

Analysis and Recommendations Concerning Profilograph Measurements on F0081(50)107 Kingsbury County

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In 1990, the South Dakota Department of Transportation (SDDOT) noted significant discrepancies between its ride-quality measurements and those taken by a contractor paving a portland cement concrete project. The contractor's measurements were consistently smoother than SDDOT's and would have generated incentive payments approximately twice as large. About half of the observed difference could be attributed to increased pavement roughness after paving, but the rest appeared to result from differences between the department's manual profilograph and the contractor's computerized unit. Analysis revealed that a numerical filtering algorithm used by the computerized profilograph strongly attenuated profile features with wavelengths shorter than 10 ft. Such attenuation was observed directly on the computerized unit's profile traces. Because of the attenuation, SDDOT considered the computerized measurements unsuitable calculating incentive payments. However, SDDOT could not use its own measurements as a basis for payment because they were not taken within the specified 48-hr period after paving. To estimate a fair incentive payment, SDDOT developed a correlation between the computerized and manually interpreted profile indexes for the project. Using the correlation, SDDOT awarded an incentive payment approximately midway between its original estimate and the contractor's. SDDOT has suspended use of computerized profilographs pending improvement of the filtering algorithm. Preliminary experiments indicate that although the computerized profilograph's first-order filter attenuates profiles too strongly and produces artificially low profile indexes, a third-order filter might generate higher profile indexes than does a manual interpreter. This suggests that a second-order filter might best approximate a human's visual interpretation of the profile. Further research is needed to confirm this hypothesis and to establish a foundation for standard filtering procedures.

During the summer of 1990, Castle Rock Construction Company placed portland cement concrete pavement on an 8.9-mi segment of US-81 south of Arlington, South Dakota (Figure 1). The project number was F0081(50)107.

In accordance with contract provisions, the contractor conducted profilograph tests (ASTM E1274-88) to determine the ride quality of the finished pavement. The contractor's measurements indicated that high ride quality had been achieved and that he was entitled to an incentive bonus of nearly \$89,000.

Profilograph tests performed by the South Dakota Department of Transportation (SDDOT) Office of Materials and Surfacing also showed good ride quality, but not as good as the contractor's tests had indicated. Profile indexes measured during SDDOT's quality control tests were typically 1 to 2

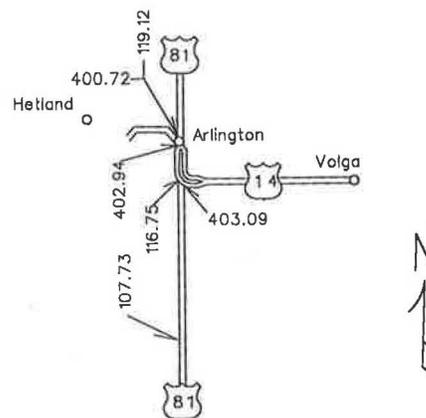


FIGURE 1 F0081(50)107 location.

in./mi higher than those measured by the contractor. Traces generated by the SDDOT unit consistently showed greater profile amplitude than did traces from the contractor's (Figure 2).

SDDOT attempted a simple check to determine whether the contractor's profilograph measured the pavement profile accurately. When the profilograph was run over a short piece of 1-x-2 lumber, it indicated approximately 1/2 in. rather than 3/4 in., the nominal wood thickness. This unexpected result seemed to suggest a problem in the contractor's profilograph.

The contractor and SDDOT also tested sections of pavement simultaneously to determine whether their profilographs produce the same profile indexes. On August 28, 1990, northbound and southbound lanes were tested at Stations 21+71 to 48+11 and 438+83 to 470+51. Again, SDDOT's profile indexes and trace amplitudes were higher than Castle Rock's.

The contractor attempted to verify the operation of his profilograph by comparing its performance with a manual unit owned by the Iowa Department of Transportation. Castle Rock's profilograph measured profile indexes that agreed closely with Iowa's. When asked why the profilograph underestimated the thickness of the 1-x-2, Iowa personnel speculated that the unit's filtering algorithm might be responsible. They also advised SDDOT to evaluate traces carefully, to avoid misinterpreting spikes as roughness.

After the discrepancies were discovered, SDDOT retested the entire project. Again, profile indexes were consistently higher than those originally measured by the contractor. On

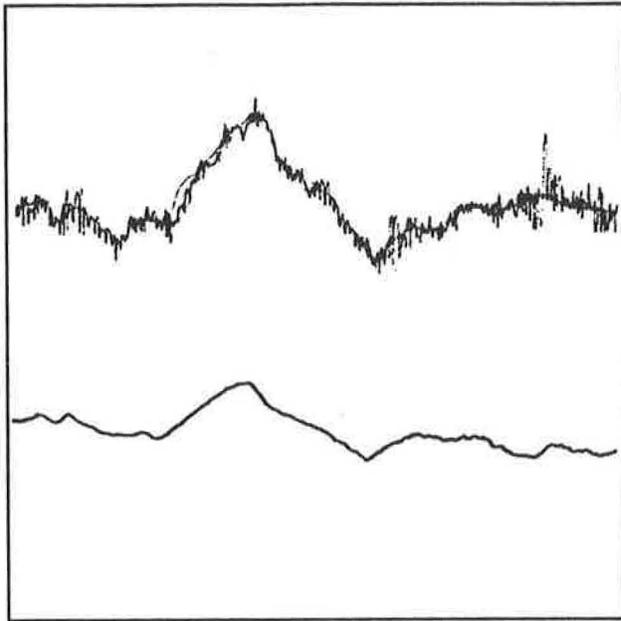


FIGURE 2 Traces from SDDOT and Castle Rock profilographs.

the basis of SDDOT's measurements, the contractor would be entitled to a bonus of less than \$48,000. It seemed clear that the contractor's profilograph performed differently than SDDOT's profilograph, perhaps because of a filtering process performed by its on-board computer. But because SDDOT's tests were performed weeks after the contractor's, direct comparisons were not possible.

Because of the unresolved questions surrounding the profilograph measurements, SDDOT's Aberdeen Region asked SDDOT's Office of Research to provide technical assistance. Specifically, the objectives of this study were to

- Determine whether profilograph measurements obtained by the contractor's automated profilograph differed significantly from those obtained by SDDOT's manual profilograph;
- Determine the cause of any differences; and
- Develop a method to determine a fair ride-quality bonus if differences were attributable to the filtering used by the contractor's profilograph.

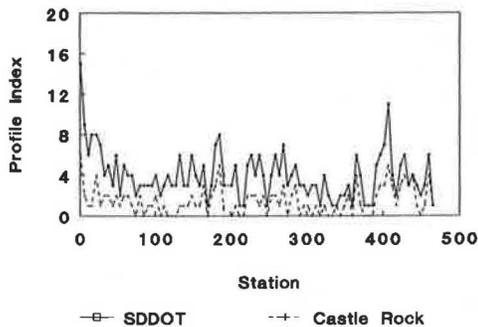


FIGURE 3 Project-wide profile indexes measured by SDDOT and Castle Rock Construction (northbound lane).

SIGNIFICANCE OF PROFILOGRAPH MEASUREMENT DIFFERENCES

It was essential to first establish that the profile indexes measured by the two profilographs were statistically different. If the observed differences represented only random variations, it would have been pointless to conclude that either instrument was in error. But if systematic differences existed, their causes might be determined. Two statistical tests were performed.

First, the projectwide profile indexes obtained by SDDOT on September 5–6 and 10–11, 1990, were compared with the profile indexes measured by the contractor within 48 hr of construction (Figures 3 and 4). The hypothesis that "projectwide profile indexes measured by SDDOT were higher than the contractor's" was tested using the one-sided *t*-statistic with unknown standard deviations. The test demonstrated the hypothesis to be true with greater than 99 percent confidence.

Second, the profile indexes obtained during head-to-head tests on August 28, 1990, were compared (Figures 5 and 6). The hypothesis that "SDDOT's profilograph generated higher profile indexes than did the contractor's" was tested, using the same statistical test. With more than 99 percent confidence, the hypothesis was also determined to be true. On the

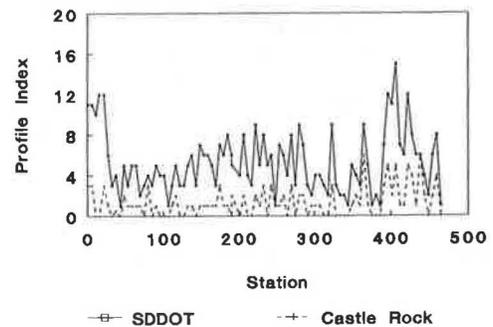


FIGURE 4 Project-wide profile indexes measured by SDDOT and Castle Rock Construction (southbound lane).

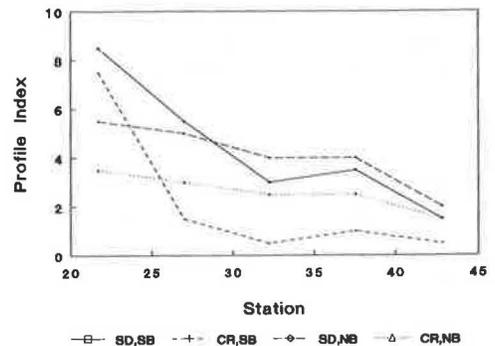


FIGURE 5 Profile indexes measured simultaneously by SDDOT and Castle Rock Construction on August 28, 1990 (Station 21+71 to 48+11).

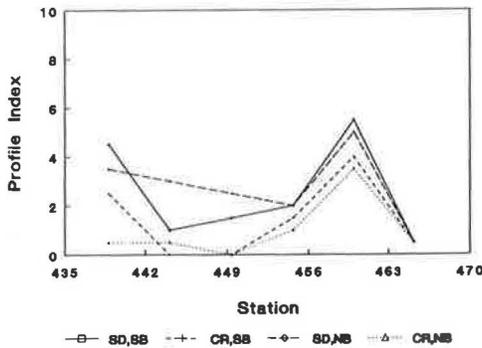


FIGURE 6 Profile indexes measured simultaneously by SDDOT and Castle Rock Construction on August 28, 1990 (Station 438 + 83 to 470 + 51).

basis of these statistical tests, SDDOT concluded that its projectwide measurements were higher than the contractor's and that its profilograph generated higher profile indexes than did the contractor's.

PROFILE INDEX DIFFERENCE CAUSES

Two causes—time between measurements and differences between manual and automated profile interpretation—were considered to be likely explanations for the differences between the profile indexes measured by SDDOT and those measured by the contractor.

Time Between Measurements

Although it appeared probable that differences between the profilographs were responsible for much of the discrepancy between the profile index measurements, it was clear that pavement roughness had changed since paving. Indexes obtained by the contractor's profilograph on August 28 were higher than those taken immediately after construction, suggesting that the pavements had become slightly rougher after construction. This was reasonable, because the curing process and temperature changes can easily affect slab shape. This observation was important, because it meant that SDDOT's measurements, which were taken too long after construction, could not be used to determine ride-quality incentive payments.

Profilograph Differences

From the comparison of profile index measurements taken with both profilographs on the same pavement sections on August 28, 1990, it was clear that the contractor's profilograph measured lower profile indexes than did SDDOT's. Because the two machines were geometrically identical, the profile filtering process incorporated in the contractor's unit was considered the most likely cause of the difference. It should be noted that SDDOT's manual procedures were also evaluated, primarily because of Iowa's concern that spikes may have been

incorrectly interpreted. However, no incorrect procedures were discovered. SDDOT's engineer had correctly smoothed the profile so spikes were ignored, just as Iowa had advised.

Castle Rock's unit was a Model CS8200 profilograph from James Cox and Sons, Inc. The CS8200 includes an on-board computer that digitizes the profile signal at 1.3-in. intervals and computes profile index automatically. To make profile interpretation less difficult, the computer uses a simple recursive digital filter to remove spikes caused by extraneous mechanical vibrations from the profile signal.

Mathematically, the filter was a first-order recursive filter of the form

$$Y_n = AY_{n-1} + BX_n \quad (1)$$

where

X_n = raw (unfiltered) digitized elevation at Point n ,

Y_n = filtered elevation at Point n , and

Y_{n-1} = filtered elevation at Point $n - 1$.

A and B are constants that determine the filter's effect, and are defined

$$B = N/65,536 \quad (2)$$

Cox recommended using a filter factor of $N = 8,000$ for most purposes.

$$A = 1 - B \quad (3)$$

The filter's performance was analyzed with standard signal processing techniques. One useful analysis determines the response of the filter as a function of profile wavelength λ . Specifically, the analysis defines the filter's amplitude response $H(\lambda)$, which is the ratio of the filter's output to its input. It can be shown analytically that the amplitude response of this filter is given by the formula

$$H(\lambda) = \frac{B}{\sqrt{C^2 + D^2}} \quad (4)$$

where

$$C = 1 - A \cos\left(\frac{2\pi\lambda_s}{\lambda}\right), \quad (5)$$

$$D = A \sin\left(\frac{2\pi\lambda_s}{\lambda}\right), \text{ and} \quad (6)$$

λ_s = sampling interval of 1.3 in. used by the Cox profilograph.

As shown in Figure 7, the filter attenuates short wavelengths most. Wavelengths shorter than 1 ft are attenuated by more than 80 percent to greatly reduce the effect of spikes. However, the filter significantly attenuates longer wavelengths as well. Wavelengths of 2 ft are attenuated by more than 60 percent; 5-ft wavelengths are attenuated by 30 percent. Even 10-ft wavelengths are attenuated by 10 percent.

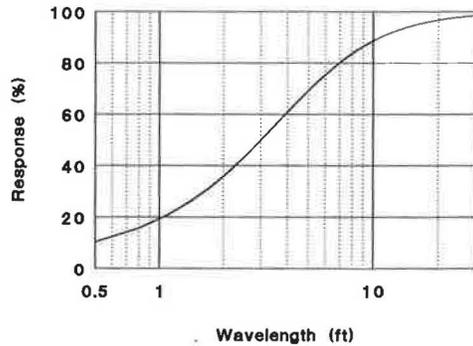


FIGURE 7 Response to Cox data filter as a function of wavelength ($N = 8,000$).

The filter can also be described in terms of its response to a step input. As Figure 8 shows, the filter is quite slow to recognize a step in the pavement profile. After the profilograph travels 1 ft past the step, it measures only 70 percent of the step's height. It is not until the profilograph has traveled 3 ft past the step that it measures 95 percent of the true height. This explains why the profilograph failed to measure the correct thickness of the 1- \times -2, which was less than a foot long.

The significance of Figures 7 and 8 is that although the filter successfully removes spikes from the raw profile, it also removes longer features that are known to affect pavement ride quality. Because the filter underestimates the amplitude of the pavement profile, estimates of profile index are low.

Cox acknowledges that the profile index is influenced by the filter. Its manual states, "It is important to understand that the test results are heavily affected by the selected filter factor" (1). However, the filter's performance is fundamentally a consequence of its simple, first-order formulation. Regardless of the filter factor used in the computation, the filter's selectivity is not good. Invariably, longer wavelengths are removed along with the short. The selectivity of the filter could be improved by using a higher-order filtering algorithm, assuming the profilograph's computer has sufficient power.

The filter's ultimate effect on computed profile index cannot be simply determined. Because the amount of attenuation depends on the wavelengths in the pavement profile, the reduction of profile index also varies. If a pavement contains predominantly short wavelengths, the profile index is reduced

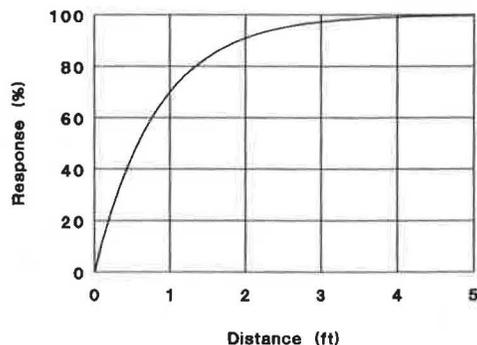


FIGURE 8 Cox filter step response ($N = 8,000$).

greatly. If only longer wavelengths are present, the reduction is slight.

This explains why Castle Rock's automated profilograph correlated well with Iowa's manual profilograph. Iowa's test section consisted of large-amplitude bumps at wavelengths predominantly longer than 20 ft. At these wavelengths, the effect of filtering was too slight to be detected either by visually inspecting profilograph traces or by observing differences in profile indexes.

INCENTIVE/DISINCENTIVE COMPUTATION

In view of the discrepancies between profilograph measurements taken by SDDOT and Castle Rock, the question of fair incentive/disincentive payments arose. The construction contract specified ride-quality incentives and disincentives according to the following schedule (2):

Profile Index	Payment (%)
0-2	105
3	104
4	103
5	102
6	101
7-10	100
11 or more	grind or replace

Because the contractor's profilograph underestimated the height of profile features on the pavement, profile indexes were artificially low and inconsistent with the measurement method assumed in the specifications. Consequently, SDDOT considered the bonuses computed from the contractor's profile indexes to be excessive. SDDOT's profilographs did not underestimate the profile, but because measurement were not taken within 48 hr of paving, they could not be used directly as a basis for incentive payment.

In the interest of fairness to the contractor and the state, SDDOT attempted to adjust the contractor's measurements to compensate for the filtering. Direct correction would have required that all profile traces taken from the contractor's profilograph be completely redigitized, complex mathematics (Fourier transforms and inverse Fourier transforms) be used to reconstruct a profile of proper amplitude, and new profile indexes be computed. That approach was deemed difficult and prone to error.

Instead, SDDOT correlated the two profilographs, using measurements taken by both instruments on August 28, 1990. The resulting regression equation was used to adjust the contractor's profile indexes to better represent unfiltered values. Figure 9 shows the profile indexes measured by the two profilographs. From the data obtained in the simultaneous testing, the best equation relating filtered (Castle Rock) and unfiltered (SDDOT) profile indexes was

$$PI_{\text{unfiltered}} = 1.95 + 0.93PI_{\text{filtered}} \quad (7)$$

When this equation was applied to the contractor's profile indexes, the adjusted values more realistically represented the ride quality of the pavements. The bonus computed from these adjusted values totaled \$68,975.36, which coincidentally fell about halfway between the contractor's original estimate and SDDOT's estimate derived from late measurements.

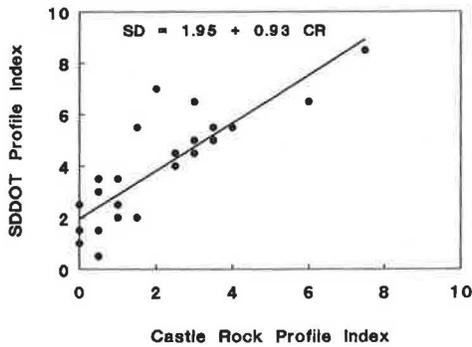


FIGURE 9 Correlation of SDDOT profile index and Castle Rock profile index.

POLICY CONSIDERATIONS

After the profile attenuation problem was discovered, SDDOT considered three alternatives for using computerized profilographs.

Prohibit Use of Computerized Profilographs

Even though computerized units remove the subjectivity associated with the manual interpretation of profile traces and greatly speed the computation of profile indexes, SDDOT believed the present filtering errors unacceptably biased measurements. In early 1991, the department disallowed the use of computerized profilographs on its paving projects. In summer 1991, SDDOT modified its policy to permit the use of computerized profilographs as long as the instruments were programmed to plot unfiltered projects that could be interpreted manually later.

Lower Ride-Quality Specifications

One alternative suggested by James Cox and Sons, Inc., (1) was to adjust ride-quality specifications to account for differences in computed profile indexes. Even though SDDOT had used an adjustment on F0081(50)107, it did not believe it had sufficient basis for a general adjustment. To eliminate possible controversy over computerized-versus-manual profilograph

specifications, the department rejected this alternative (the department did lower the ride-quality specifications for reasons unrelated to the attenuation problem, however: to encourage improved paving quality, the entire payment schedule was shifted downward 2 in./mi).

Improve Filtering Algorithm

SDDOT shared its technical information with James Cox and Sons, Inc., which manufactures Castle Rock's profilograph, and with McCracken Concrete Pipe Machinery Company, which manufactures a similar product. Both Cox and McCracken consulted the Michigan Department of Transportation to obtain suggestions for a better filter formulation. Michigan DOT suggested that a second- or third-order Butterworth filter with a cutoff wavelength of 1 ft would filter the profile more selectively (J. W. Reinke, unpublished data).

McCracken installed the third-order filter in its profilograph during summer 1991. On June 18, 1991, McCracken and SDDOT took simultaneous measurements on in-service portland cement concrete pavements near Pierre, South Dakota. SDDOT made four passes on six $\frac{1}{10}$ -mi test sections. McCracken made two passes on each section for each of three different filter selections—the original Cox filter and two settings of the third-order Butterworth filter. Average profile indexes are shown in Table 1.

Although not conclusive, the results suggest that for the chosen cutoff wavelengths of 1 ft and 2 ft, the third-order filter produced profile indexes significantly higher than either the manual interpretation or the first-order filter. For these limited tests, the first-order filter actually approximated the manual interpretation better than did the third-order filter. At low roughness levels (Station 5+78 to 11+06 in Wheelpath 2), all three filters generated lower profile indexes than did manual interpretation. It is not clear that any of the computerized methods consistently approximates a manual interpretation.

CONCLUSIONS AND RECOMMENDATIONS

Comparisons between profile indexes measured by SDDOT and Castle Rock Construction Company show that the filtering method used by computerized profilographs can strongly

TABLE 1 AVERAGE PROFILE INDEXES OBTAINED BY MANUALLY INTERPRETED PROFILOGRAPH AND BY COMPUTERIZED PROFILOGRAPH USING FIRST- AND THIRD-ORDER FILTERS

Wheelpath	Station	Manual	1st-Order Recursive (Cox)	3rd-Order, 1' cutoff	3rd-order, 2' cutoff
1	0+50—5+78	12.0	11.8	14.4	15.0
	5+78—11+06	5.1	6.5	8.4	8.6
	11+06—16+34	15.0	14.9	19.4	18.6
2	0+50—5+78	11.9	11.6	15.2	13.6
	5+78—11+06	3.4	1.2	1.8	2.2
	11+06—16+34	10.9	10.8	13.7	14.0

affect measured profile indexes. Analysis of the filtering algorithm used on the contractor's profilograph demonstrates that the Cox unit significantly underestimated profile heights at wavelengths shorter than 10 ft. Therefore, profile indexes were also underestimated.

It was possible to derive a regression equation from profile indexes measured by the SDDOT unit and the contractor's unit on the same pavement sections on the same day. The contractor's profile indexes were adjusted using this equation, yielding new indexes that more realistically described the ride quality achieved in the paving operation. The incentive payment computed from the adjusted profile indexes was about midway between the bonus computed from the contractors unadjusted indexes and the bonus computed by SDDOT from its late measurements.

In the opinion of SDDOT, the filter algorithm incorporated in the Cox unit should not be used in conjunction with SDDOT's special provision for paving incentives. Accordingly, the department has restricted use of computerized profilographs. Preliminary experiments with other filter algorithms have been inconclusive. Until a satisfactory algorithm is demonstrated, the department will require manual interpretation of profile traces.

Transportations agencies must take care how they determine whether a contractor's profilograph operates acceptably. It is common practice to accept a contractor's profile indexes if they fall within 2 in./mi of the state's indexes. This criterion fails if a profilograph generates indexes that are within 2 in./mi but are consistently high or low. Tests to determine whether mean profile indexes are statistically different would more reliably indicate measurement validity. To ensure their relevance, any validation tests should be performed on test sections with roughness characteristics similar to those anticipated on newly constructed pavements.

Finally, a standard method of profile interpretation is needed. This would be an appropriate activity for ASTM, but it could only take place after additional research is accomplished.

REFERENCES

1. *CS8200 Users Manual*. James Cox and Sons, Inc., pp. 18-19.
2. *Special Provision for Profilograph Test for PCC Pavement*. South Dakota Department of Transportation, Pierre, April 1987.

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