TRANSPORTATION RESEARCH CIRCULAR

Number 172, October 1975

Transportation Research Board, National Research Council, 2101 Constitution Avenue, Washington, D.C. 20418

IMPLEMENTING STATISTICALLY BASED SPECIFICATIONS

subject areas
31 bituminous materials and mixes
32 cement and concrete
33 construction
34 general materials
35 mineral aggregates

The following three papers were presented informally at the 54th Transportation Research Board Annual Meeting. The formal paper "Joint Effort by the Pennsylvania Department of Transportation and the State to Implement Restricted Performance Specifications" by Jack H. Willenbrock, presented at the same session, has been published in TRB Record 539.

NEW JERSEY'S THICKNESS SPECIFICATION FOR BITUMINOUS PAVEMENT

Kenneth C. Afferton, Transportation Research Engineer, New Jersey Department of Transportation

The New Jersey Department of Transportation has developed a statistically based, end result type specification for thickness of bituminous concrete pavement. The specification requires decisions on acceptability to be made for each bituminous paving item (surface, binder, and stabilized base) separately and on a lot by lot basis. A lot is established as approximately 15,000 square yards of paving item. An acceptable lot is one having a quality level of thickness equal to or better than that obtained on past projects. The methods used to determine lot acceptability are patterned after the variability unknown procedures of Military Standard 414. A reduced payment schedule for unacceptable lots was included in the specification as a practical means of dealing with slight thickness deficiencies. In developing the schedule, consideration was given to the loss in pavement serviceability that a thickness deficiency could potentially cause. An analysis was made of the first 16 projects completed under statistically based specification. A total of 269 lots containing 836,000 tons of bituminous paving materials was involved. The specification performed quite well, matching closely the performance predicted by the specification's theoretical operating characteristic curve. However, because of concern expressed by field personnel, a revision which permits crediting of thickness excesses from one paving item to another is being considered.

Over the years, thickness has continued to be a major quality indicator for newly constructed flexible pavements. This is understandable as deficiencies and excesses in pavement thickness can significantly affect both the load carrying capacity and ultimate cost of a highway. Accordingly, construction specifications for most highway agencies include some kind of requirements on the thickness of each pavement component.

The tightest thickness constraints are normally placed on the sronger layers of bituminous surfacing, binder and stabilized base. The New Jersey Department of Transportation's current specifications for these bituminous layers are somewhat unique in that they are statistically oriented. Statistical methods were used in their development with the intent of making the most of the Department's inspection capabilities while being as fair as possible to the contractor. The specifications are of the end result type and patterned after inspection criteria used by the Federal Department of Defense.

Past Pavement Construction

Prior to 1971, the Department's specifications for the thickness of its flexible pavements were not very different from those used in many other states. Cores were required to be cut from a pavement at the rate of one core for every 2000 square yards of surface area. Thickness measurements made on each core were then compared to the layer thicknesses shown on the construction plans. If the plan figure was not met within a certain tolerance, the contractor received a reduced payment. As might be expected, the magnitude of the tolerance involved had been established predominantly by engineering judgment. Unfortunately, time and usage of the specifications were proving this judgment to be in error.

By the late 1960's it became apparent that the thickness specifications were not working well and should be modified. Significant penalties for inadequate thickness were occurring on nearly every project and the state contractor associations were protesting vehemently that tolerances were too restrictive. Additionally, pavement riding on fixed paver settings to get uniform mat thicknesses and foregoing the use use of automatic screed controls.

To provide a basis for developing appropriate modifications to the thickness requirements, a joint investigative effort was initiated by the Department's construction practices and research units. A survey was made of all past state and federally financed highway projects constructed in New Jersey between 1962 and 1968. Coring records were analyzed for each project with a separate histogram of core thickness being plotted for the surface, binder and bituminous stabilized base courses. Thickness measurements for any recut or verification cores were omitted in an attempt to minimize the inclusion of bias in this data. The resulting histograms were generally found to conform fairly well to the standard normal distribution. This was a welcome finding for it meant that the established statistical procedures for the normal curve could be used in developing more equitable specification tolerances. Such procedures had already been employed by the Department with some success in choosing acceptance limits for composition of bituminous paving materials. Having the use of these procedures in mind, means and standard deviations were determined for each histogram and then average values of these parameters established for each type of paving course.

A summary of the average thicknesses and thickness standard deviations recorded from the survey of historical coring records is given in Table 1. What is immediately apparent is that all bituminous paving courses were typically being constructed to an average thickness greater than that called for the construction plans. This seems somewhat in conflict with the fact that the typical project was also characterized by a significant number of thickness penalties.

The reason for these past penalty occurrences was that the old specifications were essentially uniform thickness requirements penalizing for both deficiencies and excesses from plan thickness. Also the tolerances involved were unbelievably tight, ranging from 1/3 to 1/5 of those necessary to allow for the thickness variations indicated by the data of Table 1.

Engineering Requirements for Pavement Thickness

At first the methodology for improving the Department's thickness acceptance standards seemed quite straightforward - merely increase the tolerance about the design or plan thickness sufficiently to accommodate variations typical of the average contractor (data of Table 1). However, it became apparent that such an approach gave no recognition to any engineering requirements that might govern pavement thickness. What were these requirements? When a thickness of "t" inches was established as being necessary by a designer what was he really calling for - 100% of the pavement to be thicker than t; 70%, 50%?

Consultation with the Department's pavement designers established that layer thicknesses were being determined by use of the AASHO Interim Pavement Design Guide. It thus appeared that the desired engineering requirements could be defined by establishing how pavement thicknesses were distributed around their target values at the AASHO Road Test. Figure 1 compares the distribution of thickness for a 3-inch layer of bituminous concrete at the AASHO Road Test (1) to that typical of New Jersey construction.

It is apparent from Figure 1 that a 3-inch bituminous layer at the Road Test was far more uniform (smaller spread about the mean) than that normally placed by New Jersey's contractors. To use the AASHO distributions in a straightforward fashion for setting thickness tolerances could lead to the same type of problem created by the old specification, i.e., the tolerances would be too restrictive. The contractor could be expected to shift his mean thickness to be coincident with the design thickness but how could he practically reduce his variability to match that of the highly controlled Road Test.

The comparative data for the AASHO Road Test and typical New Jersey construction was shown to the Department's pavement design group. With their concurrence it was then decided that the average thickness quality achieved on past projects would serve as the engineering basis for the new specification. In essence, the thickness distributions given by the data of Table 1 were considered completely adequate and should be judged so when evaluated under the new specification. The reasoning here was that these average distributions for past construction were fairly safe approximations of the AASHO thickness curves. Being of higher mean thickness, a large percentage of the pavement on a New Jersey project actually exceeded the thickest area of a comparable pavement on the AASHO Road Test. Another important consideration in this matter was the actual performance of these past pavements. From a structural standpoint it was apparent that the Department was satisfied with the serviceability they had provided. The continuation of pavement thickness conditions that complied with the design assumptions as well as these did was judged desirable.

Statistical Procedures

Initially, it was expected that the development of a specification having past levels of pavement thickness as the basis for acceptance would be fairly simple. The past mean thicknesses would be used as the target thicknesses with tolerances for acceptable variation of individual cores being set at two standard deviations (data of Table 1) from these means. If core averages were to be used for determining acceptance, tolerances would simply be set equal to two standard errors.

This approach to sizing specification tolerances was being followed by a number of states and theoretically resulted in a contractor only running about a 5% risk of having good material rejected. Unfortunately, an inherent requirement in such an approach is that the variability of the material to be inspected be the same as that used in setting the tolerance. When this requirement is not satisfied, the risk of a wrong decision on material acceptability can differ markedly from the theoretical 5% and is essentially unpredictable. A review of the variability measurements for the Department's past projects revealed that the standard deviation for a particular project often differed from the average figure of Table 1 by 50 to 70 percent. This was considered too large a spread to comply with the criterion of equivalent variability. It was therefore deemed necessary to develop the new thickness specification by use of statistical procedures which allowed the variability of inspected material to be unknown.

Although a number of methods exist for designing an acceptance specification for the variability unknown condition, the most desirable were judged to be those of Military Standard 414 - Sampling Procedures and Tables for Inspection by Variables for Percent Defective (2). Aside from statistical soundness, a major advantage of these particular methods was that they had already been tried and proven successful in real world situations. It was also beneficial that their principal evaluator and user was a federal agency (U.S. Department of Defense). The latter would be helpful when it came time to obtain Federal Highway Administration approval for use of the new acceptance specification on federal aid projects.

To use Standard 414 it is necessary that measurements of the quality characteristic of concern (thickness) be obtained in a random fashion and conform to a normal distribution. Measurements of pavement thickness from randomly selected cores appear to satisfy these criteria sufficiently. Another requirement is that decisions on material acceptability be made on a lot-by-lot basis. In this context a "lot" is a quantity of material produced or constructed under essentially the same conditions. Finally, the acceptable quality level (AQL) for a lot must be defined in terms of the percentage of material that can be permitted to fall outside the governing specification limit(s). This percentage is termed "percent defective." For example, if a lot could have as much as 15% of its material outside specification limits and still truly provide adequate service, then its AQL value for use with Standard 414 methods would be 15 percent defective.

What one actually obtains from Military Standard 414 is a formal plan for evaluating from a sample the quality of a lot and determining its acceptability. In applications such as highway construction a variability unknown acceptance plan from Standard 414 works in the following fashion. A random sample of N units is taken from the lot to be evaluated. Each unit is measured and a mean and either standard deviation or range is calculated for the N measurements. These statistics are then used to estimate the percent defective for the lot with respect to the specification limits. The resulting estimate is compared to some limiting value (M) of percent defective that could reasonably be expected to occur when N random measurements are made on a lot having AQL quality. If M is not exceeded, the lot is considered acceptable; when exceeded, it is rejected.

To fully grasp how this type of acceptance plan works, it is important to understand the relationship between the parameters, AQL and M. AQL is the largest percent defective that an acceptable lot can actually possess. When such a lot is sampled, random variations in quality make it unlikely that the sample will show the lot to be exactly AQL percent defective. To allow for such sampling error and be fair to the supplier, it is necessary that the sample estimate of percent defective be permitted to exceed the AQL value somewhat before rejecting a lot. M is established in Military Standard 414 as the appropriate upper bound on the sample estimate (M is larger in magnitude than AQL). Theoretically, if sampling error did not exist, it would then be possible to drop the M parameter and directly use the AQL value to determine lot acceptability.

Design of Thickness Acceptance Plan

To extract from Military Standard 414 an acceptance plan specifically suited for bituminous concrete thickness, decisions had to be made on the lot size, sample size (N), specification limit(s), and AQL value to be used.

Lot size was set equal to approximately 15,000 square yards of contiguous pavement. This was the largest quantity of pavement for which the Department's Construction staff felt the assumption of similar construction conditions could hold. It corresponds to slightly more than one mile of two-lane roadway.

Sample size is the number of random cores to be taken from a lot to estimate lot quality. In Military Standard 414, sample size essentially established the buyer's risk of accepting poor quality, rejectable material. To minimize this risk, it was decided to use the largest sample size consistent with the Department's then current coring capacity. A sample size of 15 cores per lot was considered feasible.

For each paving item the acceptable level of thickness quality had already been established as that given by the data in Table 1. It remained only to redefine this quality in terms of an AQL value with its associated specification limit or limits. The AQL figure would then be used to enter tabulations in Military Standard 414 and establish M, the maximum sample estimate of percent defective permissible for lot acceptability. After a number of trials at this selection process, it became apparent that it would be better to follow a reverse procedure. The maximum value (M) for the sample estimate was chosen first, setting it at a figure expected to be most palatable to both contractors and Department administrators. A figure of 20% was used. By interpolating between the tabulated information of Military Standard 414 (Table C3 - Normal Inspection Plans Based on Variability Unknown Range Method) an AQL value of 10.5 percent defective was found to correspond to the selected M of 20%.

The AQL figure of 10.5% was used to select appropriate specification limits for each type of paving item. Historically, the Department had utilized a specification limit at the low end to control thickness deficiencies. An upper limit had been employed to restrict overruns of plan quantities when payment for bituminous concrete was on a tonnage basis. For the new specification it was ultimately decided to use only a lower thickness limit with each paving item. When overrun was a factor of concern, it would be controlled by placing a restriction on the asbuilt tonnage. Adoption of only a lower limit for thickness was expected to facilitate a contractor's use of automated paving equipment and hopefully result in improved pavement rideability.

Figure 2 shows the relationship between a lower limit on thickness and an AQL of 10.5%. It is noted that the lower limit must be 1.253 standard deviations below the mean to have 10.5% of the distribution of pavement thickness fall below that limit. Adhering to this requirement and using the data of Table 1, a lower specification limit was calculated for each type of paving item. The results of these calculations are given in Table 2. The limit for a nominal three-inch bituminous layer was decreased slightly to be more in line with the other limits. Also, by interpolations, a limit for 5-inch base

Table 1

Bituminous Pavement Thickness
(1962-1968)

Type of Course	Plan Thickness (in.)	Average* Thickness Achieved (in.)	Standard Deviation (in.)
Surface or binder	1.5	1.60	0.30
Surface or binder	2.0	2.10	0.35
Surface plus binder	3.0	3.25	0.45
Base	4.0	4.25	0.60
Base	6.0	6.25	0175

*Values rounded to nearest 0.05 inches

Figure 1. Comparative thickness distributions for 3 in. bituminous concrete layer.

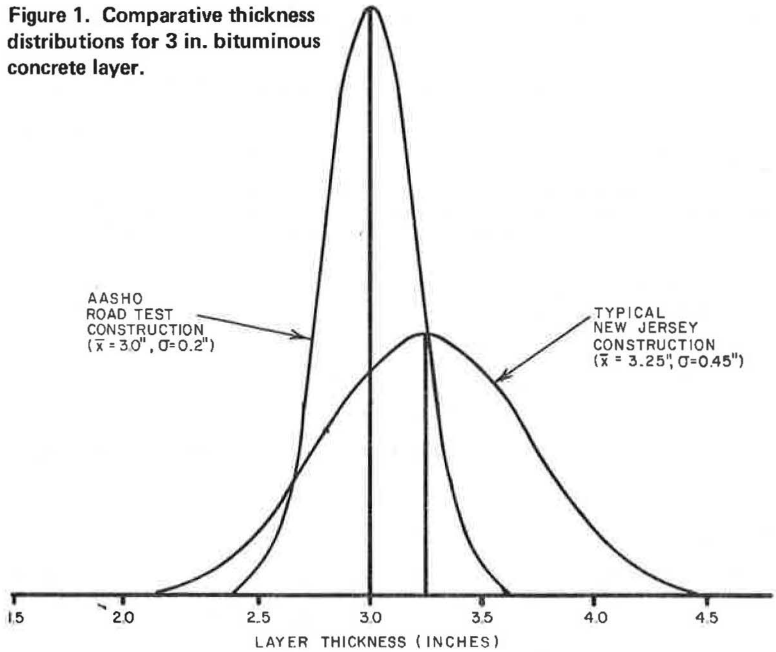
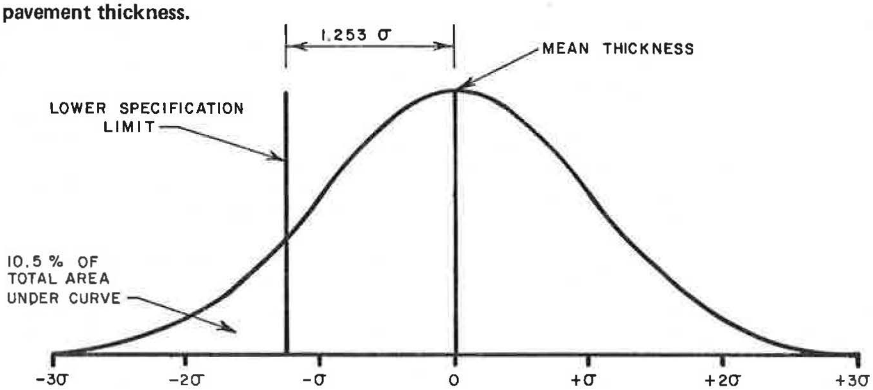


Figure 2. Relationship between AQL of 10.5 percent and lower specification limit for pavement thickness.



was added to accommodate this item's anticipated future use.

With the determination of the thickness limits, the acceptance plan was essentially complete. However, it is worth noting that at some point along the way a decision had to be made on the manner in which the estimate of lot variability was to be calculated. Military Standard 414 provides for this estimate to be obtained from either the average range of measurements on the lot sample or from the standard deviation of these measurements. The standard deviation approach is statistically more efficient but is also more laborious in application. Use of the average range method has the advantage of simplicity. The latter method was finally adopted with the idea that it would have a better likelihood of being understood and applied correctly by field personnel. Guidance in making this particular decision was obtained from the firm of Materials Research and Development which had prepared NCHRP Report #17 dealing with practical highway applications of statistical type specifications. The firm's advice was also instrumental in the decision to use only a lower thickness limit in the acceptance plan.

In summary form, the completed acceptance plan for pavement thickness is as follows:

1. A lot will consist of approximately 15,000 square yards of bituminous paving item.

2. Acceptability of a lot will be based on the percentage of a paving item having a thickness less than the governing lower specification limit, L (Table 2).

3. The percentage of the paving item below the specification limit will be estimated from a sample of 15 cores removed from random locations within each lot.

4. The estimate of % of pavement below L will be determined in the following fashion:

a. Measure the thickness of each core.

b. Compute the sample mean, $\bar{X}$, and the average range $\bar{R}$ of three successive groups of five core measurements.

c. Compute the quality index $Q_L = \frac{\bar{X} - L}{\bar{R}}$

d. Determine the estimated percent defective (% below L) is equal to or less than 20%, the lot will be considered acceptable.

The tabulation mentioned in step 4 of the plan is given in Table 3 in an abbreviated form.

Contractor and Department Risks

Since the acceptance plan calls for far less than 100% inspection of a lot, it is apparent that the quality determinations will not be correct 100% of the time. There will definitely be risks of making a wrong decision on lot acceptability. Military Standard 414 has been so designed that its acceptance plans involve approximately a 10% risk of erroneously rejecting a lot which is actually of AQL quality. This means that with our new thickness criteria, 10 out of every 100 times we inspect a lot of adequate thickness (one of exactly AQL quality) we will wrongly reject it. The risk here is borne by the contractor and admittedly is somewhat high. However, it was believed that this magnitude of risk would be tolerable if the consequences of rejection were not too harsh, at least, for slight deficiencies in thickness. A reduced payment schedule for deficient lots which is described later was developed in part to provide the desired mitigative effect.

The contractor, of course, is not the only party hurt by a wrong quality decision. If the acceptance plan erroneously accepts a lot of inadequate thickness, the Department suffers. The risk of accepting poor quality lots is not constant with the new acceptance criteria but is a function of the lot quality involved. Figure 3 gives the relationship between lot quality and probability of acceptance which is defined as the operating characteristic curve or O.C. curve for the acceptance plan.

The 10% probability point is seen on the O.C. curve to correspond to approximately 32 percent defective. Thus there is a 10% risk of accepting a lot which has 32% of its paving with thicknesses less than the specification limit. As will be shown later, percent defective figures larger than the AQL value can be equated to potential losses in pavement service life. Thirty-two percent defective would correspond to a 10 to 20 percent loss in serviceability for a high type pavement. A 10% risk of incurring such a loss in serviceability was considered tolerable, especially since it would really be unlikely that a lot of this quality would occur very often.

Table 2

Lower Specification Limits for Thickness

Type of Course	Plan Thickness (Inches)	Lower Thickness Limit (Inches)
Surface or Binder	1.5	1.25
Surface or Binder	2.0	1.70
Surface & Binder	3.0	2.60
Base	4.0	3.50
Base	5.0	4.40
Base	6.0	5.30

Table 3

Estimates of Lot % Defective from Q_L

Q_L	Estimated Lot % Defective (%)
0.88 - 0.66	1-5
0.63 - 0.53	6-10
0.51 0.44	11-15
0.42 - 0.36	16-20
0.34 - 0.29	21-25
0.28 - 0.23	26-30
0.21 - 0.17	31-35
0.16 - 0.11	36-40
< 0.11	>40

Figure 3. Operating characteristic curve for pavement thickness acceptance plan.

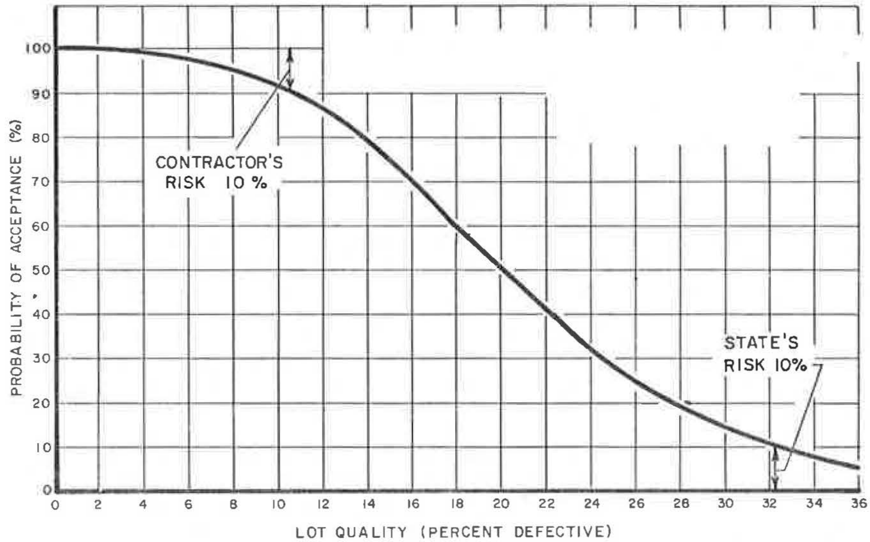


Table 4

Most Probable Thickness Deficiencies (Inches)

Estimated % of Lot Below Acceptance Limit	Nominal Course Thickness (Inches) 1.5	2	3	4	5	6
25	0.17	0.20	0.26	0.35	0.39	0.43
30	0.22	0.26	0.33	0.44	0.50	0.55
35	0.26	0.30	0.39	0.52	0.59	0.65
40	0.30	0.35	0.45	0.60	0.68	0.75

Reduced Payment Schedule

To put the acceptance plan in a specification format, it was necessary to decide what action would be taken when a lot was found unacceptable. In the old specification, unacceptable pavement which was not grossly deficient in thickness was left in place with the contractor being assessed a penalty. Only in instances of marked thickness deficiencies was the pavement totally rejected and required to be either replaced or overlaid. Although the old specification was inadequate in many respects, its use of penalties to handle minor levels of deficiency was believed to be a good approach. It was therefore decided that a graduated penalty or reduced payment schedule would be developed for use with the new acceptance plan.

The fundamental reasons for assessing payment reductions are to match payment to serviceability of the product supplied, to avoid costly total rejection of a product when it is only slightly less serviceable than specified, and to create an incentive for the supplier to provide the quality of product desired. For the most part, the Department's previous attempts at formulating payment reduction schedules were educated guesses that concentrated essentially on the incentive aspect. In the case of thickness, it was believed that the matching of payment reductions to loss in serviceability could at least be considered from a theoretical standpoint.

With the new acceptance plan, when a lot is judged unacceptable it is because the sample estimate of percent defective exceeds 20%. This excessive percent defective can be thought to have resulted from a thickness distribution which is exactly the same as that used in formulating the acceptance plan but which has a lower mean thickness. A higher estimated lot percent defective can thus be approximately equated to an average thickness deficiency in inches. Table 4 lists by various nominal course thicknesses the most probable thickness deficiencies for certain values of the sample estimate of lot percent defective. Deficiencies were calculated using the thickness distribution data of Table 1 and determining the shift in mean thickness necessary to cause percent defective to change from the AQL value (10.5%) to the value of the sample estimate.

The thickness deficiencies of Table 4 can be equated to theoretical losses in service life by working a pavement design process in reverse. The Department's pavement design methodology is that of the AASHO Interim Design Guide. Using the Guide's design procedures, the effect on service life was computed for the pavement structure of a typical primary highway. The pavement had an original structural number of 5.8 with a regional factor of 1.5, a design life of 20 years, and terminal p.s.i. value of 2.5. The accumulated 18 kip equivalencies over the 20-year design period was taken to be 10 million with a 5% compound annual growth factor. Findings of this analysis are presented in Table 5. The thickness deficiencies have been equated to probable life expectancy as a percentage of the desired 20-year design life.

The percentage figures of Table 5, along with the thickness deficiency data of Table 4, were used to formulate a reduced payment schedule, for handling unacceptable lots. This schedule, which includes four levels of payment, is provided in Table 6. In developing the schedule it was decided that the reduced payment concept would terminate when the thickness deficiency reached 1/4 inch for surface courses and when the loss in service began to exceed about 20% for other courses. At these points the contractor would be required to overlay the rejected lot using a minimum of 1 inch of surface course material. No payment would be given for the overlay but the contractor would be paid for the original lot material.

In Table 6 the second level of reduced payment (90% payment) was chosen to approximate the associated life expectancy percentages. The first level was set somewhat higher than the life expectancy factors, the third level somewhat lower and the fourth level much lower. The decision to have the first payment level at a higher rate than expected serviceability would dictate had the effect of mitigating somewhat the acceptance plan's high risk (10%) of rejecting a lot. The setting of the last two payment factors at progressively lower levels than the anticipated serviceability is believed to yield a desired incentive effect.

Introduction of Thickness Specification

As a feasibility check, use of the new acceptance plan and reduced payment schedule was simulated on the core data from a number of past paving projects. In nearly every instance it was found that the contractor would have been given a much higher percentage payment than what he actually received under the old specification. Analysis of the thickness quality involved indicated that these higher payments would indeed be justified.

Table 5

Probable Life Expectancy (% of AQL's Design Life)

Estimated % of Lot Below Acceptance Limit	Nominal Course Thickness (Inches) 1.5	2	3	4	5	6
25	94	93	91	88	87	85
30	92	91	89	85	83	82
35	91	90	87	82	80	78
40	90	88	85	80	77	75

Table 6

Reduced Payment Schedule for Excessive Percent Defective

Estimated % of Lot Below Acceptance Limit	Percent Payment Per Lot: Surface Courses	All Other Courses
21-25.	95	95
26-30	*	90
31-35	*	80
36-40	*	50
Greater than 40		

*Remove and replace or minimum 1 inch overlay

Table 7

Summary of Thickness Specification Performance

Item	Number of Lots Inspected	Number of Lots Warranting Payment Reduction: Actual	Predicted	Average % Payment Warranted Per Lot	Mean Thickness Per Lot (Inches)	Average σ Per Lot (Inches)	Average Lot Percent Defective	AQL Value for Spec. (%)
1.5 Top	80	1	0.4	99.9	1.73	0.26	2.9	10.5
2.0 Top/Binder	67	1	1.0	99.9	2.25	0.33	4.8	10.5
3.0 Top & Binder	86	1	0.4	99.9	3.37	0.42	3.3	10.5
4.0 Stab. Base	39 (35)*	19 (15)	23.0 (15.1)	74.3 (83)	3.93 (4.00)	0.56 (0.56)	22.1 (18.6)	10.5

*Values in parentheses result when data is eliminated from one project of extremely inordinate quality relative to remaining projects.

The first actual field application of the acceptance plan and allied payment schedule did not occur until long after their development. Many administrators within the Department were skeptical of the new approach and the fact that it had more than a superficial statistical basis appeared to be a deterrent to its approval. Finally, as part of a paving experiment, the acceptance plan and payment schedule were incorporated by change order in the specifications of one project. They were applied to three lots of 3-inch bituminous surface pavement (1.5 surfacing material and 1.5 inches binder material) and 3 lots of 4-inch bituminous stabilized base. The mean thickness and standard deviation for each of the two paving items proved to be only slightly larger than those of Table 1. Consequently, all lots were found to be totally acceptable warranting no payment reduction. By comparison the old specification would have called for only 80% payment for the area involved. As might be expected, the project contractor was pleased with the specification change.

With the concurrence of the state's apshalt pavement association, the proposed acceptance criteria for pavement thickness were incorporated in the Department's standard construction specifications in the spring of 1971. Also, asbuilt tonnage was established as the payment quantity for all bituminous paving items. A copy of the pertinent sections of these specifications are provided in the Appendix. As part of this change, the use of automated paving equipment was required by specification in an attempt to improve pavement riding quality. Also, to facilitate the equipment's use, the planned restriction on excessive tonnage overrun was deleted.

To insure correct field application of the new thickness provisions, special procedures were prepared for the random selection of core locations. Also, construction operations bulletins were subsequently prepared advising field personnel on the particulars of partitioning a project into lots and determining thickness compliance. To further simplify the specification's usage and insure uniform application, a computer program was eventually developed for calculating the sample estimates of percent defective and computing the payment factors. This program became operational in 1974.

Thickness Specifications Performance

By the summer of 1974, the new thickness specification had been included in the contract documents for 68 projects. Of this amount, only 16 projects had progressed sufficiently to have actually applied the pavement thickness requirements. However, the completed paving work did encompass some 836,000 tons of bituminous concrete and stabilized base distributed among 269 lots. The total dollar value for this material in place exceeded eleven million dollars with the average lot being valued at approximately $40,000. Overall, the amount of pavement construction on these completed jobs was believed sufficient to give a good indication of how the specification was performing.

Table 7 gives information on average lot quality and specification performance for the completed projects. Data for all paving items except 2-inch, and 5-inch bituminous base have been included. The excepted items had too few number of lots (5 and 8) for meaningful evaluation.

Average lot quality is given in Table 7 in terms of a mean thickness, an average thickness standard deviation, and an average percent defective (percent of lot below the specification limit). These statistics when compared to the data of Table 1 for past construction reveal some interesting contrasts. Mean thickness for the surface and binder course items has increased by 4 to 8 percent in comparison to past paving work. The stabilized base items experienced the same magnitude of change but in the form of a decrease in thickness.

Increased thicknesses were expected, of course, as the specifications included no upper limit on asbuilt tonnage. The reasons for the unanticipated lower stabilized base thicknesses were not fully determined. However, it appears that initial efforts by the Department's field inspection personnel to minimize tonnage overrun was a significant factor in this occurrence.

The average standard deviations of Table 7 are all smaller than what the Department's past construction experience would dictate. It is believed this general improvement in uniformity primarily resulted from use of improved construction equipment and techniques. The use of automated grade controls on both fine grading machines and bituminous pavers was typical for the newer construction projects. As previously indicated, the special controls for pavers were required by specification. It is worthy of note that, while the automated paving equipment improved thickness uniformity, it also achieved the desired effect of improving pavement rideability. Roughness data for these initial projects typically warranted an FHWA rating of "Good" in comparison to the "Fair" ratings normally obtained on past projects.

The overall thickness quality of pavement completed under the new specification is best described by the average percent defective factor. Percent defective combines the effects of mean thickness and thickness uniformity into one parameter which is directly comparable to the specification's target AQL value of 10.5%. The average lot percent defective for all paving items except 4-inch base is seen in Table 7 to have been either less than or essentially equal to the AQL figure. A lot of 4-inch base typically had twice as much pavement area below the specification limit than that permitted.

The adequacy of the new specification can be judged from the manner in which it dealt with the quality of pavement inspected. A superficial review of Table 7 suggests that the specification performed quite well in this regard. For each paving item listed in Table 7 with an average percent defective less than or equal to the AQL value, the vast majority of lots inspected were found acceptable under the new specifications. Also, in the instance where the average lot percent defective was excessive relative to the AQL, the specification rightly caused a large number of lots to be penalized.

If the acceptance plan portion of the specification is working correctly and if lot percent defective does not vary greatly from one lot to another, it is possible to predict the actual number of lots to be penalized for each paving item. The predications can be made by using the average lot percent defective figure and the acceptance plans operating characteristic curve (Figure 3). Table 7 reveals that the predicted and actual number of defective lots are extremely close for all items except 4-inch base. The difficulty with 4-inch base is that the assumption of uniform quality from lot to lot was not correct. Detailed analysis revealed that on one particular project all 4-inch base lots were of extremely poor quality (55 to 70% defective, all requiring an overlay), and thus differed greatly from lots typical of other projects. If these excessively deficient lots are excluded from the analysis, the specification performance statistics for 4-inch base would be those given in parentheses in Table 7. The revised statistics show that the actual and predicted number of lots to be penalized were almost exactly the same. The preceding findings indicate that the acceptance plan portion of the new specifications worked just about as intended.

The percent payment figures of Table 7 show that the payment schedule of the specification also worked remarkably well. Each item with an average lot percent defective equal to or less than the AQL value (10.5%) had nearly 100% payment per lot. Theoretically, if an item's quality were actually equal to the AQL, its average percent payment per lot with the new specification would be approximately 99%. This figure was matched closely by the 6-inch base item which had a 99.3% average lot payment with an average lot quality of 10.9 percent defective.

The 4-inch base item again serves as a slight anomaly. While the payment schedule rightly called for overlaying all the lots of the one grossly deficient project, its average payment figure for the remaining lots inspected is somewhat low. O.C. curves (now shown) for the payment schedule predict better than a 90% average lot payment when the one bad project is omitted. In contrast, Table 7 shows only an 83% figure. The difference is not believed to be a fault of the payment schedule but rather a failure of the writer to completely exclude from analysis all lots not satisfying the assumption of uniform lot quality.

Another factor of concern with regard to the performance of the new thickness requirements was the overrun of plan tonnage quantities. Without a specification provision to limit overrun, it was expected that plan quantities would be greatly exceeded. This did not occur, probably because of the control efforts of field inspection personnel. For the initial 16 projects evaluated, the total plan quantity of bituminous paving materials was exceeded by only 6.0%. By comparison, if the contractor had supplied the minimum thickness levels required to satisfy the specification, a 5.8% overrun would have occurred. Of course, some of the 6% overrun is due to other than thicknesses being larger than plan values. Based on actual thicknesses achieved, the overrun should have been 5.2%. The difference between the 5.2% and 6% figures can be attributed to slightly excessive paving widths.

As a final comment on the thickness specifications, it must be pointed out that the Department's construction personnel were not completely satisfied with its performance. The specification being designed to deal with each paving item separately did not facilitate crediting of excessive thickness from one item to another. In a number of instances where bituminous base thicknesses were deficient, excesses in surface and binder courses were more than enough to overcome the base deficiency. Yet, because of the nature of the specification and the fact that the different paving items had different payment rates, it was not legally valid to permit crediting between the items.

To correct this shortcoming, the Department is considering a revision to the current thickness specification that would have acceptance based on both surface thickness and total combined thickness of all courses. With such an approach, all bituminous paving materials would be listed under one pay item "bituminous pavement." If this change becomes a reality, the actual modifications to the specification would be minimal and only affect the specification limits. Analysis indicates that for total thickness the specification limits for 3" through 6" pavements can be the same as those already established for separate paving items of equal thickness (Table 2). For pavements having a total thickness larger than 6 inches, the governing specification limit would be set 0.7 inches below the plan figure for total thickness.

Concluding Comments

The statistical based thickness specification developed by the New Jersey Department of Transportation for bituminous concrete has been found to perform as intended. The acceptance criteria patterned after Military Standard 414 were able in actual application to distinguish quite well between acceptable and unacceptable pavement lots. The proficiency of this quality-discerning ability conformed with surprising exactness to that predicted by the criteria's theoretical operating characteristic curve. Also, the reduced payment schedule for handling deficient thickness lots proved for the most part to deal equitably with the contractor.

The only possible inadequacy detected in the thickness specification was its lack of allowance for crediting of excessive thickness from one bituminous item to another. This flaw at times resulted in payment reductions being indicated for deficient base course when there already existed an adequate excess in surface course thickness to balance the deficiency. A revision to the specifications having acceptance based on both thickness of surface course and total thickness of all bituminous layers would correct this problem. Such a revision is presently under consideration by the Department.

Acknowledgment

The author wishes to thank Mr. Michael Barrett of the Department's Construction Division for guidance and support in preparing the new thickness specification. Also, Mr. Robert Santoro of the Research and Development Division is gratefully acknowledged for writing the operations bulletins essential to the specification's actual use.

References

1. J. F. Shook. How Well Can We Expect to Control Thickness? -- Experience of the AASHO Road Test. Proc. Assoc. Asphalt Paving Tech., Vol. 33, pp. 2-10, 1964.
2. U.S. Department of Defense, Military Standard 414.

Appendix: Thickness Specification for Bituminous Concrete

3.10.3. Methods of Construction

When a uniform thickness of bituminous concrete is specified, each course shall be so constructed that not more than 20% of the lot shall be less than the acceptance limits shown in Table 4.

To determine the average thickness, 15 cores will be taken by the engineer from each lot of pavement. A lot shall consist of approximately 15,000 square yards or less of pavement. Each lot will be divided into 3 sections of approximately equal area, and 5 cores will be removed from random locations within each section.

Thickness measurement of bituminous pavements from cores will be in accordance with Article 9.1.24.

Table 4
Thickness Acceptance Limits

Specified or Plan Thickness (Inches)	Acceptance Limit (Inches)
1.5	1.25
2.0	1.70
3.0	2.60
4.0	3.50
5.0	4.40
6.0	5.30

When variations cause more than 20% of the lot of the specified bituminous concrete course to be less than the acceptance limit shown in Table 4, payment will be made at an adjusted price. For each lot of pavement, the contract unit price will be adjusted in accordance with the requirements of Article 3.10.4.

If, during the progress of construction, it is determined by the engineer that the subgrade, subbase, or any base course or pavement course has not been compacted and finished in reasonably close conformity to the specified thickness or grade, the contractor shall not proceed with construction of any subsequent course thereon until appropriate corrective measures satisfactory to the engineer have been completed.

The laboratory will compute, from drilled cores of the bituminous concrete and bituminous-stabilized base course actually constructed on the project, the weight per square yard per inch of thickness of each of the various types of bituminous concrete and bituminous-stabilized base course. The computed actual weight shall be calculated from the average specific gravity as determined in accordance with the current provisions of AASHO designation T166 except coating with paraffin will not be used, on at least ten (10) percent of the drilled cores, but not less than three (3) cores. This computed actual weight shall be used for all computations of payment quantities when necessary.

The following is included under the subheading "Thickness and Weight":

Bituminous concrete pavement Type FA-BC-2, CA-BC-2 or MA-BC-2, 3" thick, shall be constructed to a compacted depth of 3 inches, consisting of 1 1/2 inches of top course and 1 1/2 inches of bottom course material.

Bituminous concrete pavement Type FA-BC-2, CA-BC-2 or MA-BC-2 variable thickness, shall be constructed in two or more courses. The top course material shall be 1 1/2 inches compacted depth and the bottom course material shall be constructed in layers of not more than 2 1/2 inches compacted depth.

3.10.4. Quantity and Payment

Where a uniform thickness of bituminous concrete pavement is specified, payment will be made at the respective contract unit price per ton of mixture accepted and complete in place; provided however, pavement not meeting the requirements for conformance to job mix formula, stability, and air voids, as specified in Article 3.10.2. (Addenda A), and thickness, as specified in Table 5 will be paid for at an adjusted contract unit price.

Separate payment will not be made for furnishing and applying tack coat and prime coat, when required. All costs thereof shall be included in the respective contract prices per ton of mixture, accepted and completed in place.

Table 5

Contract Price Adjustment for Thickness

A: Q_L		B	C: Percent of Contract Price (Note 2)	
Equal to or Greater Than	Less Than	Percent of Lot Outside Thickness Limit	Surface Course	Base, Bottom, or Binder Course
0.36	----	0 - 20	100	100
0.29	0.36	21 - 25	95	95
0.23	0.29	26 - 30	(Note 1)	90
0.17	0.23	31 - 35	(Note 1)	80
0.11	0.11	Greater than 40	(Note 1)	(Note 1)

$$Q_1 = \frac{(\text{Average Thickness}) - (\text{Thickness Acceptance Limit})}{\bar{R}_3}$$

Where $\bar{R}_3$ is the average of 3R values and R is the absolute difference between the smallest and largest value in a group of 5 consecutive measurements.

Note 1: Remove and replace the lot or overlay (minimum 1 inch) at the option of the contractor if approved by the engineer, at no additional compensation.

Note 2: Percent of contract price will be applied to the computed tonnage for the lot, arrived at by using the average lot thickness and the computed actual weight of the material as specified elsewhere herein.

When the term Q_L is within the limits shown in Column A, the percent of the lot outside the thickness limit is indicated in Column B, and the percent to be paid for is specified in Column C.