Effect of Design Parameters on Performance of Road Profilographs

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Road profilographs are commonly used to measure roughness of new and newly surfaced pavements. Because new pavements are usually smooth, profilographs must have high measuring sensitivity, particularly in the range of profile wavelengths responsible for dynamic pavement loading applied by heavy trucks and for ride comfort. Simple analytical and computer models were developed to examine the effects of basic design parameters on the performance of California and Rainhart profilographs. It was found that the quality of measurements obtained with the two profilographs can be improved by modifying some of the design parameters (e.g., length of main truss and number and spacing of supporting wheels). The improvement should be more significant for the California profilograph. The design parameters of the existing Rainhart profilograph are close to the values recommended in the paper.

Road profilographs are low-speed devices (hand-pushed at walking speed) designed to measure the roughness of road surfaces. Road roughness is defined as "the deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage, for example, longitudinal profile, transverse profile, and cross slope" (ASTM E867). Profilographs are used primarily to measure the roughness of new or newly surfaced pavements before they are open for traffic. The results of the profilograph measurements are compared with established pavement roughness specifications to provide the basis for acceptance of the construction work. Because new pavements are usually very smooth, profilographs must be sufficiently sensitive to small variations of measured surface profiles.

Profilographs come in several different designs. Figures 1 and 2 show two of the most common types of profilographs—the California profilograph and the Rainhart profilograph. Both devices use a long, rigid member or main truss supported through minor trusses by 12 wheels. The supporting wheels provide a reference platform for the measuring wheel located at the center of the main truss. As the profilograph is pushed along the pavement, the vertical motion of the measuring wheel is recorded by a tracing pen of a strip chart recorder to provide the measurement of surface profile. In the Rainhart profilograph, the supporting wheels are uniformly spaced throughout the length of the profilograph. The spacing of the supporting wheels in the California profilograph is not uniform.

The profile recorded by a profilograph is examined to identify individual bumps that exceed acceptable limits, usually 3.175 mm (0.125 in.), and then the profile data are processed to determine the overall roughness index for a segment of road of specified length, usually 160 m (0.1 mi). The roughness index is calculated by integrating the recorded profile height that exceeds a specified blanking band over distance and then dividing the result of the integration by the length of the road segment. Road roughness calculated in this manner is expressed in meters of profile height per kilometer of road length (mpk) or in inches per mile (ipm).

There is a lack of convincing evidence in the relevant technical literature to prove that profilograph design parameters such as the length of the main truss or the number and spacing of the supporting wheels in the California and Rainhart profilographs are optimal for the performance of these devices. The main objective of the research described was to determine the effects of the basic design parameters of profilographs on their performance. In particular, an attempt was made to determine if the performance of profilographs could be improved by changing the number of supporting wheels and their locations along the profilograph or by changing the length of the main truss, or both. All results presented here were obtained through computer simulation of a kinematic model of a profilograph.

MATHEMATICAL MODEL

Just like other measuring devices, road profilographs respond with varying gain to harmonic input signals, in this case sinusoidal components of the road profile. The desired range of frequency over which the gain of profilograph frequency response characteristic should be sufficiently high and uniform is determined by two criteria—ride comfort and pavement loading exerted by truck tires. According to Janoff et al. (*1*), subjective ride quality ratings correlate best with road profile frequency components in the range from 0.4 to 2.0 cycle/m (0.125 to 0.63 cycle/ft), which corresponds to wavelengths between 0.5 and 2.5 m (1.6 and 8.0 ft). The largest truck tire forces that are the primary causes of pavement damage typically occur in the frequency ranges between 3 and 7 Hz and between 15 and 25 Hz. For speeds from 56 to 88 km/hr (35 to 55 mph), these frequencies correspond to profile wavelengths between 2.3 and 9.7 m (7.5 and 32.0 ft) and between 0.6 and 1.9 m (2.0 and 6.4 ft). Combining the wavelength ranges critical either for ride comfort or for pavement damage caused by the truck tire loading yields the range from 0.5 to 9.7 m (1.6 to 32 ft), to which a profilograph should be sufficiently sensitive to produce accurate measuring results. Because the speed of a profilograph pushed over the measured pavement surface is not higher than 5 km/hr (3.0 mph), the

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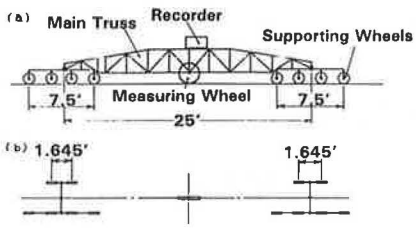

FIGURE 1 California profilograph: (a) front view, (b) wheel arrangement.

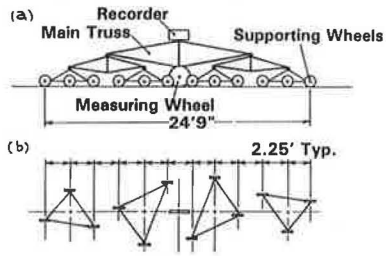

FIGURE 2 Rainhart profilograph: (a) front view, (b) wheel arrangement.

critical range of wavelengths generates an excitation input of frequencies from approximately 0.1 to 2.8 Hz. In such a low range of frequencies, the dynamics of a profilograph has negligible effects on its performance and will not be included in the mathematical model.

In addition, the following assumptions are usually made in developing a mathematical model of a profilograph (*2*):

- All structural connections are perfectly rigid,
- All hinge joints and wheel bearings are frictionless, and
- All wheels are at a point contact with the road surface at all times.

Under these assumptions, the generic mathematical model of a profilograph is given by the following equation:

$$\hat{P}(x) = P(x) - \sum_{i=1}^{N} C_i P(x - d_i) \tag{1}$$

where

$\hat{P}(x)$ = road profile measured by the profilograph,
$P(x)$ = true road profile,
x = longitudinal position coordinate in the direction of travel,
N = number of supporting wheels,
d_i = distance between ith supporting wheel and the center of the measuring wheel in the direction of motion, and
C_i = coefficients representing the effect of the ith supporting wheel on the result of measurement.

For a 12-wheel California profilograph (shown in Figure 1), the model equation takes the following form:

$$\hat{P}(x) = P(x) - \frac{1}{2}\left\{\frac{1}{N_R}\sum_{j=1}^{N_R}[P(x + \delta_j) + P(x - \delta_j)] + \frac{1}{N_L}\sum_{k=1}^{N_L}[P(x + \delta_k) + P(x - \delta_k)]\right\} \tag{2}$$

where

N_R = number of supporting wheels on the right-hand side of profilograph; in this case, $N_R = 8$;
N_L = number of supporting wheels on the left-hand side of profilograph; in this case, $N_L = 4$;
δ_j = distance between the jth wheel on the right-hand side and the center of the measuring wheel, $j = 1, 2, 3, \ldots, N_R$; and
δ_k = distance between the kth wheel on the left-hand side and the center of the measuring wheel, $k = 1, 2, 3, \ldots, N_L$.

The mathematical model of the Rainhart profilograph is

$$\hat{P}(x) = P(x) - \frac{1}{2N}\left\{\sum_{i=1}^{N}[P(x + \delta_i) + P(x - \delta_i)]\right\} \tag{3}$$

FREQUENCY RESPONSE CHARACTERISTICS

A sinusoidal transfer function of a profilograph is defined as

$$T(j\omega) = \frac{\hat{P}(j\omega)}{P(j\omega)} \tag{4}$$

where $\hat{P}(j\omega)$ and $P(j\omega)$ are Fourier transforms of the measured profile $\hat{P}(x)$ and actual road profile $P(x)$, respectively. In order to derive an expression for $T(j\omega)$ in terms of profilograph parameters, take the Laplace transform of Equation 1:

$$\hat{P}(s) = P(s) - \sum_{i=1}^{N} C_i P(s) e^{-sd_i} \tag{5}$$

where $\hat{P}(s)$ and $P(s)$ are Laplace transforms of $\hat{P}(x)$ and $P(x)$, respectively. From Equation 5, the system transfer function in the domain of complex variable s is

$$T(s) = \frac{\hat{P}(s)}{P(s)} = 1 - \sum_{i=1}^{N} C_i e^{-sd_i} \tag{6}$$

By substituting $s = j\omega$, the sinusoidal transfer function of a profilograph is obtained:

$$T(j\omega) = 1 - \sum_{i=1}^{N} C_i e^{-j\omega d_i} \tag{7}$$

The Euler identity can be used for the exponential term:

$$T(j\omega) = 1 - \sum_{i=1}^{N} C_i(\cos \omega d_i - j \sin \omega d_i) \tag{8}$$

Assuming that the number of supporting wheels N is even and that they all occur in pairs of wheels equally distanced

from the measuring wheel, one wheel in front and the other behind the measuring wheel, Equation 8 can be further simplified to obtain

$$T(j\omega) = 1 - 2\sum_{i=1}^{N/2} C_i \cos \omega d_i \tag{9}$$

Substituting

$$\omega = \frac{2\pi}{\lambda} \tag{10}$$

where λ is a wavelength, the sinusoidal transfer function of a profilograph can be expressed in terms of the profile wavelength:

$$T(\lambda) = 1 - 2\sum_{i=1}^{N/2} C_i \cos \frac{2\pi d_i}{\lambda} \tag{11}$$

In general, a system sinusoidal transfer function is a complex quantity. However, the expression on the right-hand side of Equation 11 is real. Thus, the phase of the profilograph transfer function is zero for all wavelengths $0 \leq \lambda < \infty$, and Equation 11 represents the magnitude of the transfer function equal to the ratio of amplitudes of measured and actual sinusoidal road profiles.

The frequency response characteristics calculated using Equation 11 for California and Rainhart profilographs are shown in Figures 3 and 4. The magnitude of the sinusoidal transfer function is plotted in these figures versus normalized wavelength, i.e., wavelength divided by the length of the main truss of the profilograph.

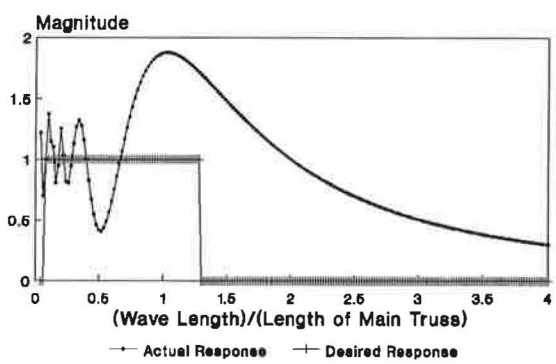

FIGURE 3 Frequency response of the 12-wheel California profilograph.

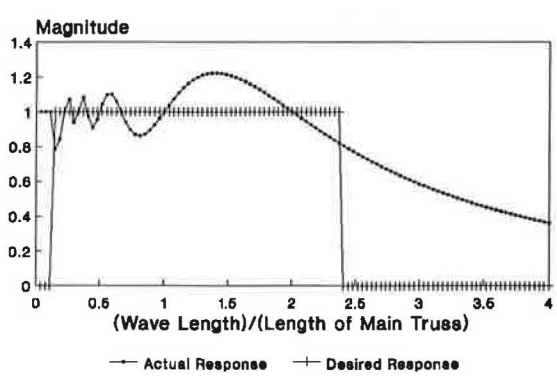

FIGURE 4 Frequency response of the 12-wheel Rainhart profilograph.

It was pointed out earlier that a desired frequency response characteristic of a profilograph would have a sufficiently high and uniform magnitude over the range of frequencies corresponding to the range of wavelength from 0.5 to 9.7 m (1.6 to 32 ft) and zero magnitude outside this range. It can be seen from Figures 3 and 4 that the characteristics of both profilographs are far from the ideal characteristic. Some wavelengths are measured by the profilographs correctly, some hardly at all, and others are measured amplified. The 12-wheel California profilograph with a 7.6-m-long (25-ft-long) main truss provides a poor measurement at 3- to 4.6-m (10- to 15-ft) wavelengths and then amplifies those in the 6.1- to 15.2-m (20- to 50-ft) range by as much as two times. In general, California profilographs have low sensitivity to wavelengths close to half the length of their main truss and high sensitivity to wavelengths close to the length of the main truss of the profilograph. The Rainhart profilograph with a 4.1-m (13.5-ft) main truss has a more uniform frequency response in the range of 0.8- to 9.7-m (2.7- to 32-ft) wavelengths. However, it slightly attenuates pavement profile components of wavelengths between 2.7 and 4.0 m (9 and 13 ft). In general, the frequency response characteristic of the Rainhart profilograph is much more uniform over the critical range of wavelengths from 0.5 to 9.7 m (1.6 to 32 ft) than the characteristic of the California profilograph, primarily because of the more uniform spacing of supporting wheels.

DESIGN CHARACTERISTICS

The most important design parameters for profilograph performance are the number and locations of the supporting wheels and the length of the main truss. The effects of these parameters on the performance of the California and the Rainhart profilographs were investigated using a computer simulation program that incorporates the mathematical model of profilograph given by Equation 1.

California Profilograph

First, the effect of the number of supporting wheels on the frequency response characteristic of the California profilograph was investigated. The profilograph configurations with 2, 6, and 12 wheels are shown in Figure 5. Figures 6 and 7 show the frequency responses of the two- and six-wheel profilographs. Comparing the plots shown in Figures 3, 6, and 7 indicates that the uniformity of the frequency response characteristic improves when the number of wheels increases. However, the improvement is only moderate, as even the 12-wheel profilograph has a poor frequency response characteristic.

The effect of the number of supporting wheels was further evaluated by comparing the roughness index (ASTM E1274) calculated from the profile generated by the computer model of a profilograph with the roughness index obtained directly from the profile data used as the input to the model. The input profile data were generated to represent a typical new

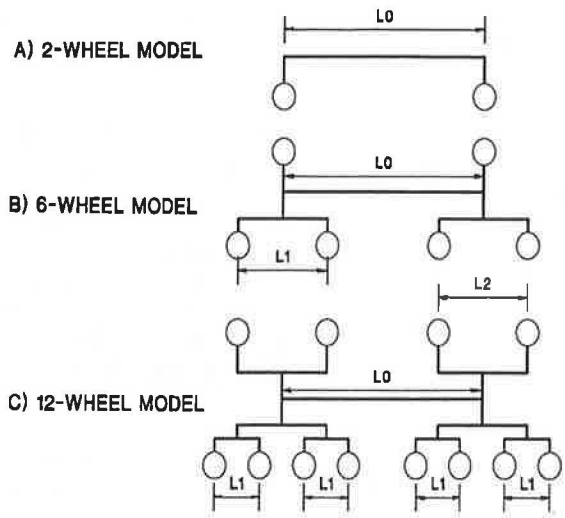

FIGURE 5 Configuration of 2-, 6-, and 12-wheel profilograph models.

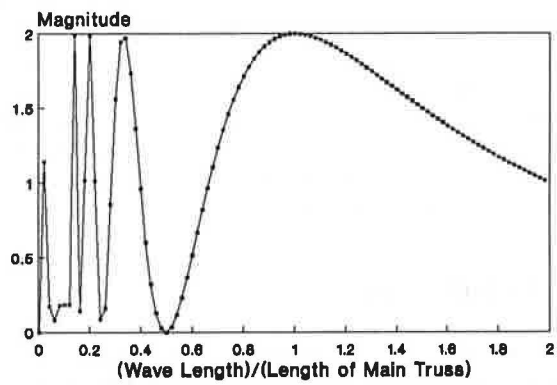

FIGURE 6 Frequency response of the two-wheel California profilograph.

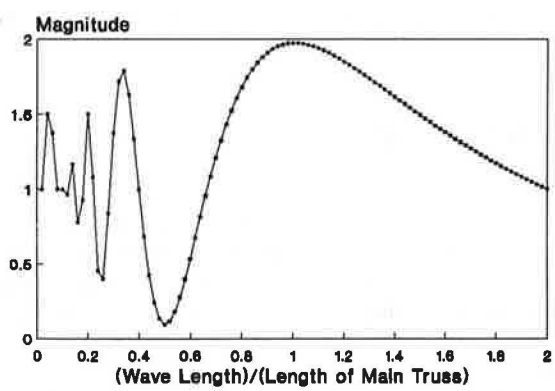

FIGURE 7 Frequency response of the six-wheel California profilograph.

pavement. In the FHWA study *Development of Procedures for the Calibration of Profilographs* (*3*), it was found that the power spectral density (PSD) function of new pavement profiles can be approximated by the following equation:

$$S_{xx} = 6.66 * 10^{-2}\lambda^2 \quad (12)$$

A computer program was developed to generate a sequence of data having specified PSD function and desired roughness index (*3*). This program was used to obtain a set of data with the PSD function given by Equation 12 and a roughness index of 5.5 in. per mile (IPM_{CA}) [87.4 mm per kilometer (MPK_{CA})]. The value of the roughness index represents a good-quality new pavement surface, and it is calculated using the 5.1-mm (0.2-in.) blanking band procedure. This procedure is commonly used in processing data recorded by the California profilograph and hence the subscript CA with the units of the roughness index (ASTM E1274).

The profile data were entered in the profilograph simulation program and the output profile was generated by the computer model of the profilograph. The values of the roughness index of the output profile from several computer simulations with different numbers of supporting wheels are shown in Figure 8. All profilograph models underestimate roughness. The measuring error is smaller for 2-, 4-, 6-, and 8-wheel models than for 10- and 12-wheel models. Figure 9 shows the correlation coefficient between input and output profiles versus number of supporting wheels. The correlation improves when the number of wheels increases; however, the improvement is not significant.

In summary, the results of computer simulation indicate that the overall performance of the profilograph with 6 or 8 supporting wheels is just as good as, or even better than in some aspects, the performance of the 12-wheel profilograph.

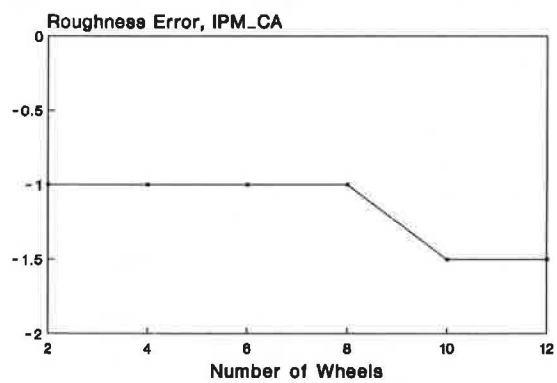

FIGURE 8 Effect of number of wheels on roughness measurement error for the California profilograph.

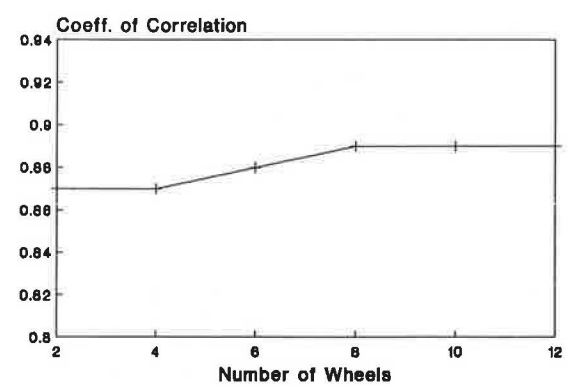

FIGURE 9 Effect of number of wheels on correlation for the California profilograph.

Next, the effects of the length of main truss and the effect of the distance between the supporting wheels were investigated. The measuring error and the coefficient of correlation between the input and output profiles were used again to evaluate performance. Figures 10 and 11 show the effect of the length of the main truss on measuring error for 6- and 12-wheel profilograph models. In these figures, the measuring error is minimal for the 9.1-m (30-ft) main truss for both models. A shorter main truss results in an underestimation of roughness, whereas a profilograph with a main truss longer than 10.7 m (35 ft) significantly overestimates profile roughness. The variation of spacing between the supporting wheels over the range from 0.5 to 1.0 m (1.5 to 3.0 ft) was found to have a negligible effect on the measuring error.

The effect of the length of the main truss on the correlation between input and output profiles for 6- and 12-wheel profilograph models is shown in Figures 12 and 13. The coefficient of correlation increases with an increasing length of the main truss; however, the improvement is very small for the truss length greater than 9.1 m (30 ft), especially for the 12-wheel model. The spacing between the supporting wheels had no effect on correlation for the six-wheel model. For the 12-wheel profilograph, the coefficient of correlation increased slightly for larger spacing of the supporting wheels.

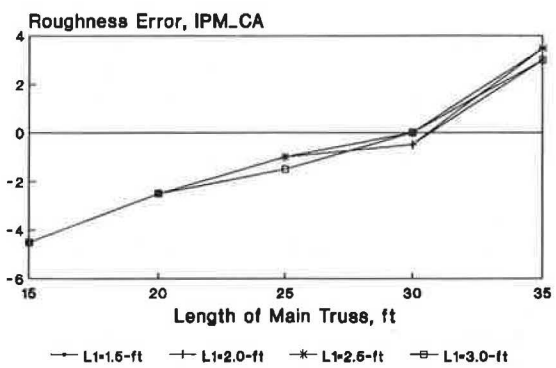

FIGURE 10 Effect of length of main truss on roughness measured with a six-wheel model (California).

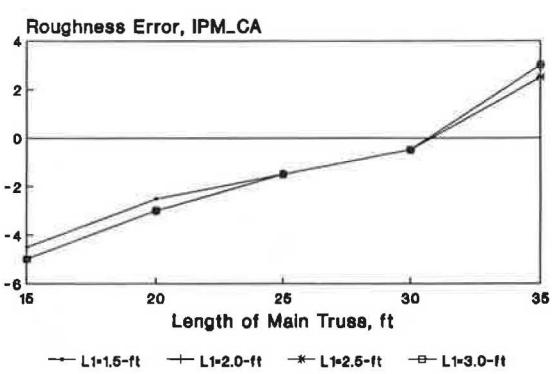

FIGURE 11 Effect of length of main truss on roughness measured with a 12-wheel model (California).

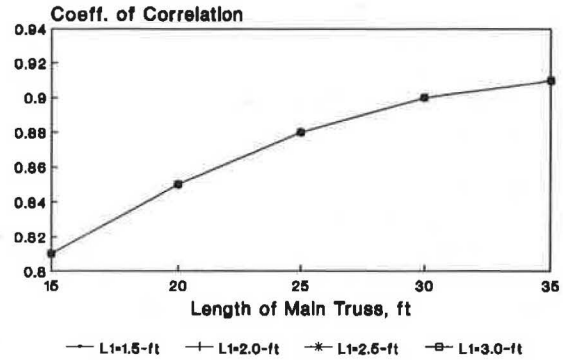

FIGURE 12 Effect of length of main truss on correlation for a six-wheel model (California).

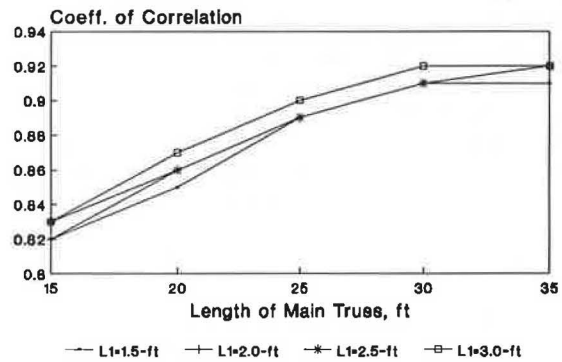

FIGURE 13 Effect of length of main truss on correlation for a 12-wheel model (California).

Rainhart Profilograph

When the design characteristics of the Rainhart profilograph are investigated, it has to be assumed that the basic constraints imposed on the number and spacing of the supporting wheels and the length of main truss of this type of profilograph are not violated. Those constraints are

- The supporting wheels are installed on tripods,
- The spacing of the supporting wheels in the direction of motion is uniform,
- From the first two constraints, it can be concluded that the three design parameters—length of main truss L_0, number of supporting wheels N, and distance between supporting wheels L_1—are interrelated by the following equation:

$$L_0 = \frac{NL_1}{2} \tag{13}$$

The most important implication of the first constraint is that the total number of supporting wheels in a profilograph model that can be considered practical is either 6 (two tripods attached directly to two ends of the main truss) or 12 (current design). The next smallest number of supporting wheels would be 24, which would require additional subminor trusses to be

attached to the ends of the minor trusses shown in Figure 2. The 24-wheel design would be substantially heavier and more difficult to operate than the existing 12-wheel profilograph to be considered practical. Thus, only 6- and 12-wheel models will be examined.

For a specified number of supporting wheels, there is only one independent design variable—either the length of main truss or the spacing between supporting wheels. If either one is selected as the independent variable, the other is determined by Equation 13. In this study, the length of the main truss was selected as the independent variable. The effect of this variable on measured pavement roughness was investigated in the same way as described earlier for the California profilograph. The results presenting actual and measured roughness of the test profile as a function of length of main truss are shown in Figure 14. The coefficient of correlation between the actual and the measured profiles is plotted in Figure 15.

Figure 14 indicates that the roughness measuring error for the 12-wheel profilograph is smallest for the main truss 3.7 m (12 ft) long. This length is close to the current design of the Rainhart profilograph, which has a 4.1-m-long (13.5-ft-long) main truss. However, a high sensitivity of the profilograph accuracy to the length of the main truss represented by a steep slope of the error curve in the vicinity of the minimum error point is rather undesirable. A main truss of approximately 4.6 m (15.0 ft) or longer would be much less sensitive.

The roughness measuring error for a 6-wheel Rainhart profilograph is considerably larger for the length of main truss

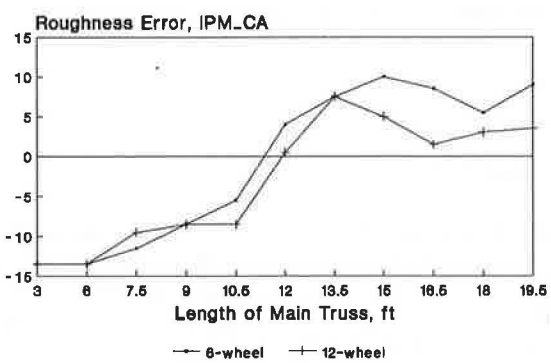

FIGURE 14 Effect of length of main truss on roughness measured with a 6-wheel and a 12-wheel model (Rainhart).

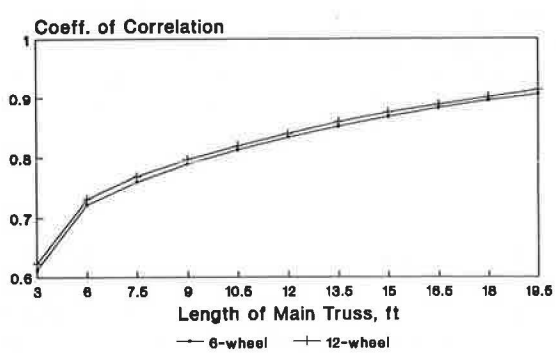

FIGURE 15 Effect of length of main truss on correlation for a 6-wheel and a 12-wheel model (Rainhart).

greater than 3.7 m (12 ft) and it follows the same general pattern as the measuring error of the 12-wheel profilograph. The coefficient of correlation between actual and measured pavement profiles shown in Figure 15 increases with increasing length of the main truss for both 6- and 12-wheel Rainhart profilographs.

CONCLUSIONS

On the basis of the computer simulation results obtained in this study, the following design specifications for road profilographs are recommended:

For the California profilograph,

- Length of the main truss: 9.1 m (30 ft).
- Number of supporting wheels: 6.
- Spacing between supporting wheels: 0.6 to 0.9 m (2 to 3 ft).

For the Rainhart profilograph,

- Length of the main truss: 3.7 to 4.6 m (12 to 15 ft).
- Number of supporting wheels: 12.
- Spacing between supporting wheels: calculated from Equation 13 for the selected values of L_0 and N.

One limitation of the computer model used in this study that may affect these design specifications is the assumption of zero gradient of lateral pavement profile. The presence of significant lateral gradient in the pavement profile would require a greater number of supporting wheels. However, the lateral variation of roughness of new pavements is usually insignificant.

The recommended designs are based primarily on predicted accuracy of roughness measurements. It should be noted that the recommended design of the Rainhart profilograph is much closer to the existing design than it is for the California profilograph.

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