Implementation Of Road Profiles For Vehicle Dynamic Simulation

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ABSTRACT

FHWA's Truck Pavement Interaction, High Priority Research, has developed an intensive research program dealing with pavement damage resulting from the repeated application of dynamic loadings of heavy vehicles. The research involves related work in a combination of disciplines including road profiling, vehicle dynamic modeling, shaker table (DYNTRAC) simulations, and pavement primary response and damage. This paper deals with an initial series of investigations concerning the proper measurement and interpretation of road profiles for input to FHWA's vehicle simulation model VSIM2d and the DYNTRAC shaker table. For this purpose the left and right wheel track profiles were measured from flexible pavement road sections representing high, medium and low levels of roughness in Ottawa, Canada. The profiles from these road sections were obtained using two different laser/accelerometer profilers the FHWA PRORUT2 profiler and the Swedish Laser RST.

Analytical comparisons of the profiles were made and presented in terms of calculated IRI values, PSD's, spatial examinations of the profiles, and comparisons of responses calculated by the VSIM2d vehicle dynamic simulation computer program using the FHWA straight 2-axle test truck as input.

Analysis has shown that once the raw signals are processed in an identical manner the filtered profiles exhibited good repeatability and good agreement between the various analytical comparisons conducted. It is also noted that the moving average currently used by PRORUT2 is inadequate and need to be replaced by a digital filter.

INTRODUCTION

The significance of dynamic loads needs to be addressed requiring quantification of these loads through experimental measurement or simulation. Simulation is an attractive alternative since it eliminates the need to instrument the vehicle and permits the efficient examination of the effect of different parameters on vehicle response.

Both computer and mechanical simulations do however require a precise description of the road profile. There are several automated road profiling systems that are now in use; many of which have been validated through experiments such as the Ann Arbor meeting [1]. Many of these validations however have focused on the ability of profilers to produce certain statistics of the profiles such as the IRI.

Since pavement roughness is that input causing dynamic response; it was judged necessary to establish the validity of its measurement. This paper therefore, reports on the findings of a study that has been conducted to test the ability of PRORUT2 to produce valid measurement profiles for use in the shaker table and the computer simulation model VSIM2d.

EQUIPMENT

The FHWA PRORUT2 is compared to the

VTI Laser RST; a brief description of the two profilers is presented.

THE PRORUT2

The sensors are installed on a van so the measurements can be obtained in both wheeltracks as well as the center of the lane. Rut depth is determined relative to the center of the lane profile. Instantaneous horizontal speed of the van is sensed by a transducer on the right front wheel.

The Laser/accelerometer units are located at either end of a metal beam mounted to the frame of the vehicle 1.83m apart in each wheeltrack, which simultaneously measure the distance between the laser and the pavement surface and the vertical accelerations experienced at the laser. The vertical acceleration of the van in response to the road profile is integrated to obtain a datum profile from which the sensor readings are subtracted to obtain the relative road profiles. A pulser connected to the transmission is used to simultaneously monitor the vehicle speed and distance traveled. The laser is infra-red with a 2mm x 5mm spot and is accurate to ±0.25mm, the accelerometer range is ±2g with ±0.05% linearity, and the pulser is accurate to 0.10%. The measurement is performed at highway speed.

The FHWA PRORUT2 was developed at TFHRC using software based on that developed for PRORUT1 by UMTRI (equations also developed for the World Bank). For further information see [2, 3, 4].

THE LASER RST

The Laser RST uses a similar concept. The following is an excerpt from [5] provided by its developers describing the system.

"The first Laser RST was developed in 1981 by the Arnberg team at the Swedish Road and Traffic Research Institute (VTI). continued with considerable research and development since then. The Laser RST is a laser-based, computer-automated, non contact road profiler system with the ability to collect simultaneously process a wide variety of data about the road surface. Road surface data is collected, analyzed, and stored in real-time at traffic speeds of up to 90 km/h. For some variables (e.g., longitudinal and cross profiles, and crossfall), measuring speed can exceed 90 km/h. The basis of this system is the laser rangefinder (LRF); 11 of these units, mounted on a support beam in front of the vehicle, collect data by accurately and rapidly measuring the distance from the beam to the surface of the road. Vertical motion of the vehicle is removed from these measurements through the use of an accelerometer which measures the beam's vertical acceleration. Longitudinal distancing information is provided by a pulse transducer mounted on one of the front wheel hubs." For more details see [5].

DATA COLLECTION

Three different sites were tested in Ottawa Canada referred to as routes 31, 16, and 43 representing low, medium and high roughness. Reflective tapes were placed on each road section to mark the beginning of the measured section. Recording of the data is begun some 100 m prior to the reflective tape position to allow for initialization. Each of the measured sections spanned 1000 m, recording is stopped at some distance further from the end of the 1000 m section. Two profiles of the same road section are recorded and processed to the same length. The measurements are performed at an approximate speed of 80 km/h and sampled every 5 cm an both left and right wheeltrack profiles are obtained. The driver makes his best attempt to traverse the pavement in the same position relative to the wheeltracks for repeatability. FHWA technicians operated the PRORUT2, VTI provided their own personnel to operate the Laser RST.

DATA PROCESSING

Figure 1 describes the different steps in the processing of the profiles obtained from PRORUT2 and the Laser RST. As it can be seen both profilers utilize the same process. The laser signal is differentiated and then added to the integral of the accelerometer signal to obtain the temporal slope of the profile. This slope is then divided by the speed of travel obtained from the pulser to obtain the spatial profile slope; the spatial slope is then integrated to get the profile. The only differences are in the type of filtering and

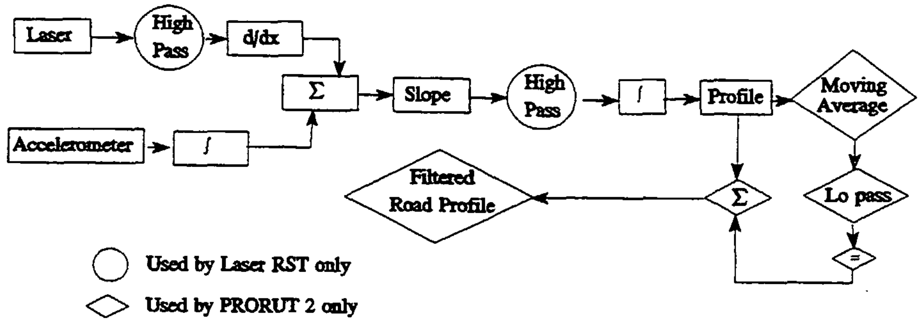

Figure 1. Profile Measurement and Processing.

when it is applied. The Laser RST applies a digital high pass filter to the laser signal and to the spatial profile slope; while PRORUT2 applies a moving average filter to the raw profile to obtain a low pass signal which is then subtracted from the raw profile to obtain the filtered profile. Data at all steps of the process of PRORUT2 was available to us; however data from the Laser RST was furnished by VTI personnel as spatial profile slope. Consequently spatial profile slopes where extracted from the PRORUT2 measurements. Both slopes where then integrated and filtered to obtain the measured profiles. The integration is performed backward to minimize the bias introduced by the forward differentiation of the laser signal.

As mentioned earlier the PRORUT2 utilizes a moving average filter. Examination of the moving average filter showed it alters the amplitudes in the wave band of interest, it was thus replaced by a second order digital filter.

THE MOVING AVERAGE

The problems with the moving average could be explored without any loss of generality by considering a single harmonic.

Assume

$$X_R = \sin(\omega t)$$

$$X_L = \frac{1}{\lambda_c} \int_{t-\lambda_c}^{t+\lambda_c} \sin(\omega s)\, ds$$

$$X_H = X_R - X_L$$

R,L, and H stand for raw, lopass, and hipass values of X respectively,λ is the wavelength of the signal, and λ_c is the cutoff wavelength of the moving average filter.

Evaluating the integral leads to

$$X_H = \left(1 - \frac{\sin(\pi \frac{\lambda_c}{\lambda})}{(\pi \frac{\lambda_c}{\lambda})}\right) X_R$$

the transfer function of the moving average filter as the ratio of X_H and X_R. Expressing it in terms of wave number instead of wavelength leads to.

$$TF = 1 - \frac{\sin(\pi \frac{k_c}{k})}{(\pi \frac{k_c}{k})}$$

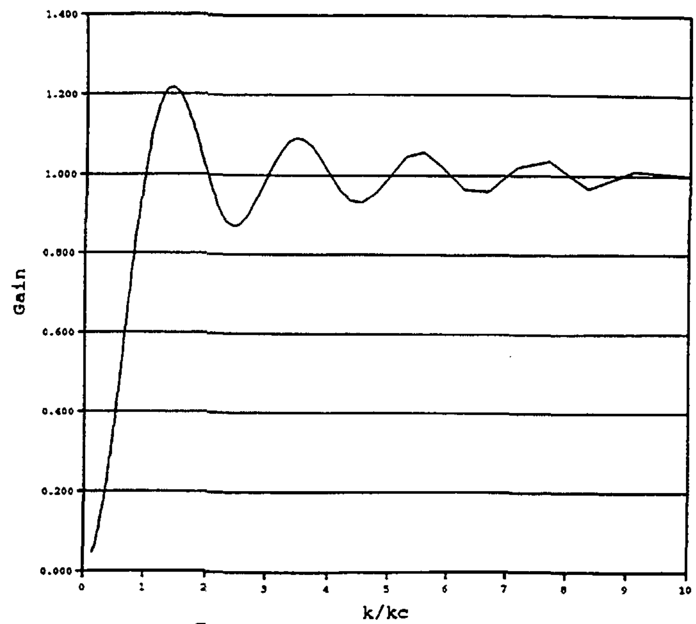

Fig. 2. Transfer Function of High Pass Moving Average Filter

Figure 2 displays the behavior of TF with respect to K/k_c, and Figures 3 and 4 show how different harmonics are filtered by a moving average with a cutoff wavelength of 100m. We can see that a wavelength of 130 m has sustained only 30 % attenuation when 100 % is desired; a 70m wavelength has undergone 22 % amplification when no amplification was desired. It can also be seen that TF will approach 1 at very large ratios k/k_c. It is also equal to 1 for integer values of this ratio. For a ratio k/k_c higher than 10 TF oscillates between 0.97 and 1.03. This means that if one is interested in generating a filtered profile that is accurate for up to 10m wavelengths, a 100m cutoff wavelength is needed. This could present a problem because it will not get rid of the longer waves normally associated with higher amplitude that could result in a profile elevation that exceeds the allowable stroke of the actuator of 76mm.

COMPARISON

The comparison between the FHWA PRORUT2 and the VTI Laser RST was performed in light of three different applications, IRI, PSD of the profiles and the PSD of the tire loads of the FHWA two axle truck as computed by VSIM2d.

The algorithm for the IRI computation described in [6, 7] was implemented in a Fortran program.

Figures 5 and 6 show the computed IRI values for left and right wheel track respectively. As it can be seen there is good agreement between the VTI Laser RST and PRORUT2 measurements. The figures show that for Route 31: the smoothest road (IRI left=0.93mm/m, IRI right=0.94mm/m) both profilers have good repeatability; the percent difference between two runs for any given profiler and any given track is less than 2%. The percent difference between VTI and FHWA measurements for any given run and any given track is also less than 2%.

Route 43: the roughest road (IRI left=2.8mm/m, IRI right=4.08mm/m). Similar conclusions can be draw except that the maximum difference between two runs for any given profiler and any given track is 3% and the percent difference between VTI and FHWA measurements is also less than 3%.

Route 16: medium roughness (IRI left=2.09mm/m, IRI right=2.08mm/m). Again similar conclusion can be drawn except that the maximum differences between two runs for any given profiler and any given track is about 4% and the percent difference between VTI and FHWA measurement is also less than 4%.

These differences already include differences because of vehicles not passing exactly over the same path. It can be concluded that in the IRI range of 0.9 - 4.1 mm/m both profiler are capable of producing repeatable values of IRI and they can be used interchangeably since the percent difference between both measurements is not any higher than the percent difference between two runs performed using the same profiler.

PSD values were computed for all profiles filtered using the digital at a 50m cutoff wavelength, typical values of these PSD 's are presented in figures 7 through 10. Again excellent agreement between the two profilers existed for all levels of roughnesses indicating that both profilers

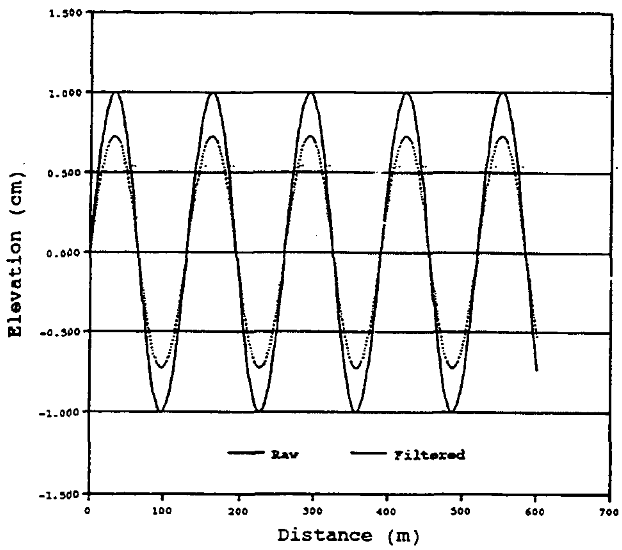

Fig. 3, A 130m Wavelength Harmonic Filtered Using a Moving Average at 100m Cutoff

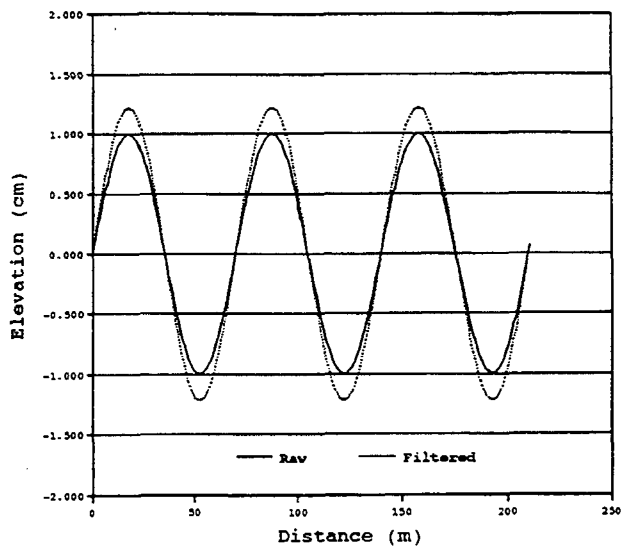

Fig. 4, A 70m Wavelength Harmonic Filtered Using a Moving Average at 100m Cutoff

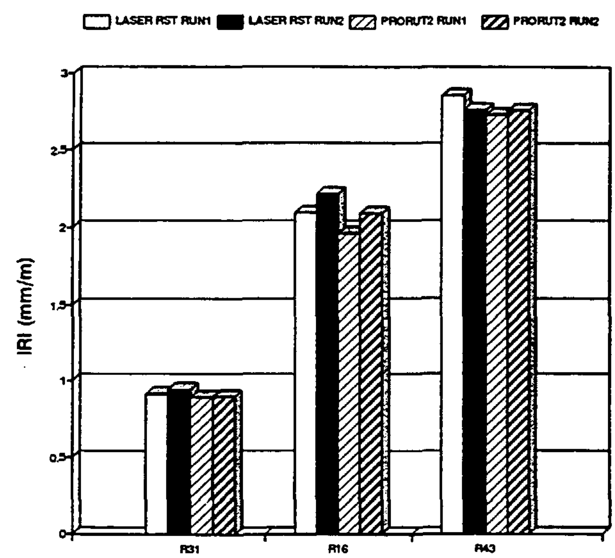

Fig. 5, LEFT TRACK

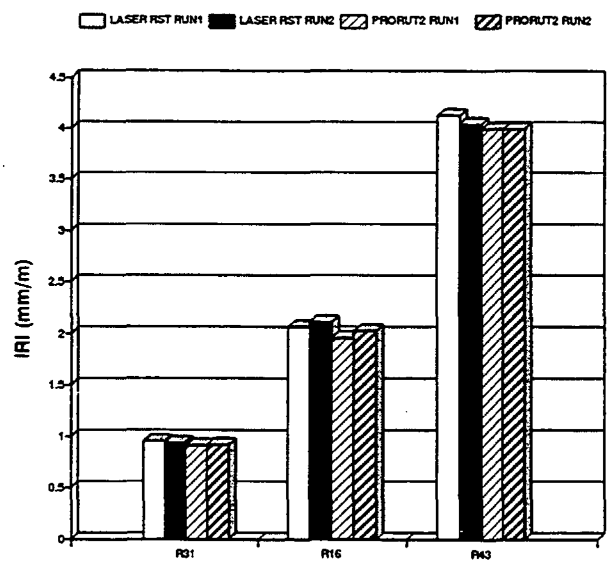

Fig. 6, RIGHT TRACK

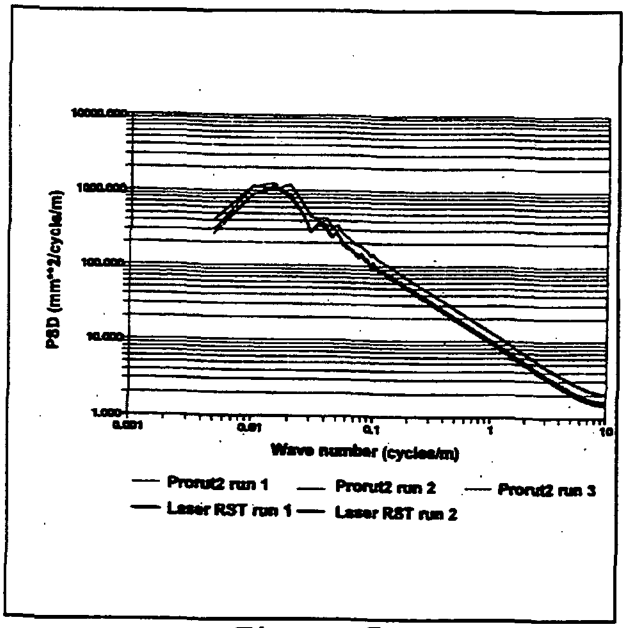

Figure 7
Route 31, low roughness, left track

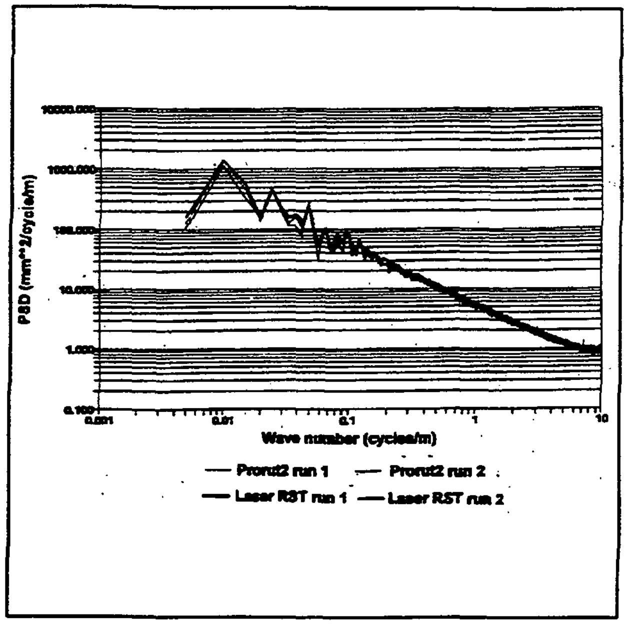

Figure 8
Route 16, medium roughness, left track

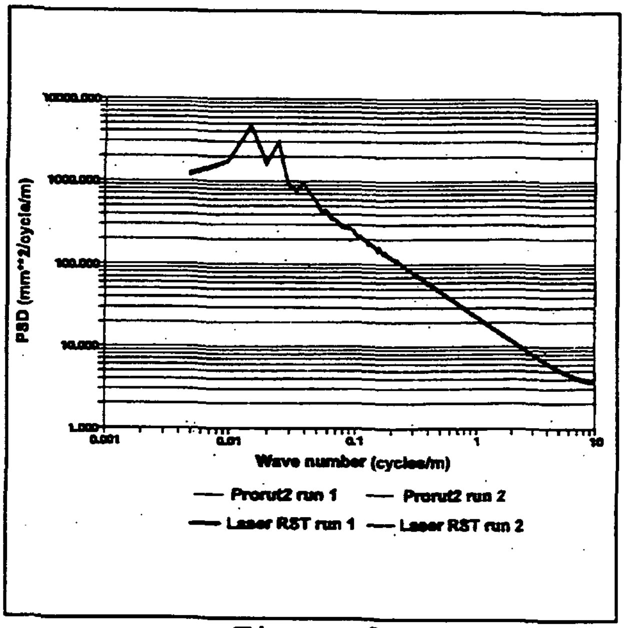

Figure 9
Route 43, high roughness, left track

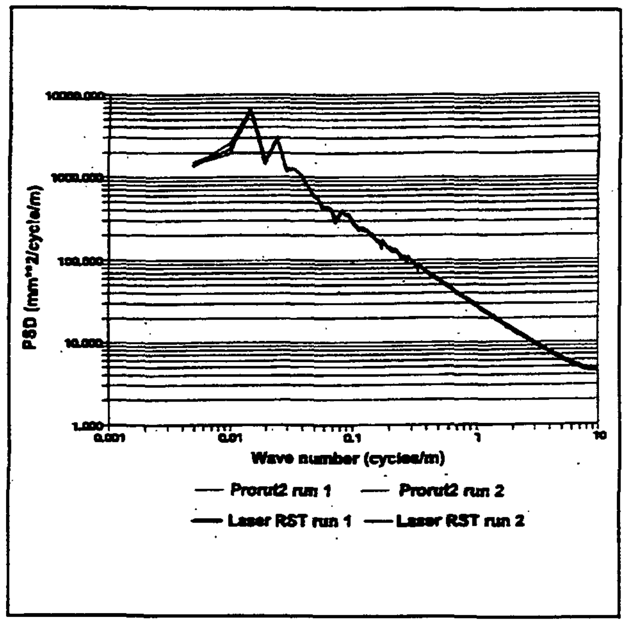

Figure 10
Route 43, high roughness, right track

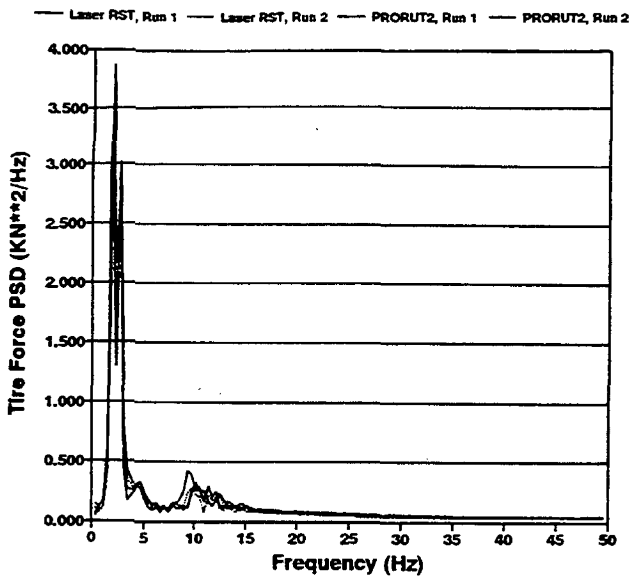

Fig. 11, Route 31 -- Low Roughness
Front Axle -- Left Track

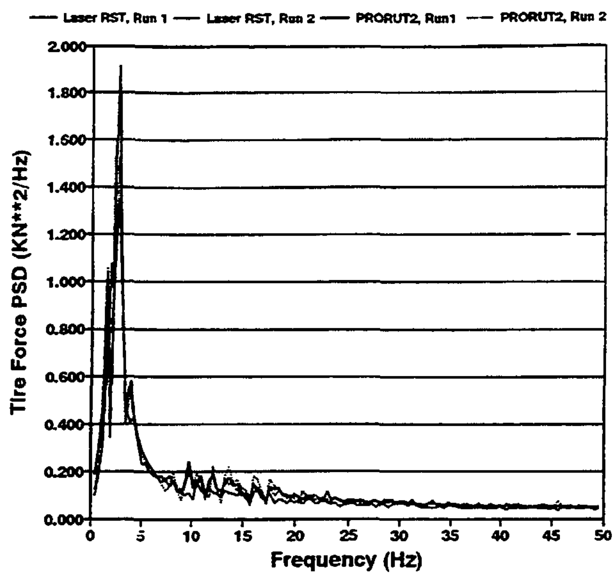

Fig. 12, Route 16 -- Medium Roughness
Front Axle -- Right Track

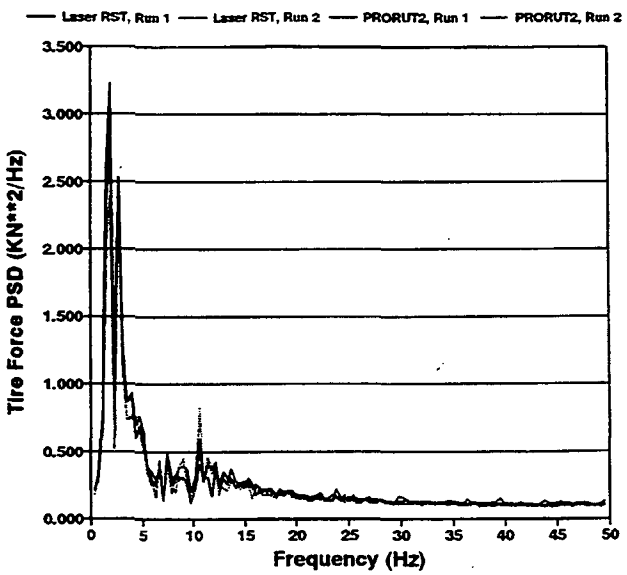

Fig. 13, Route 43 -- High Roughness
Front Axle -- Left Track

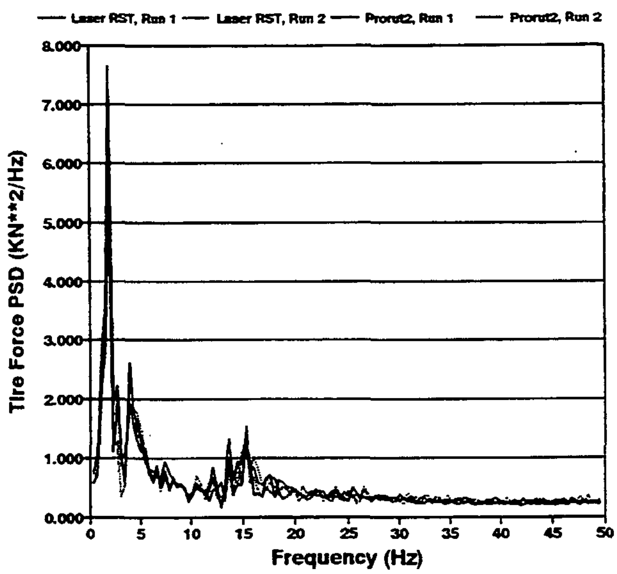

Fig. 14, Route 43 -- High Roughness
Rear Axle -- Left Track

produce the same amplitude frequency content of any given profile. Better agreement seemed to exist for the high roughness this is probably due to better signal to noise ratio.

Finally the response of the FHWA straight flat bed two axle truck to these road roughness excitations were computed using VSIM2d. The Vehicle parameters used were measured by PSU and are described in [8]. Once again excellent agreement existed between PSD values of tire loads due to excitation from the FHWA PRORUT2 and VTI Laser RST profiles. The agreement held true for the entire frequency range of the excitation.

CONCLUSIONS

It has been shown that for the roads of three levels of roughnesses described by IRI values in the range of 0.9 to 4.1 mm/m excellent agreement between both profiles existed; less than 4% differences for all runs, all tracks of the different measured profiles. Both profilers exhibited very good repeatability of less than 4% between two different runs.

PSD values of the different profiles showed that both profilers measured the same amplitude frequency content of the profile for all levels of roughnesses. Consequently when used to excite the FHWA two axle truck in the VSIM2d they produced the same vehicle response.

There is better agreement between VTI and FHWA profilers for the rougher roads, probably due to stronger signal to noise ratio.

The Moving average filter used in the PRORUT2 does not produce the desired spectrum, and could produce filtered profiles that could not be implemented in the shaker table due to improper attenuation of the long waves.

ACKNOWLEDGEMENTS

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