00
8	30	0.545	0.98	0.80	0.50	0.24	0.08	0.02	0.00
8	32	0.488	0.98	0.84	0.56	0.28	0.11	0.03	0.00
8	34	0.431	0.99	0.87	0.62	0.33	0.13	0.04	0.01
8	36	0.375	0.99	0.90	0.67	0.38	0.16	0.05	0.01
8	38	0.320	1.00	0.93	0.72	0.44	0.20	0.06	0.01
9	20	0.855	0.87	0.52	0.22	0.07	0.02	0.00	0.00
9	22	0.788	0.91	0.58	0.27	0.09	0.02	0.00	0.00
9	24	0.724	0.94	0.65	0.32	0.12	0.03	0.01	0.00
9	26	0.661	0.96	0.71	0.38	0.15	0.04	0.01	0.00
9	28	0.601	0.97	0.76	0.44	0.18	0.05	0.01	0.00
9	30	0.542	0.98	0.81	0.50	0.22	0.07	0.01	0.00
9	32	0.484	0.99	0.85	0.56	0.27	0.09	0.02	0.00
9	34	0.428	0.99	0.89	0.62	0.32	0.12	0.03	0.00
9	36	0.373	1.00	0.92	0.68	0.38	0.15	0.04	0.01
10	20	0.853	0.89	0.51	0.21	0.06	0.01	0.00	0.00
10	22	0.786	0.92	0.59	0.26	0.08	0.02	0.00	0.00
10	24	0.721	0.95	0.65	0.31	0.10	0.02	0.00	0.00
10	26	0.659	0.97	0.72	0.37	0.13	0.03	0.01	0.00
10	28	0.598	0.98	0.77	0.43	0.17	0.05	0.01	0.00
10	30	0.539	0.99	0.82	0.50	0.21	0.06	0.01	0.00
10	32	0.482	0.99	0.87	0.57	0.26	0.08	0.02	0.00
10	34	0.426	1.00	0.90	0.63	0.31	0.11	0.02	0.00

THE ACCEPTANCE PROBABILITIES IN THIS TABLE ARE ACCURATE FOR SINGLE-LIMIT PLANS AND ARE APPROXIMATELY CORRECT FOR DOUBLE-LIMIT PLANS. FOR SINGLE-LIMIT PLANS, EITHER THE MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE (M) OR THE MINIMUM ALLOWABLE QUALITY INDEX (k) MAY BE SPECIFIED. FOR DOUBLE-LIMIT PLANS, ONLY THE MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE SHOULD BE USED.

FIGURE 5 Operating characteristics of variables acceptance plans (standard deviation method).

VARIABILITY-UNKNOWN PROCEDURE

STANDARD DEVIATION METHOD

QUALITY INDEX (Q)	ESTIMATED LOT PERCENT DEFECTIVE FOR SELECTED SAMPLE SIZES												
	3	4	5	6	7	8	9	10	15	20	30	50	100
0.0	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
0.01	49.72	49.67	49.64	49.63	49.63	49.62	49.62	49.62	49.61	49.61	49.60	49.60	49.60
0.02	49.45	49.33	49.29	49.27	49.25	49.24	49.24	49.23	49.22	49.21	49.21	49.21	49.20
0.03	49.17	49.00	48.93	48.90	48.88	48.86	48.85	48.85	48.83	48.82	48.81	48.81	48.81
0.04	48.90	48.67	48.58	48.53	48.50	48.49	48.47	48.46	48.44	48.43	48.42	48.41	48.41
0.05	48.62	48.33	48.22	48.16	48.13	48.11	48.09	48.06	48.05	48.04	48.02	48.02	48.01
0.06	48.35	48.00	47.86	47.80	47.75	47.73	47.71	47.70	47.66	47.64	47.63	47.62	47.61
0.07	48.07	47.67	47.51	47.43	47.38	47.35	47.33	47.31	47.27	47.25	47.24	47.22	47.22
0.08	47.79	47.33	47.15	47.06	47.01	46.97	46.95	46.93	46.88	46.86	46.84	46.83	46.82
0.09	47.52	47.00	46.80	46.70	46.63	46.59	46.57	46.54	46.49	46.47	46.45	46.43	46.42
0.10	47.24	46.67	46.44	46.33	46.26	46.22	46.18	46.16	46.10	46.08	46.05	46.04	46.03
0.11	46.96	46.33	46.09	45.96	45.89	45.84	45.80	45.78	45.71	45.69	45.66	45.64	45.63
0.12	46.69	46.00	45.73	45.60	45.51	45.46	45.42	45.40	45.33	45.29	45.27	45.25	45.24
0.13	46.41	45.67	45.38	45.23	45.14	45.08	45.04	45.01	44.94	44.90	44.88	44.86	44.84
0.14	46.13	45.33	45.02	44.86	44.77	44.71	44.66	44.63	44.55	44.51	44.48	44.46	44.45
0.15	45.85	45.00	44.67	44.50	44.40	44.33	44.29	44.25	44.16	44.13	44.09	44.07	44.05
0.16	45.58	44.67	44.31	44.13	44.03	43.96	43.91	43.87	43.78	43.74	43.70	43.68	43.66
0.17	45.30	44.33	43.96	43.77	43.65	43.58	43.53	43.49	43.39	43.35	43.31	43.29	43.27
0.18	45.02	44.00	43.60	43.40	43.28	43.21	43.15	43.11	43.01	42.96	42.92	42.89	42.88
0.19	44.74	43.67	43.25	43.04	42.91	42.83	42.77	42.73	42.62	42.57	42.53	42.50	42.48
0.20	44.46	43.33	42.90	42.68	42.54	42.46	42.40	42.35	42.24	42.19	42.15	42.11	42.09
0.21	44.18	43.00	42.54	42.31	42.17	42.08	42.02	41.97	41.85	41.80	41.76	41.73	41.70
0.22	43.90	42.67	42.19	41.95	41.80	41.71	41.64	41.60	41.47	41.42	41.37	41.34	41.31
0.23	43.62	42.33	41.84	41.59	41.44	41.34	41.27	41.22	41.09	41.03	40.98	40.95	40.93
0.24	43.34	42.00	41.48	41.22	41.07	40.97	40.89	40.84	40.71	40.65	40.60	40.56	40.54
0.25	43.05	41.67	41.13	40.86	40.70	40.59	40.52	40.47	40.33	40.27	40.22	40.18	40.15
0.26	42.77	41.33	40.78	40.50	40.33	40.22	40.15	40.09	39.95	39.89	39.83	39.79	39.77
0.27	42.49	41.00	40.43	40.14	39.97	39.85	39.77	39.72	39.57	39.50	39.45	39.41	39.38
0.28	42.20	40.67	40.08	39.78	39.60	39.48	39.40	39.34	39.19	39.12	39.07	39.03	39.00
0.29	41.92	40.33	39.72	39.42	39.23	39.11	39.03	38.97	38.81	38.75	38.69	38.65	38.62
0.30	41.63	40.00	39.37	39.06	38.87	38.75	38.66	38.60	38.44	38.37	38.31	38.26	38.24
0.31	41.35	39.67	39.02	38.70	38.50	38.38	38.29	38.23	38.06	37.99	37.93	37.89	37.86
0.32	41.06	39.33	38.67	38.34	38.14	38.01	37.92	37.86	37.69	37.61	37.55	37.51	37.48
0.33	40.77	39.00	38.32	37.98	37.78	37.65	37.55	37.49	37.31	37.24	37.18	37.13	37.10
0.34	40.49	38.67	37.97	37.62	37.42	37.28	37.19	37.12	36.94	36.87	36.80	36.75	36.72
0.35	40.20	38.33	37.62	37.27	37.05	36.92	36.82	36.75	36.57	36.49	36.43	36.38	36.35
0.36	39.91	38.00	37.28	36.91	36.69	36.55	36.46	36.38	36.20	36.12	36.05	36.01	35.97
0.37	39.62	37.67	36.93	36.55	36.33	36.19	36.09	36.02	35.83	35.75	35.68	35.63	35.60
0.38	39.33	37.33	36.58	36.20	35.98	35.83	35.73	35.65	35.46	35.38	35.31	35.26	35.23
0.39	39.03	37.00	36.23	35.84	35.62	35.47	35.37	35.29	35.10	35.01	34.94	34.89	34.86
0.40	38.74	36.67	35.88	35.49	35.26	35.11	35.00	34.93	34.73	34.65	34.58	34.52	34.49
0.41	38.45	36.33	35.54	35.14	34.90	34.75	34.64	34.57	34.37	34.28	34.21	34.16	34.12
0.42	38.15	36.00	35.19	34.79	34.55	34.39	34.29	34.21	34.00	33.92	33.85	33.79	33.76
0.43	37.85	35.67	34.85	34.43	34.19	34.04	33.93	33.85	33.64	33.56	33.48	33.43	33.39
0.44	37.56	35.33	34.50	34.08	33.84	33.68	33.57	33.49	33.28	33.20	33.12	33.07	33.03
0.45	37.26	35.00	34.16	33.73	33.49	33.33	33.21	33.13	32.92	32.84	32.76	32.71	32.67
0.46	36.96	34.67	33.81	33.38	33.13	32.97	32.86	32.78	32.57	32.48	32.40	32.35	32.31
0.47	36.66	34.33	33.47	33.04	32.78	32.62	32.51	32.42	32.21	32.12	32.04	31.99	31.95
0.48	36.35	34.00	33.12	32.69	32.43	32.27	32.15	32.07	31.85	31.77	31.69	31.63	31.60
0.49	36.05	33.67	32.78	32.34	32.08	31.92	31.80	31.72	31.50	31.41	31.33	31.28	31.24
0.50	35.75	33.33	32.44	32.00	31.74	31.57	31.45	31.37	31.15	31.06	30.98	30.93	30.89
0.51	35.44	33.00	32.10	31.65	31.39	31.22	31.10	31.02	30.80	30.71	30.63	30.57	30.54
0.52	35.13	32.67	31.76	31.31	31.04	30.87	30.76	30.67	30.45	30.36	30.28	30.23	30.19
0.53	34.82	32.33	31.42	30.96	30.70	30.53	30.41	30.32	30.10	30.01	29.93	29.88	29.84
0.54	34.51	32.00	31.08	30.62	30.36	30.18	30.07	29.98	29.76	29.67	29.59	29.53	29.49
0.55	34.20	31.67	30.74	30.28	30.01	29.84	29.72	29.64	29.41	29.32	29.24	29.19	29.15
0.56	33.88	31.33	30.40	29.94	29.67	29.50	29.38	29.29	29.07	28.98	28.90	28.85	28.81
0.57	33.57	31.00	30.06	29.60	29.33	29.16	29.04	28.95	28.73	28.64	28.56	28.51	28.47
0.58	33.25	30.67	29.73	29.26	28.99	28.82	28.70	28.61	28.39	28.30	28.22	28.17	28.13
0.59	32.93	30.33	29.39	28.93	28.66	28.48	28.36	28.28	28.05	27.96	27.89	27.83	27.79
0.60	32.61	30.00	29.05	28.59	28.32	28.15	28.03	27.94	27.72	27.63	27.55	27.50	27.46
0.61	32.28	29.67	28.72	28.25	27.98	27.81	27.69	27.60	27.38	27.30	27.22	27.16	27.13
0.62	31.96	29.33	28.39	27.92	27.65	27.48	27.36	27.27	27.05	26.96	26.89	26.83	26.80
0.63	31.63	29.00	28.05	27.59	27.32	27.15	27.03	26.94	26.72	26.63	26.56	26.50	26.47
0.64	31.30	28.67	27.72	27.26	26.99	26.82	26.70	26.61	26.39	26.31	26.23	26.18	26.14
0.65	30.97	28.33	27.39	26.92	26.66	26.49	26.37	26.28	26.07	25.98	25.90	25.85	25.82
0.66	30.63	28.00	27.06	26.60	26.33	26.16	26.04	25.96	25.74	25.66	25.58	25.53	25.49
0.67	30.30	27.67	26.73	26.27	26.00	25.83	25.72	25.63	25.42	25.33	25.26	25.21	25.17
0.68	29.96	27.33	26.40	25.94	25.68	25.51	25.39	25.31	25.10	25.01	24.94	24.89	24.86
0.69	29.61	27.00	26.07	25.61	25.35	25.19	25.07	24.99	24.78	24.69	24.62	24.57	24.54
0.70	29.27	26.67	25.74	25.29	25.03	24.86	24.75	24.67	24.46	24.38	24.31	24.26	24.23
0.71	28.92	26.33	25.41	24.96	24.71	24.54	24.43	24.35	24.15	24.06	23.99	23.95	23.91
0.72	28.57	26.00	25.09	24.64	24.39	24.23	24.11	24.03	23.83	23.75	23.68	23.64	23.60
0.73	28.22	25.67	24.76	24.32	24.07	23.91	23.80	23.72	23.52	23.44	23.37	23.33	23.30
0.74	27.86	25.33	24.44	24.00	23.75	23.59	23.49	23.41	23.21	23.13	23.07	23.02	22.99
0.75	27.50	25.00	24.11	23.68	23.44	23.28	23.17	23.10	22.90	22.83	22.76	22.72	22.69
0.76	27.13	24.67	23.79	23.37	23.12	22.97	22.86	22.79	22.60	22.52	22.46	22.42	22.39
0.77	26.76	24.33	23.47	23.05	22.81	22.66	22.56	22.48	22.30	22.22	22.16	22.12	22.09
0.78	26.39	24.00	23.15	22.74	22.50	22.35	22.25	22.18	21.99	21.92	21.86	21.82	21.79
0.79	26.02	23.67	22.83	22.42	22.19	22.04	21.94	21.87	21.70	21.62	21.57	21.53	21.50

NUMBERS IN BODY OF TABLE ARE ESTIMATES OF LOT PERCENT DEFECTIVE CORRESPONDING TO SPECIFIC VALUES OF QUALITY INDEX AND SAMPLE SIZE. FOR Q VALUES GREATER THAN OR EQUAL TO ZERO, THE PERCENT DEFECTIVE ESTIMATE MAY BE READ DIRECTLY FROM THE TABLE. FOR Q VALUES LESS THAN ZERO, THE TABLE VALUE MUST BE SUBTRACTED FROM 100.

FIGURE 6 First of five tables for estimation of percent defective (standard deviation method).

VARIABILITY-UNKNOWN PROCEDURE SAMPLE SIZE 5 STANDARD DEVIATION METHOD

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	49.64	49.29	48.93	48.58	48.22	47.86	47.51	47.15	46.80
0.1	46.44	46.09	45.73	45.38	45.02	44.67	44.31	43.96	43.60	43.25
0.2	42.90	42.54	42.19	41.84	41.48	41.13	40.78	40.43	40.08	39.72
0.3	39.37	39.02	38.67	38.32	37.97	37.62	37.28	36.93	36.58	36.23
0.4	35.88	35.54	35.19	34.85	34.50	34.16	33.81	33.47	33.12	32.78
0.5	32.44	32.10	31.76	31.42	31.08	30.74	30.40	30.06	29.73	29.39
0.6	29.05	28.72	28.39	28.05	27.72	27.39	27.06	26.73	26.40	26.07
0.7	25.74	25.41	25.09	24.76	24.44	24.11	23.79	23.47	23.15	22.83
0.8	22.51	22.19	21.87	21.56	21.24	20.93	20.62	20.31	20.00	19.69
0.9	19.38	19.07	18.77	18.46	18.16	17.86	17.55	17.25	16.96	16.66
1.0	16.36	16.07	15.78	15.48	15.19	14.91	14.62	14.33	14.05	13.76
1.1	13.48	13.20	12.93	12.65	12.37	12.10	11.83	11.56	11.29	11.02
1.2	10.76	10.50	10.23	9.97	9.72	9.46	9.21	8.96	8.71	8.46
1.3	8.21	7.97	7.73	7.49	7.25	7.02	6.79	6.56	6.33	6.10
1.4	5.88	5.66	5.44	5.23	5.02	4.81	4.60	4.39	4.19	3.99
1.5	3.80	3.61	3.42	3.23	3.05	2.87	2.69	2.52	2.35	2.19
1.6	2.03	1.87	1.72	1.57	1.42	1.28	1.15	1.02	0.89	0.77
1.7	0.66	0.55	0.45	0.36	0.27	0.19	0.12	0.06	0.02	0.00

NUMBERS IN THE BODY OF THE TABLE ARE ESTIMATES OF LOT PERCENT DEFECTIVE CORRESPONDING TO SPECIFIC VALUES OF Q, THE QUALITY INDEX. FOR VALUES OF Q GREATER THAN OR EQUAL TO ZERO, THE ESTIMATE OF PERCENT DEFECTIVE IS READ DIRECTLY FROM THE TABLE. FOR VALUES OF Q LESS THAN ZERO, THE TABLE VALUE MUST BE SUBTRACTED FROM 100.

FIGURE 7 Alternate format for individual tables for estimation of percent defective.

VARIABLES ACCEPTANCE PLANS *** VARIABILITY-UNKNOWN PROCEDURE *** RANGE METHOD

SAMPLE SIZE (n)	MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE (M)	MINIMUM ALLOWABLE QUALITY INDEX (k)	PROBABILITY OF ACCEPTANCE FOR SELECTED LEVELS OF LOT PERCENT DEFECTIVE						
			10	20	30	40	50	60	70
3	34	0.293	0.89	0.71	0.52	0.35	0.22	0.12	0.05
3	36	0.259	0.91	0.74	0.56	0.39	0.24	0.13	0.06
3	38	0.224	0.93	0.78	0.60	0.42	0.27	0.15	0.07
3	40	0.188	0.94	0.81	0.63	0.46	0.30	0.17	0.08
3	42	0.151	0.96	0.84	0.67	0.50	0.33	0.20	0.09
3	44	0.114	0.97	0.87	0.71	0.54	0.37	0.22	0.11
3	46	0.076	0.98	0.89	0.75	0.58	0.41	0.26	0.13
3	48	0.038	0.98	0.91	0.79	0.63	0.46	0.29	0.16
4	30	0.269	0.90	0.70	0.48	0.30	0.16	0.07	0.03
4	32	0.242	0.92	0.73	0.52	0.33	0.18	0.08	0.03
4	34	0.216	0.94	0.77	0.56	0.36	0.21	0.10	0.04
4	36	0.189	0.95	0.80	0.60	0.40	0.23	0.11	0.04
4	38	0.162	0.96	0.83	0.64	0.44	0.26	0.13	0.05
4	40	0.135	0.97	0.86	0.68	0.48	0.30	0.15	0.06
4	42	0.108	0.98	0.89	0.72	0.52	0.33	0.18	0.07
4	44	0.081	0.99	0.91	0.76	0.57	0.37	0.21	0.09
5	26	0.280	0.89	0.65	0.40	0.22	0.10	0.04	0.01
5	28	0.256	0.91	0.69	0.45	0.25	0.12	0.05	0.01
5	30	0.232	0.93	0.73	0.49	0.28	0.14	0.06	0.02
5	32	0.208	0.95	0.77	0.53	0.32	0.16	0.07	0.02
5	34	0.184	0.96	0.80	0.58	0.36	0.19	0.08	0.02
5	36	0.161	0.97	0.84	0.62	0.40	0.22	0.09	0.03
5	38	0.138	0.98	0.87	0.67	0.44	0.25	0.11	0.04
5	40	0.115	0.98	0.89	0.71	0.49	0.28	0.13	0.05
5	42	0.092	0.99	0.91	0.75	0.53	0.32	0.16	0.06
6	24	0.278	0.88	0.61	0.36	0.17	0.07	0.02	0.01
6	26	0.255	0.91	0.66	0.40	0.20	0.09	0.03	0.01
6	28	0.233	0.93	0.71	0.45	0.24	0.10	0.03	0.01
6	30	0.210	0.95	0.75	0.49	0.27	0.12	0.04	0.01
6	32	0.188	0.96	0.79	0.54	0.31	0.14	0.05	0.01
6	34	0.167	0.97	0.83	0.59	0.35	0.17	0.06	0.02
6	36	0.145	0.98	0.86	0.64	0.40	0.20	0.08	0.02
6	38	0.124	0.99	0.89	0.69	0.44	0.23	0.10	0.03
7	24	0.260	0.90	0.62	0.35	0.16	0.06	0.02	0.00
7	26	0.238	0.93	0.67	0.39	0.19	0.07	0.02	0.00
7	28	0.217	0.95	0.72	0.44	0.22	0.09	0.03	0.01
7	30	0.196	0.96	0.77	0.50	0.26	0.11	0.03	0.01
7	32	0.175	0.97	0.81	0.55	0.30	0.13	0.04	0.01
7	34	0.155	0.98	0.85	0.60	0.34	0.16	0.05	0.01
7	36	0.135	0.99	0.88	0.65	0.39	0.19	0.07	0.01
8	22	0.269	0.88	0.57	0.29	0.12	0.04	0.01	0.00
8	24	0.247	0.91	0.63	0.34	0.14	0.05	0.01	0.00
8	26	0.226	0.94	0.69	0.39	0.17	0.06	0.02	0.00
8	28	0.205	0.96	0.74	0.44	0.21	0.08	0.02	0.00
8	30	0.185	0.97	0.78	0.50	0.25	0.09	0.03	0.00
8	32	0.166	0.98	0.82	0.55	0.29	0.12	0.03	0.01
8	34	0.147	0.99	0.86	0.61	0.34	0.14	0.04	0.01

FIGURE 8 Operating characteristics of variables acceptance plans (range method).

VARIABLES ACCEPTANCE PLANS *** VARIABILITY-UNKNOWN PROCEDURE *** RANGE METHOD

SAMPLE SIZE (n)	MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE (M)	MINIMUM ALLOWABLE QUALITY INDEX (k)	PROBABILITY OF ACCEPTANCE FOR SELECTED LEVELS OF LOT PERCENT DEFECTIVE						
			10	20	30	40	50	60	70
9	22	0.257	0.90	0.58	0.28	0.11	0.03	0.01	0.00
9	24	0.236	0.92	0.64	0.33	0.13	0.04	0.01	0.00
9	26	0.216	0.95	0.69	0.38	0.16	0.05	0.01	0.00
9	28	0.196	0.96	0.75	0.44	0.20	0.07	0.02	0.00
9	30	0.177	0.98	0.80	0.50	0.24	0.08	0.02	0.00
9	32	0.158	0.98	0.84	0.56	0.28	0.11	0.03	0.00
9	34	0.140	0.99	0.87	0.61	0.33	0.13	0.04	0.01
10	20	0.269	0.87	0.52	0.23	0.07	0.02	0.00	0.00
10	22	0.248	0.91	0.58	0.27	0.10	0.03	0.00	0.00
10	24	0.228	0.93	0.64	0.32	0.12	0.03	0.01	0.00
10	26	0.208	0.95	0.70	0.38	0.15	0.04	0.01	0.00
10	28	0.189	0.97	0.76	0.44	0.19	0.06	0.01	0.00
10	30	0.171	0.98	0.81	0.50	0.23	0.08	0.02	0.00
10	32	0.153	0.99	0.85	0.56	0.27	0.10	0.02	0.00
11	20	0.261	0.88	0.52	0.21	0.07	0.01	0.00	0.00
11	22	0.241	0.91	0.58	0.26	0.09	0.02	0.00	0.00
11	24	0.221	0.94	0.65	0.32	0.11	0.03	0.00	0.00
11	26	0.202	0.96	0.71	0.38	0.14	0.04	0.01	0.00
11	28	0.183	0.97	0.77	0.44	0.18	0.05	0.01	0.00
11	30	0.165	0.98	0.82	0.50	0.22	0.07	0.01	0.00
11	32	0.148	0.99	0.86	0.56	0.27	0.09	0.02	0.00
12	20	0.255	0.89	0.51	0.21	0.06	0.01	0.00	0.00
12	22	0.235	0.92	0.59	0.26	0.08	0.02	0.00	0.00
12	24	0.215	0.95	0.65	0.31	0.10	0.02	0.00	0.00
12	26	0.197	0.97	0.72	0.37	0.13	0.03	0.01	0.00
12	28	0.179	0.98	0.77	0.43	0.17	0.05	0.01	0.00
12	30	0.161	0.99	0.82	0.50	0.21	0.06	0.01	0.00
13	20	0.249	0.89	0.51	0.20	0.05	0.01	0.00	0.00
13	22	0.229	0.93	0.59	0.25	0.07	0.01	0.00	0.00
13	24	0.210	0.95	0.66	0.31	0.10	0.02	0.00	0.00
13	26	0.192	0.97	0.72	0.37	0.13	0.03	0.00	0.00
13	28	0.175	0.98	0.78	0.43	0.16	0.04	0.01	0.00
13	30	0.157	0.99	0.83	0.50	0.21	0.06	0.01	0.00
14	20	0.244	0.90	0.51	0.19	0.05	0.01	0.00	0.00
14	22	0.225	0.93	0.59	0.24	0.07	0.01	0.00	0.00
14	24	0.206	0.96	0.66	0.30	0.09	0.02	0.00	0.00
14	26	0.188	0.97	0.73	0.36	0.12	0.03	0.00	0.00
14	28	0.171	0.98	0.79	0.43	0.16	0.04	0.01	0.00
14	30	0.154	0.99	0.84	0.50	0.20	0.05	0.01	0.00
15	20	0.240	0.90	0.51	0.19	0.04	0.01	0.00	0.00
15	22	0.221	0.94	0.59	0.24	0.06	0.01	0.00	0.00
15	24	0.202	0.96	0.67	0.30	0.09	0.02	0.00	0.00
15	26	0.185	0.98	0.73	0.36	0.11	0.02	0.00	0.00
15	28	0.168	0.99	0.79	0.43	0.15	0.03	0.00	0.00

THE ACCEPTANCE PROBABILITIES IN THIS TABLE HAVE BEEN COMPUTED BY INTERPOLATION IN THE NONCENTRAL T DISTRIBUTION USING NONINTEGER DEGREES OF FREEDOM ASSOCIATED WITH RANGE ESTIMATES OF VARIABILITY. THESE PROBABILITY VALUES ARE QUITE ACCURATE FOR SINGLE-LIMIT PLANS AND APPROXIMATELY CORRECT FOR DOUBLE-LIMIT PLANS. FOR SINGLE-LIMIT PLANS, EITHER THE MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE (M) OR THE MINIMUM ALLOWABLE QUALITY INDEX (k) MAY BE SPECIFIED. FOR DOUBLE-LIMIT PLANS, ONLY THE MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE SHOULD BE USED.

FIGURE 8 (continued)

UNDERLYING THEORETICAL PRINCIPLES

The operating characteristics for attributes acceptance plans are computed by means of the hypergeometric formula:

$$P = \sum_{x=0}^{x=c} C_{d,x} C_{N-d,n-x} / C_{N,n} \qquad (5)$$

where

P = probability of acceptance;
N = population (lot) size;
n = sample size;
d = number of defects in the population;
c = acceptance number, maximum allowable number of defective items in the sample;
$C_{m,n}$ = number of possible combinations of m items taken n at a time = $m!/[n!(m-n)!]$; and
x = summation variable.

In terms of the hypergeometric distribution, the lot percent defective would be expressed as 100d/N. This distribution was used to develop the table shown in Figure 3.

As the population size increases, the hypergeometric distribution approaches the binomial distribution as a limit. For very large or infinite lot sizes, the operating characteristics for attributes acceptance plans are computed as follows:

$$P = \sum_{x=0}^{x=c} C_{n,x} p^x (1-p)^{n-x} \qquad (6)$$

where

P = probability of acceptance;
n = sample size;
p = fraction defective of the population;
c = acceptance number, maximum allowable number of defective items in the sample;
$C_{m,n}$ = number of possible combinations of m items taken n at a time = $m!/[n!(m-n)!]$; and
x = summation variable.

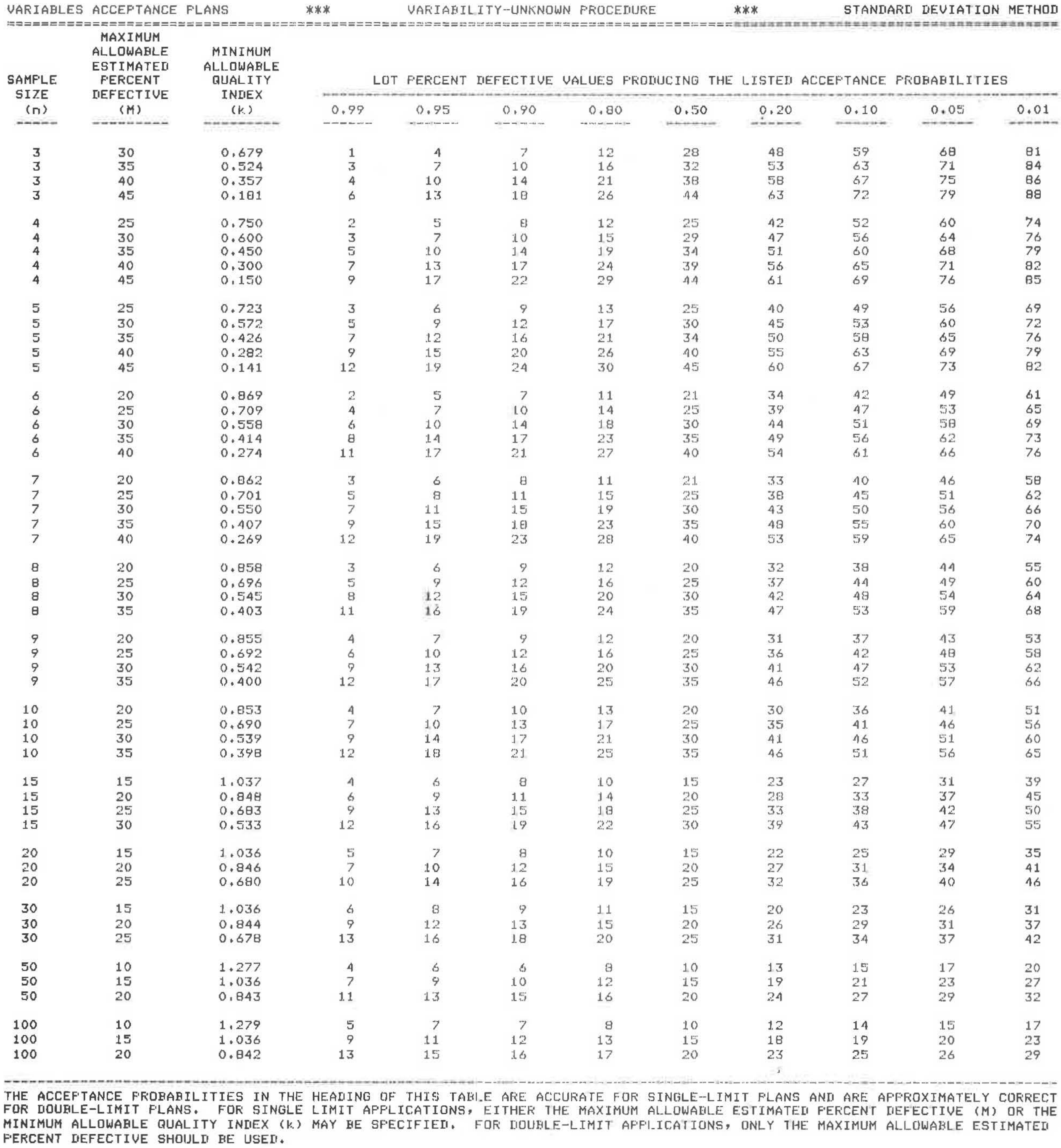
In terms of the binomial distribution, the lot

VARIABILITY-UNKNOWN PROCEDURE RANGE METHOD

QUALITY INDEX (Q)	ESTIMATED LOT PERCENT DEFECTIVE FOR SELECTED SAMPLE SIZES												
	3	4	5	6	7	8	9	10	11	12	13	14	15
0.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
0.01	49.5	49.3	49.1	49.0	48.9	48.9	48.8	48.8	48.7	48.7	48.7	48.7	48.6
0.02	49.0	48.5	48.2	48.1	47.9	47.8	47.7	47.6	47.5	47.4	47.4	47.3	47.3
0.03	48.4	47.8	47.4	47.1	46.9	46.7	46.5	46.4	46.2	46.1	46.1	46.0	45.9
0.04	47.9	47.0	46.5	46.1	45.8	45.6	45.3	45.2	45.0	44.9	44.7	44.6	44.5
0.05	47.4	46.3	45.6	45.1	44.8	44.5	44.2	44.0	43.8	43.6	43.4	43.3	43.2
0.06	46.9	45.6	44.8	44.2	43.7	43.4	43.0	42.8	42.5	42.3	42.1	42.0	41.8
0.07	46.3	44.8	43.9	43.2	42.7	42.3	41.9	41.6	41.3	41.0	40.8	40.6	40.5
0.08	45.8	44.1	43.0	42.2	41.6	41.2	40.7	40.4	40.1	39.8	39.6	39.3	39.1
0.09	45.3	43.3	42.1	41.3	40.6	40.1	39.6	39.2	38.8	38.5	38.3	38.0	37.8
0.10	44.7	42.6	41.3	40.3	39.6	39.0	38.5	38.0	37.6	37.3	37.0	36.7	36.5
0.11	44.2	41.8	40.4	39.4	38.5	37.9	37.3	36.9	36.4	36.1	35.8	35.4	35.2
0.12	43.7	41.1	39.5	38.4	37.5	36.8	36.2	35.7	35.2	34.9	34.5	34.2	33.9
0.13	43.1	40.4	38.7	37.5	36.5	35.8	35.1	34.6	34.1	33.6	33.3	32.9	32.6
0.14	42.6	39.6	37.8	36.5	35.5	34.7	34.0	33.4	32.9	32.5	32.1	31.7	31.4
0.15	42.1	38.9	36.9	35.6	34.5	33.7	32.9	32.3	31.7	31.3	30.9	30.5	30.1
0.16	41.5	38.1	36.1	34.6	33.5	32.6	31.8	31.2	30.6	30.1	29.7	29.3	28.9
0.17	41.0	37.4	35.2	33.7	32.5	31.6	30.8	30.1	29.5	29.0	28.5	28.1	27.7
0.18	40.4	36.6	34.4	32.8	31.5	30.6	29.7	29.0	28.4	27.8	27.4	26.9	26.5
0.19	39.9	35.9	33.5	31.9	30.6	29.5	28.6	27.9	27.3	26.7	26.2	25.8	25.4
0.20	39.3	35.2	32.7	30.9	29.6	28.5	27.6	26.9	26.2	25.6	25.1	24.7	24.2
0.21	38.8	34.4	31.8	30.0	28.6	27.5	26.6	25.8	25.1	24.6	24.1	23.6	23.1
0.22	38.2	33.7	31.0	29.1	27.7	26.6	25.6	24.8	24.1	23.5	23.0	22.5	22.1
0.23	37.7	32.9	30.2	28.2	26.8	25.6	24.6	23.8	23.1	22.5	21.9	21.4	21.0
0.24	37.1	32.2	29.3	27.3	25.8	24.6	23.6	22.8	22.1	21.5	20.9	20.4	20.0
0.25	36.5	31.4	28.5	26.5	24.9	23.7	22.7	21.8	21.1	20.5	19.9	19.4	19.0
0.26	35.9	30.7	27.7	25.6	24.0	22.8	21.7	20.9	20.1	19.5	18.9	18.4	18.0
0.27	35.4	29.9	26.9	24.7	23.1	21.9	20.8	19.9	19.2	18.5	18.0	17.5	17.0
0.28	34.8	29.2	26.0	23.9	22.2	21.0	19.9	19.0	18.3	17.6	17.1	16.5	16.1
0.29	34.2	28.4	25.2	23.0	21.4	20.1	19.0	18.1	17.4	16.7	16.2	15.6	15.2
0.30	33.6	27.7	24.4	22.2	20.5	19.2	18.1	17.2	16.5	15.8	15.3	14.8	14.3
0.31	33.0	27.0	23.6	21.4	19.6	18.4	17.3	16.4	15.6	15.0	14.5	13.9	13.5
0.32	32.3	26.2	22.8	20.5	18.8	17.5	16.4	15.6	14.8	14.2	13.6	13.1	12.7
0.33	31.7	25.5	22.0	19.7	18.0	16.7	15.6	14.7	14.0	13.4	12.8	12.3	11.9
0.34	31.1	24.7	21.2	18.9	17.2	15.9	14.8	14.0	13.2	12.6	12.1	11.6	11.1
0.35	30.4	24.0	20.5	18.1	16.4	15.1	14.0	13.2	12.5	11.8	11.3	10.8	10.4
0.36	29.8	23.2	19.7	17.4	15.6	14.4	13.3	12.4	11.7	11.1	10.6	10.1	9.7
0.37	29.1	22.5	18.9	16.6	14.9	13.6	12.5	11.7	11.0	10.4	9.9	9.4	9.1
0.38	28.5	21.7	18.1	15.8	14.1	12.9	11.8	11.0	10.3	9.7	9.3	8.8	8.4
0.39	27.8	21.0	17.4	15.1	13.4	12.2	11.1	10.3	9.7	9.1	8.6	8.2	7.8
0.40	27.1	20.2	16.6	14.4	12.7	11.5	10.5	9.7	9.0	8.5	8.0	7.6	7.2
0.41	26.4	19.4	15.9	13.6	12.0	10.8	9.8	9.1	8.4	7.9	7.4	7.0	6.7
0.42	25.6	18.7	15.2	12.9	11.3	10.2	9.2	8.5	7.8	7.3	6.9	6.5	6.2
0.43	24.9	17.9	14.4	12.2	10.7	9.5	8.6	7.9	7.3	6.8	6.4	6.0	5.7
0.44	24.1	17.2	13.7	11.6	10.0	8.9	8.0	7.3	6.7	6.3	5.9	5.5	5.2
0.45	23.3	16.4	13.0	10.9	9.4	8.3	7.4	6.8	6.2	5.8	5.4	5.0	4.8
0.46	22.5	15.7	12.3	10.2	8.8	7.8	6.9	6.3	5.7	5.3	4.9	4.6	4.3
0.47	21.7	14.9	11.6	9.6	8.2	7.2	6.4	5.8	5.3	4.7	4.5	4.2	4.0
0.48	20.8	14.1	11.0	9.0	7.6	6.7	5.9	5.3	4.8	4.4	4.1	3.8	3.6
0.49	19.9	13.4	10.3	8.4	7.1	6.2	5.4	4.9	4.4	4.0	3.7	3.5	3.2
0.50	19.0	12.6	9.6	7.8	6.5	5.7	5.0	4.4	4.0	3.7	3.4	3.1	2.9
0.51	18.0	11.9	9.0	7.2	6.0	5.2	4.5	4.0	3.7	3.3	3.1	2.8	2.6
0.52	17.0	11.1	8.3	6.7	5.5	4.8	4.1	3.7	3.3	3.0	2.8	2.5	2.4
0.53	15.9	10.3	7.7	6.2	5.1	4.3	3.8	3.3	3.0	2.7	2.5	2.3	2.1
0.54	14.7	9.6	7.1	5.6	4.6	3.9	3.4	3.0	2.7	2.4	2.2	2.0	1.9
0.55	13.5	8.8	6.5	5.1	4.2	3.6	3.0	2.7	2.4	2.2	2.0	1.8	1.6
0.56	12.1	8.0	5.9	4.7	3.8	3.2	2.7	2.4	2.1	1.9	1.7	1.6	1.5
0.57	10.5	7.2	5.4	4.2	3.4	2.9	2.4	2.1	1.9	1.7	1.5	1.4	1.3
0.58	8.6	6.5	4.8	3.8	3.0	2.6	2.2	1.9	1.7	1.5	1.3	1.2	1.1
0.59	6.2	5.7	4.3	3.3	2.7	2.3	1.9	1.6	1.5	1.3	1.2	1.0	1.0
0.60	1.4	4.9	3.7	2.9	2.4	2.0	1.7	1.4	1.3	1.1	1.0	0.9	0.8
0.61	0.0	4.1	3.2	2.6	2.1	1.7	1.4	1.2	1.1	1.0	0.9	0.8	0.7
0.62	0.0	3.3	2.8	2.2	1.8	1.5	1.2	1.1	0.9	0.8	0.7	0.7	0.6
0.63	0.0	2.5	2.3	1.9	1.5	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.5
0.64	0.0	1.7	1.9	1.6	1.3	1.1	0.9	0.8	0.7	0.6	0.5	0.5	0.4
0.65	0.0	0.9	1.5	1.3	1.1	0.9	0.7	0.6	0.6	0.5	0.4	0.4	0.4
0.66	0.0	0.0	1.1	1.0	0.9	0.7	0.6	0.5	0.5	0.4	0.4	0.3	0.3
0.67	0.0	0.0	0.8	0.8	0.7	0.6	0.5	0.4	0.4	0.3	0.3	0.3	0.2
0.68	0.0	0.0	0.4	0.6	0.5	0.5	0.4	0.3	0.3	0.3	0.2	0.2	0.2
0.69	0.0	0.0	0.2	0.4	0.4	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.2
0.70	0.0	0.0	0.0	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.1
0.71	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1
0.72	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
0.73	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
0.74	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
0.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.76	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.77	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.79	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

NUMBERS IN BODY OF TABLE ARE ESTIMATES OF LOT PERCENT DEFECTIVE CORRESPONDING TO SPECIFIC VALUES OF QUALITY INDEX AND SAMPLE SIZE. FOR Q VALUES GREATER THAN OR EQUAL TO ZERO, THE PERCENT DEFECTIVE ESTIMATE MAY BE READ DIRECTLY FROM THE TABLE. FOR Q VALUES LESS THAN ZERO, THE TABLE VALUE MUST BE SUBTRACTED FROM 100.

FIGURE 9 Table for estimation of percent defective (range method).



VARIABLES ACCEPTANCE PLANS *** VARIABILITY-UNKNOWN PROCEDURE *** STANDARD DEVIATION METHOD

SAMPLE SIZE (n)	MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE (M)	MINIMUM ALLOWABLE QUALITY INDEX (k)	LOT PERCENT DEFECTIVE VALUES PRODUCING THE LISTED ACCEPTANCE PROBABILITIES								
			0.99	0.95	0.90	0.80	0.50	0.20	0.10	0.05	0.01
3	30	0.679	1	4	7	12	28	48	59	68	81
3	35	0.524	3	7	10	16	32	53	63	71	84
3	40	0.357	4	10	14	21	38	58	67	75	86
3	45	0.181	6	13	18	26	44	63	72	79	88
4	25	0.750	2	5	8	12	25	42	52	60	74
4	30	0.600	3	7	10	15	29	47	56	64	76
4	35	0.450	5	10	14	19	34	51	60	68	79
4	40	0.300	7	13	17	24	39	56	65	71	82
4	45	0.150	9	17	22	29	44	61	69	76	85
5	25	0.723	3	6	9	13	25	40	49	56	69
5	30	0.572	5	9	12	17	30	45	53	60	72
5	35	0.426	7	12	16	21	34	50	58	65	76
5	40	0.282	9	15	20	26	40	55	63	69	79
5	45	0.141	12	19	24	30	45	60	67	73	82
6	20	0.869	2	5	7	11	21	34	42	49	61
6	25	0.709	4	7	10	14	25	39	47	53	65
6	30	0.558	6	10	14	18	30	44	51	58	69
6	35	0.414	8	14	17	23	35	49	56	62	73
6	40	0.274	11	17	21	27	40	54	61	66	76
7	20	0.862	3	6	8	11	21	33	40	46	58
7	25	0.701	5	8	11	15	25	38	45	51	62
7	30	0.550	7	11	15	19	30	43	50	56	66
7	35	0.407	9	15	18	23	35	48	55	60	70
7	40	0.269	12	19	23	28	40	53	59	65	74
8	20	0.858	3	6	9	12	20	32	38	44	55
8	25	0.696	5	9	12	16	25	37	44	49	60
8	30	0.545	8	12	15	20	30	42	48	54	64
8	35	0.403	11	16	19	24	35	47	53	59	68
9	20	0.855	4	7	9	12	20	31	37	43	53
9	25	0.692	6	10	12	16	25	36	42	48	58
9	30	0.542	9	13	16	20	30	41	47	53	62
9	35	0.400	12	17	20	25	35	46	52	57	66
10	20	0.853	4	7	10	13	20	30	36	41	51
10	25	0.690	7	10	13	17	25	35	41	46	56
10	30	0.539	9	14	17	21	30	41	46	51	60
10	35	0.398	12	18	21	25	35	46	51	56	65
15	15	1.037	4	6	8	10	15	23	27	31	39
15	20	0.848	6	9	11	14	20	28	33	37	45
15	25	0.683	9	13	15	18	25	33	38	42	50
15	30	0.533	12	16	19	22	30	39	43	47	55
20	15	1.036	5	7	8	10	15	22	25	29	35
20	20	0.846	7	10	12	15	20	27	31	34	41
20	25	0.680	10	14	16	19	25	32	36	40	46
30	15	1.036	6	8	9	11	15	20	23	26	31
30	20	0.844	9	12	13	15	20	26	29	31	37
30	25	0.678	13	16	18	20	25	31	34	37	42
50	10	1.277	4	6	6	8	10	13	15	17	20
50	15	1.036	7	9	10	12	15	19	21	23	27
50	20	0.843	11	13	15	16	20	24	27	29	32
100	10	1.279	5	7	7	8	10	12	14	15	17
100	15	1.036	9	11	12	13	15	18	19	20	23
100	20	0.842	13	15	16	17	20	23	25	26	29

THE ACCEPTANCE PROBABILITIES IN THE HEADING OF THIS TABLE ARE ACCURATE FOR SINGLE-LIMIT PLANS AND ARE APPROXIMATELY CORRECT FOR DOUBLE-LIMIT PLANS. FOR SINGLE LIMIT APPLICATIONS, EITHER THE MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE (M) OR THE MINIMUM ALLOWABLE QUALITY INDEX (k) MAY BE SPECIFIED. FOR DOUBLE-LIMIT APPLICATIONS, ONLY THE MAXIMUM ALLOWABLE ESTIMATED PERCENT DEFECTIVE SHOULD BE USED.

FIGURE 10 Alternate format for operating characteristic table for variables plans.

percent defective would be expressed as 100p. This distribution was used to develop the table shown in Figure 4.

The estimates of lot percent defective for the standard deviation method contained in the table shown in Figure 6 are obtained by numerically integrating the beta distribution function (13):

$$p = \int_{x=0}^{x=\mathrm{Max}\{0,\ 1/2 - Qn^{1/2}/[2(n-1)]\}} \beta(a,b,x)\,dx \qquad (7)$$

where

p = fraction defective of the population for single-limit applications (for double-limit applications, two separate integration steps must be performed and the results added to obtain the total fraction defective);
$\beta(a,b,x)$ = beta distribution function;
a,b = parameters of the beta distribution = n/2 - 1;

```
VARIABILITY-UNKNOWN PROCEDURE                             STANDARD DEVIATION METHOD
===================================================================================
           MAXIMUM
          ALLOWABLE       PERCENT DEFECTIVE            PROBABILITY OF ACCEPTANCE
          ESTIMATED     --------------------------    ----------------------------
SAMPLE     PERCENT       LOWER    UPPER               SINGLE LIMIT    DOUBLE LIMIT
 SIZE     DEFECTIVE      TAIL     TAIL      TOTAL      (COMPUTED)     (SIMULATED)
------   -----------    -----    -----     -----     ------------    ------------

  3          42            0       10        10          0.96            0.96
  3          42            5        5        10          0.96            0.96

  3          38           20        0        20          0.78            0.78
  3          38           10       10        20          0.78            0.77

  3          34           10       50        60          0.12            0.11
  3          34           25       35        60          0.12            0.12

  5          36           10        0        10          0.97            0.97
  5          36            5        5        10          0.97            0.98

  5          32            0       30        30          0.54            0.54
  5          32           15       15        30          0.54            0.52

  5          26           60        0        60          0.04            0.04
  5          26           30       30        60          0.04            0.03

 10          22            0       10        10          0.92            0.93
 10          22            5        5        10          0.92            0.92

 10          24           20        0        20          0.65            0.65
 10          24           10       10        20          0.65            0.65

 10          28           10       30        40          0.17            0.15
 10          28           20       20        40          0.17            0.15

-----------------------------------------------------------------------------------
EACH SIMULATION RESULT WAS OBTAINED BY INDEPENDENTLY GENERATING 5000 RANDOM
SAMPLES OF THE APPROPRIATE SIZE FROM A CONTINUOUS NORMAL POPULATION.
```

FIGURE 11 Demonstration that single-limit operating characteristic curves are sufficiently accurate for most double-limit variables acceptance plans.

n = sample size;
Q = quality index, $(\bar{X} - L)/S$ or $(U - \bar{X})/S$ for single-limit applications, both required for double-limit applications;
$\bar{X}$ = sample mean;
S = sample standard deviation;
L,U = lower and upper specification limits; and
x = integration variable.

The area under the beta distribution obtained in this manner is the fraction defective that must be multiplied by 100 to yield the estimate of percent defective. Although this integration can be done manually using tables of the beta function (14), it is far more practical to use computer assistance with subroutines developed specifically for this purpose.

The operating characteristics for variables plans based on the standard deviation are obtained by numerically integrating the noncentral t distribution function (12):

$$P = 1 - \int_{x=-\infty}^{x=kn^{1/2}} t(\nu,\delta,x)\,dx \qquad (8)$$

where

P = probability of acceptance,
$t(\nu,\delta,x)$ = noncentral t distribution function,
ν = degrees of freedom = $n - 1$,
n = sample size,
δ = noncentrality parameter = $K_p n^{1/2}$
K_p = normal z-score associated with each level of population percent defective for which the computation is made,
k = acceptance constant, and
x = integration variable.

If the acceptance procedure is stated in terms of the maximum allowable estimated percent defective (M) rather than the minimum allowable value (k) of the quality index (Q), this must first be converted to a k-value using tables such as those shown in Figures 6, 7, or 9. The integration step indicated in Equation 8 may be performed manually using tables of the noncentral t distribution (12) although, like the integration of the beta distribution in Equation 7, it is much more practical to use computer assistance. The table shown in Figure 5 was generated in this manner.

When these same operations are to be performed for acceptance plans based on the range (R), minor modifications must be made to account for the reduced degrees of freedom associated with range estimates of variability. The following values are obtained from Duncan (11).

Sample Size	Conversion Factor (d_2*)	Degrees of Freedom (range method)
3	1.91	2.0
4	2.24	2.9
5	2.48	3.8
6	2.67	4.7
7	2.83	5.5
8	2.96	6.3
9	3.08	7.0
10	3.18	7.7
11	3.27	8.4
12	3.35	9.0
13	3.42	9.6
14	3.49	10.2
15	3.55	10.8

To obtain estimates of lot percent defective using the range method, the upper integration limit in Equation 7 must be changed (13) to

$$x = \text{Max}\ \{0,\ 1/2 - d_2{}^{*}\ Q\ [(\nu + 1)^{1/2}]/2\nu\} \qquad (9)$$

where

x = integration variable;
Q = quality index computed by the range method,

$(\bar{X} - L)/R$ or $(U - \bar{X})/R$ for single-limit applications, both required for double-limit applications;
d_2^* = factor that, when divided into the range computed from the sample, converts it into an estimate of the standard deviation; and
ν = degrees of freedom (the appropriate noninteger values associated with the range method must be used).

To develop operating characteristic curves for variables acceptance plans based on the range, Equation 8 may be used except that is is necessary to account for the appropriate noninteger degrees of freedom associated with range estimates of variability (personal conversation with G.J. Resnikoff, California State University, Hayward, 1985). In this case, it is necessary to compute two probability values for integral degrees of freedom in order to obtain the desired value by interpolation.

POTENTIAL PROBLEM WITH VARIABLES PLANS

Although such occurrences are rare, it is possible when using variables acceptance plans that a lot may be judged rejectable even though none of the individual test results falls outside the specification limits. Provided no fundamental assumptions (normal population, random sampling, etc.) have been violated, this is a theoretically correct result. The proper inference is that, based on the mean and standard deviation (or range) estimated from the sample, the population percent defective is unacceptably large.

This same result may also be caused by one or more outliers, test results that deviate unusually far from the norm because of some assignable cause such as equipment malfunction or operator error. Because such a result may be challenged by a contractor who is unfamiliar with its theoretical basis, and may indeed be an indication of a breakdown in the sampling and testing process, it is advisable to investigate and reevaluate any lot rejected in this manner.

PAVEMENT THICKNESS EXAMPLE

A highway agency wishes to develop an acceptance procedure for pavement thickness that is as uncomplicated as possible and involves no statistical calculations or special tables. The pavement will be considered satisfactory if at least 90 percent of it has a thickness greater than the design value. Therefore the acceptable quality level (AQL) may be considered to be 10 percent defective and it is desired that this level of quality have a relatively high probability of acceptance. At the other extreme, if 40 percent of more of the pavement is less than the design thickness, it has been decided that this will be defined as the rejectable quality level (RQL) and a correspondingly low probability of acceptance is desired.

For purposes of this example, suppose that a seller's risk of $\alpha = 0.05$ and a buyer's risk of $\beta = 0.10$ are desired. The corresponding probabilities of acceptance are $P = 0.95$ at the AQL and $P = 0.10$ at the RQL.

The requirement for simplicity dictates an attributes plan. When attributes acceptance procedures are applied to continuous data (thickness in this case), the lot size is considered to be infinite. By scanning the rows and columns of the table shown in Figure 4, it is observed that a plan with a sample size of $n = 15$ and an acceptance number of $c = 3$ produces very nearly the desired risk levels. (Because the sample size and acceptance number are discrete values, it is not possible to match the risks exactly.) The following values are obtained:

Lot Percent Defective	Probability of Acceptance
10 (AQL)	0.94
20	0.65
30	0.30
40 (RQL)	0.09
50	0.02

It can be seen from these values that the basic objectives have been well satisfied. A good quality pavement that has 10 percent or less defective will have a probability of acceptance of at least $P = 0.94$. If the pavement is 40 percent or more defective, the probability of acceptance will be $P = 0.09$ or less.

The completed acceptance procedure will require that $n = 15$ cores be taken at random locations within a specified lot size. Because attributes acceptance theory makes no assumptions about the distributional form of the population, there is considerable latitude to define the lot size in any manner that the highway agency believes is appropriate. Provided that no more than $c = 3$ cores are less than the design thickness, the lot will be judged acceptable.

GRADATION EXAMPLE

An acceptance procedure is to be prepared for a crushed stone base course. The percentage by weight of material passing the No. 200 sieve is known to be a significant performance characteristic. Experience has shown that bases that have 7.0 percent or less of minus No. 200 material have performed well but bases that have more than 10.0 percent of minus No. 200 material have poor stability and drainage and tend to be frost susceptible. For this example, it is assumed that an analysis of historical data has shown the test results on minus No. 200 material to be approximately normally distributed with a typical standard deviation of about $\sigma = 1.0$ percent.

The information provided in this example is sufficient to develop a workable acceptance plan but it is not in the most useful form. For the types of acceptance plans covered in Standard R9, definitions of acceptable and unacceptable quality must be stated in terms of the percentage of material falling outside some specification limit (or pair of limits). Instead, the information is presented in terms of two average levels of minus No. 200 material that experience has shown have produced satisfactory and unsatisfactory results, respectively. As a reasonable approximation, these average values can be associated with the typical standard deviation of $\sigma = 1.0$ percent by means of normal distribution theory to provide guidance in establishing both the AQL and the RQL in terms of percent defective. The acceptance plan will then perform as desired as long as the standard deviation is reasonably close to the typical value and, if conservatively designed, it should provide ample protection even when the standard deviation is larger than usual.

Because there is no reason to impose a lower limit on minus No. 200 material, this will be a single-limit specification. A logical choice for this limit is 7.0 percent, the level of minus No. 200 material that is known to be clearly satisfactory. It is believed that the base will perform well as long as 90 percent or more of the material has a minus No. 200 value of 7.0 percent or less. Therefore the AQL is defined as 10 percent defective above the limit of 7.0 percent. This is a relatively conservative definition because, even if the standard deviation were considerably larger than the typical value, there is little chance that any of the material in the normal distribution representing AQL quality would reach the known critical value of 10.0 percent minus No. 200 material. The AQL is illustrated in the upper diagram in Figure 12.

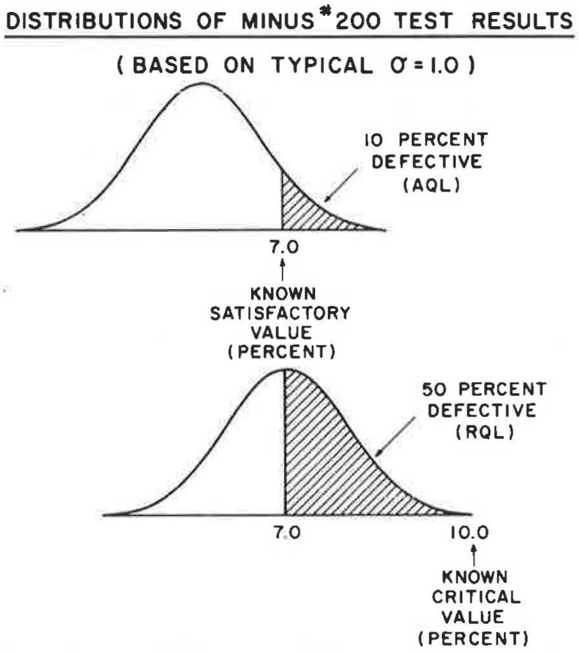


FIGURE 12 Illustration of definitions of AQL and RQL for gradation example.

To determine the level of percent defective to be defined as the RQL, it is noted that if this same distribution had 50 percent of its material above the limit of 7.0 percent, its upper tail would extend just to the critical value of 10.0 percent minus No. 200 material. On those few occasions in which the standard deviation was substantially larger than the typical value of $\sigma = 1.0$ percent, a relatively small portion of the distribution would extend above the critical value of 10.0 percent. As the amount of material exceeding 7.0 percent minus No. 200 material increases above 50 percent, however, progressively more will exceed the critical value of 10.0 percent and performance problems might be expected to develop. This provides a rational basis for defining the RQL as 50 percent defective above the limit of 7.0 percent minus No. 200 material, as illustrated in the lower diagram in Figure 12.

For this example, it will be assumed that the highway agency wishes to control both the seller's risk and the buyer's risk at $\alpha = \beta = 0.05$. The required acceptance probabilities at the AQL and RQL are $P = 0.95$ and $P = 0.05$, respectively. It is seen from the table shown in Figure 5 that a variables plan with a sample size of $n = 8$ and a maximum allowable estimated percent defective of $M = 26$ meets these requirements.

Lot Percent Defective	Probability of Acceptance
10 (AQL)	0.95
20	0.70
30	0.38
40	0.16
50 (RQL)	0.05
60	0.01

A suitable lot size must be chosen and the method of testing specified. Because variables acceptance theory assumes sampling from a normal population, care must be taken not to combine distinctly different populations into a single lot. The acceptance procedure will require that the mean ($\bar{X}$) and standard deviation (S) be calculated from $n = 8$ random samples and used to compute the Q-statistic in Equation 10. The corresponding percent defective estimate is obtained from tables such as the one shown in Figure 6 or the type shown in Figure 7. For the lot to be judged acceptable, the estimated percent defective must be no larger than $M = 26$. (Alternatively, it could be required that the Q-statistic be equal to or greater than $k = 0.665$.)

$$Q = (7.0 - \bar{X})/S \qquad (10)$$

PAY ADJUSTMENT CLAUSES

Because it is seldom possible to define a single level of quality that differentiates between satisfactory and unsatisfactory work, it has become customary to define two distinctly different quality levels--the AQL and the RQL--when developing statistical acceptance procedures. The AQL represents a clearly acceptable level of quality that the highway agency expects the contractor to deliver. The RQL represents a much lower level of quality that, when detected, requires some sort of remedial action.

In actual practice, highway agencies are often faced with the dilemma of having to deal with marginal quality, items of work that fall between the AQL and the RQL. Many agencies have found the use of adjusted pay schedules, which award payment in proportion to the quality received, to be a practical and effective solution. The percent defective parameter, on which the revised version of Standard R9 is based, is particularly well suited for this purpose. For the reader interested in pursuing this refinement, the development of pay adjustment clauses is extensively covered in the recent literature (1-3, 15-21).

SUMMARY AND CONCLUSIONS

A major revision of AASHTO Standard R9, Acceptance Sampling Plans for Highway Construction, was described. The primary goals were to correct several technical flaws and to reduce the level of complexity of the standard. The new version is oriented around the concept of percent defective as the quality measure and advocates the standard deviation method rather than the less efficient range method for variables acceptance plans. Several new tables were developed, including operating characteristic tables for a wide range of both attributes and variables acceptance plans, and it was demonstrated by computer simulation that single-limit variables operating characteristic curves are sufficiently accurate for most double-limit applications. Finally, two examples were presented to illustrate the use of the revised standard.

ACKNOWLEDGMENT

The author especially wishes to thank Jim Lyon, Chairman of AASHTO Technical Section 5c at the time this work was done, for his encouragement and support on this project. The several suggestions and review of the finished product by task group members Doyt Bolling, Ron Cominsky, Tom Stapler, and Garland

Steele are also gratefully acknowledged. Peter Kopac also made several significant contributions. This work was performed with the cooperation of the FHWA, U.S. Department of Transportation, but reflects the views of the author who is responsible for its accuracy.

REFERENCES

1. Statistically Oriented End-Result Specifications. NCHRP Synthesis of Highway Practice 38. TRB, National Research Council, Washington, D.C., 1976.
2. Quality Assurance. NCHRP Synthesis of Highway Practice 65. TRB, National Research Council, Washington, D.C., 1979.
3. R.M. Weed. Statistical Specification Development. FHWA, U.S. Department of Transportation, 1982.
4. R.M. Weed. An Introduction to Computer Simulation. Demonstration Projects Division, FHWA, U.S. Department of Transportation, 1976.
5. R.T. Barros, R.M. Weed, and J.H. Willenbrock. Software Package for the Design and Analysis of Acceptance Procedures Based on Percent Defective. In Transportation Research Record 924, TRB, National Research Council, Washington, D.C., 1983, pp. 85-93.
6. AASHTO Interim Specifications--Materials. AASHTO, Washington, D.C., 1984.
7. Sampling Procedures and Tables for Inspection by Attributes. Military Standard 105. U.S. Department of Defense, 1963.
8. Sampling Procedures and Tables for Inspection by Variables for Percent Defective. Military Standard 414. U.S. Department of Defense, 1957.
9. I. Miller and J.E. Freund. Probability and Statistics for Engineers. Prentice Hall, Inc., Englewood Cliffs, N.J., 1965.
10. W.J. Dixon and F.J. Massey, Jr. Introduction to Statistical Analysis. McGraw Hill Book Co., New York, 1969.
11. A.J. Duncan. Quality Control and Industrial Statistics. Richard D. Irwin, Inc., Homewood, Ill., 1965.
12. G.J. Resnikoff and G.J. Lieberman. Tables of the Noncentral t Distribution. Stanford University Press, Stanford, Calif., 1957.
13. J.H. Willenbrock and P.A. Kopac. Development of a Highway Construction Acceptance Plan. In Transportation Research Record 691, TRB, National Research Council, Washington, D.C., 1978, pp. 16-22.
14. K. Pearson. Tables of the Incomplete Beta Function. Biometrika Office, University College, London, England, 1934.
15. J.H. Willenbrock and P.A. Kopac. Development of Price-Adjustment Systems for Statistically Based Highway Construction Specifications. In Transportation Research Record 652, TRB, National Research Council, Washington, D.C., 1977, pp. 52-58.
16. R.M. Weed. Equitable Graduated Pay Schedules: An Economic Approach. In Transportation Research Record 691, TRB, National Research Council, Washington, D.C., 1978, pp. 27-29.
17. R.M. Weed. Unbiased Graduated Pay Schedules. In Transportation Research Record 745, TRB, National Research Council, Washington, D.C., 1980, pp. 23-28.
18. R.M. Moore, J.P. Mahoney, R.G. Hicks, and J.E. Wilson. Overview of Pay Adjustment Factors for Asphalt Concrete Mixtures. In Transportation Research Record 821, TRB, National Research Council, Washington, D.C., 1981, pp. 49-56.
19. R.M. Weed. Method to Establish Pay Schedules for Rigid Pavement. In Transportation Research Record 885, TRB, National Research Council, Washington, D.C., 1982, pp. 18-24.
20. P. Puangchit, R.G. Hicks, J.E. Wilson, and C.A. Bell. Development of Rational Pay Adjustment Factors for Asphalt Concrete. In Transportation Research Record 911, TRB, National Research Council, Washington, D.C., 1983, pp. 70-79.
21. R.M. Weed. Adjusted Pay Schedules: New Concepts and Provisions. In Transportation Research Record 986, TRB, National Research Council, Washington, D.C., 1984, pp. 32-38.

Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.

Analysis of Two Acceptance Procedures for Aluminum Welds

RICARDO T. BARROS

ABSTRACT

Radiographic procedures are used to inspect and accept welds incorporated into aluminum overhead sign support structures. Radiography is expensive, however, so it is obviously desirable to inspect no more frequently than necessary to assure that defective welds are absent from accepted structures. The principles underlying the New Jersey Department of Transportation's present radiographic acceptance procedure are discussed and an alternative procedure is proposed that may save more than $10,000 annually without diminishing the present level of protection.

Aluminum welds are used by the New Jersey Department of Transportation (NJDOT) in the fabrication of aluminum overhead sign support structures. Every weld is first subjected to a visual inspection and then, in addition, a random sample from each lot of welds is subjected to radiographic inspection. Radiographic inspection is costly, currently $43 per radiograph, so there is an obvious incentive to reduce the number of radiographs taken to the minimum required. Those that are taken must still provide adequate protection against the acceptance of defective welds.

The existing radiographic acceptance procedure appears to provide the required protection. Analysis of the risks involved indicates that, in most cases, lots that contain an excessive number of flawed welds stand a small chance of passing undetected. This inference is based on established theory using the hypergeometric probability distribution.

However, a discrepancy between statistical theory and practical application of the acceptance procedure introduces a potential flaw into conventional statistical analyses, the impact of which was not previously known. As a practical expedient, a cluster sampling technique is used rather than pure random sampling. Risk analyses that assume one sampling procedure may be invalidated if another is used. Consequently, it was necessary to quantify the nature and magnitude of the potential bias introduced. If this step had not been taken, it could have been possible that the inferred protection was nonexistent but assumed to be present simply because the quality levels submitted to date have been exceptionally high.

Prerequisite information for any analysis of risk is the concept of acceptable and rejectable weld quality. Knowledge of specific quality levels is necessary to provide reference points at which the risk of not detecting flawed welds can be meaningfully compared. It was found that these specific definitions of quality, as such, had not been explicitly developed within the NJDOT or the American Welding Society (AWS) for aluminum welds. Instead, previous attention focused on engineering acceptance limits. Because of this lack of explicit quality definitions, it was first necessary to identify reasonable quality levels that it would be in the agency's interest to consistently accept and other quality levels that should be consistently rejected. This was done by evaluating historical NJDOT data in the context of operating characteristic (OC) curve analyses.

Given quality levels thus established, it was the objective of this study to critically evaluate the current NJDOT acceptance procedure and to propose an alternative that would afford either or both of two important benefits: a reduced exposure to risk or a reduced radiographic inspection cost. The alternative acceptance procedure subsequently developed was highly successful in both regards. Considerable cost savings ($10,000 per year or more) may be realized with risks not only stabilized near but, in some cases, substantially lowered from their present levels.

Initiating a change in an accepted practice is difficult, however, particularly when appreciation of the benefits to be obtained is not reinforced by a dissatisfaction with the procedure already in place. In addition, the relative merits of competing concerns may not be clear and thus favor making no change to the status quo. Consequently, many of the topics relevant to the selection of the best weld inspection strategy, which will enable management to make an appropriate, well-informed decision, are discussed in this paper.

EXISTING RADIOGRAPHIC ACCEPTANCE PROCEDURE

The NJDOT has, for several years, used a minimum sampling rate of 25 percent of the total number of welds in a lot. (Each structure is comprised of several lots.) If more than 10 percent of the radiographed welds are found to be defective, all of the remaining welds are subsequently radiographed. In any event, all defective welds found are repaired and the lot is eventually accepted.

The NJDOT pays for the cost of all radiographs except for those that reveal a defective weld. These are paid for by the fabricator at the current rate of $43 per radiograph. The total cost to the NJDOT of administering the existing radiographic inspection program ranges from roughly $40,000 to more than $200,000 per year, depending on the intensity of construction activity.

Attempts to determine the origin of this plan have been unsuccessful. Apparently it is not explicitly patterned after any existing standard but

---

New Jersey Department of Transportation, 1035 Parkway Avenue, CN 600, Trenton, N.J. 08625.

simply "evolved" many years ago. NJDOT engineers are under the impression that 100 percent radiographic inspection was originally used but later reduced because of (a) the generally satisfactory quality that was being received, (b) the relatively high cost of radiography, and (c) a belief that there is a sufficient amount of structural redundancy to preclude the sudden collapse of a sign support structure.

It is interesting that, in an isolated case, an existing and apparently serviceable aluminum sign support structure was dismantled from its field location and transported to the laboratory where it was subjected to 100 percent radiographic inspection. A subsequent analysis revealed that the tested structure would most likely have failed to pass the initial acceptance criteria. That is, it would have triggered the 100 percent inspection provision. Implications of this finding are discussed later in this paper.

QUALITY LEVELS AND ACCEPTANCE LIMITS

Meaningful risk analyses refer to quality levels, not acceptance limits. The distinction between these two terms is subtle but important. An acceptance limit represents the critical engineering tolerance that precipitates one of two actions--the acceptance or the rejection of a material--and hence expresses the policy that is to be followed in dealing with materials that may be submitted with differing levels of quality. Quality levels, on the other hand, are a more fundamental measure and reflect the degree to which a material could be expected to meet specified serviceability requirements if it were to be accepted.

In the present case, acceptable weld quality comprises those quality levels for which weld defects incorporated into a structure do not prevent the structure from providing adequate service during the structure's intended life. Certainly flawless welds meet this criteria, but so do welds that contain flaws not sufficiently large or frequent to diminish the serviceability rendered below some designated threshold. Historical observations strongly indicate that acceptable weld quality levels in a structure can, without a doubt, include some welds that are flawed.

A basic, well-established parameter used to represent the various levels of quality in analyses of this type is percent defective. This parameter simply quantifies the proportion of the welds in a structure that are flawed. (Weld flaws are defined by specific engineering tolerances for porosity, cracking, incomplete penetration, etc.) Structures with some low value of percent defective are judged to be of acceptable quality whereas others at higher levels of percent defective are not.

The percent defective parameter is intrinsically keyed to the acceptance limit defining weld flaws by the statistical acceptance procedure. Critical information relevant to the evaluation of an acceptance limit is the frequency with which welds defined as flawed by this limit are accepted. The net effect of a seemingly stringent limit in a (poorly designed) acceptance procedure may be that the average quality actually accepted is substantially worse than the stringent limit might suggest.

Acceptance limits must be considered to be primarily the expression of a policy decision, and the adequacy of this policy decision can be evaluated only relative to the assessment of the quality levels between which it is capable of distinguishing. This study seeks to identify specific quality levels through analyses of historical data and to assess the relative discriminating power of several alternative acceptance procedures in the recognition of these quality levels. Existing engineering tolerances that characterize welds as defective or not will remain unchanged. In so doing a basis will be established on which to comparatively evaluate the merits of the various acceptance procedures.

RISKS AND ENGINEERING DESIGN

The analyses performed in this study are of an admittedly empirical nature. An abstract parameter, percent defective, is used to gauge quality in structures observed to have provided specific levels of service. Percent defective considerations do not explicitly enter into the original design considerations, however, and a question may be raised about the relevance of this specific abstraction and whether another, more tangible procedure might not more meaningfully evaluate risks in a model with physically measurable dimensions. Indeed, an alternative analytical procedure does exist. Reliability analyses quantify the risk of specific structural elements failing in prescribed modes. These analyses require comprehensive knowledge of material properties and applied loads, however, which effectively places them beyond the scope of the present investigation. A brief digression may help justify the relevance of the empirical analyses performed and demonstrate why, with historical information available, risks may be addressed in a generalized manner.

The erection of a completed structure may be viewed as the end product of many, distinct engineering analyses. Three of these are the selection of an overall structural configuration as well as individual member dimensions, the specification of engineering limits on desirable material properties, and an analysis of the risks present in (materials) quality assurance. These analyses are obviously interrelated. Stronger material properties permit a more sparse structural configuration. Low confidence in the materials acceptance procedure would require a compensating degree of redundancy in structural support or surplus in material strength.

Given a design load, a structural element, and a specified material limit, the problem becomes one of assuring that the material limit is not exceeded. If this can be accomplished with a reliability comparable to that which has historically been achieved, then it can be inferred that the existing (and satisfactory) balance has been preserved. Thus the presence or absence of defects in a weld becomes the pertinent criterion and the operating characteristic curve the primary analytical tool.

USE OF THE HYPERGEOMETRIC PROBABILITY FUNCTION IN AN ACCEPTANCE PROCEDURE

Operating characteristic curves for lots that contain a discrete number of defects are calculated with the hypergeometric probability function (1). Probabilities are determined as a function of the lot size (N), the sample (n), the total number of defects in the lot (D), and the observed number of defects in the sample (d). A lot is accepted if the sample contains c or fewer defects, where c is the maximum number of allowable defects in a sample. Typically, lots with more than c defects are then subjected to 100 percent inspection and all detected defects are repaired or replaced. Sampled observations are implicitly assumed to meet the requirements of independent, random selection.

Operating characteristic curves developed with the hypergeometric probability function are, in a sense, more limited than curves developed with continuous functions because only discrete integers may be used. It is not possible to have 1.5 defects, for example. It sometimes occurs that an incremental change in one of the foregoing variables (i.e., N, n, D, d, or c) results in a noticeable jump in the incremental probability.

The existing acceptance procedure is especially subject to this type of fluctuation. For example, because the probabilities of acceptance are more sensitive to absolute sample sizes than sampling rates, two lots from which a 25 percent sample is taken will necessarily incur different risks if one contains 60 welds and the other 80 welds. Also, if the acceptance requirement is that 10 percent or less of the sample be defective, then additional imprecision is introduced because c may be set to 1 or 2 defects but never 1.5. And, finally, the existing acceptance procedure randomly selects weld nodes of various sizes until the cumulative number of sampled welds exceeds the minimum number required. (The actual sample size used is the cumulative number rather than the minimum required.) Thus, by chance, two lots of equal size may be represented by unequal sample sizes and incur different risks.

RQL, TOLERABLE RISKS, AND AVERAGE OUTGOING QUALITY

Established tolerable risks at specified quality levels have not been universally established in the existing state of the art. The American Welding Society does not recognize statistical risks in the acceptance procedure and favors strictly controlled fabrication conditions. The American Society for Testing and Materials, the American Society for Nondestructive Testing, and the American Society for Quality Control were also contacted but were unable to provide further guidance regarding the tolerable risk of accepting marginal quality.

It is fortunate that the NJDOT has developed historical information regarding weld quality, and this information gains in authority when other references remain silent. An aluminum sign support structure, scheduled for dismantlement after about 17 years of satisfactory service, was subjected to 100 percent radiographic inspection to provide additional quality and performance data. Scattered porosity was, by far, the most common defect found. A smaller number of cracks and tungsten inclusion were also observed, and even fewer incidences of lack of fusion were detected.

Although a great deal was learned about this particular structure, the conspicuous lack of other information necessitates the making of certain assumptions if specific inferences are to be generalized. The structure must be thought of as representative. Or, more specifically, it must be assumed that the relative frequencies of defect types found in the tested sections are not unusual, that the weld defects found at the time of inspection were present at the time of fabrication, and that the field loading exposure was not atypically light. NJDOT engineers queried on this matter considered this structure to be generally representative of others in use and thought that these assumptions were reasonably met.

A conservative rejectable quality level (RQL) value can then be derived. The observed quality levels for the five sections were found to range from 17 to 56 percent defective and the weighted average value for all trusses was 33 percent defective. Thus, for the purposes of this analysis, it is assumed that the RQL is no smaller than 33 percent defective.

Setting the RQL at 33 percent defective implies that trusses with no more than this amount of defective welds would serve at least as well as the tested sections. It also implies that trusses with more than RQL defects are not acceptable. Note that this latter implication is fairly conservative because two of the five tested sections were actually in excess of 50 percent defective. Note also that the percent defective parameter applies strictly to the degree of compliance with a specified engineering limit, such as a maximum limit for linear porosity. A change in this engineering limit may necessitate a corresponding change in the definition of the RQL.

The tolerable risk at the RQL is dependent on several considerations. These include the likelihood of structural failure should an RQL situation occur, the mode of the structural failure, and the potential consequences. (Recall that all welds are subjected to a visual inspection and that the risks discussed hereafter apply exclusively to those defects detectable only through radiographic inspection.)

On the basis of these observations, the likelihood of a structural failure exactly at the RQL appears to be extremely small. Should a failure occur, PennDOT sources personally contacted report that individual struts tend to disengage first and are visually detectable from the roadway. In their experience, this allowed sufficient time for the structure to be dismantled in a timely fashion. (PennDOT failures were generally attributable to incomplete penetration and lack of fusion and were not catastrophic. Also, PennDOT's structures were accepted on the basis of fabricator certification rather than a statistical acceptance procedure.) Thus the primary consequences of historical weld failures have been engineering costs. Should a catastrophic failure someday occur, it could have a human cost as well. Therefore the risk of incorporating RQL or worse quality welds into an overhead sign support structure should be kept reasonably small.

Not a single weld defect-related structural failure has occurred in New Jersey during the roughly 20 years during which the department has installed aluminum sign support structures. The present statistical acceptance procedure has been in effect for approximately 15 of these years. Therefore, for the purposes of this paper, it is assumed that the tolerable risk at the RQL is the risk historically borne over this period. Operating characteristic curve analyses indicate this risk has ranged from virtually 0.0 to more than 0.25, depending on the lot size, and the approximate median value of 0.05 is taken to be the tolerable risk at the RQL.

The corresponding risk of rejecting acceptable quality level (AQL) lots is not a significant concern in the present application because rejected lots are simply submitted to 100 percent inspection. Thus it is not necessary to define an AQL or to quantify the risk of rejection at the AQL. The cost of unnecessary inspection is a concern, however, and this cost is very much a function of the risk of rejection. The higher the risk of rejection, the greater the overall cost of inspection.

Of the 2,833 welds radiographed in 1984, 7 percent were found to be defective. If it can be assumed that 7 percent defective reasonably represents the construction quality of recent years, in which not a single aluminum weld-related structural failure has occurred, then the optimum sampling strategy can be determined.

The reasonableness of 7 percent defective as a representative value is supported by the average outgoing quality limit (AOQL). As shown in Figure 1, the average outgoing quality (AOQ) is dependent on the incoming quality level. When rejected lots are subjected to 100 percent inspection and all defects are repaired, an AOQL is established. This is the

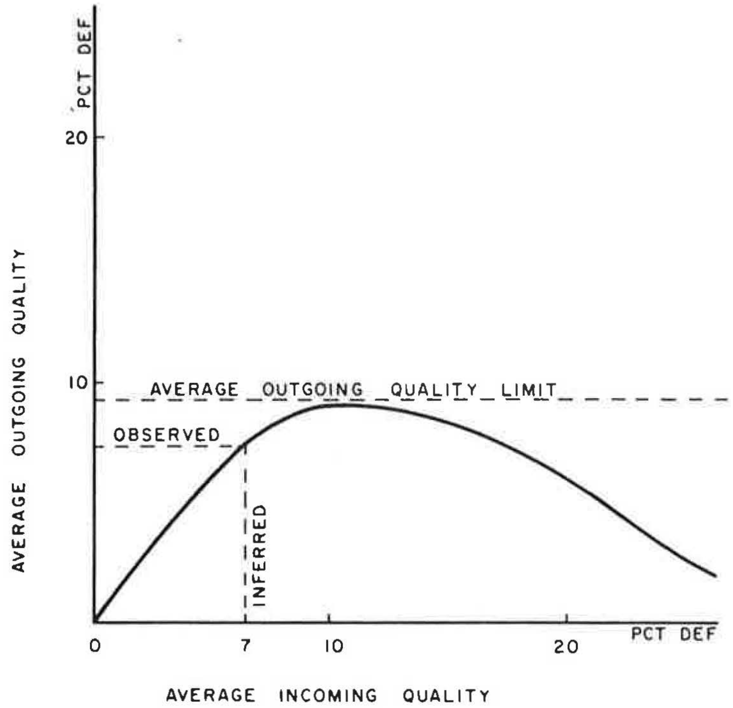


FIGURE 1 Average outgoing quality concepts.

maximum possible value for the AOQ. The AOQL for the present acceptance procedure is approximately 9 percent defective. This means that the worst the average outgoing quality could have been in the past is 9 percent defective, a value, reasonably close to the observed level.

To achieve the average outgoing quality of 7 percent defective observed in 1984, the average incoming quality level could have ranged anywhere from approximately 7 to 20 percent defective. Should the average incoming quality level have been toward the upper part of this range, however, the 100 percent inspection provision would have been triggered more frequently than actually observed. Thus it is reasonable to infer that the average incoming quality level of historical projects was truly in the vicinity of 7 percent defective, that this quality level adequately represents the quality of construction of existing structures in the field, and, based on empirical observation, that the existing quality levels in the field have been entirely satisfactory.

OPTIMUM SAMPLING STRATEGY

The optimum sampling strategy in the present application is determined by two criteria. First, for any lot size the probability of acceptance at the RQL should not be greater than 0.05. Second, the acceptance procedure should have the minimum average total inspection (ATI) at the 7 percent defective level. (The ATI is computed as the sum of two products: the probability of acceptance times the initial sample size plus the probability of rejection times the lot size. Identification of the optimum plan using these criteria is most conveniently accomplished through an iterative procedure with computer assistance.) If two plans have similar ATI values, then that plan with the smaller initial sample size is generally preferable because it must also have the lesser ATI value for smaller percent defective. Plans that meet these criteria will effectively provide protection comparable to what has historically been achieved at the minimum cost.

Two examples will illustrate the difference between the optimum sampling strategy and the existing acceptance procedure. Table 1 shows that, for relatively large lots, both the existing and the optimum sampling plans incur suitably small risks of accepting RQL lots. Further, both plans virtually never miss lots that are 40 percent defective or worse. For smaller percent defective values, however, inspection of the ATI columns reveals that the optimum plan requires fewer welds to be radiographed. Thus, although both plans afford comparable protection, the optimum plan is less expensive to operate.

TABLE 1 Comparison of Selected Characteristics of Two Acceptance Procedures for a Large Lot Size

	Plan 1, Existing Lot Size, N = 100 Sample Size, n = 25 Acceptance No., c = 3		Plan 2, Proposed Lot Size, N = 100 Sample Size, n = 17 Acceptance No., c = 2	
Percent Defective	P(accept)	Avg Total Inspection	P(accept)	Avg Total Inspection
0	1.0	25.0	1.0	17.0
2	1.0	25.0	1.0	17.0
7	0.94	29.8	0.91	24.7
33 (RQL)	0.01	100.0	0.03	97.2
40	0.00	100.0	0.00	100.0

Table 2 gives analogous information for a case in which the lot size is relatively small. The existing plan is grossly insensitive to the recognition of RQL lots, but the optimum plan maintains virtually the same risk as before. Of course, to achieve this protection the average total inspection of the optimum plan must be higher, and this is most noticeable when percent defective values are moderately large. Thus, in this case, it is the optimum sampling plan

TABLE 2 Comparison of Selected Characteristics of Two Acceptance Procedures for a Small Lot Size

	Plan 1, Existing Lot Size, N = 20 Sample Size, n = 5 Acceptance No., c = 1		Plan 2, Proposed Lot Size, N = 20 Sample Size, n = 7 Acceptance No., c = 0	
Percent Defective	P(accept)	Avg Total Inspection	P(accept)	Avg Total Inspection
0	1.0	5.0	1.0	7.0
2	1.0	5.0	1.0	7.0
7	1.0	5.0	0.65	11.6
33 (RQL)	0.41	13.9	0.02	19.7
40	0.31	15.4	0.01	19.9
60	0.06	19.1	0.0	20.0

that is more expensive to operate. It is fortunate that the increased inspection is negligible for very small lot sizes and that such small lot sizes are not very common. In any case, the increased ATI is simply the price to be paid if protection at the RQL is to be assured.

A complete set of optimum acceptance procedures for every lot size from N = 6 to N = 150 is presented in another report (2). The lot sizes that were observed in 1984, along with their frequency of occurrence, are given in Table 3. Also given are the acceptance criteria for the optimum and existing procedures as well as selected operating characteristics. Every one of the proposed acceptance procedures allows for that reasonably large acceptance number, c, which still restricts the risk of not detecting an RQL lot at 0.05 or smaller. The risk of not detecting RQL lots with the existing procedure is, of course, variable.

The product of the lot frequency and the ATI for 7 percent defective provides a reasonable estimate of the number of welds radiographed for each lot size, and the sum of these products estimates the number of welds radiographed in 1 year. Comparison of these two bottom line figures in Table 3 reveals that, on the average, the optimum plans require 334 (11 percent) fewer welds to be inspected per year than the existing acceptance procedure.

It is possible that, because of the sampling technique in which clusters of welds are selected, the actual sample size may be greater than the minimum required. Table 4 gives the same information as Table 3, except here every sample size has been increased by two welds. Under these conditions, and when the average percent defective value is 7 percent, the optimum sampling plans require 5 percent fewer welds to be radiographed annually.

As a rule, the optimum sampling plans require more welds to be radiographed than does the existing acceptance procedure when lot sizes are small. Small lot sizes occur less frequently, as inferred from 1984 data, so inspection savings for the larger lot sizes play the dominant role in determining which set of plans is most economical. Note that the net savings is expected to be greater still if percent defective values less than 7 percent are typically submitted for acceptance. Indeed, up to 20 percent savings would be realized if quality levels were to consistently approach 0 percent defective. And, finally, the optimum acceptance plans achieve this economy with a stabilized risk. Thus the optimum sampling plans appear to be clearly preferable to the plans currently in use.

COST CONSIDERATIONS

Reduced radiography rates do not translate directly into proportionately reduced costs. Many elements within the radiographic program represent fixed expenses. Travel, equipment, and film badge costs, for example, would remain virtually constant while labor and film costs might fluctuate.

In 1984 921 radiographs were shot at a total cost of approximately $42,000. Knowledgeable NJDOT personnel have indicated that this was a relatively light year and that up to five times this number of radiographs have been shot annually in the past.

TABLE 3 Summary of Operating Characteristics for Observed Lots, Minimum Sample Size

		Existing Plan					Optimum Plan				
Frequency	Lot Size	Sample Size	c	ATI (7%)	Weighted ATI	β (33%)	Sample Size	c	ATI (7%)	Weighted ATI	β (33%)
1	8	2	1	2.0	2.0	0.89	6	0	7.5	7.5	0.00
4	12	3	1	3.0	12.0	0.76	6	0	9.0	36.0	0.03
3	14	4	1	4.0	12.0	0.55	6	0	9.4	28.2	0.03
2	16	4	1	4.0	8.0	0.63	7	0	10.9	21.8	0.03
6	20	5	1	5.0	30.0	0.41	6	0	10.2	61.2	0.02
4	24	6	1	7.0	28.0	0.32	7	0	15.6	62.4	0.03
1	32	8	1	9.4	9.4	0.14	11	1	13.3	13.3	0.03
1	34	9	1	10.6	10.6	0.12	12	1	14.6	14.6	0.03
1	36	9	1	13.0	13.0	0.11	11	1	16.4	16.4	0.04
1	40	10	1	14.5	14.5	0.08	12	1	17.9	17.9	0.03
3	48	12	2	12.5	37.5	0.14	12	1	17.4	52.2	0.03
2	62	16	2	18.3	36.6	0.04	16	2	18.3	36.6	0.04
3	64	16	2	18.2	54.6	0.04	16	2	18.2	54.6	0.04
1	66	17	2	22.0	22.0	0.03	16	2	20.4	20.4	0.03
11	68	17	2	21.9	240.9	0.03	17	2	21.9	240.9	0.03
2	72	18	2	23.2	46.4	0.02	16	2	19.9	39.8	0.04
10	80	20	2	29.7	297.0	0.01	17	2	23.7	237.0	0.03
9	84	21	3	23.0	207.0	0.03	16	2	21.4	192.6	0.04
7	88	22	3	24.1	168.7	0.02	17	2	22.9	160.3	0.03
14	96	24	3	28.5	399.0	0.01	16	2	23.0	322.0	0.04
11	100	25	3	29.8	327.8	0.01	17	2	24.7	271.7	0.03
12	104	26	3	31.0	372.0	0.01	17	2	24.3	291.6	0.04
9	112	28	3	36.9	332.1	0.0	21	3	24.6	221.4	0.03
1	116	29	3	38.2	38.2	0.0	21	3	24.3	24.3	0.04
4	128	32	4	36.1	144.4	0.0	21	3	25.2	100.8	0.04
1	140	35	4	42.4	42.4	0.0	21	3	26.2	26.2	0.04
Weighted total					2,906.1					2,571.7	
Weighted average						0.10					0.03

TABLE 4 Summary of Operating Characteristics for Observed Lots, Minimum Sample Size Plus Two

		Existing Plan					Optimum Plan				
Frequency	Lot Size	Sample Size	c	ATI (7%)	Weighted ATI	β (33%)	Sample Size	c	ATI (7%)	Weighted ATI	β (33%)
1	8	4	1	4.0	4.0	0.50	8	-	8.0	8.0	0.0
4	12	5	1	5.0	20.0	0.42	8	0	10.7	42.8	0.0
3	14	6	1	6.0	18.0	0.24	8	0	11.4	34.2	0.0
2	16	6	1	6.0	12.0	0.35	9	0	12.9	25.8	0.0
6	20	7	1	7.0	42.0	0.18	8	0	12.8	96.8	0.0
4	24	8	1	9.6	38.4	0.14	9	0	18.3	73.2	0.01
1	32	10	1	12.0	12.0	0.06	13	1	16.0	16.0	0.01
1	34	11	2	11.0	11.0	0.21	14	1	17.2	17.2	0.01
1	36	11	2	11.6	11.6	0.19	13	1	19.7	19.7	0.02
1	40	12	2	12.6	12.6	0.15	14	1	21.2	21.2	0.01
3	48	14	2	14.7	44.1	0.07	14	1	20.8	62.4	0.01
2	62	18	2	21.1	42.2	0.02	18	2	21.1	42.2	0.02
3	64	18	2	20.9	62.7	0.02	18	2	20.9	62.7	0.02
1	66	19	2	25.5	25.5	0.01	18	2	23.8	23.8	0.02
11	68	19	2	25.3	278.3	0.01	19	2	25.3	278.3	0.01
2	72	20	2	26.6	53.2	0.01	18	2	23.2	46.4	0.02
10	80	22	3	24.6	246.0	0.02	19	2	27.7	277.0	0.02
9	84	23	3	25.8	232.2	0.01	18	2	25.2	226.8	0.02
7	88	24	3	26.9	188.3	0.01	19	2	26.7	186.9	0.01
14	96	26	3	31.8	445.2	0.0	18	2	27.3	382.2	0.02
11	100	27	3	33.1	364.1	0.0	19	2	29.0	319.0	0.02
12	104	28	3	34.3	411.6	0.0	19	2	28.6	343.2	0.02
9	112	30	3	40.8	367.2	0.0	23	3	27.8	250.2	0.02
1	116	31	4	33.6	33.6	0.0	23	3	27.5	27.5	0.02
4	128	34	4	39.2	156.8	0.0	23	3	28.7	114.8	0.02
1	140	37	4	46.1	46.1	0.01	23	3	30.0	30.0	0.02
Weighted total					3,178.7					3,008.3	
Weighted average						0.05					0.02

Thus the total cost of the aluminum weld inspection program could very well exceed $200,000 per year. Excluding the share paid by fabricators for defective welds found, the flexible cost associated with the 1984 construction season was approximately $32,000. This cost, which could reach the $150,000 mark in a busier year, is most conveniently evaluated as the cost rate per 1,000 radiographs shot.

Table 5 gives the annual flexible cost as a function of the radiographs shot and the anticipated savings resulting from a decrease in the sampling rate. A reasonable number of annual radiographs to consider may be the median value in Table 5, approximately 3,000 per year. For this value, an annual savings of from $5,000 to $20,000 could be realized with the implementation of the alternative sampling plan previously identified. The lower limit of this range would result if it were commonly necessary to inspect more welds than the minimum required, and the upper limit would result if, as a result of the alternative plan's implementation, fabricator quality were to be spurred to improvement. Perhaps the most reasonable value to expect is an annual savings of approximately $9,000 to $10,000. It is thought that most of this savings would result simply from the reduced sample sizes, but a small contribution from increased quality of production is also intuitively expected.

TABLE 5 NJDOT Savings per 1,000 Radiographs

No. of Radiographs Shot per Year	Annual Flexible Cost ($)	Savings ($) Resulting from % Reduction in Sampling Rate		
		5	10	20
1,000	31,870	1,594	3,187	6,374
2,000	63,740	3,187	6,374	12,748
3,000	95,610	4,781	9,561	19,122
4,000	127,480	6,374	12,748	25,496
5,000	159,350	7,968	15,935	31,870

CLUSTER SAMPLING

A discrepancy between the statistical theory assumed appropriate and practical application of weld radiography introduces a flaw into the preceding analysis. Fortunately this discrepancy was found to have a small impact in the present application, but its effects and implications represent a potential concern that could not go unaddressed.

The discrepancy arises from the known violation of a fundamental, underlying assumption. Contrary to theory, the welds inspected are not selected in accordance with standard procedures for obtaining independent, random samples. They are selected in fixed clusters as they naturally occur. Thus, after the first weld is randomly selected from all possible welds, adjacent welds are automatically inspected and nonadjacent welds may escape inspection altogether. If the weld fabrication environment is such that the defects produced tend to be correlated with one another, then the specter of clusters that are entirely defective and that may fail to be detected is raised. Conventional risk analyses are insensitive to this and, fooled by the large number of welds inspected, may substantially understate the incurred risk.

A computer simulation model was developed to investigate the nature and degree of bias introduced when the fundamental assumption of independent, random sampling is violated. Lots of varying size were generated in which the total number of defective welds was a controlled variable and in which the degree of association between two consecutively generated welds could be specified. (Serial correlation was specified within a continuous variable and converted to attribute-type data in the simulated structure. This is believed to realistically represent the manner in which defective welds would tend to be correlated.)

Each of the modeled structures was then sampled in two ways that simulate alternative acceptance procedures: cluster sampling (the current NJDOT practice) and true random sampling. It was possible to tabulate whether the acceptance procedure disposed of each structure properly because the simulated quality levels were known. The long-run average frequency with which each procedure correctly rejected defective lots and accepted nondefective lots could then be compared.

The impacts of the sampling technique and the degree of serial correlation (r_S) on the acceptance procedure are given in Table 6. It can be shown that when r_S = 0.0, application of random or cluster sampling procedures results in equivalent operating characteristics. When the degree of correlation is large, both the producer's risk and the buyer's risk are increased. When the correlation is large and cluster sampling procedures are used, these risks are increased to a still greater extent.

TABLE 6 Impact of Cluster Sampling and Serial Correlation

Sampling Procedure	r_s = 0, Independent Observations	r_s = Large, Associated Observations
Random	Reference datum	Seller's risk (α) and buyer's risk (β) slightly increased
Cluster	Same as reference datum	Seller's risk (α) and buyer's risk (β) increased to a greater extent

Serial correlation and cluster sampling have a disproportionate and increasingly larger effect on the acceptance procedure as the absolute value of r_S approaches 1.0. This effect is negligible for small percent defective values and increases as the percent defective value grows. This phenomenon is shown in Figure 2. Horizontal lines would have been produced if the probabilities of acceptance had been independent of the serial correlation. It may be observed that serial correlation introduces greater bias (a steeper slope in Figure 2) when the percent defective values are moderately large. Fortunately, the probability of acceptance (without triggering the 100 percent inspection provision) is relatively small in this region. Extremely large values of serial correlation may also affect the probabilities of acceptance even at small percent defective levels, although such high correlation values are quite improbable.

Simulation analyses indicate that the impact of cluster sampling is practically negligible in this application for low levels of serial correlation among weld defects and relatively low levels of percent defective. The degree of serial correlation would have to be rather large (e.g., r_S = 0.5) for its effect to be pronounced. At the r_S = 0.2 level of serial correlation, a value higher than actually observed in the few lots checked, probabilities of acceptance were increased by approximately 0.03 (or less) in the vicinity of the RQL. Near the 5 percent defective level, the opposite effect was observed with cluster sampling reducing the probability of accepting satisfactory lots by an even smaller amount. AOQL and ATI values were not greatly affected.

Serial correlation itself cannot be controlled, of course, so it is the manner in which it is treated by the acceptance procedure that must be considered. The computer simulation tests strongly suggest that cluster sampling is not a serious problem in the present application.

CONCLUSIONS

The influence of cluster sampling in a procedure in which random sampling is assumed has been determined.

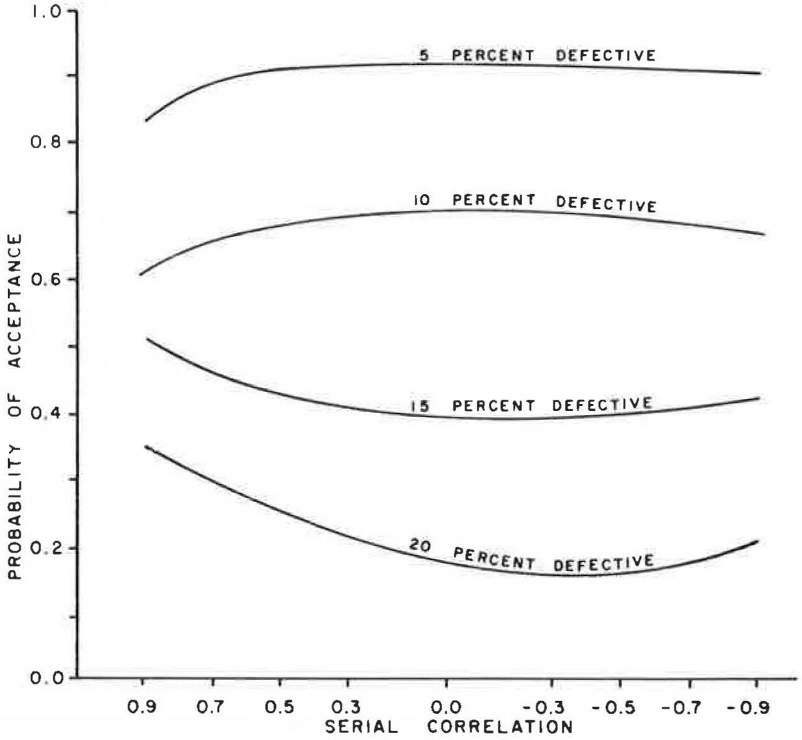


FIGURE 2 Effect of serial correlation on the probability of acceptance in clustered samples.

It is fortuitous that, in the current application, this influence was found to be negligible.

The existing aluminum weld radiographic acceptance procedure appears to provide adequate protection against the acceptance of defective welds, even if this degree of protection is not consistent. Should quality levels worse than 33 percent defective be submitted, these defects will usually be detected provided the lot size is reasonably large. The acceptance procedure becomes increasingly more lenient as the lot sizes are reduced, however, although the increased risks are somewhat offset by the relative scarcity of very small lots. The cost of administering this acceptance procedure is dependent on the level of construction activity in any given year. In general, this cost is expected to run between $40,000 and $200,000 annually.

An alternative acceptance strategy, which stabilizes the risk of failing to detect defective welds, has been identified. This risk is kept small regardless of the size of the lot. In comparison with the existing sampling strategy, small lots are inspected more thoroughly and large lots are inspected more efficiently. The net result is a reduction in the number of radiographs required to be shot. This reduction may range from 5 to 20 percent of the number presently required. Translated to dollars, one estimate of the associated savings is $10,000 per year. Reasonable lower and upper bounds on this savings might be $1,000 and $32,000, respectively, depending on the quality levels actually submitted, the level of construction activity, and the efficiency with which welds may be included on a radiograph.

Regardless of the acceptance strategy used, a risk always exists that defective welds may pass undetected. The proposed acceptance plans stabilize this risk near the existing minimum level, rendering these plans both more effective and more economical.

REFERENCES

1. E.L. Grant and R.S. Leavenworth. Statistical Quality Control. 5th ed. McGraw-Hill Book Company, New York, 1980, pp. 359-386.
2. R. Barros. Analysis of Two Aluminum Weld Acceptance Procedures. New Jersey Department of Transportation, Trenton, 1986.

Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.

Long-Term Pavement Monitoring Program: Summary of Alternative Development Workshop

J. BRENT RAUHUT, ROGER PETZOLD, MICHAEL I. DARTER, and ROBERT L. LYTTON

ABSTRACT

The purpose of the Long-Term Pavement Monitoring (LTM) Program Alternative Development Workshop, held October 15-19, 1984, and sponsored by the FHWA, was to discuss basic issues related to implementing a national LTM program for pavements. The results of this workshop are summarized. It was the consensus of the workshop participants that there were many questions of critical importance to financing and managing the nation's highways that could only be answered by a continuing monitoring effort. This appears to be the only way to successfully study the primary effects of mixed traffic and environment on the performance of pavements. The need for flexibility in experimental design offered by a mix of in-service highways, special design sections, and accelerated mechanical testing was recognized. There was strong opinion that active management from a central organization, independent of government agencies subject to political change, would be required for the success of a long-term pavement monitoring program. It was also expected that regional centers would be required to participate with the state highway agencies in the collection of the data, to train personnel, and to conduct much of the specialized field and laboratory testing to ensure data uniformity. It was concluded that the major results from this effort would be improved prediction and design models to more effectively manage the nation's highway system.

The LTM workshop was held in Alexandria, Virginia, October 15-19, 1984, and the results are summarized in this paper.

The purpose of this workshop, sponsored by FHWA, was to discuss basic issues related to implementing a national LTM program. These basic issues included

1. What questions related to the financing and management of the nation's highways need to be answered and can only be answered with a continuing data monitoring effort?
2. What data need to be collected and evaluated in order to answer these questions?
3. What is the best way to collect and evaluate these data in order to answer a number of these basic and important questions?

The question of the need for a long-term pavement monitoring program had been previously answered in the affirmative by strong consensus of the participants in the Pavement Testing Conference held in May 1984. It was the consensus opinion from that conference that long-term monitoring of in-service highways and special design sections was a critical requirement and that accelerated testing with large mechanical testers was also necessary for special studies.

The LTM workshop, held at the Old Colony Inn in Alexandria, Virginia, brought together members of the AASHTO Joint Task Force on Pavement, Pavement Management Task Group, and representatives of FHWA, state highway agencies (SHAs) participating in the LTM pilot case studies, industry, AASHTO, NCHRP, the World Bank, universities, and the private sector. To fulfill its purpose, the workshop was divided into four workshop groups, each representing a specific need for long-term pavement monitoring. These workshop groups were

1. Group 1--national level,
2. Group 2--state level,
3. Group 3--new design methods, and
4. Group 4--rehabilitation design methods.

The workshop was divided into eight sessions. Session 1 was the opening session, which included presentations that provided background information for the workshop and established workshop objectives. Session 2 included presentations by representatives of the eight state highway agencies participating in the LTM pilot case studies and by the technical support contractor evaluating the data and developing the LTM data bank for these pilot studies. This session provided the experience and insight gained from the pilot case studies. Sessions 3-7 were generally conducted separately by workshop group, with each group considering the specific issues from the viewpoint of the specific interests assigned to it. These sessions addressed the following issues:

- Session 3--information needs,
- Session 4--data analysis and outputs,
- Session 5--data needs,
- Session 6--implementation issues, and
- Session 7--synthesis of findings.

Session 8 was the "close-out" session that included

J.B. Rauhut, Brent Rauhut Engineering, Inc., 10214 I-35 North, Austin, Tex. 78753. R. Petzold, Office of Highway Planning, FHWA, U.S. Department of Transportation, 400 7th Street, S.W., Washington, D.C. 20590. M.I. Darter, ERES Consultants, Inc., P.O. Box 1003, Champaign, Ill. 61820. R.L. Lytton, Texas Transportation Institute, Texas A&M University, College Station, Tex. 77801.

reports of the findings from the four workshop groups presented by the workshop chairmen; general comments on future LTM plans by Gary Byrd, Interim Director of the Strategic Highway Research Program (SHRP); and close-out presentations by representatives of FHWA, AASHTO, the AASHTO LTM Advisory Panel, and the consultants providing technical support to FHWA for LTM.

RECOMMENDATIONS AND CONCLUSIONS OF WORKSHOP GROUPS

Although there were some differences among workshop groups in terms of the needs identified and the approaches recommended, which reflected their assigned viewpoints (national, state, design equations) and personal interests, these differences were not usually major. Therefore the primary recommendations and conclusions have been combined for the four workshop groups and reported here in terms of the issues addressed.

INFORMATION NEEDS

The following combined information needs were expressed by the four workshop groups:

1. The highest priority information need is for data to support evaluation of existing and development of new, improved design models. These design models are needed for both new pavements and rehabilitation of existing pavements. The core of a design model is one or more relationships that predict performance in terms of pavement structure (dimensions, materials, construction techniques and features, etc.), traffic, rehabilitation techniques, and environment; these predictive equations should also offer opportunity for better understanding of pavement performance and deterioration rates.
2. Because rehabilitation is probably the most important pavement issue facing the United States, it merits special emphasis in experiment design. In addition to the development of design models, better understanding is needed of (a) performance of various rehabilitation techniques, (b) effects of timing of rehabilitation on performance, and (c) effects of maintenance on performance of rehabilitation efforts.
3. Other important information needs include

   - Benefits, consequences, and results of various levels of expenditure,
   - Condition of the highway system and subsystem,
   - Effects of increased loadings on pavement performance and deterioration,
   - Effects of construction quality on performance, and
   - Evaluation of new materials and techniques.

It was generally concluded that the LTM program could not practically be structured (and funded) to respond to all information needs, so it must be planned to service priority information needs thoroughly and offer support for others to the extent feasible.

DATA ANALYSIS AND OUTPUTS

Because the priority information needs were identified as design models, the consequent highest priority for data analysis is statistically sufficient multiple-regression analyses to develop predictive equations, which may serve as design equations for models. These equations must be capable of reasonably accurate predictions (established by Group 3 as plus or minus 10 percent) of important dependent variables such as extent and severity of alligator cracking or rutting for flexible pavements, faulting or joint deterioration for rigid pavements, and loss of serviceability for all types of pavements. The measured performance data and the predictive equations may be used both to evaluate existing design models and to "calibrate" existing models to more accurately represent field conditions.

Statistical sufficiency implies that data collection has been both uniform and consistent. This means that uniform data collection procedures and generally the same measurement equipment must be used for all test sections included in the data bank and for the duration of the program. The absolute requirement for such uniformity and consistency was a consensus conclusion of the Pavement Testing Conference in March 1984 and was strongly reaffirmed by all four workshop groups during the LTM workshop. It was generally considered that lack of uniformity would destroy the validity of the data and preclude the reliability required of the output of this major research program.

Although predictive equations developed by regression techniques are expected to be the primary output, sequence graphs or tabulated values may be expected to provide valuable information where statistical techniques are not practical.

DATA NEEDS

This session dealt with what general and specific types and elements of data should be collected to provide an adequate data bank for analysis to satisfy the important information needs. Each workshop group reviewed the data needs in terms of the specific interest (or viewpoint) that it was assigned. Two of the four workshop groups offered specific lists of data items to be collected. The other two made recommendations in broader terms.

It appeared to be the consensus opinion that a number of data items now identified for collection in the current data collection guide could be eliminated without detriment to the data base, but that these would be difficult to identify until the experimental plan was developed. It was also thought that other data items needed to be added, especially those related to evaluating rehabilitation techniques and predicting performance after these techniques have been applied.

Other principal recommendations and conclusions for data needs were as follows:

1. Uniform and standardized data collection is absolutely essential.
2. Inventory data in general are one-time data and not costly, so data items of special rather than general usefulness may be included. However, it is important to limit the monitoring data to those data items of significance to the dependent variables to be studied.
3. For state-level needs, it was concluded that inventory data could best be collected from as-built drawings. However, the members of the workshops for design of new pavements and rehabilitation design thought that it was critically important that layer thicknesses be established by coring and boring and that material properties be based on uniform testing methods applied to cores and samples.
4. Accurate traffic data are extremely important and should be collected at least quarterly for sufficient periods to ensure that representative samples are obtained. Weigh-in-motion equipment should be used for measuring axle load distribution and auto-

matic vehicle classifiers for classification. Traffic should be test-site specific rather than interpolated from other locations.

5. Maintenance data are very important and must be collected in a uniform manner from all states.

6. Measurements of distress, roughness, deflections, skid resistance, and so forth that indicate performance are of primary importance, but measurements could be less frequent than the annual ones now planned. This could allow more test sections for the funds available and result in increased statistical adequacy.

7. Environmental data should be collected on a monthly basis by a central agency such as the National Weather Service instead of by individual SHAs.

IMPLEMENTATION ISSUES

It was the consensus opinion that strong, active management from a central organization, independent of government agencies subject to political change, would be required for the success of a long-term pavement monitoring program. It was also expected that regional centers would be required and that the regional staffs should participate with the SHAs in the collection of the data, to ensure their uniformity, and in training SHA personnel. it was also believed that the central organization would need to conduct much of the specialized field and laboratory testing, probably using regionally deployed equipment, to ensure its uniformity.

The support for the LTM effort was essentially unanimous, with all SHAs participating in the pilot studies wishing to continue and perhaps expand their activities. It was thought that a core group of full-time staff should be established as soon as possible to initiate organizational and experimental planning.

Dedicated, long-term funding will be required for this program, and the level of funding now proposed may need to be supplemented by state HP&R funds. There was general concern that overall state research programs might suffer as a result of LTM funding requirements.

The workshop participants agreed that the data storage facilities should be centrally located on a dedicated computer, but that the data should be accessible by SHAs and all interested parties. Data security would be critically important, with no data changes allowed other than by the central staff.

It was agreed that experiment design to optimize results for the funding available was of paramount importance. In view of the almost limitless possibilities for studies and data collection to accommodate special interests, it will be necessary to carefully select dependent variables for study and to distribute them among in-service highways, special design sections, and mechanical testing to optimize results. SHAs should be encouraged to select design sections for monitoring in newly constructed or rehabilitated pavements because such sections offer better control of the variables than do pavements that have been in service for some time. Appropriate fractional factorials and subexperiments must be considered to provide the output required within practical funding constraints.

The number of the test sections to be implemented was discussed. It was recognized that increasing the number of test sections increases reliability of the results and offers the possibility of more studies, but it was expected that some 1,000 to 2,000 in-service highway sections and 500 design sections would be a reasonable goal.

SUMMARY

It was the consensus of the workshop participants that there were many questions of critical importance to financing and managing the nation's highways that could only be answered by a continuing pavement monitoring effort. This appears to be the only way to successfully study the primary effects of mixed traffic and environment on the performance of pavements. The need for the flexibility in experiment design offered by a mix of in-service highways, special design sections, and accelerated mechanical testing was recognized.

There was general concern expressed that the momentum of FHWA LTM initiatives might be lost during the transitional period for establishing dedicated funding and an organization to manage the program. Appropriate measures to expedite the formation of a core organization and maintain momentum were urged.

Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.

Model for Forecasting Highway Construction Cost

ZOHAR HERBSMAN

ABSTRACT

In recent years there has been a substantial increase in the number and complexity of projects in the highway construction industry. The complexity of these projects is one of the main reasons it takes so much time from inception to completion of a project. Those involved in decision making and budgeting need "tools" to help evaluate future costs. The literature survey conducted during this study has shown that the use of existing economic models is inadequate because of the unique factors that influence the highway industry. The development of a model for long-range forecasting of highway construction cost is described. This model is based on a statistical analysis of data gathered from Florida Department of Transportation projects around the state of Florida from 1968 to 1984. The research revealed that, in addition to the inflationary changes in the cost of basic elements (labor, materials, equipment), there are other factors that affect total cost. One of those factors, the bidding volume, was analyzed and incorporated into the model. Although this model was developed for a specific sponsor, it is based on general principles that can be adapted to other users.

Forecasting cost is one of the main elements of planning, budgeting, and decision making in the highway construction industry. Early knowledge of future costs is essential. In most cases 1 or 2 years will pass between the preliminary decision to start a new project and project completion.

Estimators and those responsible for budgeting need techniques to assist them in forecasting costs. The Florida Department of Transportation (FDOT), as well as other state and federal agencies, is required to prepare a multiyear budget in order to plan future requirements and expenditures. Recognizing the need for such a tool, which would assist the FDOT in their long-range estimating, the FDOT requested that the University of Florida develop a model to simulate the process of budget preparation. The development of such a model and the results obtained by the application of the model by the FDOT are described.

SURVEY OF EXISTING METHODS

A survey was performed to evaluate the existing methods of forecasting construction cost. The survey was based on three sources:

1. A general literature survey,
2. Review of methods used by other state DOTs, and
3. Review of contractors' and suppliers' forecasting techniques.

Literature Survey

The results obtained showed a variety of forecasting models in use. However, only a few were related to the specific conditions of the highway construction industry. Among these was the work of Erickson and Boyer (1) who examined the estimators' dilemma of how to forecast escalation in prices from the bidding time until construction. Other sources that dealt with cost forecasting (cost elements only) were Jones (2) who discussed change trends in oil products, Schexnayder and Hancher (3) who investigated the changes in the cost of replacing equipment, and Warszawski and Rosenfeld (4) who pointed out the problem of cost control in times of escalating prices. Lazar and Getson (5) suggested that commodity futures should be used in estimating. All of these sources recognized the problem of forecasting but did not find any comprehensive solution.

Other authors deal with statistical methods and their application to forecasting procedures. Koppula (6) suggests analyzing historical cost records with two methods:

- The Box Jenkins stochastic method and
- The Hout-Winters smoothing technique.

The author's computations were based on the Engineering News Record's (ENR's) cost indices. Using these indices from 1962 to 1978, Koppula found that if the Hout-Winters technique was used, the forecasting results were quite close to the actual data.

In a review of common statistical techniques used for forecasting, Globerman and Baesel (7) compared three methods:

- Weighted autoregression of past inflation rates,
- Forecasting based on expectation data from surveys, and
- Forecasting based on changes in interest rates.

The authors did not find any significant differences in the forecasting results using these methods. This conclusion is important because it shows that the highly complex statistical methods do not necessarily yield better results.

Results of Department of Transportation Survey

The task of preparing a multiyear budget is not unique to the FDOT. Many state and federal agencies

---

Department of Civil Engineering, College of Engineering, University of Florida, Gainesville, Fla. 32611.

are required by law to prepare such budgets. To determine how other states are dealing with this subject, a questionnaire was sent to various DOTs inquiring about their methods of preparing long-range forecasts.

Analysis of the information in 45 survey replies showed that only 22 percent of the states participating in the survey have any type of systematic method. Most of the states use national cost indices prepared by FHWA, the ENR cost index, simple mathematical methods (regression), or in some cases even pure guesswork to try to forecast the budget. Only a few states like California and Minnesota have developed local models based on a limited number of cost elements.

Survey of Contractors and Suppliers

The third source consisted of contractors and suppliers from all over Florida who were facing similar problems in producing construction estimates. Estimators have to evaluate the escalation rate from the bidding time to the actual construction time, which in transportation projects can be relatively long (1 to 3 years). This escalation rate has to be figured and incorporated into the estimates.

The results of the survey indicate that contractors' and suppliers' forecasting methods were mainly based on the intuition of professionals who had extensive experience with and knowledge of local conditions. The material supplier evaluates price escalations (concrete, steel, pipes, etc.) and the general contractor adds his forecast of labor and equipment cost changes to the supplier's quotations. Only a few contractors or suppliers had any systematic forecasting techniques.

METHODOLOGY IN MODEL DEVELOPMENT

General Principles

Following the literature survey, the decision was made to develop a forecasting model based on general principles that can be used universally even though the model was tailored to the specific conditions and needs of the highway construction industry in Florida. The design of the model is flexible enough so that every user can modify it to his specific needs, and future technological changes can be easily incorporated into the model.

Six submodels have been developed to forecast specific types of works. These submodels are

- Submodel 01--earthwork,
- Submodel 02--asphalt pavement,
- Submodel 03--concrete pavement,
- Submodel 04--structural concrete,
- Submodel 05--reinforcing steel, and
- Submodel 06--structural steel.

The combination of these submodels will create a composite model that will be used to forecast the

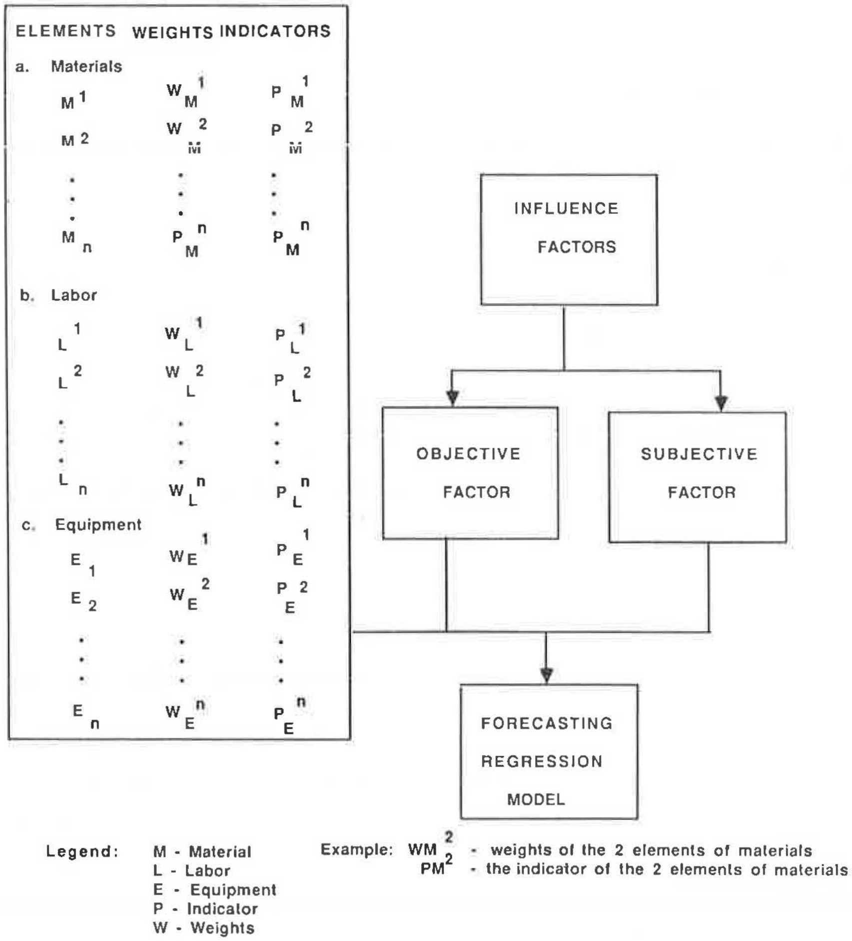


FIGURE 1 Schematic description of the model.

total cost (or budget) for the entire state of Florida. The submodel form and the composite model will give the user the flexibility to deal with only a certain type of job or with the total volume, depending on his need.

The data for the statistical analysis for the development of the model came from two large data bases that contained the records of most FDOT projects executed in Florida since 1968.

The first data base, Contract Administration System (CAS) (8), contains the results of the winning bids for projects executed throughout Florida since 1968. The data base includes the following records for each project: list of standard pay items, quantity of each item, and unit price and total price of each item. It also contains information about the total cost of every project, the total cost of a series of projects, and the total bidding volume per quarter and per year for the entire state.

The second data base is the Contract Estimating System (CES) (9), which contains a computerized library of about 3,000 standard pay items used in FDOT bids. Each item is analyzed for the different cost elements: labor, material, equipment, and overhead. This data base depends on price escalation and is updated on a quarterly basis.

Model Description

The model is based on the following four components:

- The weight component,
- The indicator,
- The influence factor component, and
- The forecasting process component.

Figure 1 is a schematic flow chart of the model.

Weight Component

The first step in the development of the model was to determine a series of elements for each of the submodels and for the composite model. These elements were defined as direct cost elements (labor, material, equipment) and indirect cost elements (overhead and profit). Using historical records (CAS), a list of common pay items was developed for each submodel. The combination of those pay items will generate the list for the composite model. Using the CES analysis of each item the weight of each element in every pay item was calculated to obtain the weight of each element for every submodel. Finally, the weight of each submodel and the element weights for the composite model were calculated. All calculations were performed using a 3-year moving average technique (10) with the earliest record being dropped from the system each time the most recent quarter was added.

An example of the computation for one submodel, 01--earthwork, will be shown later. (All the other computations were done in a similar way.) From the CES a list of common pay items was determined. Table 1 gives the list of pay items for submodel 01.

TABLE 1 List of Pay Items for Submodel 01–Earthwork

Pay Item No.	Pay Item Description
120-1	Regular excavation
120-2	Borrow excavation
120-3	Lateral ditch excavation
120-4	Subsoil excavation
120-5	Channel excavation
120-6	Embankment

For each pay item the breakdown of the cost elements was calculated. The following calculations were performed for Item 120-2, borrow excavation.

Labor costs	
One foreman working 8 hr/day	\$ 67.68
Two laborers working 8 hr/day	\$ 64.64
Two dozer operators working 8 hr/day	\$ 84.32
Two grader operators working 8 hr/day	\$ 93.28
Two scraper operators working 8 hr/day	\$ 79.36
One equipment mechanic working 8 hr/day	\$ 46.40
Total labor cost	\$ 435.68
Total material cost	\$2,670.50
Equipment (based on a standard crew from CES 8 hr/day)	
Two motor graders (150 hp plus)	\$ 665.44
Two motor diesel power scrapers	\$1,800.00
Two dozers (straight heavy)	\$ 909.60
One half-ton pickup truck	\$ 73.44
One 1 1/2-ton flatbed truck	\$ 73.16
Total equipment cost	\$3,522.64

Cost for 1 yd^3 of borrow exclusively (productivity rate = 2,820 yd^3/8 hr)	
Labor costs = \$435.68/2,820 yd^3	\$0.151/yd^3
Material costs = \$2,670.50/2,820 yd^3	\$0.951/yd^3
Equipment cost = \$3,522.64/ 2,820 yd^3	\$1.251/yd^3
Total unit cost	\$2.351/yd^3

Therefore the percentage breakdown for Item 120-2 is as follows:

Labor = (0.155/2.352) x 100 = 6.66%
Material = (0.947/2.352) x 100 = 40.20%
Equipment = (1.250/2.352) x 100 = 53.14%
Total 100.00%

Table 2 gives a summary of the results for all the pay items of submodel 01 (this was calculated in the same way as Item 120-2). Table 3 gives the aver-

TABLE 2 Element Cost Breakdown per Pay Item in Submodel 01

Pay Item No.	Material (%)	Labor (%)	Equipment (%)	Total (%)
120-1	0.00	11.14	88.86	100.00
120-2	40.20	6.66	53.14	100.00
120-3	0.00	13.33	86.67	100.00
120-4	0.00	9.36	90.64	100.00
120-5	0.00	4.69	95.31	100.00
120-6	43.65	8.67	47.68	100.00

TABLE 3 Work Volumes per Item in Submodel 01

Pay Item No.	Annual Work Volume (\$)	Percentage of Total
120-1	810,820.00	3.64
120-2	2,113,410.00	9.50
120-3	94,653.00	0.43
120-4	1,887,150.00	8.48
120-5	63,888.00	0.29
120-6	17,287,000.00	77.67
Total	22,255,921.00	100.00

age yearly bid volume for 1979-1981 for each pay item in submodel 01 using the information from the CAS file.

Table 4 gives the relative weight of the main elements in each pay item based on the results of Tables 2 and 3. For example, for Item 120-2 the labor weight in the item is 6.66 percent (from Table 2) and the pay item weight is 9.50 percent of the submodel total (Table 3). Therefore the relative weight for labor in Item 120-4 is 6.66 percent x 0.095 = 0.63.

TABLE 4 Breakdown of Weights for Each Item in Submodel 01

Pay Item No.	Submodel (%)	Material (%)	Labor (%)	Equipment (%)
120-1	3.64	0.00	0.41	3.23
120-2	9.50	3.82	0.63	5.05
120-3	0.43	0.00	0.06	0.37
120-4	8.48	0.00	0.79	7.69
120-5	0.29	0.00	0.01	0.28
120-6	77.67	33.90	6.73	37.03
Total	100.00	37.72	8.63	53.65

Table 5 gives a summary of the results of the element weights for all six submodels.

TABLE 5 Element Cost Breakdown by Submodels

Model No.	Model Description	Material (%)	Equipment (%)	Labor (%)	Total (%)
01	Earthwork	37.72	53.65	8.63	100.00
02	Asphalt pavement	82.04	14.16	3.69	100.00
03	Concrete pavement	64.57	27.17	8.26	100.00
04	Structural concrete	28.45	35.53	36.02	100.00
05	Reinforcing steel	74.39	7.40	18.20	100.00
06	Structural steel	97.21	1.72	1.07	100.00

Indicator Component

To calculate future changes in the cost elements a series of indices had to be defined as indicators. For example, to forecast changes in equipment cost, a suitable indicator must be determined to represent this element. The selection of suitable indicators was one of the main considerations in developing the model. The guideline for selection was the availability of historical data for a substantial period of time. This information was necessary so that a detailed statistical analysis of each indicator could be calculated in order to check its performance against actual costs. It is also essential that data for indicators be available on a regular basis in the future. Because of user needs, it was decided to concentrate only on the main elements that constitute more than 3 percent of the total cost of the composite model. After historical records were analyzed, eight direct cost elements were defined. There are a few ways to calculate indirect cost, which consists of job overhead material, overhead, and profit. However, most of the participants in the highway construction process prefer to use one factor defined as markup. Therefore the indirect cost elements were calculated as a percentage of the total direct cost. For each element, several indicators were checked, and the one with the highest correlation with previous records was chosen. Table 6 gives the list of elements, their percentage of the total direct cost of the composite model, and related indicators.

Most of the indicators are based on information from the U.S. Bureau of Labor Statistics (BLS). BLS provided accurate data in the past for Producer Price Indices (PPI), which are related to the model elements. The BLS values for the indicators are given in Table 7.

Because the BLS does not forecast its indices, another source of future values was required. The source chosen for this research was Data Resources Inc. (DRI) (11), which is one of the most important research institutes dealing with forecasts. However, because the DRI does not project values for all the indicators of the model, some form of correlation between the DRI variables and the indicators had to be developed. Regression models were constructed that related to the historical data from the BLS and to the historical value of indices for which the DRI provided forecasts. For this purpose, three indices forecast by DRI were chosen to represent the model indicators. These indices were (a) fuels and related products, (b) metals and metal products, and (c) machinery and equipment.

By using the three DRI indices, autoregressive and ordinary least squares regression models were constructed for each indicator. An equation correlating the DRI value with historical data from the BLS was found and the equation with the best statistical properties (high correlation, significant coefficients, and low autocorrelation) was chosen to forecast future values of the indicator. From these regressions, an equation was developed that relates to past BLS values and to the future projection given by the DRI. The procedure is demonstrated using structural steel indicators as an example. The autocorrelation coefficient was sufficiently small for the straight regression method (0.060); therefore, this regression was chosen to represent the index. When the regression with the best statistical properties had been chosen, an equation was constructed

TABLE 6 Elements and Indicators in the Composite Model

No.	Element	Percentage of Direct Cost[a]	Indicators
1	Aggregate fill	22.10	Construction sand and gravel
2	Liquid asphalt	11.40	Refined petroleum and products
3	Concrete and others	6.10	Concrete ingredients
4	Structural steel	3.40	Structural steel
5	Reinforcing steel	3.40	Rebars
6	Embankment	14.40	Construction sand and gravel
7	Labor	10.60	Highway and street workers
8	Equipment	28.60	Construction machinery
Total		100.00	

[a] Overhead and profit were calculated as a percentage of direct cost.

TABLE 7 Data Base Indicators on BLS Producer Price Index

Year	Fabricated Structural Steel	Reinforcement Bars	Construction Machinery and Equipment	Paving Mixtures	Construction Sand and Gravel	Concrete Ingredients	Refined Petroleum Products	Average Hourly Earnings
1968		99.3	105.7	101.7	104.6	103.2	98.1	109.2
1969		100.3	110.4	102.7	108.8	106.7	99.6	117.4
1970		110.3	115.9	105.8	115.3	112.6	101.0	126.3
1971		117.0	121.8	121.8	120.8	121.9	107.2	137.5
1972	126.1	114.7	125.7	123.9	123.3	126.9	108.9	143.4
1973	130.6	124.1	130.7	125.2	127.6	131.2	128.7	151.5
1974	159.1	201.5	152.3	222.9	139.1	148.7	223.4	163.6
1975	195.9	199.2	185.2	256.9	157.0	172.3	257.5	176.8

Note: Base year 1967 = 100.

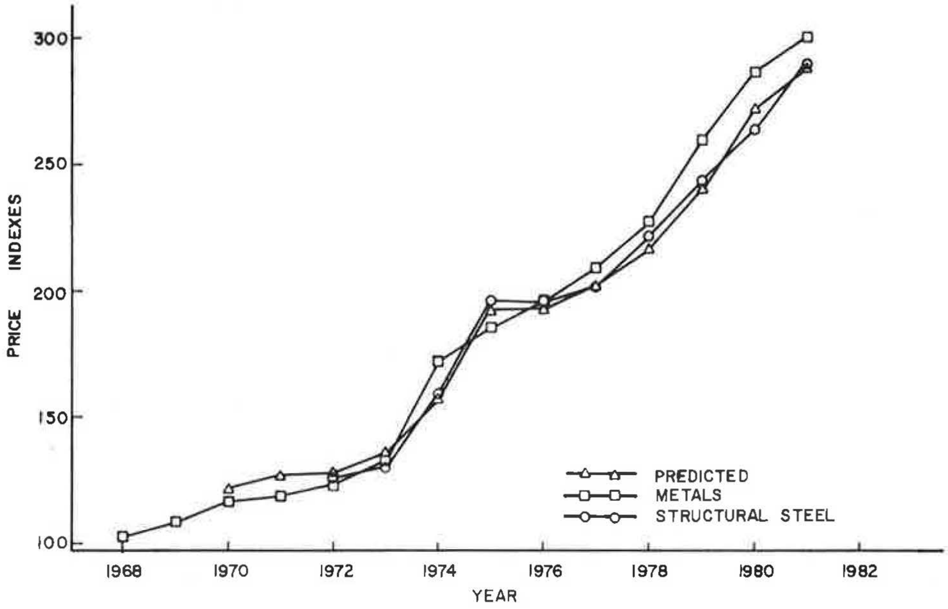


FIGURE 2 Comparison of structural steel indicators.

to calculate future values for each indicator. This equation is

$$(PF) = 21.22971 + 0.44817 (M) + 081601 (M1) - 0.39167 (M2)$$

where

PF = desired indicator value in year Y,
M = value of the DRI metals index in year Y,
M1 = DRI metals index in year Y - 1, and
M2 = DRI metals index in year Y - 2.

The equation is used to calculate the future values of the structural steel indicator at intervals of 1 year. An example of the results for this element is shown in Figure 2. The same procedure was followed for each element. At the end of this procedure an equation was established for forecasting the cost of each element.

Adjusting Process

If the inflationary fluctuation in prices were the only factor influencing the changes in the cost of transportation projects, the model could be based on the element weights and their indicators. However, because there are more factors involved, those factors must be identified and incorporated in the model. To verify the existence of additional factors a statistical analysis was performed on the historical cost of projects during the years 1968-1981. The actual cost represented by the FDOT composite cost index was compared with the composite model cost based on inflated element prices and using suitable indicators. If there were not any other factors, a high correlation between those figures had to be found. Table 8 gives the results of those calculations.

TABLE 8 Composite Model Cost Compared with Actual Cost

Year	FDOT Composite Cost Index (1)	Composite Model Cost (2)	Differentiated Cost Indices [(1) - (2)]
1978	126.60	108.40	18.20
1979	152.80	124.60	28.20
1980	173.20	147.00	-26.20
1981	150.50	163.10	-12.60
1982	138.40	167.00	-28.60
1983	133.00	167.00	-34.00
1984	155.00	176.00	-21.00

Note: Base year 1977 = 100.

It was obvious that there are factors other than "pure inflation" that have an effect on cost fluctuation. Those factors, such as interest rates (12), unemployment (13), public expectation (14), and others, were defined as influence factors, although they can be found in professional literature under various names (15).

To incorporate these factors into the model a quantitative relationship between the factors and the cost had to be calculated. One factor was found to have a systematically dominant effect. This was the bidding volume factor, which is the total volume of bids in a certain area (county, district, state) during a defined period of time. By using historical records from the CAS the effect of the bidding volume was calculated and incorporated into the model.

Without sacrificing the flexibility of the design of the model, the option of including more factors was added. These factors are called subjective factors and they do not have an accurately quantifiable influence. The user can add these factors according to his knowledge, experience, or intuition. An example of such a factor can be the influence of election years (1988, 1992, etc.). If the user finds that in those years project costs will be 1 percent more than the escalation that is caused by all the other factors, he can add this percentage to his forecast for those years.

Forecasting Computations and Results

The final step was to combine all the components into one system based on a combination of subprograms for each separate step and a central program that produced the final reports. All the data were based on the existing data bases of FDOT that were also incorporated into the system.

The system has been in operation since 1983, on a regular basis, using a 3-year moving average. Figure 3 shows the schematic chart of the forecasting system.

The format for introducing the results was developed to meet the users' needs in the form of cost indices that represent cost changes compared with a base year (1977 = 100). The system can provide six different cost indices for different types of projects and a composite cost index for the general budget of the agency. The results can forecast a 10-year budget based on calendar or fiscal years.

To test the validity of the model a simulation test was performed. This was done by "forecasting" previous FDOT composite cost indices and comparing them with actual data. The results of the simulation, from 1969 to 1981, were found to be quite accurate within a 95 percent confidence interval. The results showed that if an FDOT estimator had used this model in the past, his budget projections would have been quite close to the actual cost. Figure 4 shows the results of this simulation.

The FDOT has been using the model on a regular basis since 1982 and the actual results of the Florida composite cost index (FCCI) compared with the ones predicted by the model are quite accurate and prove the validity of the model. For the regular operation of the model, the user supplied the data for future bid volumes.

Table 9 gives the forecast of the FDOT composite price index for calendar years 1985-1991. An option is also provided to produce the output per fiscal year for the composite cost index as well as for every submodel.

SUMMARY AND CONCLUSIONS

The objective of this research project was to provide those who deal with budgeting and estimating highway construction cost with a mathematical tool to help them forecast costs in a systematic way. The model developed is based on only a few principles that can be adjusted to the specific needs of any user. By using a system of submodels and a composite model, the user can forecast the cost of certain types of work such as asphalt or concrete or deal instead with the total cost of the system (district, state, etc.).

The conclusion drawn from the research is that it

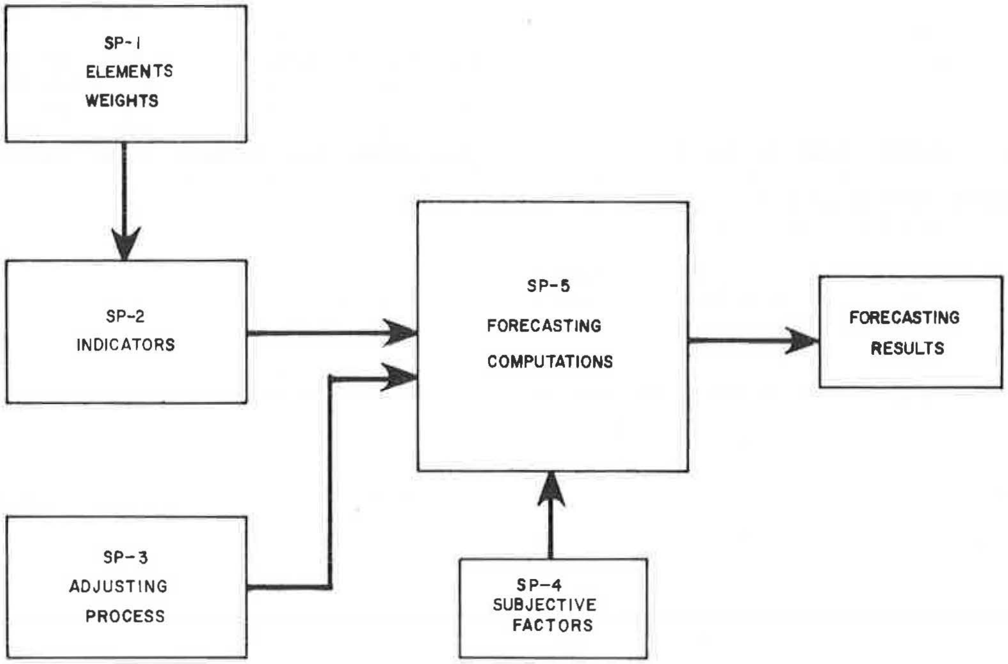


FIGURE 3 Schematic description of the forecasting system.

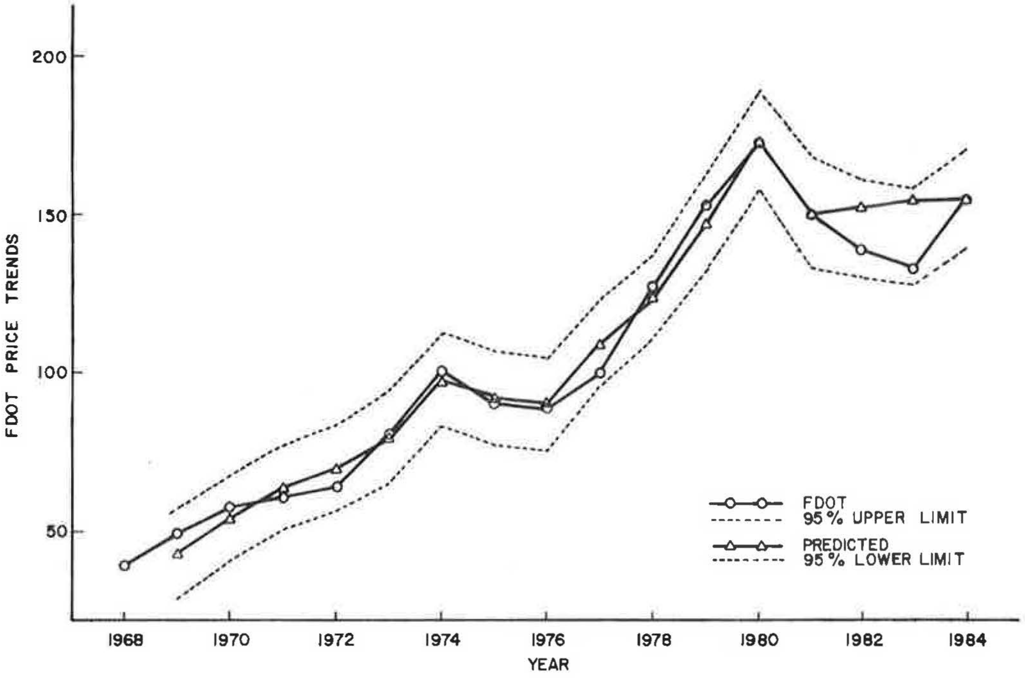


FIGURE 4 FDOT composite cost index versus model-predicted value.

TABLE 9 Forecast of the FDOT Composite Cost Index

No.	Year	Limit	FCCI	Limit	Percentage Change
1	1985	136.6	180.7	224.7	16.6
2	1986	144.7	188.9	233.0	4.5
3	1987	155.5	199.1	242.7	5.4
4	1988	175.8	221.2	266.6	11.1
5	1989	194.0	240.5	287.0	8.7
6	1990	208.9	256.6	304.2	6.7
7	1991	222.6	271.6	304.2	5.9
8	1992	236.8	287.7	338.5	5.9
9	1993	250.9	315.4	359.8	9.6

Note: The forecast results are per calendar year and are based on future bidding volume provided by FDOT.

is not adequate to figure the expected price escalation of different elements; there are more factors that affect the cost of projects and sometimes their influence is much greater than that of direct price escalation. One of these factors, the bidding volume factor, was quantified and incorporated into the model. This conclusion is significant to those involved in budgeting and resource allocation. The sensible spread of bids over a certain period of time can substantially reduce the cost of heavy construction projects.

The second conclusion stresses the importance of managing data bases of cost records for a long period of time. The existence of those records is of utmost importance and without them the development of this model would have been impossible.

ACKNOWLEDGMENTS

The research was conducted under a contract to the FDOT by a team from the University of Florida, led by the author. Special thanks to the other members of the team who helped to conclude this research, T.P. Rothorock and W.W. Coons. The project would not have been possible without the help of the personnel from the Bureau of Estimates of the FDOT, especially the State Estimates Engineer, T. Drawdy, and the Preliminary Estimates Engineer, C.F. Grimsley. Valuable help was also provided by H. Presley, W.L. Chance, F. Maier, and B.T. Dietrich. Special thanks should be given to T.E. Dady who helped with the initial steps of the project and contributed throughout.

REFERENCES

1. C.A. Erickson and L.T. Boyer. Estimating--State-of-the-Art. Journal of the Construction Division, ASCE, Vol. 102, No. C03, Sept. 1976, pp. 455-464.
2. L.R. Jones. Estimating Cost Escalation. Engineering Department Report. Standard Oil of California, undated, pp. 58-63.
3. C.J. Schexnayder and D.E. Hancher. Inflation and Equipment Replacement Economics. Journal of the Construction Division, ASCE, Vol. 108, No. C02, June 1982, pp. 289-298.
4. A. Warszawski and Y. Rosenfeld. Financial Analysis Under Inflation in Construction. Journal of the Construction Division, ASCE, Vol. 108, No. C02, June 1982, pp. 341-354.
5. B.E. Lazar and P. Getson. Forecasting Construction Costs with Commodity Futures. Journal of the Construction Division, ASCE, Vol. 103, No. C03, Sept. 1977, pp. 381-386.
6. S.D. Koppula. Forecasting Construction Cost: Two Case Studies. Journal of the Construction Division, ASCE, Vol. 107, No. C04, Dec. 1981, pp. 733-743.
7. S. Globerman and J. Baesel. Comparison of Alternative Inflation Forecasts. Business Economics, Vol. 11, Sept. 1976, pp. 60-64.
8. Contract Administration System. Florida Department of Transportation, Tallahassee, June 1974.
9. Contract Estimating System. Florida Department of Transportation, Tallahassee, June 1974.
10. D.R. Cox. Prediction by Exponentially Weighted Moving Average and Related Methods. Journal

Royal Statistical Society, London, England, Series B, Vol. 23, 1961, pp. 414-422.
11. U.S. Long Term Review by Data Resource, Inc. McGraw-Hill Book Co., New York, 1981.
12. L.A. McMahon. Analysis of Factors that Cause Inflation. 1978 Transactions of the American Association of Cost Engineers, pp. 36-39.
13. P. Saunders. Inflation Expectation and the National Rate of Unemployment. Applied Economics, Vol. 10, 1978, pp. 187-193.
14. K. Lahiri. Inflation Expectations--Their Formation and Interest Rate Effects. American Economic Review, Vol. 66, No. 1, March 1976.
15. M.D. Levi and J.H. Makin. Anticipated Inflation and Interest Rates: Future Interpretation of Findings on the Fisher Equation. American Economic Review, Vol. 68, Oct. 1978, pp. 810-812.

Publication of this paper sponsored by Committee on Construction Management.

Using Accelerated Contracts with Incentive Provisions for Transitway Construction in Houston

UPTON D. OFFICER

ABSTRACT

The Metropolitan Transit Authority of Harris County and the State Department of Highways and Public Transportation agreed to jointly construct authorized vehicle lanes or transitways in Houston, Texas. Federal assistance was provided by UMTA and FHWA. Some unique agreements were reached for funding and construction. To build a transitway on Interstate 45 North as quickly as possible and terminate an experimental contraflow lane, some innovative contracting techniques were used to shorten the construction period. Contractors were given the opportunity to bid the number of days for project completion with each day representing a specific dollar value. The number of days bid was used along with unit item quantities to determine the low bidder. In addition, an incentive provision allowed the contractor to earn a bonus for each day the project was completed early. It is believed that competitive bidding shortened the contract performance period from 975 to 360 days and that the incentive further reduced the performance period by 90 days, because the contractor developed innovative construction methods that allowed him to go for the full incentive. This paper provides the results of the construction effort and an initial look at the impacts on the Metropolitan Transit Authority, the State Department of Highways and Public Transportation, the contractor, and the motoring public. A contract management and administration system, which could be used as a model for future joint projects, evolved from this project.

The Metropolitan Transit Authority (Metro) of Harris County and District 12 of the State Department of Highways and Public Transportation (SDHPT) in Houston, Texas, agreed to jointly construct an authorized vehicle land (AVL) on the North Freeway at the same time the main lanes were widened and new breakdown shoulders were added. It was decided that Metro would award the first three contracts for construction of the first 9.6 mi of this project and the SDHPT would contract for the next 4.6 mi. To build the AVL as quickly as possible and terminate an existing contraflow operation on Interstate 45 North (North Freeway), Metro proceeded with an accelerated, incentive-type contract to build a temporary or interim AVL. The historical background of this initiative is reviewed and how the incentive contract was administered is described. An analysis of the estimated period for construction using critical path method (CPM) techniques and the results of competitive bidding played a key role in reducing the construction performance period.

During construction a unique project management system evolved that became the standard for contract execution and coordination among Metro's project manager and contract administrator, the SDHPT resident engineer, and the contractor. The most significant lessons learned from the incentive contract were ascertained by looking at its impact on the contractor and the agencies involved. This analysis will provide an insight into the costs, not necessarily in dollars, to participants in an accelerated

---

Metropolitan Transit Authority of Harris County, P.O. Box 61429, Houston, Tex. 77208-1429.

incentive contract. Metro's experience with the first incentive contract was used as a model for development and award of the next contract, which is in progress. Some conclusions and recommendations can be drawn from a review of this unique contracting initiative.

BACKGROUND

As early as August 1981 Metro and the SDHPT were looking for ways to build the North Freeway transitway as soon as possible in order to terminate contraflow operations--an experimental project on the North Freeway that borrowed a main freeway lane from the off-peak side for the exclusive use of buses and vanpools. It was necessary to build an AVL quickly because the increasing volume of traffic in the off-peak direction would soon prohibit borrowing a main freeway lane.

Because time was critical and design had to be completed in order to start construction, it was decided to approach the project in three stages for the initial AVL segment from the Houston central business district to the North Shepherd interchange, a distance of 9.6 mi. The first and easiest part of the project was the relocation of signs and the installation of high-mast lighting systems that would meet the requirements of the future transitway and widened freeway. This segment of construction was quickly designed, bid, awarded, and completed in October 1984.

The second segment consisted of building an interim AVL in the freeway median with a less-than-desired width in order to terminate contraflow. Major objectives were to remove the median guardrail and fence, enclose both sides of the median and the construction zone with a concrete traffic barrier (CTB), and pave the median with a concrete surface that would be used for the interim AVL. Because the objective was to construct an interim facility as quickly as possible, Metro was willing to accept an AVL that was narrower than standard (12 ft wide versus 19.5 ft).

In the third segment, which will take longer to design and construct, the freeway will be widened, new shoulders will be added, and the AVL will be modified to 19.5 ft wide to provide sufficient room to pass. A fourth segment will extend the AVL from North Shepherd to Beltway 8, an additional 4.6 mi.

When the construction sequence had been confirmed, the agencies began to approach project funding. During September 1981 federal funding assistance was discussed by Metro, Texas SDHPT, UMTA, and FHWA. It was agreed that Metro with UMTA support would fund the construction of the AVL and related facilities and that the SDHPT with FHWA assistance would pay for freeway construction, repairs, and related costs.

However, the actual contracting was complicated by differences in the minority business enterprise and women-owned business enterprise (MBE/WBE) requirements of UMTA and FHWA. These differences would not allow mixing of funds and resulted in an agreement that Metro would let the contracts that received UMTA support. To formalize this understanding Metro and the SDHPT executed an agreement in which Metro (with UMTA funding assistance) would let three contracts for the construction of the AVL segment from the Houston central business district to North Shepherd, a distance of 9.6 mi. The remaining contracts would be let by SDHPT (with FHWA support) for the segment from North Shepherd to Beltway 8, an additional 4.6 mi.

A consultant was placed under contract to identify the separate costs for public transit and high-occupancy vehicle (HOV) use and for general highway use. The report was received on November 13, 1981, and reflected $51.9 million for public transit and $33.6 million for general highway costs. These costs were included in the agreement between Metro and the SDHPT. The first three contracts let by Metro would be for the $51.9 million in public transit, which would be shared by Metro and UMTA on a 20 to 80 percent ratio. General highway use costs would be shared by the SDHPT and FHWA in accordance with the standard 4R funding ratio of 10 to 90 percent.

This paper is a report on the results of the second contract, which was awarded by Metro on November 30, 1983, and completed April 13, 1985.

CONTRACT DEVELOPMENT

When Metro began to develop the second construction contract the primary consideration was to build an interim AVL as quickly as possible in order to eliminate the contraflow operation that was facing closure because of increased main freeway lane traffic in the off-peak direction. Specific traffic counts were available from the Texas Transportation Institute (TTI) to document the increased off-peak direction traffic volume, which was as high as 92,000 during a 24-hr period or an average of 3,800 vehicles per hour or more than 1,200 vehicles per hour per lane at some locations. With a lane taken away for contraflow this resulted in congestion with 3,800 vehicles carried in only two lanes in the off-peak direction. This condition was confirmed through visual observation during contraflow operations. Furthermore, the setup and take-down procedures were expensive and exposed contraflow personnel to main freeway lane hazards during implementation. Setup and take-down costs were averaging $50,000 per month.

Initially Metro weighed the possibility of using only an incentive or bonus payment to induce the contractor to complete the project early; however, the final contract bid package contained an incentive-disincentive provision and redefined a working day. In combination it was believed that these two concepts would get the job done early.

Performance Period Determination

The primary objective of constructing the interim AVL early could be achieved by compressing the schedule as much as possible. When design had been completed the SDHPT submitted the engineer's estimate of construction cost and recommended a performance period of 750 working days. This figure was based on the performance of an average contractor working 5 days a week, 8 hr a day, not including 30 weather days per year and all major holidays. When weather days, weekends, and holidays are added to the working days the total contract performance period equaled 975 calendar days.

According to the SDHPT a good contractor working 6 days a week, 10 hr a day, could complete the project in 540 working days or 702 calendar days. The 540 days for a good contractor's performance became a key figure when a calendar day was redefined. This will be discussed later.

Metro was not satisfied with a performance period of almost 2 years for a good contractor and decided to approach the contract performance period in two parts. The first was to complete the interim AVL quickly and the second was to complete the remainder of the project using a good contractor's performance criteria. At the same time a critical path method (CPM) schedule was developed using the criteria of outstanding performance, which redefined a working day as a calendar day. This redefinition translated into a working day of 24 hr, 365 working days a year, and no allowance for weather or holidays.

Using the outstanding performance criteria, the new definition of a working day, and results of the CPM analysis, it was determined that the interim AVL could be completed in 360 days (calendar day = working day). If successful this approach would save 615 calendar days in construction time (975 - 360 = 615). This then became Metro's goal--to construct the interim AVL in not more than 360 days.

Contractors Bid Completion Time

With this tight performance period, it was decided to let potential bidders select the number of days for completion with 360 the minimum they would be allowed to bid and 540 (the redefined working day for good contractor performance) the maximum for overall contract completion. The results were quite encouraging because three of the four contractors bid the minimum of 360 days for interim AVL completion; the fourth bid 420, which still would have been a significant time savings had that contractor submitted the lowest bid.

An obvious question arises as to why Metro set 360 as the minimum number of days that could be bid. Because the CPM analysis showed that only an outstanding effort by a contractor would enable completion in 360 days it was selected as the minimum. In addition, failure to set a minimum would encourage unrealistically low bids for performance with no intentions of completing the project in accordance with the days bid. The contractor then could challenge the performance period in court when he failed to complete the project on schedule. Each day of the contractors' selected completion time was valued at $5,000 and the resulting figures were used to determine the low bidder. How the value of $5,000 per day was established will be discussed later.

To recapitulate, Metro's goal was outstanding performance through accelerated construction to obtain the interim AVL portion sooner. This was accomplished through defining a working day as equal to a calendar day, which allowed the contractor to work multiple shifts, 7 days a week, with no allowance for weather or holidays. By combining this definition with competitive bidding (the contractor selected the completion time for the interim AVL) it was possible to reduce the performance period from 975 to 360 calendar days--a reduction of 615 calendar days.

Incentive-Disincentive Provisions

Metro's innovative concepts for reducing the performance period squeezed potential contractors to the maximum. Therefore it was thought that some provision should be made to ensure contract compliance.

Because it was highly desirable that the interim AVL be completed on time, an incentive-disincentive provision was included in the contract to encourage the contractor to put forth his best effort. As an incentive for better performance Metro offered a bonus of $5,000 per day for each day the AVL portion was completed early for a maximum of $450,000, which could be earned if completion occurred 90 days early (on the 270th day based on 360-day bid). In arriving at the daily dollar value for the incentive it was necessary to determine a realistic figure that could be justified.

Contact was made with highway departments in other states that had used incentive contracts to accelerate highway construction. Some of the agencies responding included the Illinois Department of Transportation, the Mississippi State Highway Department, the FHWA (in reference to projects in Kentucky and Georgia), the Colorado Highway Department, and the Texas Transportation Institute of the Texas A&M University System. Information received helped Metro develop an incentive-disincentive provision based on hard, justifiable dollar values. They included administrative costs to Metro and the SDHPT, the salaries of each agency's employees who supported the project (which included SDHPT engineering and inspection staff personnel assigned to the project), and the cost of operating the contraflow lane. These hard costs, all of which were direct costs and easily justified, were estimated to be in excess of $5,000 per day. There were additional freeway user delay costs estimated to be in excess of $38,000 per day, but these were not included because they were more difficult to quantify and substantiate. A maximum period of 90 days was selected for the incentive and disincentive because the CPM developed by Metro showed that even with unlimited people and resources it would be almost impossible for a contractor to complete the interim AVL 90 days early. However, the contractor should be given the opportunity to earn the bonus, and completion more than 90 days early was unrealistic.

As a counterbalance to the incentive a disincentive would be assessed for every day the project was delayed past the 360-day selected completion date. The rational used for establishing the disincentive payment of $5,000 per day was the same as that for the incentive in reverse: Metro and SDHPT costs would continue.

Liquidated Damages

Contract completion time, which included the interim AVL, main freeway lane repairs, and improvements to the AVL near downtown Houston, had been set at 540 days for good performance. Because any delay past that date was unacceptable from a performance view and it could adversely affect the next construction contract, liquidated damages of $5,000 per day were set to start on the 541st day. The value of liquidated damages was established using the same criteria that were used for the incentive-disincentive provision.

CONSTRUCTION COSTS

Engineer's Estimate and Contractor Bid Prices

The effectiveness of the bidding process that was developed for this contract can be gauged by comparing the engineer's estimate (which reflected existing prices for similar construction at market value in the local area) with actual bids. An unusually high bid price by the contractors could indicate that they believed the cost for accelerating construction would be significant and were including this factor in their bid proposal. Indeed, this may have been the case for all except the low bidder. The engineer's estimate was $8,683,867.90 and the low bid came in at $8,186,855.99, which was below the estimate. The other three contractors bid $10,250,808.38, $10,627,868.42, and $10,979,814.66, respectively. This could be interpreted as an attempt by the three higher bidders to offset the cost of acceleration.

Impacts of the Accelerated Contract

Accelerating this contract resulted in an operational interim AVL on September 14, 1984--269 days after the notice to proceed was issued. After completion of this accelerated contract on April 13, 1985, a quick look at each agency's involvement revealed some adverse impacts and benefits that resulted from the compressed schedule and incentive provisions. A majority were a direct result of the contractor's effort to earn all of the bonus money. Impacts to Metro, the SDHPT, and the contractor will be discussed separately.

Metro

As a result of the accelerated contract, Metro increased its staff and involved more people in supporting increased contract management and administration requirements such as project management, contracts, risk management, insurance, and operations. Contract management salary costs for FY 84, the period when maximum effort was devoted to the incentive part of the contract, were $97,000. Administrative costs were in addition to that figure; however, the savings to Metro from terminating contraflow operations by finishing the interim AVL early would approach $50,000 per month. By reducing the AVL completion time from 975 to 270 days, contraflow operations were terminated about 23 1/2 months early, which saved an estimated $1,150,000; the bonus cost was $450,000, which resulted in an overall savings of $700,000 to Metro.

SDHPT

Having an accelerated contract resulted in significant adverse impacts on the engineering and inspection staff of the SDHPT. The state was not manned to support a construction schedule based on 24 hr a day, 7 days a week, and a cap had been placed on hiring additional personnel. A solution was to transfer people within residencies to get more support for the Phase 1B contract and to work engineers and inspectors overtime. Nineteen people accumulated 2,695 overtime hours, and the highest individual total was 461 hr (which amounted to more than $9,000 in overtime pay).

What was the impact on the state of this large overtime accrual? State policy until September 1984 was to offset overtime with compensatory time off. Cash payment was not permitted for accrued overtime, so it became necessary to modify that policy. When the large overtime accrual became a problem, the local district engineer began to work with the state office in Austin to get the policy changed. A favorable decision was reached and cash payment for overtime was authorized effective September 1984. However, the overtime accumulated before September 1984 was a major problem because the offsetting compensatory time had to be taken (state policy) within 1 year of accrual. Allowing state engineers and inspectors to take compensatory time off after this contract was completed would severely affect support for Metro's Phase 2 incentive contract.

Metro approached the state with a proposal to reimburse the state for a portion of the overtime costs, which would allow sufficient support for the forthcoming Phase 2 contract. An existing agreement between Metro and the SDHPT was modified to authorize payment by Metro and resolved the overtime issue. In spite of the difficulties encountered, the SDHPT resident engineer stated that the incentive and accelerated contract provisions were the biggest factor in early completion of the interim AVL.

Contractor

The contractor experienced some significant impacts as a result of the accelerated provisions. His work schedule was based on a calendar day instead of a workday, and in order to earn the bonus he was forced to work 24 hr a day, 7 days a week, with no weather days or holidays. These long hours resulted in a high turnover rate in construction workers, which was 600 percent during the life of the contract (according to Champagne-Webber's office manager). They hired 100 people to start the job, completed it with 98, and hired 600 between start and job completion. To complete the contract in the minimum time the contractor was forced to work around the clock, which resulted in a lot of overtime and increased labor costs. An in-house assessment by Metro estimated labor costs to be about 150 percent of the normal amount. The contractor stated that his average labor cost for the project was $15.42 per hour, which verifies the in-house determination because normal costs should be between $9 and $10 per hour.

Metro required the contractor to maintain a dedicated AVL lane for use during peak traffic periods during construction. Sometimes this was a temporary AVL within the work zone and sometimes it was a contraflow operation, and it was successfully maintained until the interim AVL became operational in November 1984. Maintaining the AVL between 6:00 a.m. and 8:30 a.m. and between 4:00 p.m. and 6:30 p.m. limited the contractor's flexibility and the times when he had free access to the protected work zone. Barrier protection for the work zone both helped AVL operation and provided safety for the construction workers. No serious injuries occurred, but many small incidents drove the constructor's insurance rates up 33 percent.

How much of the $450,000 bonus was profit? According to the contractor only about $100,000 was realized as profit to the company; the remainder was absorbed in increased costs for accelerating the construction schedule.

RESULTS OF CONSTRUCTION

Accelerated and Incentive Contract Portion

In spite of the tight schedule and support problems the contractor finished this portion of the contract in 269 days and earned the full bonus of $450,000. The contract performance period for this part was reduced from 975 to 269 working days, which was a reduction of 706 days or more than 23 months.

Contract Completion Time

The momentum developed while constructing the interim AVL continued through final project completion. The contract was completed in 470 days instead of 540, which saved another 70 days on the overall contract. Modifications late in the contract performance period prevented an even earlier completion date.

CONTRACT MANAGEMENT AND ADMINISTRATION

After this contract was let, the key element that made possible the end results was the way in which the contract was managed and administered. The general guidelines for execution of the north transitway and freeway widening contract were spelled out in an agreement between Metro and the SDHPT. In this agreement under "Scope of Performance by the State," Paragraph 5, the following language is found:

> The State will serve as the duly authorized agent of Metro for the limited purpose of managing construction, including the inspec-

> tion of all work to be performed under such contracts for compliance with engineering and design specifications; provided, however, that this shall not change the legal responsibilities set out in such contracts and in . . . this Agreement. Field changes will be initiated and handled with the Contractor solely by State personnel acting for Metro, but subject to approval by Metro prior to being accomplished. To assure Contractor accountability to the State's on-site inspectors and engineering personnel, Metro agrees that Metro personnel will not directly interact with Contractor personnel, but will communicate with the contractor through State personnel in all matters concerning engineering, design, or construction performance. All other matters pertaining to said contracts will be handled by Metro directly with said Contractors/subcontractors.

To implement this agreement Metro was represented by personnel from project management and contracts. The project manager was designated by the director of bus facility project management and communicated directly with the SDHPT resident engineer on all matters concerning engineering, design, or construction performance. A contract administrator was appointed by the director of contracts and procurement and dealt directly with the contractor and subcontractors on all matters pertaining to contract administration. He also acted as spokesperson for Metro in negotiations required for contract modification and was assisted by the project manager and resident engineer as needed.

In simple terms, the Metro project manager worked directly with the state resident engineer on all construction and related issues. The contract administrator, in turn, dealt directly with the contractor on contract modifications and contract administration issues. To illustrate the relationship that exists among the project manager, the contract administrator, the SDHPT resident engineer, the contractor, and Metro support staff, a spheres of influence chart was developed (Figure 1). Each individual's and agency's role is outlined in the paragraphs that follow. The basis of these roles and responsibilities can be visualized by referring to Figure 1.

Project Manager

Duties and responsibilities of the project manager are based directly on his role as Metro's representative and how he fulfills that role with the SDHPT resident engineer. This role is spelled out in the agreement between Metro and the SDHPT. This interface between the project manager and the SDHPT resident engineer provides for two-way processing of design, construction performance, or engineering changes that originate with the contractor, the SDHPT resident engineer, or Metro. To process contract modifications, the project manager develops the supporting documents and provides them to the contract administrator. Contractor proposals and claims for extra work are analyzed and engineering estimates are obtained from the SDHPT resident engineer and Metro. These estimates are combined with previous correspondence to support the contract modification prepared by the contract administrator. The contract modification is submitted to the contractor for approval and signing and then presented to the Metro staff for final approval before execution.

Contract Administrator

Duties and responsibilities of the contract administrator are based on his role as outlined in Metro's agreement with the SDHPT. How he fits into the overall contract management process is shown in Figure 1. The contract administrator is authorized to work directly with the contractor on issues that involve contract administration. The contract administrator maintains close coordination with the project manager on all issues that concern contract modifications required as a result of changes in construction or plan sheet drawings. Contract administration issues dealing with insurance, affirmative action, and so forth are handled with inputs from Metro staff departments. In the case of safety, Metro's safety engineer deals directly with the contractor and his subcontractors. However, even in this case the safety engineer is responsible for coordinating actions with the contract administrator. In addition, the project manager is informed and takes the lead when a safety issue involves engineering, design, or construction performance.

Contract administrator interface with the contractor is maintained on contract-related issues to ensure compliance. The contract administrator is directly responsible for writing contract modifications for change orders (field changes) directed by the state resident engineer, which require Metro approval. When contract modifications have been approved, the contract administrator is responsible for ensuring that they are properly executed and distributed. When negotiations are required to resolve differences, the contract administrator represents Metro as the chief negotiator.

State Resident Engineer

Duties and responsibilities of the SDHPT resident engineer are spelled out in the agreement between Metro and the SDHPT. He provides the link between Metro's project manager and the contractor and is directly responsible for directing engineering, design, and construction performance of the contractor. How the SDHPT resident engineer fits into the management of the contract is shown in Figure 1. The SDHPT provides the resident engineer and inspection support staff for the actual construction. He informs the project manager of any changes in construction that need to be made and directs the contractor to perform the work when a change has been approved by Metro.

In emergency situations in which execution of a field change would delay the contractor and contract performance, the resident engineer informs the project manager of the circumstances in order to initiate a change notice to direct the contractor to do the work. Subsequently, detailed costs and a contract modification are developed to authorize payment.

The resident engineer is Metro's direct representative to the contractor and is responsible for managing the construction schedule, inspecting the work, and ensuring contractor compliance with standard SDHPT specifications and plans for transitway construction. When field changes are necessary, the resident engineer provides the project manager with an engineer's estimate of the cost of the work; this estimate is independent of any estimates submitted by the contractor.

Contractor

The contractor is responsible to the state resident engineer for all matters concerning engineering,

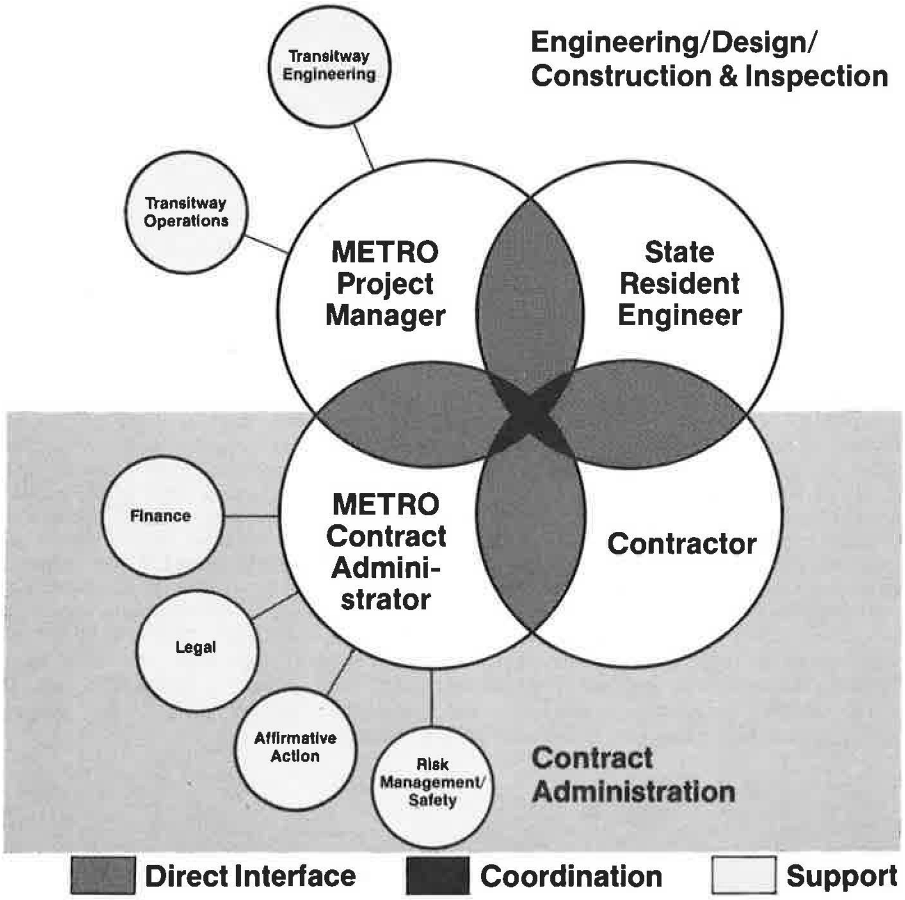


FIGURE 1 North Freeway transitway Phase 1 contract management spheres of influence.

design, and contract performance. The contractor is specifically forbidden to accept directions from Metro personnel on these three items. However, the contractor provides schedules, insurance forms, extra work cost data, and any other items called for in the contract directly to the contract administrator. Issues relating directly to safety, finance, MBE/WBE participation, and AVL operations are handled through contact with the contract administrator or the appropriate Metro staff agency. However, in each case the project manager and the contract administrator are included in discussions and coordination. Figure 1 shows how the contractor interfaces with the SDHPT resident engineer and Metro's contract administrator.

CONCLUSION

Because this was Metro's first attempt to use unique competitive bidding techniques and an incentive to get accelerated construction performance, the jury is still out on any firm conclusions. That performance time was slashed dramatically would indicate success, but it is difficult to pin down who paid the additional costs of acceleration. In this case it is believed that the contractor paid the majority of these costs with the incentive providing some offset. Bidding on future contracts could alter this situation so that the owner would pay through higher bid prices.

CONTINUING INITIATIVE

The interim AVL constructed in Phase 1 is narrow and creates some operational problems as a result. To correct this and other deficiencies Metro has let a second contract for Phase 2, which will add a new freeway lane in each direction, build new shoulders, and widen the transitway to a standard width. Incentive provisions and the requirement for accelerated performance have been included in this $43.4 million contract, which is now 30 percent complete. Some firm conclusions may be forthcoming after this latest effort.

RECOMMENDATION

No firm recommendation can be made about the use of accelerated construction contracts with incentive provisions until further analysis can be done. Metro has requested the Texas Transportation Institute of the Texas A&M University System to review the results of the contract completed and the one in progress to form a basis for future recommendations.

Publication of this paper sponsored by Committee on Construction Management.

Construction Management Practices in Saudi Arabia

MOHAMMED I. AL-JARALLAH and SATISH MOHAN

ABSTRACT

Construction projects worth $270 billion have been executed in Saudi Arabia during the last 14 years. Widely varying construction management (CM) techniques have been used on these projects. Some special features that make the construction industry in Saudi Arabia different from that industry in the rest of the world include shortage of local contractors, local consultants, and local labor force; shortage of local materials; extreme climate; a working year of 305 days; and a multinational influence. The results of a survey conducted on the management aspects of 43 construction projects, in progress during 1984-1985, are presented. These 43 projects were studied through site visits and interviews with the project managers. The cost of these projects ranged from $1.6 million to $3,714.3 million, and the average cost was $226.9 million. The most popular organizational structure was the traditional architect/engineer (A/E) type used on 17 projects followed by the design/construction(D/C) manager type, which was used on 13 projects. Eight of the projects used the professional CM type of organizational structure, and four used the turnkey type. The performance of each project was measured in terms of timely completion, cost overruns, quality of work, and goodwill. It was observed that the professional CM type fared the best, followed by the D/C manager type, the traditional A/E type, and the turnkey type in that order. Project control methods, settlement of disputes, quality control, tender evaluation, changes and payments, delay penalties, project closeout, and other management aspects are also discussed.

During the last decade Saudi Arabia has experienced unprecedented construction activity that has attracted construction professionals from all over the world. During the second development plan (1975-1980), expenditure on construction projects totaled about $30 billion, 32 percent of the total government expenditure during this period. During the third development plan (1980-1985), an estimated $210 billion was spent. The construction industry employs 15 percent of the total labor force and consumes 14 percent of the total energy in the country.

Projects of all types and sizes have been executed: more than 400,000 housing units, 35,000 km of high-specification highways, more than 60 dams, two major international airports, seaports, refineries, a diplomatic enclave, and many ministry buildings. The demand for basic infrastructure and housing has largely been met and a shift has started toward construction of industrial and commercial projects. The two industrial cities of Jubail and Yanbu are examples of this shift. These two industrial cities, to be completed by the year 2000, will cost $135 billion and will employ 144,000 full-time workers. Details about these cities and other important projects are documented elsewhere (1). The physical facilities created so far will carry development forward and enhance the quality of life of Saudi citizens.

Widely varying construction management (CM) techniques have been used in Saudi Arabia depending on the contractor's background, public or private ownership of the project, the size and type of project, and so forth. Most of the CM techniques are well documented. However, the social attitudes and the forces that affect CM practices (local regulations, multinational influence, and the work environment) create a unique construction industry in Saudi Arabia. Some special features of the construction business in Saudi Arabia are

1. There has been a shortage of local contractors. Most consultants and contractors are foreign based, may not be in Saudi Arabia after the 1-year maintenance period, and will have no lien on the project after it is handed over. This situation has led the Saudi owner to select only those firms that have good international reputations and proven experience in their specific field of construction work.
2. Because both the consultant and the contractor are often foreign based, a joint venture of two or more firms from different countries is preferred to one reputable firm from one nation. Lately this concept has been extended to joint ventures between a Saudi firm and a foreign firm.
3. The emphasis in every phase of a project is on excellence. The words "biggest," "best," and "latest" sell. Sometimes the utility or worth is compromised in favor of the "best."
4. All unskilled and semiskilled labor is imported from Far Eastern and Middle Eastern countries. The extra costs of trips home, annual vacation, housing, transport, medical care, food, and insurance can be as much as 100 percent of base wages. These workers live in temporary labor camps without their families. They are readily available for overtime work.
5. The working time is 10 hr a day, 6 days a week. Annual holidays total from 6 to 10 days. This leaves a working period of about 305 days a year.
6. There are no organized labor unions and no strikes.
7. Inflation is minimal. In the last 4 years it has been zero and, on some goods, even minus.
8. Trust on the part of the owner is very important. To survive, a construction management company, a consultant, or a contractor has to work hard to create an impression of trustworthiness.

Department of Civil Engineering, King Saud University, P.O. Box 2454, Riyadh 11451, Saudi Arabia.

9. Most sizable projects involve a major component of foreign equipment and engineering. As much as 40 to 50 percent of materials is imported, and therefore the proportion of material cost is relatively high. Poor material planning has been the cause of delay on some projects.

10. Safety and environmental requirements are minimal and of a quite basic nature. Institutions like the Occupational Safety and Health Administration (OSHA) in the United States do not yet exist.

11. Ten percent of the contract value is advanced to the contractor for mobilization expenses, at the time of the notice to start work, against a bank guarantee. This amount was 20 percent until 1984. This advance payment is recovered through deductions of the same percentage from progress payments.

12. The harsh climate reduces labor productivity and machine life. High day and night temperature differentials induce severe temperature stresses in structures during construction.

Management of construction projects cannot be standardized because it is largely a function of the ingenuity and experience of a particular construction company and depends on many project-related and other extraneous factors. The diversity in management methods has been further compounded in Saudi Arabia by the different national origins of the construction professionals. A review of the various CM methods followed on projects in Saudi Arabia appears to be necessary at this stage so that the various CM techniques can be evaluated. Such a review would provide guidance to those who are seeking efficiency in their management procedures. This paper is an effort in that direction.

DATA BASE

For the purpose of collecting data for this paper, 43 projects in progress were visited. A list of these projects and their costs is given in Table 1. In order to obtain survey results that could be generalized, different types and sizes of projects were selected. A questionnaire was prepared, and the project engineer or manager at the site was interviewed. Most of these projects were located in the central region of Saudi Arabia. Although some of the people interviewed were open-minded and gave information without reservations, many others were apparently suspicious of the effort and hesitated to answer some questions. In the early years some contracts were awarded after brief negotiations, in some cases with high unit costs, and under these circumstances the hesitation of the project managers to divulge all information, particularly financial, was understandable. Therefore, although 43 projects were studied, the results reported in this paper are based on fewer than 43 answers to each question.

DETAILS OF COST AND TIME AND CONTRACT TYPES

The tendered cost of the projects included in the survey ranged from $1.6 million to $3,714.3 million with an average cost of $226.9 million. The planned time of construction ranged from 6 months for a $7.5 million building project to 46 months for a $149.4 million road project; average time was 27.6 months. According to these figures, an average project spent $8.2 million each month.

One of the 43 projects was executed using an in-house design team and construction organization. This project included the construction of a shopping center. Information on the type of contract awarded was not available in two other cases. Types of contracts awarded on the remaining 40 projects are given in Table 2.

Two lump sum contracts had cost overruns on the order of 18 percent, and others had cost overruns of less than 5 percent. In the case of unit price contracts, one project overspent by 16.7 percent, four

TABLE 1 Construction Projects Included in the Study

Project Name	Estimated Cost[a] (million U.S. $)
Building Projects	
Arab security studies and training center	120.3
Al-Iftaa and Al-Dawa	26.1
Second housing for special security forces	125.7
General Organization for Social Insurance housing	42.8
Nammal compound in Rabwah	42.9
Residential area for unmarried people, Islamic University	54.5
Sport complex project	48.6
Internal security forces housing project site, Jeddah	375.0
KSU faculty housing, Phase II	133.3
Oleya shopping center	68.6
Sama head office building	171.4
Al-Nasr sports club, Class A	57.1
RSNF headquarters expansion	110.0
Al-Khozama plaza complex	54.9
Al-Mousa center	61.4
Security forces hospital, Phase II	157.1
SFD headquarters office building	31.4
MOFA staff housing project	54.6
Council of Ministers extension building	7.2
Vocational training facilities	69.6
King Faisal specialist hospital	–
Taif ordinance coprs facilities	117.1
New Riyadh passports building	37.2
Extension for the officers' club, National Commercial Bank	11.0
National Commercial Bank branch	1.6
New Ministry of Commerce building	18.9
Riyadh DQ international school	40.0
Sports club, Riyadh diplomatic quarter	34.3
Construction of new campus of King Saud University	3,714.3
PTT building project	143.0
Rush housing in Riyadh	285.7
Defense housing	1,142.0
Sewage Treatment and Water Supply Projects	
Riyadh sewage treatment plant	68.9
Sanitary and storm drainage system	137.1
Riyadh sewage pump station	45.7
Bridges	
Al-Khaleej Road bridge, Riyadh	111.7
Road Projects	
Riyadh Ring Road, east leg	61.7
Al-Jumah descent project	149.7
Riyadh, Dammam Expressway Contract D	60.7
Riyadh, Dammam Expressway Contract E	59.1
Miscellaneous Projects	
Trabah Dam in Taif area	34.7
TV center, Riyadh	342.8
King Khalid International Airport	3,142.8

[a] In cases in which estimated cost was not available, tendered cost has been given.

TABLE 2 Contract Types

Contract Type	No. of Projects
Lump sum	14
Unit price	18
Fixed price	2
Unit price with top ceiling	2
Lump sum with top ceiling	1
Lump sum with unit price for extra items and variations	3

projects overspent by from 5 to 7 percent, and others were completed within 4 percent cost overruns. In one case, in which a lump sum contract with unit prices for extra items and variations was followed, the project expenditure was 3.1 percent less than the bid amount. In another case, in which a lump sum contract with a top ceiling was awarded, the cost overrun was 14.1 percent.

ORGANIZATIONAL STRUCTURES

Almost all of the known forms of relationships among the owner, the designer, and the builder were followed with slight variations from classic forms in a few cases. The breakdown of various structures is given in Table 3.

TABLE 3 Organizational Structures Used on Surveyed Projects

	Type of Project					
Organizational Structure	Buildings	Sanitary and Water Supply	Bridges	Roads	Misc	Total
Traditional A/E	13	1		2	1	17
D/C manager	8	1	1	2	1	13
Professional CM	6	1			1	8
Turnkey	4					4
In-house						1

The traditional A/E contract situation, in which the owner signed separate contracts with the designer and the construction supervisor and the designer and the construction supervisor had no relationship, obtained on 40 percent of the projects. The D/C manager contract was used on 30 percent of the projects. The professional construction management contract was next in popularity and was used on 19 percent of the projects. Turnkey contracts were followed on building projects only. Two examples of organizational structures are shown in Figures 1 and 2. In most cases the contractual relationship among the owner, the consultant, and the contractor was designed to relieve the owner of responsibility for all technical matters and site supervision. The owner was responsible for financial matters like variations, change orders, time extensions, and progress payments.

The project managers were asked if they faced any bottlenecks or problems during construction. Projects following traditional A/E contracts were reported to experience delays caused by the supervising consultant at every stage. There were also many instances of design error. Projects following D/C manager contracts also reported design errors and delays in approvals. Projects following professional CM contracts or turnkey contracts did not report any approval delays or design errors.

The performance of each project was measured on four counts:

- Timely completion,
- Cost optimality,
- Quality of work, and
- Goodwill.

Each count was given 0, 1/2, or 1 point depending on the level of its fulfillment. Each project could thus receive a maximum of four points, and the performance of all projects following a particular type of organizational structure was totaled. Average performance versus organizational structure is given in Table 4.

TABLE 4 Average Performance of Each Organizational Structure

Organizational Structure	Average Performance
Traditional A/E	2.26
D/C manager	2.69
Professional CM	2.79
Turnkey	1.33

CONSTRUCTION MANAGEMENT PROCEDURES

Methods of Project Control

Almost all of the projects visited used bar charts for schedule control. Thirty-two of 43 projects used computerized methods along with bar charts. In a few cases like King Khalid International Airport, a full-fledged computer center was in place and up-to-date programs were being used for project control and monitoring.

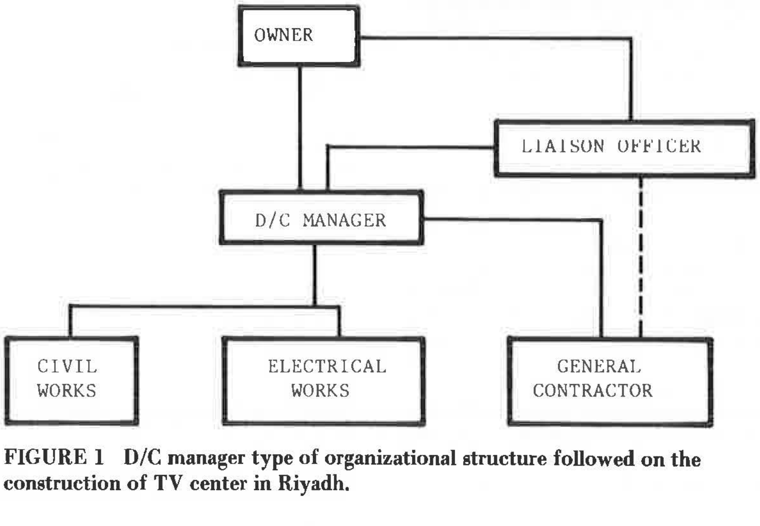


FIGURE 1 D/C manager type of organizational structure followed on the construction of TV center in Riyadh.

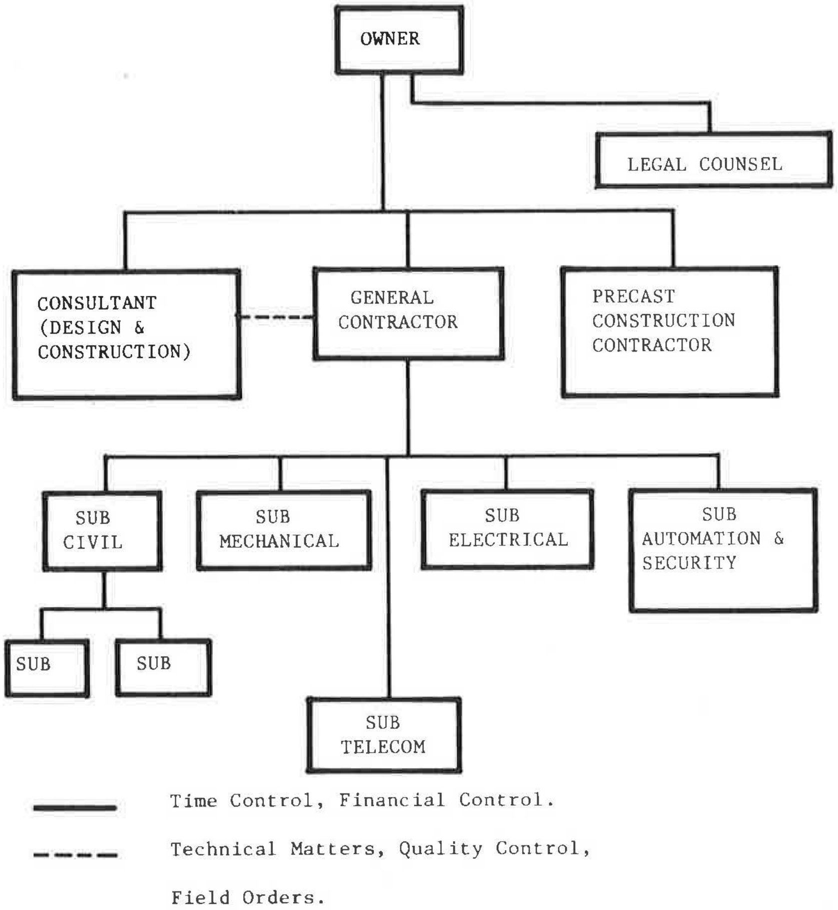


FIGURE 2 D/C manager type of organizational structure followed on the construction of the new campus for King Saud University, Riyadh.

Critical path method networks and time listings were in common use on all projects on which computers were used. Use of computer methods was more popular on projects following professional CM contracts than on those following traditional A/E contracts, as indicated by the data in Table 5.

TABLE 5 Computer Usage for Project Control

Organizational Structure	Computer Usage (%)
Traditional A/E	65
D/C manager	85
Professional CM	88
Turnkey	75

Value Engineering and Management

Value engineering (VE) and value management procedures have not been popular in Saudi Arabia. Although the projects represent huge amounts, there was no value engineer on any of the 43 projects. For two projects specifications and drawings were reviewed by the CM, and on one of them $150,000 was saved as a result. Three other projects had a VE incentive clause in the contract, one of them on a 50-50 sharing basis between the owner and the contractor. On another project $1 million in material changes was saved as a result of VE review. The project manager, however, reported that VE was not worthwhile because the procedure incurred delays.

Settlement of Claims and Disputes

Disputes range from specification problems to contractual problems and from a few thousand dollars to more than $100 million per claim. It goes without saying that the number and value of disputes in a contract are inversely proportional to the clarity of contract documents. These documents are usually prepared by the consultants who come from all parts of the world and are executed by contractors who are sometimes unfamiliar with the consultants' backgrounds. Changes and variations in the size and type of work, however, have been the source of most disputes, both claims for money and time extensions.

The method of settlement of contract disputes in Saudi Arabia depends on whether the project is public or private. In the project is public, disputes arising out of the contract must be settled at the "Grievance Board," which is an Islamic court fully authorized to settle such disputes. Its ruling is final and binding on both parties. If no governmental institution is directly involved, the contract provisions determine the way in which claims are settled. In most cases, each party is given the right to choose one member and the two members so chosen select a third member to form an arbitration committee that will settle the claim. Approximately twothirds of all disputes are settled out of court through direct negotiations in Saudi Arabia.

Resource Management

Of the four basic resources, men, machines, money, and materials, money has not been a problem in Saudi Arabia so far. Only one of the 43 projects experienced some financial problems.

Men

All construction workers, skilled, semiskilled, and unskilled, are imported from Far Eastern and Middle Eastern countries as well as from Europe and the United States. In addition to wages, these workers are provided with camp housing, food, insurance, bus transport, limited recreational facilities, medical care, and annual air transport to their home country. All of these fringe benefits add up to more than 100 percent of wages.

The importation of labor takes from 4 to 6 months, and after the men arrive they are paid whether or not they are put to work. Labor planning is therefore crucial. Most contractors prepare manpower loading schedules and keep updating them. Two examples of manpower loading patterns are shown in Figures 3 and 4. Peak manpower may exceed 12,000 men on one job. Manpower employed on a $59 million, 23-month road project is given in Table 6.

Machines

Because of the shortage of a permanent labor force in Saudi Arabia, construction equipment is used to the maximum possible extent. Usually the contractor imports equipment from his country or buys used equipment locally. The number of pieces of construction equipment of all types has ranged from 20 on a $157 million building project to 1,500 on a $1,142 million building project. A list of typical equipment used on a $59 million road project is given in Table 7.

An effort was made in this study to determine the cost of construction equipment as a fraction of project cost. Although the number of pieces of each type of equipment was available, in most cases their approximate cost could not be determined. According to the figures given by the project managers in a few cases, equipment cost ranged from 8 to 18 percent of project cost. About 10 to 12 percent was quoted as a common figure.

Quality Control

Quality control (QC) has been exercised rather well on most government projects in Saudi Arabia, and a considerable amount of resources is expended on this function. Thirty-one of 43 projects reportedly had a QC plan and 21 reportedly had a quality assurance (QA) plan as well. Staff to execute QC ranged from a single engineer to a group of 30. Qualified engineers have been employed by the owners. On one project, an engineer with a Ph.D was supervising the QC testing.

On most projects both in-house and outside laboratories were used for testing. Thirty-four projects had in-house testing laboratories under the supervision of the consultant. Twenty-five projects used the services of outside independent testing laboratories.

Construction Safety

Institutions like OSHA in the United States have not yet arisen in Saudi Arabia. Local rules require fencing the construction area, in most cases by a tin sheet wall; wearing hard hats and boots in the construction zone; and access to an ambulance and

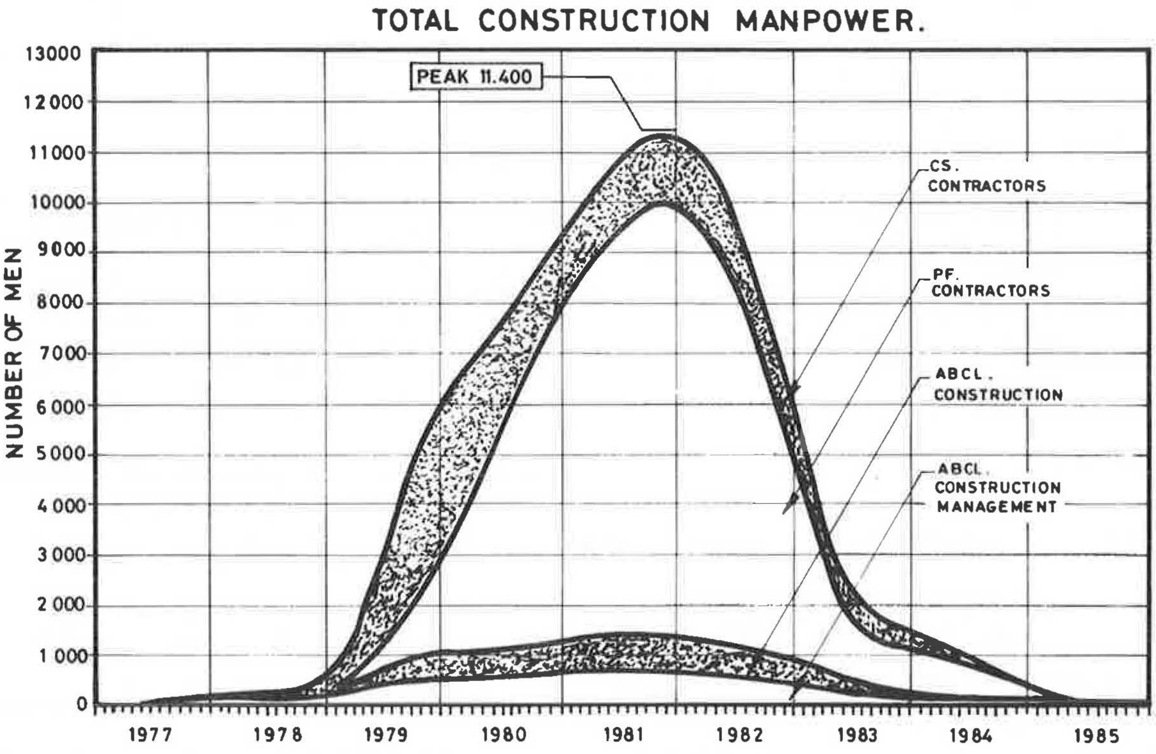


FIGURE 3 Manpower schedule for King Khalid International Airport, Riyadh.

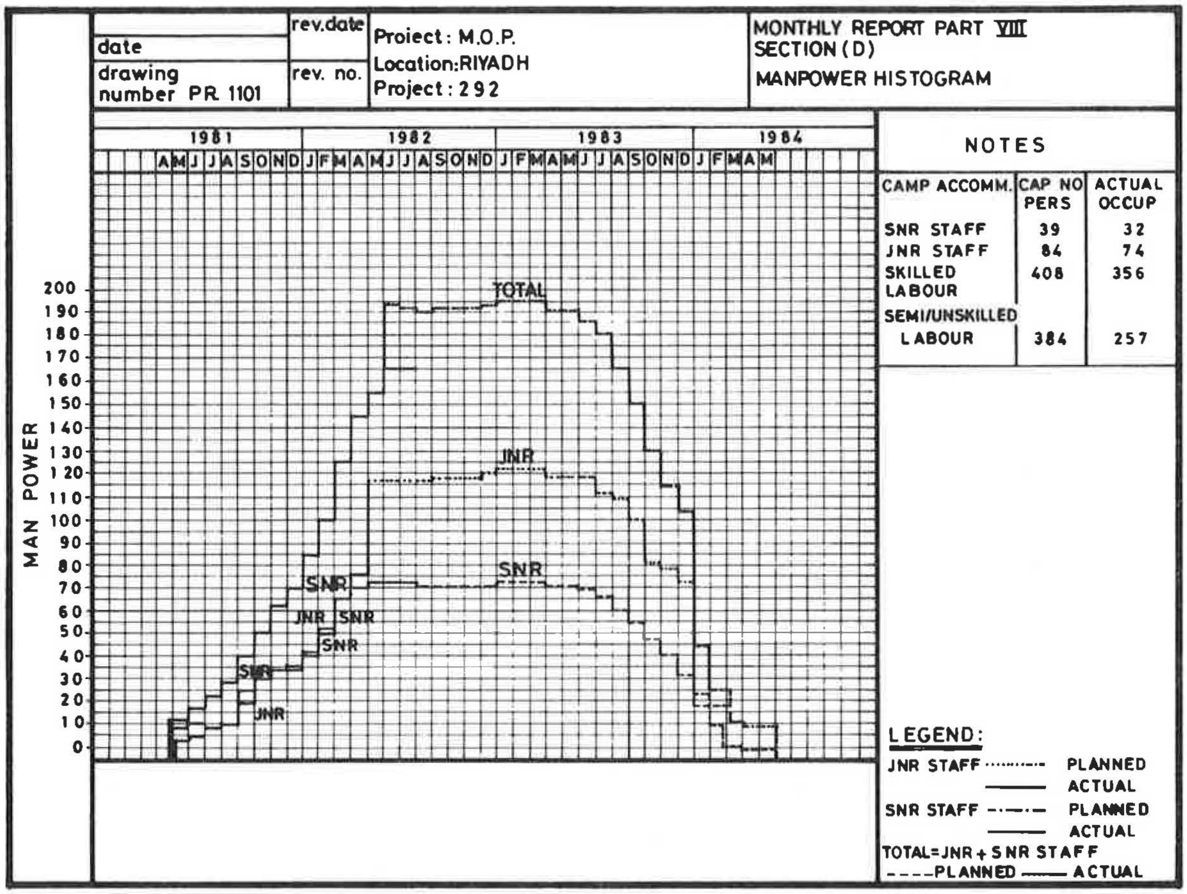


FIGURE 4 Manpower loading on a $112 million bridge project.

TABLE 6 Manpower for Riyadh Dammam Expressway Contract E

Description	No.
Project manager	1
Assistant project manager	2
Staff	8
Engineer (civil)	8
Engineer (mechanical)	2
Supervisor	29
Surveyor	4
Chainman	13
Draftsman	6
Laboratory technician	7
Foreman	24
Mechanic	27
Operator	129
Driver	101
Skilled labor	315
General labor	171
Total	847

fire-fighting equipment. When the number of laborers exceeds 100, the construction company has to employ a qualified doctor and run a clinic on site.

Thirty-seven of the 43 projects studied had a safety plan. Twenty-four of these employed various kinds of personnel for the job. Three of the projects had clinics operating on site and two of them had fire-fighting vehicles. The size of safety staff ranged from 1 to 25 depending on the size and type of project.

TABLE 7 Equipment Used on a $59 Million Road Project

Description	No.
Bulldozer	11
Loader	23
Dump truck	56
Scraper	–
Motor grader	9
Water tank truck	8
Sprinkler	12
Sheepfoot roller	1
Vibratory roller	19
Pneumatic roller	10
Backhoe	1
Crane	3
Asphalt distributor	3
Asphalt finisher	5
Truck mixer	11
Concrete pump	2
Portable generator	6
Tractor	1
Concrete batching plant	2
Crushing plant	2
Asphalt mixing plant	2
Total	187

CONTRACT ADMINISTRATION

The prime objectives of management are time, economy, and quality. The way these objectives are achieved, however, depends on many factors: the type of contractor's organization, terms and conditions of the contract, and whether the project is private or government owned, to mention just a few.

The type of organization determines the hierarchial order of decision making. The degree of centralization or decentralization and the impact on the administrative process depend on the company's administrative chart.

The contract form of a project shapes the three-dimensional relationship among the contractor, the consultant, and the owner. The function of the consultant varies from a minimum, when the owner takes over the duties of the consultant by his own forces, to the other extreme at which the owner simply pays the monthly bills that are certified by the consultant. There is no standard national contract form in Saudi Arabia. Government departments and institutions draw up their own contract forms. These could be modified versions of the forms of the Fédération Internationale des Ingénieurs-Conseils or the American Institute of Architects or something different.

Finally, government contracts are different from private contracts. The former have to follow certain rules and must be in line with the Government Tender Law. The latter are usually written to protect the owner's interests regardless of any rules or regulations. Because of space limitations, only government contracts will be considered in the discussion of the major functions of contract administration.

Bid Evaluation

With the exception of the case in which a CM is hired, all government bids are evaluated by a technical committee. The number of committee members, their ranks, and their duties are outlined in the Government Tender Law as amended from time to time. The award of a contract depends heavily on the committee's recommendations. The Ministry of Finance and National Economy must approve the form of any government contract before signing to make sure it conforms to the Tender Law and regulations. Contracts that have a time of 1 year or less are exempted from this requirement. When a CM is hired, bid evaluation is usually carried out by him. CMs are used on defense-related contracts, civil aviation contracts, and other extremely large contracts like the Jubail and Yanbu industrial projects (1).

Change Orders

The Saudi Arabian Tender Law requires the inclusion of a clause in the contract that gives the owner the right to increase or decrease the volume of work by 20 percent of the total contracted scope of work. The flexibility to increase the scope of work has lately been reduced to 10 percent. The impact of change orders on both time and cost has to be evaluated. Disputes over the cost of such changes can be minimized by including a priced schedule of unit rates for some anticipated items of work in the bid documents.

Progress Payments

At the end of each month the contractor submits a payment application for work executed during that month. The way in which the payment certificate is checked before payment differs according to the procedure described in the contract. Under most government contracts, the consultant must check, inspect, and certify the payment. He forwards it to the owner who may check and randomly inspect the work to make sure he is not overpaying the contractor. Payment is then made after deductions are made to cover such items as retention money and advance payment.

Penalty for Delays

The owner, in any project, is as concerned about the timing of his project completion as he is about the cost. In Saudi Arabia timeliness is critical because a good number of construction projects are on a crash program. For this reason the Government Tender Law requires a clause in the contract that penalizes the contractor or the consultant for being late. The maximum penalty is limited to 10 percent of the total contract value, including change orders.

Management Cost

An effort was made in this study to determine the average cost of management as a percentage of project cost. Adequate data, however, were not available; partial information was obtained about only 8 of 43 projects. On the basis of this limited sample, owner's management cost including planning, design, and construction supervision ranged from 4.6 to 5.3 percent of the project cost on building works. The contractor's management cost on one $120 million building was 4.75 percent of the project cost. In one case in which the design and construction were managed by the owner himself, using his in-house staff, the total management cost was 10 percent of the project cost. It should be noted, however, that the sample represents primarily large-scale projects. For smaller projects, management costs will be higher than the figures cited here.

BOTTLENECKS AND PROBLEMS

During the interviews, project managers were asked if they faced any bottlenecks and problems during construction. Problems cited are summarized in Table 8 in the order of the number of citations. There had been no problems on 17 projects at the time of the interviews.

TABLE 8 Bottlenecks and Problems Ranked in Order of Number of Citations

Nature of Problem	No. of Citations
Material delays	6
Design errors	6
Geotechnical problems	6
Lack of initiative by consultant	5
Labor problems	4
Diversion of road traffic and utilities	4
Specifications and/or drawings not clear	3
Short contract time	3
Lack of coordination between contractors	2
Delay in progress payments	1
Many change orders	1
Difficult working area	1
Delay in urban land procurement	1

PROJECT CLOSEOUT

Construction contracts in Saudi Arabia are written to include a "maintenance year" as a general practice. Project closeout is a long and tiresome procedure. It starts the day the contractor officially informs the consultant and the owner that the work is substantially complete and ready for inspection. Preparation for closeout, however, starts much earlier with the preparation of as-built documents and a punch list. For two reasons the concern here is with public works: first, the rules and regulations are mostly meant for government jobs and, second, a majority of construction works carried out during the last 10 years are publicly owned.

When the contractor informs the owner and the consultant that the project is ready for inspection, a preliminary takeover committee is formed. This committee is responsible for making sure that the contractor has executed the work according to the specifications and other contract documents. If the work is found to be substantially complete, the committee will recommend the issuance of a substantial completion certificate. The procedure could differ slightly from one project to another depending on the procedure described in the contract. A substantial completion certificate is issued with a punch list of defective or incomplete items. The contractor is required to complete these items within 365 days from the effective date of the certificate of substantial completion. If any parts or components of the permanent works become defective during the maintenance year, the contractor is required to fix or replace them. The owner, however, is usually responsible for operation and preventive maintenance from the delivery date.

When the contractor completes his maintenance year and fulfills his responsibility regarding the punch list items, he notifies the owner and the consultant again and a new and final takeover committee is formed. If the committee finds that the contractor has completed his contractual obligations, it will recommend the issuance of the final completion certificate and the settlement of accounts with the contractor. That involves securing certain documents from the contractor. These include proof that he has paid his taxes; settled his labor problems (including residence status); settled all accounts with his subcontractors, suppliers, and so forth, and a latent defect guarantee. The latent defect guarantee is simply a written statement from the contractor, if it is a Saudi firm or from the Saudi partner in the case of a consortium, certifying that he thereby undertakes the guarantee of smooth functioning of the permanent works free from any structural failures. If such failure occurs, he will fix it free of charge.

On 30 of the 43 projects studied, there were no closeout problems and the people interviewed about 11 others did not yet know because the projects were still under construction. The manager of one project reported that the handing-over inspection was delayed by the owner.

FUTURE OUTLOOK

Saudi Arabia has completed most of the infrastructure (housing, roads, agriculture, airports, seaports, defense establishments, educational and health institutions, and basic industries) for its population of 8 million who occupy some 2.25 million km^2. Oil revenues have dropped, and this will cause a slowdown of construction activity, at least in the near future.

The construction boom of the last decade has created a large number of local firms in the management as well as in the construction field. Some of them have entered into joint ventures with foreign firms. The government has issued regulations that give priority to national firms in the award of public contracts. In addition, foreign firms have to award at least 30 percent of the volume of their work to local firms. The entry of construction companies from the East and the Far East has almost ousted western companies because of their higher overhead and wage costs. There will be more competition in future bids, which should result in a downward trend in construction costs. Contractors will have to use local materials and local expertise to the extent they are available. There will perhaps be no fast-track projects, and the need for efficiency in construction management will be felt more and more. Operation and maintenance (O&M) problems will influence the thinking of the designers and planners of future projects. The market for O&M is expected to grow rapidly in both quality and quantity.

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions of this work and the recommendations, based thereon, are summarized as follows:

1. An unmatched evolution in construction has taken place in Saudi Arabia. Government statistics show that more than $270 billion was spent on public construction projects between 1970 and 1984. A wide range of CM techniques has been used on these projects. Shortage of local contractors, local consultants, local labor, and local materials; harsh climate; local regulations; and a multinational influence have contributed to the creation of a unique construction industry in Saudi Arabia.
2. Lump sum contracts with a priced schedule of unit rates for change orders offered the best method for controlling cost overuns and time delay.
3. The best organizational structure was the professional CM type, followed by D/C manager, traditional A/E, and finally the turnkey type. This ranking was established on the basis of timely completion, cost optimality, quality of work, and goodwill.
4. The Grievance Board, with no appeal allowed, is in charge of settling claims resulting from public contracts in Saudi Arabia. The best and least expensive way of settling disputes is out of court through direct negotiations.
5. There is no standard form of contract in Saudi Arabia, but there are certain requirements dictated by the Government Tender Law. Among these requirements are a penalty clause with no incentive for acceleration, a maintenance year, submission of certain surety bonds, payment of taxes before settling the contract accounts, and the use of the Arabic language in all communications between the owner and contractor. There is a definite need for a standard form of contract.
6. Bid evaluation must be carried out by a qualified, honest, and unbiased team. The bid evaluation committee system followed for government contracts may result in the selection of less qualified contractors simply because they have offered the lowest price.
7. The construction industry in Saudi Arabia is changing direction. During the next 10 years concentration on industrial and commercial projects is expected.
8. To cut their running costs, foreign consulting firms have employed young, inexperienced engineers to do their field supervision. The design teams in most cases do their work abroad with little or no consideration of local conditions, culture, or heritage. This has resulted in design errors, geotechnical problems, and time delays. Consulting firms will have to avoid these practices in the future.

9. Project closeout is much more difficult than securing the contract itself. It requires a sincere joint effort by the owner and the contractor. The cases studied in this work indicate that Saudis are not claim oriented. They prefer settling differences through direct negotiations.

10. There has been a noticeable improvement in the quality of construction. It is expected that the industry will even be more efficient in the future.

REFERENCE

1. M.I. Al-Jarallah. Construction Industry in Saudi Arabia. Journal of Construction Engineering and Management, Construction Division, ASCE, Vol. 109, No. 4, Dec. 1983, pp. 355-368.

Publication of this paper sponsored by Committee on Construction Management.

Use of Microwave Oven for Rapid Determination of Moisture Content of Highway Materials

MUMTAZ A. USMEN and HWEE YAN KHENG

ABSTRACT

An overview of research findings on the use of a microwave oven for the rapid determination of the moisture content of soils, aggregates, waste materials, and stabilized materials is presented in this paper. Principles of microwave heating and factors that affect the test results are briefly reviewed. Conventional and microwave oven moisture content test results are compared to assess the accuracy of the microwave drying technique. Regression analyses are performed to establish the statistical relationship between the two parameters. It is shown that granular materials produce more accurate results than do cohesive soils. It is also shown that although discrepancies exist between conventional and microwave oven moisture contents, the two measurements are quite strongly correlated, and one can be consistently predicted from the other. Conclusions and recommendations, including research needs, are provided at the end of the paper.

The engineering properties and service behavior of highway materials such as soils, aggregates, and stabilized materials are greatly affected by the presence of moisture. Moisture content, defined as the ratio (as a percentage) of the weight of water contained in the material to that of the solid particles, is therefore considered a key parameter that must be accurately determined in the testing phases of all highway construction projects.

The standard and most widely accepted procedure for establishing moisture content is based on oven drying wet samples to constant weight at a controlled temperature of 110°C ±5°C (see, for example, ASTM D 2216). Although this method is fairly simple and accurate, it is rather time consuming because of the slow nature of the drying process in the conventional oven. Depending on the soil type and sample size, a drying period of from 4 to 24 hr may be required in the conventional oven. To meet the needs of expeditious construction control, various rapid moisture measurement techniques based on nuclear, hygrometric, electrical resistance, capacitance, electromagnetic, thermal, and gravimetric principles have been developed. However, success in obtaining the desired accuracy by these techniques has been varied (1).

Recently, because of their increased popularity and availability in the consumer market at a low cost, microwave ovens have attracted considerable attention as rapid moisture measuring devices. Research (2-8) performed to assess the feasibility of using a microwave oven in measuring the moisture contents of various highway materials has generally produced favorable results in terms of time savings and accuracy. However, some limitations have also surfaced. The purpose of this paper is to present an overview of the findings of this research.

In the following sections, principles of microwave heating and factors that affect the test results are briefly reviewed. Data obtained by the authors and data published by others form the basis for a comparison of moisture contents determined by microwave and conventional ovens. Predictive regression equations relating the two parameters are presented. Finally, conclusions and recommendations, including research needs, are provided at the end of the paper.

M.A. Usmen, Department of Civil Engineering, West Virginia University, Morgantown, W.Va. 26506. K.Y. Kheng, Department of Civil Engineering, University of Florida, Gainesville, Fla. 32611.

PRINCIPLES OF MICROWAVE HEATING

Microwaves are a part of the electromagnetic spectrum with wavelengths in the centimeter range, bounded by the longer radio waves and the shorter infrared light waves. The frequencies of microwaves range roughly between 10^3 and 10^6 MHz. The microwave oven is a device in which dielectric heating is effected by high-frequency electromagnetic waves. This type of heat forms as a result of dielectric losses that occur in a material that is located between the metal walls of the oven, which act as a capacitor connected to a high-frequency generator, the magnetron.

The effectiveness of dielectric heating in a microwave oven is strongly dependent on the polarity of the material exposed to the electromagnetic field. Polar molecules (called dipoles), in which the centers of positive and negative charge do not coincide, are in thermal equilibrium in the absence of an electromagnetic field. When an electromagnetic field in applied, the dipoles orient themselves quickly and repeatedly in the direction of the field. The continual molecular motion generated by the alternations of the field causes the material to heat by intermolecular friction. This type of heating is rapid because, unlike conventional heating, the heat does not need to be conducted through the material starting from the surface but is generated rather uniformly inside the material.

Microwaves are similar to lightwaves and can be absorbed, reflected, or transmitted by a given material. Only those materials capable of absorbing the microwaves can be effectively heated by them. The energy absorbed per unit volume of the material is directly proportional to the microwave frequency applied, the square of the field strength, and the dielectric constant of the material being heated (9). Water, having dipolar molecules, has a high dielectric constant (about 80 at room temperature) compared with most minerals found in soils (about 3 in the dry state and increasing with moisture) and will absorb the microwave energy readily. Thus it will heat at a much faster rate than will soil solids and will evaporate rapidly in a microwave oven. It has been found that the dielectric properties of a wide range of moist soils are completely dominated by the water phase (5,10).

FACTORS THAT AFFECT TEST RESULTS

Effective use of a microwave oven in drying or measuring the moisture content of highway materials depends on consideration of a number of factors, which are interrelated. These factors may be listed as (a) material type, (b) power setting, (c) exposure time and temperature, (d) sample size and use of multiple samples, (e) sample containers, and (f) alteration of material properties on exposure to microwaves.

Material Type

A wide variety of materials, including inorganic and organic clays, bentonite, diatomaceous earth, silt, sand, gravel, crushed stone, shale, coal-associated wastes, chalk, gypsum, and stabilized earth materials, has been tested in the microwave oven for moisture content. It has been found that, with the exception of organic soils, high-carbon-content waste materials, gypsum products, and metallic soils, most of the soils and aggregates commonly used in highway construction are suitable for microwave oven drying (2-8).

Materials such as bottom ash, fly ash, colliery shale, and fine coal refuse may contain appreciable quantities of unburnt carbon (coal). Such materials have been observed to smolder, smoke, or ignite on intensive exposure to microwaves, except when the coal content is quite low (i.e., below 1 or 2 percent) (4,8). According to Gilbert (5), organic materials such as peat also exhibit smoking and ignition problems when heated by microwaves and are thus not suitable for microwave oven drying. Ryley (4), however, has reported that a soil with high organic content could be successfully dried in the microwave oven (even at high power levels).

Complications exist with gypsum and gypsum-containing materials when dried in the microwave oven (2,4,8). In materials of this type, the loosely bound water of hydration can be driven off rapidly on exposure to microwaves at temperatures around 70°C, which are below the boiling point of free water. This causes inaccurate test results. Ryley (4) has shown that dehydration may occur even when gypsum is mixed with soil. Soils with high metal contents (iron ore, bauxite, etc.) apparently have a high affinity for microwave energy and overheat quickly when all the free water has been evaporated (5).

Stabilized materials, especially those treated with cement, are particularly suited for microwave oven drying because hydration is minimized during the rapid heating (2,4). The microwave oven has also been successfully used in determining the water content of plastic concrete mixtures (11,12).

Power Setting

Most of the microwave ovens presently available can be set to different power levels that vary from low to high. The amount of useful power absorbed affects the heating rate. Faster rates of heating and water evaporation can be achieved at the higher power settings of the microwave oven (7,8).

Ryley (4) studied the effect of power setting on the moisture content of various materials. Slight increases in moisture content were observed with increased power setting in soils and aggregates, and the problem of ignition was eliminated in some coal wastes at the lowest power setting. One soil exhibited a tendency to "jump off" the container at the highest power setting. A similar problem was noted by Kheng (8) with materials that are either too wet or too dry. It was observed that if the sample had excess moisture, splashing would occur, particularly at the high power setting. If the material was powdery and relatively dry, particles began to spread in the microwave oven after it was turned on. Air circulation in the oven appeared to play a role in this latter behavior. Both splashing and spreading in the microwave oven cause inaccurate moisture content results.

Exposure Time and Temperature

It is important to recognize that the time required to dry a wet sample at a particular power setting of the microwave oven depends on the amount of water present in that sample. Because temperature is normally not controlled in the microwave oven during heating (in contrast to the conventional oven), some adsorbed water may be driven off in addition to the free water if the samples are dried to constant weight. This phenomenon is more significant in plastic clays than in granular materials because of the presence of adsorbed as well as interlayer (hydroxyl) water (6,7). Figures 1 and 2 show, respectively, the relationships between microwave exposure time and temperature and exposure time and

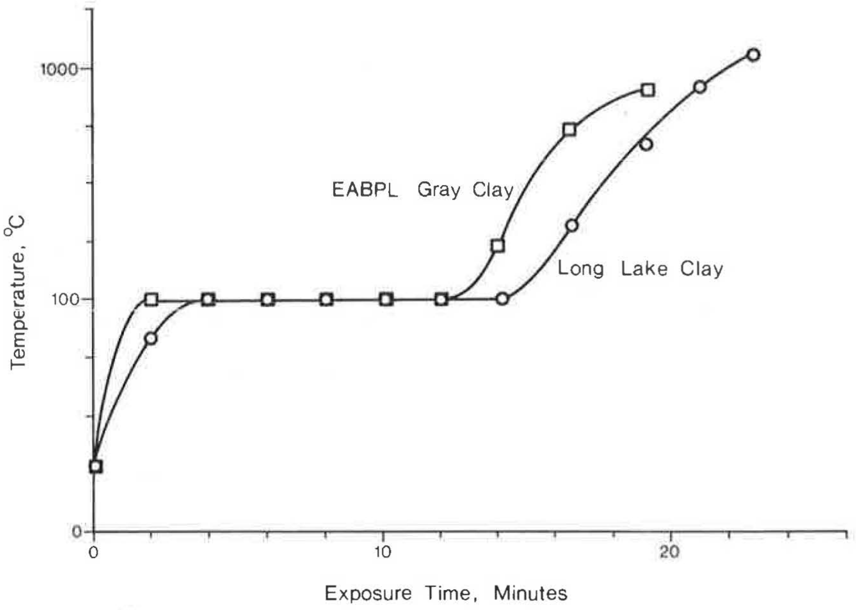


FIGURE 1 Temperature versus exposure time for two clays.

moisture loss for some clays. The temperature curves shown in Figure 1 indicate a plateau around 100°C after which a rapid heating of the sample occurs. This is typical of many soils heated by microwaves. The moisture loss curves shown in Figure 2, based on Ryley (4), are also quite typical of the drying behavior of soils in a microwave oven and a conventional oven until a constant weight is attained.

On the basis of a water evaporation temperature of 100°C and assuming a soil specific heat of 0.2 cal/g°C, Gilbert (5) derived an equation for the microwave exposure time needed to produce moisture contents comparable to those obtained by the conventional oven:

$$T = \{M\ [(0.2/W + 1)(100 - t) + 539]\ (4.18896)\}/P \quad (1)$$

where

T = time in microwave oven (sec),
M = mass of water present in the sample (g),
W = moisture content of the sample in decimal form,
t = ambient temperature (degrees Celsius), and
P = power output of the oven (watts).

A power-load calibration curve and a preestimate of the moisture content are required before this equation is used.

Studies have shown that in most practical situations an average period of from 5 to 30 min is sufficient for drying samples to constant weight in the microwave oven, which indicates a substantial time savings over the conventional oven drying process. However, the actual exposure times to obtain a constant weight in the microwave oven have been found to usually be longer than those predicted by Equation 1 (6,8). This is as expected because there is moisture loss beyond the 100°C plateau observed in

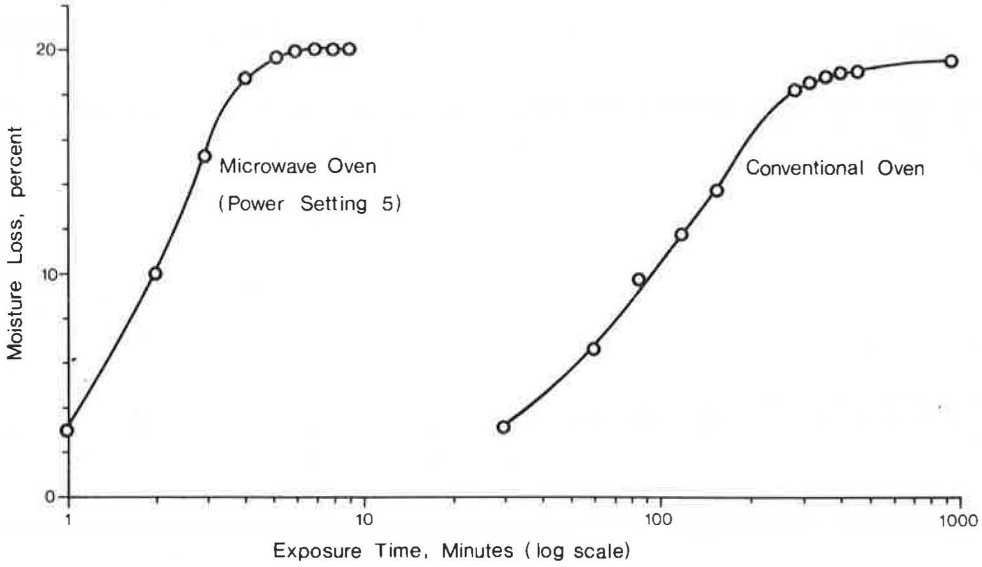


FIGURE 2 Moisture loss versus exposure time for London clay.

exposure time-temperature curves, and a constant weight is not necessarily attained on that plateau.

Because of the extended heating, moisture contents determined by the microwave oven are generally higher than those obtained by the conventional oven. This will be discussed in greater detail later. However, according to Charlie et al. (7), this problem can be alleviated for the most part if a temperature-controlled microwave oven is used.

Sample Size and Use of Multiple Samples

Studies by Lade and Nejadi-Babadai (6) and Charlie et al. (7) on different sized samples of homogenized cohesive soils indicate that increased sample size generally results in a reduction of the microwave oven moisture content. However, on the basis of comparisons of microwave and conventional oven test results for samples of different sizes, Charlie et al. (7) have also reported that sample size does not influence the accuracy of moisture content determinations, provided the sample is large enough to be accurately weighed. Sample weights in the range of from 10 to 500 g have been successfully used, with a 100- to 200-g range being the most common.

Drying multiple samples simultaneously in the microwave oven is not feasible, particularly if the samples belong to different materials or contain different amounts of water, or both (4,5). Not only would it take much longer for the specimens to dry together, but also a different exposure time would be required to dry each specimen, which renders this procedure highly impractical.

Sample Containers

It is essential that the sample containers used for drying materials in a microwave oven do not impede the microwaves, do not burn or deform, and do not experience any weight loss. Metal containers are not suitable because they reflect microwaves and spark when in contact with the shelf of the oven (4,5). Containers made of porcelain, borosilicate glass (Pyrex), polypropylene, and silica are preferable because of the favorable microwave transmission properties of these materials. Plastic and paper are also good microwave transmitters but they may be deformed and burned by the heat from the glass plate in the microwave oven (6).

Sample containers made of materials that heat by microwaves appear particularly suitable because water condensation on the cool container walls during heating will be minimized (4). Porcelain and borosilicate glass heat under microwave influence, whereas polypropylene and silica do not.

Alteration of Material Properties

Clays and clayey soils are known to experience changes in plasticity, shrinkage, and swelling characteristics when heated to temperatures above 100°C (13). Depending on the temperature, both adsorbed and interlayer water may be lost resulting in reduced plasticity and reduced swelling potential.

Lade and Nejadi-Babadai (6) studied the effects of microwave oven heating on the Atterberg limits of some clays. The liquid limit, the plastic limit, and the plasticity index were found to decrease for all soils when they had been preheated in the microwave oven. The largest reductions in these limits occurred for the highly plastic clays, and the smallest reductions were observed for the low-plasticity soils. The shrinkage limits tended to increase indicating a reduction in swelling potential. These effects are similar to those caused by drying soils in a conventional oven at high temperatures.

CONVENTIONAL VERSUS MICROWAVE OVEN MOISTURE CONTENTS

The accuracy and reliability of the moisture content test results determined by a microwave oven can be best evaluated by comparing these results with moisture content test results obtained on identical samples using a conventional oven. A good agreement or a good correlation between the two measurements would attest to the feasibility of using the microwave oven as a rapid moisture content measuring device. A modest amount of research data is available from studies conducted by the authors (8) and by other investigators (2,4,6,7) for such comparisons. A tabulation, analysis, and discussion of these data are presented herein.

Conventional versus microwave oven moisture contents for various highway materials, categorized as cohesive soils, granular soils and aggregates, special materials (wastes, shale, chalk, and bentonite), and stabilized materials, are given in Tables 1-4. The microwave oven moisture contents (W_m) shown in these tables are based on drying the materials to constant weight at the highest power setting of the oven, except for two samples as noted

TABLE 1 Conventional Versus Microwave Oven Moisture Contents for Cohesive Soils

W_c (%)	W_m (%)	ΔW ($W_m - W_c$) (%)	Material		Reference
			Description	Class	
13.46	13.80	+0.34		CH	(8)
19.52	19.72	+0.20			
24.75	24.64	−0.11			
44.07	44.33	+0.26			
67.31	67.52	+0.21			
14.20	14.70	+0.50		CL	(8)
19.42	19.57	+0.15			
23.81	24.33	+0.52			
34.26	34.67	+0.41			
64.83	65.45	+0.62			
11.45	11.65	+0.20		ML	(8)
16.73	16.94	+0.21			
21.78	21.87	+0.09			
30.45	30.82	+0.37			
40.69	40.97	+0.28			
85.39	85.60	+0.21	Wyoming brown clay	CH	(7)
100.38	103.28	+2.90	Black cotton soil	CH	
27.76	27.60	−0.16	Red brown clay	CL	(2)
30.65	30.42	−0.23	Quartzite silt		
147.3	148.6	+1.3	Haley clay	CH	(6)
119.8	121.2	+1.4			
86.1	88.3	+2.2			
60.9	63.3	+2.4			
96.3	97.8	+1.5	Grundite clay	CH	(6)
59.8	61.5	+1.7			
52.2	54.1	+1.9			
38.4	40.8	+2.4			
55.1	56.2	+1.1	H-soil	CL	(6)
49.0	50.4	+1.4			
40.1	41.6	+1.5			
42.7	43.0	+0.3	M-soil	CL	(6)
30.5	31.2	+0.7			
29.3	30.4	+1.1			
40.7	41.6	+0.9	L-soil	ML	(6)
32.4	33.5	+1.1			
26.5	27.9	+1.4			
20.1	20.5	+0.4	Gault clay		(4)
19.7	20.8	+1.1	London clay		
20.5	20.7	+0.2	Organic soil		
20.0	20.7	+0.7	Brick earth (A)		
21.4	22.3	+0.9	Brick earth (B)		

TABLE 2 Conventional Versus Microwave Oven Moisture Contents for Granular Soils and Aggregates

W_c (%)	W_m (%)	ΔW ($W_m - W_c$) (%)	Soil		
			Description	Class	Reference
2.19	2.28	+0.09	No. 57 limestone	GP	*(8)*
4.24	4.41	+0.17			
5.23	5.40	+0.17			
6.22	6.39	+0.17			
8.24	8.33	+0.09			
7.57	7.49	−0.08	Limestone sand	SM	*(8)*
10.55	10.70	+0.15			
13.39	13.74	+0.35			
16.49	16.78	+0.29			
26.54	26.76	+0.22			
3.33	3.31	−0.02	Ohio River sand	SP	*(8)*
6.35	6.41	+0.06			
9.36	9.41	+0.05			
12.43	12.47	+0.04			
20.37	20.44	+0.07			
19.44	19.69	+0.25	Medium-graded sand		*(2)*
22.55	22.60	+0.05	Coarse sand		
3.68	3.68	0.00	Gravel 3/8 in.-No. 4		
1.15	1.19	+0.04	Gravel 3/4–3/8 in.		
11.1	11.6	+0.05	Antelope Valley sand		*(6)*
15.1	15.3	+0.02	Silty sand		
8.0	8.0	0.00	Ottawa sand		
9.4	9.3	−0.1	Sulehay sand		*(4)*
9.3	9.1	−0.2	Wheatley gravel		
1.4	1.1	−0.3	Limestone (passing 20 mm)		

TABLE 3 Conventional Versus Microwave Oven Moisture Contents for Some Special Materials

W_c (%)	W_m (%)	ΔW ($W_m - W_c$) (%)	Material		
			Description	Class	Reference
Waste Materials					
12.70	13.99	+1.29	Bottom ash	GW-GM	*(8)*
16.73	18.21	+1.48			
20.65	21.74	+1.09			
24.70	25.57	+0.87			
13.42	13.70	+0.28	Low-carbon fly ash	ML	*(8)*
17.47	17.91	+0.44			
21.69	21.86	+0.17			
25.82	25.88	+0.06			
56.53	57.36	+0.83			
29.45	30.07	+0.62	Waste calcium sulfate	SM-SM	*(8)*
36.19	37.10	+0.91			
43.62	44.48	+0.86			
50.22	51.24	+1.02			
57.49	58.75	+1.26			
22.90[a]	25.00	+2.10	Weald clay + 20% calcium sulphate		*(4)*
10.2	10.4[b]	+0.2	Homs Hall pulverized fuel ash		
26.9	27.0	+0.1	Chalk (passing 5 mm)		
Shale					
133.70	134.47	+0.77	Bear Paw shale	CH	*(7)*
5.2	5.4[c]	+0.2	Colliery shale (unburnt, passing 20 mm)		*(4)*
Bentonite					
846.67	854.10	+7.43	Wyoming bentonite		*(7)*
906.5	926.1	+19.6	Black Hills bentonite		*(6)*
660.8	692.7	+31.9			
603.0	659.0	+56.0			
127.3	138.4	+11.1	Dixie Bond bentonite		*(6)*
116.6	130.3	+13.7			
70.1	84.1	+14.0			

[a] Dried at 80° C.
[b] Medium power setting.
[c] Low power setting.

TABLE 4 Conventional Versus Microwave Oven Moisture Contents for Stabilized Materials

W_c (%)	W_m (%)	ΔW ($W_m - W_c$) (%)	Material Description	Reference
37.95	37.88	−0.07	Clay with 3% lime	*(2)*
11.94	11.90	−0.04	Soil cement	
19.4	20.3	+0.9	Brick earth + 10% cement	*(4)*
20.2	21.7	+1.5	London clay + 10% cement	
9.6	9.9	+0.3	Sulehay sand + 10% cement	
8.7	9.2	+0.5	Wheatley gravel + 10% cement	

in Table 3. Except for the results obtained by Charlie et al. (7), no temperature control has been imposed on the samples in the microwave oven drying process. The conventional oven moisture contents (W_c) are based on drying the materials to constant weight at a controlled temperature of 110°C ±5°C, in line with the standard procedure, with one exception as noted in Table 3. To facilitate comparisons, the discrepancies between the two measurements ($\Delta W = W_m - W_c$) are provided in the tables. Material descriptions or unified soil classifications, or both, are also listed along with the original sources of data.

An examination of the ΔW values in Tables 1-4 reveals that a positive discrepancy exists between W_m and W_c in a great majority of cases. This clearly demonstrates the previously described observation that microwave oven moisture contents are predominantly higher than conventional oven moisture contents. It can also be easily seen from the same data that the discrepancies between the two measurements are greater for cohesive soils (Table 1), in most cases, than for granular materials (Table 2), with extremes being observed with bentonite (Table 3). Among the special materials listed in Table 3, the relatively large discrepancy noted for bottom ash is attributed to the high percentage of combustibles (a loss on ignition of 15 percent) in that material. The waste calcium sulfate materials (gypsum) also show large discrepancies, as would be expected. The results shown for stabilized materials in Table 4 show negative ΔW values in one case and positive ΔW values in the other. It is the authors' belief that the latter case would prevail most of the time if moisture losses due to hydration were eliminated by rapid drying in the microwave oven.

Quantitatively, the discrepancy between microwave and conventional oven moisture contents for granular materials appears to be generally within 0.25 percent, indicating an excellent agreement between the two measurements. The discrepancies between the two measurements in cohesive soils vary over a much wider range, exceeding 0.5 percent in many cases. The discrepancies for bentonite are enormously high, mostly above 10 percent. The agreement between microwave and conventional oven moisture content results is obviously not very good for cohesive soils in general and is particularly poor for highly plastic clayey materials.

The conventional versus microwave oven moisture content data provided in Tables 1-4 are presented graphically in Figures 3-6 for further analysis. Only the data on cohesive soils (Figure 3), granular soils and aggregates (Figure 4), bentonite (Figure 5), and stabilized materials (Figure 6) are included. Because of the potential unreliability of test results, or insufficiency of data, no attempt is made to further analyze the waste materials, chalk, and shale. The dashed diagonal lines shown in Figures 3-6 depict the case of perfect agreement between the

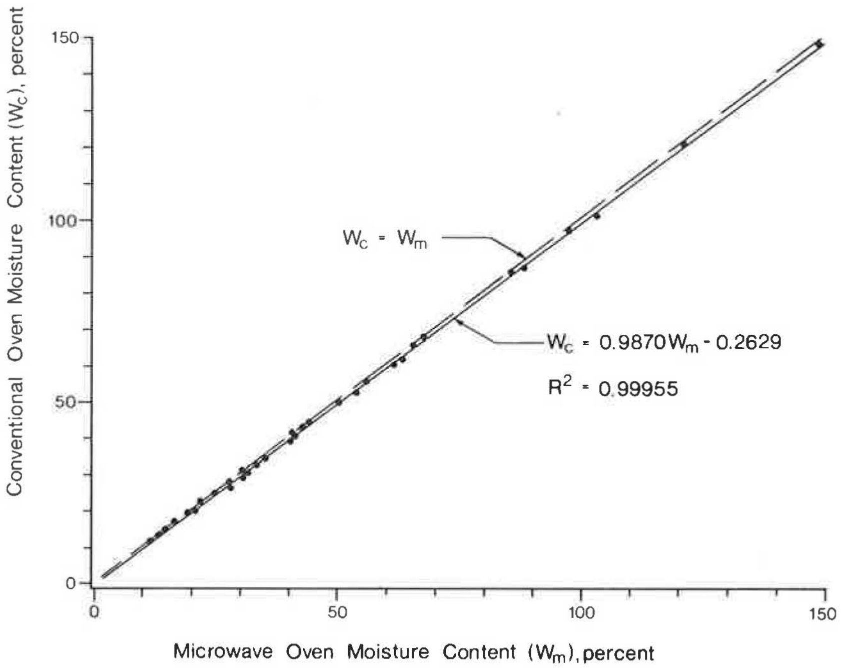


FIGURE 3 Conventional versus microwave oven moisture contents for cohesive soils.

two test results ($W_c = W_m$), around which the scatter of the data points (W_m, W_c) can be observed. The solid lines are obtained by linear regression analyses, and the appropriate regression equations and the corresponding R^2 (square of the coefficient of correlation between W_m and W_c) values are also shown in the figures.

It can be readily seen in Figures 3-6 that, in all cases, a great majority of the data points and their regression lines fall below the $W_c = W_m$ line, reinforcing the predominant positive discrepancy between W_m and W_c. The exceedingly high R^2 values suggest that the variables W_m and W_c are strongly correlated, and one (W_c) can be con-

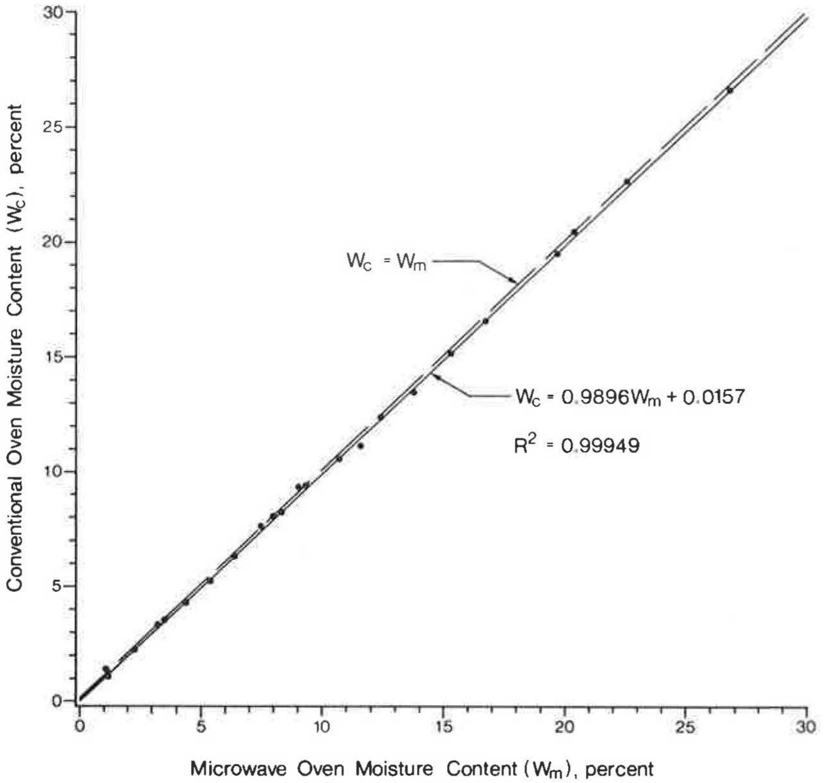


FIGURE 4 Conventional versus microwave oven moisture contents for granular soils and aggregates.

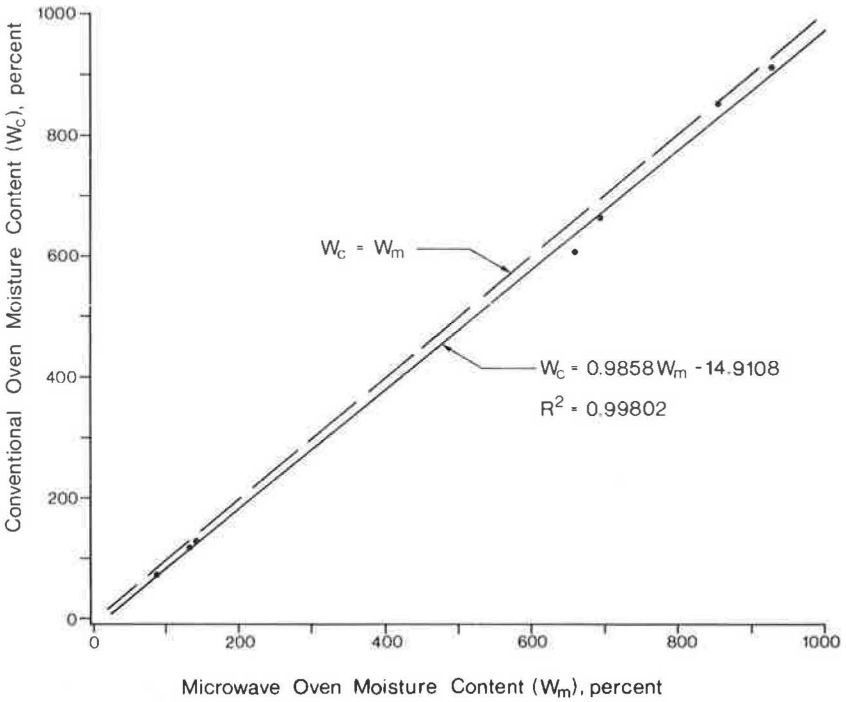


FIGURE 5 Conventional versus microwave oven moisture contents for bentonite.

sistently predicted from the other (W_m). Although the data base used in this analysis is not extensive, the regression equations provided can serve as predictive models for estimating the standard conventional oven moisture contents from microwave oven test results for materials that are similar to the ones used in this analysis.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the review and analysis of research results presented in this paper, the following conclusions and recommendations are warranted:

1. The microwave oven shows good potential as a

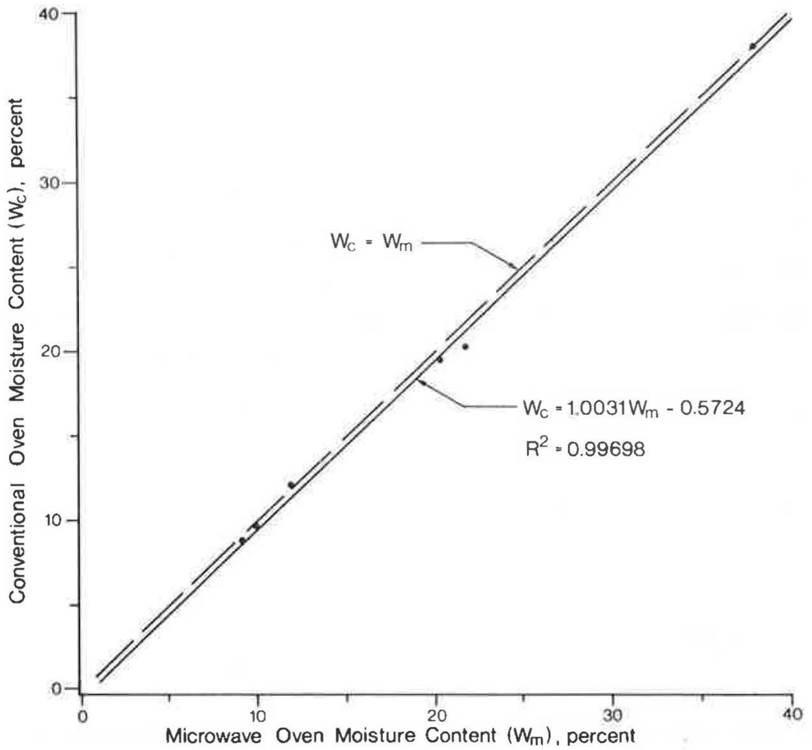


FIGURE 6 Conventional versus microwave oven moisture contents for stabilized materials.

practical and inexpensive device that can be used for rapid determination of the moisture content of many soils and aggregates used in highway construction. Because of practical constraints, the microwave oven is not recommended at this time for drying organic soils, metallic soils, coal-associated wastes, and gypsum-containing materials. It is, however, applicable to stabilized materials such as soil-cement.

2. Granular materials produce the most accurate microwave oven moisture content test results. The accuracy of the method is relatively poorer for cohesive soils, and the accuracy decreases with increasing plasticity. Microwave oven moisture contents are mostly higher than conventional oven moisture contents for all materials because of the lack of temperature control in microwave drying. It appears that temperature control may improve accuracy.

3. The time required to dry soil samples in the microwave oven at a given power setting will depend on the amount of moisture present. However, in most practical cases, materials can be dried to a constant weight at the high power setting within less than 30 min. This is a substantial time saving over the standard procedure using the conventional oven.

4. Simultaneous drying of multiple samples in the microwave oven and use of metal, plastic, and paper sample containers are not recommended. Porcelain and borosilicate glass containers are the most appropriate.

5. Soils (especially clays) dried by microwaves experience changes in plasticity, shrinkage, and swelling characteristics. Thus it is not advisable to use the microwave oven for preparing (drying) soils for other tests in which these factors may be significant.

6. Although discrepancies exist between microwave and conventional oven moisture contents, the two variables are strongly correlated. Hence, regression equations, such as the ones provided in this paper, can be used to predict the standard conventional oven moisture contents from rapid test results obtained by the microwave oven, when experience indicates that such a procedure is warranted.

7. There is an apparent need for further research aimed at the standardization of the microwave oven drying process for moisture content determination. The effects of factors discussed in this paper on the accuracy of the test results must be fully studied as part of this research. Basic research is also needed to further understand the mechanisms involved in the drying of various soils and other highway materials with particular focus on the physicochemical and dielectric properties of the materials.

8. Finally, users of microwave ovens should be cautioned against the potential hazards of the microwaves. Besides presenting radiation hazards if proper safety precautions are not observed, microwaves affect heart pacers at substantial distances.

ACKNOWLEDGMENTS

The support of Triad Engineering Consultants, Inc., Morgantown, West Virginia, in providing the funds and materials to perform the work to produce the data and information presented in this paper is gratefully acknowledged.

REFERENCES

1. L.F. Ballard. Instrumentation for Measurement of Moisture: Literature Review and Recommended Research. NCHRP Report 138. HRB, National Research Council, Washington, D.C., 1973.
2. A.E. Creelman and V.E. Vaughan. Determination of Moisture Contents of Soil Samples by Microwave Heating. Proc., 1966 Convention of the Canadian Good Roads Association, Halifax, Nova Scotia, Sept. 1966, pp. 459-464.
3. B.B. Algee, J.C. Callaghan, and A.E. Creelman. Rapid Determination of Moisture Content in Soil Samples Using High Power Microwaves. IEEE Transactions on Geoscience Electronics, GE-7, No. 1, Jan. 1969, pp. 41-43.
4. M.C. Ryley. The Use of a Microwave Oven for the Rapid Determination of Moisture Content of Soils. RRL Report LR 280. Road Research Laboratory, Ministry of Transport, Crowthorne, Berkshire, England, 1969.
5. P.A. Gilbert. Feasibility Study--Microwave Oven Used for Rapid Determination of Soil Water Contents. Evaluation of Soil Mechanics Laboratory Equipment, Report 13. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Aug. 1974.
6. P.V. Lade and H. Nejadi-Babadai. Soil Drying by Microwave Oven. ASTM STP 599: Soil Specimen Preparation for Laboratory Testing. ASTM, Philadelphia, Pa., 1976, pp. 320-340.
7. W.A. Charlie, M.W. Von Gunten, and D.O. Doehring. Temperature Controlled Microwave Drying of Soils. Geotechnical Testing Journal, Vol. 5, Nos. 3/4, Sept./Dec. 1982, pp. 68-75.
8. H.Y. Kheng. Use of the Microwave Oven for the Rapid Determination of Soil Moisture Content. Master's thesis. West Virginia University, Morgantown, Dec. 1984.
9. H. Puschner. Heating with Microwaves. Phillips Technical Library, Springler-Verlag, Inc., New York, 1966.
10. J.R. Lundien. Terrain Analysis by Electromagnetic Means: Laboratory Measurement of Electromagnetic Propagation in the 1.0 to 1.5 GHz Microwave Spectral Region. Technical Report 3-693, Report 5. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1971.
11. R.T. Peterson and D. Leftwich. Determination of Water Content of Plastic Concrete Using a Microwave Oven. Final Report, FCP 44F3-313. North Dakota State Highway Department, Bismarck; FHWA, U.S. Department of Transportation, Sept. 1978.
12. D.E. Beecroft and R.L. Dominick. Rapid Test Methods for the Evaluation of Concrete Properties. Final Report, DOT-FH-11-8876. Oregon State Highway Division, Salem; FHWA, U.S. Department of Transportation, Jan. 1982.
13. R.E. Grim. Applied Clay Mineralogy. McGraw-Hill Book Co., New York, 1962.

The contents of this paper reflect the views of the authors based on their interpretation of the available research data. This paper should not be regarded as a specification or standard for performing moisture content tests using the microwave oven.

Publication of this paper sponsored by Committee on Mineral Aggregates.

Comparative Study of the Cost of Portable Concrete Barriers for Construction Zones

RODGER J. KOPPA

ABSTRACT

One of the bases for comparatively rating different designs of portable concrete barriers for use in construction zones is the cost of fabricating, transporting, installing, and removing these units. Ten different designs for joining these barriers and three different lengths (10, 20, and 30 ft) were considered in this theoretical cost analysis. The analysis was supplemented by a limited amount of field research in which typical operations of installation and relocation were observed. Standard sources were used for estimating costs of fabrication of the barriers and joint hardware, and these estimates were compared with actual costs reported for some of the concepts that were actually being used. Transport, installation, and removal costs were derived from actual time studies of operations, contractor charges, and analyses. Maintenance costs were extrapolated from previous studies in which encroachments as a function of roadway geometry and traffic data were estimated and then combined with transportation and installation costs that had been previously obtained. A methodology for a complete cost estimate for the engineer contemplating use of portable concrete barriers in a construction site is presented and illustrated by several examples. There appears to be a clearcut cost advantage to using longer length barriers (30 ft) instead of shorter sections for any design joint.

To develop a solid basis for comparative rating of portable concrete barrier concepts, a number of cost estimates were performed on various aspects of fabricating, installing, relocating, maintaining, and removing these barriers at construction sites. Some of this work was based on field observations carried out in the early summer of 1983, and some was based on estimates of the tasks and manpower and equipment times and costs that it might take to perform these operations. As will be described later, man-minute and equipment-time estimates for analytic cases were based on standard construction industry information such as that obtainable from the Dodge Manual (1). Other pricing guides were used as a backup, and industrial engineering standard references were used to estimate time for jobs such as joint fabrication.

DESCRIPTION OF BARRIER CONCEPTS

Ten different portable concrete barrier (PCB) concepts were used in this analysis. They run the gamut, as far as joint design is concerned, from the simplest tongue-and-groove or mortise design to a complex interlocking joint. All but one of these joints (bottom T-lock, Concept C8) are in use somewhere in the United States. Except for details of reinforcing steel and hardware cast into the body of the barrier itself, these 10 concepts differ only in joint design. Each design is also considered for three different lengths: 10, 20, and 30 ft. Other lengths, of course, are both feasible and occasionally found in use, but the results of the analyses presented in this paper can readily be interpolated for any length less than 30 ft. For lengths greater than 30 ft physical limitations of cranes and flatbed truck trailers assumed or observed in this study would greatly and nonlinearly change these cost estimates.

The 10 concepts studied were as follows:

C1: Tongue and groove (Figure 1),

C2: Steel dowel joint (Figure 2),

C3: Grid slot--a gridiron inserted down a slot in the ends of abutting PCBs (Figure 3),

C4: Top T-lock--a T-shaped connector is pinned on each side of a joint (Figure 4),

C5: Lapped joint--each end of a PCB at a joint is scarfed to overlap and a single bolt holds the joint together (Figure 5),

C6: Pin and rebar--a long bolt drops through rings embedded in the ends of each PCB to form a hingelike joint (Figure 6),

C7: Vertical I-beam--the joint consists of an I-beam that is dropped through a split pipe embedded in each PCB end (Figure 7),

C8: Bottom T-fork--somewhat like C4 but pins become short pipe ends and the PCBs are placed over the joint assembly (Figure 8),

C9: Channel splice--channel sections are bolted across the two PCB ends to form the joint (Figure 9), and

C10: Welsbach--steel T-hooks engage matching slots in the mating end of a PCB to form an interlocking joint (Figure 10).

FIELD RESEARCH

Field research was performed in the late spring and early summer of 1983 to witness at first hand actual operations by several different contractors and to conduct time and motion studies of representative PCB handling procedures. With the very kind assistance of the Texas State Department of Highways and Public Transportation (SDHPT), resident maintenance engineers in all the major urban districts of the department were contacted and asked to alert TTI

Texas Transportation Institute and Department of Industrial Engineering, The Texas A&M University System, College Station, Tex. 77843.

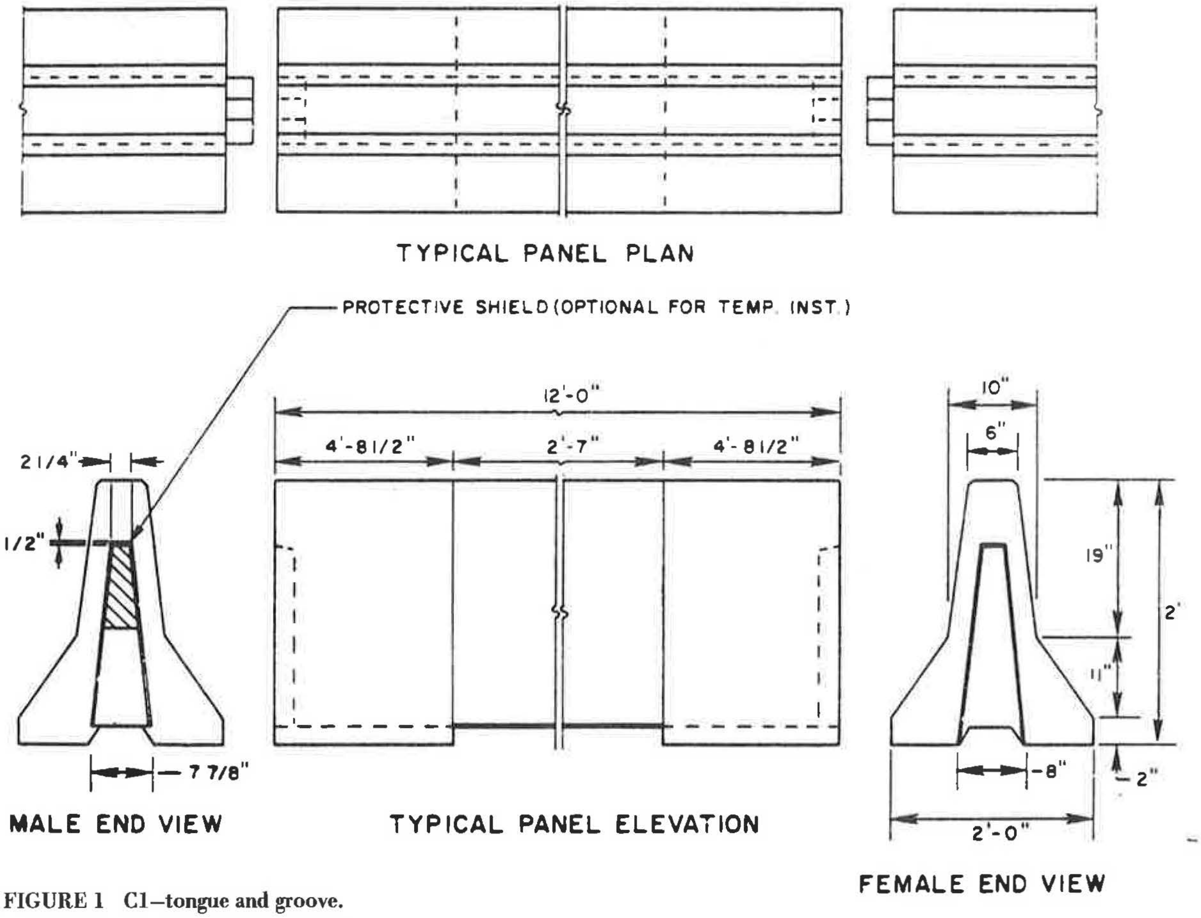


FIGURE 1 C1—tongue and groove.

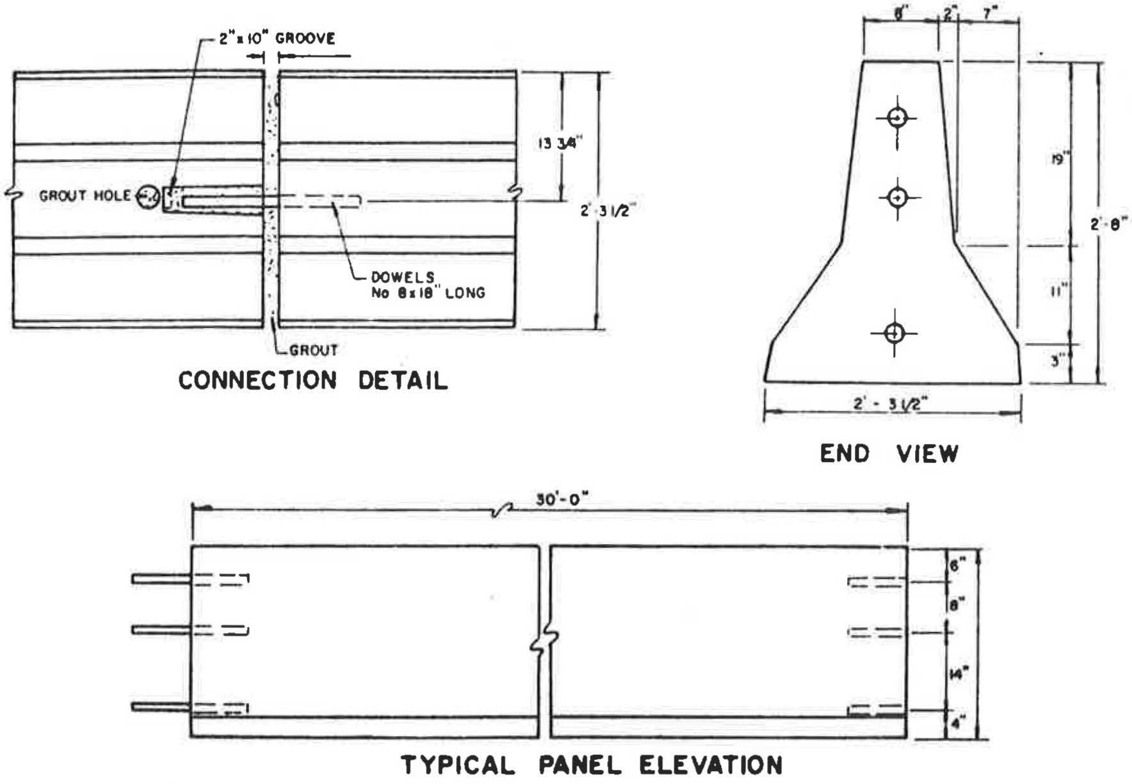


FIGURE 2 C2—dowel.

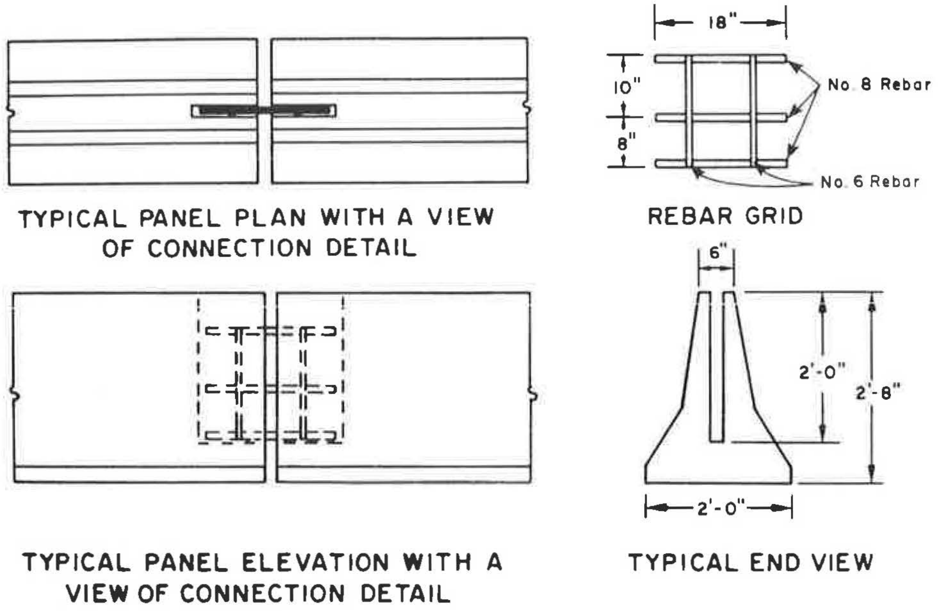


FIGURE 3 C3–grid slot.

researchers when movement, installation, or removal of PCBs was scheduled in their district. Three field trips resulted from this. Each trip followed the same protocol, which is described next.

Researchers traveled to the site and checked in with the SDHPT supervisor and the contractor supervisor. After observing several cycles of manipulation of the PCBs, individual procedure times were taken by stopwatch. Still photographs of the joint design and representative stages in moving, loading, and placement of PCBs were made. Then several complete cycles were videotaped. Supervisory personnel were debriefed to clear up any details. The three sites visited were

1. State Highway 288, just north of city limits of Angleton, Texas. This was a relocation job, ancillary to widening the pavement. The barriers were of the C9 type, channel splice.

2. I-35 west of the Dallas downtown area, relocation job to protect the median while the median barrier was being improved from a steel W-beam to a concrete median barrier. The joint type was C5, lapped joint.

3. I-10 west of Houston, PCB placement job as part of the creation of a median dedicated lane for a mass transitway. These barriers will ultimately become permanent CMBs. The joint design was C3, grid slot.

COST OF FABRICATION OF PORTABLE CONCRETE BARRIERS

Estimates for Casting Barriers

Cost estimates for casting the main structure of portable concrete barriers (PCBs) were derived from several sources. The Dodge Manual (1) indicated a

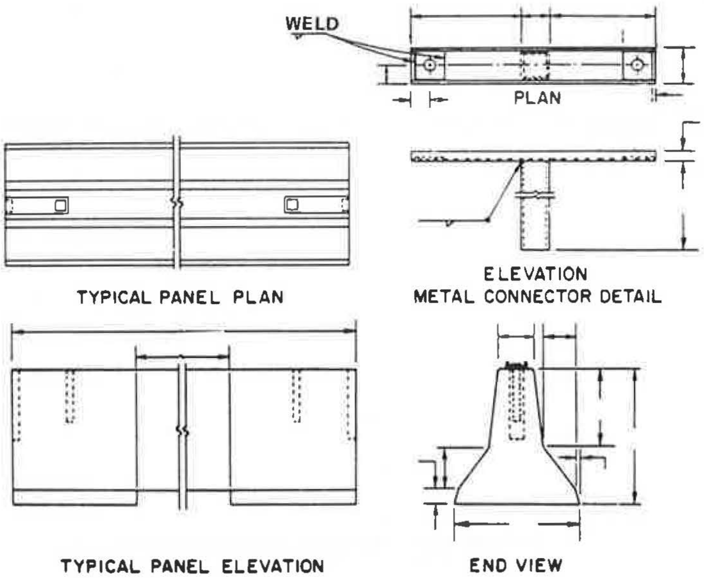


FIGURE 4 C4–T-lock.

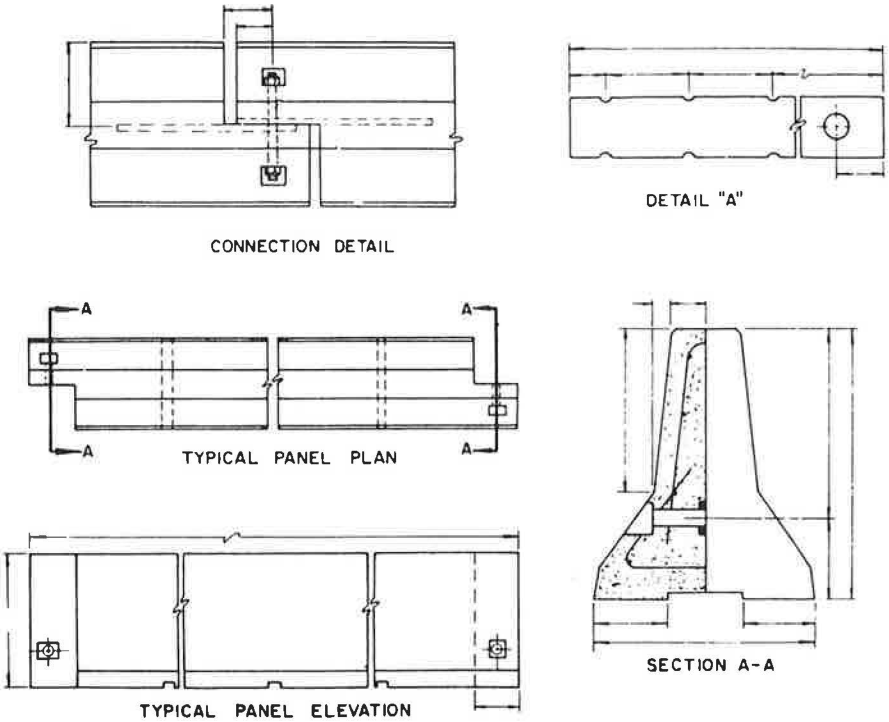


FIGURE 5 C5—lapped joint and bolt.

cost per linear foot of nearly $84 for the construction of precast beams that are approximately the size (through not the shape nor for the same purpose) of PCBs. The cost to TTI for special experimental PCBs was $80 per foot. Reports from other sources in state highway departments suggested that in large quantities (which would characterize operational purchases of PCBs) the price for these barriers would be on the order of $16 to $30 per foot. The $16 price was for materials, casting, and labor exclusive of any special provisions for joints. For purposes of comparing different concepts, because they differ principally in the design of the joint, a figure of $16 per linear foot was used for all PCBs in this study. The value is a reasonable approximation of cost to produce without overhead or profit to the contractor (i.e., direct costs to fabricate).

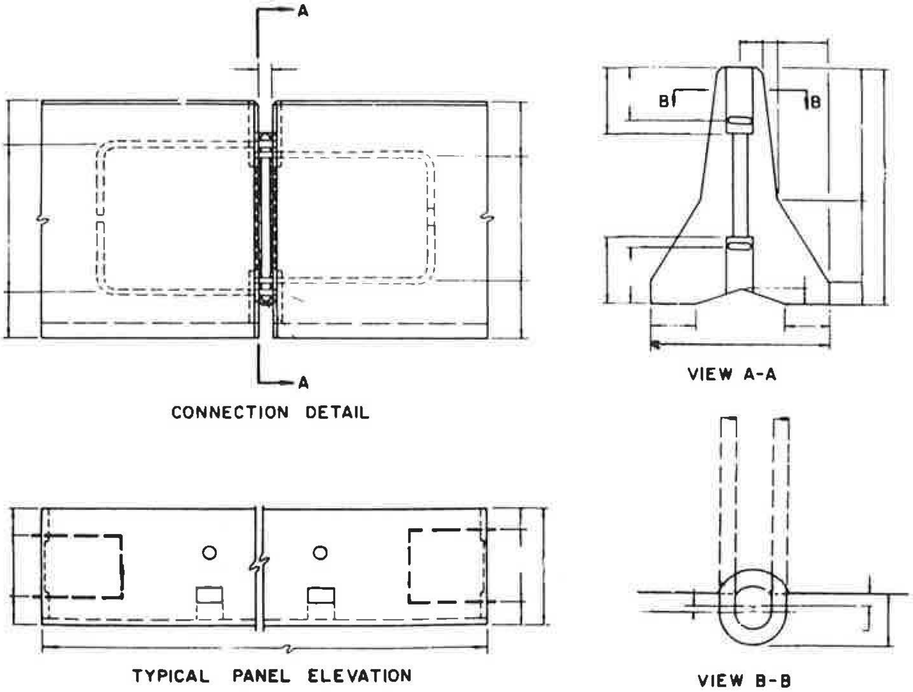


FIGURE 6 C6—pin and rebar.

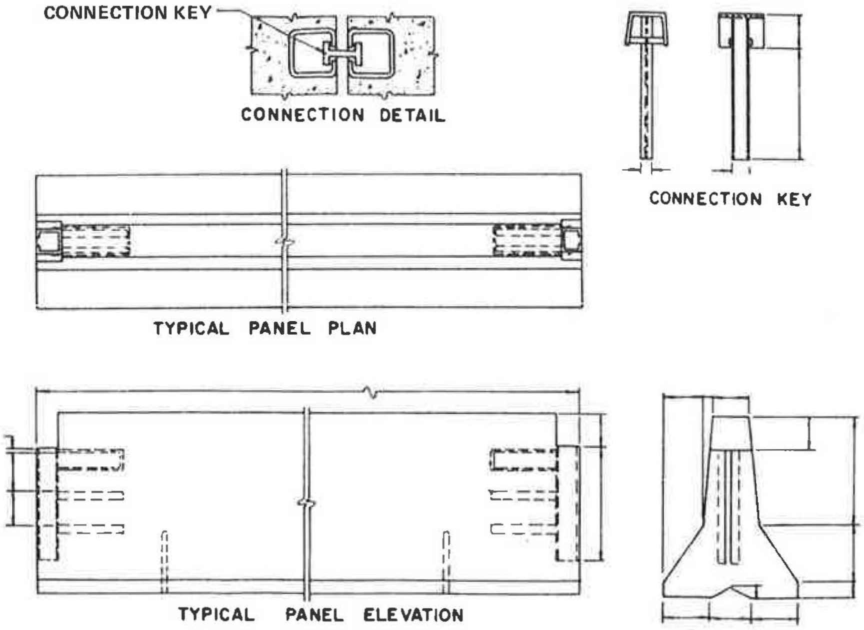


FIGURE 7 C7–I-lock.

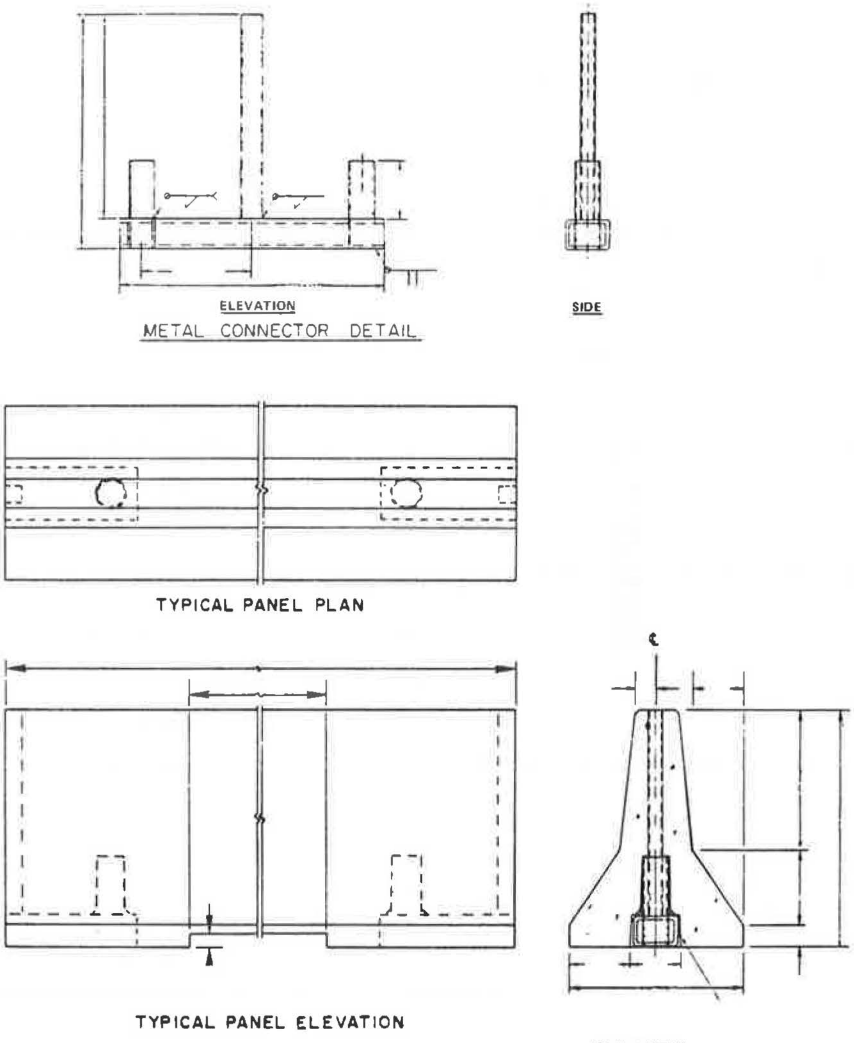


FIGURE 8 C8–T-fork.

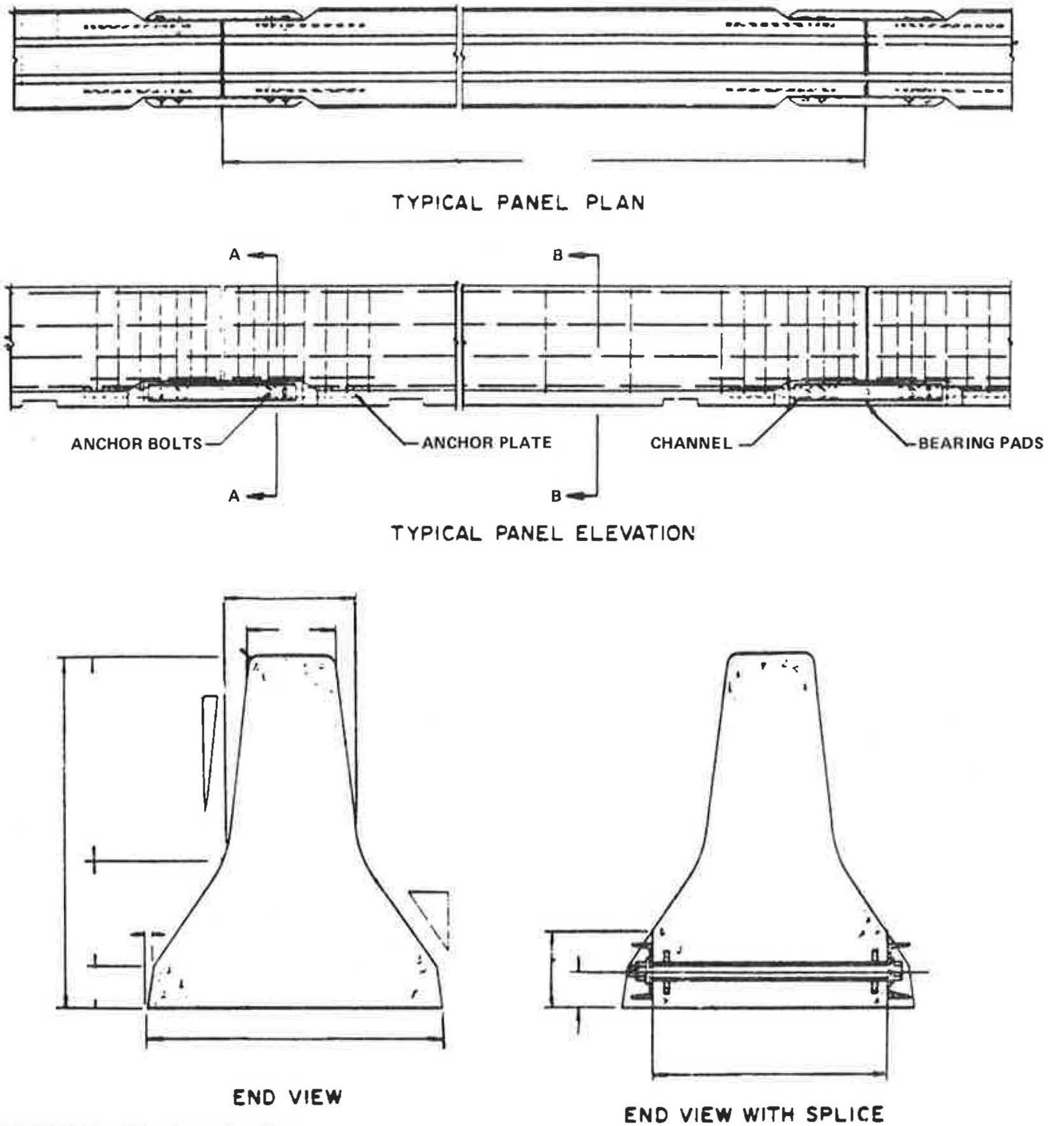


FIGURE 9 C9—channel splice.

Estimates of Costs of Joint Fabrication

It was necessary to make a number of assumptions in analyzing the work and materials involved in fabricating joints. The 20-city labor cost average from the Dodge Manual was used as a basis for all fabrication labor. The categories of general work or laborer, welder, and skilled metal worker/machinist were used. These labor costs do not include overhead or profit for the contractor but do include fringe benefits and a 22 percent surcharge for insurance and taxes. Costs are as follows:

General labor	$16.54 per hour
Welder	$20.00 per hour
Skilled machinist	$21.50 per hour

Material costs were obtained by inquiry to several local suppliers of building and construction metal. Fabrication times were estimated by using the following rationale.

It was assumed that no special tooling or mandrels except for stamped metal parts would be used and that fabrication would involve only general shop machinery such as drill presses, lathes, brakes, bending machines, and electric arc welders. It was assumed that suitable modifications could be made in any PCB casting assembly to accommodate the joint system without extra cost to the major casting operation. Another assumption was that fasteners (i.e., bolts and nuts) would be purchased at commercial rates and not specially fabricated. Costs for the purchase of these items were estimated from the Dodge Manual, and prices were cross-checked in Engelsman (2). Cutting, welding, and forming man-minute rates were estimated by reference to standard sources such as Niebel (3) and Carmichael (4). These estimates should thus be considered to be quite conservative (i.e., high, because a large contract to fabricate PCB would lead most fabricators to invest in some kind of special tooling and mass production techniques to facilitate joint fabrication). Although the cost per joint might be less if mass production techniques were used, the relative cost for fabrication of one joint versus another should hold.

Analysis, with a good measure of engineering judgment, of the 10 different PCB joints yielded Table 1. Each joint is considered as a unit. Column 1 identifies the concept; Column 2 briefly lists the

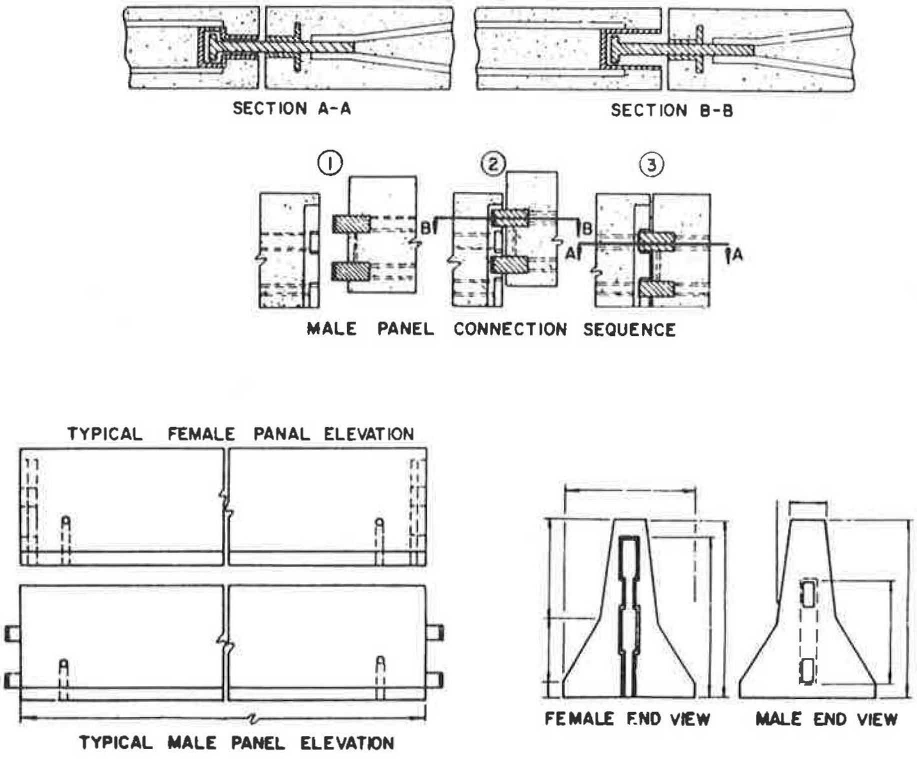


FIGURE 10 C10–Welsbach interlock.

hardware that must be fabricated or procured to make the joint. The manufacturing operations needed to ready the joint parts for incorporation in the casting of the PCBs are listed in Column 3. These costs range from a minimum of about $3 for C1, tongue and groove, to a high of $87 for the complex Welsbach design (C10).

These joint fabrication costs operate on the base cost of $16 per linear foot for casting PCB as shown in Table 2 for three different lengths of PCB, 10, 20, and 30 ft. Obviously, cost per foot decreases as the length of PCB increases. These costs run from a minimum of $16.10 for a 30-ft tongue-and-groove PCB to $24.70 for a 10-ft Welsbach jointed section.

TABLE 1 Joint Fabrication Cost Analysis

Concept	Hardware Required	Manufacturing Operations	Material Cost ($)	Labor Cost ($)	Total Direct Cost ($)	Nearest $1.00
C1	Nose cap over tongue	Cut Stamp	2.40	0.69	3.09	3.00
C2	Steel rods	Cut	3.20	0.33	3.53	4.00
C3	Grid of steel bars	Cut Weld	5.33	1.69	7.02	7.00
C4	Channel Tubes Plates Pins	Cut Drill Weld	9.00	3.52	12.52	13.00
C5	Bolt Re-plates	Cut notch Drill	8.55	1.72	10.27	10.00
C6	Rebars Bolt	Cut and form bars	13.62	7.08	20.70	21.00
C7	I-beam Tubes Re-plates	Cut Slot Weld	24.27	14.82	39.09	39.00
C8	Tube base Pipe Tubes	Cut Split Weld	34.00	4.15	38.15	38.00
C9	Channel 4 bolts Re-plates	Cut Drill Clear	50.00	5.35	55.35	55.00
C10	T-rails L-anchors Socket assembly Anchors	Cut Form Bend Weld	45.96	41.16	87.12	87.00

TABLE 2 Fabrication Costs

Concept	Length (ft)	Joint Cost (to nearest $1.00)	Total Cost per Foot ($)	Total Cost per Section ($)
C1	10	3.00	16.30	163.00
	20	3.00	16.15	323.00
	30	3.00	16.10	483.00
C2	10	4.00	16.40	164.00
	20	4.00	16.20	324.00
	30	4.00	16.13	484.00
C3	10	7.00	16.70	167.00
	20	7.00	16.35	327.00
	30	7.00	16.23	487.00
C4	10	13.00	17.30	173.00
	20	13.00	16.65	333.00
	30	13.00	16.43	493.00
C5	10	10.00	17.00	170.00
	20	10.00	16.50	330.00
	30	10.00	16.33	490.00
C6	10	21.00	18.10	181.00
	20	21.00	17.05	341.00
	30	21.00	16.70	501.00
C7	10	39.00	19.90	199.00
	20	39.00	17.95	359.00
	30	39.00	17.30	519.00
C8	10	38.00	19.80	198.00
	20	38.00	17.90	358.00
	30	38.00	17.27	518.00
C9	10	55.00	21.50	215.00
	20	55.00	18.75	375.00
	30	55.00	17.83	535.00
C10	10	87.00	24.70	247.00
	20	87.00	20.35	407.00
	30	87.00	18.90	567.00

COST ESTIMATES FOR BARRIER ASSEMBLY, DISASSEMBLY, AND RELOCATION

Bases for Cost Estimates

The primary basis for estimating the costs of (a) picking up barrier sections from a depot, transporting them to a construction site, and placing them; (b) relocating barrier sections from one location to another within a construction site as the work progresses; and (c) picking up barrier sections and returning them to a depot was observation of typical operations of this type at three construction sites: the C9, channel splice, concept at Angleton on TX-288; the C5, lapped joint, on Stemmons Freeway, I-35 in Dallas; and the C3, grid slot, on I-10 west of Houston. Table 3 gives a summary of these observations in terms of man-minutes of labor required plus some estimated times based on similarity to these operations.

Some contractors were much more labor intensive than others in hoisting and placing these barriers. In one operational sequence two men place hoisting rods and lifting cables on a flatbed trailer (four barriers are carried at one time). Two other workers wait below. Four men under a supervisor's direction are used to maneuver the barrier section into place (one of the workers, just before final placement, places a plywood spacer between the sections to assure proper clearance for the joint. The workers then remove the hoisting rods after final placement of the section. A typical time for this operation was 2 min. The final task is to drop the grid in the slots to complete the joint.

Another contractor uses C-shaped hooks on a spreader beam to expedite handling of PCBs. The crew consists of only two individuals for maneuvering (and sometimes securing or releasing the hooks) and the supervisors operate the crane. This operation takes about 1 min with less than half the manpower of the first contractor.

For costing typical operations, it was assumed that most contractors would use the more labor-intensive, less specialized equipment approach for lifting and moving the sections. It was assumed that contractors would use forklift trucks for 10-ft sections but a "cherry-picker" or similar self-propelled crane (approximately 20- to 30-ton capacity) for longer sections. Contractors informed researchers that at least three flatbed trucks were used for relocating barrier sections within a construction zone (less than 2 mi) but five were used for initial placement from a depot or for return to a depot if the depot was more than 2 but less than 10 mi distant. These numbers were used in this analysis. It was further assumed that the crane or forklift was rented equipment but that trucks were owned by the contractor. Only operating costs and 5-year straight-line depreciation on the trucks were considered plus, of course, direct costs for operator or driver labor. These costs worked out as follows (1):

- Truck, flatbed, 1/2 day = $64,
- Crane, 22-ton capacity, 1/2 day = $165, and
- Forklift, 9-ton capacity, 1/2 day = $138.

Not considering direct costs for transportation but only labor required for operations at site, the labor man-minutes estimates shown in Table 4 were derived and used as a basis for further analysis.

TABLE 3 Summary of Man-Minutes for Operations[a]—Comparison of PCB Designs with Respect to Disassembly, Pickup, Placement, and Reassembly

Design	Disassembly	Pickup	Placement	Reassembly	Total
Concept					
C3	0.10	9.00	$\boxed{12.54}$	$\boxed{0.10}$	21.74
C5	$\boxed{0.60}$	$\boxed{3.88}$[b]	$\boxed{5.40}$[b]	0.60	10.48
C9	$\boxed{6.00}$	$\boxed{8.75}$	12.30	6.00	33.05
Rank Order					
C3	1	2.5	2.5	1	8
C5	2	1	1	2	6
C9	3	2.5	2.5	3	11
Typical		8.88	12.42		

Note: Actual costs are boxed; others are estimates.

[a] Exclusive of transportation costs.

[b] Ratio of placement to pickup is 1.40.

TABLE 4 Labor (man-minutes) for Moving PCB

Design	Disassembly	Pickup[a]	Placement[a]	Reassembly	Comments
C1	0	2.69	3.00	0	1 (perhaps)
C2	0	2.69	3.00	0	1
C3	0.03	2.69	3.77	0.03	2
C4	0.11	2.69	3.77	0.11	2
C5	0.17	2.69	3.00	0.17	3, 4
C6	0.55	2.69	3.77	0.55	2
C7	0.03	2.69	3.77	0.03	2
C8	0	2.69	3.77	0	2
C9	2.00	2.69	3.77	2.00	2, 3, 4
C10	0	2.69	3.77	0	1, 2

Note: Placement requires 12.42 man-minutes (including penalty) and pickup requires 8.88 man-minutes.

Comments: 1. Constrains replacement of individual sections. 2. Requires precise alignment and spacing (20% penalty on placement). 3. Bolts become damaged; disassembly cost can be much higher. 4. Crew size of two for disassembly/assembly.

[a] Mean cost is average of four laborers at $16.54/hr, one crane operator at $21.50/hr, and one supervisor at $21.50/hr = $18.20.

Transportation of barrier sections was costed at $64 per truck for a 4-hr period, and $17.33 per hour for the driver.

Cost Estimates for Relocating Barriers

A nominal job consisting of moving 1,000 ft of barrier was used through this and the following movement analyses. Because 10-ft sections can be picked up by one man on a forklift, at a wage of $21.50 per hour, and he can place 1,000 ft of barrier in 4 hr, the cost of initial pickup is $21.50 x 4/100 or $0.86 per section. Costs of labor for a 30-ft section are, of course, much higher, $2.69, but because there are only 33 sections to be moved, the total cost of pickup is comparable. These cost estimates plus others are shown in Table 5. Note that transportation cost is invariant because a 60,000-lb capacity flatbed, a standard size in the industry, can handle four 30-ft sections, four 20-ft sections, or twelve 10-ft sections.

Section placement costs are taken from Table 4 for the 30-ft section operations already described. The 10-ft sections are assumed to require a two-man crew: one on a forklift at $21.50 per hour and a worker on the ground to assist in placement and use the spacer at $16.54 per hour. These costs multiplied by a 4-hr time period total $152 for 100 sections placed, or $1.52 per section.

Joint disassembly times are costed out from observational or analytic data summarized in Table 4 and then multiplied by the number of joints that must be disassembled for a 1,000-ft barrier. This same logic applies to assembly costs. Then equipment rentals are totaled in, assuming that equipment cannot be rented for less than a half day and that a 1,000-ft job would indeed require 4 hr. Finally, total estimated costs for this 1,000-ft relocation within a site are presented. As a check on this entire analysis, several contractors doing work for the Texas State Department of Highways and Public Transportation were queried for the direct cost they charge for this operation. These estimates were in the range of $1 per foot, an excellent agreement with the results of this analysis.

The mean cost per foot for relocating 10-ft sections is $1.19, with a range of from $1.11 to $1.54, whereas the mean cost for 30-ft sections is $0.95, and the range is from $0.92 to $1.07. The major cost differential in this 25 percent difference is attributable to joint disassembly and assembly operations, even though less manpower is required for 10-ft sections. Twenty-foot sections would tend to reflect an intermediate cost more like the 30-ft sections because handling equipment is much the same for these sections as it is for 30-ft sections.

Cost Estimates for Initial Installation of Barriers

Costs for bringing barriers from a depot to the construction site can be estimated by considering this operation as a special case of relocation, with the subtraction of the disassembly operation and the addition of two extra trucks and their drivers to keep up a steady flow from the depot to the site. Thus, for 1,000 ft of barrier for each of the 10 concepts, Table 6 was generated at the limiting case lengths of 10 and 30 ft. These costs closely correlate with those for relocation.

Costs for removal of barriers, in those cases in which the barriers are not going to be permanently installed somewhere on the site, can also be estimated in a similar way from the relocation analysis. The total cost of relocation is reduced by the cost for assembly of joints and increased by two extra trucks to transport the sections back to the depot for storage. This analysis is given in Table 7.

Supplementary Data from State DOTs

A complementary study in the Texas Transportation Institute (FHWA Contract DOT-FH-11-9688, "Use and Delineation of Traffic Barriers in Work Zones") has obtained some preliminary work and cost estimates for operations similar to those discussed here. Re-

TABLE 5 Job: Relocate 1,000 Ft of PCB

Concept	Length (ft)	No. of Joints	Cost/Joint Disassembly ($)	Total Joint Disassembly Cost ($)	Pickup/Section Cost ($)	Total Pickup Cost ($)	Transportation Cost ($)	Placement/Section Cost ($)	Total Placement Cost ($)	Cost/Joint Assembly ($)	Total Joint Assembly Cost ($)	Equipment (2)	Equipment Cost ($)	Total Cost 5+7+8+10+12+14 ($)	Cost/Ft ($)
C1	10	98	0	0	0.86	86.00	400.00	1.52	152.00	0	0	Forklift	475	1,113	1.11
	30	31	0	0	2.69	88.77	400.00	3.00	99.00	0	0	Crane	330	917	.92
C2	10	98	0	0	0.86	86.00	400.00	1.52	152.00	0	0	Forklift	475	1,113	1.11
	30	31	0	0	2.69	88.77	400.00	3.00	99.00	0	0	Crane	330	917	.92
C3	10	98	0.03	2.94	0.86	86.00	400.00	1.82	182.00	0.03	2.94	Forklift	475	1,149	1.15
	30	31	0.03	0.93	2.69	88.77	400.00	3.77	124.41	0.03	0.93	Crane	330	945	.95
C4	10	98	0.11	10.78	0.86	86.00	400.00	1.82	182.00	0.11	10.78	Forklift	475	1,165	1.17
	30	31	0.11	3.41	2.69	88.77	400.00	3.77	124.41	0.11	3.41	Crane	330	950	.95
C5	10	98	0.17	16.66	0.86	86.00	400.00	1.52	152.00	0.17	16.66	Forklift	475	1,146	1.15
	30	31	0.17	5.27	2.69	88.77	400.00	3.00	99.00	0.17	5.27	Crane	330	928	.93
C6	10	98	0.55	53.90	0.86	86.00	400.00	1.82	182.00	0.55	53.90	Forklift	475	1,252	1.25
	30	31	0.55	17.05	2.69	88.77	400.00	3.77	124.41	0.55	17.05	Crane	330	977	.98
C7	10	98	0.03	2.94	0.86	86.00	400.00	1.82	182.00	0.03	2.94	Forklift	475	1,149	1.15
	30	31	0.03	0.93	2.69	88.77	400.00	3.77	124.41	0.03	0.93	Crane	330	945	.95
C8	10	98	0	0	0.86	86.00	400.00	1.82	182.00	0	0	Forklift	475	1,143	1.14
	30	31	0	0	2.69	88.77	400.00	3.77	124.41	0	0	Crane	330	943	.94
C9	10	98	2.00	196.00	0.86	86.00	400.00	1.82	182.00	2.00	196.00	Forklift	475	1,535	1.54
	30	31	2.00	62.00	2.69	88.77	400.00	3.77	124.41	2.00	62.00	Crane	330	1,067	1.07
C10	10	98	0	0	0.86	86.00	400.00	1.82	182.00	0	0	Forklift	475	1,143	1.14
	30	31	0	0	2.69	88.77	400.00	3.77	124.41	0	0	Crane	330	943	.94

Summary: Mean cost/ft, 10-ft sections = $1.19 range 1.11 to 1.54. Mean cost/ft, 30-ft sections = $.95 range .92 to 1.07. 25% penalty by going with 10-ft versus 30-ft sections.

TABLE 6 Installation of PCB at Construction Site ($)[a]

Concept	Length (ft)	Relocation Total	Less Disassembly	Plus Two More Trucks	Total Installation	Cost/ Ft
C1	10	1,113	0	267	1,380	1.38
	30	917	0	267	1,184	1.18
C2	10	1,113	0	267	1,380	1.38
	30	917	0	267	1,184	1.18
C3	10	1,149	2.94	267	1,413	1.41
	30	945	0.93	267	1,209	1.21
C4	10	1,165	10.78	267	1,421	1.42
	30	950	3.41	267	1,213	1.21
C5	10	1,146	16.66	267	1,396	1.40
	30	928	5.27	267	1,190	1.19
C6	10	1,252	53.90	267	1,465	1.47
	30	977	17.05	267	1,227	1.23
C7	10	1,149	2.94	267	1,413	1.41
	30	945	0.93	267	1,211	1.21
C8	10	1,143	0	267	1,410	1.41
	30	943	0	267	1,210	1.21
C9	10	1,535	196.00	267	1,606	1.61
	30	1,067	62.00	267	1,272	1.27
C10	10	1,143	0	267	1,410	1.41
	30	943	0	267	1,210	1.21

[a] 1,000 ft of barrier.

TABLE 7 Cost Estimates for Removal ($)

Concept	Length (ft)	Relocation Cost	Assembly Cost	Total Cost
C1	10	1,113.00	0	1,380.00
	30	917.00	0	1,184.00
C2	10	1,113.00	0	1,380.00
	30	917.00	0	1,184.00
C3	10	1,149.00	2.94	1,413.06
	30	945.00	0.93	1,211.07
C4	10	1,165.00	10.78	1,421.22
	30	950.00	3.41	1,213.59
C5	10	1,146.00	16.66	1,396.34
	30	928.00	5.27	1,189.73
C6	10	1,252.00	53.90	1,465.10
	30	977.00	17.05	1,226.95
C7	10	1,149.00	2.94	1,413.06
	30	945.00	0.93	1,211.07
C8	10	1,143.00	0	1,410.00
	30	943.00	0	1,210.00
C9	10	1,535.00	196.00	1,606.00
	30	1,067.00	62.00	1,272.00
C10	10	1,143.00	0	1,410.00
	30	943.00	0	1,210.00

searchers sent a questionnaire to cognizant construction engineers in Florida, North Carolina, Tennessee, and Virginia. These results are summarized in Table 8. They are not inconsistent with the cost estimates produced analytically in this project. The joint concepts involved were C6, pin and rebar; C9, channel splice; and C1, tongue and groove.

MAINTENANCE COST ESTIMATES FOR PCBs

Assumptions and Basis of Estimates

There are many ways in which a PCB can be affected by passing traffic and damaged, but for the purposes of this analysis it was assumed that the supervising agency would not repair a section in situ but would allow a damaged section to remain unless it was no longer able to perform its function of redirecting an impinging motor vehicle. Hence, in this analysis "maintenance" means outright replacement of one or more sections. Conversations with construction engineers suggest that this is not an unrealistic assumption.

A maintenance activity therefore consists of

1. Special traffic control or diversion (not costed here),
2. Pickup of replacement sections from the depot,
3. Transportation of sections to the construction site,
4. Removal of damaged sections to a position near original position,
5. Offloading of sections and placement in original barrier,
6. Pickup of damaged sections or debris, and
7. Transport of damaged sections to depot or other disposal.

It was further assumed, as was done for the analyses in previous sections of this study, that the depot is less than 10 mi from the site. Flatbed trailer capacities and load limits will permit four 30-ft sections to be transported, four 20-ft sections, or twelve 10-ft sections.

A cherry-picker crane was assumed to go with transport trucks to the depot or meet them there to load sections, although a forklift truck could also serve at the depot. After the needed sections are loaded, both the crane and the flatbed trucks proceed to the construction site. It was further assumed that sufficient trucks would be requisitioned to accomplish the maintenance activity in one trip from the depot to the site and return. The handling crew for attaching lift cables and maneuvering the PCBs into place was assumed to ride to the depot in some fashion (perhaps the supervisor took them) but to

TABLE 8 Summary of Reports from State DOTs

	North Carolina		Tennessee				
Cost Category	Winston-Salem	Old Fort	Site 1	Site 2	Virginia	Florida	Mean Times and Costs
Relocation (m-m)	6.00	0.30	5.40		6.00	6.00	4.74
Relocation cost/ft ($)	1.82	0.09	1.64		1.82	1.82	1.44
Removal (m-m)	6.00	6.60	6.00		6.00	6.00	6.12
Removal cost/ft ($)	1.82	2.00	1.82		1.82	1.82	1.86
Transport per ft/mile ($)	0.15	1.20	1.3	0.00	0.02	0.02	0.45
Fabricate cost/ft ($)	20.00	13.30	13.80	21.00	15.00	16.50	16.60
Install cost/ft ($)	2.50	4.90	2.04	2.00	0.65	1.00	2.18
Relocation cost/ft ($)	2.50	9.81	2.39	7.00	0.65	1.00	3.89
Removal cost/ft ($)	6.60	6.39	2.41	11.50	0.85	2.25	5.00

Note: m-m = man-minutes.

ride back to the site in the trucks after loading the sections. It was finally assumed that equipment would have to be paid for in 4-hr (half-day) increments.

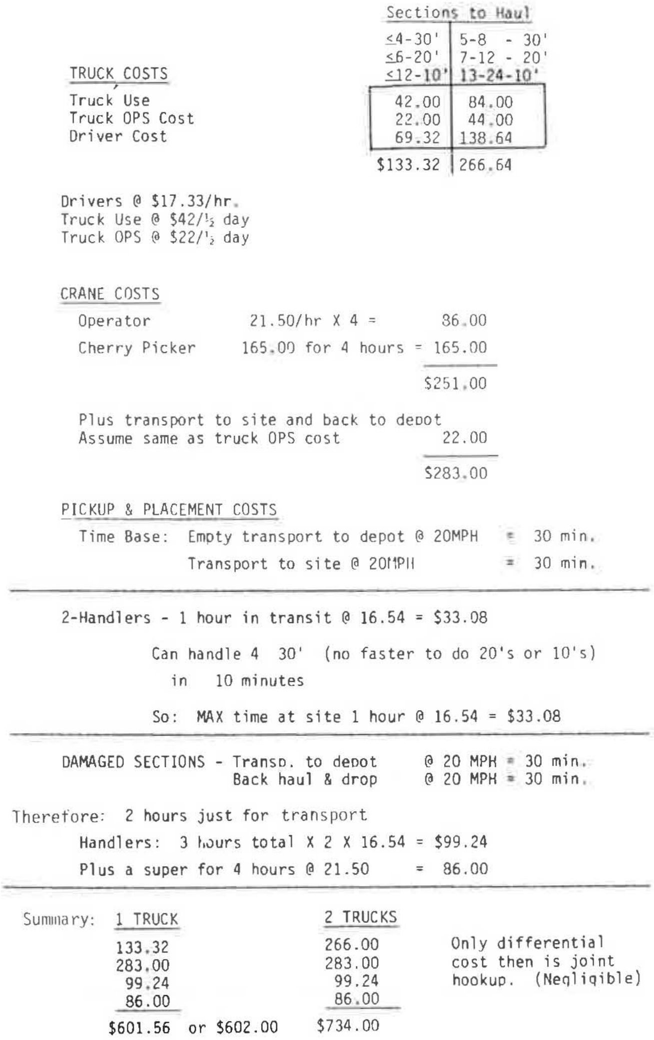
To estimate the cost of the effort required to replace sections, it is necessary to consider how many sections might need to be replaced at a site as a result of a collision. The dynamic and structural analysis presented in Ivey and Buth (5) provides an estimate of the number of sections that would be damaged in absorbing varying levels of energy as a function of joint design. If the conservative assumption is made that a damaged section must be replaced, it is possible to arrive at some conclusions about the amounts of time and the numbers of trucks that would be required as a maximum. Table 9 gives estimates of the number of sections damaged as a result of levels of collision energy ranging from 20.4 to 322 kip-ft (27.7 to 437 kN-m). An examination of this table reveals that no more than one truck would be required for repair of barriers hit with energy levels no greater than Level 3. These data lead directly to Figure 11, which gives the cost breakdown for a half-day maintenance activity (it could hardly be less, as the data in the table show).

Because no cases involved more than one flatbed truck, a flat rate of $602 was taken for the cost of the maintenance activity associated with a single collision. If it is assumed that these sections must be replaced, then the cost associated with that replacement must be taken into account in estimating the total cost of maintenance. Because of the small numbers of joints that must be fastened in such maintenance jobs, the cost of that operation can be safely neglected. The per section fabrication costs for each concept (Table 2), multiplied by the number of sections expected to be damaged (Table 9), plus $602 was taken for the cost of the maintenance activity associated with a single collision (Table 10). In this table, the total costs for a collision at a given level are presented for each joint concept for each of three section lengths, 10, 20, and 30 ft.

TABLE 9 Damage Estimates

Type of Barrier Connection	Section Length (ft)	Representative Collisions[a] 4,500/15/45 Level A 20.4 kip-ft	4,500/15/60 Level 1 36.5 kip-ft	4,500/25/60 Level 2A 97.3 kip-ft	40,000/15/60 Level 3 322 kip-ft
C1	10	1	2	4	8
	20	1	2	3	4
	30	1	2	2	3
C2	10	1	2	4	8
	20	1	2	3	4
	30	1	2	2	3
C3	10	1	2	4	8
	20	1	2	3	4
	30	1	2	2	3
C4	10	0	1	4	8
	20	0	1	2	4
	30	0	1	2	3
C5	10	1	1	4	8
	20	1	1	2	4
	30	1	1	2	3
C6	10	0	0	2	8
	20	0	0	2	4
	30	0	0	1	3
C7	10	0	0	2	8
	20	0	0	2	4
	30	0	0	1	3
C8	10	0	0	2	8
	20	0	0	2	4
	30	0	0	1	3
C9	10	0	0	2	8
	20	0	0	2	4
	30	0	0	1	3
C10	10	0	0	2	4
	20	0	0	2	3
	30	0	0	0	2

[a] Number of sections damaged.



Sections to Haul

TRUCK COSTS	≤4-30' ≤6-20' ≤12-10'	5-8 - 30' 7-12 - 20' 13-24-10'
Truck Use	42.00	84.00
Truck OPS Cost	22.00	44.00
Driver Cost	69.32	138.64
	$133.32	266.64

Drivers @ $17.33/hr.
Truck Use @ $42/½ day
Truck OPS @ $22/½ day

CRANE COSTS

Operator 21.50/hr X 4 = 86.00
Cherry Picker 165.00 for 4 hours = 165.00
$251.00

Plus transport to site and back to depot
Assume same as truck OPS cost 22.00
$283.00

PICKUP & PLACEMENT COSTS

Time Base: Empty transport to depot @ 20MPH = 30 min.
Transport to site @ 20MPH = 30 min.

2-Handlers - 1 hour in transit @ 16.54 = $33.08

Can handle 4 30' (no faster to do 20's or 10's)
in 10 minutes

So: MAX time at site 1 hour @ 16.54 = $33.08

DAMAGED SECTIONS - Transp. to depot @ 20 MPH = 30 min.
Back haul & drop @ 20 MPH = 30 min.

Therefore: 2 hours just for transport
Handlers: 3 hours total X 2 X 16.54 = $99.24
Plus a super for 4 hours @ 21.50 = 86.00

Summary:	1 TRUCK		2 TRUCKS	
	133.32		266.00	Only differential cost then is joint hookup. (Negligible)
	283.00		283.00	
	99.24		99.24	
	86.00		86.00	
	$601.56	or $602.00	$734.00	

FIGURE 11 Cost bases.

Hypothetical Case for PCB Cost Analysis

In the preceding section a picture was presented of the costs associated with a collision, but the construction engineer needs a more complete perspective of the total costs that he is facing in using PCB for protection of a construction site; that is, cost of the barrier itself, costs for installation, and costs for maintaining the barrier once in place at any given place in his site for a period of time. How many collisions should he expect, and what will the consequences of these be on the total cost picture for construction protection?

To illustrate how such a costing estimate might be done, recourse was had to the AASHTO "Guide for Selecting, Locating, and Designing Traffic Barriers" (6). The model in Section VII of the guide provides an estimate of collision frequency per year, given

TABLE 10 $602 plus Replacement Costs ($)

Concept	Section Length (ft)	Collision Level A	1	2A	3	Joint Assembly
C1	10	765	928	1,254	1,906[a]	0
	20	925	1,248	1,571	1,894[a]	0
	30	1,085	1,568	1,568	2,051[a]	0
C2	10	766	930	1,258	1,914[b]	0
	20	926	1,250	1,574	1,898[b]	0
	30	1,086	1,570	1,570	2,054[b]	0
C3	10	769	936	1,270	1,938	0.03
	20	929	1,256	1,585	1,910	0.03
	30	1,089	1,576	1,576	2,063	0.03
C4	10	0	775	1,294	1,986	0.11
	20	0	935	1,268	1,934	0.11
	30	0	1,098	1,594	2,090	0.11
C5	10	772	772	1,282	1,962	0.17
	20	932	932	1,262	1,922	0.17
	30	1,091	1,091	1,582	2,072	0.17
C6	10	0	0	964	2,050	0.55
	20	0	0	1,284	1,966	0.55
	30	0	0	1,103	2,105	0.55
C7	10	0	0	1,000	2,194	0.03
	20	0	0	1,320	2,038	0.03
	30	0	0	1,121	2,159	0.03
C8	10	0	0	998	2,186	0
	20	0	0	1,318	2,034	0
	30	0	0	1,120	2,156	0
C9	10	0	0	1,032	2,322	2.00
	20	0	0	1,352	2,102	2.00
	30	0	0	1,169	2,302	2.00
C10	10	0	0	1,096	2,084[b]	0
	20	0	0	1,416	1,823[b]	0
	30	0	0	0	1,736[b]	0

[a] May require moving undamaged PCBs to reconnect.
[b] Will require moving undamaged PCBs.

certain parameters of the highway and its geometrics with respect to a barrier or obstacle:

A = lateral placement from edge of pavement (EOP) of PCB line,
L = length of barrier array,
W = width of barrier,
ADT = two-way volume flow,
E_f = vehicle encroachments per mile per year,
Y = lateral displacement of encroaching vehicle measured from edge of traveled way to longitudinal face of the barrier,
$P[Y \geq \ldots]$ = probability of vehicle lateral displacement greater than some value, and
J = number of 1-ft increments of width of barrier (i.e., a 2-ft-wide barrier would have a J-value of 2).

Obtain estimate of collision frequency per year (C_f).

$$C_f = (E_f/10{,}560) \cdot (L + 62.9) \cdot P[Y \geq A]$$

$$+ 5.14 \sum_{u}^{\omega} P\{Y \geq A + 6.0 + [(2J - 1)/2]\}$$

Let us now adapt an actual site in Texas (Stemmons Freeway, I-35, on the west side of Dallas) for the purpose of demonstrating this approach to cost analysis.

ADT = 200,000 for all eight lanes, divided median;
A = 3 ft,
L = 5,000 ft,
W = 2.3 ft,
$P[Y \geq A]$ = 98%, and
E_f = 40%.

$$C_f = (E_f/10{,}560) \cdot (L + 62.9) \cdot P[Y \geq A]$$

$$+ 5.14 \sum_{J=1}^{\omega} P\{Y > A + 6 + [(2J - 1)/2]\}$$

$$= (0.40/10{,}560) \cdot (5{,}000 + 62.9) \cdot 0.98$$
$$+ 5.14\ [.935 + .925]$$

If $J = 2$; $P\{Y > 3 + 6 + [(2 - 1)/2]\} = [P\ Y > 9.5$
$= 93.5]\ P\{Y > 3 + 6 + [(4 - 1)/2]\}$
$= P\ [Y > 10.5 = 92.5]$
$= .004\ [4{,}961.6 + 9.56] = 19.88$ or, approximately 20, collisions per year.

Given a vehicle mix of 16 percent heavy trucks and 84 percent passenger vehicles, there will be 3.2 collisions involving heavy trucks and 16.8 involving passenger vehicles per year. The barrier will be in place for 1 year.

Because encroaching vehicles are "selected" randomly and might be distributed approximately normally, a good method of roughly estimating the energy of collision with the barrier might be the mean of energies associated with passenger vehicles at various speeds and angles of encroachment. This would be the mean of Levels A, 1, and 2A, or 51.4 kip-ft.

By a similar argument, small trucks at 60 mph and 25 degrees encroachment expend the same energy as larger trucks at lower speeds and angle combinations, and distribute up to the extreme of 40,000-lb vehicles impacting at 15 degrees at 60 mph (322 kip-ft). An estimator of the energy associated with truck collisions would thus be the mean of level 2A and 3, which is 209.7 kip-ft.

Suppose (as was the case in this real-life example) the resident engineer is considering the C3, grid-slot, concept but his contractor can supply the C5, lapped joint. Which concept should be used on this busy freeway, and which length, 10, 20, or 30 ft, should be used? The costs of maintenance for 1 year for 5,000 ft are given in Table 11.

TABLE 11 Costs of Maintenance for 1 Year

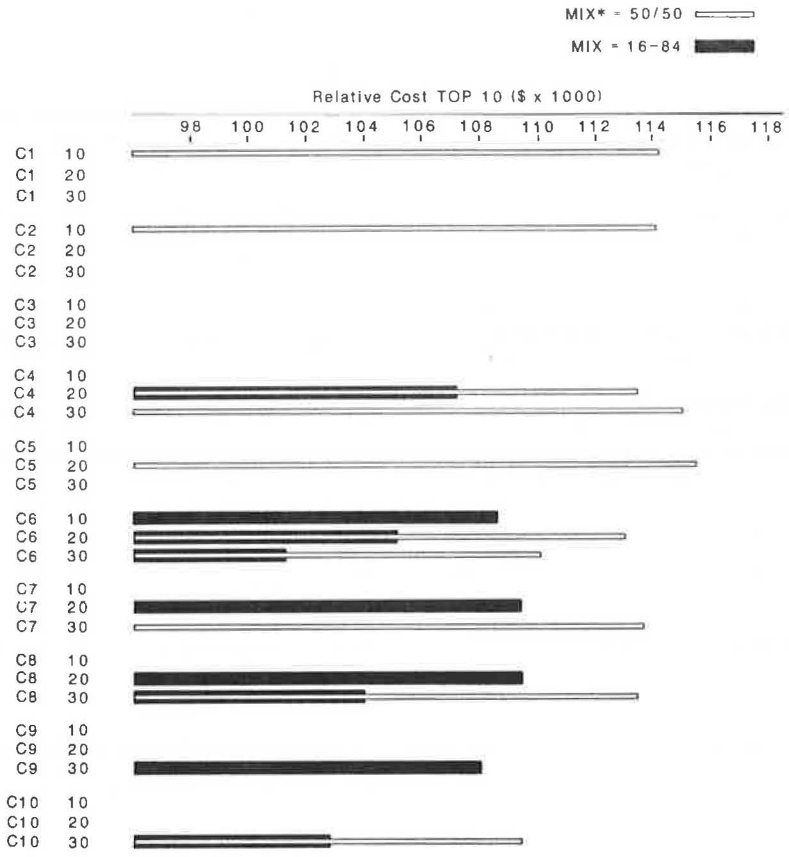
Length (ft)	Passenger Vehicle Levels		Heavy Truck Levels		Total Cost ($)
For C3					
10	($922 x 16.8)	+	($1,604 x 3.2)	=	21,798
20	($1,257 x 16.8)	+	($1,748 x 3.2)	=	26,942
30	($1,413 x 16.8)	+	($1,820 x 3.2)	=	29,562
For C5					
10	($942 x 16.8)	+	($1,622 x 3.2)	=	21,016
20	($1,042 x 16.8)	+	($1,592 x 3.2)	=	22,600
30	($1,255 x 16.8)	+	($1,827 x 3.2)	=	26,930

From a maintenance standpoint, a 10-ft C5 is the most attractive in this example; however, installation costs and relocation costs must also be considered; 5,000 ft of 10 ft C5 would cost

Fabricate	$17.00/ft x 5,000 =	$ 85,000
Install	$1.40/ft x 5,000 =	$ 7,000
Maintain		$ 21,010
Total cost		$113,016

TABLE 12 Total Costs ($) Including Maintenance for 1 Year for 16 Percent Trucks and 84 Percent Passenger Cars

Concept	Length (ft)	Fabricate	Install	Level A	Level 1	Level 2A	Level 3	Maintenance	Total
C1	10	81,500	6,900	765	928	1,254	1,906	21,559	109,959
	20	80,750	6,400	925	1,248	1,571	1,894	26,510	113,660
	30	80,900	5,900	1,085	1,568	1,568	2,051	29,428	116,228
C2	10	82,000	6,900	766	930	1,258	1,914	21,618	110,518
	20	81,000	6,400	926	1,250	1,574	1,898	26,555	113,955
	30	80,650	5,900	1,086	1,570	1,570	2,054	29,464	116,014
C3	10	83,500	7,050	769	936	1,270	1,938	21,793	112,343
	20	81,750	6,550	929	1,256	1,585	1,910	26,704	115,004
	30	81,150	6,050	1,089	1,576	1,576	2,063	29,572	116,772
C4	10	86,500	7,100	0	775	1,294	1,986	16,834	110,434
	20	83,250	6,600	0	935	1,268	1,934	17,460	107,310
	30	82,650	6,050	0	1,098	1,594	2,090	20,970	109,670
C5	10	85,000	7,000	772	772	1,282	1,962	21,016	113,016
	20	82,500	6,500	932	932	1,262	1,922	22,600	111,600
	30	81,650	5,950	1,091	1,091	1,582	2,072	26,925	114,525
C6	10	90,500	7,350	0	0	964	2,050	10,221	108,071
	20	85,250	6,750	0	0	1,284	1,966	12,390	104,390
	30	83,500	6,150	0	0	1,103	2,105	11,310	100,960
C7	10	99,500	7,050	0	0	1,000	2,194	10,710	117,260
	20	89,750	6,550	0	0	1,320	2,038	12,765	109,065
	30	86,500	6,050	0	0	1,121	2,159	11,526	104,076
C8	10	99,000	7,050	0	0	998	2,186	10,683	116,733
	20	89,500	6,550	0	0	1,318	2,034	12,744	108,794
	30	86,350	6,050	0	0	1,120	2,156	11,514	103,914
C9	10	107,500	8,050	0	0	1,032	2,322	11,146	126,696
	20	93,750	7,200	0	0	1,352	2,102	13,098	114,048
	30	89,150	6,350	0	0	1,169	2,302	12,100	107,600
C10	10	123,500	7,050	0	0	1,096	2,084	11,226	141,776
	20	101,750	6,550	0	0	1,416	1,823	13,112	121,412
	30	94,500	6,050	0	0	0	1,736	2,778	103,328



*Percentage of trucks and passenger cars respectively.

FIGURE 12 Comparison of 10 least expensive PCB concepts.

TABLE 13 Total Costs ($) Including Maintenance for 1 Year for 50 Percent Trucks and 50 Percent Passenger Vehicles

Concept	Length (ft)	Fabricate	Install	Level A	Level 1	Level 2A	Level 3	Maintenance	Total
C1	10	81,500	6,900	765	928	1,254	1,906	25.614	114,014
	20	80,750	6,400	925	1,248	1,571	1,894	29,793	116,943
	30	80,900	5,900	1,085	1,568	1,568	2,051	32,151	118,951
C2	10	82,000	6,900	766	930	1,258	1,914	25,697	114,597
	20	81,000	6,400	926	1,250	1,574	1,898	29,848	117,248
	30	80,650	5,900	1,086	1,570	1,570	2,054	32,193	118,743
C3	10	83,500	7,050	769	936	1,270	1,938	25,947	116,497
	20	81,750	6,550	929	1,256	1,585	1,910	30,029	118,329
	30	81,150	6,050	1,089	1,576	1,576	2,063	32,318	119,518
C4	10	86,500	7,100	0	775	1,294	1,986	23,290	116,890
	20	83,250	6,600	0	935	1,268	1,934	23,346	113,196
	30	82,650	6,050	0	1,098	1,594	2,090	27,384	116,084
C5	10	85,000	7,000	772	772	1,282	1,962	25,631	117,631
	20	82,500	6,500	932	932	1,262	1,922	26,330	115,330
	30	81,650	5,950	1,091	1,091	1,582	2,072	30,804	118,404
C6	10	90,500	7,350	0	0	964	2,050	18,280	116,130
	20	85,250	6,750	0	0	1,284	1,966	20,526	112,526
	30	83,500	6,150	0	0	1,103	2,105	19,713	109,363
C7	10	99,500	7,050	0	0	1,000	2,194	19,300	125,850
	20	89,750	6,550	0	0	1,320	2,038	21,186	117,486
	30	86,500	6,050	0	0	1,121	2,159	20,133	112,683
C8	10	99,000	7,050	0	0	998	2,186	19,243	125,293
	20	89,500	6,550	0	0	1,318	2,034	21,149	117,199
	30	86,350	6,050	0	0	1,120	2,156	20,110	112,510
C9	10	107,500	8,050	0	0	1,032	2,322	20,207	135,757
	20	93,750	7,200	0	0	1,352	2,102	21,772	122,722
	30	89,150	6,350	0	0	1,169	2,302	21,248	116,748
C10	10	123,500	7,050	0	0	1,096	2,084	19,550	150,100
	20	101,750	6,550	0	0	1,416	1,823	20,910	129,210
	30	94,500	6,050	0	0	0	1,736	8,680	109,230

whereas 30-ft sections of C5 would cost

Fabricate	$16.33 x 5,000 =	$ 81,650
Install	$1.19 x 5,000 =	$ 5,950
Maintain		$ 29,562
Total cost		$117,160

The much simplier C3 concept, for 10-ft lengths, would cost

Fabricate	$16.70/ft x 5,000 =	$ 83,500
Install	$1.41/ft x 5,000 =	$ 7,050
Maintain		$ 21,798
Total cost		$112,348

30-ft lengths of C3 would cost

Fabricate	$16.23/ft x 5,000 =	$ 81,150
Install	$1.21/ft x 5,000 =	$ 6,050
Maintain		$ 29,564
Total cost		$116,764

CONCLUSIONS

The results of cost estimates for fabrication, installation, and maintenance of all of the varieties of joints and PCB lengths are summarized in Table 12, which assumes the nominal vehicle mix on the nation's highways of 16 percent heavy trucks and 84 percent passenger or similarly sized vehicles. To determine how sensitive the relative total costs are to vehicle mix, the vehicle mix ratio was changed from 16:84 to 50:50 (an extremely high and unrealistic ratio of trucks) and Table 13 was generated. Then, from these figures, the histogram of Figure 12 was constructed showing the 10 least expensive concepts for a vehicle mix of 16:84 trucks:cars (realistic) and the worst-case 50:50 mix. All costs, of course, go up for this worst case, but the relative standing of most of the barrier joint concepts for the three lengths of interest do not change a great deal.

The least costly concept for both traffic mix cases is the familiar vertical pin with rebar, C6, at a length of 30 ft, with C8, the bottom T-lock at 30 ft the next least expensive (tied with C7, vertical I-beam) for the heavy truck mix case. Others of the 10 least expensive can be seen by studying this figure. Note that the longer lengths predominate in overall costs, and positive joints appear to have an advantage in cost over those less positive, although this relationship is not completely straightforward.

Analyses such as that presented here can be generated for a wide variety of different traffic situations at proposed construction sites to assist the construction engineer in choosing an appropriate design of PCB for particular needs.

ACKNOWLEDGMENT

The invaluable assistance of the Texas State Department of Highways and Public Transportation is gratefully acknowledged.

REFERENCES

1. 1982 Dodge Manual for Building Construction Pricing and Scheduling. McGraw-Hill, Princeton, N.J., 1981.
2. C. Engelsman. Heavy Construction Cost File. Van Vostrand Reinhold Co., New York, 1981.
3. B.W. Niebel. Motion and Time Study. Richard D. Irwin, Homewood, Ill., 1976.
4. C. Carmichael, ed. Kent's Mechanical Engineer's Handbook. 12th ed., Vol. on Design and Production, John Wiley and Sons, New York, 1950.

5. D.L. Ivey and C.E. Buth. Barriers in Construction Zones. Final Report, Vol. III, Appendices C and D, DOT-FH-11-9458. Texas Transportation Institute, Texas A&M University System, College Station; FHWA, U.S. Department of Transportation, April 1985.
6. Guide for Selecting, Locating, and Designing Traffic Barriers. AASHTO, Washington, D.C., 1977.

This paper (in a slightly expanded version) appears as Appendix E of Volume III, "Barriers in Construction Zones," Final Report DOT-FH-11-9458 to Office of Research, Federal Highway Administration, U.S. Department of Transportation, Texas Transportation Institute, College Station, Texas, April 1985. The contents of this paper reflect the views of the author and do not necessarily reflect the official views or policy of the U.S. Department of Transportation. This paper does not constitute a standard, specification, or regulation.

Publication of this paper sponsored by Committee on Construction Management.