Kansas Experience with Smoothness Specifications for Concrete Pavements

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Because it affects road users directly, smoothness, or riding comfort, determines the quality of newly constructed pavements. There is a growing interest in the industry in attaining increasingly smoother pavement surfaces. Smoothness specifications for portland cement concrete pavements (PCCP) now in effect in Kansas have evolved through applications over the last 8 years. Pavement profiles of short wavelengths and smaller amplitudes than the industry-accepted 5.1 mm (0.2 in.) can decrease the ride quality of pavements. This experience has led the Kansas Department of Transportation (KDOT) to eliminate the blanking band width in the profilograph trace reduction process. The implementation of this zero or null blanking band was successful and has resulted in better-quality pavements. The latest proposed specifications will increase the amount of bonus that can be achieved but might result in more grinding unless the PCCP pavers were able to improve the pavement smoothness in the middle (full-pay/grind) ranges. An analysis of effect of as-constructed smoothness on the roughness history of pavements has shown that the ride quality over the service life of pavements is highly dependent on the smoothness achieved during construction. Limited cost analysis has shown an increasing amount of bonus achieved in PCCP construction over the last few years, indicating quality paving.

Pavement smoothness or roughness can be described by the magnitude of profile irregularities and their distribution over the measurement interval. The road surface smoothness on newly constructed pavement is a major concern for the highway industry. Because it affects the road users directly, this smoothness, or riding comfort, is a measure of the quality of the newly constructed pavements. According to Hudson (*1*), the primary purpose for smoothness measurement is to maintain construction quality control. There is a growing interest in the industry for attaining increasingly smoother pavement surfaces. Results from a 1992 NCHRP study show that of the 22 states reporting, 91 percent utilized smoothness criteria on new pavement construction (*2*). A 1990 NCHRP Synthesis study (*3*) showed that of the 36 states reviewed, 80 percent used smoothness criteria on new pavement construction. The increasing trend in the use of ride quality specifications is also evidenced by the 1992 study in which respondents from 21 states out of 25 queried believe that there will also be a future increase in ride quality requirements. The 1987 AASHTO survey results showed that 53 percent of the states using profilographs for acceptance of concrete pavements used incentive and disincentive specifications (*4*). The incentive/disincentive values in smoothness specifications typically ranged from 1 to 5 percent of the bid item price, with 31 percent of these states reporting allowable incentives up to 5 percent. The relatively high incentives now possible with many of the profilograph specifications place an ever-increasing burden on the measurement and data reduction processes. Variability in test results can significantly affect contractor payments (*5*).

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DEVELOPMENT OF PORTLAND CEMENT CONCRETE PAVEMENT SMOOTHNESS SPECIFICATIONS

In 1985 the Kansas Department of Transportation (KDOT) selected a 7.63-m (25-ft) California-type profilograph using the 5.1-mm (0.2 in.) blanking band for evaluation of the profilogram for determining smoothness of portland cement concrete pavement (PCCP) construction (*6*). In 1985 the first three PCCP projects having smoothness requirements were constructed. The specifications implemented on these projects are shown in Table 1. However, the incentive clauses were not exercised. Profilograph measurements were taken on each wheelpath. The profilograph results in terms of profile roughness index (PRI) on 0.16-km (0.1-mi) intervals on these projects were analyzed and are shown in Table 2. The first two projects had a high percentage of sections in the bonus range, indicating smoothness of 0 to 63 mm/km (0 to 4 in. mi) was practical and easily achievable. The relatively high percentage of sections in the penalty range on the I-70 project was caused by contractor negligence.

The eastbound lanes of the I-70 project paved in 1986 by the same contractor were remarkably smoother. The profilograph results showed that on the eastbound lanes there were 84 sections with 41 sections (49 percent) in the bonus range, 41 sections (49 percent) in the full-pay range, and 2 sections (2 percent) in the penalty zone. These figures showed a significant improvement in 1 year. These projects showed that the smoothness specifications shown in Table 1 were achievable and resulted in better-quality pavements. In 1990 the specifications shown in Table 3 were adopted as standards for control of concrete pavement smoothness in the state of Kansas.

REVISED TRACE REDUCTION PROCEDURE

In 1990 there was a noticeable high-frequency vibration on a PCCP reconstruction project on I-70. However, this vibration was not noticed for another concurrent new PCCP project on I-470. A closer review of the profilograph traces on these projects showed that on the I-70 project there was a significantly consistent sine

TABLE 1 Schedule for Adjusted Payment for PCCP (Special Provision 80P-232)

Profile Index millimeter per kilometer per 0.16 km segment	Price Adjustment Percent of Contract unit bid price
190 or less	100
191 to 206	98.0
207 to 222	96.0
223 to 238	90.0
238 or higher	Corrective work required or replace

Incentive was based on the initial profile index and on a section which was a break in paving such as a bridge or day's end joint or other interruption.

0 to 64 millimeter per kilometer 105.0 Percent of unit bid

TABLE 2 Specification Compliance of 1985 Projects

Roadway	No. of 0.16 km sections	Compliance with specified PRI (mm/km)					
		Bonus (0 - 64)	(%)	Full Pay (65 -191)	(%)	Penalty (>191)	(%)
US 73*	80	24	30	51	64	5	6
US 50 EB**	99	64	65	28	28	7	7
US 50 WB**	103	64	62	26	26	13	12
I-70 WB*	94	5	5	43	46	46	49
All 1985	376	157	42	148	39	71	19

* PRI values were average of four traces (one trace in each wheel path)
** PRI values were average of two traces (one trace in each wheel path)
Note: 1 in = 25.4 mm, 1 mile = 1.6 km

TABLE 3 Schedule for Adjusted Payment for PCCP (1990 Specification 502.06)

Profile Index millimeter per kilometer per 0.16 kilometer segment	Price Adjustment Percent of Contract unit bid price
48 or less	106
49 to 64	103
65 to 159	100
160 to 191	96
192 to 222	92
223 to 238	90
239 or more	88 (Corrective Work required or replace)

Note: 1 in = 25.4 mm
1 mile = 1.6 km

wave cyclic oscillation of about 2.44-m (8-ft) spacing and with 5.1-mm (0.2-in.) amplitudes, as shown in the example trace of Figure 1. Most of these surface deviations were covered up by the 5.1-mm (0.2-in.) blanking band during trace reduction. On the I-470 project, the oscillation waves had a spacing of about 9.14 m (30 ft) and an amplitude of about 5.1 mm (0.2-in.) (also shown in Figure 1), which were, again, covered up by the 5.1-mm (0.2-in.) blanking band during trace reduction. This issue of the effects of short wavelengths on PRI was tied to the question about the proper blanking band width. It is interesting to note that this issue is not new and dates back to the mid-sixties when General Motors decided to use a 2.54-mm (0.1-in.) blanking band for the construction of one of their test facilities, even though the practice of using the 5.1 mm (0.2-in) blanking band was then well established. According to the engineers of General Motors (*7*),

> On-site evaluations of the roughness of recently constructed California roads indicated that, while they exhibited very few long wavelength irregularities, they seemed to have a considerable amount of short wavelength roughness of very low amplitude. This is felt in the vehicle more as a sensation of wheel motion than of noticeable road roughness. It was reasoned that this problem could be caused by the existence of many small-amplitude bumps that might well lie within the 5.1 mm (0.2 inch) tolerance California allows. In an attempt to minimize this, the Proving Ground decided to reduce this band to 2.54 mm (0.1 inch), but otherwise adopt the California method.

The blanking band concept was originally developed as a convenient method for analyzing mechanical profilograph traces 30 years ago. This makes the resulting PRI an artifact of the test and data reduction procedures. According to Hveem (*8*), developer of the profilograph:

> While the profile index appears to be reasonably satisfactory for use in specification, it fails to differentiate between bumps or irregularities of different shape and of different lengths. This numerical expression does not adequately emphasize the annoyance in terms of

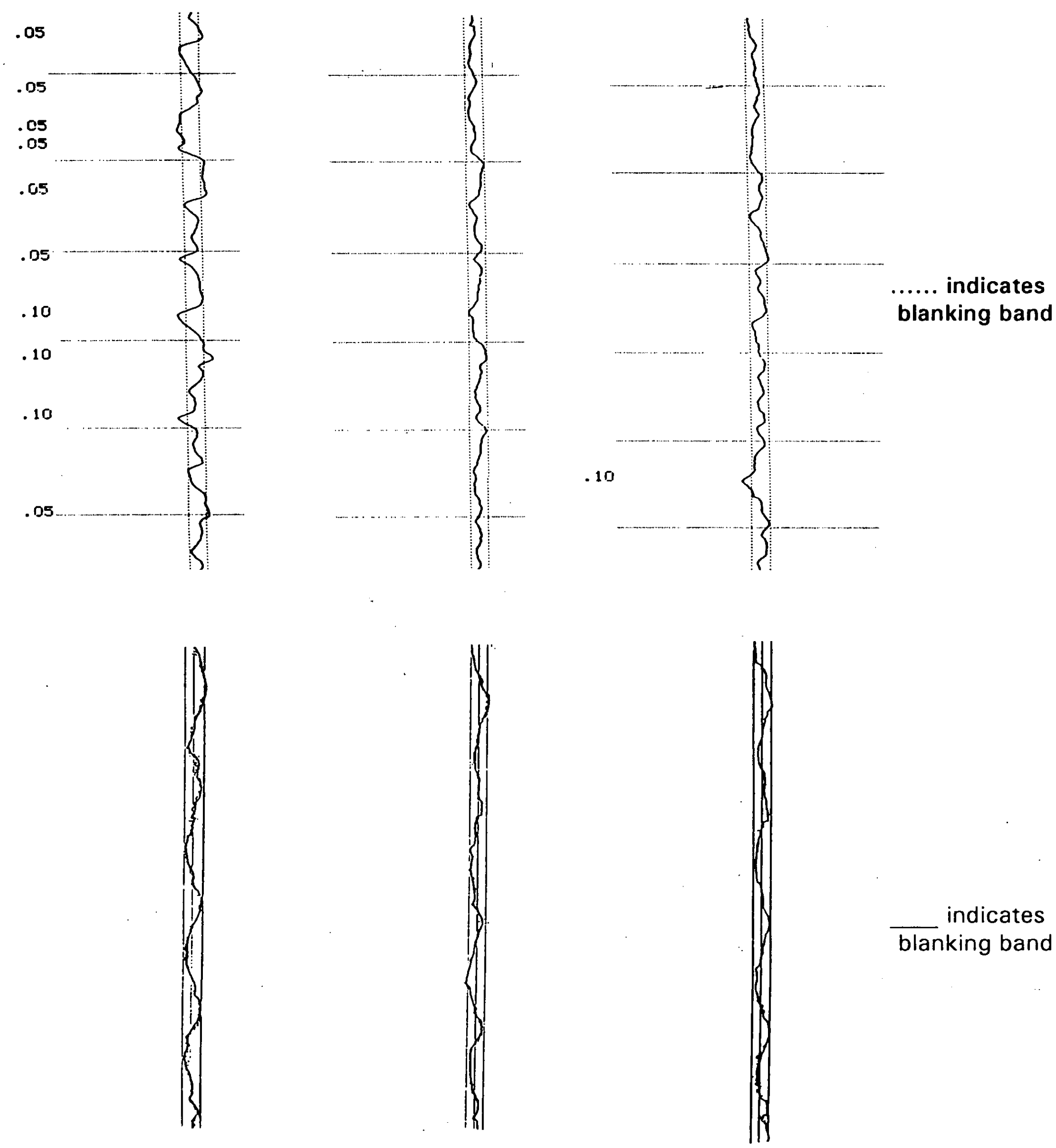

FIGURE 1 Profilograph traces from I-70 and I-470 projects: sample traces from I-70 Geary County (*top*) and I-70 Shawnee County (*bottom*) (*6*).

riding qualities generated by badly faulted pavement for example. A somewhat more elaborate system of deriving a numerical index will be necessary if it becomes important to assign numbers to existing highways or airfields.

Research conducted by the Pennsylvania Transportation Institute (*9*) has shown that the blanking band concept is not acceptable for smoothness levels of less than 110 mm/km (7 in./mi).

The I-70 and I-470 projects of 1990 prompted KDOT to experiment with the blanking band width to quantify the apparent visual difference of profilograph traces on these projects. It was decided to use a zero blanking band width or null blanking band. The null blanking band is nothing but a reference line usually placed approximately at the center of the trace having the line equally dividing the scallops above or below the center line. In addition to these projects, traces from all the PCCP projects on which profilographs had been used in 1990 were reanalyzed using the null blanking band. Tables 4 and 5 show the results of this comparative study of blanking band widths on I-70 and I-470 sections, and all 740 of the 0.16-km sections.paved in 1990. Results from Table 5 indicate that the majority of the sections on the I-70 projects were in the bonus range when analyzed with the 5.1-mm (0.2-in.) blanking band even though the ride quality on this project was perceived by the state personnel to be very poor. As shown in Table 5, the use of zero blanking band results in a wider distribution of PRI values and movement of data points away from the range of 0 to 158 mm/km (0 to 10 in./mi) [proposed to replace the previously used range of 0 to 64 mm/km (0 to 4 in/mi) or bonus range]. This apparently indicates that achieving bonus would be harder with the zero blanking band. However, it is beyond any doubt that this improved the ability of the profilograph to measure PCCP smoothness quality, taking into account the lower-quality ride produced by roughness waves of short wavelengths and smaller amplitudes with no increased demand or hardship on the contractor or the inspector. Only the trace reduction procedure was changed, and the entire procedure for using the zero blanking band was included in KT-461, the revised KDOT test method for operation of a profilograph and trace reduction (*10*). On the basis of these results, a new set of special provisions (90P-111) were incorporated for the 1992 construction projects. This required use of the null blanking band (0.25 mm or 0.01 in. for the computerized profilographs) for profilograph trace reduction and established separate limits on the calculated PRI for roadways with posted speed limits higher or lower than 72 km/hr as shown in Table 6. The profilograph results for the 1990 through 1992 projects with zero blanking band are shown in Table 7. The results indicate almost no change in the number of sections in the three broad ranges. The PRI limits required by the specifications were easily achievable with the current practice of paving. One of the concerns for the "null" blanking band was whether the repeatability of trace reduction could be achieved with this type

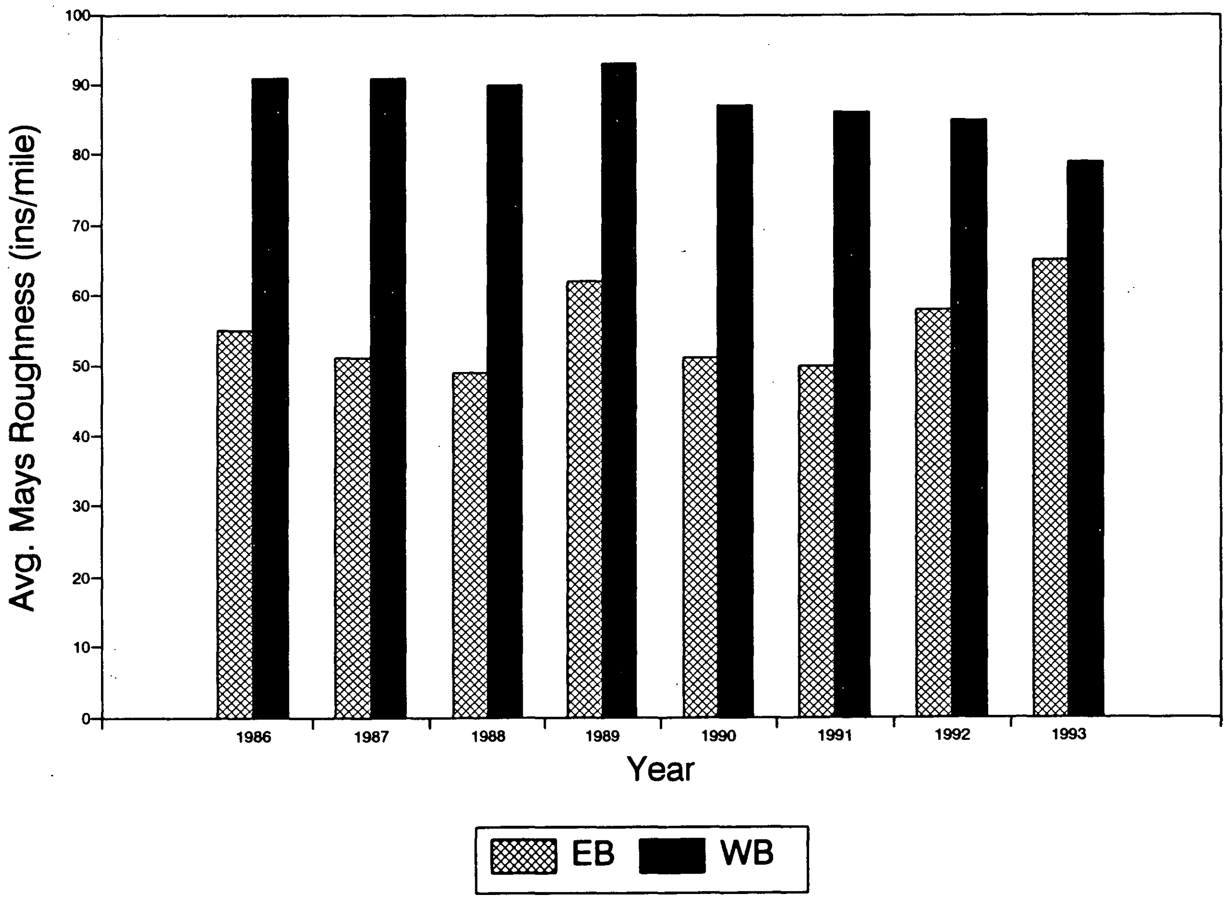

FIGURE 2 Mays roughness history of 1985 I-70 PCCP project, MP 9.27–17.00.

of blanking band. KDOT, in cooperation with Kansas State University, has fully automated the process of trace reduction using a user-friendly personal computer-based methodology (*10*).

REVIEW OF PROPOSED SPECIFICATIONS FOR 1993

Currently, special provisions 90P-111-R1 shown in Table 8 are being proposed for 1993. The maximum amount of bonus has been increased from 6 percent of the bid item price to 8 percent; however, the full-pay range has been narrowed to include slightly more rigid grind-back provisions. Table 9 compares the compliance with the proposed 1993 specifications using data from the 1992 projects for roadway segments with posted speed limits greater than 72 km/hr. It is evident that the revised ranges in the proposed specifications might result in more grinding unless the PCCP pavers were able to improve the pavement smoothness in the middle (full-pay/grind) ranges (*11*).

EFFECT OF INITIAL SMOOTHNESS ON ROUGHNESS HISTORY OF PAVEMENTS

Roughness histories of the 1985 and 1986 I-70 PCCP projects were analyzed using the Mays roughness data from the pavement management system (PMS) data base. The Mays roughness data are collected annually for the PMS data base on each mile of the KDOT highway system. Figure 2 shows the average Mays roughness for 13 km (8 mi) for each year the pavement has been in service since 1985. The eastbound direction was built smoother and, thus far, has remained so as compared with the westbound direction.

The roughness history of the 1990 I-70 PCCP project was also analyzed as shown in Figure 3. As-built smoothness on both directions of this project were comparable and has remained so 3 years after construction with slightly rougher eastbound lanes. However, because of poor ride quality, predominantly large portions of the eastbound lanes were ground in the fall of 1992.

COST ANALYSIS

It is well known that there is a speculation in the industry that changes in specifications result in higher cost. Table 10 shows an analysis of average statewide PCCP unit bid costs from 18 projects between 1990 and 1992. The results indicate that the contractor price differs slightly from the state estimate and may be higher or lower without any definite trend. Table 11 shows the smoothness-related payments made out to the contractors in 1990 and 1991. Data from eight projects covering 72.2 lane-mi in 1990 and three projects with 4.4 lane-mi in 1991 are shown. Most of

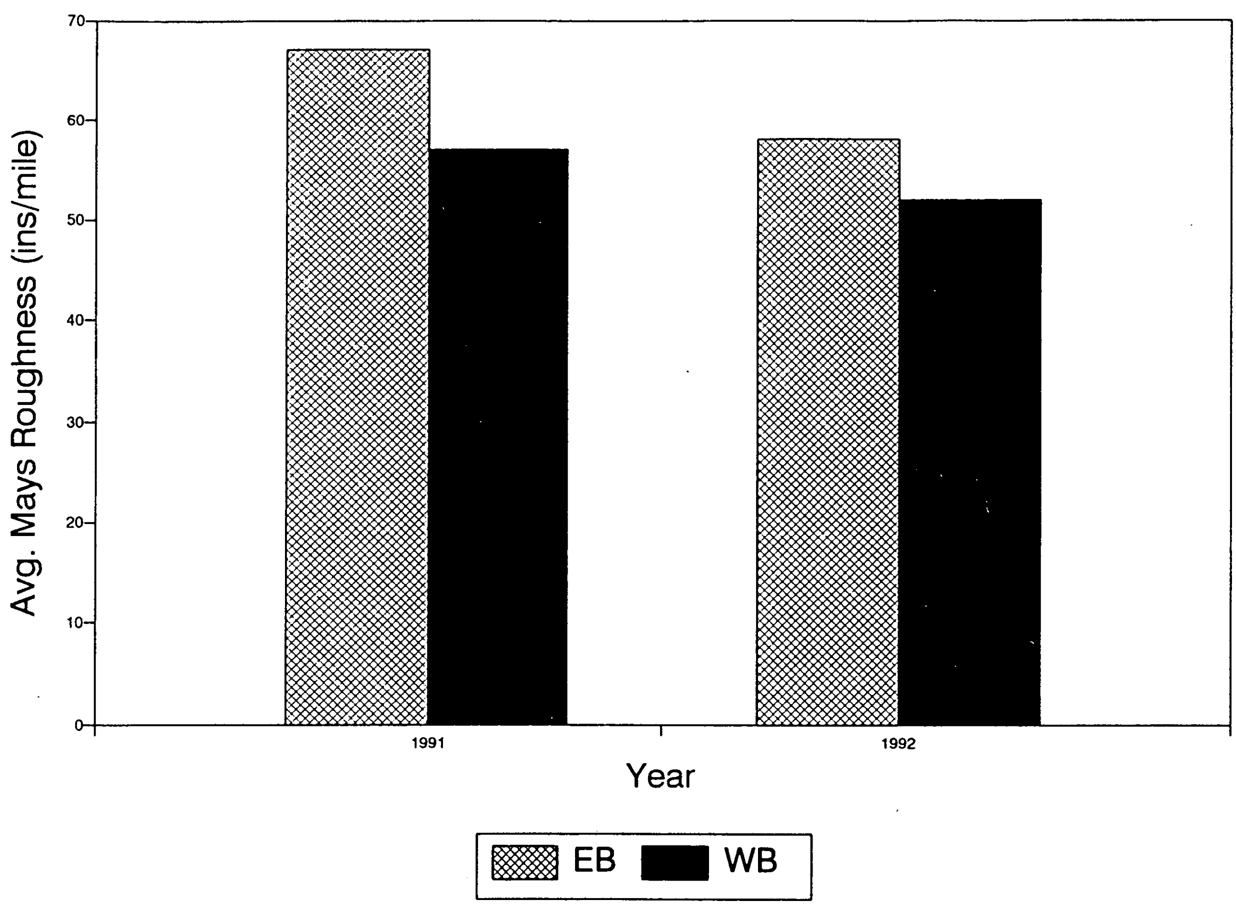

FIGURE 3 Mays roughness history of 1990 I-70 PCCP project, MP 0.00–7.00.

TABLE 4 Specification Compliance of Projects Blanking Band

Roadway	No. of 0.16 kilometer sections	Compliance with specified PRI (mm/km)					
		Bonus (0 - 64)	(%)	Full Pay (65 - 159)	(%)	Penalty (>159)	(%)
I 70	132	62	47	51	64	5	6
I 470	77	50	65	26	34	1	1
All 1990	740	469	63	197	27	74	10

Note: Profilograph results were attained with a 5.1-mm (0.2-in.) blanking band width.

TABLE 5 Profilograph Results with Null Blanking Band and Proposed Specified Ranges

Roadway	No. of 0.16 kilometer sections	Compliance with specified PRI (mm/km)					
		(0 - 159)	(%)	(160-635)	(%)	(>635)	(%)
I 70	132	0	0	91	69	41	31
I 470	77	0	0	77	100	0	0
ALL 1990	740	10	1	656	89	74	10

Note: 1 in = 25.4 mm
1 mile = 1.6 km

TABLE 6 Schedule for Adjusted Payment for PCCP (Special Provision 90P-111)

Profile Index millimeter per kilometer per 0.16 kilometer section (> 72 km/h)	Profile Index millimeter per kilometer per 0.16 kilometer section (72 km/h or less)	Price Adjustment Percent of contract unit bid price
175 or less	238 or less	106
176 to 238	239 to 397	103
239 to 635	398 to 794	100
636 to 952	795 to 1111	100 (Grind Back)
953 to more	1112 to more	95 (Grind back or remove & replace)

TABLE 7 Profilograph Results on PCCP in Kansas for 1992 Special Provisions 90P-111

Roadway	No. of 0.16 kilometer sections	Compliance with specified PRI (mm/km)					
		PRI (0 - 238) Bonus	(%)	PRI (239 - 635) Full-pay	(%)	PRI (>635) Penalty	(%)
1990 (reanalysis)	740	111	15	555	75	74	10
1991 (reanalysis)	290	55	19	203	70	32	11
1992	682	123	18	484	71	75	11

Note: 1 in. = 25.4 mm
1 mile = 1.6 km
Results were attained using zero or 0.254-mm (0.01-in.) blanking band.

TABLE 8 Schedule for Adjusted Payment for PCCP (1992 Special Provisions 90P-111-R1)

Profile Index millimeter per kilometer per 0.16 km section (72 km/h or greater)	Profile Index millimeter per kilometer per 0.16 km section (72 km/h or less & ramps)	Price Adjustment Percent of Contract unit bid price
175 or less	238 or less	108
176 to 238	239 to 397	104
239 to 476	398 to 715	100
477 to 794	716 to 1032	100 (Grind back)
795 or more	1033 or more	95 (Grind back or remove and replace)

TABLE 9 Effect of Proposed 1993 PCCP Smoothness Specifications (90P-111-R1) on Construction in Kansas

Specification	No. of 0.16 km sections	Compliance with specified PRI (mm/km)							
		PRI (0 - 238) Bonus	(%)	PRI (239 - 635) Full-pay	(%)	PRI (636-952) Full-pay/ Grind	(%)	PRI (>952) Penalty	(%)
90P - 111	529	127	24	370	70	27	5	5	1
90P - 111- R1	529	(0-238)	(%)	(239-477)	(%)	(478-794)	(%)	(> 794)	(%)
		127	24	280	53	111	21	11	2

Note: 1 in. = 25.4 mm
1 mile = 1.6 km
Roadways were marked as having speed limits greater than 72 km/hr (45 mph).

TABLE 10 Average PCCP Unit Bid Cost for 1990–1992

Year	No. of Projects	Avg. PCCP unit bid cost ($/ meters sq.) state	Avg. PCCP unit bid cost ($/ meters sq.) contractor	Difference (%)
1990	7	21.4	21.7	+1.4
1991	5	27.03	24.27	-10.0
1992	6	21.89	24.17	+10.0

TABLE 11 Cost Analysis of Smoothness Specifications

Year	No. of Proj-ects	Smoothness-related Cost ($)						
		Total	Bonus	% of Total	Full-Pay	% of Total	Pen-alty	% of Total
1990	8	16,703,551	599,258	3.6	16,041,437	96	62,856	0.40
1991	3	1,639,067	80,083	4.9	1,541,159	94	17,825	1.1

the projects of 1991 are still not closed. In 1990, the contractors received 3.6 percent bonus and 96 percent full payments. The penalty represented only 0.4 percent of total payment. The penalty rose to 1.1 percent of total payments in 1991. However, bonus payments also rose to 4.9 percent (an increase of 1.3 percent) over 1990, negating a higher penalty. It appears that incentive payments have had a positive impact and resulted in quality paving.

CONCLUSIONS

Smoothness specifications for PCCP pavements now in effect in Kansas have evolved over the last 8 years. Pavement profiles with short wavelengths and smaller amplitudes than the industry-accepted 5.1 mm (0.2 in.) can adversely affect the ride quality of pavements. This experience has led KDOT to eliminate the blanking band width in the profilograph trace reduction process. The implementation of this zero or null blanking band was successful and has resulted in better-quality concrete pavements in Kansas. The latest proposed specifications will increase the amount of bonus that can be achieved by a contractor but might result in more grinding unless the PCCP pavers were able to improve the pavement smoothness in the middle (full-pay/grind) ranges. An analysis of effects of as-constructed smoothness on the roughness history of pavements showed that the ride quality over the service life of pavements is dictated by the initial smoothness, i.e., the smoothness achieved during construction. Limited cost analysis has shown that an increasing amount of bonus achieved in PCCP construction over the last few years indicated quality paving.

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REFERENCES

1. Hudson, W. R. Road Roughness: Its Elements and Measurement. In *Transportation Research Record 836*, TRB, National Research Council, Washington D.C., Dec. 1981.
2. Scofield, L. A. *NCHRP Project 20-7, Task 53: Profilograph Limitations, Correlation, and Calibration Criteria for Effective Performance Based Specifications.* Final Report. TRB, National Research Council, Washington D.C., Dec. 1992.
3. Woodstrom, J. H. *NCHRP Report 167: Measurement, Specifications, and Achievement of Smoothness for Pavement Construction.* TRB, National Research Council, Washington, D.C., Nov. 1990.
4. *Summary of Results of the 1987 AASHTO Rideability Survey.* AASHTO Highway Subcommittee on Construction, AASHTO, Washington, D.C., 1988.
5. Scofield, L. A., S. Kalevela, M. Anderson, and A. S. M. Hossain. *A Half Century with the California Profilograph.* Report FHWA-AZ-SP9102, Arizona Department of Transportation, Phoenix, Feb. 1992.
6. Parcells, W. H. Jr. *Control of Pavement Trueness in Kansas.* Interim Report. Kansas Department of Transportation, Topeka, Jan. 1992.
7. Lundstrom, L. C. and P. C. Skeels. *Surface Control Methods Employed on General Motors Proving Ground Circular Test Track.* Internal Report. General Motors Engineering Services, Milford, Mich. May 1964.

8. Hveem, F. N. *Profilograph 2*. California Highway and Public Works, March–April 1960, pp. 51–57.
9. Kulakowski, B. T. and J. W. Wambold. *Development of Procedures for the Calibration of Profilographs*. Report FHWA-RD-89-110. Pennsylvania Transportation Institute, Pennsylvania State University, University Park, Aug. 1989.
10. Devore, J. and M. Hossain. *An Automated System for Determination of Pavement Profile Index and Location of Bumps for Grinding from the Profilograph Traces*. K-TRAN Project 92-2. Kansas State University, Manhattan, July 1992.
11. Parcells, W. H. Jr. *Control of Pavement Trueness in Kansas*. Interim Report. Kansas Department of Transportation, Topeka, Jan. 1993.

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