CURRENT CALIFORNIA PROFILOGRAPH SIMULATIONS AND COMPARISONS

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ABSTRACT

Many agencies within the Department of Transportation (DOT) have developed and used profiling equipment for pavement roughness. In airfield and highway pavement, one of the most popular devices for newly constructed pavement roughness evaluation is the California profilograph that has been used since 1940. Along with the developments and improvements of the devices, the software for processing pavement profile data and computing roughness indexes corresponding to the profiles was needed. The Federal Aviation Administration (FAA) took measurements of the same pavement profiles utilizing a California profilograph and a FAA developed inertial profiler at the National Airport Pavement Test Facility (NAPTF) for comparison. The FAA developed roughness software ProFAA that reads and analyzes pavement profiles used the acquired profiles from the FAA profiler to simulate the movement of the profilograph recording wheel and calculate a Profile Index (PI). The mechanical simulation of the wheel responses are compared with directly measured profiles from the profilograph. In addition, the profilograph simulation and PI results from ProFAA are compared with those from the Federal Highway Administration (FHWA)'s software ProVal using the same profiles from the FAA profiler. The ProFAA and ProVal profilograph simulation methods are also compared using typical airfield and highway profile data sets.

INTRODUCTION

Many agencies within the DOT have developed and used profiling equipment for pavement roughness evaluation. Roughness is also referred to as "smoothness" although both terms refer to the same pavement qualities. The profilograph is one of the most popular devices used for construction quality control of pavements over the last several decades. In the mid-1980's, computerized data collection was introduced to record and analyze the pavement surface profile. In many instances, the profile index has become a standard index for smoothness measurement in construction specifications. Operationally, pavement profiles are typically measured with high-speed inertial profilers for computing roughness indexes corresponding to the California profilograph.

The Federal Aviation Administration (FAA) has developed an inertial profiler and software, ProFAA, that reads and analyzes pavement profile data and computes a variety of pavement profile indexes. Measurements of the same pavement profiles utilizing a California profilograph and the FAA developed inertial profiler were taken at the National Airport Pavement Test Facility (NAPTF) for comparison of index calculations. The acquired profiles from the FAA profiler were used to simulate the movement of the profilograph's recording wheel and a Profile Index (PI) was calculated. The mechanical simulation of the wheel responses were compared to the directly measured profiles from the California profilograph. In addition, the California profilograph simulation and PI results from ProFAA were compared with those from the Federal Highway Administration (FHWA)'s software, ProVal, using the same profiles from the FAA profiler. The ProFAA and ProVal profilograph simulation methods were also compared using typical airfield and highway profile data sets.

PROFILING DEVICES

The FAA profiling device has the typical components of a modern inertial profiling device used to measure highway profiles as reported in Song and Hayhoe [1]. Figure 1 shows a non-contact vertical displacement transducer (laser) used in the FAA device.

Figure 1. Non-Contact Vertical Displacement Transducer.

The NAPTF also utilizes a typical truss type California profilograph manufactured by Surface Systems & Instruments, LLC (SSI) as shown in Figure 2. ProFAA simulates the same mechanical configurations as this device.

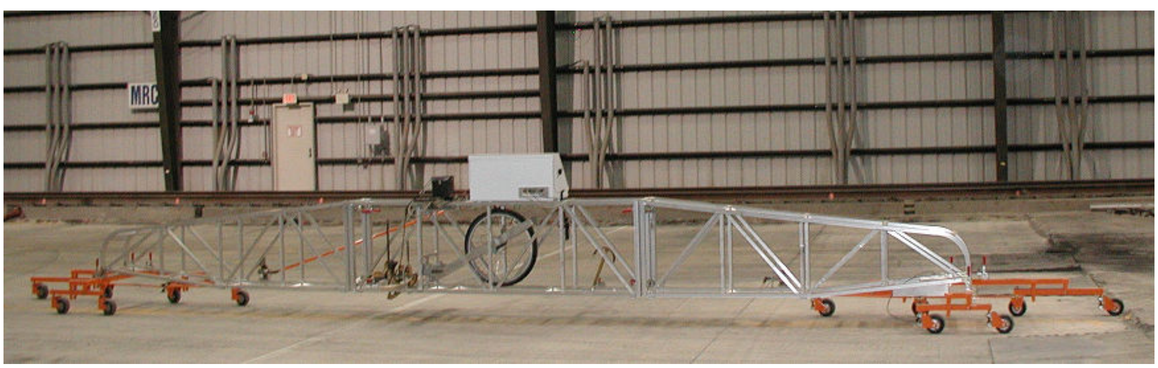

Figure 2. The FAA California Type Profilograph.

PROFILE MEASUREMENTS

Pavement profiles were measured with the FAA profiler and CA profilograph on Portland Cement Concrete (PCC) pavements of differing levels of condition at the NAPTF located at the FAA William J. Hughes Technical Center, Atlantic City, New Jersey. The FAA operated NAPTF is a state-of-the-art, full-scale pavement test facility dedicated solely to airport pavement research. As can be seen in Figure 3, the exclusively designed rail-based test vehicle is capable of being configured with twelve test wheels to represent two complete landing gear trucks having one to six wheels per truck.

Figure 3a. NAPTF Test Vehicle.

Since the test vehicle is operated on rails located outside of the test pavement area, the rails provided a stable (flat) platform for the profiler which was mounted on one of the vehicle's carriages (suspended over the test pavement) as depicted in Figure 3. Therefore, the profiles measured by the profiling device were not influenced by the pavement condition.

Figure 3b. The FAA Profiler Mounted on the NAPTF Test Vehicle.

Each of the four longitudinal profiles measured with the FAA's profiling device was 250 feet long originating from about 30 feet into a 300 foot test pavement section. All profiles lines were measured from the test vehicle at the speed of 3.29 mile/hr (4.83 km/hr). The transverse pavement locations were based on precise test carriage positions utilized during traffic testing which resulted in profile locations at the test pavement centerline, 4.0 feet (1.22 m) south of centerline, 14.6 feet (4.45 m)north of centerline and 19.7 feet (6 m) north of centerline. These four tracks represented two different pavement conditions. One was indicative of new pavement, the other was in a condition requiring repair or rehabilitation. All profile measurements were taken after traffic testing was completed, not in conjunction with traffic testing.

The FAA CA profilograph was manually operated (guided by a string line) to replicate the same tracks measured from the test vehicle. The profilograph operation speed was approximately 1.24 mile/hr (2 km/hr).

PROFILE COMPARISONS

Figure 4a and 4c show one of the longitudinal test pavement profiles as measured by the profiling device (Figure 4a) and the California profilogragh (Figure 4c). At first glance, the first profile in Figure 4a appears to be only slightly similar to the simulated profile (Figure 4b) and measured profilograph profiles (Figure 4c). This is because the profiling device directly measures the vertical distance from the laser head to the pavement surface without any lateral support. However, the California profilogragh records the response of the recording wheel which is under the influence of the condition of the pavement supporting the six small wheels on each side of the profilograph truss (Figure 5).

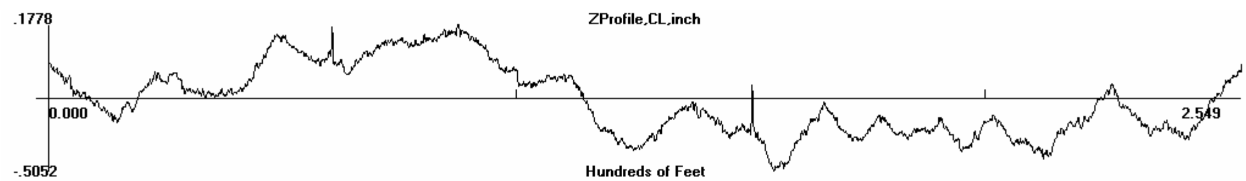

Figure 4a. Profile Produced with the FAA Profiling Device.

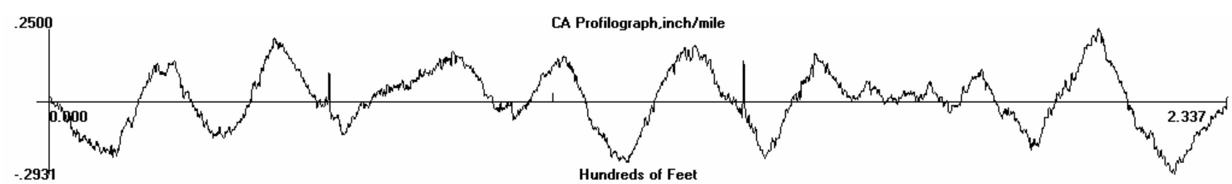

Figure 4b. Simulated California Profilograph Profile.

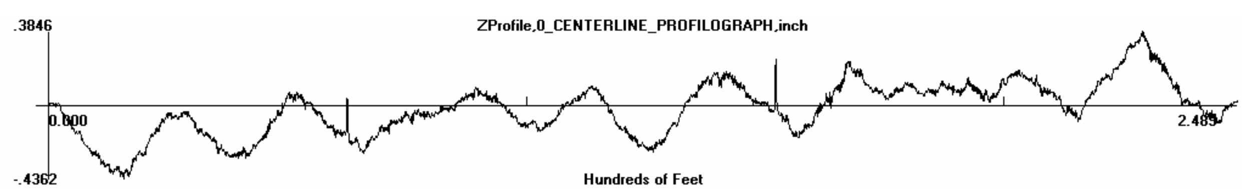

Figure 4c. Profile Produced with the California Profilograph.

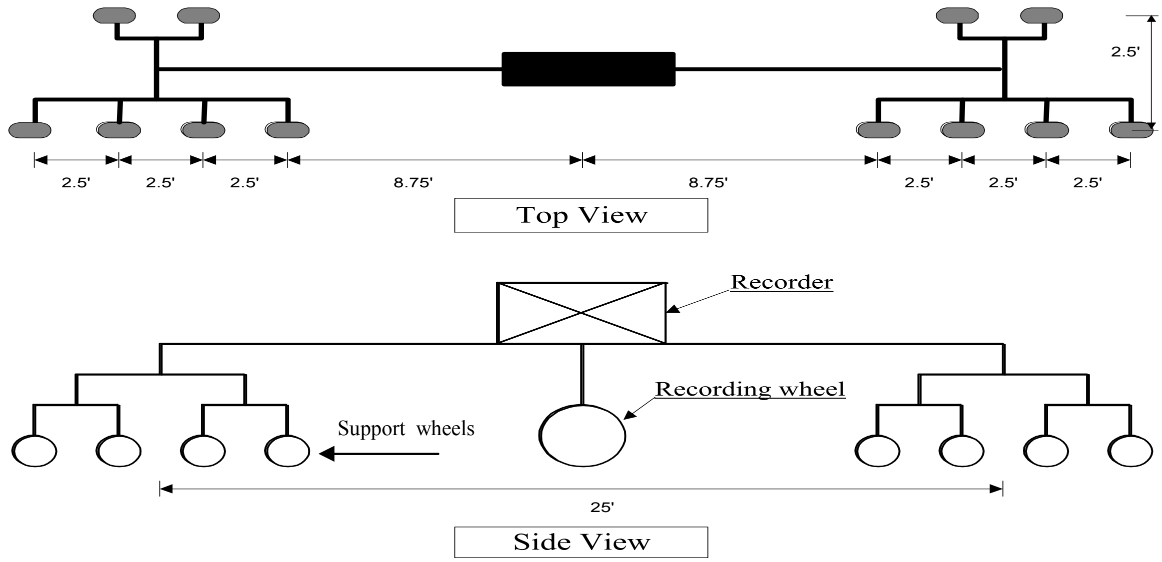

Figure 5. California Profilograph.

PROFILE SIMULATION

The raw data from the FAA profiling device is initially recorded at 32 kHz and then processed to a constant spacing of 0.9843 inch (25 mm) for input to ProFAA. Utilizing ProFAA's simulation routine detailed in reference [2], California profilograph profiles were produced from the profiles produced with the FAA Profiling Device as follows:

$$R(x) = (\sum_{i=1}^{N} C_i P_i (x - d_i)) - P_r (x - d_r) \qquad (1)$$

Where:

R(x) = the computed profilograph recording at the position x

N = the total number of the wheels in the left and right side of the support system

Pi = the profile on which the ith wheel is traveling

Ci = the influence coefficient corresponding to the ith wheel. It is equal to the vertical displacement at the recorder position caused by an unit vertical movement at the ith wheel

di = the offset distance from position x for each wheel

Items with subscript r refer to those of the recording wheel

The results of the profilograph simulations are depicted in Figure 6.

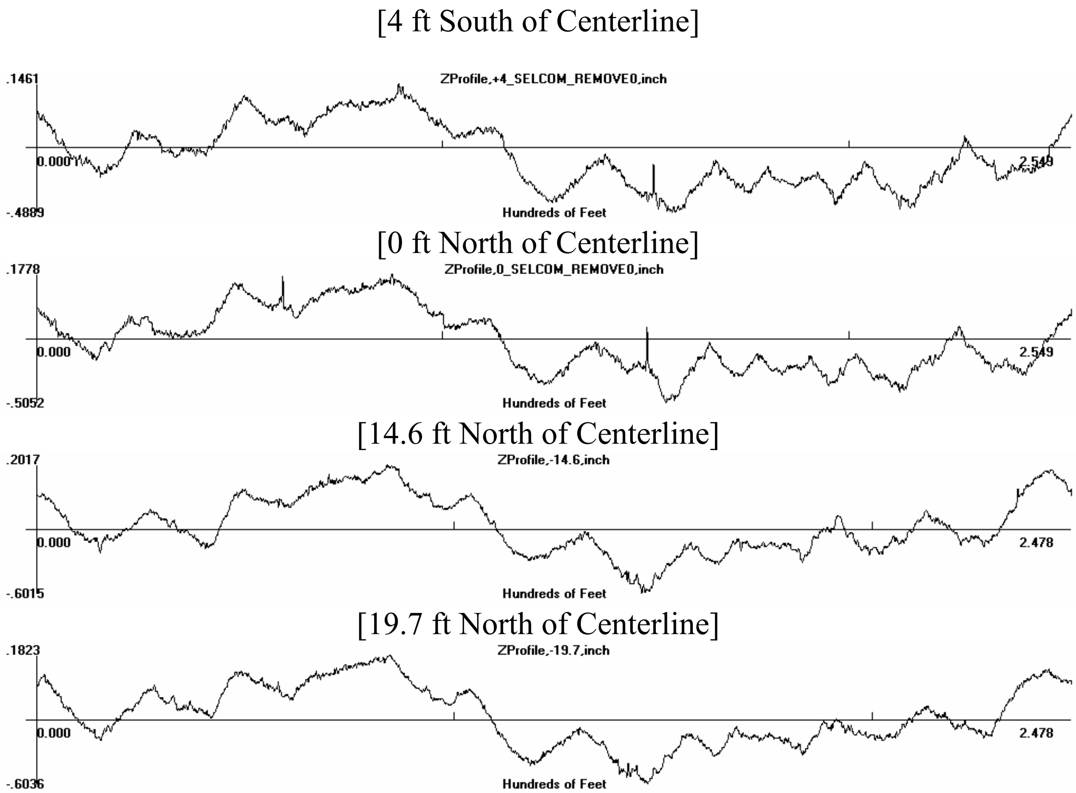

Figure 6a. Profiles Produced with the FAA Profiling Device.

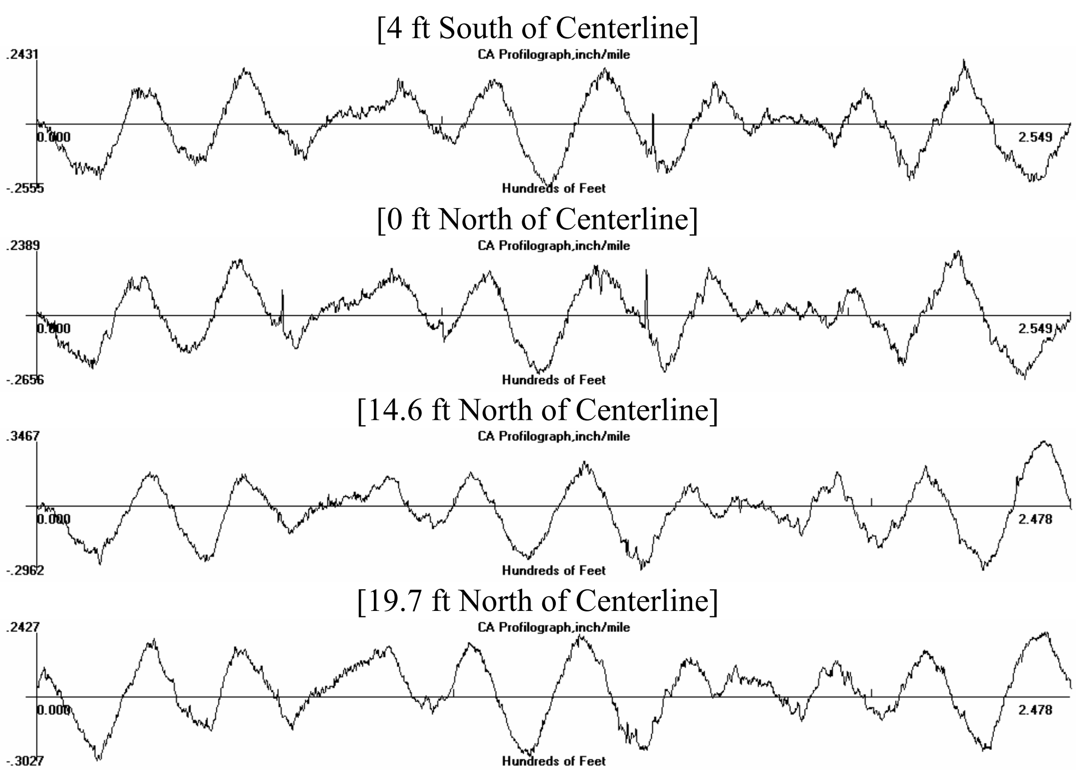

Figure 6b. “Simulated” California Profilograph Utilizing Profiles in Figure 6a.

PROFILE INDEX (PI) COMPUTATION

The Profile Index is calculated from California profilograph traces. This is done by adding the absolute value of the vertical deviations or "scallops" (inches) outside of a blanking band and dividing the sum by the length of the test section (miles). The resulting Profile Index is in units of inches per mile.

The "blanking band" is a band of uniform height with its longitudinal center positioned optimally between the highs and lows of the profilograph trace depicting at least 100 ft of pavement. And, as illustrated in Figure 7, scallops are the excursions of the trace above and below the blanking band [3]. The vertical maximum of a scallop must not be less than 0.03 inch and the longitudinal length must be longer than 2 feet [3, 4, 5].

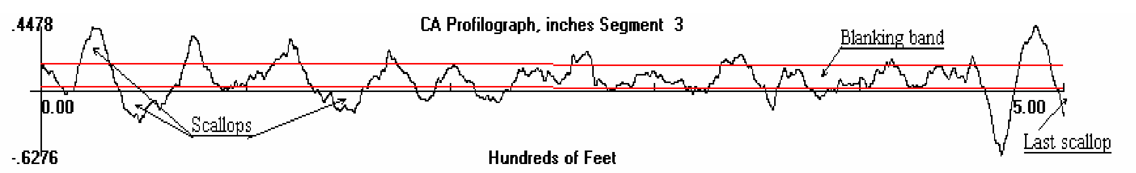

Figure 7. An Example of CA Profilograph Response Simulation in Pavement Segment.

PI for each segment of a pavement are calculated by

$$PI_{segment} = \frac{\sum_{j=1}^{m} \text{the maximum of absolute height in the j}^{\text{th}} \text{ scallop}}{\text{the segment length}} \quad \text{(inch/mile)} \qquad (2)$$

Where:

m = total number of scallops in the segment

PI for whole pavement can be obtained from a weighted average

$$PI = \frac{\sum_{k=1}^{s} PI_k * L_k}{\sum_{k=1}^{s} L_k} \quad \text{(inch/mile)} \qquad (3)$$

Where:

Subscript k indicates the k*th* segment in the pavement divided into s segments. L is the segment length.

DATA ANALYSIS

The plots of the actual California profilograph and the ProFAA profilograph simulation of the pavement centerline is shown in Figure 8. These profiles have a correlation coefficients (R^2) of 0.9570. The relationships of all profiles are illustrated in Figure 9 and are summarized in Table 1 which includes a simple linear regression model for each profile line. The table shows that the calculated wheel response data from the profilograph and the ProFAA differ by no more than 9 percent.

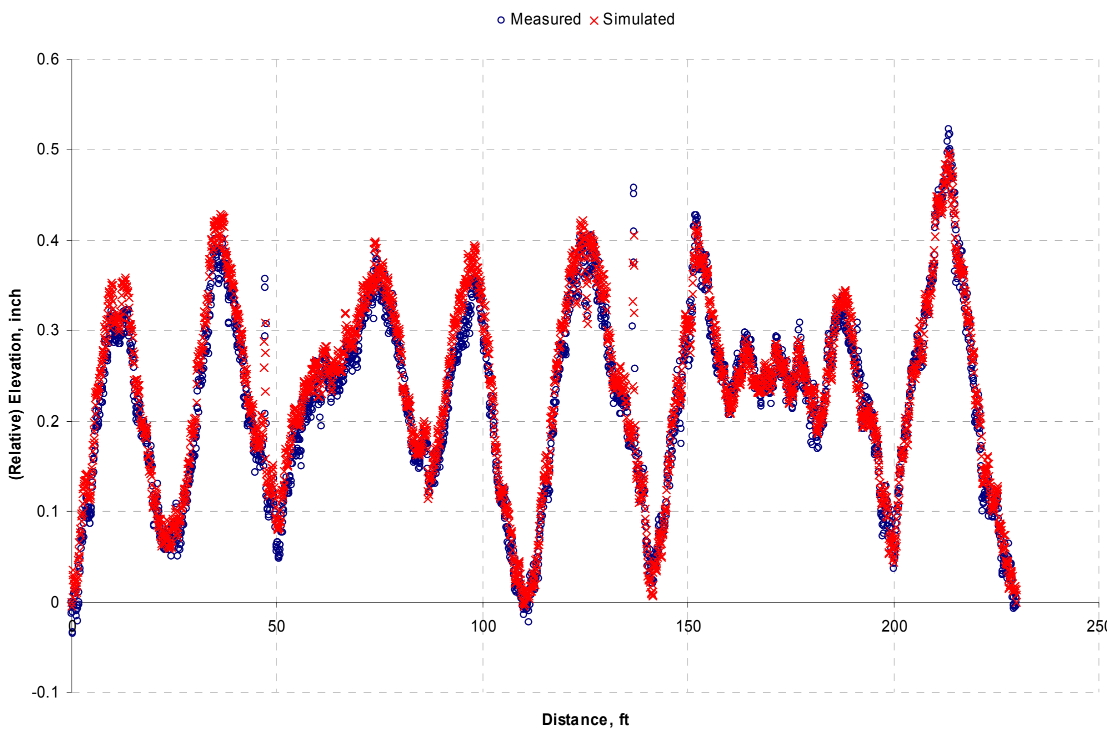

Figure 8. Measured and simulated Profilograph Profiles at Centerline.

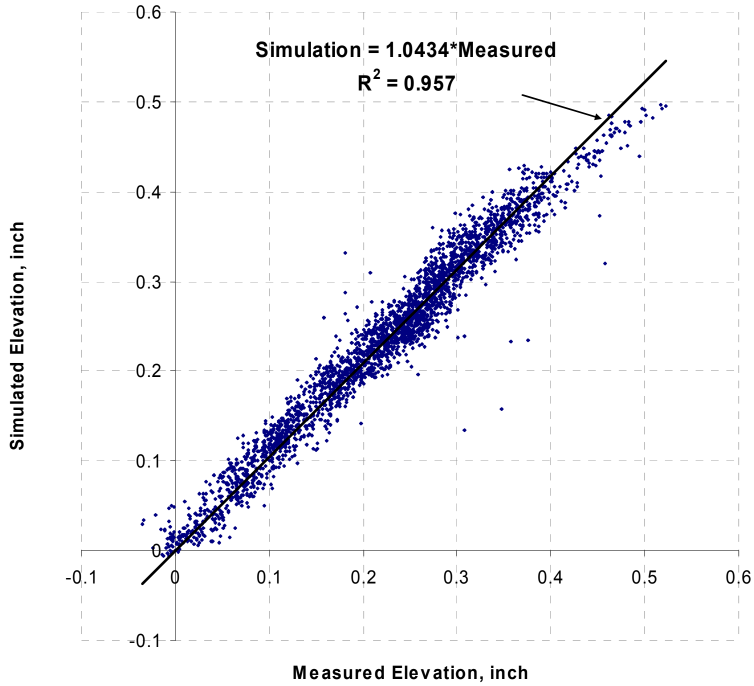

Figure 9. Correlation of Measured and Simulated Profilograph Profiles at Centerline.

Table 1. Regression Model for Measured and Simulated Profilograph Traces Using ProFAA.

Profile Location, Offset from Centerline	Regression Model	Correlation Coefficient (R^2)
4 feet South (PI = 23.0219)	Sim. = 0.9205×Meas.	0.9173
0 (PI=24.8944)	Sim. = 1.0434×Meas.	0.9570
14.6 feet North (PI=35.50)	Sim. = 1.0888×Meas.	0.9542
19.7 feet North (PI=29.9069)	Sim. = 1.0475×Meas.	0.9352

COMPARISON WITH FHWA SOFTWARE

The FHWA's roughness software, ProVAL, is also equipped with a profilograph simulation function that is based on a report by Kulakowski and Wambold [6]. Figure 10 compares the results of the profilograph simulation methods in ProFAA and ProVAL (version 2.70.004) using the profile data obtained from the NAPTF. Considering that different file formats were adopted for each program, "*.erd" for ProVAL and "*.pro" for ProFAA, the data sets correlate very well at more than 2,000 data points.

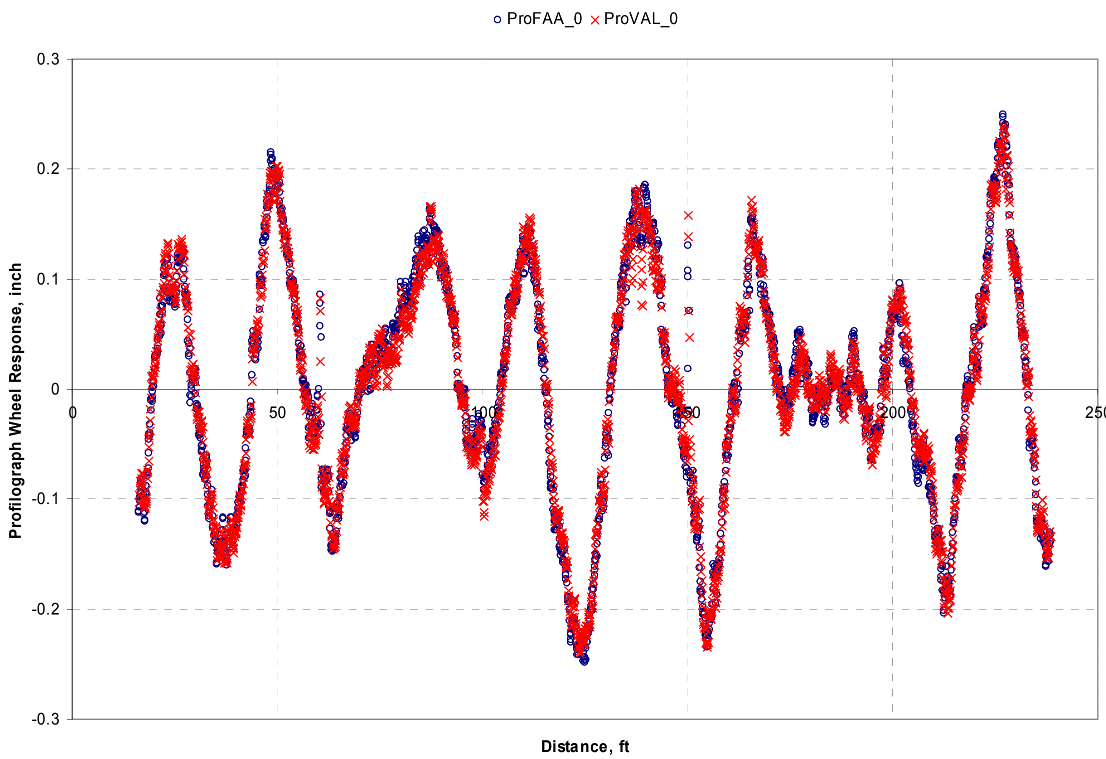

Figure 10. ProFAA and ProVAL Centerline Simulations.

The correlations along with regression models for the different profiles are listed in Table 2. The table shows that the profilograph simulation functions in ProFAA and ProVAL are almost identical, having correlation coefficients ranging from 0.9865 to 0.9982.

Table 2. Relationships between ProFAA and ProVAL Profilograph Simulation.

Profile Location, Offset from Centerline	Regression Model	Correlation Coefficient (R^2)
4 feet South	ProVAL = 0.9787 × ProFAA	0.9898
0	ProVAL = 0.9744× ProFAA	0.9865
14.6 feet North	ProVAL = 0.9888 × ProFAA	0.9982
19.7 feet North	ProVAL = 0.9868 × ProFAA	0.9982

To further compare the relationship between the ProFAA and ProVAL Profilograph simulations, highway data collected during a “Roughness Rodeo” [7] held during April 4 – 8, 2004 was used. This data included asphalt pavement as well. For this comparison, all software input parameters for the PI computations were the same for both programs. A 0.2 inch blanking band, 0.03 inch minimum scallop height, and 2 feet minimum scallop width was used. The PI comparison is shown in Figure 11. Although the relationship differs from the tests conducted at the NAPT, the correlation coefficient is still very good at 0.972.

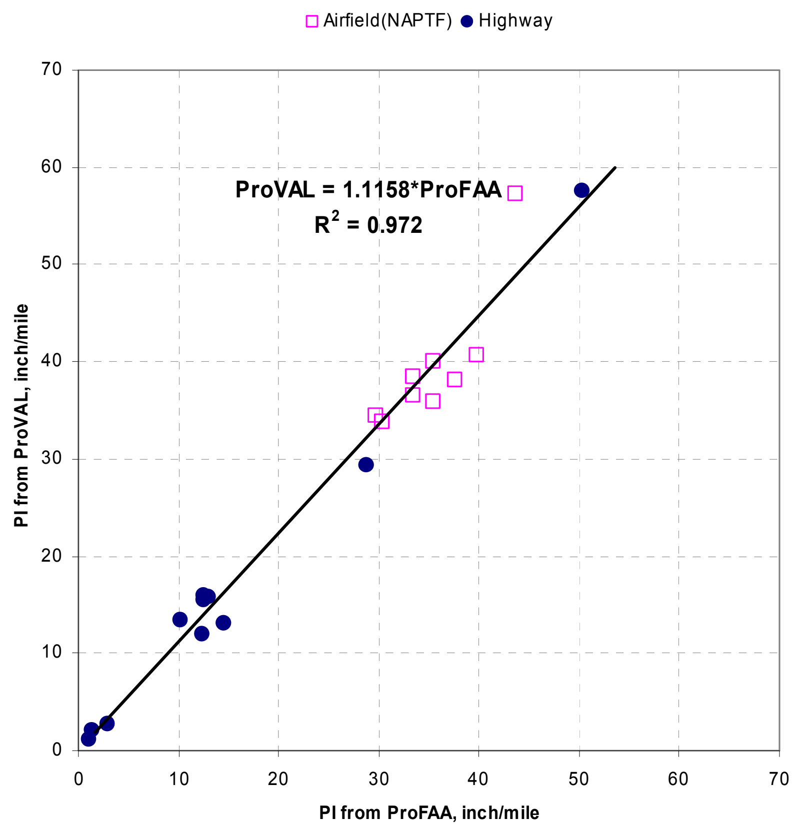

Figure 11. Profile Index Comparison by ProFAA and ProVAL.

CONCLUSIONS

Directly measured profiles from California type profilograph were compared with the simulated profilograph recording by means of the FAA roughness software ProFAA. Pavement profiles were measured by the FAA inertial profiler that was mounted on the rail-based operated test vehicle and by the typical truss type FAA California Profilograph at NAPTF in New Jersey. The mathematical simulation function in ProFAA was validated by trace comparisons and by very high correlation coefficient values between 0.9173 and 0.9570.

Current California type profilograph simulations are available in FAA's ProFAA and FHWA's ProVAL. The simulation methods were compared using profile data from the NAPTF and highway. The comparisons were performed using simulated California profilograph profiles and calculated PI with the same parameters settings. The correlation coefficients from the simulation results and PI computations are from 0.9865 to 0.9982 and 0.972 respectively.

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