Roughness Computer Program for Engineers and Management

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In this paper, a computer program developed to analyze pavement profile data is reported. The main functions of the program are to determine the present serviceability index and to analyze ride quality, either by use of the International Organization for Standardization (ISO) standard 2031 or the University of Virginia (UVA) model. The primary input is the pavement profile data. The present serviceability index analysis gives the user a value for every 0.1 mile, or any interval up to the total length of the pavement profile, at a user-specified vehicle velocity. The ride-quality analyses give the user the estimated exposure time of reduced comfort or fatigue if the ISO weights are used; if the UVA model is used, a ride quality index is given. For either model, the user can select the vehicle type, a linear or nonlinear transfer function, and the vehicle velocity. The program also includes some auxiliary functions, such as a paver-grinder simulator and a profilometer simulation that can produce, from the raw profilometer signals, a digital file of the profile as a function of distance. This paper discusses the models and simulations used. Although some of the analysis methods have been discussed in the literature, they have not previously been integrated into a single versatile package. Thus, a complete pavement surface analysis program (including several methods not reported in the literature) is available for pavement management.

Two major functions of a highway department are the planning of maintenance schedules for a system of existing roads and the acceptance of newly built or resurfaced roads. The decision to resurface a particular section of road in preference to others is not a simple one, for many factors must be taken into consideration. A large quantity of information is available to support an objective evaluation, and research is under way to permit the development of pavement management systems that use this information. The purpose of the program described here is to process and analyze the highway profile data collected by a profilometer or other road roughness measurement system.

PAVEMENT ROUGHNESS

The measurement of road roughness is of importance to the maintenance manager in determining pavement safety and serviceability. Recent developments in measuring equipment and data reduction systems will greatly expand the available data base. For example, at the present time, skid resistance and roughness are measured with operational equipment that collects data at a rate adequate for routine surveys. Research now in progress should make the measurement of pavement texture operational in the near future and thus provide additional information on skid resistance. Similarly, several noncontact sensors for roughness measurement are operational. Currently, most states that have General Motors Research Laboratories (GMR) profilometers use them to calibrate other road meters rather than as a tool for measuring surface conditions directly.

Both the type and the quantity of pavement condition data available to the management engineer will increase dramatically in the near future. These data must be analyzed and made available in a format that is compatible with maintenance management systems. For years a number of data formats, such as pavement power spectrum, seat acceleration, and vehicle roll rate, have been either directly or indirectly related to the pavement profile. Pavement profile can be measured by an inertial type of profilometer that sums the double integration of profilometer body acceleration and the relative displacement between body and test wheel (1-3).

Compared with the results of other road meters, the profilometer produces the profile as a description of the pavement. The profile is not affected by differences in measurement technique or by the use of different types of vehicles to make the measurement. Because of this reliability, profiles have been considered the most basic input to a pavement analysis system.

To avoid much of the work in processing profile data, the handling of each analysis program, and the matching of input-output data structure with other programs, a package of programs has been developed to give the user greater simplicity and flexibility in the reduction and analysis of profile data.

PROGRAM OVERVIEW

The simplicity of the program is achieved by a control program that links various analysis programs according to the user's input command and by an internal handshake of each analysis program, which frees the user from most input-output considerations. The package can be easily modified, and modules can be exchanged to fit particular needs. The purpose of this package is to enhance the use of pavement profile data.

The package includes a collection of programs that encompass the various practical methods used in analyzing pavement profile data. The overall program flowchart is shown in Figure 1. These programs were either developed by Pennsylvania State University or taken from work published by other universities or by state highway departments. The functions of these programs are in both the cascade and the parallel form. Some programs are in parallel to provide different methods of data analysis; other programs are cascaded to reach a final result. This package unifies the input-output section of all programs by using a standard 1024-points buffer for all time-based data, a 512-points format for all frequency spectrums and linear transfer functions, and a 51x51 matrix format for all the amplitude-frequency distribution (AFD) format (4,5) and nonlinear transfer functions. Sets of data that take up a large volume are stored on tapes or disks and are divided into blocks. The user need not be concerned with their length; the program handles this function automatically.

The package can be divided into six branches--three major paths [one for the analysis of present serviceability index (PSI) and two for ride quality], two minor paths (two auxiliary support paths, a pavement paver-grinder simulator, and a profilometer simulator), and a branch to make pavement signature comparisons. A path is any path that links through the data to the final results (see Figure 1). A branch is a collection of paths that lead to a single result.

PSI

From the pavement profile data, a quarter-car or half-car model (see Figure 2) simulation is performed to obtain the relative displacement between vehicle body and axle. This relative displacement

Figure 1. Flowchart for a roughness program for engineers and management.

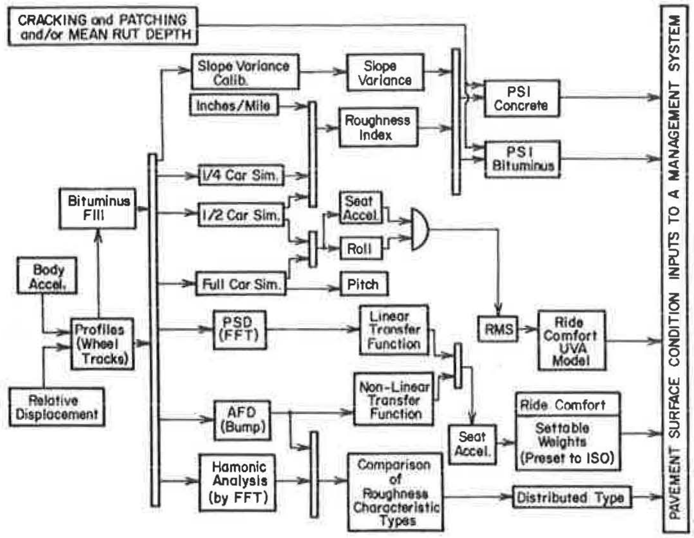
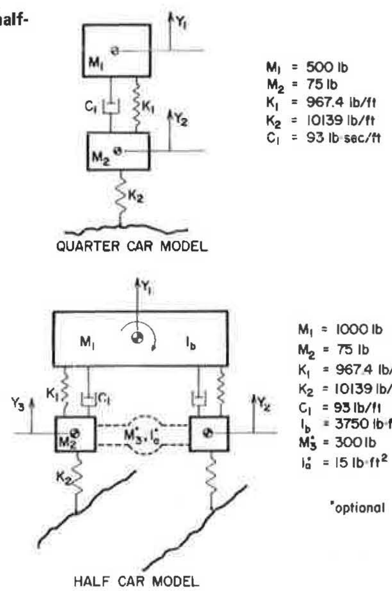


Figure 2. Quarter-car and half-car models.



is then used as an input to a Mays meter simulator to obtain the roughness index in inches per mile (see Figure 1). A set of American Association of State Highway Officials (AASHO) regression equations (6) is selected to yield PSI. For concrete pavement,

$$PSI = 5.03 - 1.11 \log_{10} (1 + SV) - 1.38\ Rut - 0.01 \sqrt{C + P} \qquad (1)$$

For bituminous pavement,

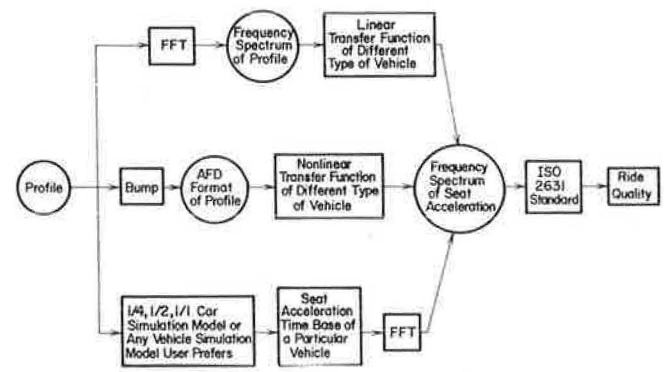
$$PSI = 5.41 - 1.78 \log_{10} (1 + SV) - 0.09 \sqrt{C + P} \qquad (2)$$

where

SV = slope variance,
Rut = mean rut depth, and
C+P = measures of cracking and patching in the pavement surface.

The user can change the regression equations in the program. The program is set up to report the PSI value for every 0.1-mile pavement until the end of data.

Figure 3. Ride quality path, ISO method.



Ride Quality Model I

The International Organization for Standardization (ISO) standard 2031 (7), a data set in tabular form that relates the endurance time of a human body to the vibration, is used to evaluate ride comfort objectively. This model determines the exposure time of reduced comfort boundary or fatigue of a human body from the frequency spectrum of the seat acceleration. The ISO data tables are reduced to two regression equations,

$$t_c = 2.980\,11 (-0.117\,78 - \ln a)^{0.621\,37} + 1.4 \qquad (3)$$

and

$$t_f = 3.0 (1.03 - \ln a)^{0.6177} + 1.38 \qquad (4)$$

for the frequency components from 4 to 8 Hz,

where

t_c = exposure time for reduced comfort boundary (min),
t_f = exposure time for fatigue (min), and
a = acceleration frequency component (m/s^2 Hz).

For the frequency component above 8 Hz or below 4 Hz, the equations are converted to the equivalent strength in the 4-8 Hz range by 20 dB down per decade and 10 dB down per decade, respectively.

Three paths can be used to obtain the seat acceleration frequency spectrum (see Figure 3, the

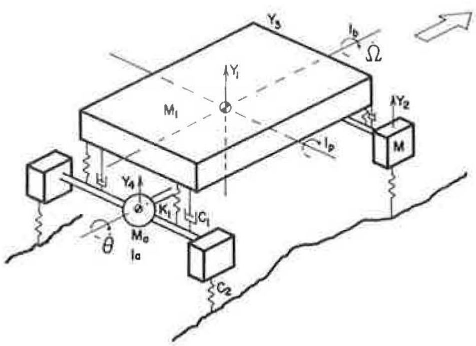


Figure 4. Full-car model, 7 df.

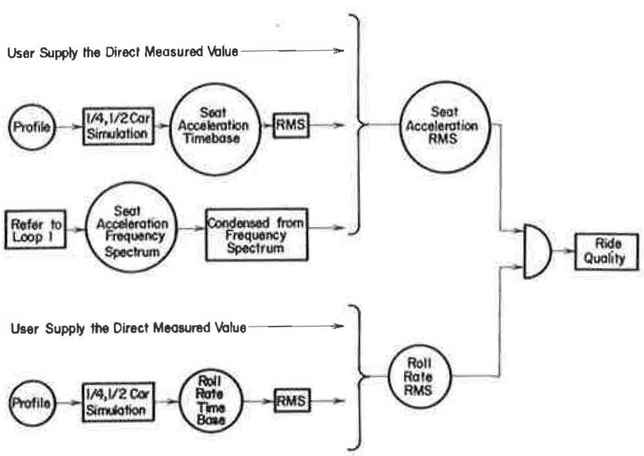


Figure 5. Ride quality path, UVA method by using RMS.

structure of path 2). The first method uses the Fast Fourier transform of the profile time base data to obtain the space frequency spectrum of the profile. The user selects the vehicle speed and one of the several types of vehicle transfer functions, and the frequency spectrum of seat acceleration is determined by the fact that the power spectral density (PSD) of the response is equal to the PSD of the input times the square of the transfer function. This is the conventional and most commonly used method.

The second method uses the AFD Bump analysis on the profile data to obtain the AFD format of the profile (8). The Bump analysis breaks the data into components of frequency and amplitude domain. The profile AFD format is then multiplied by a predetermined nonlinear transfer function (from a selection of different vehicle types stored in the program data bank) to obtain the AFD format of seat acceleration. This seat acceleration AFD format is further condensed into frequency spectrum by summing the components vertically (5). This method is different from the frequency-oriented linear transfer function method and the employment of a nonlinear transfer function is an advantage. The main shortcoming of this method is that the nonlinear transfer functions are valid only over the range of vehicle speed and amplitude levels at which the functions were established. The nonlinear transfer functions are determined by direct measurement of the seat acceleration and profile (4). The user can replace nonlinear transfer function data to fit his or her own case. Similarly, the user can easily change the equations in the linear transfer function.

The third method uses a vehicle simulation model to generate the seat acceleration time base from the profile. A quarter-car, half-car (Figure 2), or full-car model (Figure 4) can be used, or any other model can be added in the program. Then a Fast Fourier transform is used to obtain the seat acceleration frequency spectrum. The disadvantage of this method is that lengthy computation is required in the simulation of the vehicle. The time depends on the length of the profile data and the complexity of the vehicle simulation model. For example, on a given length of road, the full-car model takes about 12 times longer than the quarter-car model, and the half-car model takes 4 times as long.

Ride Quality Model II--UVA Method

This model, which uses a set of regression equations for different types of vehicles such as a bus, small, medium, or large automobile, and so on, was developed at the University of Virginia (6). The dependent variable of this model is the so-called ride quality index, which ranges from 1 (very comfortable) to 7 (very uncomfortable). The independent variables in this model include the root mean square (rms) values of the accelerations in three dimensions--roll, pitch, and yaw. Currently, only the equations for the automobiles are included in this package, and the independent variables used are the rms values of vertical acceleration and roll rate. The equation is

$$C' = 1.43 + 0.41\,\omega r + 11.84\,A_v \quad (5)$$

where

C' = comfort scale,
ωr = rms of roll rate (degrees/s), and
A_v = vertical acceleration (g's).

The rms value of seat vertical acceleration can be obtained in many ways (see Figure 5). The user can supply the measured value directly to the program or can supply the measured vertical acceleration time base and let the program calculate the rms value. If the program is required to calculate the rms values of seat acceleration, it first tries to condense the seat acceleration frequency spectrum; then, if the frequency spectrum is not available, the program calculates the seat acceleration spectrum by the method of path 2. However, if the vehicle simulation model has been run in the previous step, the program calculates the rms values directly from seat acceleration.

The rms value of roll rate is supplied to the program by the user or calculated from the roll rate time base, which can be obtained from the profile data of the two-wheel tracks via the half-car or full-car simulation model. Again, the user can replace any vehicle simulation model and can add equations for buses and trucks, or include the pitch as the third independent variable. The program structure has reserved space for expansions.

Paver-Grinder Simulator Branch

The paver-grinder simulator branch (see Figure 1) is an auxiliary program based on a program developed by the Michigan Department of Transportation that simulates the motion of an asphalt paver. The user can specify up to five different repavement thicknesses. The paver simulator will generate five sets of simulated profiles from the actual profile data. These simulated profiles are then used on other branches to obtain an estimate of improvement in

Figure 6. Sample control input.

```
                         INPUT CONTROL CARD DECK

     0         1         2         3         4         5         6         7         8
Col. 12345678901234567890123456789012345678901234567890123456789012345678901234567890

     PSIØ

                         QCAR                CONCrete pavement

                                             END

     DATA

                         VARB     2

                         CVEL 65.0

                         PSAD 0.1016
------------------------------------------------------------------------------------
     RIDE quality

                         LINEAR transfer function
------------------------------------------------------------------------------------
     RIDE

                         UNAM                ROLU

     DATA

                         VARB     2

                         ACCU 2.0

                         RROL 0.8
------------------------------------------------------------------------------------
     FINISH
```

ride quality or PSI. The paver simulator also reports the amount of material needed to repave the section studied. A user can check the estimates of improvement and the cost of various asphalt repaving thicknesses to decide which is the most cost-effective way to improve the pavement.

Profilometer Simulator

The profilometer simulator program was developed by the Federal Highway Administration (FHWA) (7) to solve the scale and filter problem in analog computation in a profilometer. The profilometer is a complex instrument to maintain and operate; it records the body acceleration of the vehicle and the body-test wheel relative displacement. The acceleration is double integrated and summed with the relative displacement by an on-board analog computer to yield the profile data. Because of the integration process, all instruments located upstream of the integrators need very accurate balance to prevent the signal from going out of bounds on integration.

The profilometer simulator takes digitized body acceleration and body-test wheel relative displacement as inputs, performs second finite difference on relative displacement, sums the second finite difference with acceleration, and then double integrates the summation digitally to yield the profile data. It includes a filter with selectable cutoff wavelengths to remove the terrain effect from the profile; unlike the analog filter, these digital filters work with zero phase shift. It also takes a series of distance pulses as input and converts the time-based profile into the equal-distance-based profile. This feature removes the requirement of constant vehicle velocity of the profilometer during operation.

A large amount of data needs to be processed to apply this method. To yield one channel of profile data, three channels of signal--acceleration, relative displacement, and distance pulse--are needed for accurate results in the integration process. The sampling rate for this method must be higher than that for profile data. The raw data of a simulated profilometer are 30 times greater in volume than that of direct profile data if the sample rate is 10 times the profile sample rate. At the present time small on-board computers have difficulty in sustaining this kind of data collection rate continuously. Thus, it is recommended that this method be used only for a short section of pavement, unless a large computer system is available.

PAVEMENT SIGNATURE COMPARISON

AFD is used with harmonic analysis to find slab or joint faulting. The harmonic analysis is used to find harmonic content in the same wavelength as the slab length. AFD analysis is then used to determine whether the pavement has joint faulting or slab curl.

SAMPLE INPUT-OUTPUT

The control program locates the large volume data sets, such as profile by International Business Machine's (IBM) job control language (JCL), and then recodes these data into standard format and block size on the disk. It follows another set of control input supplied by the user to perform the analysis task. An example of a set of control input is shown in Figure 6.

In this example the user specifies the PSI analysis first but prefers a quarter-car simulation model and a concrete pavement rather than the default paths. He or she also supplies two parameters of profile data, sample distance and vehicle speed, to the program. Next he or she asks for ride quality analysis by default; the ISO method is executed. Following that, he or she asks for ride quality analysis, this time by using the Virginia model, and he or she also puts in the rms value of the roll rate. Note that CONC is all that is read by the computer in the PSI request, but CONCRETE PAVEMENT was input by the user for his or her understanding. Similarly, RIDE is all that is required, but the first time RIDE QUALITY was used. This feature is useful.

Figure 7. Sample program output generated by input given in Figure 6.

```
                    ECHO USER INPUT
   PSIØ
                    QCAR                     CONCrete pavement
                                             END
   DATA
                    VARB    2
                    CVEL  65.0
                    PSAD  0.1016
   RIDE quality
                    LINEAR transfer function
   RIDE
                    UNAM                     ROLU
   DATA
                    VARB    1
                    RROL  0.8
   FINISH
          ****** PRESENT SERVICEABILITY INDEX ANALYSIS *****

OPTIONS AND PARAMETERS USED:
   ROUGHNESS EXPRESSED IN : ROUGHNESS INDEX(INCHES/MILE)
   PAVEMENT:  BITUMINUS
      PAVEMENT PARAMETERS:
         CRACK AND PATCHING=  0.0  (IN FT**2/1000FT**2 OR FT/1000FT**2)
         MEAN RUT DEPTH=  0.0  INCHES
   PSI FORMULA:THE ASSHO FORMULA
   ROUGHOMETER:MAYSMETER WITH MEASURED ROUGHNESS INDEX    130.700INCHES/MILE

THE RESULTS:
   THE ROUGHNESS INDEX =    130.7000INCHES/MILES
   THE PSI (PRESENT SERVICEABILITY INDEX) = 2.58

***MESSAGE:ALL PARAMETERS AND PATH SELECTIONS ARE SET TO DEFAULT VALUES.
  ALSO ALL DATA SETS ARE ZEROED

              ****** RIDE QUALITY ANALYSIS ******

OPTIONS AND PARAMETERS USED:
   ANALYSIS MODEL:  ISO STANDARD 2631
      LINEAR TRANSFER FUNCTION OF VEHICLE IS USED
         VEHICLE TYPE:  A STANDARD CAR OR MIDSIZE CAR
   ADDITIONAL DATA REQUESTED:  LINEAR FORM OF AMPLITUDE-FREQUENCE
         DISTRIBUTION FORMAT OF PROFILE
   ADDITIONAL DATA REQUESTED:  LINEAR FORM OF POWER SPECTRUM DENSITY
         OF PROFILE
      PROFILE SAMPLE DISTANCE    0.07620 METER
      VEHICLE VELOCITY    17.66660  METER/SECOND

THE RESULTS:
   AVAILABLE FREQUENCY DATA POINTS:  50
   THE AVERAGE TIME FOR A RIDE BECOMES UNCOMFORT IS   525.10 MINUTES
   THE MINIMUM TIME FOR UNCOMFORT IS     18.20 MINUTES

              ****** RIDE QUALITY ANALYSIS ******

OPTIONS AND PARAMETERS USED:
   ANALYSIS MODEL:  UNIVERSITY OF VIRGINIA MODEL
      USER PROVIDES THE RMS VALUE OF VEHICLE VERTICLE ACCELERATION
      USER PROVIDES THE RMS VALUE OF VEHICLE ROLL RATE
      PROFILE SAMPLE DISTANCE    0.07620 METER
      VEHICLE VELOCITY    17.66660  METER/SECOND

THE RESULTS:
   THE RMS VALUE OF SEAT ACCELERATION IS    2.0000000 METER/(SECOND**2)
   THE RMS VALUE OF ROLL RATE IS    0.8000000  DEGREE/SECOND
   THE UVA RIDE QUALITY INDEX IS    4.1743240
      ON A SCALE OF 1-- THE BEST TO 7--THE WORST

***MESSAGE:ALL PARAMETERS AND PATH SELECTIONS ARE SET TO DEFAULT VALUES.
  ALSO ALL DATA SETS ARE ZEROED
```

The program first echoes all user control input. After performing the task, it prints out the option taken and the results of the analysis. An example of the output is shown in Figure 7.

CONCLUSION

This package is a part of the computer program (MAPCON) developed for FHWA. Intermediate data sets are temporarily stored to increase the efficiency of the program. For example, once the half-car simulation is performed, the three output data sets can be used by different branches: relative displacement between vehicle body and axle used by the PSI branch; seat acceleration used by both ride quality branches; and roll rate used by the Virginia model. In this way, repeated computation is avoided. Thus, the package provides the highway engineers and management personnel with a useful and simple tool and removes most routine manual data processing.

Although many of the programs and analysis methods have been published in bits and pieces, some have not. They have never been integrated into a single versatile package. Thus, for the first time, a complete analysis program is available to pavement researchers and managers for use in analyzing pavement characteristics such as serviceability, ride quality, and safety.

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