DEVELOPMENT OF A SPECIFICATION TO CONTROL RIGID PAVEMENT ROUGHNESS

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During a recent study of factors influencing the riding quality of rigid pavement, compliance with the existing roughness specification was found not to ensure a smooth pavement. Because the 10-ft (3.05-m) straightedge used to check the surface can detect only large bumps, the remaining undetected roughness may result in unsatisfactory riding quality. This paper describes the development of a specification to ensure good riding quality in new pavements. The California profilograph was selected as the measurement device because it provides detailed information. Based on results of a subjective panel rating of pavement riding quality in New York State, a project average profile index of 12 in./mile (190 mm/km) and a daily average of 15 in./mile (237 mm/km) are allowed. A limit is also placed on the size of individual bumps. These limits ensure user satisfaction but can be met by paving contractors using current procedures and equipment. Responsibility for controlling roughness during paving is left to the contractor, and the state measures the quality of the completed pavement. To ensure compliance with the specification, the payment received depends on the riding quality achieved. Development of the reduced payment schedule—based on the cost of overlaying the pavement before the end of its design life—is outlined. The years of service expected are related to the initial roughness by means of equations developed in the AASHO Road Test.

•IN 1973, the New York State Department of Transportation completed a study of the causes of built-in roughness of rigid pavements in New York State (1, 2). A number of factors affecting initial riding quality of portland cement concrete pavements were identified, and several changes in design, construction methods, and specifications were made to implement the research findings. That study further found that some pavement being constructed was very rough, partly because of the factors identified and partly because the 10-ft (3.05-m) straightedge used to control roughness during construction was not capable of ensuring smooth pavement.

In 1971, the Department launched a pavement management program (which included an inventory of ridability) to establish maintenance and reconstruction needs and priorities for in-service pavements (3). Because of the emphasis this program placed on pavement roughness and the recognition that the riding quality of a pavement in service depends considerably on initial riding quality, implementation of this research included development of a new specification to ensure acceptable built-in riding quality on rigid pavements. This paper describes the development of that specification.

SELECTING A MEASURING DEVICE AND ESTABLISHING A QUALITY LEVEL

Before deciding on the form of the specification, a device for measuring pavement roughness had to be selected and a satisfactory quality level established. The final

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research report on roughness (2) included a discussion of 3 measuring devices—the fixed 10-ft (3.05-m) straightedge, the rolling 16-ft (4.88-m) straightedge, and the California profilograph—with the following conclusions:

1. The fixed straightedge is the most economical to buy, the least complex to use, and the only one that can be used on plastic concrete. Its value however, is limited to detecting large bumps during paving, and it cannot adequately control roughness of the finished pavement.
2. Although a rolling straightedge can detect more roughness than a fixed one, it too is still mainly a bump detector and provides only limited information; in addition, it cannot be operated until the concrete hardens.
3. The profilograph is more expensive to purchase and more complex to operate than the other two, but it does provide much more complete information about pavement riding qualities as well as a permanent record of surface profile.

The extra information provided by the profilograph far outweighs its disadvantages, and it was selected as the measuring device for roughness control purposes. The measure obtained with the profilograph is the Profile Index (PI), expressed in inches per mile. The data reduction technique is explained elsewhere (1). The statewide roughness measurements on the existing highway system are made with a Portland Cement Association "roadmeter" and are expressed in terms of Present Ridability Index (PRI), which is a mechanical approximation of a subjective panel rating of pavement riding quality based on an ascending scale from 0 (worst) to 5 (best). Because the initial quality level affects roughness for the entire life of the pavement, these two mechanical measurements had to be related so that initial roughness could be discussed in the same terms as that measured later with the PCA roadmeter.

In the summer of 1973, 30 rigid pavements were measured with both devices. Most test sections were approximately 0.5 mile (0.8 km) long, although a few were limited to 0.4 mile (0.32 km) by intersections or restricted sight distances that made it hazardous to operate the profilograph in traffic. Both measurements were made on a given section within a few days of each other to minimize any effects of weather or subgrade moisture condition. The results are given in Table 1 and shown in Figure 1 along with the regression line relating the two measurements. The data reveal two distinct zones in the relationship. For very low values of PI, the PRI shows little change with an increase in PI. Because of this, pavement sections with a PI less than 7 in./mile (111 mm/km) were not included in the regression analysis.

Although this zone in the relationship may at first seem puzzling, it has a logical explanation. The PRI is a mechanical estimation of the rating a pavement would receive from a panel of highway users. Below a certain level, the panel would no longer be able to discern any appreciable changes in roughness and would rate all such pavements close to 5. The profilograph, on the other hand, is a more precise instrument capable of detecting small differences even at very low levels of roughness. Therefore, while the profilograph reported measurable differences in roughness between four test sections (sites 25, 26, 27, 28), the roadmeter rated all of them very close to 5. For the other 26 test sections, however, PRI decreases as PI increases. Although the relationship shows some scatter, a correlation coefficient of 0.942 was obtained, indicating a close relationship. The 90 percent confidence limits for predicting PRI from PI by use of the regression equation are also shown in Figure 1.

Once the relationship between the profilograph and roadmeter has been determined, a desirable initial riding quality can be selected that will be consistent with both. The California Division of Highways uses a profilograph to judge the acceptability of new pavements and specifies a maximum initial PI of 7 in./mile (111 mm/km). As can be seen in Figure 1, a pavement this smooth would probably receive a rating very close to a perfect 5 by a New York State panel. Although such perfection may be ideally desirable, it could be very expensive and difficult to obtain. The roughness specification used in New York has generally limited surface deviations to ⅛ in. (3 mm) in a 10-ft (3.05-m) straightedge. Based on the preliminary results of this research, a special specification has been used on a small number of contracts. It requires mea-

Figure 1. Correlation of roadmeter and profilograph.

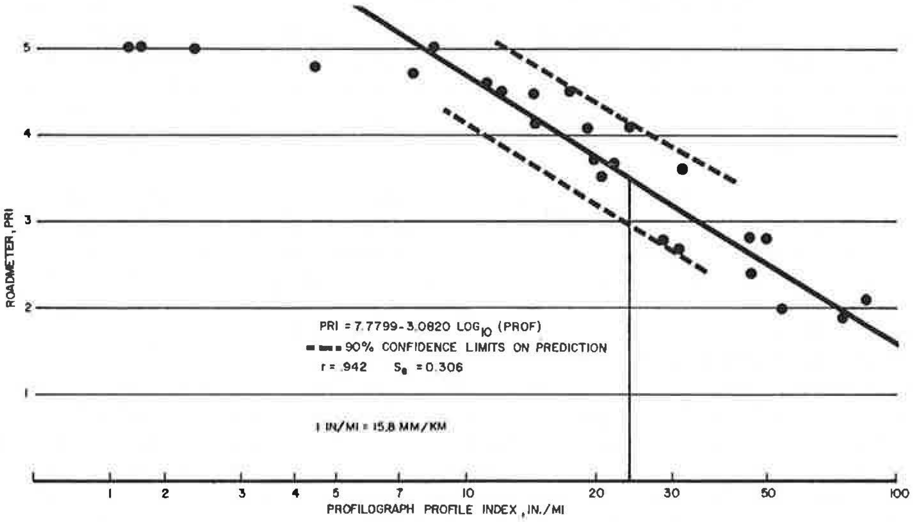


Table 1. Profilograph-roadmeter correlation sites.

		Roadmeter		Profilograph	
Site	Year Built	PRI	Length, miles	Roughness, in./mile	Length, miles
1	1941	2.10	0.52	83.9	0.50
2	1951	3.42	0.51	24.9	0.50
3	1958	3.55	0.53	20.5	0.52
4	1971	4.57	0.52	11.2	0.51
5	1941	3.58	0.50	31.9	0.49
6	1971	4.01	0.51	23.7	0.50
7	1970	4.79	0.52	4.4	0.51
8	1950	3.47	0.51	16.6	0.50
9	1926	2.09	0.40	54.5	0.40
10	1958	2.69	0.50	31.2	0.50
11	1947	2.78	0.51	28.6	0.50
12	1960	3.35	0.40	26.5	0.40
13	1940	2.81	0.51	49.1	0.41
14	1957	4.15	0.51	14.8	0.49
15	1957	4.50	0.54	12.0	0.53
16	1949	4.46	0.50	17.2	0.49
17	1970	4.71	0.53	7.5	0.52
18	1971	3.68	0.43	21.7	0.42
19	1971	4.07	0.51	18.9	0.50
20	1966	4.47	0.49	14.3	0.47
21	1966	4.45	0.50	17.3	0.49
22	1941	2.41	0.51	45.7	0.51
23	1943	1.92	0.53	74.9	0.52
24	1962	3.75	0.50	19.7	0.49
25	1967	5.00	0.51	2.3	0.50
26	1967	5.00	0.52	1.3	0.51
27	1967	5.00	0.52	1.5	0.50
28	1960	5.00	0.51	8.5	0.50
29	1958	4.15	0.51	14.4	0.50
30	1948	2.80	0.52	45.2	0.51

Note: 1 mile = 1.6 km, 1 in./mile = 15.8 mm/km.

surement of pavement roughness with the profilograph, limits the size of bumps on the profilograph trace to ½ in. in 25 ft (13 mm in 7.62 m) and limits the PI to 30 in./mile (474 mm/km). Bump occurrence, however, increases dramatically when the PI exceeds 10 to 15 in./mile (158 to 237 mm/km). The specification thus advises the contractor to strive for a PI below 12 in./mile (190 mm/km) to guard against a large number of out-of-specification bumps. In terms of PI and PRI, 7 of 9 slipformed contracts monitored under that specification were below 12 in./mile (190 mm/km) and above a PRI of 4.5 (Figure 2).

Figure 3 shows the roughness of all pavement samples measured during the research project. These are not completely representative of all paving in the state during that period, since some changes in paving procedures were made deliberately to effect the results. However, overall state results would be similar to these. Although it is evident that achieving a smooth pavement was difficult with form paving equipment, the results with slipform equipment were very good. Most slipform samples were below 12 in./mile (190 mm/km) and had PRIs above 4.

With these historical data and the known relationship between the profilograph and roadmeter, a roughness level to be sought on new construction could be selected. Three major criteria must be satisfied by this value. First, it must be smooth enough so that most highway users would express satisfaction with the riding quality of new pavements. It need not be too smooth, however, because the user cannot discern differences between very smooth pavements. Any extra effort to obtain such very smooth pavement would be wasted. Finally, the level selected must be reasonably obtainable by experienced contractors using present methods and equipment; if not, bid prices would be expected to rise sharply.

The roughness level selected to meet these criteria was 12 in./mile (190 mm/km). There is approximately a 95 percent certainty that the PRI is above 4 for a PI of 12 in./mile (190 mm/km), so most road users would judge that the pavement rides very well, and there would be no dissatisfaction with it. However, 12 in./mile (190 mm/km) is still within the zone where the rating panel can discern differences in riding quality. If the pavement is much smoother than 12 in./mile (190 mm/km), the probability of increased user satisfaction decreases rapidly. At 8 in./mile (126 mm/km), for example, there is only about a 50 percent likelihood that the PRI would be higher than at 12 in./mile (190 mm/km). Going the other way, user satisfaction decreases markedly above 12 in./mile (190 mm/km). For example, at 17 in./mile (269 mm/km), there is less than 50 percent probability that the PRI will be above 4.

Although roughness data presented indicate some difficulties in achieving 12 in./mile (190 mm/km), much of the rough pavement can be attributed to the causes reported in the research study, many of which can be corrected by the changes already implemented. Experienced contractors using slipform equipment thus would have little difficulty in meeting this specification.

In addition to the roughness level of 12 in./mile (190 mm/km) for the entire project average, 15 in./mile (237 mm/km) was selected as a maximum for any particular day's paving. Although experienced contractors can maintain a project average below 12 in./mile (190 mm/km), occasional sections may be rougher due to bad weather, equipment breakdowns, or other unavoidable circumstances. At expressway speeds, a motorist passes over an entire day's paving in less than a minute. A slightly higher roughness level for this short section thus would not have a very unfavorable effect on one's overall impression of the project. At the same time, the contractor is not unnecessarily penalized for what often are unavoidable circumstances.

A maximum limit on individual bumps is important, because large ones are noticed by all highway users and have an adverse effect on their opinion of riding quality, particularly on pavement that is otherwise very smooth. Therefore, a maximum size for individual bumps was set at ½ in. in 25 ft (13 mm in 7.62 m) on the profilograph trace. This limit has been specified on a number of paving projects under the special specification mentioned earlier and, in the opinion of Department engineers, is in the range where noticeable discomfort becomes apparent. Since the profilograph and the 10-ft (3.05-m) straightedge respond differently to bumps of different wavelengths, roughness cannot be compared directly from one to the other. However, a bump of ½ in. in 25 ft (13 mm in

Figure 2. Roughness measured under special specification.

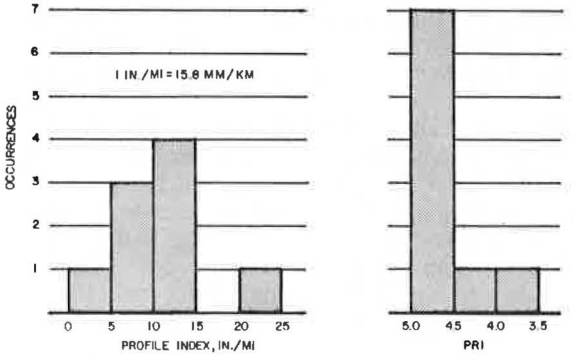
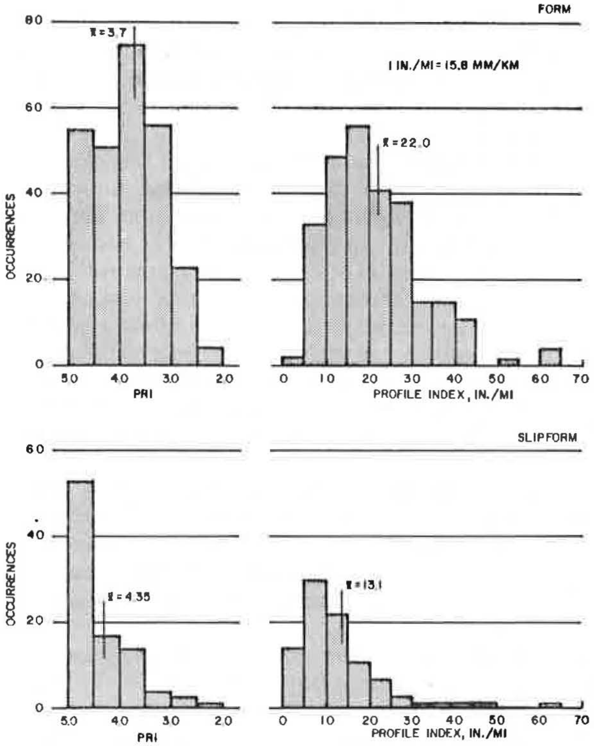


Figure 3. Roughness measured on research project.



7.62 m) on the profilograph trace is roughly equivalent to a deviation of ⅛ in. (3 mm) from a 10-ft (3.05-m) straightedge—the traditional Department specification for rigid pavement roughness. Experience of the Materials Bureau on three projects under the special specification has shown this to be a reasonable value from the standpoint of contractor compliance. On those contracts, less than 2 percent of the pavement had to be corrected to meet this figure.

To summarize, the profilograph was selected as the roughness-measuring device to be used because of the completeness of the data it provides. Average roughness for an entire paving project was set at 12 in./mile (190 mm/km), while the limit for an individual day's paving was raised to 15 in./mile (237 mm/km) to allow for unavoidable circumstances that sometimes result in rougher pavement. The limit for individual bumps was set at ½ in. in 25 ft (13 mm in 7.62 m) on the profilograph trace. These values all ensure a smooth-riding pavement but do not require a pavement smoother than can be appreciated by the user. In addition, these limits can be met by experienced contractors using modern equipment.

SPECIFICATION FORMAT

Once the riding quality level was selected, the next step was to decide on the type of specification to achieve it. Traditionally, the Department has employed a method-type specification—i.e., the contractor is told step by step how to place and finish the pavement. In addition, the finished pavement profile was limited to a maximum deviation of ⅛ in. in 10 ft (3 mm in 3.05 m). Any larger deviations had to be corrected or the contractor was forced to remove and replace the pavement.

That specification, however, has not always yielded smooth pavement in the past. In the first place, the quality level specified, ⅛ in. in 10 ft (3 mm in 3.05 m), did not ensure a smooth ride. Even when maximum bump size was not exceeded, considerable roughness could be present in the form of small bumps. In addition, the present specification has another shortcoming: The primary responsibility for quality control is retained by the state rather than being placed with the contractor. When following a step-by-step specification, the contractor cannot be expected to have complete control over the finished product. At the same time, the state can only try to control those items that are directly covered, and even the most comprehensive specification cannot cover every detail. As a result, control over product quality is not complete, and on occasion rough pavement is built in spite of the best efforts of both the contractor and state forces.

The alternative approach is to place responsibility for finished product quality primarily with the contractor, since he is doing the work and can best control the paving process. The state would protect its interests by placing only general limitations on the methods used by the contractor and specifying an acceptable quality level to be achieved in the finished pavement. A suitable acceptance sampling procedure would ensure that the desired quality level is achieved.

Since the second approach places responsibility for quality control with the contractor, the state must retain some method of ensuring compliance with the specification. The first method would be to remove most process controls but to require correction or removal of all defective material. Correction of pavement roughness by grinding the surface with a diamond cutting tool can achieve fairly good results, but this process is very expensive if more than small areas of pavement are involved (2). Therefore, grinding has not generally proved effective, in New York's experience, for general reduction of average roughness, and its use is generally reserved for correction of individual bad bumps. Complete removal and replacement of the pavement are very expensive and can be justified only in cases of extremely rough pavement.

Pavement built somewhat rougher than the desirable quality level can still provide a number of years of service, although the comfort level is lower and the total years of service would be fewer. Therefore, the second method is to base the contractor's payment on the quality of the finished pavement. This provides a strong monetary incentive to meet the specified quality level but at the same time leaves the contractor relatively free to choose the methods and equipment that he feels will best achieve the desired results. This also answers the question of what the Department should do about pavement of lower quality, since it can now be bought at a bargain price.

Theoretically the reduced payment could be applied to pavement of any riding quality, but it is not desirable to accept very rough pavement at any price. The complaints generated would be very serious if the pavement were too rough, and the available life before resurfacing would be very short; any economic advantage of the lower price would therefore be lost. In this case, the roughness level chosen as an absolute maximum is 36 in./mile (569 mm/km). At that point, the PRI would most likely be between 2.4 and 3.7, with a mean value of 3.0. Certainly, pavement at that level would not feel very smooth to most highway users and would even border on being unsatisfactory in some cases. Therefore, any pavement rougher than 36 in./mile (569 mm/km) will not be accepted and must be removed and replaced by the contractor at no cost to the state.

In conclusion, the most effective means of controlling quality is to make it the responsibility of the contractor. To ensure that he provides the desired quality level, his payment will be based on the riding quality of the finished pavement.

REDUCED PAYMENT CALCULATION

Several approaches were considered in establishing the payment schedule. The easiest would be a completely arbitrary schedule, the only consideration being that the penalty is sufficiently harsh so the contractor will try very hard to comply with the specification. No weight would be given to the amount of reduced comfort experienced by the pavement user or the reduction in pavement life. This, however, has two serious drawbacks. First, because it lacks a rational basis, it is difficult to justify the figures chosen and may not be accepted by the paving industry. Second, the penalty chosen may be either too severe or not severe enough, resulting in either increased bid prices or ineffective roughness control.

The second approach is the opposite: The payment schedule would be based entirely on the degree of comfort afforded the motorist and the pavement life provided. This is completely rational and seemingly completely fair but is very difficult to implement. It is possible to measure the initial ridability and predict the years of service to be provided, but overall quality of service for the life of the pavement is very difficult to predict. Therefore, the reduced payment schedule would still have to be based on some arbitrary assumptions, which would be difficult to derive.

A third approach, used here, bases the reduced payment on the extra cost of rehabilitating the pavement earlier than was assumed in its initial design. This has the advantage of being rationally based on performance of the pavement, with only a minimum of assumptions required to derive the payment schedule. Although it does not consider that motorists using the pavement will be subjected to a rougher ride until the pavement is overlaid, it does consider what may perhaps be the most important problem in pavement management—the expenditure of extra capital construction funds at an earlier date than originally planned. If funds are not available to resurface a pavement when it reaches the terminal PRI, the motorist will be subjected to even greater discomfort.

To compute the payment schedule, the initial riding quality was related to the number of years of service provided before reaching the terminal PRI. The equations developed at the AASHO Road Test (4) were used as follows:

$$P = C_0 - (C_0 - C_1)\left(\frac{w}{W}\right)^{\beta}$$

where

P = PRI at the time in question,

C_0 = initial PRI,
C_1 = terminal PRI,
W = load applications to C_1,
w = load applications to P, and
β = a constant depending on certain pavement characteristics.

For these calculations, the following assumptions were made:

$C_0 = 4.0$
$C_1 = 2.0$
$\beta = 2.0$

To make the equation general to fit any pavement, W was taken as 100 percent and w as a lesser percentage. This is based on the assumption that each pavement is designed to carry 100 percent of its design traffic load before reaching the terminal PRI at the end of the design life. Although actual design traffic load will vary from pavement to pavement, the design thickness is selected to last for the design life of the pavement, regardless of traffic.

Figure 4 shows this equation. The upper solid curve is a pavement starting at a PRI of 4.0 and carrying 100 percent of its design traffic before falling to a PRI of 2.0. The lower broken curve is identical except it started at a lower initial PRI, retained the same vertical offset from the upper curve for the life of the pavement, and reached a PRI of 2.0 before the end of its design life.

Some other assumptions were necessary in these calculations. The design life of a pavement with initial PRI of 4.0 was assumed to be 15 years to the construction of the first overlay at a PRI of 2.0; this is the design life currently used by the Department. The life of the overlay was taken as 8 years, and it was assumed to deteriorate on a straight-line basis. The cost of the original pavement was assumed to be $10/yd^2 (\$12/m^2). Finally, the time cost of money was set at 6 percent annually (1.5 percent quarterly).

The calculations involved in deriving the payment schedule for each level of roughness are given in Table 2. For the sake of clarity, these calculations will be explained here for one level of roughness—24 in./mile (380 mm/km). Calculations for this value are underlined in the table. Column 1 lists the measured profilograph roughness, 24 in./mile (380 mm/km) for our example, and column 2 gives the predicted PRI from the regression equation. Referring to Figure 1, we see that the corresponding PRI is 3.53. Column 3 gives the PRI that is 95 percent certain to be exceeded for the particular roughness level, which is equivalent to the lower 90 percent confidence limit in Figure 1. In this case, the value is 3.00. By using this value as the starting point in the analysis rather than the value predicted by the regression equation, we have much greater confidence that the pavement life calculated will be reached or exceeded. Column 4 is the numerical difference between the predicted PRI and 4.0, which for our example is 0.47. Assuming that the y residuals about the regression line are normally distributed, which seems reasonable for these data, we divide the column 4 value by the standard error (0.306) to obtain the value in column 5—1.54 in the example. From a normal distribution table, one can determine the proportion of the total area under the curve below this value. This proportion, appearing in column 6, is 0.9382 in our example. In other words, based on the scatter of data obtained in this correlation, for an initial roughness of 24 in./mile (380 mm/km), the probability is 0.9382 that the PRI as measured by the PCA roadmeter will be below 4.0.

By constructing curves parallel to those shown in Figure 4, one can estimate the percentage of design life (15 years) that would be achieved for any initial PRI. For our example, the dashed curve starts at an initial PRI of 3.0 and results in an expected life of 71.5 percent of the design life (column 7). This percentage is converted to 10.72 years in column 8 and 43 quarters in column 9. Column 10 is the present-worth factor used to express the value of money at the end of the pavement's predicted life as a

Table 2. Reduced payment calculation.

Measured Profile Index, in./mile (1)	PRI Predicted (2)	PRI 95 Percent Confidence (3)	PRI 4.0 Minus Predicted (4)	PRI Z Statistic (5)	PRI Probability PRI <4.0 (6)	Percent Design Life Expected (7)	Expected Life Years (8)	Expected Life Quarters (9)	Present-Worth Factor (10)
10	4.70	4.15	-0.70	-2.29	0.0110	100.0	15.00	60	–
11	4.57	4.02	-0.57	-1.86	0.0392	100.0	15.00	60	–
12	4.45	3.90	-0.45	1.47	0.0708	99.0	14.85	59	0.4154
13	4.35	3.81	-0.35	-1.14	0.1271	96.5	14.47	58	0.4217
14	4.25	3.71	-0.25	-0.82	0.2061	93.5	14.02	56	0.4344
15	4.16	3.62	-0.16	-0.52	0.3015	91.0	13.65	55	0.4409
16	4.07	3.53	-0.07	-0.23	0.4090	88.5	13.27	53	0.4543
17	3.99	3.45	+0.01	+0.03	0.5120	86.0	12.90	52	0.4611
18	3.91	3.38	+0.09	+0.29	0.6141	83.0	12.45	50	0.4750
19	3.84	3.31	+0.16	+0.52	0.6985	81.5	12.22	49	0.4821
20	3.77	3.24	+0.23	+0.75	0.7734	79.0	11.85	47	0.4967
21	3.71	3.18	+0.29	+0.95	0.8289	77.0	11.55	46	0.5042
22	3.64	3.11	+0.36	+1.17	0.8790	75.5	11.32	45	0.5117
23	3.58	3.05	+0.42	+1.37	0.9147	73.5	11.02	44	0.5194
24	3.53	3.00	+0.47	+1.54	0.9382	71.5	10.72	43	0.5262
25	3.47	2.94	+0.53	+1.73	0.9582	69.0	10.35	41	0.5431
26	3.42	2.89	+0.58	+1.90	0.9713	67.5	10.12	40	0.5513
27	3.37	2.84	+0.63	+2.06	0.9803	65.5	9.82	39	0.5595
28	3.32	2.79	+0.68	+2.22	0.9868	63.5	9.52	38	0.5679
29	3.27	2.74	+0.73	+2.39	0.9916	61.0	9.15	37	0.5764
30	3.23	2.70	+0.77	+2.52	0.9941	59.5	8.92	36	0.5851
31	3.18	2.64	+0.82	+2.68	0.9963	58.0	8.70	35	0.5939
32	3.15	2.61	+0.85	+2.78	0.9973	56.0	8.40	34	0.6028
33	3.10	2.56	+0.90	+2.94	0.9984	54.5	8.17	33	0.6118
34	3.06	2.52	+0.94	+3.07	0.9989	52.5	7.88	32	0.6210
35	3.02	2.48	+0.98	+3.20	0.9993	50.5	7.57	30	0.6398
36	2.98	2.44	+1.02	+3.33	0.9996	48.5	7.27	29	0.6494

Measured Profile Index, in./mile (1)	Present Value of Overlay, dollars (11)	Remaining Overlay Life, quarters (12)	Overlay Salvage Value, dollars (13)	Present Value of Overlay Salvage, dollars (14)	Net Overlay Cost, dollars (15)	Net Cost Times Probability PRI <4.0, dollars (16)	Payment Reduction, percent (17)	Grouped Payment Reduction, percent (18)	Payment Schedule, percent Entire Project (19)	Payment Schedule, percent Single Day (20)
10	–	–	–	–	–	–	–	0.0	100.0	100.0
11	–	–	–	–	–	–	–			
12	1.66	31	3.87	1.62	0.04	0.0028	0.02			
13	1.69	30	3.75	1.56	0.13	0.0165	0.16	2.0	98.0	100.0
14	1.74	28	3.50	1.46	0.28	0.0577	0.58			
15	1.76	27	3.37	1.41	0.35	0.1055	1.06			
16	1.82	25	3.12	1.30	0.52	0.2127	2.13	5.5	94.5	98.0
17	1.84	24	3.00	1.25	0.59	0.3020	3.02			
18	1.90	22	2.75	1.15	0.75	0.4606	4.61			
19	1.93	21	2.62	1.10	0.83	0.5798	5.80	9.0	91.0	94.5
20	1.99	19	2.37	0.99	1.00	0.7734	7.73			
21	2.02	18	2.25	0.94	1.08	0.8952	8.95			
22	2.05	17	2.12	0.89	1.16	1.0196	10.20	12.5	87.5	91.0
23	2.08	16	2.00	0.83	1.25	1.1434	11.43			
24	2.11	15	1.87	0.78	1.33	1.2478	12.48			
25	2.17	13	1.62	0.68	1.49	1.4277	14.28	16.0	84.0	87.5
26	2.20	12	1.50	0.63	1.57	1.5249	15.25			
27	2.24	11	1.37	0.57	1.67	1.6371	16.37			
28	2.27	10	1.25	0.52	1.75	1.7269	17.27	19.5	80.5	84.0
29	2.30	9	1.12	0.47	1.83	1.8146	18.15			
30	2.34	8	1.00	0.42	1.92	1.9087	19.09			
31	2.38	7	0.87	0.37	2.01	2.0026	20.03	23.0	77.0	80.5
32	2.41	6	0.75	0.31	2.10	2.0943	20.94			
33	2.45	5	0.62	0.26	2.19	2.1865	21.86			
34	2.48	4	0.50	0.21	2.27	2.2675	22.68	26.0	26.0	77.0
35	2.56	2	0.25	0.10	2.46	2.4583	24.58			
36	2.60	1	0.12	0.05	2.55	2.5490	25.49			

proportion of its present value, based on the 1.5 percent quarterly time cost of money. The overlay cost of $\$4/\text{yd}^2$ ($\$4.80/\text{m}^2$) at the end of the expected life is multiplied by the present-worth factor to obtain the present value for the overlay given in column 11. In this case, the present worth factor of 0.5262 results in a present value for the overlay of $2.11.

Because an overlay's life is assumed to be 8 years, it may have some useful life remaining at the end of the 15-year analysis period. Based on a straight-line deterioration of the overlay, its remaining life in quarters and salvage value in dollars at that time are given in columns 12 and 13, which in this example are 15 quarters, with a value of $1.87. Column 14 is the present value of column 13, $0.78. Column 15 is the net cost of the overlay in terms of present value, which is simply the initial cost (column 11) less the salvage value (column 14). For this example, this amount is $1.33. Because the predicted life of the pavement was based on the lower confidence limit, there is 95 percent certainty that this cost will not be exceeded if the pavement deteriorates according to the curve in Figure 4.

Using this value as the basis of the reduced payment would provide high assurance of regaining any losses caused by reduced pavement life, but such an approach may be unduly harsh. Column 6 lists the probability that reduced pavement life would occur because of initial PRI less than 4.0. The cost of reduced pavement life can be combined with the chance of its actually occurring to obtain the probable cost to the state. This value, the product of columns 6 and 15, appears in column 16—$1.25 for the example. Column 17 is that cost expressed as a percentage of the original pavement cost, $\$10/\text{yd}^2$($\$12/\text{m}^2$)—12.5 percent in this case.

To lessen difficulties in administering the specification that might arise from minor measurement and data reduction difficulties, the reduced payment schedule is set up for roughness intervals of 3 in./mile (47 mm/km). To obtain the reduced payment for each interval, the percentages in column 17 were plotted in Figure 5. Since several roundings were applied in the calculations, there are small deviations from the straight line. The actual reduction to be used for each roughness interval was fitted to the line as seen in the figure. The reductions in payment appear in column 18 and the percentage to be paid in column 19. Since daily roughness averages may reach 15 in./mile (237 mm/km) instead of 12 in./mile (190 mm/km), the contract payment schedule was offset by one roughness group to obtain the daily payment schedule in column 20. For the sample calculations, the reduction in payment is 12.5 percent for contract average roughness up to 24 in./mile (380 mm/km), which is equivalent to a payment of 87.5 percent of the bid price. For a single day's paving, roughness up to 24 in./mile (380 mm/km) would receive a 91 percent payment.

SPECIFICATION HIGHLIGHTS AND USE

The main points of the proposed specification are noted here, and three examples are given to show how it will be applied. The specification is an addendum to the New York State Department of Transportation Standard Specifications of January 2, 1973, and contains appropriate references to those specifications[1]. Its main features are as follows:

1. It applies only to main-line paving. Ramps, acceleration and deceleration lanes, and bridge approaches and decks are excluded, since meeting the proposed limits would be very difficult in those areas. Accepting a lower riding quality in those isolated areas is preferable to paying the high cost of meeting the limits.
2. The profilograph for roughness measurements will be provided by the contractor and operated by state personnel. Each day's production will be profilographed in each wheel path after paving, and the contractor will be informed of results, allowing him to take corrective action if necessary.

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[1] The proposed specification is available in Xerox form at cost of reproduction and handling from the Transportation Research Board. When ordering, refer to XS-56, Transportation Research Record 535.

Figure 4. Deterioration in pavement serviceability with traffic.

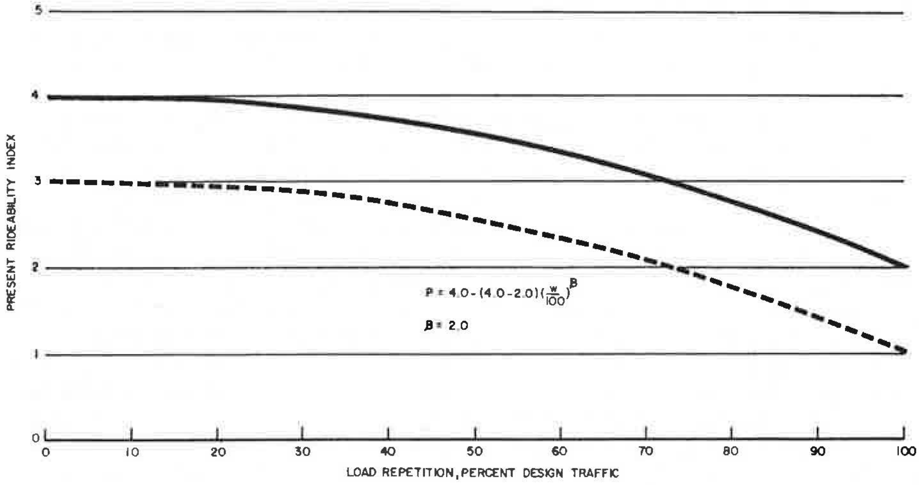

Figure 5. Reduced payment schedule.

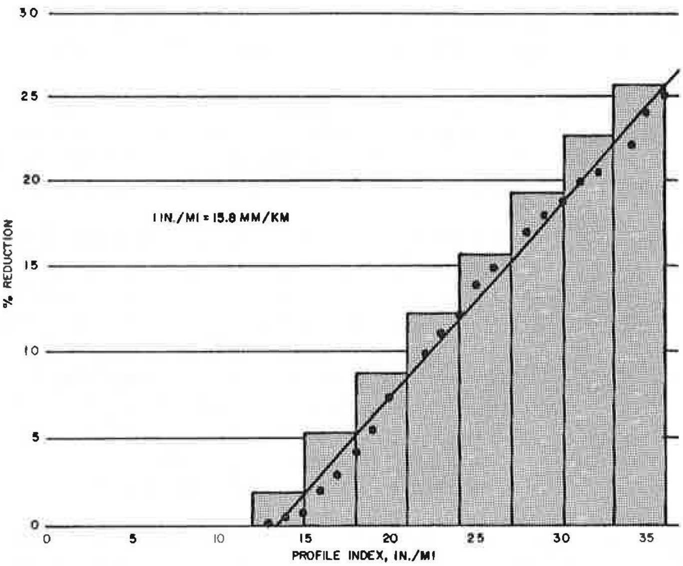

Table 3. Example 1, application of proposed specification.

Day	Final Profile Index, in./mile	Length, miles
1	13.1	0.85
2	12.7	0.76
3	10.5	1.02
4	15.2	0.97
5	18.3	0.35
Total		3.95

Contract average final profile index = 13.33 in./mile (210 mm/km).

Table 4. Example 2, application of proposed specification.

Day	Final Profile Index, in./mile		Length, miles	
1	9.7		0.65	
2	8.6		0.97	
3	17.2	10.3	0.10	0.95
4	9.5		0.85	
5	16.5		0.57	
6	11.2		0.92	
Total			4.06	

Contract average final profile index = 10.87 in./mile (172 mm/km).

Table 5. Example 3, application of proposed specification.

Day	Final Profile Index, in./mile	Length, miles
1	7.2	0.95
2	5.1	0.62
3	10.3	0.73
4	11.4	1.05
5	14.2	1.02
Total		4.37

Contract average final profile index = 10.66 in./mile (168 mm/km).

3. All control of the longitudinal profile during paving will be the responsibility of the contractor. State personnel, however, will continue to check the transverse profile with a straightedge during paving, which must still meet a tolerance of ⅛ in. in 10 ft (3 mm in 3.05 m).

4. Bumps on the profile trace will be checked with a template to determine compliance with the limit of ½ in. in 25 ft (13 mm in 7.62 m). Any bumps exceeding that limit must be corrected by grinding or by removal and replacement of the pavement. After correction, the affected areas will be remeasured with the profilograph.

5. A final profile index is computed for the entire main-line pavement on the project, and for each separate day's paving, after all bumps are corrected. A day's paving of less than 1,000 ft (305 m) will be grouped with the following day for purposes of this specification, to avoid penalizing the contractor for small areas of rough pavement that result from uncontrollable circumstances such as rain or equipment breakdown.

6. The project average profile index must be below 12 in./mile (190 mm/km), and each day's paving must be below 15 in./mile (237 mm/km). If the project average is above 12 in./mile (190 mm/km), all pavement will receive the same reduced payment shown in the specification. If the project average is below 12 in./mile (190 mm/km), each day's profile index must still be below 15 in./mile (237 mm/km). Any day exceeding 15 in./mile (237 mm/km) will receive a reduced payment in accordance with the specification. If any day exceeds 36 in./mile (569 mm/km), the pavement must be removed and replaced at the contractor's expense.

The following examples show how this specification would be applied. The profile indexes used in these examples were measured after all bumps were corrected and are final profile indexes.

In the first example (Table 3), because the final profile index exceeds 12 in./mile (190 mm/km), the contractor would receive a reduced payment for the entire project. The contract average—13.3 in./mile (210 mm/km)—falls between 12.1 and 15.0 in./mile (191 and 237 mm/km), so the contractor would receive a 98.0 percent payment for the entire main-line pavement (Table 2, column 19).

In the second example (Table 4), production for the third day was less than 1,000 ft (305 m) in length, so it was lumped with the fourth before applying the specification. For this example, the contract average is less than 12.0 in./mile (190 mm/km), so the entire contract is not subject to reduced payment. Each individual day must still meet the 15 in./mile (237 mm/km) limit. Day 3, which was less than 1,000 ft (305 m) in length, was combined with day 4. Because the resulting profile index for the 2 days is below 15.0 in./mile (237 mm/km), no penalty results. Day 5, which exceeded 1,000 ft (305 m) in length, has a profile index of 16.5 in./mile (261 mm/km). Therefore, a reduced payment must be paid for that day. According to the specification, the payment for a profile index between 15.1 and 18.0 in./mile (239 and 284 mm/km) for a single day is 98 percent (Table 2, column 20).

In the third example (Table 5), the contract average is below 12.0 in./mile (190 mm/km), and no individual day's average exceeds 15.0 in./mile (237 mm/km). Therefore, the contractor would receive full payment for the entire pavement.

SUMMARY

The research on rigid pavement roughness conducted by the New York State Department of Transportation confirmed that the present specification does not ensure the construction of smooth pavement. A new specification has thus been developed, shifting the emphasis for quality control to the contractor and providing for acceptance sampling of the completed pavement by the state. The California profilograph was selected as the roughness-measuring device, since it provides more detailed information than the 10-ft (3.05-m) straightedge presently specified.

The initial riding quality levels selected were based on considerations of what can realistically be achieved and what is necessary to ensure user satisfaction and reasonable pavement life. Finally, a reduced payment schedule based on the cost of overlaying rougher payment at an earlier age was selected as the most effective means of enforcing the quality levels specified.

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This paper's contents reflect the author's opinions, findings, and conclusions and not necessarily those of the New York State Department of Transportation or the Federal Highway Administration.

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