Evaluation of Computation Methods for Accelerometer-Established Inertial Profiling Reference Systems

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Current accelerometer-established inertial profiling reference (AEIPR) methods are reviewed, and their computation methods are evaluated. Four AEIPR were reviewed and computer-simulated to test profile computation. These methods are installed in the K. J. Law Profilometer, the Swedish Road and Traffic Research Institute's (VTI) Laser Road Surface Tester, the University of Michigan Transportation Research Institute/FHWA Road Profiling (PRORUT) system, and the Pennsylvania Transportation Institute profiling vehicle. The South Dakota system was not included when this work started, but it uses a computation method similar to the VTI and PRORUT methods. Seven tests were developed to examine the profiling methods from many angles: amplitude errors, wavelength response, phase shift, transient response, roughness errors, profile reproduction, and computational time.

One of the main concerns of highway agencies is the maintenance and improvement of road surface quality. Highway engineers evaluate pavement conditions to manage maintenance and to support requests for maintenance funds. This evaluation must include (but is not limited to) the factors of safety, pavement performance, pavement distress, and structural capacity (*1*, p. 21). Roughness, a measure of pavement condition, is the main characteristic of the pavement used to describe pavement performance; an effective evaluation requires reliable measurement of road roughness.

ROAD ROUGHNESS AND MEASURING EQUIPMENT

Rough roughness in the United States is measured primarily by two types of equipment: equipment that measures the vehicle's response to roughness, or response-type road roughness meters (RTRRMs), and equipment that measures road profiles, or profiling devices. RTRRMs are not discussed in this paper because they do not measure profiles. Ideally, the road profiling method gives accurate, scaled reproductions of the pavement profile along a reference plane. According to Claros et al., "In practice, the range and the resolution of any profiling device is limited, but within these limits the measurement may be called absolute" (*2*). They also state: "The most universal purpose of these road profile measurements at the present time is to assess the roughness for pavement encountered by motor vehicles" (*3*).

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ROAD PROFILE MEASURING DEVICES

Several devices are used to obtain road profiles: rod and level, dipstick, profilograph, straight edge, and accelerometer-established inertial profiling reference (AEIPR) systems. Profiling vehicles other than AEIPR include the French APL system, British HRM system, Canadian ARAN system, and Nevada Automotive Testing Center's DFMV (*4–9*). These devices are not discussed in this paper.

The rod-and-level method is the most time- and labor-consuming way to measure longitudinal profile (*10*). The dipstick is a new product for measuring profile samples at 1-ft intervals. Although the dipstick is more efficient than the rod and level, it still is considered a static, time-consuming instrument when compared with dynamic road profiling devices.

There are three types of profilograph: the California profilograph, the Reinhart profilograph, and the Ames profilograph (*11–13*). Profilographs do not measure road profiles because their responses are not uniform over the wavelength range of interest (*14*, p. 189).

A straight edge is, in theory, the simplest way of measuring road profile (*1,15*). But it is also a slow way, and the wavelengths measured are limited by the length of the straight edge.

An AEIPR system is usually a vehicle installed with instrumentation that measures the elevation of the road surface along the direction of travel. This technology allows highway engineers to measure road profiles with acceptable accuracy more efficiently than any other road profiling method does. A research study of measurements given in Table 1 shows that the profiling vehicle and the dipstick measurement are within 4 percent of each other.

AEIPR Vehicle

The AEIPR model was invented by General Motors Research Laboratory in 1966 (*17*). This early version of an AEIPR vehicle used a pair of accelerometers to measure left and right vertical acceleration, a pair of spring-loaded "road wheels" (in addition to the traveling wheels) to measure the distance between the vehicle and the pavement, and a tachometer to measure the speed of the vehicle. An analog computer was used to compute the road profile. K. J. Law Engineers, Inc., of Novi, Michigan, acquired a patent license from General Motors and is now the commercial source of the Model 690DNC Surface Dynamic Profilometer.

TABLE 1 ROUGHNESS INDEXES OBTAINED BY DIPSTICK AND AEIPR SYSTEM

Site	Dipstick	AEIPR Profiling Device	Difference in Percentage
4	131.0	129.9	0.84%
5	171.3	169.1	1.28%
6	131.4	130.2	-0.91%
11	92.9	94.4	1.61%
13	128.8	130.3	1.16%
14	124.4	123.9	-0.41%
18	231.1	228.1	-1.29%
25	121.4	122.8	1.15%
26	154.3	148.4	-3.82%

Source: Data provided by Pennsylvania Department of Transportation Bureau Bridge and Roadway Technology. (Measurement date: 9/16/1990)

Note: Roughness indices shown are the averages of left and right tracks.

Roughness is given as the International Roughness Index Standard.(16,26)

Other AEIPR vehicles are currently based on the General Motors design, such as the PRORUT system developed by the University of Michigan Transportation Research Institute (UMTRI) for FHWA, the Laser Road Survey Tester developed by the Swedish Road and Traffic Research Institute (VTI), and the South Dakota system (*18–20*). These systems have similar hardware configurations but use a different displacement transducer and different software for signal processing and profile analysis. A special feature of the VTI design is its data acquisition rate: at 32,000 sample/sec, the macrotexture of the pavement can be recorded and analyzed. Each of these systems can measure rutting to a different degree depending on the number of sensors used.

Many different models of AEIPR vehicles have been made available to highway agencies. FHWA invited companies with different profiling vehicles to measure the same sites and compare their results (*3*). Some transducers are more accurate than others; some signal processing units are more delicate than others. The performance of each profiling vehicle equals the combined performance of all its measurement devices, instrumentation, and profile computation methods. Determination of what instrumentation is to be used in the profiling vehicle was not addressed in this research work.

Objective

The objective of this paper is to evaluate the performance of the profiling computation method associated with each AEIPR available. These methods are used in K. J. Law's 690DNC Surface Dynamic Profilometer, UMTRI/FHWA's PRORUT system, VTI's Laser Road Survey Tester, and the Pennsylvania Transportation Institute's (PTI) AEIPR vehicle (*21*). For the South Dakota system and other devices, computation methods are based entirely or partially on these methods. A computer simulation of each profiling method was performed. All of the profiling methods were subjected to a number of tests with the same criteria and then compared for performance.

REVIEW OF AEIPR METHODS

Spangler's Method in K. J. Law 690DNC Surface Dynamics Profilometer

K. J. Law's 690DNC Surface Dynamics Profilometer is commercially available from K. J. Law Engineering, Inc. The computer measurements are triggered by spatial pulses generated by vehicle wheels. This profiling method was designed to give a real-time profile from measurements that are taken every inch and averaged over a 12-in. interval to provide profile samples of a 6-in. interval. This profiling method applied in the 690DNC was developed by Elson Spangler. The system design and the profile computation methods are detailed and illustrated in a U.S. patent (*22*). The profile computation is based on the following equation:

$$P = (W - Y) + \iint_{x_1}^{x_2} \frac{\ddot{Y}}{V^2}\, ds\, ds \qquad (1)$$

where

P = computed profile,
$(W - Y)$ = instantaneous height measurement (distance from vehicle to pavement),
V = vehicle's instantaneous speed measurement,
ds = integration distance interval (set fixed for 6 in. or otherwise),
$\ddot{Y}$ = vertical acceleration measurement, and
x_1, x_2 = distance traveled corresponding to the adjacent samples.

Processing the acceleration signal does not produce the true inertial reference. It produces the highpass-filtered form of the double-integrated acceleration for removing the low-frequency part of the signal, which is usually for wavelengths longer than 300 ft. From the functional block diagram in the patent description, the equation for the inertial reference can be derived into

$$Y_f(S) = \frac{S}{S^3 + T_1S^2 + T_2S + T_3}\, \mathcal{L}\left\{\frac{\ddot{Y}}{V^2}\right\} \qquad (2)$$

where

$Y_f(S)$ = vehicle's motion history in Laplace domain,
T_1, T_2, T_3 = filter constants determining the cutoff wavelength,
S = Laplace variable, and
$\mathcal{L}$ = Laplace operator.

Equation 2 shows that Spangler's method contains a third-order filter equation. The profile is obtained by either of the following equations:

$$P = (W - Y) + Y_f \qquad (3)$$

$$P = W - (Y - Y_f) \qquad (4)$$

These equations produce a calculated profile with the long-wavelength portion removed.

UMTRI/FHWA PRORUT Method

The UMTRI/FHWA PRORUT system measures both longitudinal and transverse profiles (rut). It incorporates laser infrared noncontact displacement sensors, an analog-to-digital converter, anti-aliasing filters, and a PC. Measurement is triggered by a signal from an inductive distance pickup on one of the wheels. The profile is computed after data acquisition. The computation of slope profile involves six to seven steps:

1. The bias in the acceleration measurement is calculated and subtracted to minimize error after integration.
2. The bias-removed acceleration signal is converted from temporal acceleration into spatial acceleration:

$$\ddot{Y}_s(i) = \frac{\ddot{Y}(i)}{V(i)^2} \quad (5)$$

where

$V(i)$ = ith sample of the vehicle's instantaneous speed,
$\ddot{Y}(i)$ = ith sample of vertical acceleration measurement, and
$\ddot{Y}_s(i)$ = ith sample of spatial acceleration.

3. The spatial acceleration signal is integrated once to obtain a first slope signal:

$$S_1(i) = C_f * S_1(i - 1) + \ddot{Y}_s(i) * \Delta s \quad (6)$$

where $S_1(i)$ is the ith sample of first part of slope profile from acceleration measurement and Δs is the distance sampling interval. C_f is given by

$$C_f = 1 - \frac{\Delta s}{\lambda_f} \quad (7)$$

where λ_f is the longest wavelength of interest.

4. The height measurement is differentiated once with a highpass filter to obtain a second slope signal:

$$S_2(i) = \frac{C_f * H(i + 1) - H(i)}{\Delta s} \quad (8)$$

where $S_2(i)$ is the ith sample of the second part of slope profile from height measurement and $H(i)$ is the ith sample of height measurement.

5. The first and the second slope signals are added to obtain slope profile

$$S(i) = S_1(i) + S_2(i) \quad (9)$$

where $S(i)$ is the ith sample of the slope profile.

6. If roughness is the desired result, no further processing of the data is required. The slope profile is used for roughness computation. If the road profile is desired, the slope profile is integrated backward with the same highpass filter so that the phase lag from the previous integration is canceled. Because the profile computation is a postprocessing, the integration can be performed backward. The profile is

$$P(i) = C_f * P(i + 1) + S(i) * \Delta s \quad (10)$$

where $P(i)$ is the ith sample of computed profile.

7. If the road profile is plotted, a highpass filter with moving average algorithm is applied to remove the long-wavelength portion in the profile.

VTI Profiling Method

The VTI method is currently used in the Laser Road Surface Tester (*20,23*). The method is a variation of the Sayers time-domain method used in South Dakota's system (M. W. Sayers, personal communication, June 1989) with a high-order filtering process. The measurements are triggered by a constant frequency of 32,000 Hz while the profilometer is traveling. All the signals are passed through an anti-aliasing filter before the digitizing process begins. The signal processing is described in the following steps:

1. The acceleration signal is integrated and highpassed by a second-order filter. The transfer function of the filter is

$$F_{hp}(S) = \frac{S^2}{S^2 + 2\,DS + \omega_n^2} \quad (11)$$

where

$F_{hp}(S)$ = filter transfer function in Laplace domain,
D = damping characteristics of the filter,
ω_n = natural frequency of the filter or the cutoff frequency, and
S = Laplace variable.

Combining the integration and filtering process yields

$$VSM(S) = \frac{\mathcal{L}\{\ddot{Y}\}}{S} \cdot \frac{S^2}{S^2 + 2\,DS + \omega_n^2} \quad (12)$$

where $VSM(S)$ is the vertical velocity of profilometer body in Laplace domain and $\mathcal{L}\{\ddot{Y}\}$ is the Laplace transform of vertical acceleration measurement.

2. The height measurement is differentiated and highpass-filtered

$$HDD(S) = F_{hp}(S) * H(S) \quad (13)$$

$$HD(S) = S * HDD(S) \quad (14)$$

where

$HD(S)$ = highpass-filtered and differentiated height signal in Laplace domain,
$HDD(S)$ = intermediate variable in Laplace domain, and
$F_{hp}(S)$ = highpass filter function in Laplace domain.

3. The profile slope is the combination of time-domain samples of Equations 12 and 14 as follows:

$$YD(i) = \frac{VSM(i) - HD(i)}{V(i)} \quad (15)$$

where $YD(i)$ is the ith sample of profile slope and $V(i)$ is the ith sample of vehicle speed measurement.

4. The time-domain profile slope must be mapped into a spatial domain. This is accomplished by an interpolation process. The distance traveled is given by

$$X(i) = X(i-1) + V(i) * \Delta t \tag{16}$$

When $j \cdot \Delta s$ falls in the distance interval between $X(i-1)$ and $X(i)$, the value T can be determined as

$$T = \Delta t \cdot \frac{j\Delta s - X(i-1)}{X(i) - X(i-1)} \tag{17}$$

The interpolation is given by

$$SP(j) = YD(i-1) + [YD(i) - YD(i-1)] \cdot \frac{T}{\Delta t} \tag{18}$$

where

j = sampling index for desired sampling distance interval,
$T < \Delta t$ = time that maps the distance $j\Delta s$ with the traveled distance,
$SP(j)$ = jth sample of spatial profile slope, and
Δs = desired sampling distance.

5. The slope profile is integrated and highpass-filtered by a third-order filtering process. The filter transfer function is defined by

$$F_3(S) = \frac{1}{S + \omega_n} \cdot \frac{S^2}{S^2 + 2DS + \omega_n^2} \tag{19}$$

and the profile is obtained by

$$P(S) = SP(S) * F_3(S) \tag{20}$$

where

$SP(S)$ = slope profile in Laplace domain,
$P(S)$ = profile in Laplace domain, and
$F_3(S)$ = third-order filter transfer function in Laplace domain.

All these filtering and profile computation processes are programmed in a TM32010-RST chip to perform high-speed, real-time signal processing. In this paper, these equations were coded in FORTRAN and computer-simulated.

PTI AEIPR Profiling Method

This profiling method was developed for use at PTI by Pong (*21*). The method was designed to work with off-the-shelf equipment such as the data acquisition A/D board, analog filters, and an IBM-compatible PC; no custom-made instrument is needed. The profile computation algorithm includes a double-integration routine for processing acceleration signals and a highpass filter routine to remove unwanted low-frequency profiles. Two accelerometers are used to acquire left and right vertical acceleration; Selcom noncontact displacement sensors are used to acquire the vehicle's instantaneous height above the pavement surface; and a pulse encoder is used to measure the vehicle's speed. A digital computer installed with an A/D converter records, processes, and stores the signals from all sensors. Analog filters are used to eliminate the unwanted aliasing effects.

Three steps for signal processing were performed. First, acceleration signals were double-integrated over the time period for the vehicle to pass the distance sampling interval. The time period was obtained by dividing the distance interval by the instantaneous speed. In equation form, the three steps are

$$\dot{Y}_i = \ddot{Y}_i \Delta t + \dot{Y}_{i-1} \tag{21}$$

$$Y_i = \dot{Y}_i \Delta t + Y_{i-1} \tag{22}$$

$$\Delta t = \frac{\Delta x}{V_i} \tag{23}$$

where

$\ddot{Y}_i$ = ith sample of vertical acceleration measurement,
Y_i = ith sample of double-integrated acceleration or the inertial reference,
V_i = ith sample of vehicle speed measurement, and
Δx = distance interval.

Second, both the integrated signals and the height signals pass digital highpass filters to remove profiles with wavelengths longer than 300 ft as well as the integration drift and low-frequency noise caused by the analog instrument.

$$Z_i = a_{21}Z_{i-1} + a_{22}Z_{i-2} + b_{20}Y_i + b_{21}Y_{i-1} + B_{22}Y_{i-2} \tag{24}$$

$$G_i = a_{21}G_{i-1} + a_{22}G_{i-2} + b_{20}H_i + b_{21}H_{i-1} + B_{22}H_{i-2} \tag{25}$$

where

Z_i = ith sample of the after-filtered version of signal Y_i,
H_i = ith sample of the before-filtered version of height measurement,
G_i = ith sample of the after-filtered version of signal H_i, and
a, b = filter constants.

Third, the profile is the sum of both the filtered integrated acceleration and height signals. The sum of both signals represents the effect of adding the longer-wavelength portion of the profile measured by accelerometers and the shorter portion measured by height sensors.

$$P_i = Z_i + G_i \tag{26}$$

where P_i is the ith sample of computed profile.

Summary of Profiling Methods

Table 2 summarizes the four profiling methods with regard to their collection of signals, sampling mode, types and orders

TABLE 2 SUMMARY OF FEATURES REGARDING DATA ACQUISITION AND PROCESSING OF AEIPR METHODS

	PRORUT	VTI	Spangler	Pong
Signals Required	A H V	A H V	A H V	A H V
Sampling Base	S	T	S	S
Integration Domain	S	T and S	S	T
Number of Filters[a]	2	2	1	1
Type of Filter	B	B	B	B
Orders of Filters	1 and 1	2 and 3	3	2
Filtering Domain	S	T and S	S	S
Real-Time Profile	No	Yes	Yes	Yes
Special Hardware[b]	No	Yes	Yes	No

Abbreviations:
A: Acceleration H: Height
V: Vehicle Velocity B: Butterworth
T: Time S: Spatial

[a] "Filter" refers to the digital filter to process the digitized signals up to elevation profile. All methods are equipped with the anti-aliasing analog filters before signals are digitized.

[b] "Special hardware" refers to the hardware that is not available from sources other than the profilometer manufacturer.

of digital filters, and whether they are computed in real-time or postprocessed. From this table, the essential features can be seen clearly and referred to for comparing the test results.

EVALUATION OF AEIPR METHODS BY COMPUTER SIMULATION

To establish a reference for comparison, the following items were required: a common set of input data, a computer quarter-car simulation to calculate road profile data into accelerometer as well as height sensor signals, and a set of tests to evaluate their performance.

Preparing Common Data Base

The common data provided for all profiling analysis methods were a road profile with the appropriate distance interval (an array of real numbers with intervals of 0.5 or 1.0 ft). The selection of the profile data was intended to achieve each of the evaluations proposed and explore the performance as well as the weakness of each profiling method.

The common data sets include a single-wavelength sinusoidal profile, a multiwavelength profile, a step, and real sampled road profiles. The single-wavelength sinusoidal profile was used to evaluate precision. The multiwavelength profile was used to find the response function and phase shift of each method to the wavelength range of interest. The step was used to identify the transient response of each method. The actual profile was used to examine how well each method produced the original profile. The actual profile was also used to calculate a roughness index, which was used to evaluate the overall performance.

Quarter-Car Model Simulation

A quarter-car computer model simulation was applied to transfer road profile data into a transducer signal of the vehicle's vertical acceleration and height above the pavement. The method and differential equations for this simulation model are given in ASTM E1170-87.

A computer routine was coded to accept profile data as input. Using an assumed vehicle speed of 40 mph, both the acceleration and height were obtained digitally, with a third-order Runge-Kutta integration algorithm, for use as input to the different computation methods (*23*).

Design of Tests for Evaluating Profiling Methods

Seven tests were prepared to analyze the performance of each profiling method: amplitude errors, frequency response, transient response, phase shift, international roughness index (IRI) error, profile reproduction, and computation time.

Amplitude Errors

The amplitude error test was done to validate the correctness of profiling program coding, to calibrate the orientation of sensors, and to determine if the amplitude error was frequency-dependent. A set of input data generated by simulating the vehicle's bouncing was provided for each method to compute the profile. The bounce test assumed that the profiling vehicle did not travel but vibrated vertically with a certain amplitude and at designated frequencies. In other words, a sinusoidal vertical displacement was imposed on the vehicle body, and the corresponding acceleration was generated accordingly. In this test, the displacement amplitude was 1 in. and the frequencies used were 0.1, 0.25, 0.5, 1, 2, 5, and 10 Hz. The sampling time was selected to set the corresponding speed and sampling distance.

Wavelength Response Function

The purpose of the wavelength response function test was to determine the amplitude ratio (output versus input) of each profiling method as it responded to different wavelengths. A sinusoidal profile with an amplitude of 1 in. and a wavelength range from 10 to 500 ft was provided as input to the quarter-car simulation to generate the necessary sensor's signals. Each profiling method computed a profile based on the same input. The amplitude of the computed profile represented the amplitude ratio. A plot of the wavelength response function was obtained for each profiling method.

Phase Shift

The phase shift test was given to observe the phase changes for profiles of different wavelengths. The phase is the relative phase angle between the original and computed profiles. A series of sinusoidal profiles of 1-in. amplitude with wavelengths from 10 to 500 ft was used. The phase shift was recognized as the time delay or advance of the computed profile with respect to the input of each wavelength. A plot of phase shift angle for various wavelengths was obtained for comparison of the methods.

Transient Response

The transient response test was intended to determine how these profiling methods behave in response to a sudden elevation change. Because all profile computation method incorporate their own highpass filters to remove LWL profile and lowpass filters to eliminate noise (Spangle and PRORUT methods), a sudden elevation change of road profile can cause the filter to overshoot and ring. A step of 1 in. was provided as input to test the behavior of each profiling method. In the computed profile, the amount of overshooting and the distance (or time) required to settle to 5 percent of input amplitude was used as its transient response performance.

IRI Errors and Profile Reproduction

Samples of real profiles obtained by using a dipstick method were used as input for a quarter-car simulation that generated the signals for all profiling methods. The computed profiles were used to calculate the IRIs as well as for comparison to the original profile. For the PRORUT and VTI methods, the IRIs are computed from slope profiles without going through the final elevation profile integrating procedure. The IRIs from the original profile and each computed profile were observed and compared. The profile reproduction was observed by comparing the computed profile with the filtered original profile.

Computation Time

The purpose of this test was to determine the amount of time required to actually compute the profile. The results showed which methods were less time-consuming and more suitable for real-time profiling application. The computation time required for processing 5,280 profile samples was obtained for each method and compared.

Speed Sensitivity

The speed sensitivity test was included in a previous thesis study (*24*). It was found to be unnecessary in the current study because a computer simulation of perfect data preparation has no error due to speed variation. However, in the real profiling system, the speed compensation is variable because of the speed measurement and hardware effects. Therefore, speed sensitivity should be included if the complete profiling system is to be evaluated.

Computer Simulation of Profiling Methods

The four profiling methods were coded into FORTRAN subroutines with an identical input and output parameters format. The programs were coded according to their original programs with minor adaptations so as to be compatible with the Microsoft FORTRAN compiler. Single precision was used. The computation method developers were consulted to verify the correctness of their profiling programs and the results of their method.

The sampling distance was generally set at 0.5 ft, but the VTI method used 0.05 in. because the actual sampling is 32,000 sample/sec, averaging over a number of samples. For Spangler's method, the profilometer's sampling rate was every inch, averaging more than 12 in. For the PRORUT and Pong methods, the user set the sampling distance at 0.5 in. for the final profile report. A main program for each test was coded to call all subprograms to perform the same test on the same data base. The results of all profile computations were to be stored in a file for later plotting and analysis.

Test Results and Findings

The results of the bounce tests were tabulated for easy comparison in Table 3. The error generally increased as the vehicle's bouncing frequency neared the sampling interval. The sum of the absolute error of each frequency is given to identify the overall error. Spangler's and Pong's methods have the least amplitude errors.

The profile wavelength responses of all four methods are plotted with the same scale in Figure 1 for comparison. The VTI method had the steepest roll-off because it has the highest-order filter, which was a cascade of two filters in a series. Spangler's method is the next highest in roll-off. PRORUT's and VTI's responses fall off in the range of 10 to 70 ft, which corresponds with the quarter-car's resonance frequency at 40 mph. This is consistent because both methods were based on the same design. The plot shows a uniform response for the VTI method because it was simulated using a finer interval.

The results of the phase shift are plotted in Figure 2. As expected, the phase shift was found to be proportional to the order of the filtering process. The PRORUT had almost no phase shift.

The results of the step response test are plotted in Figure 3. The amount of overshoot and the settling time in the transient test were found to be proportional to the order of the filter in each method. A quadratic-curve removing process was performed on the PRORUT's step response because of its runaway due to low-order filtering. The PRORUT has the highest fidelity with respect to long wavelength. After the PRORUT method, Pong's method has the least overshooting and fastest settling time, followed by the Spangler and VTI methods.

The percentage roughness errors from the original profile for all sample sites are plotted in Figure 4*a*. A closer comparison was conducted by filtering the original profile to remove the long-wavelength parts and resubmitting the filtered

TABLE 3 AMPLITUDE RATIO OF INITIAL TEST

	Frequency (cycles per second)							
	0.10	0.25	0.50	1.00	2.00	5.00	10.0	Sum of Errors
PRORUT[a]	1.0708	0.8691	1.0251	0.9803	0.9861	0.9976	1.0232	0.0408
VTI-2	1.0074	1.0075	1.0075	1.0077	1.0084	1.0110	1.0323	0.0104
Spangler	1.0000	1.0000	1.0001	1.0002	1.0010	1.0060	1.0242	0.0045
Pong	1.0003	1.0001	0.9999	0.9991	1.0001	1.0065	1.0238	0.0045

Note: Value represents the ratio of the profiles computed by blocking out acceleration or height signal.

[a] PRORUT method does not have high-order lowpass filter to remove the integration runaway; the author had to use statistical methods to purify the post-integrated results for this purpose.

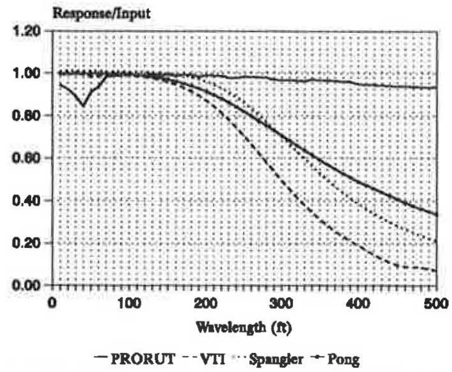

FIGURE 1 Comparison of wavelength response of AEIPR methods using computer simulation at simulation speed of 40 mph.

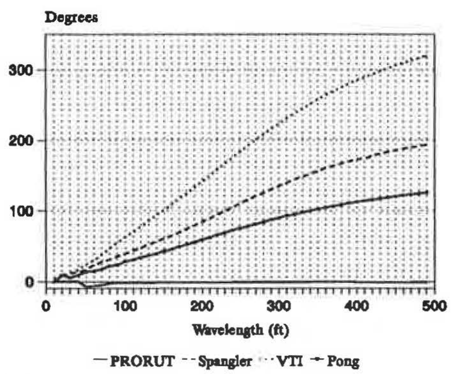

FIGURE 2 Comparison of phase shift of AEIPR methods using computer simulation at simulation speed of 40 mph.

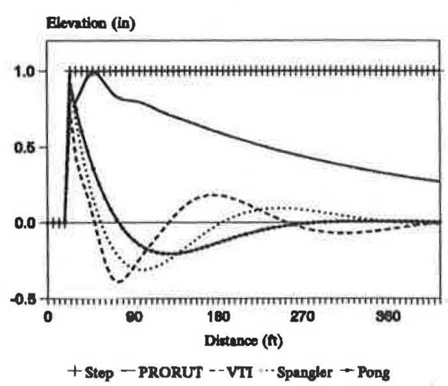

FIGURE 3 Comparison of step response of AEIPR methods using computer simulation at simulation speed of 40 mph.

profile for roughness reproduction. The plots with filtered original profile are given in Figure 4*b*. The difference in error magnitude was due to the removal of the long-wavelength profiles, which contribute a certain amount of roughness.

One test site was chosen as a profile for visual comparison with the reproduced profiles. The original and the reproduced profiles are plotted in Figure 5. The criterion for evaluation was the sum-of-square-error between the reproduced and the

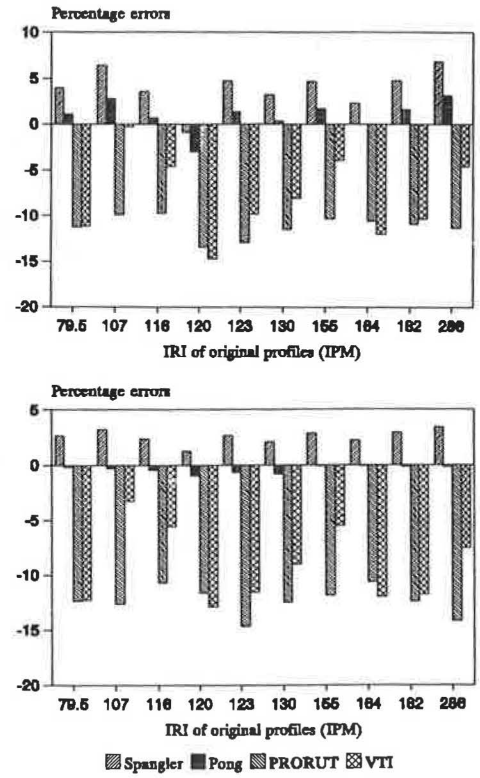

FIGURE 4 Percentage IRI errors of AEIPR methods using as references original profiles as reference, *top*, and highpass-filtered profile, *bottom*.

original profiles. The PRORUT method came the closest to reproducing the original profile, followed by the Pong, Spangler, and VTI methods. It should be noted that the errors are larger if more long-wavelength profiles are removed or distorted from the original profile.

The times required to compute 5,280 profile samples are for Spangler, 2.25 sec; Pong, 2.36 sec, PRORUT, 2.91 sec; and VTI, 6.86 sec. The result was obtained using an Intel 8088 with 8087 processors. Spangler's method is the least time-consuming, and Pong's comes in a close second. Both were

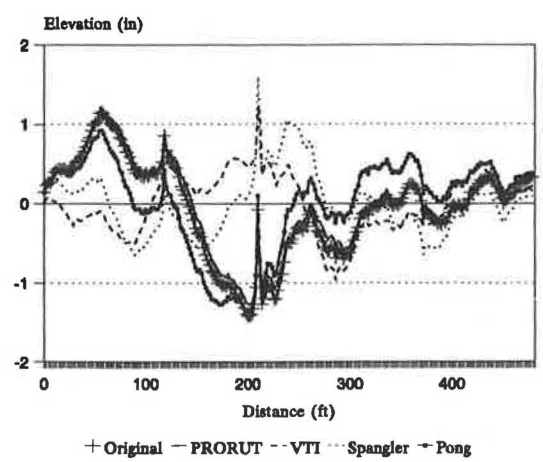

FIGURE 5 Comparison of road profile reproduction by AEIPR methods.

programmed for real-time profiling. VTI's method took the longest, but the VTI commercial system incorporates a real-time digital signal process (DSP) unit to compute profile and requires virtually no time.

Grading of Test Results

Each test result in the evaluation was given a performance index from 1 to 4 (worst to best) based on its ranking. For the amplitude errors test, both the Spangler and Pong methods had the same scores for their absolute error sum. For wavelength response, there was no preference as to how steep the long-wavelength profiles were to be filtered out. The results in this column were better for the lower filter order because filtering is a cutback in measurement fidelity. For phase shift response, the smaller the phase was, the higher the score. For IRI errors, the smaller the error was, the higher the score. The score for the profile reproduction was evaluated by the sum-of-square-error between the reproduced and the original profiles: the smaller the square error, the higher the score. For computation time, the shorter the time, the higher the score. The VTI method was an exception. VTI uses DSP hardware to perform the operation parallel in real-time and took virtually no computer time, which is reflected in the cost of the system.

Two kinds of summary analyses can be conducted: an analysis with equal weight or an analysis with unequal weight. Because the weighted analysis can vary from one to many possible combinations, other researchers can easily perform the analysis with their chosen weight based on these test results. In this paper, two cases were performed in summarizing the scores of the test performance: (a) a summary using equal weight shown in Table 4, and (b) a summary using selected weight. Based on PTI's needs for a profiler, the weight and the weighted scores are listed in Table 5. The sums of the indexes are close for three of the methods. Other users may have different requirements for their profilers and assign different weights for their needs, so these differences are likely to change the evaluation results. For example, if the user puts significant weight on the profile reproduction, the PRORUT system may be chosen. If the weight is on the IRI errors, either the Spangler or the Pong method may stand out. If the user prefers high-speed profiling with texture report, VTI is the only possible method. The profiling devices installed with profiling method of low scores in this evaluation do not necessarily produce unreliable measurements. The quality of a profile measurement also relies on the performance of the overall hardware instrumentation; only a good profiling method combined with precision instrumentation can provide a reliable profile measurement. Choosing the suitable method is as important as choosing the hardware. Once a good method is chosen, high cost-effectiveness will be the reward.

TABLE 4 SUMMARY OF PERFORMANCE RANKING SCORES OF AEIPR COMPUTATION METHODS

	Ampl. Errors	W.L. Resp.	Phase Shift	Step Resp.	IRI Errors	Profile Repr.	Computer Time	Sum of Indices
PRORUT	1	4	4[a]	4[a]	2	4	2	21
VTI	2	1[b]	1	1	1	1	1[c]	8
Spangler	3.5	2	2	2	3	2	4	18.5
Pong	3.5	3	3	3	4	3	3	22.5

[a] PRORUT method does not have a high-order lowpass filter to remove the integration runaway. The results were achieved with a quadratic curve removal procedure for the purpose of comparison.

[b] The result was obtained by setting VTI's sampling distance interval at 0.05 in; all others were set at 0.5 in. If it had been the same interval as the others, the pass band would be similar to PRORUT's.

[c] The VTI system used a Digital Signal Process (DSP) unit to compute the profiles in real time.

TABLE 5 SUMMARY OF PERFORMANCE RANKING SCORES OF AEIPR COMPUTATION METHODS USING PTI SELECTED WEIGHT

	Ampl. Errors	W.L. Resp.	Phase Shift	Step Resp.	IRI Errors	Profile Repr.	Computer Time	Sum of Indices
PTI Weight	1.5	1.1	0.5	0.3	1.5	0.9	0.2	
PRORUT	1.5	4.4	2	1.2	3	3.6	0.4	17.3
VTI	3	1.1	0.5	0.6	1.5	0.9	0.2	7.8
Spangler	5.25	2.2	1	0.3	4.5	1.8	0.8	15.85
Pong	5.25	3.3	1.5	0.9	6	2.7	0.6	20.25

CONCLUSION

In this paper, six computer simulation profiling performance tests were performed using four profile computation methods. The performances of the four methods were compared using a weight of 1 on each comparison. However, each comparison is not equal, and individual users must choose their own relative weights for what is important to them. The best AEIPR method can be identified only when the weights on the tests are chosen. The test results are provided as a reference for those concerned with selecting a profiling method for highway survey or research applications.

REFERENCES

1. J. C. Wambold, L. E. Defrain, R. R. Hegman, K. McGhee, J. Reichert and E. B. Spangler. State of the Art of Measurement and Analysis of Road Roughness. In *Transportation Research Record 836*, TRB, National Research Council, Washington, D.C., 1982.
2. G. J. Claros, W. R. Hudson, and C. E. Lee. *Performance of the Analog and the Digital Profilometer with Wheels and with Non-Contact Transducers.* Research Report 251-3F. Center for Transportation Research, University of Texas, Austin, April 1985.
3. M. W. Sayers and T. D. Gillespie. *The Ann Arbor Road Profilometer Meeting.* Report FHWA/RD-86/100. FHWA, U.S. Department of Transportation, 1986, pp. 1–2.
4. Report of Technical Committee on Slipperiness and Evenness. *Proc., 15th Congress, Permanent Association of Road Congresses,* Mexico City, Mexico, and Paris, France, 1975.
5. R. S. Dickerson and D. G. W. Mace. *A High-Speed Road Profilometer: Preliminary Description.* TRRL Report SR 182UC. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1976.
6. P. B. Still and M. A. Wennett. *Development of a Contactless Displacement Transducer.* TRRL Report LR690. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1975.
7. D. R. C. Cooper, *Measurement of Road Surface Texture by a Contactless Sensor.* TRRL Report LR639. U.K. Transport and

Road Research Laboratory, Crowthorne, Berkshire, England, 1974.
8. *A New Roughness Measurement System*. Highway Product International. R. R. #1. Paris, Ontario, Jan. 1986.
9. S. C. Ashmore and H. C. Hodges, Jr., *Dynamic Force Measurement Vehicle and Its Application to Measuring and Monitoring Road Roughness*. Nevada Automotive Testing Center, 1991.
10. C. B. Breed. *Surveying*, 3rd ed. John Wiley and Sons, Inc., New York, N.Y., 1977, pp. 91–107.
11. J. H. Woodstorm. The California Profilograph. *Proc., ASTM Symposium on Measurement Control and Correction of Pavement Roughness in Construction*, Phoenix, Ariz., Dec. 1982.
12. *Operation of California Profilograph and Evaluation Profiles*. Test Method Calif. 526-E. State of California Department of Public Works, Division of Highways, Sacramento, Oct. 1972.
13. R. S. Walker and H. T. Lin. *Automated Pavement Data Collection Profilograph Correction Study with Present Serviceability Index*. Report FHWA-DP-72-3. FHWA, U.S. Department of Transportation, 1987.
14. B. T. Kulakowski and J. C. Wambold. *Development of Procedures for the Calibration of Profilographs*. Report FHWA-RD-89-110. FHWA, U.S. Department of Transportation, 1989.
15. F. N. Hveem. Devices for Recording and Evaluating Pavement Roughness. *Bulletin 264*, HRB, National Research Council, Washington, D.C., 1960, pp. 1–26.
16. M. W. Sayers, T. D. Gillespie, and W. D. O. Paterson. *The International Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements*. World Bank Technical Paper 45. Washington, D.C., Jan. 1986.
17. J. R. Darlington and P. Milliman. A Progress Report on the Evaluation and Application Study of the General Motors Rapid Travel Profilometer. In *Highway Research Record* 214, HRB, National Research Council, Washington, D.C., 1968, pp. 50–67.
18. M. R. Hegman and M. W. Sayers. *Reference Manual for the UMTRI/FHWA Road Profiling (PRORUT) System*. Report FHWA-RD-87-004. FHWA, U.S. Department of Transportation, 1987.
19. D. L. Huft. *Description and Evaluation of South Dakota Road Profiler*. Report FHWA-DP89-72-002. FHWA, U.S. Department of Transportation, Nov. 1989.
20. P. W. Arnberg. *The Laser Road Surface Tester (RST): Synopsis of Presentation in Sydney and Melbourne, Australia*. March 1986.
21. M. M. Pong. *The Development of an Extensive-Range Dynamic Road Profile and Roughness Measuring System*. Ph.D. thesis. Department of Mechanical Engineering, Pennsylvania State University, University Park, 1992.
22. E. B. Spangler. Method and System for Measurement of Road Profile. U.S. Patent 4,422,322, issued Dec. 27, 1983.
23. A. J. Cadzow and R. H. Martens. *Discrete-Time and Computer System*. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1970, pp. 383–387.
24. J. J. Lu. *Evaluation of Road Profile Computation Methods*. M.S. thesis. Department of Mechanical Engineering, Pennsylvania State University, University Park, 1989.
25. M. W. Sayers, T. D. Gillespie, and W. D. O. Paterson. *Guidelines for Conducting and Calibrating Road Roughness Measurements*. World Bank Technical Paper 46. Washington, D.C., Jan. 1986.

DISCUSSION

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It is to be regretted that VTI was not given the opportunity to review this report prior to presentation, although it is said that "The developers were consulted to verify the correctness of their profiling programs and the results of their method." The VTI method for computing IRI and the highpass-filtered profile has thus not been interpreted correctly in the paper.

Already, on April 17, 1989, when VTI commented on the subroutine VTIPROF for the purpose of a similar PTI study by Jiunn-Jye Lu (who came to completely different results), we remarked that ω_n is set to the constant value of 0.25 in the second-order filter in the time domain. In the program used in the paper the cutoff frequency for this filter is set to the frequency corresponding to the cutoff wavelength 300 ft when the simulated speed is 40 mph, that is, $\omega_n = 1.23$. The same cutoff wavelength is also used for the third-order filter in the spatial domain.

An easy test of the function of the measurement method is to perform a so-called bounce test, meaning that the test vehicle will be put in a vertical bouncing mode while stationary. The profile output shall be a straight line. In the paper this test was simulated by blocking out the acceleration or the height signal and the error calculated as the ratio between the two signals thus generated. However, this method does not consider the effect of the phase shift between the signals. A correct bounce test performed at 1-Hz bounce frequency gives the error 0.0008, as compared with 0.0077 in Table 3. At 10 Hz, the error is about 0.005, as compared with the 0.03 found by the authors.

The use of the same cutoff wavelength in the second-order and the third-order filters in effect means that the VTI method is supposed to use a fifth-order filter—or even sixth, as was said at the presentation. This will of course very much influence the wavelength, phase shift, and step response, as illustrated in Figures 1 through 3.

This wrongly calculated highpass-filtered profile is then used for the calculation of IRI, resulting in too low a value, as illustrated in Figure 4. In the Laser RST, the IRI values furthermore are always calculated from the slope profile.

The use of the incorrectly simulated filtering process also has an adverse effect on the profile reproduction, as illustrated in Figure 5. It should also be pointed out that this comparison is meaningless, or at least not fair, because the PRORUT profile is linearly filtered and the VTI and Spangler profiles are not; as for the Pong profile, we do not know. Figure 6 shows that if the VTI profile is linearly filtered, the agreement with a profile established by rod and level or dipstick is excellent.

We do not understand the significance of the calculated time for computing 5280 profile samples. It seems more to be characteristics of the simulation programs used than for the measurement devices studied. About the VTI system, it works in real time and consequently makes the calculations within the time limits required in each case, at measurement speeds up to 90 km/hr. This is also observed by the authors.

CONCLUSION

Our conclusion is that the evaluation of the VTI system as presented is incorrect because the processing of the input data is not in concordance with the actual procedures used in the Laser RST. Although this is only a theoretical analysis of different methods, all divergences from the original procedures must be clearly stated so that the readers will be given the possibility to judge for themselves.

COMMENT

As is pointed out in the paper, the VTI system is a real-time measurement method; it is possible to store the computed slope profiles and also highpass-filtered profiles as a function

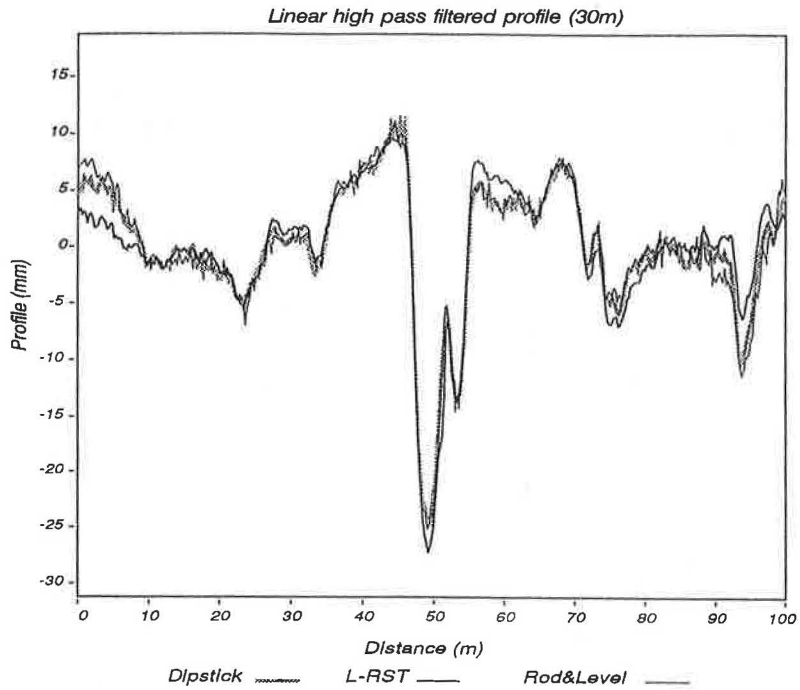

FIGURE 6 Linear highpass-filtered profile (30 m).

of distance. By postprocessing it is subsequently possible, for example, to obtain a linear phase response of the highpass-filtered profile by backward filtering or to choose another filter order or cutoff wavelength for the filter in the spatial domain.

AUTHORS' CLOSURE

The study performed by Jiunn-Jye Lu at PTI in 1989 was found to lack a few installments in the quarter-car simulation model. After the problem was identified and corrected, a second paper was written that also included comments from the readers of the original paper. The VTI-method computer simulation program used in this paper was reviewed and corrected by VTI staff in 1988. We have been using this version since. Unless there were more improvements made in this period, the results presented in the paper should be reliable.

We all know that each road profiling system has different filter. The cutoff wavelength of the filter can always be adjusted to get the best result for wavelength range of interest. In this paper, we wished to make the comparison straightforward by using the same cutoff wavelength for all methods, so a 300-ft wavelength was used. The results presented in the paper matched the order of filter in each method theoretically. VTI used a second- and a third-order (a fifth-order) filter. Please allow me to apologize that I mistakenly called it a sixth-order filter in the presentation. We fully understand that each method could be optimized by choosing the filter cutoff setting, but to compare the methods we used the same for all because we did not know the optimal setting in some cases.

The bounce test was performed using computer simulation. The purpose of blocking out one of the sensors was to avoid any alteration of the original program codings for extracting only one signal. No careful phase-matching procedure was done to any profiling method. The different results that VTI presented in the discussion might be from a different approach. However, the procedures for testing all four methods were identical.

The IRIs in the original paper were calculated from the profile according to the Mike Sayers procedure presented in the World Bank paper. I took time to recalculate the IRIs from the slope profiles according to the original VTI and PRORUT specification. The results showed no significant difference to the original.

The purpose of the profile visual comparison presented in Figure 5 was to show that the amount of profiles of long wavelengths was removed from the original. Theoretically, the VTI method contains a "fifth-order" filter that is the highest of any method and thus attenuates the most when the same cutoff settings are used. The computer simulation shows the proof.

The paper explained exclusively that the computation time was the time requirement for a profiling method to finish 5280 profile samples in a IBM-PC XT with math coprocessor. In the heavily computer-aided engineering stage, computation efficiency is also a factor to be observed. Because all profiling systems are computer-processed, we felt the need to look into this aspect. We had made it clear that VTI use a real-time DSP unit in the paper, regardless of the comparison.

I wish to thank the VTI for pointing out the typing errors in the paper. I have made the correction in the final revision. However, there was no such mistake in the computer simulation program.

CONCLUSION

As I have clearly stated in the paper: the readers should judge for themselves of the evaluation procedures and the results presented in this paper. Readers must perform a final evaluation based on their own needs.

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