Quality Control in Highway Construction and Maintenance When the Measurement Parameters are Highly Nonuniform

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In this paper, an original method is presented for quality control based on Weibull's law for the distribution of random quantities with variable parameters. The nomographs obtained for determining the extremal values of the parameters and the defectiveness index can be used for various cases in the statistical reduction of research results. The proposed method can be used for quality control for both highly uniform data (in the United States, the measured values are assumed to have a normal distribution for this purpose) and highly nonuniform data. The method described here is widely used in the USSR for quality control in the construction and maintenance of roads.

The existing methods of quality control in various countries are based on the normal distribution of measured quantities. The use of this law is completely valid when the quality of the road construction is high. However, one must frequently deal with construction of insufficiently high quality, when the parameters being monitored are highly nonuniform. The normal distribution may not be used in this case. Some parameters (the water saturation and swelling of the paving asphalt, the compressive strength in samples of binder-strengthened material, Weibull's pavement roughness, etc.) are always highly nonuniform. Results of these experiments are also not subject to the normal distribution law.

It has been shown in many papers in the USSR that it is necessary to use Weibull's law with variable parameters when the parameters being measured are highly nonuniform (*1-5*). This law is universal, and it may be used for the control of both uniform and nonuniform processes; however, it has been difficult to use because of the complexity of the mathematics.

The aim of the present paper is the development of an engineering method for quality control in road construction and maintenance. This method is based on the use of Weibull's law. The main stages in the statistical method of quality control are as follows:

1. Sampling plan, consisting of
   - Identifying the inspection parameters and defining the nomenclature,
   - Identifying the quantities to be measured, and
   - Identifying where the quantities are to be measured.

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2. Carrying out the inspection.
3. Statistical treatment of the inspection results, consisting of
   - Ordering the results,
   - Determining the extreme values of the ordered series,
   - Obtaining the mean values and coefficients of variance,
   - Determining what the extrema mean, and
   - Determining the defectiveness index.
4. Evaluation of the quality, consisting of
   - Evaluating the individual parameters and
   - Evaluating the quality of the road or its elements.

SAMPLING PLAN

Identification of the Inspection Parameters and Definition of Nomenclature

Industrial quality control can be divided up in the following way:

1. Incoming inspection;
2. Operational control, consisting of adjustment of process and process control;
3. Acceptance inspection; and
4. Ongoing inspection.

The incoming inspection and operational control are carried out by the organization building the road. The acceptance inspection is performed by a special commission made up of representatives from the organization building the road and the customer. The ongoing inspection is carried out periodically by various governmental inspectorates.

The nomenclature for the parameters to be sampled during the operational quality control, which is critical in road construction (Table 1), will now be discussed.

Determining the Quantities to be Measured

The number of measurements required to sample any given parameter is given by the Chebyshev transformation formula,

TABLE 1 NOMENCLATURE FOR THE PARAMETERS TO BE SAMPLED

Layer	Parameters To Be Sampled	
	In Process Adjustment	In Process Control
Earth fill	T, h, γ ,n, R, n, V	T, h, r, V
Sand layer	T, h, γ, n, R, V	T, h, R, V
Broken stone or gravel layer	T, h, R, n, V, γ	T, h, R, V
Stabilizer	T, h, Q, γ , R, n, V	T, h, Q, R, V
Asphalt concrete	T, h, γ, t, R, n, V	T, h, t, R, V
Cement	T, h, γ, R, t_a O_c	T, h, R

T, compaction time; h, layer thickness; Q, content component; t, temperature; γ, density; w, moisture content; R, roughness; γ_d, density of dry soil; n, number of roller passes; V, roller speed; t_a, air temperature; O_c, concrete setting.

$$n = (tC_v/\rho)^2 \quad (1)$$

where t is the standard deviation, which depends on road category and number of measurements n (Table 2); C_v is the coefficient of variation; and ρ is the measurement accuracy index.

The numbers of measurements recommended for typical values of the coefficient of variation C_v of the parameter being measured and the measurement accuracy index ρ are given in Table 3.

This required number of measurements can be used for any volume to be inspected, that is, it does not depend on the dimensions of the region being inspected. Because of this, the larger the region to be inspected, the more efficient the proposed inspection method becomes.

Determining Where the Measurements Are to be Carried Out

In order to improve the reliability of the inspection results, it is essential to create a random sample. Various methods can be used to do this, but the simplest one is to use a table of random numbers (Table 4).

For purposes of determining where measurements are to be carried out, the entire region to be inspected is divided into 100 sections (Figure 1), each of which is assigned a number from 00 to 99. An arbitrary first number is then selected from the table of random numbers (Table 4), and all of the subsequent numbers are written down. The total number of numbers must be equal to the required number of measurements. For example, if 72 is chosen as the first number, the following series consisting of n = 15 numbers is then selected: 72, 58, 79, 30, 00, 89, 68, 87, 84, 16, 27, 55, 99, 95, and 24.

The numbers chosen on the diagram are then marked and the rational route shown by the dashed line in Figure 1 to take when carrying out quality control inspection is worked out. Inspections are made only in those sections whose numbers were obtained as a result of the random sampling in Table 4.

This method may also be used for inspecting one- and three-dimensional objects.

TABLE 2 STANDARD DEVIATION *t*

Number of Terms in Ordered Series	t for Various Road Categories			
	(I and II)	I and II (III and IV)	III and IV (V)	V
4	4.54	3.18	2.35	1.64
8	3.00	2.37	1.90	1.41
12	2.72	2.20	1.80	1.36
16	2.60	2.13	1.75	1.34
20	2.54	2.09	1.73	1.33
30	2.46	2.04	1.70	1.31
60	2.39	2.00	1.67	1.30

* Road categories not in parentheses indicate the columns to be used for the two-sided limit, and those in parentheses indicate the columns to be used in the one-sided limit.

TABLE 3 RECOMMENDED NUMBER OF MEASUREMENTS

Parameter	C_v	ρ	Various Road Categories		
			I - II	III-IV	V
Density of Fill and Materials	0.03	0.015	18	13	8
Modulus of Elasticity of Fill	0.30	0.100	36	26	16
Modulus of Elasticity of Pavement Layers	0.25	0.100	26	18	12
Thickness of Layers	0.20	0.080	36	26	18
Strength of the Asphalt Concrete	0.10	0.050	18	13	8
Roughness	0.80	0.20	64	45	28
Temperature of Asphalt Mixture	0.18	0.030	36	26	16
Ride	0.25	0.100	36	26	18
Width of Layers	0.10	0.050	25	18	13
Density of Asphalt Concrete	0.02	0.010	18	13	8
Strength of the Soil Stabilization	0.15	0.050	36	26	16
Moisture Content	0.10	0.050	25	18	13

Road categories I - II are analogous to interstate highways,

Road categories III - IV are analogous to major state highways,

Road categories IV - V are analogous to local roads.

TABLE 4 TABLE OF RANDOM NUMBERS

89	51	59	07	95	66	15	56	64	34	56	55	81	23	32	94	37	75	78	02
69	18	60	33	93	42	50	29	92	24	88	95	55	37	58	91	64	11	88	67
41	68	64	21	63	85	18	13	89	76	33	18	17	26	64	53	80	70	06	07
86	52	24	71	71	88	05	98	93	42	67	24	80	90	82	12	31	19	03	60
72	58	79	30	00	89	68	87	84	16	27	55	99	95	24	14	48	05	09	61
52	45	24	24	99	33	34	68	39	35	79	13	09	04	10	45	42	07	77	57
76	77	39	75	26	27	15	66	64	47	25	73	23	75	25	16	28	76	61	81
04	82	58	21	34	80	31	77	51	20	45	80	47	56	01	70	49	21	02	74
87	13	38	47	78	45	86	32	45	20	19	92	50	49	25	07	82	47	60	44
87	75	45	47	18	38	13	26	42	94	15	21	84	92	86	89	51	74	29	03

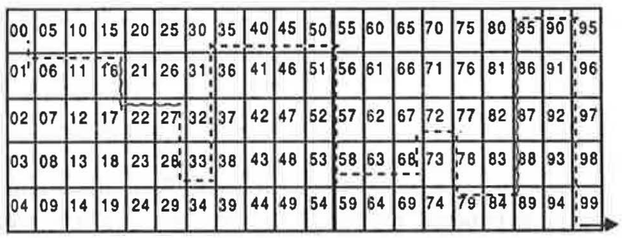

FIGURE 1 Diagram for determining the locations where measurements are to be made. The dashed line indicates a rational route to be taken during the inspection.

STATISTICAL TREATMENT OF THE CONTROL RESULTS

Ordering the Results and Evaluating the Extreme Terms in the Ordered Series

For convenience in the calculations, the measurements of the parameter being sampled are placed in order of increasing value, that is, an ordered series is generated.

For example, the following results were obtained upon measuring the thickness of the ballast layer: 22, 21, 20, 17, 20, 21, 18, 21, 17, 17, 20, 19, 19, 20, and 21 cm. The following ordered series was obtained: 17, 17, 17, 18, 19, 19, 20, 20, 20, 20, 21, 21, 21, 21, and 22 cm.

The extreme terms are now tested to see if they belong to the series. To do this, the following formulas are used:

$$\tau_{max} = (x_n - x_{n-2})/(x_n - x_2) = (22 - 21)/(22 - 17) = 0.2$$
$$\tau_{min} = (x_2 - x_1)/(x_n - x_2) = (17 - 17)/(22 - 17) = 0.0$$

The values obtained for the τ criterion are smaller than the allowable value $[\tau]$ = 0.486 taken from Table 5, so that the extreme terms in the series may not be rejected. If $\tau_{max} < [\tau]$ or $\tau_{min} > [\tau]$, the extreme left-hand or extreme right-hand term, respectively, in the ordered series must be thrown out.

Definition of the Mean Value and Coefficient of Variation

The mean value and coefficient of variation for the results of the quality control with respect to a particular parameter can be determined either approximately or by using the exact formulas.

The exact formulas may be written in the following way:

$$x_{avg} = \frac{\sum_{i=1}^{n} x_i}{n}$$

$$C_v = \frac{1}{x_{avg}} \left[\frac{\sum_{i=1}^{n} (x_i - x_{avg})^2}{n - 1} \right]^{1/2} \qquad (2)$$

The approximate method of calculation involves defining the mean value as the median of the improved ordered series. Thus, in the example discussed, the number of terms in the improved series is 15, so that the median of this series will be the middle (eighth) number, that is, x_{avg} = 20 cm.

The coefficient of variation will be approximately defined as

$$C_v = (x_{max} - x_{min}) / (2t \cdot x_{avg}) = 0.058 \qquad (3)$$

TABLE 5 ALLOWABLE VALUES OF THE CRITERION $[\tau]$

Number of Terms in Series	$[\tau]$	Number of Terms in Series	$[\tau]$
3	1.000	12	0.541
4	0.991	15	0.486
5	0.916	20	0.430
6	0.805	24	0.400
7	0.740	30	0.369
8	0.683	40	0.345
9	0.635	50	0.324
10	0.597	60	0.311
11	0.566	70	0.302

The Meaning of Extremal

Determining the extremal values is important for quality evaluation. In order to determine these values, it is essential to know how the random quantities are distributed. Over a period of 7 years, the author has carried out a systematic inspection of the quality of road construction and maintenance in 12 regions of the Soviet Union. The quality inspections were carried out in a total of 49 organizations. Approximately 40-60 people participated in the work each year. An impressive sample with a total size of 400,000 measurements was obtained. Reducing these measurements provided the means for concluding that the variable-parameter Weilbull's law is the most appropriate for quality control in road construction and maintenance. Several examples of the kinds of distributions observed for the measured quantities are shown in Figure 2; it is obvious that the quantity being measured is not always normally distributed.

Weibull's law with three variable parameters may be written mathematically as

$$f(x,\kappa,\lambda_0,\nu) = \begin{cases} \lambda_0\kappa(x - \nu)^{(\kappa - 1)}\exp\text{-}\lambda_0(x - \nu)^{\kappa} \\ 0, \text{ otherwise} \end{cases}$$

$$\text{for } x \geq \nu,\ \nu \geq 0,\ \kappa > 0, \text{ and } \lambda_0 > 0 \qquad (4)$$

where λ_0 is the scale parameter, κ is the form parameter, and ν is the position parameter.

For practical calculations, the origin may be shifted to the point with $x = n$; the distribution law will then have two parameters. In this case, it is simple to determine the values of the parameters. Once the experimental values of the mean and coefficient of variation are known, the parameters λ_0 and κ can be determined:

$$C_\nu = \left(\{\Gamma[1 + (2/\kappa)] \big/ \Gamma[1 + (1/\kappa)]^2\}\text{-}1\right)^{1/2}$$

$$x_{avg} = \Gamma[1 + (1/\kappa)] \big/ (\lambda_0)^{1/\kappa} \qquad (5)$$

where Γ is the gamma function.

Weibull's law with variable parameters is universal, because it is possible to obtain practically any distribution law (normal, Poisson, binomial, hypergeometric, geometric, gamma, beta, etc.) by adjusting the three parameters λ_0, κ, and ν.

The variation in the shape of the distribution of the measured quantities as a function of the form parameter κ is shown for several examples in Figure 3. For $\kappa = 1$, an exponential law is obtained; for $\kappa \geq 3$, a normal distribution law is obtained.

To determine the extremal values ($x^p{}_{max}$; $x^p{}_{min}$) of the quantity being measured for a particular confidence level p, the definite integral of Equation 4 is taken.

$$p = \int_0^{x^p_{max}} \lambda_0\kappa x^{\kappa\text{-}1} \exp(-\lambda_0 x^{\kappa})\, dx$$

$$x^p{}_{max} = \{\ln[1/(1 - p)/\lambda_0]\}^{1/\kappa}$$

$$= x_{avg}Z_2 = x_{avg}\{\ln[1/(1 - p)]\}^{1/\kappa} \big/ \Gamma(1 + 1/\kappa)$$

$$x^p{}_{min} = x_{avg}Z_1$$

$$= x_{avg}[\ln(1/p)]^{1/\kappa} \big/ \Gamma(1 + 1/\kappa) \qquad (6)$$

A nomogram for determining the extremal values of the parameters being inspected (Figure 4) was constructed using the formulas obtained in Equation 6. For Category I and II roads, $p = 0.975$; for Category III and IV roads, $p = 0.95$; and for Category V roads, $p = 0.90$.

Definition of the Defectiveness Index

The quality is evaluated using the defectiveness index Q, which is the ratio of the number of measurements with

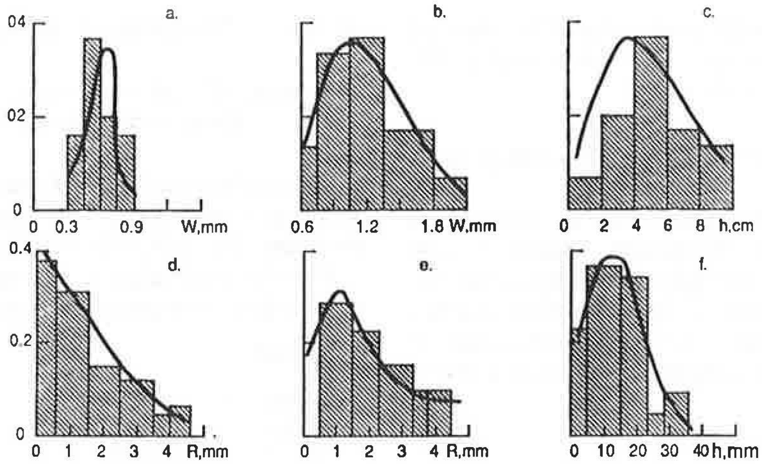

FIGURE 2 Examples of the random distribution for the quantities. (a) and (b) Pavement deformation; (c) Thickness of asphalt concrete layer; (d) and (e) Roughness of the asphalt concrete covering; and (f) Thickness of crushed stone layer.

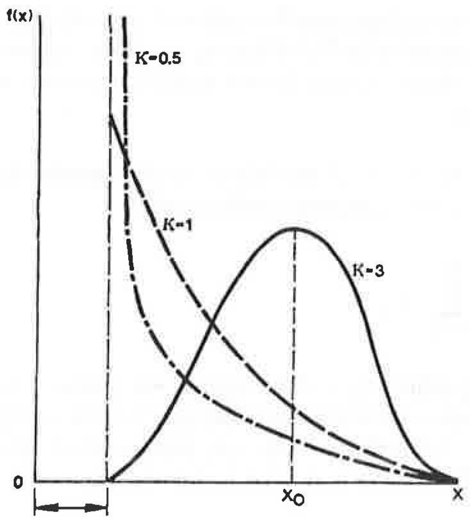

FIGURE 3 Graphs of the Weibull distribution function for various values of κ.

production flaws to the total number of measurements. The defectiveness index can be determined in the following ways:

1. By constraining the minimum value of the parameter (left-hand constraint),

$$Q_l = \int_0^{[x]} \lambda_0 \kappa x^{\kappa-1} \exp -\lambda_0 x^{\kappa} dx \Big/ \int_0^{\infty} \lambda_0 \kappa x^{\kappa-1} \exp -\lambda_0 x^{\kappa} dx$$

$$= 1 - \exp - [\Gamma(1+1/\kappa)R]^{\kappa} \quad (7)$$

where $R = [x]/x_{avg}$, and $[x]$ is the acceptable value of the parameter.

2. By constraining the maximum value of the parameter (right-hand constraint),

$$Q_r = \int_{[x]}^{\infty} \lambda_0 \kappa x^{\kappa-1} \exp -\lambda_0 x^{\kappa} dx \Big/ \int_0^{\infty} \lambda_0 \kappa x^{\kappa-1} \exp -\lambda_0 x^{\kappa} dx$$

$$= \exp - [\Gamma(1+1/\kappa)R]^{\kappa} \quad (8)$$

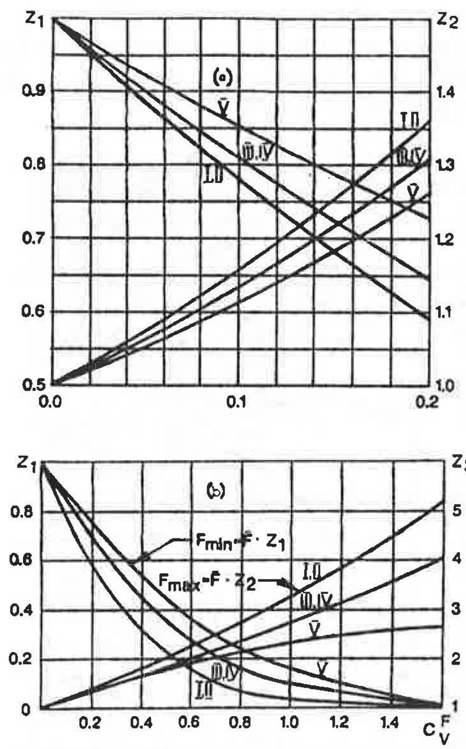

FIGURE 4 Nomograms for determining the extremal values of the parameters.

3. Simultaneous left- and right-hand constraints on, for example, the layer thickness,

$$Q_{sum} = Q_l + Q_r \quad (9)$$

The nomogram shown in Figure 5 was calculated using Equations 7 and 8.

EVALUATION OF QUALITY

Evaluation of the Quality of Individual Parameters

Each individual road parameter (roughness, thickness, width, etc.) being inspected is evaluated according to the defectiveness index Q obtained using Table 6.

If the defectiveness index Q is greater than 0.300, the road is broken up into 3-4 sections and an additional quality inspection is carried out in each section.

Evaluation of the Quality of the Road and Its Components

The overall evaluation of the pavement or the entire road is carried out by taking all of the measured parameters into account. For example, the strength of the subgrade and its transverse slope have different significance for the evaluation of the quality of the subgrade. Hence, the overall evaluation of the quality is carried out using Equation 10 and Table 7:

$$p = \sum_{i=1}^{n} \alpha_i O_i \sum_{i=1}^{n} \alpha_i \qquad (10)$$

where p is the quality parameter; O_i is a numerical estimate of the quality of each element, derived in accordance with the previous section; and α_i is a significance coefficient describing the significance of each individual parameter. From the value determined for p and from Table 7, the quality of the road and its components can now be evaluated.

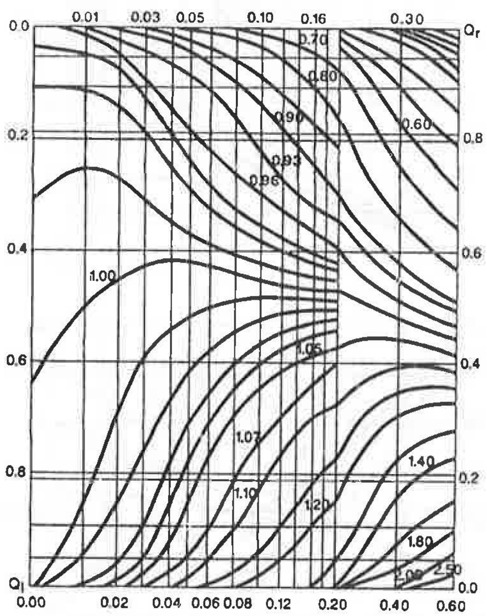

FIGURE 5 Nomogram for determining the defectiveness index in which the numbers on the curves indicate values of $R = [x]/x_{avg}$.

QUALITY CONTROL OF ROAD MAINTENANCE

The quality of road maintenance may also be evaluated on the basis of the theoretical groundwork presented in Sections 2-4.

An overall evaluation of the maintenance state of a road or all of the roads in a given region may be obtained using Equation 10 and the data in Table 7.

The numerical values of the significance coefficient α_i for various factors are given in the following list:

Factor	α
Pavement	1
Subgrade and drainage system	0.4
Bridges and overpasses	0.8
Location of road	0.7
Planting and fencing	0.4
Maintenance buildings and equipment	0.2
Protection of environment	0.25

A numerical estimate for each road element O_i is obtained in accordance with Table 6 using the defectiveness index Q.

The value of Q can be obtained by one of the following methods:

1. For the various defects in the pavement, earthen roadbed, water drainage, and so forth,

$$Q = \sum_{i=1}^{n} l_i / L \qquad (11)$$

where l_i is the length of the segment with defect i, and L is the total length of road being inspected. The value of l_i must be increased by 150 m for the pipe, sign, and vertical marking.

2. For defects in the road environment,

$$Q = m/n \qquad (12)$$

where m is the number of defective elements and n is the total number of these elements in the section being inspected.

An example of the determination of the defectiveness index Q by this method is given in Figure 6.

The number of sections required for the quality control of road maintenance may be determined from Table 8, using the arbitrary road significance index B:

TABLE 6 EVALUATION OF THE QUALITY OF THE INDIVIDUAL PARAMETERS

Q	0.000 - 0.050	0.051 - 0.100	0.101 - 0.180	0.181 - 0.300
Evaluation (O_i)	Excellent	Good	Satisfactory	Poor

TABLE 7 EVALUATION OF THE QUALITY OF THE ROAD AND ITS COMPONENTS

p	5.00 - 4.51	4.50 - 3.51	3.50 - 3.01	3.00 and less
Evaluation	Excellent	Good	Satisfactory	Poor

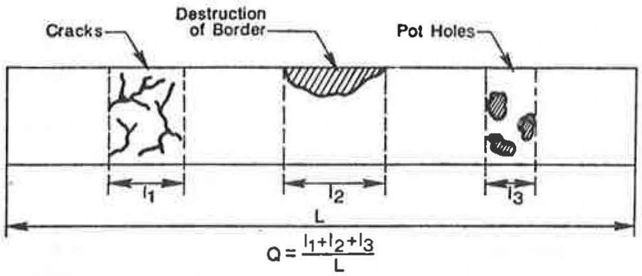

FIGURE 6 Diagram for determining the defectiveness index of the pavement.

$$B = (2L_{\text{Fed}} + 1.5L_{\text{Rep}} + L_{\text{Reg}} + L_{\text{Loc}})/(L_{\text{Fed}} + L_{\text{Rep}} + L_{\text{Reg}} + L_{\text{Loc}}) \quad (13)$$

where L_{Fed}, L_{Rep}, L_{Reg}, and L_{Loc} are the lengths of the corresponding types of roads within federal, republic, regional, and local regions.

If the organization being monitored consistently does good work, it is transferred to the weak inspection level. If the organization does bad work, the strong inspection level is used. An organization is usually monitored at the normal inspection level.

The sections to be inspected are selected in the following way using the table of random numbers (Table 4). The required number of sections for the inspection is determined using Table 8, and section numbers are selected at random using Table 4. The quality inspection is carried out only on the sections selected.

TABLE 8 NUMBER OF SECTIONS REQUIRED FOR QUALITY CONTROL OF ROAD MAINTENANCE

Level of Control	Number of Plots as a Function of Mean B					
	2.0	1.8	1.6	1.4	1.2	1.0
Weak	18	14	11	9	8	7
Normal	28	23	18	14	12	11
Strong	44	36	28	21	18	16

Example: A road organization maintains 120 mi of federal roads, 160 mi of regional roads, and 120 mi of local roads. First, the index B is determined:

$$B = (2 \cdot 120 + 160 + 120)/(120 + 160 + 120) = 1.3$$

From Table 8, the required number of sections (13) for the normal inspection level is obtained. The length of a section is (120 + 160 + 120)/100 = 4 mi.

The following 13 numbers are selected from Table 5: 76, 77, 39, 75, 26, 27, 15, 66, 64, 47, 25, 73, and 13.

The sections with these numbers are marked by asterisks in Figure 7. A rational route is then selected, and the quality inspection is carried out.

The method developed here is currently in use in all road organizations in the USSR. Approximately 8 hr of work by two technicians is required to evaluate the road quality in a region having 200 mi of roads.

CONCLUSIONS AND RECOMMENDATIONS

The method discussed in the present paper for inspecting the quality of road construction and maintenance is universal, because it allows quality control to be performed no matter how inhomogeneous the processes and parameters being inspected are. The method is easy to use in practical work and scientific research. Practical use of this method in the USSR has shown its economic merit. Conscientious use of this method makes it possible to substantially increase the quality of road construction and maintenance. The special statistical planning of the inspection allows it to be substantially decreased in size, that is, to be performed more cheaply while still being sufficiently accurate. The present inspection method is especially appropriate for final inspection, input inspection, and acceptance inspection.

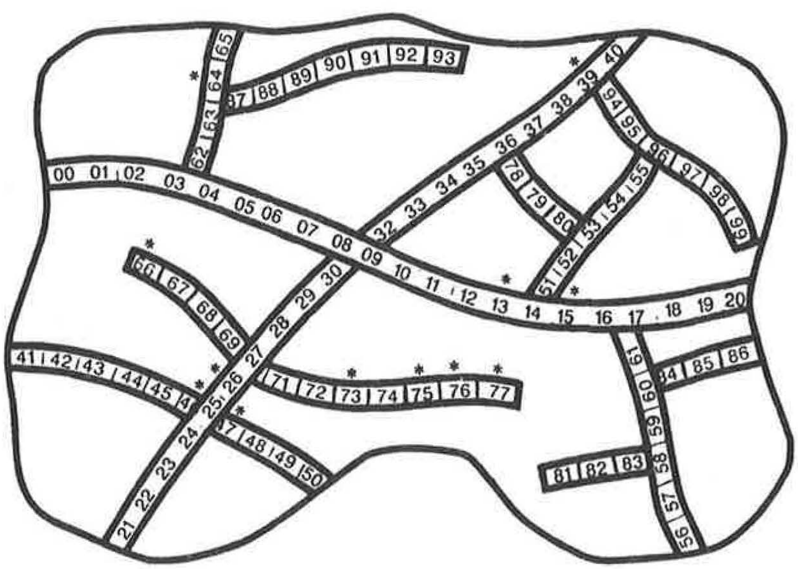

FIGURE 7 Diagram for determining the locations where the maintenance state of the road is to be evaluated.

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