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Contents

Foreword

This Record contains information on statistically based specifications, life-cycle performance of bridges, robotics in construction, and nighttime construction operations. It should be of interest to state and local engineers of materials, construction, maintenance, and bridge design, as well as contractors and material producers.

Parker et al. point out that for statistically based quality control/quality assurance methods currently in use, either absolute deviations, which can lead to process manipulation in order to control central tendency, are not used, or incorrect statistics are used with absolute deviations. They describe the development of a simple, statistically correct procedure for using absolute deviations from target values to control hot-mix asphalt (HMA) construction. Kandhal et al. describe the development and implementation of statistically based end-result specifications for HMA in Pennsylvania. They contend that the implementation of these specifications has improved the overall quality of HMA pavement in the state.

Yanev and Chen summarize the results of deterioration modeling for bridges and bridge components performed at the New York City Department of Transportation. They regard the deterioration modeling as a fundamental tool of their bridge management program.

Najafi discusses and analyzes the involvement of different countries in the application of robotics in construction. Ellis and Kumar discuss a research study conducted for the Florida Department of Transportation in which they evaluated the effects of nighttime operations on construction cost and productivity. They report that total program cost was found to be less for nighttime work than for daytime work and that the difference between the productivity values for daytime and nighttime projects were insignificant. Rho et al. report on a systems approach for identifying construction tasks that could potentially be automated. They describe in detail a two-step system for automation analysis as it applies to drilled shaft foundation construction.

Development of New Criteria for Control of Hot-Mix Asphalt Construction

FRAZIER PARKER, JR., E. RAY BROWN, AND ROBERT L. VECELLIO

Statistically based quality control/quality assurance procedures are designed to control accuracy in achieving target values and variability. Properties of construction materials, such as hot-mix asphalt, are known to be normally distributed, and this is used in the establishment of limiting criteria. However, the use of nuclear asphalt content and nuclear density gauges has increased the potential for process manipulation to achieve average values approximating target values. Owner agencies often resort to the use of the mean of absolute deviations from target values instead of the mean of arithmetic deviations to control process manipulation. Distributions of absolute deviations are not normally distributed (for small sample sizes) and, therefore, properties of normal distributions cannot be used directly to establish criteria limits. Distributions of absolute values from target values were examined and statistics of the distributions computed. Procedures for using the statistics of distribution of absolute deviations to produce consistent mathematically correct limiting criteria are demonstrated. These procedures are simple and control both central tendency and variability, thus reducing possibilities for process manipulation.

The move toward statistically based quality control/quality assurance (QC/QA) construction specifications is motivated by the desire to control the quality of the finished product while maintaining reasonable costs. Quality is judged by accuracy and precision of selected properties of the finished product. Accuracy is measured in terms of the proximity of average measured values to target values. Precision is measured in terms of variability of measured values.

An important part of QC/QA specifications is the limiting criteria for controlling central tendency and variability. Statistical concepts applied to historical construction data are used to set specification limits, and the methodology developed must control both central tendency and variability.

As applied by some agencies, "mean deviation" or "variability known" procedures do not control variability and may lead to process manipulation. The proposed methodology uses absolute deviations from target values and will control variability and prevent process manipulation. The quality level analysis as proposed by FHWA (*1*) and adopted by the Western Association of State Highway and Transportation Officials (WASHTO) (*2*) controls both central tendency and variability. However, some agencies have been reluctant to adopt these procedures. Reasons given include the complexity of required computations and a lack of understanding of the consequences of application of the procedures. Contractors should reasonably expect to know the standards by which they are to be judged (acceptable or achievable accuracy and precision) and be able to understand the consequences of performance above or below the accepted norm.

This paper is focused on the construction of hot-mix asphalt pavements, but the principles are applicable to the production and placement of any construction material. The concepts of statistical QC/QA procedures and the process of developing limiting criteria will be discussed. Examples of procedures used to set limiting criteria for hot-mix asphalt construction will be examined. A simple but statistically correct method that maintains consistent levels of control for both central tendency and variability of absolute deviations from the job mix formula (JMF) will be presented.

STATISTICAL QC/QA CONCEPTS

The objective of the use of construction control procedures is to ensure that quality products are produced. A critical aspect of these procedures is the selection of control properties that are important in determining product performance. All properties that influence product performance cannot be measured during construction, but if advantage is taken of the interrelationships among properties, a practical, manageable subset may be selected. For example, asphalt content, gradation, voids, and voids filled with asphalt are important properties of hot-mix asphalt. However, because of their interrelationship, it is not necessary to control all of these properties.

Historical data and experience provide the basis for determining (a) properties that are important, (b) realistically achievable quality (central tendency and variability), and (c) at least qualitatively, how quality level influences product performance. These three factors may be used to determine which properties are controlled and their limiting criteria.

Limiting criteria should be designed to achieve target values (central tendency) and to control variability. These concepts are shown in Figure 1. Figure 1 (top) shows two distributions with means equal to the target value, but with different standard deviations. The second distribution, with a smaller variability, represents a higher level of control. Figure 1 (bottom) shows two distributions, each with different means and standard deviations. The first distribution, with mean equal to the target value, has better central tendency control, but the second distribution, with the smaller standard deviation, has better variability control.

Criteria with limits set about target values are designed to control the mean as well as variability. Two-sided limits around either side of the target value are shown in Figure 2. However,

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F. Parker, Jr., Highway Research Center; E. R. Brown, National Center for Asphalt Technology; and R. L. Vecellio, Civil Engineering Department, Auburn University, Ala. 36849.

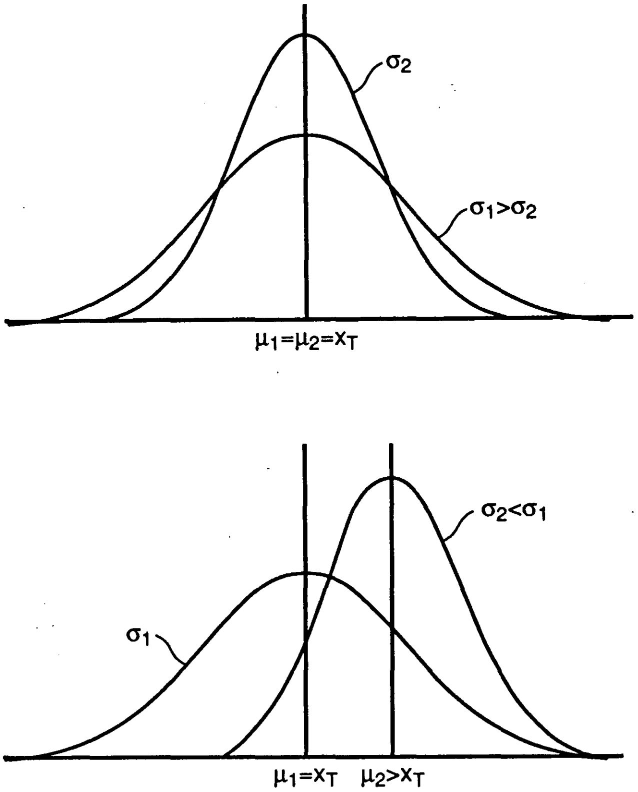

FIGURE 1 Central tendency and variability control: *top,* distributions with same mean and different variabilities; *bottom,* distributions with different means and variabilities.

one-sided limits may be applicable in instances where values higher or lower than the target are undesirable. Symmetrical criteria about the target are shown in Figure 2, but unsymmetrical criteria may be applicable if the underlying distribution is skewed or if there is reason to believe that high or low values affect product performance differently.

Allowable deviation about the target value is set at $C\sigma$, where C is a constant and σ is the standard deviation of the measured property. The standard deviation, based on historical data, provides a basis for the variability that can be realistically achieved. The value of C selected is a rather subjective management decision, but should be supported by available historical data and knowledge of statistical procedures. Intuitively, the decrease in product performance should be related to the deviation from the target value, larger than historical variability, or both. Quantification of this decrease has not been established, and selection of C is often based on tolerable probabilities for pay reduction. For example, limits for 100 percent pay are often set from $\pm 2\sigma$ to $\pm 3\sigma$. If the average of all test data is equal to the target value X_T, and if variability is consistent with historical data, limits of $\pm 2\sigma$ to $\pm 3\sigma$ will mean probabilities for pay reductions of 4.55 to 0.27 percent, respectively. The hatched areas in the tails of the distribution in Figure 2 represent these probabilities. The hatched areas also represent the seller's risk (α), which is the probability that a satisfactory product will be rejected. If the average of all test data is not equal to the target value or actual variability is greater than historical variability or both, the probabilities for pay reductions will be greater. Likewise, if actual variability is less than historical variability, probabilities for pay reductions may be smaller or larger depending on the magnitude of differences between mean and target values.

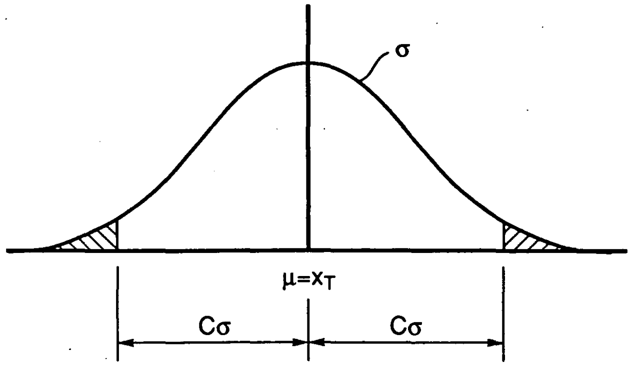

FIGURE 2 Criteria limits.

To decrease the buyer's risk (β) and to break production into manageable size portions (LOTs) for application of pay adjustments, limiting criteria are included for the mean of multiple samples. Buyer's risk is the probability that an unsatisfactory product will be accepted. Consistent criteria for multiple samples are based on the concept that the variability of distributions of mean values can be calculated from the variability of the distribution of individual values using the following equation:

$$\sigma_n = \sigma/n^{1/2} \tag{1}$$

where

σ_n = standard deviation of mean values,
σ = standard deviation of individual values, and
n = sample size.

The reduced variability of means is shown in Figure 3.

Limits for consistent seller's risk (α) may be set for the mean of multiple samples by using Equation 1. For example, if limits for 100 percent pay are set at $\pm 2\sigma$ for individual values, consistent criteria for the mean of multiple samples will be $\pm 2\sigma_n$. These criteria will give the same probability for a pay reduction (4.55 percent) and represent the same area in the tails of the distribution means.

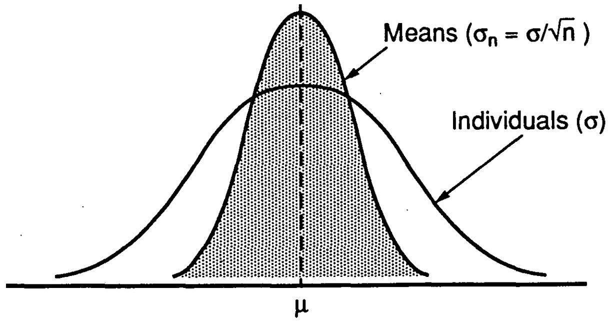

FIGURE 3 Distribution of individual values and means.

The use of multiple samples is desirable to reduce buyer's risk. Limits set at $\pm 2\sigma$ or $\pm 2\sigma_n$ provide the same level of seller's risk (i.e., $\alpha = 4.55$ percent) for any number of samples. However, buyer's risk is reduced from $\beta = 50$ percent for $n = 1$ to $\beta = 2.3$ percent for $n = 4$.

Selection of consistent limits for application of pay reductions or bonus payments is similar to selection of acceptance criteria limits. The decision process is somewhat subjective but should be based on assessments of the influence of material quality on product performance. This applies to pay reductions for quality less than design or bonuses for quality better than design. Bonus payments are not made as often as pay reductions because of the perception that it is more difficult to assess the influence of quality better than design on final product performance than the influence of quality poorer than design.

The usual approach is to set limits, which are intuitively correct and consistent with concepts of causes of failures in final products (i.e., the probability of failure increases as deviation from the target increases). Table 1 presents statistics for setting criteria limits. It follows that pay reductions should increase as deviation from the target increases. The system may be extended to means for any sample size. It also provides the producer with expected probabilities for achieving pay adjustments. For example, if the job mean equals the target and job variability equals historical variability, there would be a 3.32 percent probability of obtaining a pay factor (PF) of 95 percent.

DEVELOPMENT OF LIMITING CONTROL CRITERIA

To illustrate the development of limiting control criteria incorporating the statistical concepts just discussed, an example case will be considered. The example involves the asphalt content of hot-mix asphalt. In the total study from which the data were extracted, asphalt content and air voids of laboratory compacted specimens were selected as the two properties for controlling quality of produced hot-mix asphalt. Level of mat compaction was selected as the property for controlling placement quality.

Historical Data

Historical data are required to establish realistic expectations for variability and for achieving target values. Asphalt content data were collected by the Alabama Highway Department on 11 resurfacing projects during the summer of 1991. A total of 517 measurements was taken using nuclear asphalt content gauges. The variable analyzed was the difference between measured asphalt content and JMF asphalt content as defined by the following equation:

$$\Delta = X - JMF \qquad (2)$$

where

Δ = deviation of individual measured asphalt content from JMF asphalt content,
X = individual measured asphalt content, and
JMF = JMF asphalt content.

The mean deviation for the data set was $\Delta = -0.01$ percent, and the standard deviation was $\sigma = 0.218$ percent. These values indicate an ability to achieve target asphalt content and variability that is similar to that reported by FHWA (*3*) and provide a basis for establishing limiting control criteria that can be reasonably achieved.

TABLE 1 Statistics for Setting Criteria Limits

Pay Factor (PF)	Criteria Limits	Probability of PF
100%	±2.0σ	95.44%
95%	±2.5σ	3.32%
90%	±3.0σ	0.98%
80%	>3.0σ	0.26%

Setting Limits for Control Criteria

Following the procedure outlined in the previous section, historical data may be used to set limits for control criteria. Since the mean of the data set was near zero, symmetrical limits about a mean of 0 will be set using $\sigma = 0.22$ percent (0.218 percent rounded). This is shown in Figure 4 for sample size $n = 1$, with limits of ± 2, 2.5, and 3σ defining PFs of 100, 95, and 90 percent, respectively. A PF of 80 percent applies if Δ lies outside the 3σ limits.

The percentages for the various areas under the curve represent the probability that a PF will be obtained on a project that has expected variability and a mean asphalt content equal to the JMF asphalt content. For example, there would be a 3.32 percent probability of obtaining a PF of 95 percent. If the JMF was 5 percent, samples with measured asphalt con-

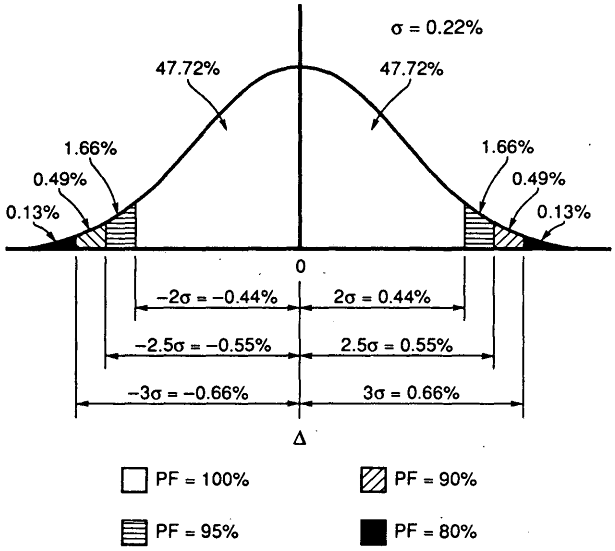

FIGURE 4 Example arithmetic deviation criteria limits for $n = 1$.

tents of 5.45 to 5.55 percent or 4.55 to 4.45 percent would give this PF.

The use of individual values for control is discouraged and the use of means of multiple samples is encouraged to decrease the buyer's risk (β). Consistent criteria limits for $n = 4$ are shown in Figure 5. These criteria use Equation 1 to reduce the standard deviation and, as a result, criteria limits. Again, there would be a probability of 3.32 percent of obtaining a PF of 95 percent. For a target JMF of 5 percent, four samples with mean measured asphalt contents of 5.23 to 5.28 percent or 4.77 to 4.72 percent would give this PF.

Process Manipulation

Criteria limits, as shown in Figures 4 and 5, control central tendency, but provide no control of variability caused by process manipulation. For hot-mix asphalt, the ability to manipulate the construction process is accentuated by the use of nuclear gauges for asphalt content and mat density. These gauges provide almost instant results, which allow for process manipulation during subsequent sampling to ensure that mean values approximating target values are achieved.

For example, assume the JMF asphalt content is 4 percent and that four samples are to be taken from a LOT. Samples of 2 percent, 2 percent, 6 percent, and 6 percent will result in a mean deviation of 0 percent and a 100 percent PF. This will occur despite all individual measurements being well outside the 100 percent PF limits.

Because more than one property is often used to control quality and because of the interaction between properties, process manipulation may be restricted. Nevertheless, it is a concern, particularly when only one property, such as mat density, is used. In response, some agencies modify control procedures to control process modification.

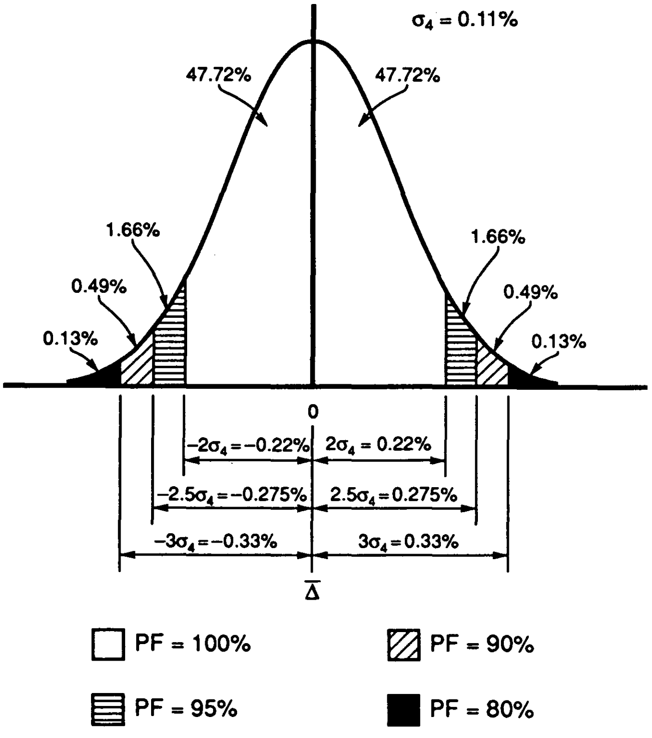

FIGURE 5 Example arithmetic deviation criteria limits for $n = 4$.

The simplest method, and one often used, is to use the mean of absolute deviations from target values instead of the mean of arithmetic deviations. In the example of the four asphalt contents considered previously, this would have given a mean absolute deviation of 2 percent, which is more representative of the quality of the hot-mix asphalt produced.

Application of criteria that specify absolute instead of arithmetic deviations from target values often does not take into consideration that absolute values are not distributed normally. The use of statistics based on normal distributions will then result in inconsistent criteria for sample sizes greater than one (i.e., the use of Table 1 and Equation 1 is no longer valid). To address this problem, procedures that permit use of absolute deviations from target values were developed.

Proposed Procedure for Setting Limiting Criteria

If the absolute value of Δ (ABSΔ) represents the random variable for the absolute difference between measured asphalt content and JMF asphalt content, and if Δ is normally distributed with mean 0 and standard deviation 1, then the distribution of ABSΔ is defined as:

$$f(\text{ABS}\Delta) = [2/(2\pi)^{1/2}]e^{-(\Delta^2/2)} \qquad 0 \leq \text{ABS}\Delta \leq \infty$$

This distribution is plotted in Figure 6 with the standard normal distribution. It is apparent that the ABSΔ distribution has smaller variance. The mean or first moment of the distribution is found by integrating (ABSΔ)·f(ABSΔ) over its range, 0 to ∞. The second moment is found by integrating $(\text{ABS}\Delta)^2 \cdot f(\text{ABS}\Delta)$ over the same range. The variance is then found by subtracting the $(\text{mean})^2$ from the second moment.

Following these procedures the distribution of ABSΔ will have a mean equal to

$$\mu' = (2/\pi)^{1/2} \tag{3}$$

and with a second moment equal to one, the standard devia-

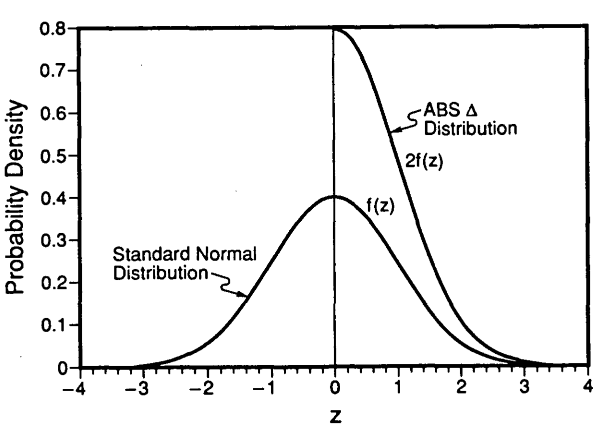

FIGURE 6 Distribution of ABS in comparison with standard normal distribution.

tion is equal to

$$\sigma' = (1 - 2/\pi)^{1/2} \tag{4}$$

Normalized histograms for the average absolute deviations from the arithmetic mean computed numerically from normal distributions of arithmetic deviations are shown in Figure 7 for $n = 1$ to 6. For $n = 1$, the histogram shows the probability that Z, the standard normal deviate, lies between 0 and 0.20 is 0.16. This histogram was generated by manipulating values from the standard normal distribution table.

The other five histograms were developed by numerically estimating the probabilities within given ranges using the normalized histogram for individual values in Figure 7. For example, the probability that the average of two samples ($n = 2$) is between 0 and 0.2 is approximately $(0.16)^2 + 1/2[(0.16)(0.15) + (0.15)(0.16)] = 0.0496$. The values 0.16 and 0.15 are probabilities for individual ($n = 1$) samples.

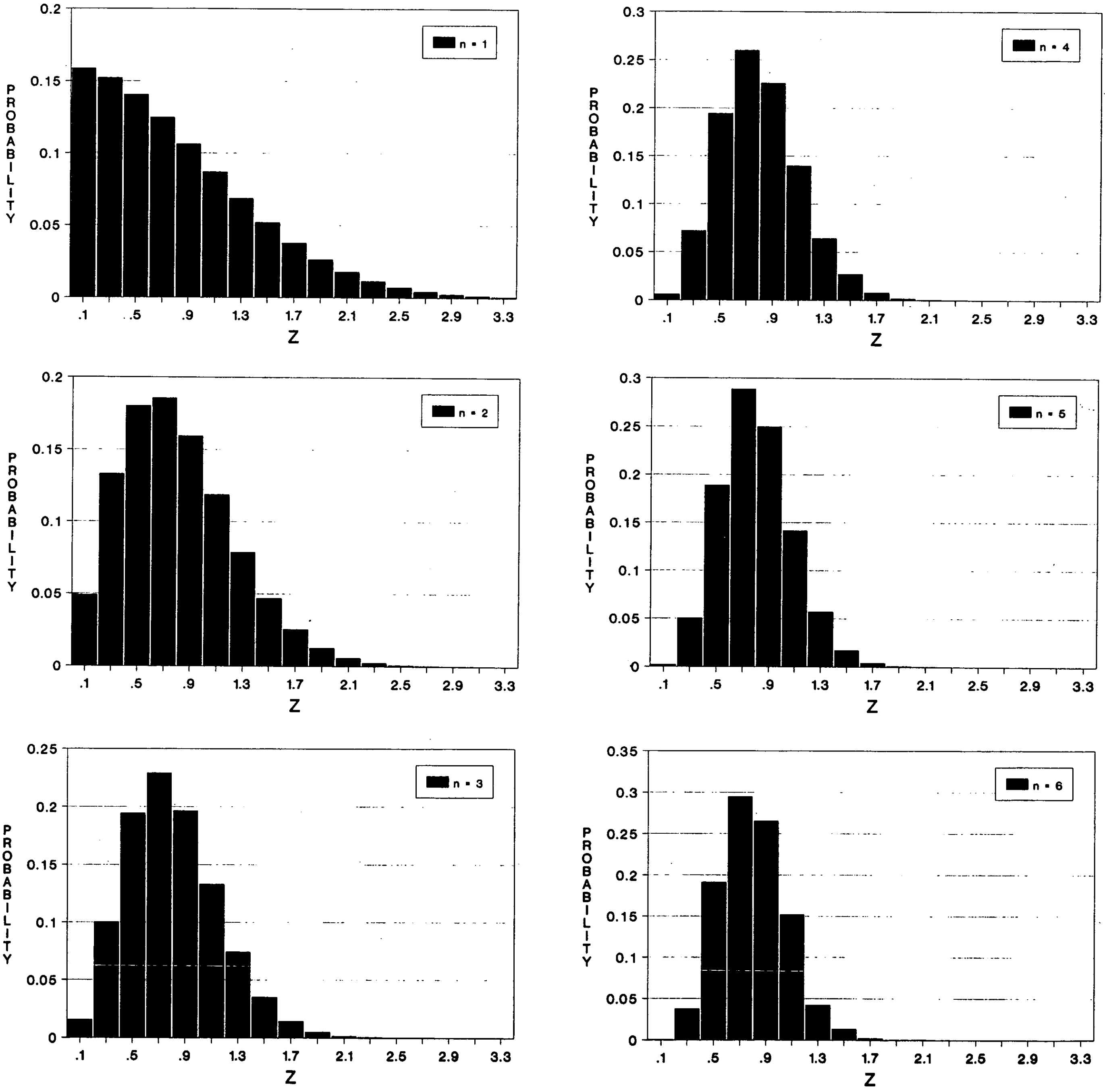

FIGURE 7 **Normalized histograms for absolute deviations from arithmetic mean.**

As shown in Figure 7, the discrete distribution for $n = 1$ follows that of the continuous ABSΔ distribution in Figure 6. However, the shapes of the other distributions are a function of n and, as n increases, they approach normal distributions according to the Central Limit Theorem.

Standard deviations for $n > 1$ are computed as follows:

$$\sigma'_n = \sigma'/n^{1/2} \tag{5}$$

To check the shape of the distributions and the equations for computing mean and standard deviations, the data set of 517 asphalt content measurements was analyzed. Histograms of arithmetic and absolute deviations for $n = 1$, 2, and 4 are shown in Figure 8. Comparing these shapes with the normalized histograms in Figure 7 for the same n values reveals good agreement. Means and standard deviations for the distributions are compared with values computed using Equations 1 and 3–5 in Table 2. Excellent agreement is indicated.

Properties of the distributions of absolute values can be used to develop consistent criteria limits when absolute deviations from target values are used to control process manipulation. The normalized histograms in Figure 7 are numerically integrated to determine offsets from the arithmetic mean (Z values) that give areas in the tail of the distributions

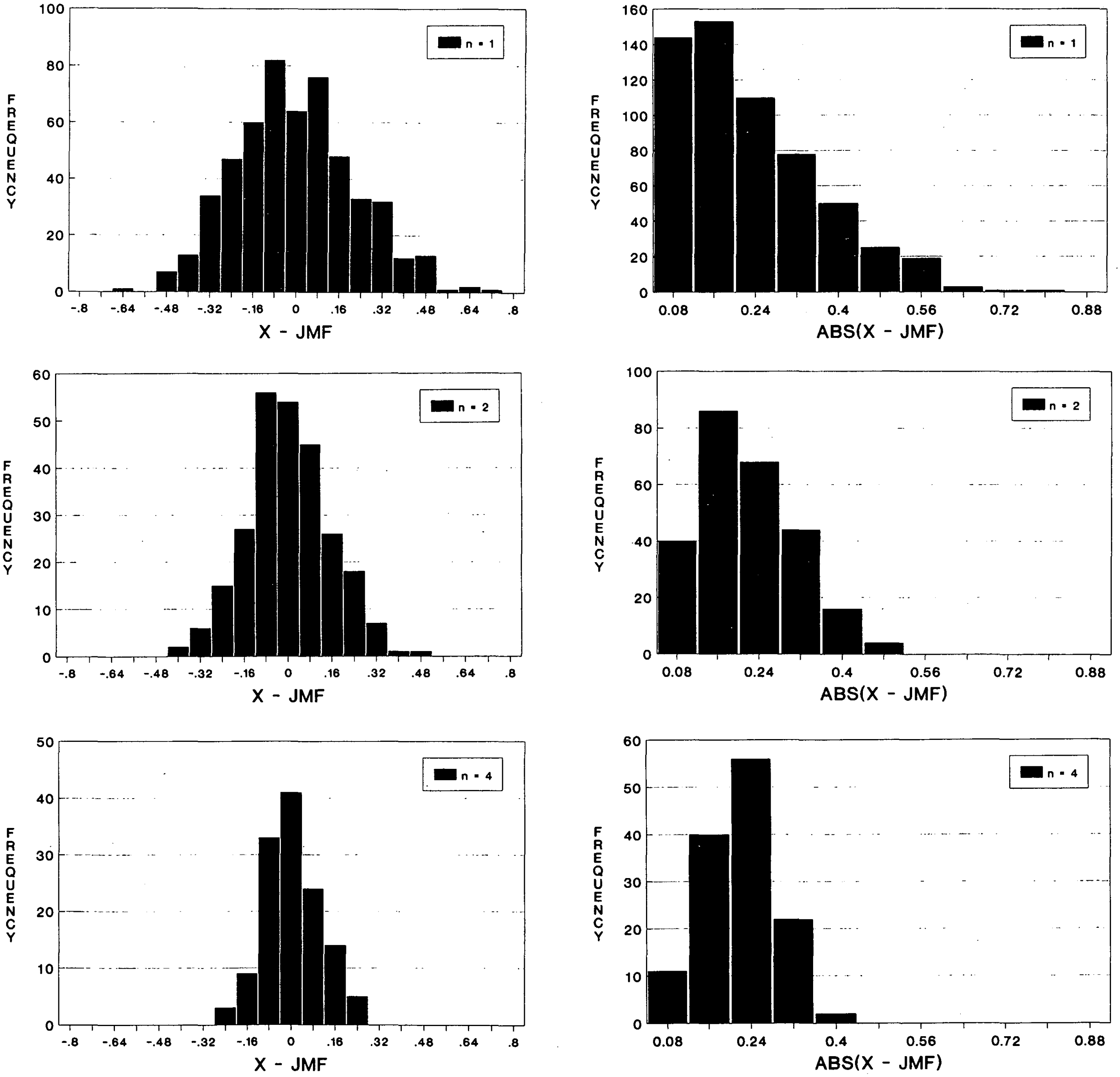

FIGURE 8 Histograms for arithmetic and absolute deviations from target.

TABLE 2 Comparison of Means and Standard Deviations

	$\bar{\Delta}$	σ		$\overline{\lvert\Delta\rvert}$		σ'	
n	Distribution	Distribution	Equations	Distribution	Equations	Distribution	Equations
1	-0.010	0.218	--	0.176	0.174	0.129	0.132
2	-0.001	0.155	0.154	0.176	0.174	0.094	0.091
3	-0.001	0.122	0.126	0.176	0.174	0.075	0.074
4	-0.001	0.103	0.109	0.176	0.174	0.067	0.065

TABLE 3 Offsets, Z, from Arithmetic Means

n	α = 4.55%	α = 1.24%	α = 0.60%	α = 0.26%	α = 0.05%
1	2.000	2.500	2.750	3.000	3.500
2	1.625	1.944	2.127	2.298	2.615
3	1.463	1.727	1.851	1.982	2.322
4	1.375	1.585	1.713	1.795	2.134
5	1.318	1.514	1.590	1.720	1.989
6	1.214	1.381	1.480	1.576	1.938

equivalent to the area in both tails of the normal distribution with Z values of ± 2, 2.5, 2.75, 3, and 3.5. These Z values are presented in Table 3 for $n = 1$–6 and correspond to areas in the tails of the distribution of 4.55, 1.24, 0.60, 0.26, and 0.05 percent.

It should be noted that the Z values for $n = 1$ in Table 3 are the same as for a normal distribution. This is because the distribution of the absolute deviations from the mean for $n = 1$, shown in Figure 6, has ordinate values twice the normal distribution. Therefore, the area under the absolute deviation distribution curve at a particular offset from the arithmetic mean will be twice the area corresponding to a normal distribution.

Application of the Proposed Procedure

To demonstrate application of Table 3, limits for $n = 4$ were developed with the asphalt content data used previously for the example in Figure 5. To develop criteria consistent with those shown in Figure 5, Z values of 1.375, 1.585, and 1.795 were selected from Table 3. These values were multiplied by the standard deviation of the historical data, $\sigma = 0.22$ percent, to give offsets from the arithmetic mean of 0.30, 0.35, and 0.39 percent. These offsets, corresponding PFs and areas representing probabilities are shown in Figure 9. These limits are statistically correct when the absolute deviation from target asphalt content is used as the control. The limits are also less restrictive than two-sided limits developed for arithmetic deviations that are often applied to absolute deviations. For example, LOTs with average absolute deviations less than or equal to 0.30 percent would have PFs of 100 percent based on the limits in Figure 9, whereas, the limit from Figure 5 for normal distributions of arithmetic deviations would be 0.22 percent.

Table 4 presents a set ($n = 1, 2$, and 4) of consistent criteria limits for both arithmetic and absolute deviations from the target JMF asphalt content. Limits for absolute deviation are shown in parentheses and are numerically larger than limits for arithmetic deviations.

Producers are interested in the consequences of noncompliance and knowledge of the possibilities of noncompliance. Using Figures 4, 5, or 9, simple explanations are readily avail-

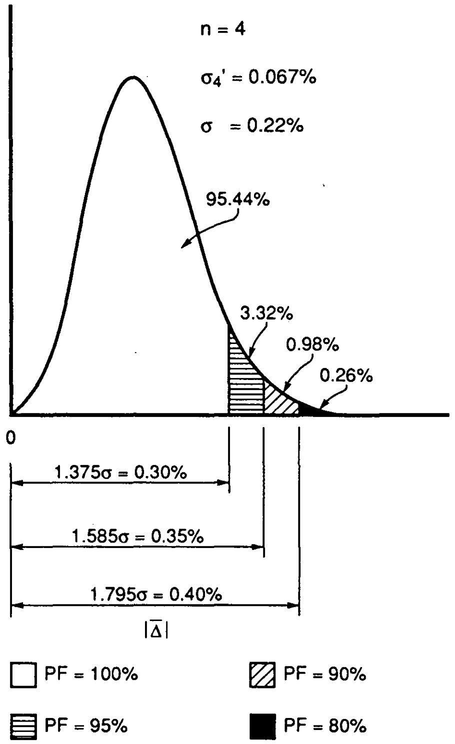

FIGURE 9 Example absolute deviation criteria limits for $n = 4$.

TABLE 4 Example Criteria Limits for Arithmetic and Absolute Deviations

Pay Factor	Sample Size 1	Sample Size 2	Sample Size 4
100	0 to ± 0.44 (0 to 0.44)	0 to ± 0.31 (0 to 0.35)	0 to ± 0.22 (0 to 0.30)
95	± 0.45 to ± 0.55 (0.45 to 0.55)	± 0.32 to ± 0.38 (0.36 to 0.42)	± 0.22 to ± 0.28 (0.31 to 0.35)
90	± 0.56 to ± 0.66 (0.56 to 0.66)	±0.39 to ± 0.46 (0.43 to 0.50)	± 0.29 to ± 0.33 (0.36 to 0.39)
80	< -0.66 or > +0.66 (> 0.66)	< -0.46 or > +0.46 (> 0.50)	< -0.33 or > +0.33 (> 0.39)

Limits for absolute deviations in parentheses.

able. A producer with product quality comparable to average historic quality can expect a pay reduction only 4.55 percent of the time. If a LOT is equal to 1 day's production, this translates into about 1 production day in 20. Furthermore, the producer has some idea of the probability of application of a particular PF. For example, a PF of 80 percent can be expected 0.26 percent of the time or translated into a day's production 1 day in 400.

CONCLUSION

A simple, statistically correct procedure for using absolute deviations from target values to control hot-mix asphalt construction was developed. Methods currently in use either do not use absolute deviations, which can lead to process manipulation in order to control central tendency, or incorrect statistics are used with absolute deviations. Statistics in Table 3 can be used with historical data to develop statistically sound specifications that use absolute deviations from target values and control both central tendency and variability.

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Development and Implementation of Statistically Based End-Result Specifications for Hot-Mix Asphalt in Pennsylvania

PRITHVI S. KANDHAL, RONALD J. COMINSKY, DEAN MAURER, AND JOHN B. MOTTER

In the past, the Pennsylvania Department of Transportation (PennDOT) used the concept of single samples (the so-called "representative" samples) and tests to determine the quality of hot-mix asphalt (HMA) mixtures. This study was undertaken to develop statistically based end-result specifications for HMA pavements, which would make the contractor responsible for quality control and would make PennDOT responsible for quality assurance. Field data from several HMA paving projects were analyzed statistically to establish realistic numerical limits for the various test parameters to be used in the specifications. The type of samples (loose mixture behind the paver screed or core specimens) to determine the mix composition (asphalt content and gradation) of the end product was also established. The proposed specifications require loose-mix samples behind the paver to determine the mix composition, and core samples are required to determine the compacted mat density. All acceptance testing is done by PennDOT. Three pay items (asphalt content, the percent passing 75μm or No. 200 sieve, and mat density) were included in the specifications. Realistic numerical tolerance limits for these test parameters were based on the statistical analyses of the field data and ASTM precision statements. A weighted-price adjustment formula (which gives 50 percent weight to mat density and 25 percent each to asphalt content and minus 75μm material) was incorporated in the specifications. The implementation of these specifications has improved the overall quality of HMA pavement in Pennsylvania. The specifications have provided PennDOT with a means of evaluating and comparing the dollar value of the improvement in HMA quality year-by-year.

The Pennsylvania Department of Transportation (PennDOT) had for years used extraction, density, and Marshall tests for the quality control of hot-mix asphalt (HMA) construction. Associated with these procedures was the concept of single samples (the so-called "representative samples") and tests to indicate the quality of HMA mixtures. If the results were not within some arbitrary limits, it was common for researchers to obtain additional samples—sometimes called investigation, confirmation, check, or referee samples—to decide whether to accept or reject the material.

By using the old HMA specifications, PennDOT had placed itself in the undesirable position of assuming the responsibility for both quality control and acceptance of the material or construction. It was decided that the contractor should be responsible for quality control of the product and that PennDOT should be responsible for defining the acceptance standards for the product and ensuring compliance with these standards. Therefore, it was important to develop and implement statistically based end-result specifications for HMA. The advantages of such specifications are as follows:

1. The required quality may be stated more clearly by including reasonable variation tolerances.
2. When ground rules for acceptance, rejection, and adjusted compensation are clearly stated in the specifications, the time and expense involved in negotiations and settlements of claims will be minimized.
3. The concepts of random sampling and formulated acceptance plans will minimize the risk of making wrong decisions.
4. The judgment factor, which has constantly plagued the engineer, will be minimized. Consequently, the engineer's decisions will be legally defensible.

The main objective of this study was to develop such specifications based on the statistical analysis of field data from HMA paving projects in Pennsylvania. The intent was not to develop performance-based specifications, although they would be a desirable result. It was necessary to determine whether core samples or loose-mix samples behind the paver screed should be used for determining the acceptance of HMA composition (asphalt content and gradation).

FIELD DATA

It was necessary to gather and statistically analyze field data from several HMA paving projects to establish realistic numerical limits for the statistically based end-result specifications. This work was done in three phases.

P. S. Kandhal, National Center for Asphalt Technology, 211 Ramsay Hall, Auburn University, Ala. 36849-5354. R. J. Cominsky, University of Texas at Austin, Rockville, Md., office, 1 Metro Square Building, 51 Monroe Street, #707E, Rockville, Md. 20850-2419. D. Maurer and J. B. Motter, Materials Testing Division, P.O. Box 2926, Pennsylvania Department of Transportation, Harrisburg, Pa. 17105.

Phase 1

This phase was conducted from 1968 through 1972 and involved statistical analysis of data from two sources: (a) historical data consisting of about 4,600 measurements of random samplings of HMA mixtures at the job site during 1968 and 1969 and (b) data obtained from a series of statistically designed experiments during 1969 and 1970 involving about 6,600 unbiased measurements of normal HMA materials and routine construction. Measurements investigated included asphalt content, gradation, Marshall properties, and pavement density of dense graded wearing and binder mixtures. The detailed data are presented elsewhere (*1*).

Tables 1 and 2 present the standard deviations for wearing and binder mixtures, respectively, for the projects constructed in 1970. The standard deviations for the asphalt content, 75 μm (No. 200) material, Marshall stability, and air voids for the wearing and binder course mixtures compare favorably with the following national standard deviation averages published in 1966 (*2*) by the Office of Research and Development, Bureau of Public Roads (now FHWA).

	Asphalt Content	*75 μm (No. 200)*	*Stability*	*Air Voids*
Wearing course	0.27	0.88	246	0.77
Binder course	0.33	0.93	258	0.74

TABLE 1 Standard Deviations for Wearing Course Mixtures (*1*)

Characteristic	Project					
	70-A1	70-C1	70-E1	70-E	70-4	Pooled
3/8 inch	0.9	0.9	2.0	1.6	1.6	1.56
No. 4	3.8	2.1	3.1	2.9	3.6	3.19
No. 8	3.3	1.5	2.2	2.3	2.7	2.47
No. 16	2.9	1.9	2.1	2.0	2.0	2.15
No. 30	2.3	2.4	2.2	1.9	1.2	1.93
No. 50	1.0	2.1	2.0	1.8	0.9	1.58
No. 100	1.0	1.6	1.3	1.5	0.6	1.18
No. 200	0.2	1.1	0.8	1.2	0.5	0.80
Asphalt Content	0.10	0.13	0.21	0.24	0.32	0.20
Stability, lbs.	290	251	281	247	275	269
Flow, unit	1.54	1.41	1.65	1.38	1.79	1.55
Bulk Specific Gravity	0.0287	0.0289	0.0271	0.0260	0.0281	0.0278
Air Voids	1.17	0.85	0.85	0.71	0.92	0.90
VFA	5.95	3.26	3.89	4.11	4.01	4.24
VMA	1.09	1.25	1.13	1.31	1.05	1.17

TABLE 2 Standard Deviations for Binder Course Mixtures (*1*)

Characteristic	Project					
	70-A2	70-C2	70-D2	70-1	70-2	Pooled
1 inch	2.2	2.2	3.5	3.1	1.9	2.58
1/2 inch	4.0	3.9	6.2	6.4	5.2	5.18
No. 4	3.0	2.5	3.4	4.4	3.6	3.47
No. 8	2.7	2.1	2.0	2.8	2.2	2.27
No. 16	2.3	1.3	1.4	1.5	1.4	1.62
No. 30	1.7	0.9	1.2	1.0	0.9	1.16
No. 50	1.1	0.8	1.0	0.7	0.9	0.89
No. 100	0.2	0.7	0.5	0.6	0.8	0.60
No. 200	0.6	0.8	0.5	0.5	0.7	0.62
Asphalt content	0.20	0.20	0.20	0.29	0.33	0.24
Stability, lbs.	309	303	315	299	307	307
Flow, unit	4.66	4.12	4.31	4.09	4.55	4.35
Bulk Specific Gravity	0.0241	0.0172	0.0255	0.0185	0.0196	0.0210
Air Voids	0.85	0.65	0.79	0.83	0.71	0.77
VFA	4.05	3.27	3.39	4.13	4.02	3.77
VMA	1.09	1.04	1.04	1.07	1.08	1.06

Phase 2

It appeared necessary to use the mix composition (asphalt content and gradation) and the mat density (compaction) as the acceptance criteria in the proposed specifications. Pavement cores have to be obtained after the compaction of the mat to determine pavement density, and the question of whether these density cores may also be used to ascertain the mix composition arose. This would eliminate the need to take additional loose-mix samples behind the paver screed for mix composition and thus minimize the number of samples per lot. The feasibility of this idea was examined in Phase 2 in 1979.

Several paving projects were selected across Pennsylvania that would provide core versus loose-mix composition data for both wearing and binder courses. Different aggregate types—gravel, sandstone, and slag—were used in the HMA mixtures sampled from these paving projects. The loose samples were taken directly behind the paver screed by means of a flat-bottom, high-sided scoop. Pavement cores 152.4 mm (6 in.) in diameter were drilled with a power-driven, water-cooled drill.

Statistical data summaries were prepared for both loose sample and core extraction results. The conformal index (CI) was used to evaluate target miss (deviation) of HMA mixtures in relation to job-mix formulas (JMFs). This procedure affords the opportunity to evaluate HMA mixtures of different JMFs. CI, like the standard deviation, is a measure of dispersion. However, the standard deviation (σ) is the root mean square of differences from the average, or central value, whereas CI is the root mean square of the differences from a target (JMF), or specified value. In other words, the standard deviation is a measure of precision, whereas CI is a measure of exactness or degree of accordance with a standard (*1*). The following equations are used to calculate the standard deviation (σ) and CI:

$$\sigma = \sqrt{\frac{\Sigma (X - \bar{X})^2}{(n - 1)}}$$

$$CI = \sqrt{\frac{\Sigma (X - T)^2}{n}}$$

where T is a target value, such as JMF asphalt content.

CI values were calculated for asphalt content, material passing 2.36 mm (No. 8) sieve, and material passing 75 μm (No. 200) sieve for both wearing and binder mixtures used on each project. CI values were also calculated for the material passing 12.7 mm (1/2 in.) sieve in case of binder mixtures. Table 3 presents the average CI value ($\bar{X}$) and the standard deviation (σ) of the CI values for all wearing course projects. The data have been broken down for gravel and sandstone aggregates. Table 4 presents similar data for all binder course projects. Although the data are rather limited, some generalizations can be drawn. The CI values for the aggregate gradations associated with the core samples are generally greater than those shown by the loose sample aggregate gradations. Consequently, it appears that there is substantial degradation associated with the core sampling. Degradation of the aggregate may occur during compaction of the mat and subsequent coring and sawing operations. The extent of degradation appears to be dependent on the aggregate and mix types. It is apparent that the aggregate degradation is more pronounced with the sandstone aggregate as compared with the gravel aggregate, and with the binder course mixtures as compared with the wearing course mixtures. According to the Student's *t*-test analysis, the differences in CI values (of 2.36 mm and 75 μm materials) between core and loose samples were generally statistically significant at the 5 percent level (*3*). Therefore, it was established that core samples cannot be used for mix composition acceptance, and loose-mixture samples have to be obtained behind the paver screed.

Phase 3

Six HMA paving projects were selected in 1980 to evaluate the specification tolerances obtained in Phase 1. Loose-mix samples were obtained behind the paver screed lot by lot. Lots were 5,601 m^2 (6,700 yd^2) or 1,525 m (5,000 linear ft). Each lot was stratified into five equal sublots. A loose sample was obtained at random in each sublot and extracted to determine the mix composition.

The mix composition data (asphalt content, material passing 2.36 mm sieve, and material passing 75 μm sieve) from these six projects, which consisted of wearing course only, were analyzed statistically. Table 5 presents a comparison of specification tolerance limits (derived from the sample standard deviation values) obtained in Phases 1 and 3 with the existing PennDOT limits based on one sample ($n = 1$). The standard deviation values given in the table include variations resulting from sampling, testing, and material type. The standard deviation values for Phase 1 are based on the data obtained in 1969 and 1970, unlike Table 1, which is based on data from 1970 only.

TABLE 3 Mean and Standard Deviation of CIs for Core and Loose Samples (Wearing Courses)

Aggregate Type	Core Samples						Loose Samples					
	Percent AC		Percent Passing 2.36 mm Sieve		Percent Passing 75 μm Sieve		Percent AC		Percent Passing 2.36 mm Sieve		Percent Passing 75 μm Sieve	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Gravel	-0.33	0.20	0.95	2.24	1.40	1.37	-0.36	0.13	0.13	2.58	0.48	1.27
Sandstone	-0.07	0.14	3.02	2.09	1.40	0.90	-0.004	0.20	-0.27	2.59	0.77	1.31

TABLE 4 Mean and Standard Deviation of CIs for Core and Loose Samples (Binder Courses)

Aggregate Type	Core Samples								Loose Samples							
	Percent AC		Percent Passing 12.7 mm Sieve		Percent Passing 2.36 mm Sieve		Percent Passing 75 μm Sieve		Percent AC		Percent Passing 12.7 mm Sieve		Percent Passing 2.36 mm Sieve		Percent Passing 75 μm Sieve	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Gravel	-0.05	0.23	5.39	4.35	2.46	1.79	2.16	0.94	-0.30	0.17	1.00	2.00	-0.67	1.16	1.37	0.58
Sandstone	0.12	0.26	7.50	2.81	0.50	1.38	2.50	0.84	-0.13	0.06	-3.67	3.79	-3.33	0.58	2.00	0.00

Based on normal distribution theory, the total dispersion expected from individual measurements is $\pm 3\sigma$ units, and for multiple sample or sample means, it is $\pm 3\sigma_{\bar{X}}$.

$$\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}}$$

where σ is the standard deviation of individual measurements and n is the sample size. The symbol $\sigma_{\bar{X}}$ is commonly referred to as the standard error of the mean.

It would appear from Table 5 that the existing PennDOT specification limits are too restrictive for single or individual ($n = 1$) samples. The existing specification limits are more in agreement for a sample size of 5. The standard deviation values and resultant specification limits also indicate that the existing PennDOT specification limits are too tight for individual samples.

The same technicians performed the experimental work throughout Phase 1. However, different technicians performed the sampling in Phase 3, which resulted in somewhat higher standard deviation values than those obtained in Phase 1.

Cores were also obtained from these six projects to measure the mat density. The minimum specification limit for compaction was 92 percent of theoretical maximum specific gravity. The contract governing the six projects stated that for 100 percent payment the lot average for compaction ($\bar{X}$) must be 92 percent or greater, with no individual sublot value below 90 percent of theoretical maximum specific gravity. The average compaction ($\bar{X}$) for all six projects was computed to be 92.8 percent, with a standard deviation (σ) of 0.87 percent. On the basis of these data it appears that the specification limits were proper and realistic:

$$\bar{X} - 3\sigma = \text{lower specification limit}$$

$$92.8 - 3(0.87) = 90.2$$

DEVELOPMENT OF SPECIFICATIONS

A department-industry task force was organized by PennDOT to review the statistical analysis of the extensive test data obtained in Phases 1, 2, and 3, and develop statistically based end-result specifications. These specifications were to be established on the basis of acceptable existing construction quality levels. The contractor would submit a quality control plan (with no minimum numbers of tests mandated by PennDOT) to PennDOT and would be entirely responsible for quality control. PennDOT would obtain acceptance samples (loose-mix samples behind the paver for mix composition and core samples for compaction testing) at random on a lot-by-lot basis. These samples would be tested in the PennDOT Central Laboratory, where the lot statistics [such as percent within limits (PWL)] and the pay factors would also be computed.

On the basis of the experience from 6 pilot projects in 1980 and 16 pilot projects in 1981 (*3*), the following observations were made and conclusions were reached:

1. The statistical acceptance criteria should be based on three items only: asphalt content, percent passing 75 μm (No. 200) sieve, and percent compaction in the mat based on theoretical maximum specific gravity. It was believed that the percent passing 2.36 mm (No. 8) sieve need not be a pay item because this characteristic would be reflected indirectly by the percentage compaction. However, contractors must maintain quality control charts showing day-to-day fluctuations in the materials passing all specified sieves. When adverse trends are noted or the material is consistently outside the JMF gradation limits or other Marshall test parameters (such as stability, flow, air voids, and voids in the mineral aggregate), the HMA facility may be shut down.
2. The multiple deficiency formula, when applied to the 1980 pilot projects, resulted in severe price adjustments. For example, if the asphalt content for a given lot was calculated to be paid at 100 percent of the contract unit price, the minus

TABLE 5 Comparison of Proposed Specification Limits from Phases 1 and 3 with Existing PennDOT Limits (Wearing Course)

Mix Property	Phase 1			Phase 3			Existing PennDOT Spec. Limits (n=1)
	Sample Standard Deviation σ	Proposed Spec. Limits 3σ (n=1)	Proposed Spec. Limits $3\sigma_{\bar{x}}$ (n=5)	Sample Standard Deviation σ	Proposed Spec. Limits 3σ (n=1)	Proposed Spec. Limits $3\sigma_{\bar{x}}$ (n=5)	
Asphalt Content	0.22	±0.66	±0.30	0.25	±0.75	±0.34	±0.4
2.36 mm (No. 8) Sieve	2.58	±7.74	±3.46	3.35	±10.05	±4.49	±4
75 μm (No. 200) Sieve	0.78	±2.34	±1.05	0.98	±2.94	±1.31	±2

75 μm (No. 200) material to be paid at 90 percent of the contract unit price, and the compaction to be paid at 85 percent of the contract unit price, the resultant payment would be the product of the three percentages:

100 percent × 90 percent × 85 percent = 76.5 percent

The value 76.5 percent is more severe than the individual percentages used to make the calculations.

Approximately 23 percent of the total bid price for the six projects in 1980 sustained a price adjustment. It has been reported that equitable price adjustments associated with statistical acceptance plans should be expected between 5 and 10 percent (*4*).

It was decided to use a weighted price adjustment approach, which would be based on the criticality of the three characteristics evaluated (asphalt content, minus 75 μm material, or mat density) on the performance of the HMA pavement. Most asphalt paving technologists would agree that of the three characteristics, the mat density is by far the most important to avoid premature failure and to ensure reasonable serviceability and performance of an HMA pavement. Therefore, 50 percent payment was made attributable to mat density (or compaction), 25 percent payment to asphalt content, and 25 percent payment to minus 75 μm (No. 200) material.

3. The specification tolerances developed in Phases 1 and 3, the experience from the pilot projects in 1980 and 1981, and ASTM's precision statement for the extraction testing procedure (ASTM D2172) were considered to develop specification tolerances for asphalt content and minus 75 μm (No. 200) material (Table 6). According to ASTM, the results of two properly conducted tests from two different laboratories, on samples from the same batch, should not differ by more than ±0.81 for asphalt content. This is reflected in the proposed specification tolerances (Table 6) for a single sample ($n = 1$).

4. A screening process must be incorporated in the specifications to provide an incentive for the contractor to target the JMF. This process must be simple and easily understood by contractors who are not well versed in statistics. Therefore, a bonus-penalty point approach should be placed in the specifications to reward or penalize the contractor depending on the precision with which the JMF was reproduced. Sampling, testing, and materials variations should be taken into account. The same approach should be applied to the density acceptance criteria.

The following sections summarize the acceptance criteria and basis of payment included in the statistically based end-result specifications.

Mix Characteristic Acceptance

After the JMF is approved, the contractor shall test for asphalt content and aggregate gradation in accordance with the submitted quality control plan. The mixture shall be controlled for individual test samples ($n = 1$) within ±0.7 percentage points of the JMF for asphalt content in the wearing course, ±0.8 percentage points of the JMF for asphalt content in the binder course, and ±3.0 percentage points of the JMF for the 75 μm (No. 200) sieve for both wearing and binder courses.

The mixture shall be controlled for the lot average ($\overline{X}$) of multiple test samples ($n = 5$) within ±0.4 percentage points of the JMF for asphalt content in the wearing course, ±0.5 percentage points of the JMF for asphalt content in the binder course, and ±2.0 percentage points of the JMF for the 75 μm (No. 200) sieve for binder and wearing course materials.

The lot shall be accepted with respect to asphalt content and percent aggregate passing the 75 μm (No. 200) sieve under the following three conditions.

Condition 1

The lot will be accepted at 100 percent payment factor for percent asphalt content when no individual test result for the lot, based on the JMF, deviates from the requirements for binder or wearing (Table 6), and the lot average ($\overline{X}$) of all tests within the lot falls within ±0.2 percentage points of the JMF for wearing course material and ±0.3 percentage points of the JMF for binder course material. One bonus point shall be assigned for the lot.

The lot will be accepted at 100 percent payment factor for percent aggregate passing the 75 μm (No. 200) sieve when no individual test result based on the JMF deviates from requirements for binder or wearing course (Table 6) and the lot average ($\overline{X}$) of all tests within the lot falls within ±1.0 percentage points of the JMF. One bonus point shall be assigned for the lot.

Condition 2

Whenever the lot average ($\overline{X}$) for asphalt content (wearing) falls between ±0.2 and ±0.4 percentage points of the JMF and no individual test result deviates more than ±0.7 percentage points from the JMF, one penalty point will be assigned for the lot.

Whenever the lot average ($\overline{X}$) for asphalt content (binder) falls between ±0.3 and ±0.5 percentage points of the JMF

TABLE 6 Specification Tolerances for Asphalt Content and Minus 75 μm Material from JMF

Mix Characteristic	Individual Sample (n = 1)		Sample Average (n = 5)	
	Binder	Wearing	Binder	Wearing
Asphalt Content (%)	± 0.8	± 0.7	± 0.5	± 0.4
75 μm Sieve (% Passing)	± 3.0	± 3.0	± 2.0	± 2.0

and no individual test result deviates more than ±0.8 percentage points from the JMF, one penalty point will be assigned for the lot.

Whenever the lot average ($\overline{X}$) for percent aggregate passing the 75 μm (No. 200) sieve falls between ±1.0 and ±2.0 percentage points of the JMF and no individual test result deviates more than ±3.0 percentage points from the JMF, one penalty point will be assigned for the lot.

Condition 3

Whenever an individual test result or the lot average ($\overline{X}$) for the percent asphalt content or percent aggregate passing the 75 μm (No. 200) sieve deviate from the tolerances (Table 6), the percent within tolerance or limits for that characteristic(s) and the payment factor percentage will be determined (*5*). Lot payment will be determined in accordance with the weighted price adjustment formula.

Density Acceptance

For the binder and wearing course, the lot will be accepted with respect to compaction for one of the following conditions.

Condition 1

The lot shall be accepted at 100 percent payment factor for density if the lot average ($\overline{X}$) of the density results is 92 percent of theoretical maximum density or greater and no sublot test is below 90 percent of theoretical maximum density. Two bonus points shall be assigned for the lot.

Condition 2

Whenever the lot average ($\overline{X}$) of the density results falls between 90 percent and 92 percent of theoretical maximum density and no sublot test falls below 90 percent of theoretical maximum density, two penalty points will be assigned for the lot.

Condition 3

If one or more sublot tests fall below 90 percent of theoretical maximum density, a quality index value, Q_L, will be computed for the lot from the following formula:

$$Q_L = \frac{\overline{X}n - 0.90\,T}{s}$$

where

n = number of density measurements on the lot,
$\overline{X}$ = average of n density measurements (lb/ft^3),
T = theoretical maximum density (lb/ft^3),
s = standard deviation, and
Q_L = quality index value.

The PWL for the lot will be determined for the previously determined quality index value (Q_L). The payment factor percentage will then be determined from PWL. Lot payment will be determined in accordance with the weighted price adjustment formula.

Basis of Payment

The ID-2 binder and wearing courses will be paid for at the contract unit price per square yard or contract unit price per ton as follows:

1. If the percent aggregate passing the 75 μm (No. 200) sieve, the percent asphalt content, and percent compaction all fall within Condition 1, the contract unit price per lot will be paid at 100 percent.
2. If the percent aggregate passing the 75 μm (No. 200) sieve, percent asphalt content or percent compaction fall within Condition 2, the bonus (positive values) and penalty points (negative values) will be accumulated algebraically for the lot. One bonus point will cancel one penalty point. A lot indicating a negative cumulative total for the bonus and penalty points will be paid at 98 percent of the contract unit price. A lot indicating zero or a positive total will be paid at 100 percent of the contract unit price.
3. If one or more of the acceptance characteristics do not fall under items 1 or 2, the adjusted percentage of contract price to be paid per lot will be computed as follows:

$$Lp = Cp\,\frac{(2P_D + P_M)}{400}$$

where

Lp = lot payment,
Cp = contract unit price per lot (unit price times lot quantity),
P_D = payment factor percentage for density, and
P_M = payment factor percentage (sum) for percent asphalt content and percent aggregate passing 75 μm (No. 200) sieve.

For those characteristics meeting items 1 or 2, the applicable payment factor will be entered into the formula for calculation purposes.

The engineer reserves the right to remove and replace the lot when any one of the three acceptance parameters (percent asphalt content, percent 75 μm material, percent compaction) falls below 64 PWL. In lieu thereof, the contractor and the engineer, after review, may agree in writing that, for practical purposes, the deficient lot should not be removed and should be paid for at 50 percent of the contract unit price.

IMPLEMENTATION OF SPECIFICATIONS

These statistically based end-result specifications developed through the joint effort of PennDOT and the HMA industry were implemented in 1982.

Training

An extensive training program was undertaken in 1981 to train PennDOT and industry personnel in basic statistics and all aspects of this specification, such as random sampling, lots and sublots, PWL, and pay factors. This training program was continued for several years.

Testing

These end-result specifications require acceptance testing by PennDOT; some other states use contractors' test data. Since the lot size is approximately equal to one lane 1.61 km (1 mi) long, five loose-mix samples and five core samples are obtained and tested by PennDOT for each lane mile of HMA paving. This is a large task of testing undertaken by PennDOT's central laboratory. In 1 of the past 10 years, about 1,600 lane mi were paved by PennDOT under these specifications, which required performing about 8,000 extraction tests (on loose samples behind the paver) and about 8,000 density tests (on pavement cores) by the central laboratory. However, the asphalt laboratory crew has consistently delivered quality test results during the past 10 years.

The extraction laboratory staff consists of one materials supervisor and four materials technicians. The laboratory has 24 extractors. Each technician is responsible for six extractors. During a regular work day (7.5 hr), 48 extraction tests (12 per technician) are performed. On a day with overtime (12.5 hr), the output is doubled, and 96 tests can be performed.

The density laboratory staff consists of one materials supervisor and two materials technicians. During a regular work day, density tests are performed on 75 cores. When overtime is used, the output is doubled, and 150 cores can be tested.

The testing quality of the laboratory personnel is checked frequently by introducing referee samples (of known mix composition or density) in the testing system without the knowledge of the testing technicians.

The asphalt laboratory testing staff of only eight people has been able to cope with testing of all acceptance samples from the entire state. This has enabled PennDOT to reduce the number of HMA plant inspectors significantly because the end product behind the paver screed is tested for acceptance. PennDOT's district personnel are satisfied with these specifications because the judgment factor in evaluating the quality of the end product and deciding the price adjustments has been practically eliminated. The districts and contractors now get a lot-by-lot printout of extraction and density test results, PWL, and the pay factor. Although the test results are not available to contractors to make timely adjustments or corrections in the HMA paving operations, contractors may perform their own tests (with no minimum number of tests mandated by PennDOT) to maintain quality control.

Retests

When a lot involves price adjustments, all sublot samples (loose mix or cores) in that lot are saved by the central laboratory because the contractor may request a retest of that lot. If requested, retesting of all sublot samples (although only one or two of the five sublot samples may be outside tolerance limits) is done in the presence of the contractor's representative. Both the original test values and the retest values are analyzed statistically to determine if they are significantly different at the 5 percent level. Pennsylvania Test Method No. 5, which is used to compare the means and standard deviation of the two sets, is used for this statistical analysis. This process eliminates the judgment factor. If the retest values indicate repeatability, the original test values are used, and the cost of the additional testing for the lot (10 times the unit bid price per ton of HMA) incurred by PennDOT is borne by the contractor. However, if the retest values indicate a lack of repeatability, the retest values are used, and the cost of the additional testing is borne by PennDOT.

Results

Both PennDOT and HMA industry personnel have adapted to the statistically based end-result specifications during the past 10 years. These specifications have practically eliminated premature distress and have increased the serviceability and durability of HMA pavements in Pennsylvania by improving the quality of the end product on the roadway. This paper was prepared belatedly to include these long-term observations.

The specifications have provided PennDOT with a means of evaluating and comparing the dollar value of the improvement of HMA quality year-by-year. Overall, the percentage of lots subjected to price adjustments has ranged from 4 to 6 percent during the last 4 years. During 1991, 5 percent of the total lots tested had price adjustments. Of these lots, 73 percent were deficient in mat density, 12 percent were outside the tolerance for minus 75 μm (No. 200), 6 percent were deficient in asphalt content, and 3 percent were excessive in asphalt content.

PennDOT now allows computer printed tickets from an automated HMA facility in lieu of loose-mix samples behind the paver. Reduced tolerances are used for asphalt content in such cases. However, verification samples are obtained for each 454 Mg (500 tons) and tested by the central laboratory.

ACKNOWLEDGMENTS

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Life-Cycle Performance of New York City Bridges

B. YANEV AND XIAOMING CHEN

The 1991 annual report of the New York City Department of Transportation (NYC DOT) Bridge Bureau lists 872 bridge structures under its purview. Included are the 4 East River crossings, 25 movable bridges, 5 tunnels, and a large variety of structures over land, with a total number of spans approaching 6,000. The average age of the bridges in this network is approximately 68 years. This is in sharp contrast with the average age of 28 years of the nearly 600 bridges in the metropolitan area, which are managed by New York State Department of Transportation (NYS DOT). As a result of the federally mandated bridge inspection program, which was originated in the late 1970s, it is currently possible to consider the bridge structural condition as a variable with respect to time. The length of the period since inspections began and the large variety of bridge conditions reveal for the first time certain patterns in the life-cycle performance of the bridges in New York City. This deterioration model analysis is regarded as a fundamental tool of the bridge management program stipulated by the Intermodal Surface Transportation Efficiency Act of 1991. Of particular interest are certain bridge components, such as deck, primary member, joints, and the like. The inspection records established by NYS DOT allow review of the performance of such components over time. The results may yield not only an insight into the behavior of various structural members, but also certain indications of their relationship. From the deterioration patterns obtained from inspection records and the knowledge of maintenance, repair, and reconstruction costs, it is possible to select optimal strategies of bridge management and superior design. The conclusions are specific to the geographic area under consideration and the period of the data on which they are based. The term "optimal" implies a certain set of constraints. It is recognized that the optimal state of a bridge network may not be the highest priority in optimizing a local budget. The overall optimization process is beyond the scope of this paper. It is pertinent, however, to investigate the degree to which bridge life-cycle behavior may be assessed in an unconstrained environment and the potential effects of budget constraints during design, construction, and maintenance. Results of deterioration modeling for bridges and bridge components performed at the Bridge Bureau of NYC DOT during the past 2 years are summarized.

Life-cycle cost considerations in the design selection for new bridges and the optimal operation of existing ones are among the most frequently discussed issues related to bridge management. Noteworthy articles on the subject include those by T. R. Kuesel (*1*) and R. L. Nickerson and D. Veshosky (*2*). These authors favor incorporating life-cycle cost considerations in bridge design and management. In another article, D. Veshosky and C. R. Beidleman (*3*) argue that life-cycle cost analysis does not work for bridges, at least for the present. The authors point out that the number of significant variables associated with life-cycle decisions is considerable and the knowledge of these variables is both limited and restricted to the past. As a result, life-cycle analysis might introduce more uncertainty than useful forecasting. In a move that appears to support this view, FHWA has discontinued the use of the bridge inventory bracket for estimating remaining structural life.

Foremost among the variables necessary for a life-cycle cost estimate is the bridge deterioration rate. This rate is clearly (although not exclusively) a function of (a) structural type and design, (b) construction quality, (c) local climate, (d) traffic, and (e) maintenance.

Because items c–e may vary during the life of the structure, it is questionable whether a deterioration rate can be reliably established over a time comparable to the expected period of bridge use. Within certain limitations, however, information exists that may be translated into patterns of bridge deterioration. This is primarily because of the federally mandated biennial and interim bridge inspections, which have provided a consistent rating of bridge conditions for approximately 15 years.

The resulting bridge inspection reports provide for the first time insight into the behavior of bridges over a significant time period. No such data are available for bridge structures in other developed countries. Consequently the inspection program is the subject of considerable international interest (*4,5*). Two main points should be considered during a review of the information available from bridge inventory and inspection reports. First, all meaningful information should be extracted from the inspection reports and used to its maximum value. Second, the limitations of the available data should be fully recognized. This would serve to prevent the formulation of erroneous conclusions and provide guidance for future bridge data acquisition.

Certain deterioration curves for bridges and bridge components with respect to time are discussed here. The reported results were obtained at the New York City Department of Transportation (NYC DOT) Bureau of Bridges using data from inspection reports primarily from New York State bridge inspection files. Although confined to bridges located in the New York metropolitan area and to a period of only 15 years, the results are intended to show the possibilities open to life-cycle performance considerations with the refinement and expansion of bridge condition data.

BASIC ASSUMPTIONS AND LIMITATIONS

The bridges examined in this study are located in the New York City metropolitan area. They include 872 bridges owned

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Bureau of Bridges, New York City Department of Transportation, 2 Rector Street, 4th Floor, New York, N.Y. 10006.

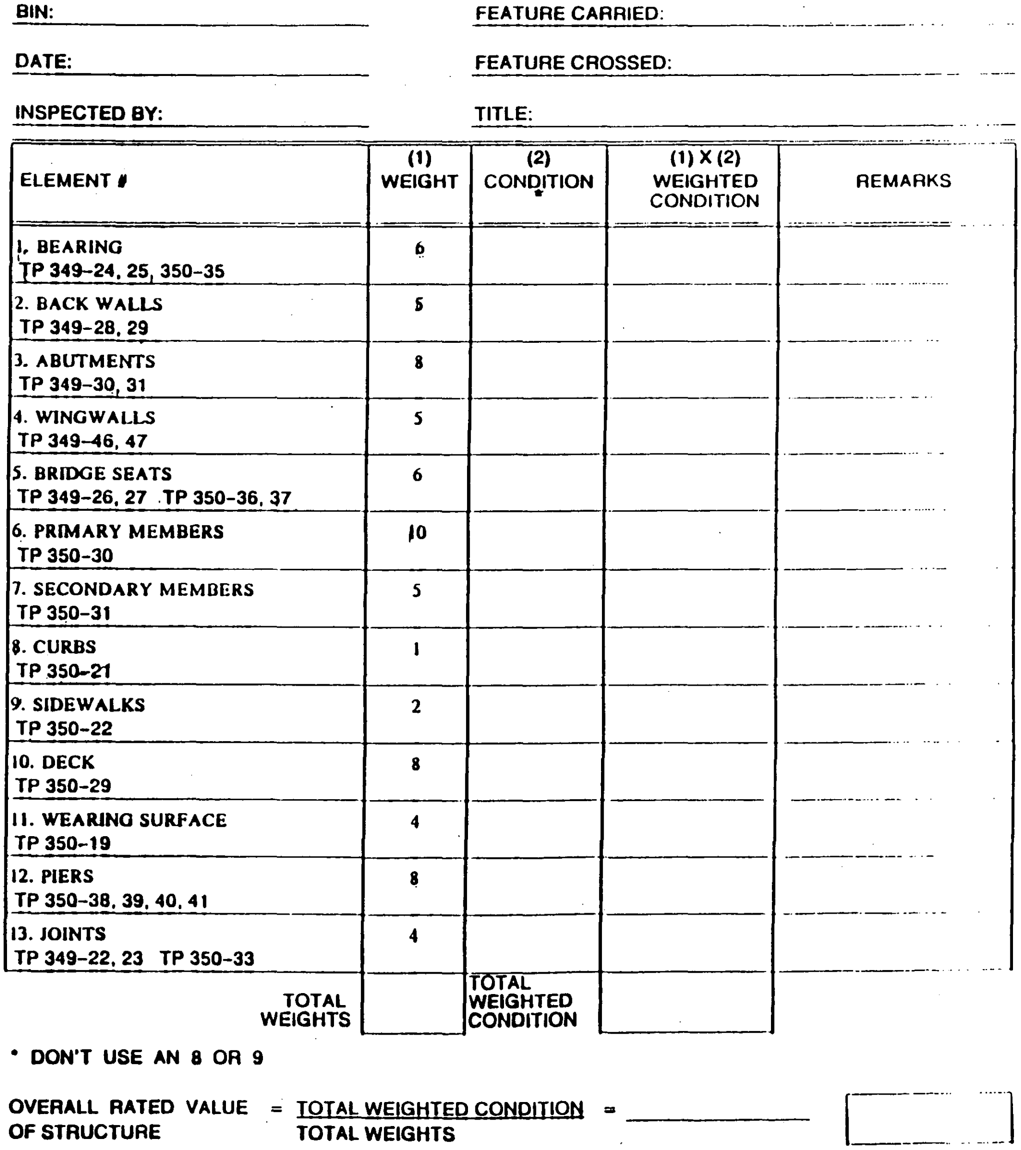
by New York City with approximately 5,200 spans and an average age of 68 years and 550 state-owned ones with approximately 3,000 spans and an average age of 28 years. Approximately 600 bridges managed by other organizations in the area are also included.

All bridges support street and highway vehicular traffic. The magnitude of traffic varies according to the bridge location. The East River crossings carry an average daily traffic of up to 250,000 passengers, whereas certain street bridges carry well below 25,000 passengers. The difference in traffic volume has not been used to distinguish between different structures.

The source of bridge condition data consists of biennial and interim inspections performed by consultants for the New York State Department of Transportation (NYS DOT) or NYC DOT according to state standards. The inspections date from 1978 to the present.

The bridge condition is a real number from 1 to 7 computed on the basis of weighted averages of certain bridge component conditions, as shown in Figure 1. Bridge components receive integer condition ratings from 1 to 7:

- Rating 1: Potentially hazardous;
- Rating 2: Used to shade between a rating of 1 and 3;
- Rating 3: Serious deterioration or not functioning as originally designed;
- Rating 4: Used to shade between a rating of 3 and 5;
- Rating 5: Minor deterioration, but functioning as originally designed;
- Rating 6: Used to shade between a rating of 5 and 7;
- Rating 7: New condition;
- Rating 8: Not applicable;
- Rating 9: Unknown [due to inaccessibility (e.g., footings or piles)].



BIN:

DATE:

INSPECTED BY:

FEATURE CARRIED:

FEATURE CROSSED:

TITLE:

ELEMENT #	(1) WEIGHT	(2) CONDITION *	(1) X (2) WEIGHTED CONDITION	REMARKS
1. BEARING TP 349-24, 25, 350-35	6			
2. BACK WALLS TP 349-28, 29	5			
3. ABUTMENTS TP 349-30, 31	8			
4. WINGWALLS TP 349-46, 47	5			
5. BRIDGE SEATS TP 349-26, 27 TP 350-36, 37	6			
6. PRIMARY MEMBERS TP 350-30	10			
7. SECONDARY MEMBERS TP 350-31	5			
8. CURBS TP 350-21	1			
9. SIDEWALKS TP 350-22	2			
10. DECK TP 350-29	8			
11. WEARING SURFACE TP 350-19	4			
12. PIERS TP 350-38, 39, 40, 41	8			
13. JOINTS TP 349-22, 23 TP 350-33	4			
TOTAL WEIGHTS		TOTAL WEIGHTED CONDITION		

* DON'T USE AN 8 OR 9

OVERALL RATED VALUE OF STRUCTURE = $\frac{\text{TOTAL WEIGHTED CONDITION}}{\text{TOTAL WEIGHTS}}$ = ______

FIGURE 1 Average bridge condition rating, New York state bridge inspections.

These ratings (both individual elements and weighted average) are recorded on NYSDOT Inspection Report Forms. Together with photos and explanatory descriptions, the ratings provide the bureau with information on the existing condition of each bridge. In addition, bridge inspectors assign a general recommendation integer rating from 1 to 7 to the bridges.

The bridge condition rating incorporates two significant assumptions. One is the set of structural components and corresponding weights assigned to them, as shown in Figure 1. The selection is based on engineering experience and reliability estimates which, even if fundamentally sound, are not always formally defined. Second is the decision to use only the lowest condition rating of all spans for each of the structural components in Figure 1. This is motivated by the objective to identify the weakest link on any bridge. Consequently a single poor span affects the rating of an entire multispan structure.

The general recommendation rating reflects the assessment of the inspecting engineer. This rating should be assigned at the conclusion of the bridge inspection, subsequent to rating all individual components in all spans, but before and independently of computing the condition rating.

The correlation between the general recommendation and the bridge condition ratings is shown in Figure 2. Despite the inevitable scatter, which varies over the years, the two ratings appear to compare well, suggesting that the two rating procedures are in general compatible.

It must be noted that the bridge rating system serving as the basis for the deterioration models obtained herein has the significant limitation of being subjective. The judgment of one inspector is not identical to that of another who inspects the same bridge. The state requires that the same inspector not inspect the same bridge two consecutive times.

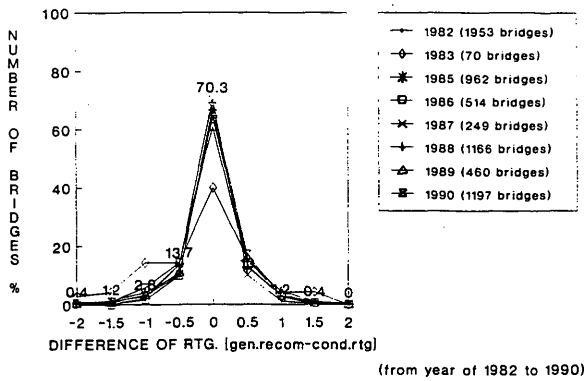


FIGURE 2 **Comparison of general recommendation with condition rating for all inspection years.**

There is no quantifiable basis for the ratings. The rating system is essentially a relative one, despite efforts to introduce quantities of deterioration as much as possible in the inspection reports. The load-bearing capacity of a bridge does not change significantly over a rating change from 7 to 4, but is presumably reduced by the time the bridge is rated 3. This, however, is not always the case. Load-rating procedures are established independently of the condition ratings.

Subjectivity affects the deterioration models to a varying degree at the different ratings from 1 to 7. It is noted that inspectors show a propensity for rating toward the middle of the scale (e.g., 4) and not toward the extreme values. This tendency coincides with the objectively normal distribution of bridge conditions observed for the general bridge population, as shown in Figure 3. The degree to which the objective

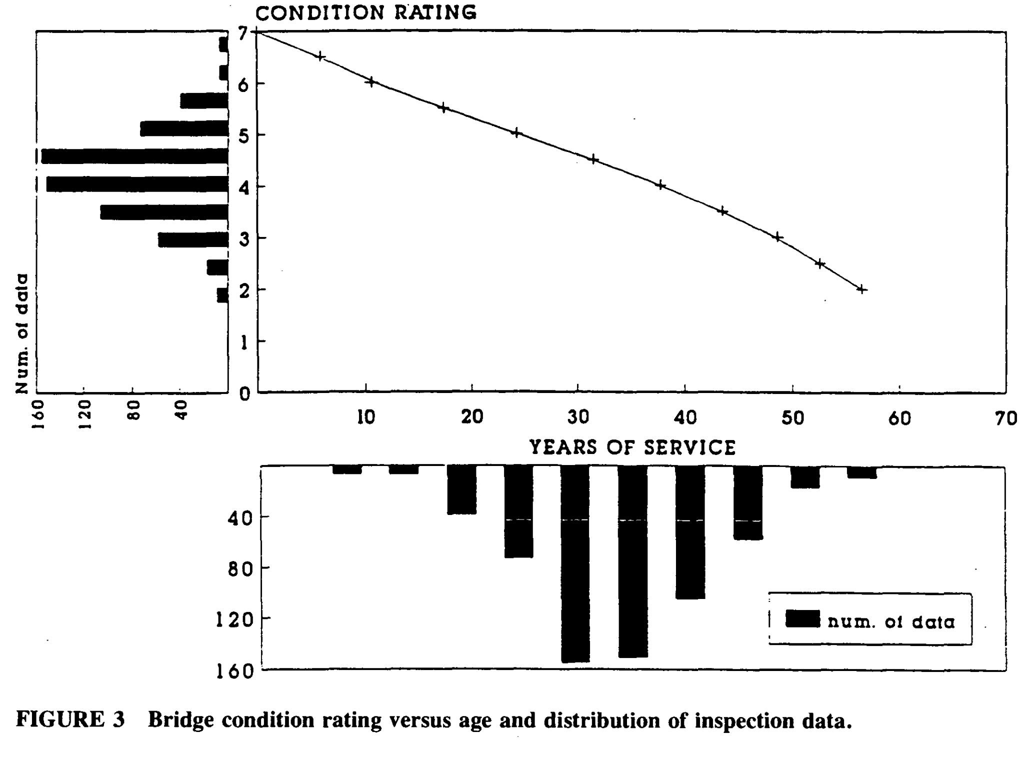


FIGURE 3 **Bridge condition rating versus age and distribution of inspection data.**

and subjective influences contribute to the normal distribution of ratings is not known.

The bridge rating system is a combination of serviceability and physical deterioration criteria. Needs for repairs are not immediately apparent from any rating level. Bridge ratings are increasingly considered as fuzzy sets. Probabilistic techniques such as Markov chain models are applied to the problem, as for instance in work by M. Cesare et al. (*6*)

Bridge condition ratings were used in this study on the assumption that they have the same bias throughout the data acquisition period (1978–1990).

Maintenance is expected to significantly affect the deterioration rate. The exact effect, however, can only be estimated. It is assumed herein that maintenance was constant during the study period. Further, it is assumed that the maintenance was negligible. Maintenance consists primarily of painting, spot painting, and cleaning of wearing surfaces and drainage systems.

Most major rehabilitations of bridges are recorded in the bridge files. Repairs of various components such as joints, decks, steel primary members, and the like, however, are not possible to identify from the records. As a result, the effects of certain such repairs are implicit in the deterioration models. These repairs do not include temporary measures, such as timber shoring, steel deck plates, and so forth, which eliminate hazardous conditions but do not improve the rating of a bridge component.

DETERIORATION MODELS

Within the prescribed assumptions and limitations, the rating of overall bridge conditions, bridge decks, and primary members are considered as a function of their age. Two methods are used for generating the bridge rating versus age models.

Model 1

The rate of change is calculated for each rating (e.g., from 7 to 6.5, from 6.5 to 6, and so on). The average rate of change is plotted over time. The results for the bridges of the metropolitan area with no record of major rehabilitation are shown in Figure 3.

Also plotted is the data distribution as a function of the bridge age and as a function of the bridge ratings. Both distributions are normal, indicating that the most voluminous data are in the central portion of the structural lifespan.

The resulting deterioration model is near linear, with an average loss of one rating point per 10 years. Thus, the condition of 3 (not functioning as designed) is reached in 40 to 45 years and 1 (defunct) is reached in an average of 60 years.

Figure 4 shows the same curve, along with the deterioration model for bridges that have undergone capital rehabilitation. The slope of deterioration for rehabilitated bridges is steeper. This suggests that, in all cases, the rehabilitated bridges do not revert back to rating of 7 but instead improve to a rating of 6 and proceed to decline at a rate faster than that of a new bridge.

The conclusion that rehabilitated bridge components are improved only to a level of 6 instead of 7 has been incorporated in the New York State bridge management system. It is shown here that the same holds true for the rehabilitation of entire bridges.

Model 2

In this model the bridge ratings for bridges of all ages are simply averaged. This method has been applied for obtaining several deterioration curves.

The ratings of all bridges in the metropolitan area and their respective ages are shown in Figure 5. It indicates that bridges are maintained at a level of approximately 4.3. In contrast with the preceding figures, this one shows the effect of all repairs and rehabilitations performed on the bridges. The ratings and respective ages for steel and concrete primary members with and without joints in the deck are shown in Figure 6. Ostensibly the joints accelerate the deterioration process. The respective performance of bridge decks with and without overlays are shown in Figure 7. Once again, the presence of joints demonstrates the same detrimental effect.

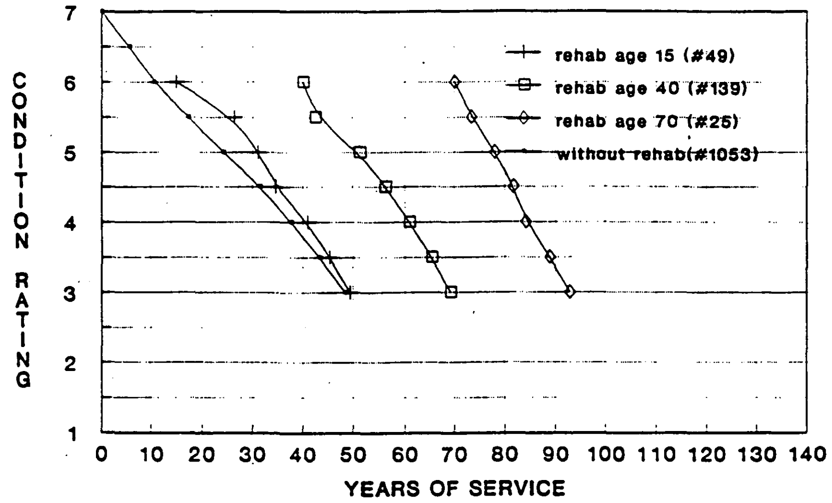


FIGURE 4 **Bridge condition rating versus years of service.**

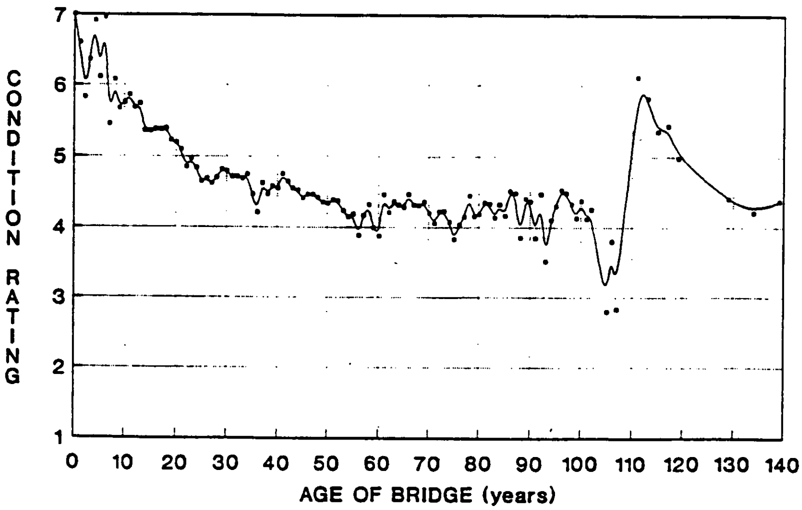


FIGURE 5 Bridge condition rating versus age.

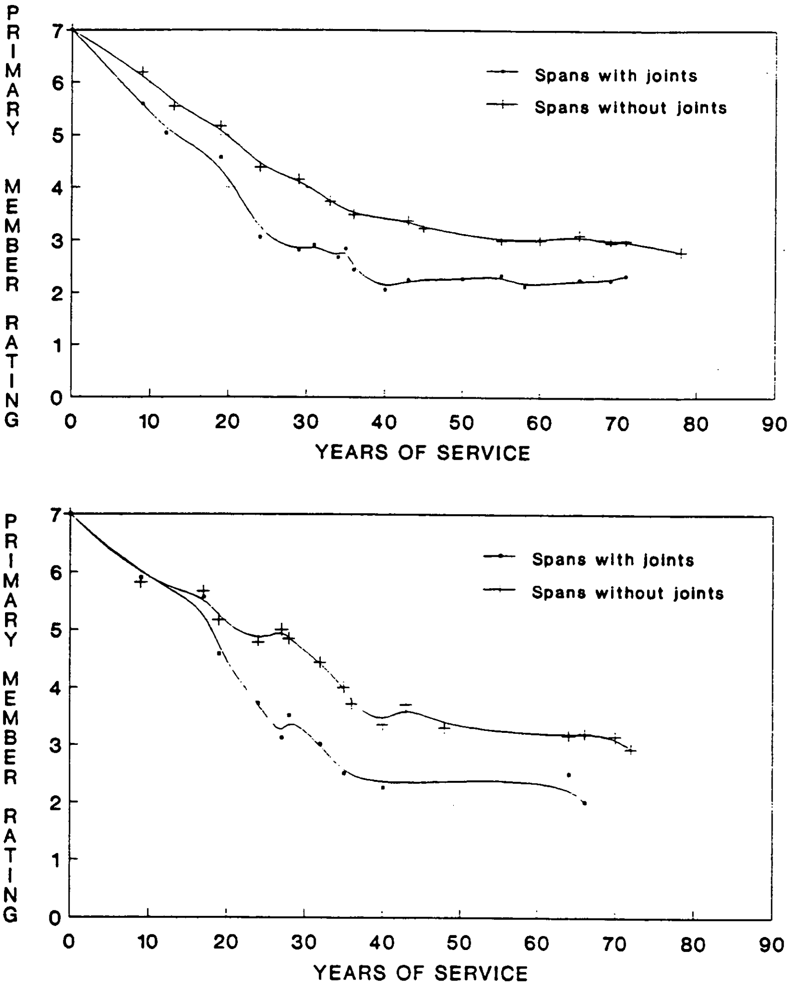


FIGURE 6 Steel (*top*) and concrete (*bottom*) primary member rating versus age.

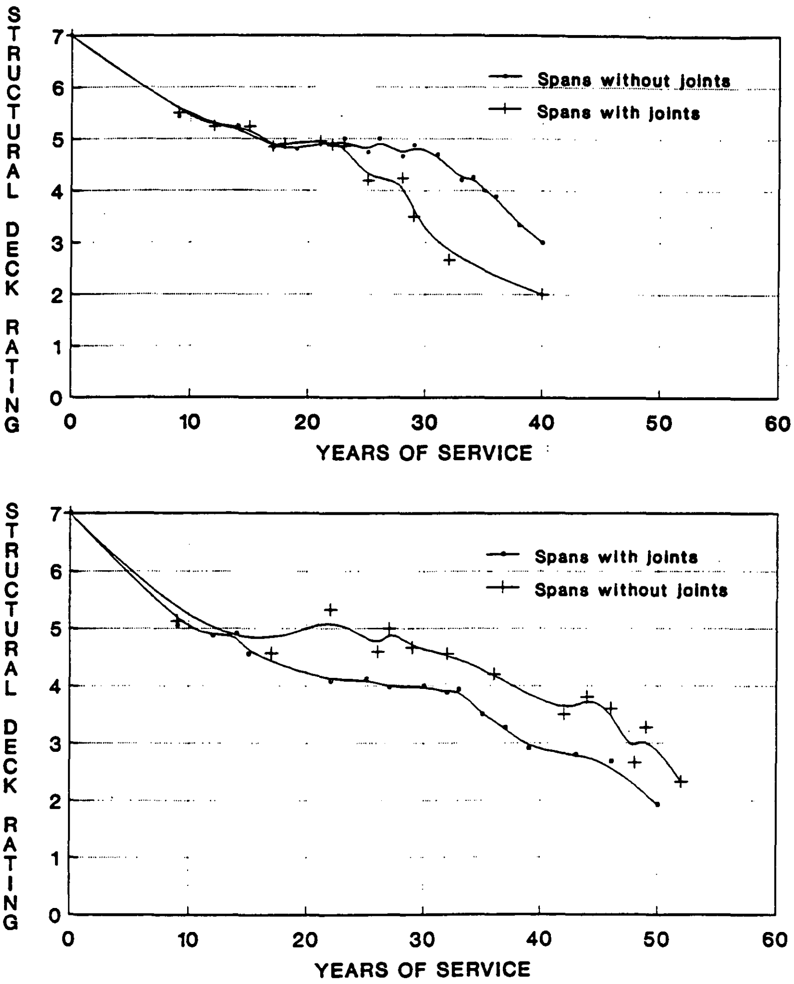


FIGURE 7 **Structural deck rating versus age, spans with overlays (*top*) and without overlays (*bottom*).**

Deck deterioration rates in the cases with and without overlays have been investigated by J. Llanos and B. Yanev (*7*). The resulting deterioration models are shown in Figure 8. These models are based on a limited number of decks without replacement or major repair. Rehabilitated decks are included in Figure 7. A comparison of the results suggests that deck repairs have been performed on most bridges without overlays, bringing their deterioration rate up to that of the decks with overlays. In all cases the data pertain to decks with uncoated reinforcement. Asphalt resurfacing of decks with overlays has regularly occurred for most New York City bridges at 5- to 10-year intervals.

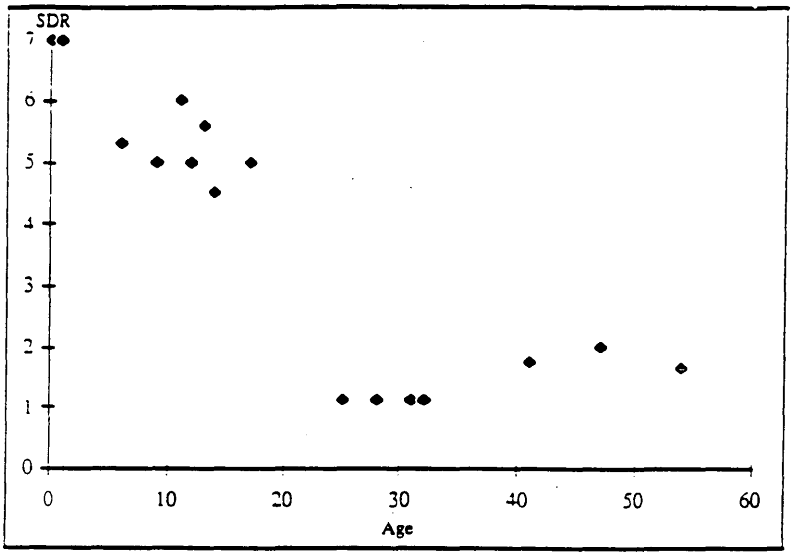
The deck deterioration patterns appear to agree with similar results obtained for the bridges managed by the New York Thruway Authority, as reported by K. E. Giles (*8*).

CONCLUSIONS AND RECOMMENDATIONS

The ultimate goal of obtaining bridge deterioration models is to gain knowledge of the expected bridge useful life and level of service. The following conclusions may be drawn from the models discussed in this paper.

At the past level of maintenance, and in the absence of rehabilitation, New York City bridges may be expected to reach the rating of 3 (not functioning as designed) in 40 years and to reach the end their useful lives in 60 years. Bridge decks would have to be replaced at least once if they have no overlay (or resurfaced regularly if they do) during this period.

The bridges of New York City are maintained at an average condition level of approximately 4.3 during most of their service lives. This average is below the level of 5, which is considered serviceable. Consequently the bridges do not provide optimal service to the community. Further, the maintenance of the bridge population at this average level implies a considerable number of bridges below, as well as above, the mean. Such a state involves certain hazardous conditions and substantial repairs, frequently under emergency conditions. It is therefore highly probable that this strategy, besides yielding less than optimal service, is a more expensive one than keeping the bridge condition at 5.5 by intensified maintenance. Further investigation, which should include maintenance versus repair costs and could serve as a guide toward an optimal maintenance strategy, is required.



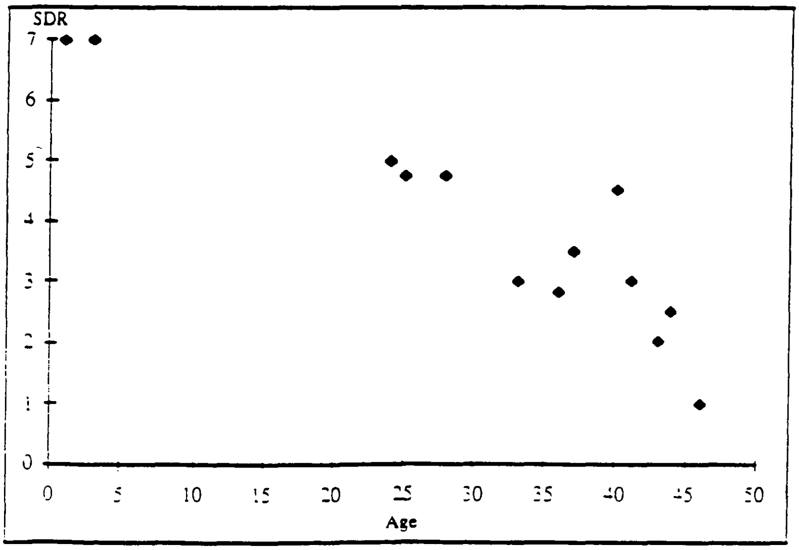


FIGURE 8 Condition rating as a function of time for bridge decks without overlays (*top*) and with overlays (*bottom*) (data from NYC DOT bridge inspection and management data base).

Concrete and steel primary members appear to decline at a similar rate. It should be noted that steel primary members have not received adequate painting and therefore did not perform optimally. Further, steel primary members outnumber concrete ones by approximately 4 to 1, and their average age is roughly twice that of the concrete members. The similarity between the two models is therefore inconclusive.

Joints have a pronounced detrimental effect on both steel and concrete primary members and on concrete decks with and without overlays.

Bridge rehabilitation restores bridge condition ratings to approximately 6 instead of 7, and the ensuing deterioration rate is faster than that of a new bridge.

All of these conclusions should be viewed as specific to the New York City environment and the negligible maintenance of the 1970s and 1980s. Further sensitivity studies could improve the insight into the performance of bridge types and components during the period under consideration.

The current policy of improving bridge maintenance with added cleaning, spot painting, and regular full repainting ought to have a retarding effect on bridge deterioration. The modeling methods used here, however, would not reflect such an effect from the first few years of implementation. Future modeling would require an accurate statement of the maintenance level in order to remain distinct from the one in which maintenance was assumed to be negligible.

In order to derive accurate conclusions from the obtained models, it is necessary to identify the significant factors determining the deterioration rate. For instance, the presence of alkali-silica gel in concrete decks may have been typical for bridges of a certain age. The elimination of alkali-silica reactions would affect the deterioration rate in a significant way, which has yet to be demonstrated.

The recent introduction of condition rating for each bridge span in New York State adds another refinement to the modeling procedure. Past inspection reports can be reviewed in the light of this enhancement and the effect on the models of deterioration can be evaluated.

With further refinement and added data, bridge deterioration models can become an accurate indicator of bridge management efficiency and a reliable guide to improved bridge design and maintenance.

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Current Worldwide Status of Robotic Applications in Construction

FAZIL T. NAJAFI

Worldwide, small-scale robotic construction applications have existed for approximately 3 decades. Government, universities, industry (e.g., construction companies and construction equipment manufacturers), research laboratories, and research institutions have all been involved and are still pursuing work in the application of robotics in construction. The participation of different countries in this area is summarized; only those countries that have been comparatively active in their efforts are included. On the basis of analysis and some field observations, the author concludes that the Japanese are advanced in the application of robotics in construction. However, worldwide efforts, cooperation, and dedication are needed to improve, develop, and capitalize on the potential worldwide benefits of construction robotization.

During the past 3 decades, the field of robotic applications in construction has challenged relevant government construction participants, the construction industry, construction equipment manufacturers, construction engineering firms, and the engineering academic community. In the United States, the government is transferring research and development activity to industry and the community through technology transfer programs. Although budget constraints are slowing these efforts, great emphasis is being placed on the importance of technology transfer programs. The number of robots in the United States grew from 200 in 1970 to more than 100,000 at present. There are 20 to 25 academic research centers and government laboratories, along with a similar number of commercial enterprises, that experiment with robots. The volume of government-sponsored research in robotics in the United States was about $20 million in 1982 (*1*). However, according to a January 1992 CBS Evening News television report, the United States lags behind Japan, Germany, and Sweden in related research.

In the United States, robotics development efforts are focused on such new technologies as artificial intelligence, robotics vision, and parallel processing computer architecture (*2*).

Robotization investments have been made by the Japanese manufacturing industry since the mid-1970s. The tendency of young Japanese people to not work in construction created a labor shortage that forced government and industry to progress further in robotization. The Japanese are aggressively looking at the long-range future benefits of robots in the construction field.

In Europe, progress of automation and robotics in construction has not been particularly aggressive. Economic problems in Europe and Australia have slowed progress in this field. In general, close coordination among the active European countries, Australia, United States, and Japan is essential for ensuring successful technology transfer. Traditional sources of government funding in these countries could be used to support joint research and development of construction automation and robotics. Sources of financial support in the United States include the National Science Foundation, National Aeronautics and Space Administration (NASA), U.S. Department of Defense, Associated General Contractors of America, Construction Industry Institute, American Road and Transportation Builders Association, and Construction Industry Manufacturer's Association. Most private associations are not active in promoting robotics technology among their members.

Most of Japan's robotic research was begun at Waseda University System Science Institute in 1978; the program is supported by private and public funding. Japan's Ministry of International Trade and Industry and the Industrial Robot Association specifically identify and support construction-related activities that can be performed by robots (*3*). In Australia and Europe, most support comes from government sources.

STATUS OF CONSTRUCTION AUTOMATION AND ROBOTICS

United States

Examples of some of the robots built in the United States are presented in Table 1 (*4*). Many universities are currently conducting robotics research, including the University of Florida, Purdue University, University of Texas at Austin, North Carolina State University, University of Illinois at Urbana-Champaign, Ohio State University, University of Colorado at Boulder, University of Wisconsin at Madison, and Texas A&M.

The U.S. Army Construction Engineering Laboratory is also interested in automation, particularly for the cleanup of hazardous or toxic materials.

Japan

In Japan during the past 15 years, efforts have been made by general contractors to integrate joint development for building construction robots. The Japanese realize the importance of close cooperation and coordination among general contractors, robot manufacturers, lease or rental companies, and subcontractors. They recognize that cooperation and coor-

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Department of Civil Engineering, University of Florida, 345 Weil Hall, Gainesville, Fla. 32611-2083.

TABLE 1 Examples of Robotics Developed in the United States (*4*)

Robot Type	Application	Developer
John Deere Excavator, Model 690C	Teleoperated excavation for rapid airport runway repair	John Deere, Inc., Moline, Illinois
Laser-Aided Grading System	Automatic grading control for high-volume earthwork	Gradeway Construction Co. & Agtec Development Co., San Francisco, California; Spectra-Physics Co., Dayton, Ohio
Automatic Slipform Machines	Placement of concrete sidewalks, curbs and gutters	Miller Formless Systems Co., McHenry, Illinois; Gomaco, Ida Grove, Iowa
Micro-Tunneling Machine	Teleoperated micro-tunneling	American Augers, Wooster, Ohio
Robotic Excavator ("REX") and Autonomous Pipe Mapper	Autonomous excavation around buried utility metallic pipes, potentially for several types of autonomous nondestructive testing	Carnegie Mellon University, Pittsburgh, Pennsylvania
"NavLab"	Autonomous navigation in unstructured terrain	Carnegie Mellon University, Pittsburgh, Pennsylvania
Remote Work Vehicle	Nuclear accident recovery work, demolition of structures after nuclear accidents, structural surface decontamination, cleanup and treatment, transport of materials	Carnegie Mellon University, Pittsburgh, Pennsylvania
"Wallbot," "Blockbot," Shear Stud Welder	Construction of building interior partitions with metal track studs, concrete masonry work, welding of shear connections in composite steel/concrete structures	Massachusetts Institute of Technology, Cambridge, Massachusetts
Automated Pipe Manipulator	Teleoperated pipe system assembly in industrial processing plants	University of Texas, Austin, Texas
Automatic Pipe Bending System	Robotic bending and connection of metallic of pipe sections	University of Texas, Austin, Texas
Experimental Maintenance Device	Automated pavement crack sealing	Carnegie Mellon University, Pittsburgh, Pennsylvania

dination are the key concepts in a successful construction robotization program.

More than 40 major construction companies in Japan are active in robotics development and application in construction. For instance, Shimizu has now developed a multipurpose vehicle called MTV1. It includes a powered mobile-control module, sensors, navigation devices, and controllers, and it performs various floor-finishing operations (*3*).

In June 1992, the author attended the 9th International Symposium on Automation and Robotics in Construction (ISARC) in Tokyo, Japan, and visited the Landmark Tower in Yokohama, which was under construction. This is a new city center for Yokohama with a building area of 253,011 ft^2, 3 floors below ground, and 70 floors above ground, with a steel frame and reinforced concrete structure. Robotics applications on this site included a directional controlled lifting system, a remote shackle, manipulators for placing steel doors and aluminum curtain walls, an automatic lifting system for materials for finishing work, and an automatic positioning system for the steel frame building block. The automation and robotics in construction application on this site was quite impressive and cost-effective in terms of safety, liability, and labor shortages. It was evident that the Japanese are quite successful in using robots in construction of buildings, foundation work, lifting operations, uniform finishing of concrete floors, automatic paint spraying of exterior walls, finishing jobs, and plasterboard positioning in which the robot picks up individual panels and moves them to a preprogrammed position for ceiling installation. Robots are also used for lifting and erecting heavy precast concrete panels. In addition, robots are used for tunneling. For example, the Shimizu company presented a video to the conference members showing a tunneling shield equipped with a steering mechanism between the rotating cutting wheel and the bulkhead. This allows the machine to be steered precisely, reducing excavation volume and allowing segment placement to progress alongside excavation.

Another product is a submarine shield that has a connecting mechanism that allows long undersea tunnels to be excavated without the need for an excess shaft where the two tunnels from each shore meet. Another machine is used in tight spaces, such as shafts, for tunneling and building foundations to position the heavy braces that support cofferdams. The Japanese have also developed automatic concrete surface scabbles to scabble the surface of vertical construction joints; these machines scabble the concrete surface of bridge piers reinforced for road expansion 20 times faster than hand-held machines. Another product is an automated formwork that can be elevated without a crane. The dam concreting system, consisting of a mobile tower crane, bucket carts, and transfer cars, transported concrete and workers efficiently and safely. Many cranes are built with a control system that is made of a collision prevention system and an operational management system for erecting heavy steel frame in tall buildings.

The Japanese have also built an automated glass roof washer that safely cleans vast slanted glass roofs. In another video presented at the conference, a biological shield concrete-cutting robot was used to dismantle the concrete structure surrounding a reactor while people remained at a safe distance to avoid radiation.

The new generation of robots has the potential to reduce human resource requirements, enhance productivity, and perform hazardous and repetitive work. Japanese experts believe that the Japan Ministry of Construction, Ministry of International Trade and Industry, Tukuba University, Japan Building Contractors Society, and the U.S. Construction Industry Institute are important organizations that could enhance construction robotization. These organizations should extend and coordinate their research activities with those of organizations in Europe and Australia.

Germany

The Germans do not have an overall aggressive robotics development program and approach comparable to the one in Japan. However, construction-related developments include the following (*5*).

- Excavation:
  - –Hydraulic pumps are able to control the energy in reference to the requirements;
  - –Computer-assisted loading with Teach-In and automatic excavation of that movement is used; and
  - –Computer-assisted profiling by means of an external sensor system and a specific controller is used.
- Earthwork equipment:
  - –Graders feature moldboard control (slope, angle, external control by laser) and front wheel electronic drive control;
  - –Loaders feature torque converters to optimize fuel consumption; and
  - –Dumpers feature power program for high-driving performance on difficult terrain.
- Road construction: road pavers feature automatic leveling, including controllers and servo valves to achieve better quality.
- Concrete distribution: enhanced functions of concrete distributors control large reach manipulators with a rotary axis.
- Telescopic cranes include controllers with the following features: load limitation control; measurement of the wind forces, with a warning to the operator; platform control; and test, diagnostic, and maintenance system.
- Concrete panel fabrication: a system that has achieved a high industrial standard and integrates design, time scheduling, and fabrication with highly automated stations. For the placement of reinforcement, two robots are in operation per plant.
- Brickworks:
  - –An outdoor handling system features simple small mobile cranes; and
  - –A stationary plant manufacturing system features automated placement of bricks and mortar.
- Tunneling: one major drive to robotics development could come from a coal mine application. Robots are used for inspection and repair of concrete sewers.
- Nuclear applications: robots are used for the decommissioning of nuclear power stations. Research efforts are directed toward further development of robotics in nuclear applications (*5*).

Sweden

In 1983 Sweden established the Swedish Construction Industry (SBUF) to promote development work in the construction industry. It was set up to be co-financed by the government, mostly by the Swedish Council for Building Research, with the goal of seeking further financial support from municipalities and the building material industry. By 1993 the yearly support for SBUF reached MSEK 70 (MSEK = million Swedish Crowns; $1.00 = 6 SEK). The support is preferably intended for research and development at technical universities. Seven areas of priority for research and development have been identified to be supported by this fund (*6*):

1. Material technology,
2. Information technology (robotics),
3. Mechanical services,
4. Indoor climate,
5. Facility management,
6. Infrastructure, and
7. Economizing of resources.

Robotics in construction in Sweden is applied to working tasks with a difficult construction environment such as demolition, tunneling, and handling of materials. Robotics are used for soil reinforcement works in existing buildings. Most robotics in use in Sweden are remotely controlled. The Swedes believe that success requires joint research and development—cooperation among contractors, manufacturers, and universities (*6*).

United Kingdom

The United Kingdom Advanced Robotics Programme was initiated in 1985 with the support of the Department of Trade and Industry. For tunneling, robots are used for segment erection and grouting of tunnel walls. In mines, a continuous system of temporary roof support robots is used that "walks" in space with a cutting machine, provided with a sensor-driven robotics control system for semi-autonomous tunneling within a coal seam (*7*).

In 1988 the Advanced Robotic Research Center at Salford planned to design robots that could operate in unstructured environments. This program has resulted in the lab-scale demonstration of the ability of robot systems to operate autonomously in unstructured environments. The program included

Advanced Robotic functional architecture, a manipulator general-purpose controller and free-ranging mobiles concentrating on the capabilities required for an indoor truly free-ranging Automatic Guided Vehicle (7).

At the City University in London, researchers continue to develop the enabling technology for automating masonry tasks in a quality assurance environment. The main functions of masonry construction were simulated in an experimental robot cell composed of a gantry-type robot that operates the grippers, material conveyor, and the laster beacon. The robot has been assisted by a supplementary navigation system to improve its positioning function. It is intended that a cell will be developed in which a mobile robot will replace the experimental gantry. In the experimental trials, construction of a dry wall was simulated because no provision was made for a mortar dispensing function, which has yet to be developed. The results so far have been encouraging, with emphasis on quality control, in particular in the assessment of the supply material (7).

Work on the inspection robot for nuclear reactors at the polytechnic of Portsmouth is progressing with the construction of three prototypes. The robot is joystick driven and pneumatically actuated. It has a 600-mm-wide and 150-mm-high control and moves on eight nonjointed legs with suction-cup feet. Using two frames with four feet mounted on each, it moves by disengaging one set of feet while the other set adheres. It carries lights and two cameras and can haul a payload of 25 kg. The robot is designed to climb about 10 m from the equator of the 20-m-diameter spherical reactor pressure vessel (7).

Automation of the inspection of tall buildings is the subject of research work at the City University in London (7).

A mini-excavator robot has been developed. The depth of a required trench is used as input; then the machine takes over and digs a high-quality flat-bottomed trench. A robot that provides soil strengthening by launching long reinforcing nails into the ground using compressed air is also commercially operational (7).

A recent report produced for the U.K. National Economic Development Council suggests that the adoption of Information Technology and electronic data exchange could cut overall building costs between 15 and 25 percent with similar or greater gains in productivity. At the University of Nottingham work has been in progress in automation of management functions and is moving closer to robot intelligence. Research topics include automatic generation and evaluation of plans and schedules, automatic budgeting and network generation, and layout optimism of building services (7).

Finland

The Technical Research Center of Finland (UTT) has been involved in research on construction robotics for several years. Still, construction robotics is in its infancy. UTT is supported by a federation of the Finnish building industry, of which all construction firms are members, and has established a system of cooperative research and development. A number of research committees, nominated by the federation, initiate and fund contract research projects, which are carried out by UTT, universities, and consultants. The major research themes are codes and information files, construction management systems, production technology, product development, and personnel development. One such program supported by UTT is the Logistics of Construction Production. This program was proposed because the construction industry has developed such that work on the construction site is decreasing and the use of prefabricated parts and components is increasing. The industrialization of construction has resulted in increased logistics costs. The Logistics of Construction Production project has four parts: supervision of the design of the construction project from the logistics viewpoint, development of the logistics on the construction site, purchasing business, and product-related logistics (*8*).

Australia

In Australia robotics research is in its infancy and going through an exploratory and learning phase. In 1989 construction robotics studies at the University of New South Wales (UNSW) in Sydney were begun at the undergraduate and graduate levels. In 1991, the School of Civil Engineering joined with the Schools of Mechanical and Electrical Engineering and Cognitive Sciences as an equal partner in an ambitious robotics and intelligent machines project to develop sensorially complex and problem-solving robots. In March 1992 the first formal construction robotics laboratory in Australia was established in the School of Civil Engineering at UNSW. A variety of strategic research areas is being addressed at the university. These include the following (*9*):

- Robot architecture and configuration research,
- Mechanical engineering aspects of construction robots,
- Sensor technology research,
- Real-time control systems research,
- Artificial intelligence controller research,
- Computer vision research,
- Economic aspects of construction robots research,
- Social aspects of construction robots research, and
- Research into the integration of construction robots with computer-aided design systems.

The following is a list of projects under study at UNSW.

- Robotic arm research with both high-dexterity and high-lift capacity with large reach systems:
  - High-dexterity robotic arms have high-speed precision similar to that of the human arm. With such arms one can perform delicate and complex physical operations such as those required to work on high-voltage power line insulators and to secure nuts and bolts. These arms may be controlled by telerobotic control arms or by a full computer system.
  - Prototype robotic arms have been tested, and a number of large machine forms are under development (*9*).
- Economic and technical feasibility studies are currently being carried out on the following topics:
  - Fully automated vertical slipforming of structures using large capacity and reach on-deck robotic arms,
  - Robotized shotcreting and tunnel lining with general purpose robotic arms,

-Automated steel reinforcement placement and tying,

-Concrete surface finishing with dexterous robotic arms equipped with finishing tools, and

-Automated precast concrete quality control with robotic inspection test stations.

Most of the major universities in Australia have mechatronics or industrial robot teaching and research groups. It is encouraging that Australia has at least begun work in the construction robotics field and has developed a broadly based program in this field (*9*).

Israel

In Israel, research and development at the Technion is directed toward integration and automation of the total delivery process. The National Building Research Institute in Israel involves the interior finishing robot and the automated crane. Interior finishing includes partition building, plastering, and floor finishing. The Israelis are using an expert system for evaluation of the components of a given building design, detailed design, and cost estimate of prefabricated building elements. The expert system is used to generate a list of activities necessary to complete a given building, the resources required to complete the building, and a work progress schedule. In addition, an automated vehicle has been developed by the mechanical engineering faculty at the Technion. The vehicle is able to navigate toward a specified target and omit possible obstacles in its way (*10*).

In addition, to date the Israelis have studied the following aspects of robot-related modules (*10*):

- Performance specification and preliminary design of the robot and its components, including the arm, carriage, sensors, effectors, and control system. The findings are described by Yavani et al. (*11*).
- Adaptation of building technologies to robotic constraints. The main works have included partitions building, plastering, and floor finishing. This study is discussed by Bentur and Puterman (*12*).
- Analysis of optimal configuration in relation to cost, productivity, and operation, as described by Warszawski and Navon (*13*). The computer simulation and measurement of performance of various configuration alternatives have been cited in this study.
- Planning of robotized work with a computerized procedure for the analysis and the feasibility of using robots for different types of buildings is described by Argaman (*14*).
- Testing of physical performance of automated tasks with a small robot (Scorbot of Eshed Robotec, arm reach of 0.60 m and payload of 1.0 kg) adapted to building works. The experiments are described by Argaman and Warszawski (*15*).
- Testing of physical performance of automated tasks with a full-scale robot (with a reach of 1.50 m and payload of 30 kg) adapted to building works. The robot can perform various finishing tasks—painting, plastering, tile setting, partitions, building, and others. It will employ several types of sensors—for avoidance of obstacles, for materials handling, for mapping and navigation, and for identification of openings. The robot is described by Rosenfeld et al. (*16*, *17*).
- Economic analysis of performance involved three applications, which were developed and studied, namely tiling, painting and plastering, and partitions building, and included comparison of robotic versus manual productivity and construction cost. The findings are presented by Rosenfeld et al. (*18*).
- Autonomous control system for the finishing robot employs ultrasonic or laser sensors for mapping of an unknown building environment and artificial intelligence for planning of the work procedures. The progress in this study is detailed by Shohet et al. (*19*).

The scale of research and development research in Israel is quite encouraging. It appears that progress will be made in the areas of excavation, road construction machines, concrete distribution, and the like.

CONCLUSION

The status of automation and robotics is still not at an advanced stage, although the Japanese are advanced in the application of robots in construction. However, important areas of construction still affect human health and safety. Some examples are sand blasting; excavating deep trenches; deep sea work; desert work during sandstorms; mining; some cleaning operations; framing steel high in the air in the cold of winter in such places as Chicago, New York, and Tokyo; and controlling traffic during highway construction, maintenance, and so forth.

Construction work is strenuous and often performed under harsh and hazardous conditions, which require high wages and high insurance rates and often involve large economic losses as a result of work accidents. A robot is capable of working in foul weather, darkness, hazardous areas, and without problems involving motivation and administration, which affect the efficiency of humans. Furthermore, when shortages of skilled labor are a problem, the substitution of robotics for humans has the potential for high productivity, and robots might become more economical to use for a series of simple or repetitive tasks. In the future more advanced research and cooperation among advanced nations are essential for developing more sophisticated automation and robotics in construction.

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Influence of Nighttime Operations on Construction Cost and Productivity

RALPH D. ELLIS, JR., AND ASHISH KUMAR

There has been a shift in emphasis from building new facilities to rehabilitation of highways in the United States. However, with traffic levels approaching or exceeding highway capacities, any maintenance work on highways disrupts traffic, often resulting in severe congestion, delays, and accidents. As a result, various highway agencies are shifting toward nighttime construction and maintenance when traffic densities are relatively low. The decision to work at night, however, involves a number of complex issues. Some factors involved in such decision making were identified in a research study conducted for the Florida Department of Transportation. The effects of nighttime construction on construction cost and productivity are evaluated in this paper. Comparisons are made for daytime and nighttime highway projects in Florida. Unit cost comparisons do not suggest any trend in the cost differential of individual items; however total program cost is found to be less for work at night as compared with work during the day. The results do not confirm any significant difference between the productivity values for daytime and nighttime projects.

Recently many states have changed the focus of their operations from constructing new highways and roads to maintaining the existing ones. This shift creates many problems. One such problem arises from daytime lane closures, which result in heavy congestion on roads already loaded to capacity. This problem is not limited to roads in urban areas but also includes some rural highways that are often as crowded during certain times of the year as urban areas. According to one state highway agency official, it has become difficult to distinguish morning rush hour from evening rush hour, and congestion lasts for 12 to 13 hr a day (*1*). This creates a situation in which the normal, ordinary solution of lane closure becomes unrealistic or impossible during peak times. Daytime lane closures are also hazardous, costly, and inconvenient for the traveling public. As a result, more construction and rehabilitation work is being performed during hours when traffic flow is minimal. For this reason, many highway agencies have started working at night.

In addition to several obvious advantages of nighttime work, such as cooler temperatures for equipment and material, less traffic problems, and delays, there are certain disadvantages. Many complex issues, including safety, costs, productivity, lighting conditions, manpower availability, and administrative decisions, are associated with nighttime work.

Recent literature on highway construction confirms this trend toward nighttime work and addresses the problems associated with it. However, the number of references dealing directly with nighttime operations, as a whole, is limited. Only a few studies provide a comprehensive approach and valuable information toward night-shift construction. The manufacturing industry has dealt with night-shift operations for many years and has had numerous research studies conducted. Because of the distinctly different nature of the two industries, only a few of those studies are applicable to the construction industry. Those that apply are in the area of human factors. Several published reports in the transportation area have provided information on issues relating to the planning, safety, and traffic control aspects of nighttime maintenance and construction work and their advantages and disadvantages. Price (*2*) addressed the overall nighttime paving operation with respect to lighting, personnel, and communication. He also included comparisons of quality, cost, and safety in his research. Shepard and Cottrell (*3*) conducted a study in which information was compiled on current practices in nighttime highway construction and maintenance operations. This information was used to develop guidelines for determining when work should be done at night and what traffic control devices should be used. The major areas covered in their nighttime construction feasibility study were scheduling of lane and road closures, work-zone costs, safety, public relations and user costs, and traffic control. Hinze and Carlisle (*4*) further evaluated the important factors in nighttime construction. They have focused their research on rehabilitation and maintenance activities on major metropolitan highways. Qualitative and quantitative factors related to nighttime construction were detailed in their study, along with a discussion of advantages and disadvantages.

The Florida Department of Transportation (FDOT) has determined that nighttime work is one major solution to the problem of traffic congestion associated with highway maintenance. Researchers at the University of Florida recently attempted to study all the parameters involved in a night operation (5). The objective was to provide assistance to FDOT in developing a more structured decision-making system concerning when to make a project a nighttime operation. Most of the information obtained for the study from a literature survey and other sources is based on opinions and is not quantitative. Although these opinions are based on substantial experience and are important, more accurate and quantified data are needed. The researchers, in addition to identifying these parameters and evaluating their effects, also quantified the effects on construction cost and productivity. The information presented in this paper is based on that research effort.

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

OVERVIEW OF FACTORS AFFECTING NIGHT OPERATIONS

From the literature survey, analysis of several case studies, and meetings with experts in Florida and other states, a number of factors have been identified that affect the decision of shift times for highway construction. These factors play important roles in determining whether to work at night. These factors are divided into five categories on the basis of their characteristics:

- Construction-related factors:
  - Cost,
  - Productivity,
  - Quality, and
  - Noise;
- Traffic-related factors:
  - Congestion,
  - Safety, and
  - Traffic control;
- Human factors:
  - Sleep,
  - Circadian rhythms, and
  - Social and domestic issues;
- Miscellaneous factors:
  - Public relations,
  - Information,
  - Supervision,
  - Communication,
  - Material supply, and
  - Equipment repair; and
- Work-zone lighting.

Some of these factors have qualitative and some quantitative attributes. For instance, cost and productivity are quantitative factors; quality, noise, safety, and congestion are both qualitative and quantitative; and human factors and other factors are qualitative. Analysis of construction-related factors revealed that cost, quality, and productivity had some project-by-project variations caused by various factors. Construction cost and productivity are discussed in detail in this paper. The number of noise complaints is higher for nighttime work for projects in urban areas, and those projects take longer to finish. Although human factors are usually given some consideration, they are not constitute a major decision-making criterion. Traffic-related factors are considered to be the most important. Congestion is often found to be the one single factor resulting in the decision to use a night shift on many projects. Safety is a major concern during nighttime work because accidents tend to be more severe, even though the rate is relatively low. To enhance safety, appropriate traffic control is emphasized. Slower speeds, lane closures, detours, use of flashing arrow boards, use of appropriate warning devices, layouts, sufficient lighting, and use of police patrol cars are found to be some of the more effective measures for better traffic control. In addition, public relations and information are found to be important elements in nighttime construction. Not only do announcements reduce the congestion and accident rate, but the public has a positive attitude toward the delays and noise. Supervision and communication are difficult for nighttime work because most offices are only open during the day. Similarly, supply and repair also create some problems because parts and materials are not easily available at night. Although most of these factors have some effect on nighttime work, work-zone lighting has a considerable influence. It not only affects quality and productivity, but also influences traffic control, safety, and human factors.

Cost, productivity, and quality are the basic project attributes and are affected by the way work is performed. There have been various opinions with regard to variations in these factors as a result of a change in the work shift. According to some, construction costs and total project costs are normally expected to be higher for nighttime construction than for daytime construction. The reasons are attributed to overtime pay, shift differential, lighting, higher bids, and the like. However, user and public costs may follow a reverse trend. Similarly, nighttime work may have negative effects on quality and productivity.

CONSTRUCTION COST COMPONENTS

Similar to most decision-making processes, selection of a night shift over a day shift or vice versa is influenced by economics. The literature review indicated a lack of cost information for an effective comparison between daytime and nighttime construction. In highway construction, the attributable costs can be categorized into four types of costs (a) construction or owner costs, (b) user costs, (c) accident costs, and (d) maintenance costs. Construction costs are usually the estimated project costs, whereas user costs are incurred by traveling motorists as a result of ongoing construction. Accident costs are difficult to obtain and quantify. Pavement maintenance costs refer to postconstruction costs, which depend on quality control during the work. In absence of sufficient data, this discussion is confined to construction and user costs.

Construction or Owner Costs

Construction or owner costs are essentially the costs borne by the state highway agency as a result of the construction of a facility. This includes the costs of the contract (labor, material, equipment, and contractor) and agency costs (planning, evaluating, and monitoring). Construction costs can vary from shift to shift. Additional construction costs that can be attributed to nighttime work include lighting, additional traffic control, inspection, labor premiums, overtime pay, and increased material costs.

Material costs may be higher during a night shift because batch plants may charge higher rates. According to a study in Denver on two similar overlay projects, the price for hot bituminous pavement (patching) (haul and asphalt) per ton was found to be 23 percent higher than that of the day project. The price for emulsified asphalt (CSS-1H) per gallon was 42 percent higher (*2*). A cost comparison done by a resident engineer of FDOT indicates a 2 to 3 percent increase in material costs for asphalt roadway work during the night (*5*).

Labor and inspection costs are additional cost items for night construction. Shift premiums accounted for an increase of 18 percent in direct labor costs, and overtime costs for agency personnel required an additional 16 percent (*4*). One

Florida contractor agreed to pay $0.50 per hr extra for all personnel involved in nighttime operations (*5*).

Lighting is a significant factor in the differential cost between daytime and nighttime construction. Because the cost of artificial lighting is unique to nighttime work, it may be regarded as a project-specific cost. For nighttime construction, there is an added cost for traffic control because of the need for additional signs in a low-visibility environment. Additional signs for night-shift work may include changeable message signs, arrow boards, warning signs, and channelizing devices. An analysis of paving projects in Colorado mentions that the cost of flagging per hour was 71 percent higher for the I-70 nighttime paving project (*2*).

User Costs

The cost incurred by traveling motorists due to on-going construction and maintenance work on the roadway is classified as user costs. This category mainly includes vehicle operating costs, personal costs, and accident costs. Operating costs and time value are determined using tables to obtain unit user costs. Nighttime construction greatly reduces user costs related to vehicle delays. In an attempt to measure a reduction in user costs on a nighttime project in Colorado, Price found that the cost was reduced from $119,110 for daytime work to $10,100 for nighttime work (*2*). The total savings to public in the same study for one project was estimated to be more than $1 million. However, accident costs are difficult to estimate.

In the following section an attempt has been made to compare construction cost differentials for daytime and nighttime projects in Florida. For cost evaluation, two comparisons are made: (a) variations in individual item unit costs and (b) variations in total program costs for daytime and nighttime projects.

EVALUATION OF FDOT NIGHTTIME CONSTRUCTION COSTS

Research Methodology

Most highway projects are unique and usually consist of different sets of work items, which makes it difficult to compare the construction costs of nighttime and daytime jobs by directly comparing daytime and nighttime projects. To overcome this problem, a set of typical work items has been selected for this study. These work items were chosen on the basis of (a) their presence in typical day- and night-shift highway projects, (b) their significant contribution to project costs, and (c) their large quantities. A list of these work items follows:

- Removal of existing pavement (110–4),
- Regular excavation (120–1),
- Bituminous material—prime coat (300–1–1),
- Bituminous material—tack coat (300–1–3),
- Milling of existing asphalt pavement—2-in. average depth (327–70–5),
- Class I concrete—miscellaneous (400–1–15),
- Type S asphalt concrete—including bitumen (5331–2), and
- Asphalt concrete friction course—including bitumen (5337–1–2).

Rates for these work items were obtained for all projects conducted by FDOT in 1990. The statistics of these rates for work items performed during daytime are presented in Table 1. Similarly, statistics of rates for eight selected work items for nighttime jobs were also obtained. Standard deviations for nighttime unit prices were found to be extremely high. These high deviations may be attributed to the small sample of nighttime projects considered for the study and other project-specific conditions. It was speculated that unit price of an item was influenced by its quantity and its share in the total project cost. A correlation analysis performed between quantity and unit prices of items also indicated a certain trend. Bid prices for items having large quantities were relatively lower than those having small quantities. To overcome this effect, weighted unit prices were used for nighttime projects instead of the actual mean of unit prices. The weighted unit prices were obtained by dividing actual item costs for nighttime projects by their respective quantities. The actual mean of unit prices was used for daytime projects because of the large sample size.

To determine the variation in means, an item-by-item comparison of rates was performed; results are presented in Table 1. Columns 5 and 8 present the means for nighttime and daytime jobs, respectively. The differences in the means are provided in Column 9, where negative numbers indicate lower nighttime costs. The differences between daytime and nighttime unit prices were found to be negative for nearly all the items.

To quantify the difference of nighttime and daytime unit prices and to demonstrate the effect on the total program costs, further evaluation was conducted. Results of the comparison are presented in Table 2. Column 3 gives the total quantities of items for selected nighttime projects. Column 5 shows the actual nighttime costs for respective items, and Column 7 shows the projected costs if the projects were done during the daytime. Columns 8 and 9 indicate the savings in cost and percentage of daytime costs as a result of eight selected items. Except concrete, all items have a lower nighttime cost; the average percent saving in cost is found to be 36.1 percent.

Results

An analysis of the information presented in Tables 1 and 2 reveals that the variations in unit costs for the eight selected items are very high. Standard deviation in most of the cases is nearly 100 percent of the mean, which shows that unit costs are highly project oriented and depend more on project-related conditions than on type of shift.

The comparison of the two unit prices in Column 9 of Table 1 shows that seven of the eight items have a greater daytime mean unit cost and that the miscellaneous concrete has a greater nighttime mean unit cost. This shows a certain trend in the unit costs. Unit prices are generally lower for nighttime work than for daytime work. The higher concrete unit price may be attributed to the work-item characteristics. It may involve activities that are more expensive to do at night.

TABLE 1 Summary of Rates for Selected Work Items for FDOT Projects in 1990

			Daytime Projects			Nighttime Projects		
Pay Item Number (1)	Name of Item (2)	Unit (3)	No. of Projects (4)	Mean ($/unit) (5)	Std. Dev. ($/unit) (6)	No. of Projects (7)	Weighted Mean ($/unit) (8)	Diff. ($/unit) (9)
110-4	Rem exist. pavement	sq.m	104	12.58	13.14	21	8.92	-3.66
120-1	Regular excavation	cu.m	151	9.68	10.08	19	3.90	-5.78
300-1-1	Bit mat'l-prime coat	L	55	0.61	0.45	11	0.33	-0.28
300-1-3	Bit mat'l-tack coat	L	190	0.36	0.36	25	0.22	-0.14
327-70-5	Milling exist. asphalt pavement	sq.m	23	0.81	0.31	18	0.71	-0.1
400-1-15	Class I conc.-misc.	cu.m	70	455.4	306.4	17	514.3	58.9
5331-2	Type S asph. conc.	Mg	188	50.58	37.64	22	29.96	-20.62
5337-1-2	Asph. conc. friction	sq.m	102	1.51	0.98	24	1.31	-0.2

NOTE : 1 square yard = 0.836 sq.m 1 cubic yard = 0.765 cu.m
1 gallon = 3.785 litres (L) 1 ton = 0.907 Megagrams (Mg)

From the comparison of the total costs of eight items for selected projects in Table 2, nighttime costs are observed to be less than the corresponding daytime costs. On all selected FDOT nighttime projects for the eight typical highway pavement construction items, the difference in night and day costs is negative. Percentage difference for projects ranges from −12.09 percent to −59.73 percent, with an average of −36.1 percent, which indicates that nighttime costs are generally lower than daytime costs for FDOT projects.

However, it may argued that a comparison of eight items is inadequate to conclude a definite lower nighttime project cost, and the large quantities of these items and their contribution to program cost also cannot be ignored. Although the contribution of these item costs to the total contract cost varies, the trend gives an indication of the probable lower nighttime cost.

EVALUATION OF FDOT NIGHT CONSTRUCTION PRODUCTIVITY

Factors Relating to Productivity

The unique aspects of night construction can have both negative and positive effect on productivity. Productivity during

TABLE 2 Comparison of Nighttime (Actual) Versus Daytime (Average) Construction Costs for Selected Pay Items for All FDOT Nighttime Projects

Pay Item	Unit	Total Quantity (unit)	Actual Nighttime Costs		Projected Daytime Cost		Difference of Night and Day Costs	Percentage Difference of Day Cost
(1)	(2)	(3)	Weighted Price ($/Unit) (4)	Cost ($) (5)	Mean Price ($/Unit) (6)	Cost ($) (7)	($) (8)	(%) (9)
Rem existing pavement	sq.m.	24,648.20	8.92	219,745.0	12.58	310,074.34	-90,329.3	-29.13
Regular excavation	cu.m.	194,544.86	3.90	759,092.4	9.69	1,885,139.63	-1,126,047.3	-59.73
Bit. material-prime coat	L	57,846.30	0.33	19,247.0	0.61	35,286.25	-16,039.3	-45.45
Bit. material-tack coat	L	1,706,199.13	0.22	377,451.3	0.36	614,231.69	-236,780.4	-38.55
Milling existing asphalt pavement	sq.m.	1,128,398.75	0.71	803,537.4	0.81	914,003.0	-110,465.6	-12.09
Class I concrete misc.	cu.m.	172.51	514.3	88,733.0	455.4	78,565.61	10,167.4	12.94
Type S asphalt concrete	mg	316,465.25	29.96	9,483,435.0	50.58	16,006,813.0	-6,523,378.0	-40.75
Asphalt concrete friction	sq.m.	2,636,828.75	1.31	3,465,001.7	1.51	3,981,611.5	-516,609.7	-12.97
Total						23,825,726.0	-8,609,482	-36.1

a night shift is affected by several factors, including traffic volume, type of work, material delivery, lighting, supervision, communication, and workers' morale. Traffic volume has a negative impact on productivity. Artificial lighting required for construction operations at night varies with the type of job and has the potential to affect the output of the construction crew. In addition to lighting, certain human factors also govern the productivity of crew members at night. During typical daytime construction operations in Florida, two peak traffic loads actually reduce a work day to a 5½-hr work shift. At night, the work shift and actual daily working hours are extended (*5*). The availability and supply of materials and spare parts for equipment also affect productivity at night. Different agencies have different experiences with productivity. Although the hourly production rate at night for the same duration may not be higher than that during the daytime, the effective total productivity may be high as a result of total road closure and less interference. Sometimes as much as 50 percent of the project duration can be saved. In Florida, however, it was found that because of setup and takedown time, productivity is 28 to 30 percent less than normal (*6*). In this study, the productivity of two construction operations on different projects in Florida were compared and analyzed.

Research Methodology

To test the daytime and nighttime productivity rates of typical construction operations for highway facilities, relevant information was obtained from various sources. Daytime production rates were collected from another study done by the University of Florida for FDOT (*7*). The information includes (a) number of observations, (b) mean, (c) standard deviation, and (d) high and low production rates for each operation, which are categorized by type of project, local conditions, and traffic conditions. A summary of this data is presented in Table 3.

Nighttime production data were obtained for a construction project from the daily reports of FDOT. The project was in progress on I-95 in St. Johns County, Florida, at the time of the study. A summary of the information is presented in Table 4. Data were collected for two work items: plant-mixed surface and milling of existing pavement. Columns 3 and 4 in Table 4 provide mean and standard deviations of production rates for respective work items as observed during the night project.

To compare the two production rates for nighttime and daytime construction, hypothesis tests were performed. For

TABLE 3 Summary of Production Rates for FDOT Construction Projects

Category (1)	Number of Samples (2)	Mean (3)	Standard Deviation (4)	High (5)	Low (6)
a) Plant Mixed Surfaces: Structural Course (Mg/day)					
Project Type					
Reconstruction	147	755.5	483.4	2139.6	5.4
Construction	27	565	579.6	2596.7	103.4
Intersection	15	110.6	100.6	322.9	9.1
Bridge	9	161.4	63.5	248.5	76.2
Local Conditions					
Rural	111	775.5	558.7	2596.7	5.4
Urban	72	395.4	351.0	1485.6	15.4
Limited	15	988.6	142.4	1131.0	527.8
Traffic Conditions					
Light	20	1078.4	690.2	2139.6	107.9
Medium	81	745.5	509.7	2596.7	12.7
Heavy	97	488.8	386.4	12.7	5.4
Total Combined	198	653.0	512.4	2596.7	5.4
b) Milling Existing Pavement (sq.m/day)					
Project Type					
Reconstruction	94	10,325	6,211	26,775	371.2
Construction	1	1,901	0	1,901	1,901
Intersection	0	0	0	0	0
Bridge	0	0	0	0	0
Local Conditions					
Rural	48	12,415	6,778	26,775	371.2
Urban	32	7,513	4,052	17,166	1,965
Limited	15	9,074	5,655	22,089	3,204
Traffic Conditions					
Light	14	16,976	6,821	26,775	4,588
Medium	32	10,147	6,420	24,558	371.2
Heavy	49	8,369	4,330	22,089	1,901
Total Combined	95	10,236	6,237	26,775	371.2

TABLE 4 Summary of Production Rates for FDOT Nighttime Construction Projects

Project Number (1)	Number of Samples (2)	Mean (3)	Standard Deviation (4)	High (5)	Low (6)
a) Plant Mixed Surface: Structural Course (Mg/day)					
78080-3420	14	862.3	316.1	1,295.3	291.0
78080-3421	32	1,007.1	296.6	1,453.6	296.7
78080-3422	29	991.8	383.6	1,697.2	178.3
78080-3424	20	946.4	344.1	1,492.0	295.6
Total Combined	95	968.3	343.4	1,697.2	178.3
b) Milling Existing Pavement (sq.m/day)					
78080-3420	7	9,402	4,667.2	14,078.2	2,312.4
78080-3421	10	6,169.2	887.7	7,590.8	4,458.4
78080-3424	12	6,902.4	2,472.2	11,590.3	3486.1
Total Combined	29	7,252.9	3,103.1	14,078.2	2,312.4

nighttime productivity values, the combined results of all the projects in Table 4 are used. Because all night-shift projects considered are on I-95, for daytime productivity values only, limited access facility observations from Table 3 are used. The two rates are compared with the guidelines provided by FDOT for activity duration. These guidelines are the result of analysis of actual production rates achieved on FDOT projects. The guidelines for the two items are as follows:

- Milling of existing pavement: 5,016 m^2 (6,000 yd^2) per day;
- Plant-mixed surface: 453 Mg (500 tons) per day for average jobs (less than 50,000 tons) and up to 1,088 Mg (1,200 tons per day) for large jobs (more than 50,000 tons).

Results

Statistical analysis of the available data was done by performing t-tests on independent samples. Although for plant-mixed surface the mean production rate for nighttime projects [968.3 Mg/day (1,067.6 tons/day)] appears to be less than that for daytime limited access projects [988.6 Mg/day (1,090 tons/day)], the test does not confirm a difference between the production rate of plant-mixed surface for daytime and nighttime jobs at a 95 percent significance level. However, if compared with the total combined production rate [653 Mg/day (720 tons/day)] in Table 3, the nighttime production rate is considerably higher. From the guidelines for estimating production rates, daily production of plant-mixed surface is given as 453 Mg/day (500 tons/day) to 1,088 Mg/day (1,200 tons/day) for average and large quantity jobs, respectively. Because all the projects considered for analysis are large quantity jobs on Interstates, the range given is in agreement with the obtained daytime and nighttime production rates of 988.6 Mg/day (1,090 tons/day) and 968.3 Mg/day (1,068 tons/day), respectively.

For milling of existing pavement, the test does not confirm a difference between day and nighttime production rates, although the mean daytime rate is higher than the mean nighttime rate. However, because of the small sample size and high variation for daytime jobs, no definite conclusion may be drawn at a 95 percent significance level. However, both the obtained daytime production of 9,074 m^2/day (10,854 yd^2/day) and nighttime production of 7,253 m^2/day (8,675.7 yd^2/day) are higher than the rate of 5,016 m^2/day (6,000 yd^2/day) suggested in the guidelines.

Analysis and subsequent study indicate that nighttime work does not significantly affect productivity. Project-by-project variations are attributable to several factors, including (a) longer working hours, (b) less traffic interference, (c) total road closure, (d) inadequate lighting, (e) workers' morale, and (f) equipment breakdown and repair. However, productivity does not appear to be a major deciding criterion in the determination of whether to perform work at night.

SUMMARY AND CONCLUSIONS

Unit costs of items are found to be highly dependent on project-specific conditions and not type of shift. Because variations in the nighttime unit prices were high, and there was a significant correlation observed between quantities and unit prices, weighted unit prices were used for comparison.

From the comparison, nighttime weighted means were found to be less for all the items except miscellaneous concrete, which may be attributed to work-item characteristics. To obtain an idea of variation in project costs, total cost comparisons were made for eight items in eight selected projects. Nighttime costs were found to be less than daytime project costs, which is contrary to popular belief. From these findings it can be suggested that nighttime construction costs are less than daytime construction costs for FDOT projects. However, more nighttime data may help to derive conclusions with greater confidence. On the other hand, if user costs and cost savings to the public are also considered in total project cost, nighttime construction may be even more economical.

According to Price (*2*) the average per item costs were 40 percent higher and total costs were 159 percent higher. From the study discussed here, it was concluded that the cost differential is not significant. The reason for such a change may be that as nighttime work becomes more common and routine, and as the contractor becomes more familiar with various aspects of nighttime construction, the risk factor for new work decreases. As a result, bid prices for nighttime work go down and item unit costs do not vary with shift time.

Similarly, for the productivity of the two items, the *t*-tests failed to confirm any significant difference between daytime and nighttime productivity. Here it may be noted that daily output, which affects the total project duration, is different from hourly productivity. Various project-related factors, such as (a) longer working hours, (b) less traffic interference, (c) total road closure, (d) adequate lighting conditions, (e) higher workers' morale, and (f) reduced equipment breakdown, repair, and the like, may lead to higher daily output on a nighttime project, consequently reducing the total project duration. However, as far as hourly item productivity is concerned no appreciable difference was found between nighttime and daytime operations.

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Systems Approach to the Use of Automation Technology in Drilled Foundation Construction

JAE-JEUNG RHO, DEBORAH J. FISHER, AND MICHAEL W. O'NEILL

A systems approach for identifying potential tasks of automation within a construction process is described. A two-step system analysis for automation is described in detail as it applies to drilled shaft foundation construction. The first step of the analysis includes data collection and productivity analysis to justify automation of the proposed process. More than 100 hr of field data was collected through site observations. A time-lapse videocassette recorder was used to quantify the productivity ratings of the process. The second step includes taxonomy development and feasibility analysis to identify tasks to be automated. A taxonomy that includes 8 tasks, 47 subtasks, and 106 activities was developed from the collected data. Surveys were conducted and statistically evaluated to determine the feasibility of selected tasks. It was concluded that, from the original list of 47 subtasks, 4 subtasks had the highest potential to be automated. These subtasks were inspection, cleaning, excavating, and balancing. As one of the recommendations for future research, a tool for design analysis and economic analysis of the candidate automated method is introduced.

The creeping erosion of construction productivity is having a negative impact on the entire U.S. economy because construction is the nation's largest industry and is a particularly seminal industry (*1*). The advantage of using automation technology to improve productivity has long been realized in the manufacturing industry. It has been reported that successfully adapted automation technology can improve the productivity from 20 to 30 percent (*2*). However, the construction industry has been slow to adapt to automation technology for the following reasons. First, compared with factory-based manufacturing industries, the field-oriented construction industry has a severe situation to which to adapt automation technology, for example, minimal standardization, a large variety of tasks for each laborer, a harsh working environment, frequently reconfigured operations for each project, and divided authority (*3*). Second, the construction industry in general has traditionally been conservative in accepting new technologies. "It appears that the new approach should be evolutionary rather than revolutionary. That is, automation in construction will have to yield productivity improvement higher than a skilled worker" (*4*). Therefore, it is not possible for the construction industry to merely adopt the same automation technology that the manufacturing industry has adopted to its factory-based processes. Also, the automation technology, not to be revolutionary, should be applied only to those tasks that can clearly improve the productivity of the construction process.

PURPOSE OF RESEARCH

The purpose of this research was to develop and implement a methodology for identifying potential automation in construction processes using a systems approach, as shown in Figure 1. This systems approach is composed of three stages: system analysis, design analysis, and economic analysis (*5*). In this paper, a system analysis methodology is developed through a two-step process: productivity analysis and feasibility analysis.

This approach is being used in the development of software to assist in decision making for construction of drilled foundations for bridges called "Decision Support System for Drilled Shafts" (DS^2). DS^2, under development by the authors, consists of several modules. One is a simulation module for the design analysis, which will compare the productivity of the conventional method and the proposed automated method. Another is a cost data base module for the economic analysis, which will estimate the project cost and the cost of owning and operating equipment over the economic life cycle, so that the proposed automation method can be justified from an economical point of view.

Implementation of the system analysis method has been applied to drilled shaft foundation construction. Drilled shaft foundations are becoming more popular in the highway foundation construction because of the following advantages: structural (able to carrying large loads, applicable to various soil conditions, and minimum disturbance to the surrounding soils), operational (mobile equipment, easy to change process, readily available resources), and environmental-social (reduced noise levels) (*6*). For example, foundations for 22 percent of the approach bends on the Highway 146 cable-stayed bridge over the Houston Ship Channel were drilled shafts. Drilled foundations were used to prevent layers of loose sand within the penetration depth of the foundations from settling under the action of pile driving and crank thin, overlying clay aquicludes that separated possibly contaminated runoff water from shallow well supplies. The reason that the drilled shaft construction process was selected is that its productivity is lower than the norm for overall construction processes (see Productivity Analysis section).

J. J. Rho and D. J. Fisher, Department of Industrial Engineering, and M. W. O'Neill, Department of Civil and Environmental Engineering, University of Houston, Houston, Tex. 77204-4812.

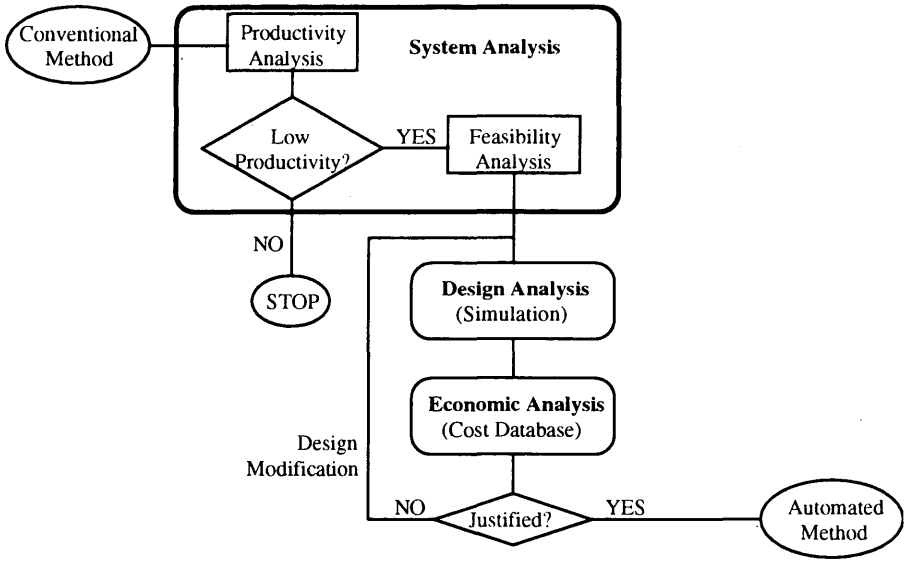

FIGURE 1 Systems approach to construction automation.

COMPARISON OF METHODOLOGIES

Several researchers have addressed issues of task identification for construction automation. A comparison of methodologies has been performed to determine the most common approaches, using those described by Kangari and Halpin (*4*), Tucker et al. (*7*), and Fisher and O'Connor (*8*), whose methodologies are also compared with the one suggested here in Table 1. The following attributes are considered: criteria used, rating methods, construction level on which focused, implemented construction area, and field data collection method. The criteria used in this research were generally based on work by Tucker et al. (*7*). Technology criteria were used instead of cost impact because economic analysis (cost impact) was performed in detail at the third stage of the systems approach. Field data were collected through site observation and time-lapse video-cassette (TLV) recording, which is more accurate and reliable than other sources.

METHODOLOGY DESCRIPTION

The two-step system analysis used to evaluate the potential automation of the construction tasks is described in this section. These steps are productivity analysis and feasibility analysis.

TABLE 1 Results of Methodology Comparison

Attribute	Kangari & Halpin	Tucker *et al*	Fisher & O'Connor	Authors
Criteria	10 Need 5 Technological 3 Economic	5 Concern & Cost Impact	9 Issues on Productivity Impact	6 Feasibility Criteria
Rating Method	Normalized & Weighted	High-High Score (2-D graph)	Criticality & Difficulty	Normalized & Weighted
Level Focused	Process & Task	Subtask	Task	Task & Subtask
Applied to	33 Construction Processes	Piping, Electrical Structural Steel	Piping Erection	Drilled Shaft Foundations
Field Data Collection	Did not do	References & Site Visit	References & 8mm Video	Time Lapse Videocassette

Productivity Analysis

In order to evaluate the productivity of a given construction process, field data were collected through site observation. The objectives of field data collection were (a) to develop a taxonomy of the drilling construction operation by a breakdown of the process into activities, (b) to evaluate the productivity of the process by calculating the percentage of productive work in the total process, and (c) to provide an opportunity to determine general process problems by interviews with field personnel.

As shown in Table 1, field data collection, by time-lapse videotaping, is apparently not used as often as other methods, such as collecting data from industry or government statistics, from drawings or specifications, or from functional requirements of activities. However, conventional field data collection methods require several observers and are usually time-consuming. To reduce these shortcomings of traditional data collection methods, the authors elected to collect field data from the sites using a TLV recorder. TLV, a more accurate and reliable data collection method, can take the place of several observers because it captures all activities around the site in an extensive time period without any interruptions to the construction process (*9*). Moreover, once the observer sets up the TLV recorder on a site, he or she is free to interview crew members or to investigate the detailed procedure. Because drilling procedures vary according to the subsurface geologic conditions, field data were collected for five different subsurface conditions for comparison. A total of 109 hr of drilled shaft foundation construction activities was taped using the TLV recorder. A summary of site observation appears in Table 2.

The random sampling method was adopted to collect data from the TLV recordings. Twenty-five random numbers be-

TABLE 2 Summary of Site Observation

Subsurface Soil Condition	Project Sites Visited	Hours
Clay	6 Sites in Houston Vicinity	45 Hrs
Rock	Kansas City, Mo.	14 Hrs
Pinnacled Limestone	Birmingham, Al.	28 Hrs
Sand (Over Water)	Jacksonville, Fl.	14 Hrs
Sandy Clay	College Station, Tx.	8 Hrs
Total		109 Hrs

tween 1 and 7,200 were generated and converted to time in seconds for each 2-hr recording period. Data were extracted from the observation of the selected random time and categorized by type of productivity. The total number of observations required for statistical significance, N, was determined by the following equation, based on the work-sampling principle (*10*).

$$N = \left(\frac{z_{\alpha/2}}{\Delta}\right)^2 [\hat{p}(1 - \hat{p})] \tag{1}$$

where

$z_{\alpha/2}$ = the value of standard normal variable with an area $\alpha/2$ to its right,
$\hat{p}$ = the best estimation of probability that productive work will happen,
p = the real probability that productive work will happen,
Δ = the interval within which p lies, and
$(1 - \alpha)$ = a confidence level for the best estimation $\hat{p}$.

For this reasearch, the confidence level was set at 95 percent, so the $z_{\alpha/2}$ value from the cumulative normal distribution table is 1.96. Also, the satisfactory range of $\hat{p}$ is set to ±10 percent. Therefore, the total number of observations required for statistical significance can be calculated from Equation 1. The results for each type of subsurface condition are summarized in Table 3. Data from three sites of clay and from sandy clay were excluded because of insufficient recordings of process cycles for the statistical significance to be valid. For this analysis, there is a 95 percent confidence that the true percentage value of productive work lies within a ±10 percent range of the results described later.

Collected data were analyzed to quantify the productivity of the construction process. Productivity ratings carefully define the individual tasks or subtasks and, in turn, classify them into three categories: productive work, supportive work, and ineffective work. There is no perfect way to categorize the multitude of activities for productivity-rating purposes. Instead, it is necessary only to make clear the conditions that are to be measured and how they are to be classified. In this research, the following definition of each category was used (*11*), and the examples of subtasks for drilled shaft foundations are listed in the following section.

TABLE 3 Required and Actual Number of Observations from TLV

Subsurface Condition	Productivity Estimation ($\hat{p}$)	Required # of obs. per site(N)	# of sites visited	Total required # of obs.	Actual # of obs. collected
Clay	0.35	88	3	264	276
Rock	0.40	93	1	93	141
Pinnacled Limestone	0.45	96	3	288	296
Sand (Over Water)	0.25	72	1	72	75

Productive work is the work directly involved in the actual process of putting together or adding to a unit being constructed, including necessary disassembly of a unit that must be modified and movements essential to the process that are carried out in the immediate area where the work is being done (e.g., drilling, concreting).

Supportive work is the work not directly adding to, but (through associated processes) essential to, finishing the unit, such as handling material at the work station, cleanup, receiving instructions, reading plans, and necessary movement outside the work station but within a radius of 10 m (e.g., mobilization, wall supporting).

Ineffective work is work that is not useful or involves being idle, such as walking empty handed, moving materials or oneself outside a radius of 10 m from the work station, or redoing a job done incorrectly in the first place (e.g., waiting for material).

Productivity ratings are calculated as percentages of the number of discrete data samples for each of these categories out of the total number of data samples. The rating for productive work can be one of the productivity measurements for a given process. The productive work rating is used in this paper as a tool for justification of selected process for automation. If the rating is lower than a prescribed level, the automation analysis can be advanced to the next step, the feasibility analysis.

Feasibility Analysis

The next step of the system analysis necessitated the development of a taxonomy. Although a variety of taxonomy structures exist, the four-level indentured structure was applied in this research. Definitions of each level—process, task, subtask, and activity follow:

1. Level 1, the process level, is composed of a set of tasks. The summation of all the tasks in the taxonomy must be equal to the total process. Drilled shaft construction is defined as the process in this research.
2. Level 2, the task level, is composed of a set of subtasks. Tasks may be defined as the indispensable component to complete a process. Tasks may easily be distinguished from each other.
3. Level 3, the subtask level, is defined as a component of a task that may often be associated with several tasks. Some subtasks may be optional for given job conditions.
4. Level 4, the activity level, is the most basic component of the taxonomy structure. If the activity were broken down further, it would be physical motions of the human workers.

The drilled shaft construction process can be broken down into 8 tasks, 47 subtasks, and 106 activities. The first and second level of the taxonomy result are shown in Figure 2. Figure 3 shows the expansion of the excavation task.

The objectives of developing a taxonomy and the ensuing feasibility analysis are to define the sequence of the process,

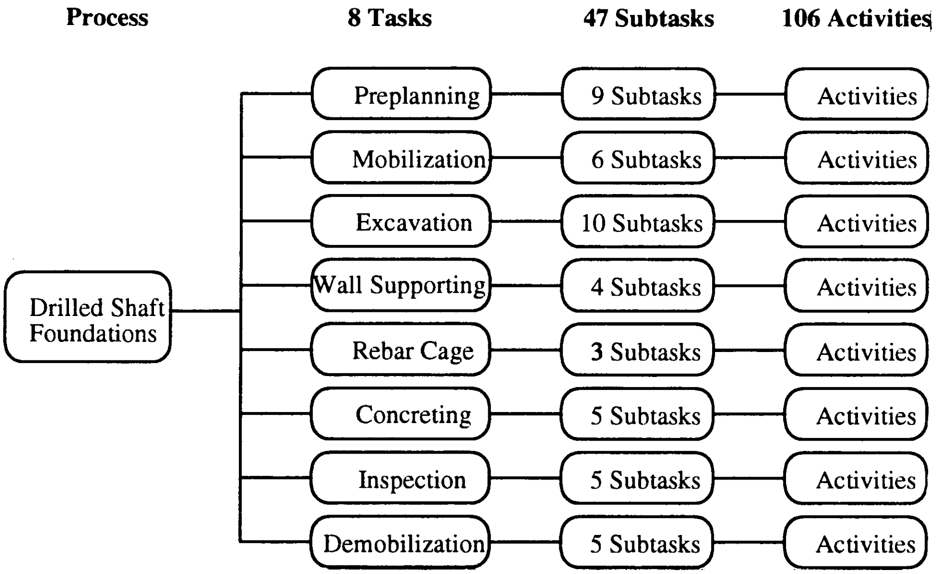

FIGURE 2 **Taxonomy of drilled shaft foundation process.**

prepare a list of tasks, and determine which tasks are feasible for automation. Whereas the critical path method breaks a project down into many activities and focuses the project manager on the 20 percent of the critical activities on the critical path to optimize the project duration, the task taxonomy and feasibility analysis break the construction process down into many tasks and allow the automation engineer to focus on the tasks that are selected from the feasibility analysis (feasible tasks).

Over the years, five major criteria have been developed to evaluate a task or subtask for identifying potential for automation in construction: safety, worker use, productivity, quality, and super-human handling (7). It is generally agreed that these five criteria represent the range of possible rationales for automating a construction process. A sixth criterion, technology, was suggested by Kangari and Halpin (*4*).

1. Safety is an important issue in all construction processes. Construction has one of the worst industrial safety records in the United States. Thus, any task that imposes a safety hazard to crew members should be a candidate for automation.
2. Worker use is a criterion because the construction industry will suffer an increasing shortage of skilled workers in the near future. Thus, any task that requires multiple workers or is tedious or boring should be a candidate for automation.
3. Productivity can generally be increased when automation is used for tasks that can be completed more easily by using machines than human workers. Repetitive or cyclic tasks,

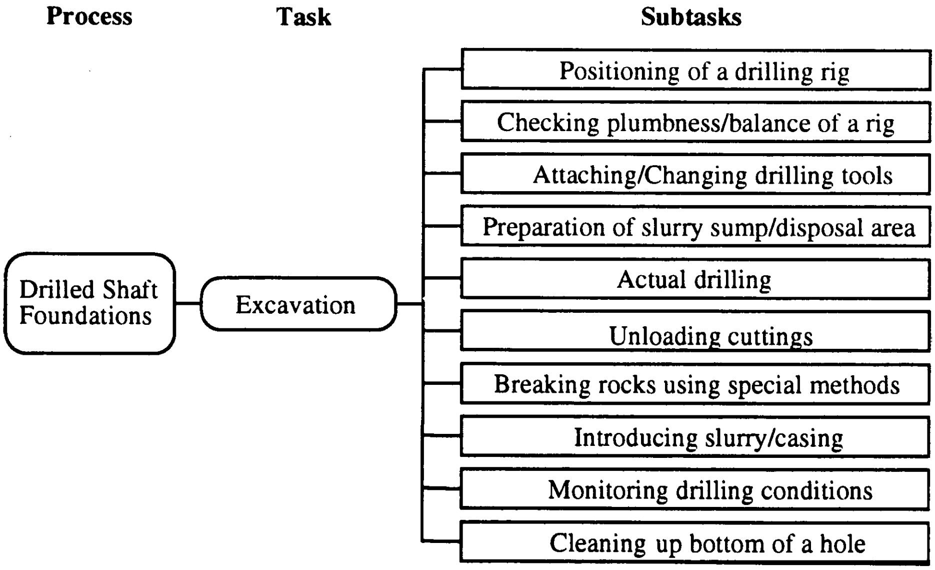

FIGURE 3 **Expansion of excavation task.**

time-consuming tasks, and environment-dependent tasks are good candidates under this criterion.

4. Quality of the constructed output can be decided by the consistency, accuracy, and repeatability of tasks. Because quality is the main concern of the owner, this criterion is of great importance.

5. Super-human handling represents the limitation of human workers. An advantage of automation is freeing the crew members from physically difficult tasks, such as heavy or high lifting, meticulous work, and exhaustive work.

6. Technology is a criterion that evaluates the technological feasibility within the context of the existing or projected state of the art in construction automation. The greater the near-term availability of a particular support technology, the higher the numerical rating given for this criterion.

Three subcriteria for each criterion are provided for the purpose of comprehensive consideration of the criteria. For example, the "safety" criterion consists of "elevated work," "physically dangerous work," and "hazardous work to health" subcriteria. Any task with the characteristics of a subcriterion will have higher ratings than one without. Even though subcriteria are provided, the rating is given to each criterion, not to the subcriteria individually, because the rated tasks may or may not involve all of the subcriteria. Feasibility analysis criteria, subcriteria, and examples for drilled shaft foundation construction are summarized in Table 4.

Surveys were conducted to evaluate the automation feasibility of selected tasks or subtasks. Tasks and subtasks were selected from the results of the developed taxonomy. Even though the selection is based on the general automation potential of each task, some tasks are represented by several subtasks. The excavation task, for example, is represented by six subtasks because it is judged to be an important task and consumes most of the drilled shaft construction process time. The questionnaire form used in this feasibility analysis survey is shown in Figure 4.

Rating points are divided into five levels (10 points for high, 8 for relatively high, 6 for medium, 4 for relatively low, and 2 for low feasibility). Nonresponsive answers were assigned 2 points. Each of the listed tasks was rated for the six criteria individually, and the six scores were multiplied by the associated weighting factors. Weighting factors were assigned to each criterion on the basis of its judged importance relative to the feasibility of automation. The weighted scores were added to produce a total score between 2 and 10. Higher total scores mean higher levels of need for automation. Since each questionnaire participant has a tendency of rating, all criteria high and low total scores were normalized in order to set the highest total score among the listed tasks to 10 points and the lowest to 2 points. Finally, the normalized scores were averaged for each group of participants: soil contractors, rock contractors, manufacturers, and academia. These four groups were included in the feasibility analysis in order to represent various viewpoints to construction automation. A total of 21 participants—5 soil contractors, 5 rock contractors, 7 manufacturers, and 4 academics—was included in the survey.

TABLE 4 Criteria for Feasibility Analysis

Criterion (Weighting Factor)	Subcriteria	Examples
Safety (0.2)	Elevated work Physically dangerous Hazardous to health	Concrete pouring using tremie Working at the bottom of a shaft Dust/explosives
Worker Utilization (0.15)	Multiple worker Special skilled worker Tedious/boring	Concrete pumping Operation of a rig Rock drilling
Productivity (0.2)	Repetitive/cyclic Time consuming Environment impact	Operation of a rig Unloading of cuttings Weather/obstructions
Quality (0.15)	Consistency Accuracy Repeatability	Concrete flow control Vertical tolerance Drilling & unloading
Super-Human Handling (0.1)	Heavy/high lift Meticulous work Exhaustive work	Handling of rebar cage/casing Positioning/plumbness of a rig Cleaning around a drilled shaft
Technology (0.2)	Control software Hardware system Sensor technology	Software for acoustic test Camera for inspection Concrete/slurry flow sensor

IMPLEMENTATION AND DATA ANALYSIS

The results of the productivity analysis are summarized in Figure 5. The drilled shaft construction process under different subsurface condition shows different productivity rates. The productivity rating of construction in clay is 33 percent, in normal rock 46 percent, in pinnacled limestone 49 percent, and in sand over water 30 percent. The productivity ratings for drilling in clay and drilling over water are below 40 percent, which is lower than the average in the construction industry (*11*). This result justifies the implementation of automation technology to the drilled shaft construction process.

Tasks or subtasks used in the questionnaire form were selected from the task taxonomy based on the results of the qualitative productivity analysis. The list of 14 tasks or subtasks follow:

- Balancing or positioning of a drilling rig,
- Checking plumbness and centering of a rig,
- Excavating or operating a rig,
- Removing the auger and unloading cuttings,
- Exchanging excavation tools,
- Introducing or pumping slurry,
- Placing and recovery of casing,
- Measuring depth of a hole or concrete tremie,
- Monitoring flow of slurry or concrete,
- Inspection of a drilled shaft wall or bottom concrete,
- Cleaning of the bottom of a drilled shaft,
- Placing and setting rebar cage,
- Concrete pouring into a hole, and
- Assembling and dissembling of equipment.

The average normalized scores of automation feasibility ratings calculated for these tasks are shown in Figure 6. Detailed feasibility analysis results are summarized in Table 5. Four tasks were evaluated with more than 6 points: inspection of a drilled shaft or bottom concrete, cleaning of the bottom of a shaft, excavating or operating a rig, and balancing or positioning of a rig. All other tasks were evaluated between 4 and 6 points, except for the task of removing the auger and unloading cuttings, which is clearly not a candidate for automation.

Among all the tasks and subtasks, inspection was identified as having the highest potential by academia and soil and rock

	Safety	W. U.	Prod.	Quality	S. H. H.	Tech.	Score
Balancing							
Plumbness							
Excavating							
Unloading							
Tools							
Slurry							
Casing							
Measuring							
Monitoring							
Inspection							
Cleaning							
Rebar Cage							
Concrete							
Assembling							
W F	0.20	0.15	0.20	0.15	0.10	0.20	1.00

* Rating Points : Very High : 10 pts
High : 8 pts
Medium : 6 pts
Low : 4 pts
Very Low : 2 pts

* Information of Respondent
- Name of Company :
- Name of Respondent :
- Position in Company :

* Comments :

FIGURE 4 Questionnaire form.

contractors. Manufacturers identified the task as the third highest candidate for automation. Many participants pointed out that the automation of inspection is necessary, especially for the bottom of a drilled shaft, which cannot be inspected directly if it is under water or in pinnacled limestone. Cleaning of the bottom of a drilled shaft was ranked as the second highest potential subtask. This subtask was rated among the top four by all participant groups. For rock contractors, cleaning the bottom was considered as a hazardous subtask because a human being must work in the shaft bottom. For soil contractors, the subtask is normally accomplished by special tools, which cause an interruption in construction resulting in decreased productivity, but do not result in hazards to human beings. Excavating and operating a drilling rig is identified as the third highest potential subtask overall. This subtask was ranged with different potentials by the four participant groups: second by academics, fourth by manufacturers, fifth by rock contractors, and seventh by soil contractors. Positioning and balancing of a drilling rig was identified as the fourth highest potential subtask. Manufacturers rated this task highest among the four participating groups.The four groups of survey participants were in general agreement in their ranking of the top four subtasks (Table 6).

Several recommendations can be made for automation of these tasks.

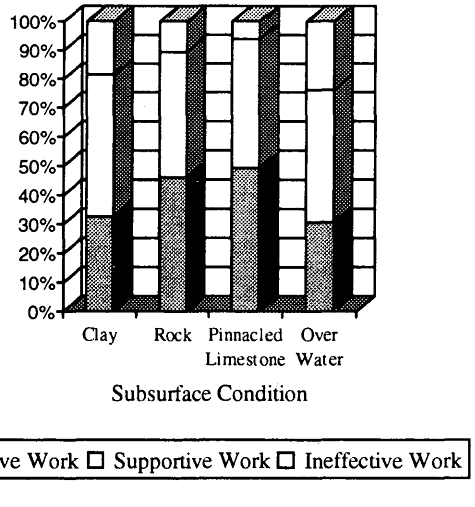

FIGURE 5 Productivity under different subsurface conditions.

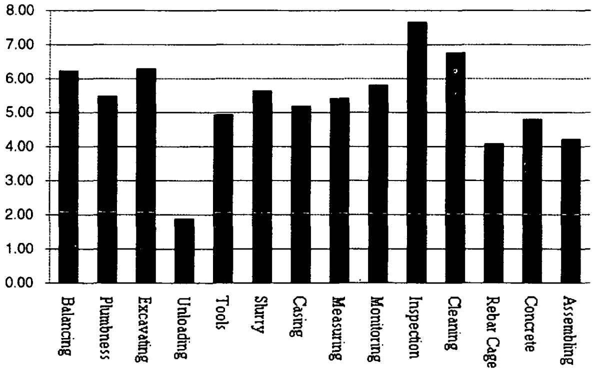

FIGURE 6 Feasibility analysis results of tasks.

TABLE 5 Detailed Feasibility Analysis Results

Weighting Factor	Academia 0.25	Soil Contractor 0.25	Rock Contractor 0.25	Manufacturer 0.25	Average Score	Rank
Balancing	7.29	6.24	4.37	7.04	6.24	4
Plumbness	5.14	5.90	5.88	5.00	5.48	7
Excavating	7.62	5.06	6.09	6.42	6.30	3
Unloading	1.53	2.14	1.50	2.36	1.88	14
Tools	5.09	4.31	6.84	3.52	4.94	10
Slurry	4.27	7.25	5.53	5.50	5.64	6
Casing	4.14	6.71	3.52	6.36	5.18	9
Measuring	5.18	6.41	4.17	5.91	5.42	8
Monitoring	4.39	7.57	6.58	4.73	5.82	5
Inspection	9.23	7.12	7.58	6.69	7.66	1
Cleaning	7.46	5.25	7.13	7.23	6.77	2
Rebar Cage	3.06	3.33	4.16	5.78	4.08	13
Concrete	4.23	4.10	5.66	5.21	4.80	11
Assembling	4.09	4.01	3.89	4.85	4.21	12

First, because inspection is closely related to the quality, productivity, and safety of the drilled shaft construction, it is necessary to automate this activity in order to yield better results. Socket inspection device cameras for the inspection under water or slurry or seismic testing for the inspection of solid rock bases are some of the available technologies that can be applied today. In addition, an expert system is being developed at the University of Houston to assist contractors and designers to better prepare construction specifications for a variety of conditions (*12*).

Second, more research efforts are recommended to develop better cleaning methods that do not require personnel to work in the shaft bottom to increase productivity and safety while ensuring better end bearing behavior.

Third, excavation of the drilled shaft has to be performed under various constraints such as low overhead, tight accessibility, and various different geologic conditions. Hence, an automated approach to excavation must vary according to the geological conditions. Several new technologies are currently being applied to drilling rigs worldwide, in order to increase productivity: BIG STAN (Anderson, USA), a large and powerful rig for larger and deeper shafts; customer-ordered rigs (Watson, USA), for variety of subsurface conditions: MACH (Tone, Japan), for continuous drilling using reverse circulation in highly variable rock profiles; the VG-11 (Bauer, Germany), for simultaneous excavation and casing in environmentally sensitive areas; and the STARSOL-ENBESOL process (Soletanche, France), for continuous flight drilling and continuous records of concreting parameters (*13*).

Fourth, productivity, quality, and safety of drilling are greatly affected by the correctness of rig positioning and balancing. In conventional drilling methods, this task is performed using the operator's experience, with the help of laborers. Simple sensors can increase accuracy and reduce the time required to set up the rig. The R-10 rig (Soil Mec, Italy), which adapts feedback instruments to help the rig operator control the drilling process, is an example of available technology in this area.

TABLE 6 Ranking of Top Four Subtasks by Survey Participants

Rank	Academia	Soil Contractor	Rock Contractor	Manufacturer	Combined Result	Combined Score
1st	**IN**	**IN**	**IN**	**CL**	**IN**	7.66
2nd	**EX**	MO	**CL**	**BA**	**CL**	6.77
3rd	**CL**	SL	TO	**IN**	**EX**	6.30
4th	**BA**	**CL**	MO	**EX**	**BA**	6.24

NOTE: IN = inspection; CL = cleaning bottom of drilled shaft; EX = excavating and operating drilling rig; and BA = positioning and balancing drilling rig.

TABLE 7 Examples of State of the Art in Drilled Shaft Construction Technology

Machine (Company, Country)	Feature	+Advantage / -Disadvantage
Concrete Pumping Truck (Beck, USA)	Continuous concrete pumping	+ Continuous material handling + Safety increase + Productivity increase
Customer Ordered Drilling Rig (Watson,USA)	Variety of drilling conditions	+ Versatility increase + Fit to local drilling condition - Expensive & not compatible
BIG STAN (Anderson,USA)	Large & deep shafts	+ Up to 26' diameter & 130' deep shaft + Powerful and easy to drill - Expensive & not versatile
MACH Drill (Tone, Japan)	Continuous rock drilling using reverse circulation	+ Productivity increase - Expensive & complex to drill - Only for wet method
VG-11 (Bauer, Germany)	Simultaneous drilling & casing	+ Productivity increase + Elimination of drilling fluid - Slower process
R-10 (Soil Mec, Italy)	Instruments & sensors	+ Feedback control of drilling & balance + Quality increase - Expensive and slow drilling
STARSOL (Soletanche, France)	Instruments, sensors, & recorders	+ Feedback control of drilling & concreting + Assurance of structural integrity - Require well-trained operator

CONCLUSIONS

As an example of the systems approach to integrating automation technology in drilled foundation construction, the drilled shaft foundation construction process was considered to identify tasks and subtasks for automation. Using this approach, from the original list of 47 tasks, 4 tasks were identified as having the highest potential to be automated. These four tasks are, in order, inspection of drilled shaft wall or bottom and concrete, cleaning of the bottom of a drilled shaft, excavating or operating a rig, and balancing or positioning of a drilling rig.

A summary of some state-of-the-art technologies in the drilled shaft construction industry that can be adapted to automation is presented in Table 7. In order to complete the systems approach suggested in this paper, research efforts are recommended to use and expand DS-2 as a tool for design and economic analysis of specific automation alternatives.

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