Representation of Pavement Surface Topography in Predicting Runoff Depths and Hydroplaning Potential

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ABSTRACT

The sensitivity of the prediction of runoff depths and hydroplaning potential to variations in the elevation information used to define the pavement surface topography has been investigated. Different grid densities of elevation points, ranging from 8-in. to 36-in. spacing, and different levels of elevation data precision, ranging from 0.0003 ft to 0.05 ft, were evaluated. Topographic data, with elevation readings to 0.1 mm, were collected at a grid density of 4 in. over a 12- ft by 50-ft section of severely rutted roadway pavement. Runoff depths were computed using a one-dimensional, steady state computer model, employing a kinematic wave approximation. Maximum water depths for the severely rutted section were approximately 1 in. Predictive equations based on recent hydroplaning studies were used to estimate hydroplaning speeds. The results for the single section of pavement show that for a state-of-the-art prediction of runoff depths and hydroplaning potential, it appears adequate to collect elevation data points at a precision of 0.01 ft with a grid spacing of 36 in., being sure to include elevation points in the wheelpaths. It is recommended that additional test sites be observed and analyzed, especially under the conditions where maximum water depths range between 0.01 and 0.1 in. In this range, a more refined elevation precision and grid spacing may be required under certain circumstances.

Hydroplaning is a phenomenon in which a tire is completely separated from a pavement surface by a fluid layer, resulting in a reduction of the friction force at the tire-pavement interface to nearly zero. The primary factors influencing hydroplaning are the pavement surface, the vehicle and its operation, and the environment (typically rainfall). Presence of a fluid layer on the pavement is largely a function of the surface texture and topography in combination with significant rainfall accumulation and runoff. The friction characteristics of the tire-pavement interface differ considerably when the pavement is damp from when it is flooded with water. When the uplift resulting from fluid pressures within the tire-pavement contact zone exceeds the vertical load of the vehicle, the tire moves upward to maintain a dynamic equilibrium of the forces. Under these conditions, a gust of wind or a change in roadway superelevation or vehicle direction can create an unpredictable and uncontrollable sliding of the vehicle. Other variables influencing this phenomenon are the tire design, tread wear, tire-inflation pressure, and vehicle speed.

Efforts in the measurement of pavement surface topography have for the most part been directed toward the evaluation of road roughness. Road roughness is defined as the deviation of a pavement surface from a true planar surface with characteristic dimensions (e.g., roughness amplitude and frequency) that affect vehicle dynamics, ride quality, dynamic pavement loads, and pavement drainage (1). Road roughness is measured by two general types of equipment: profilometers, which measure the above characteristic dimensions directly, and response-type equipment, which measure surface roughness as a dynamic response of the measuring equipment to that roughness. There are two features of typical road roughness measurement that make it unsuitable for use in the measurement of pavement surface topography for the prediction of hydroplaning potential. Road roughness measurement is generally along only one of the wheelpaths, with some systems measuring both wheelpaths. This amount of data transverse to the roadway is inadequate to define where water may accumulate in the formation of hydroplaning fluid layers. Second, the profile reference datum for road roughness measurements is a moving, arbitrary datum, not tied precisely to true vertical (the direction of gravity). Thus, the roughness measurements do not in general yield correctly referenced topographic data (2).

Recent development of noncontact surface probes includes acoustic, infrared, white light, laser, and microwave radiation sources. The trailer-mounted System for Inventorying Road Surface Topography (SIRST), presently under evaluation by the Federal Highway Administration (FHWA), uses 12 infrared sensors spaced at 1-ft intervals transverse to the roadway. Pavement surface data points are collected at either 1-ft or 2-ft intervals, depending on whether the vehicle is traveling at 35 mph or speeds up to 55 mph. An inertial reference unit provides roll, pitch, and azimuth orientation, thus allowing for the maintenance of a stable reference datum referred to true vertical. This system has been developed particularly for the purpose of rapidly collecting the pavement surface topography for input to the prediction of hydroplaning potential (3).

In the measurement of road roughness, it is currently considered necessary that profiling equipment be capable of measuring amplitudes down to 0.01 in. (1). Preliminary tests by the Southwest Research Institute of the FHWA infrared sensors system have indicated that the height-sensing accuracy of the system is better than 0.01 in. (3). Although this accuracy is considered necessary for the measurement of road roughness, the accuracy required for the prediction of runoff depths and hydroplaning potential has not previously been investigated. Furthermore, it is of interest to determine the optimum density of the pavement surface data points to evaluate, for example, whether or not a 1-ft lateral and longitudinal spacing of data points is adequate, or whether a 2-ft or 3-ft spacing would cause any appreciable change in the prediction of runoff depths and hydroplaning potential for a given pavement surface.

Results of a study to evaluate the elevation precision and grid point spacing requirements of pavement surface topographic data collected for the prediction of runoff depths and hydroplaning potential are reported in this paper. This study was conducted in conjunction with the evaluation and modification of the SIRST vehicle and sensors at the Pennsylvania Transportation Institute.

PAVEMENT SURFACE TOPOGRAPHIC DATA COLLECTION

Detailed topographic data of the roadway surface were collected at a 12-ft by 50-ft test site to: (a) establish a part of the topographic standard against which the SIRST data could be evaluated, and (b) provide a topographic data base for use in development of a hydroplaning potential prediction computer program, HYDROP. These data were ideally suited for use in this sensitivity analysis.

Following are the physical characteristics of the test site selected.

1. General location: Pennsylvania Transportation Research Facility Test Track, a controlled access facility.
2. Length and width: 50 ft long by 12 ft (1 lane) wide.
3. Roadway alignment geometry: straight level section.
4. Roadway surface material: bituminous pavement.
5. Pavement surface condition: severe rutting in the wheelpaths.

Selection of the measurement system and procedures used to collect the topographic data was based on the following criteria:

1. Perceived data point accuracy and density requirements of the roadway surface topography for use in predicting hydroplaning potential.
2. Stated data point accuracy and density capabilities of the SIRST vehicle.
3. Available topographic survey instrumentation.

These considerations led to the choice of differential leveling procedures. An automatic level with optical micrometer and level rod was used for the relative elevation measurement of roadway surface points at a spacing of 4 in. in both the longitudinal and transverse directions over the entire test site.

USE OF GRID POINTS

The SIRST vehicle was designed to collect topographic data points at a fixed lateral spacing of 12 in. and at a longitudinal spacing of either 12 in. or 24 in., depending on the speed at which the vehicle is pulled along the roadway.

A uniform grid of discrete topographic data points is a logical organized system to use to approximate a continuous topographic surface. In establishing the topographic surface data base standard, a fixed lateral and longitudinal spacing of 4 in. was used. This dense set of data points could then be used as a reasonable standard of comparison with which to evaluate data for larger grid spacings. The 4-in. spacing of data points had a significant impact on the effort involved in data collection for the topographic data standard. In a 12-ft by 50-ft test site, there are 663 data points at a uniform 12-in. spacing, and an equivalent 5,587 data points at a uniform 4-in. spacing.

In preparing the roadway surface for measurement, circular marks were painted on the roadway at the 4-in. spacing, using a 4-ft by 8-ft plywood pattern board in which 0.25-in. diameter holes had been correspondingly drilled. On the average, 2 hrs were required to lay out the 4-in. spacing marks over a 12-ft by 50-ft test site.

Measurement of elevations continued from fall 1980 into spring 1981. Selected sections of the test site were then remeasured during the summer of 1982. Reference marks were used to reposition the plywood pattern board when weathering made remarking of the points necessary.

MEASUREMENT PROCESS

To collect the elevation data at each of the marked data points, a Leitz/Sokkisha B-2A Automatic level and K&E Metagrad Philadelphia metric level rod were used with a Leitz parallel plate optical micrometer, capable of being read directly to 0.1 mm with estimation to 0.01 mm. The SIRST vehicle is reported to collect elevation information accurate to 0.01 in. averaged over a 4-in. diameter spot. To collect direct topographic data for the standard, level rod readings were reported to 0.1 mm, equivalent to 0.004 in., an increment 2.5 times smaller than the 0.01-in. requirement reported for profiling equipment.

A reference mark was identified to serve as the elevation datum for the topographic data for the site. Rod readings were collected in a uniform manner, with the rod-person moving to consecutive data points in a column, longitudinally along the test site, then returning in sequence along points in the adjacent column. The rod was held plumb using a bull's-eye rod level such that the foot of the rod was at the elevation of the circular paint mark on the roadway surface. Recording of the rod readings was expedited by using a finger-controlled tape recorder to voice-record both the rod reading (to the nearest cm) and the optical micrometer reading (mm and tenths of mm). Each column of 151 data points, covering the 50-ft-long roadway surface, took 15 to 20 min to observe and record. Allowing for rest breaks, the 12-ft by 50-ft test site took 16 hr to survey. The recorded data values were transcribed from the tape recorder onto data forms, then to computer data cards that were checked against the tape-recorded data, and finally read into a data file. This process took approximately 12 hr.

ERROR CONSIDERATIONS

Choice of the least increment for the level rod readings of 0.1 mm was principally based on the reported 0.01 in. accuracy of the SIRST vehicle data. In light of the task of defining the continuous topography of a bituminous or concrete roadway surface, using data points every 12 in. or even every 4 in., such elevation accuracies (0.01 in. and 0.1 mm) are of no practical value. This can be readily demonstrated by noting the variation in elevation over any section of a test site. The 0.1-mm detail is clearly in the noise level compared to the macro variation in topography of the roadway surface.

Error sources of concern are those in which magnitude affect the definition of the road surface topography. Use of the optical micrometer and short sight distances observed with the automatic level, while holding the level rod plumb with a rod level, removes concern for significant level instrument and rod reading errors, or earth curvature and atmospheric refraction errors.

One important concern is the ability to hold the foot (i.e., bottom surface) of the level rod precisely at the elevation of the circular paint mark. The foot of the level rod is a flat surface approximately 1.7 in. square. Depending on the road surface topography in the immediate area about the circular paint mark, there may be difficulty in placing the foot of the rod precisely at the elevation of the mark. In addition, temporary irregularities in the road surface topography due to such items as loose road chips, also have a significant effect on the rod readings at the required level of accuracy.

With the level rod held plumb over the point of interest, the foot of the rod rests at the top of the pavement surface asperities. However, the reference elevation used to compute the volume of water traveling over the pavement surface must also take into consideration the texture depth of the asperities, determined in this study on a volumetric average basis using a sandpatch test (4). This necessary correction for the texture depth is applied during the data processing in the hydroplaning potential prediction computer program.

The largest error in road surface definition is the variation of the pavement surface with time, temperature, and related environmental changes. These variations result in significant changes in the roadway surface during a single day and over a period of weeks and months.

PAVEMENT SURFACE STABILITY

It is well-known that both bituminous and concrete pavement surfaces tend to expand and contract with environmental changes in temperature and moisture (5). Temperature differentials through the thickness of the pavement to the subgrade cause the pavement surface to warp, often resulting in pavement cracks. Other environmental effects on the pavement and pavement subgrade, such as rainfall and frost heave, give rise to even greater variations in the road surface topography. These deformations change throughout a given day as well as with longer periods of time.

In determining pavement surface variation of the test site after the original measurements were taken in 1980-1981, two sections, each 5 ft long by 12 ft wide (the width of one lane), were remeasured in 1982. Maximum differences of approximately 1 cm were observed in each of the remeasured sections. In the time interval between the two sets of measurements, the test site was subjected to severe heavy truck traffic, in support of other research projects at the test track. It is likely that this significant pavement loading, in conjunction with environmental conditions, caused movement in the surface topography.

Besides changes because of vehicular traffic and environmental effects, these elevation differences may also have been caused by not having the level rod at precisely the same point for both sets of measurements, and also by possible movement of the elevation reference mark. However, use of the pavement surface topographic data in a hydroplaning potential prediction computer program requires the availability of only relative elevation data. Absolute elevation data are not of critical importance. Elevation differences due to possible movement of the elevation reference mark are therefore of no effect, because all elevations of the pavement surface would appear to move the same amount.

GRAPHIC PRESENTATION OF TOPOGRAPHIC DATA

The most efficient means available to portray elevation differences over a topographic surface is through a graphic contour map of the surface. Computer-driven plotter generation of contours for the pavement surface of the test site was accomplished using the computer program package Surface II, developed by the Kansas Geological Survey (6). The plot is presented in Figure 1. The dimensions of the axes are in inches, the contours are labeled in meters, and the contour interval is 5 mm. The severe rutting in the wheelpaths is clearly noted. The maximum rut depth is approximately 6 cm.

The Surface II program is capable of accepting either a regular grid of elevation data values or a data set of irregularly spaced elevation values. Because the data set for the test site was collected on a regular 4-in. grid, the associated elevations were input directly into the Surface II program and the contours generated by a linear interpolation between the grid node values. The connection of like values formed the contour line. Piecewise Bessel interpolation was applied to smooth the contours, using a smoothing band 0.07 in. in width (6).

PREDICTING RUNOFF DEPTHS AND HYDROPLANING POTENTIAL

The topographic measurements enable the definition of a surface over which runoff occurs. Hydraulic analysis of the runoff leads to the prediction of runoff depths (water film thickness). These thicknesses are required to predict hydroplaning potential.

Water film thickness at nodes on the grid was computed using HYDROP, a one-dimensional, steady state, computer model that uses a kinematic wave approximation (7). The model itself is not the main focus of this paper and, thus, only a brief descrip-

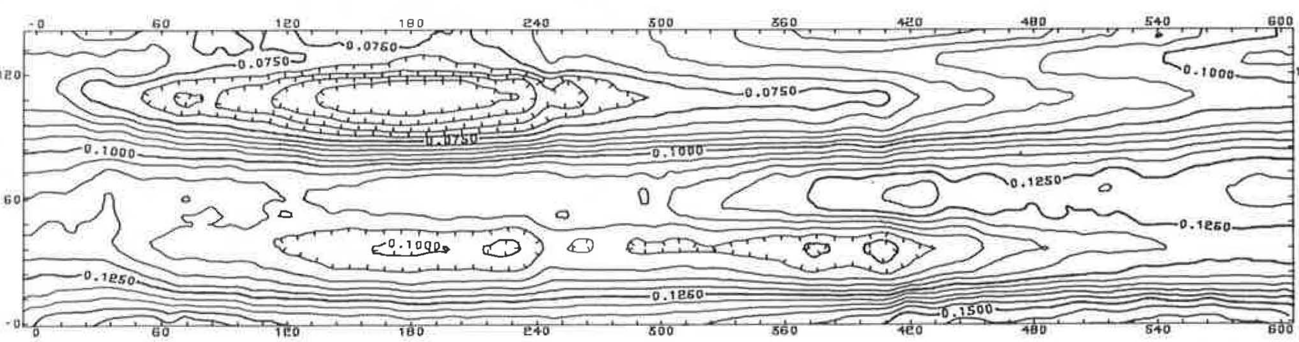

FIGURE 1 Contour plot of the test site pavement surface (perimeter axes in inches, contours labeled in meters, contour interval = 5 mm).

tion of its capabilities is included. The program, developed on an IBM 3081 computer and requiring 350K bytes of total storage for a 24-ft by 50-ft road section using a 12-in. by 12-in. grid, was specifically designed to account for the occurrence of rutting on highway pavements. Provided with the topography of the road surface, the program located the boundaries of areas that contributed rainfall runoff to local depressions. The area within the boundaries was divided into a series of cascading planes and collector channels. The selection of boundaries by the program introduced only minor continuity errors. The nodes where ponding would occur within each depression were also identified. The water surface elevation within each ponded area was determined by the conditions at a single outlet for each local depression. If not ponded, flow in ruts was treated as channel flow. The Chezy equation with Manning's C was used to model channel flow and overland plane flow.

Water depths computed by the Chezy equation or determined by outlet conditions for the ponded areas of the pavement were converted to water film thicknesses by subtracting the average texture depths of the pavement. This was done because the depth variable used in predictive models of hydroplaning speed is usually defined as "water depth above the asperities" (8). It was observed that texture depths vary laterally across a pavement, notably, in rutted areas and out of rutted areas. Thus, texture depths were assigned to each grid column. Manning's roughness coefficient was determined from texture depths (7) but was used in the computation of water depth based on whether a node was within a depression, for example, channel flow in a rut, or not in a depression, for example, overland plane flow.

Two predictive equations were used to estimate hydroplaning speeds at each node. Gallaway et al. (8) using multiple linear regression with a sample size of 1,038 cases found that hydroplaning speed could be expressed as:

$$HPS = SD^{0.04}\, p^{0.3}\, (TRD + 1)^{0.06}\, A \qquad (1)$$

where A is the greater of

$$(10.409/WFT^{0.06} + 3.507) \text{ and } (28.952/WFT^{0.06} - 7.817)\, TD^{0.14}$$

where

- HPS = vehicle speed at which hydroplaning occurs (mph);
- TRD = tread depth in 32nd of an inch;
- TD = texture depth in inches (silicon putty method);
- WFT = water depth above the asperities in inches (water film thickness);
- p = tire pressure in psi; and
- SD = spindown in percent

for a range of water film thickness from 0.095 to 0.15 in. Gallaway reported a correlation coefficient of 0.85, indicating that 72 percent of the variation in hydroplaning speed, HPS, could be explained by the equation. For film thicknesses less than 0.095 inches, an equation based on a regression of data points collected by Agrawal et al. (9) was used.

$$HPS = 26.04\, WFT^{-0.259} \qquad (2)$$

where HPS is vehicle speed at which hydroplaning occurs (mph), and WFT is water depth above the asperities, in inches (water film thickness). The regression had a correlation coefficient of 0.82, indicating that 68 percent of the variation in hydroplaning speed could be explained by the equation. Summary statistics for pavement sections were generated from computed hydroplaning speeds at each node but typically concentrated on conditions at nodes within the path of travel or wheelpaths.

Predicted waterfilm thicknesses by HYDROP were tested against measured waterfilm thicknesses at seven points on three field sites, using artificial rain-making equipment that produced average intensities of 1.0 to 2.5 in. per hour, spatially. The deviation of predicted values from measured values averaged 10 percent for six of the seven points, with a range of 3 to 15 percent for films of 0.08 to 1.1 in. The results were considered good in light of the uncertainty of the experimental rainfall rate averaged spatially, while HYDROP used the equivalent uniform rate. Pursuit of additional test data was deterred by instrumentation difficulties.

It should be noted that the analysis described here was restricted by several key limitations. First, water depths computed by the one-dimensional model were subject to the definition and location of boundaries for each contributing area. Also, depths within ponded areas were predicated on the assumption of a single outlet for each depression. Second, computed depths are significantly affected by the value chosen for Manning's roughness coefficient. When this study began, there was no conclusive means of selecting appropriate roughness coefficients for flow over pavements. Finally, the weakest parts of the analysis were the predictive equations used to estimate hydroplaning speed. Much more definitive work is required in this area before the results of an analysis of water depths on a pavement surface can be used to reliably predict the speed at which hydroplaning will occur.

VARIATIONS WITH GRID DENSITY AND ELEVATION PRECISION

The topographic data taken at the severely rutted test site, at lateral and longitudinal grid spacings of 4 in. and at the elevation least count of 0.1 mm, provided the basis for two significant evaluations. Comparison of predicted runoff depths and hydroplaning potential for different grid point spacings are presented in Table 1 and those for different elevation precisions are presented in Table 2.

Seven grid point spacings, varying in both the lateral and longitudinal directions from 8 in. to 36 in. are presented in Table 1. Computer run time for the 4-in. grid spacing was too excessive for it to be included. Evaluation of the sensitivity of the hydroplaning potential and runoff depth predictions to these different grid point spacings gives an indication of how far apart the elevation data points can be before the hydroplaning potential prediction is affected. It also points out the importance of having elevation data points in the wheelpath. The minimum hydroplaning speed, averaged over three consecutive data points, is 43 mph for all cases with elevation data in the wheelpath. This leads to the conclusion that as long as the elevation data includes points in the wheelpath, the data points may be as far apart as 36 in., with no degrading effect on the prediction of the minimum hydroplaning speed.

It is further noted from Table 1 that the maximum water film thickness and total depression storage vary greatly for cases without elevation data in the wheelpath. For cases with elevation data in the wheelpath, maximum water film thickness varies up to 14 percent, and total depression storage varies up to 28 percent, as the grid spacing increases.

Evaluation of the sensitivity of the hydroplaning potential and runoff depth predictions to various levels of precision of the grid point elevation data

TABLE 1 Sensitivity of the Prediction of Runoff Depths and Hydroplaning Potential for Different Grid Point Spacings (elevation precision = 0.0003 ft = 0.1 mm, rainfall intensity = 1 in. per hr)

	Grid Point Spacing (lateral x longitudinal)						
	8 x 8 (in.)	8 x 8 (in.)	12 x 12 (in.)	12 x 24 (in.)	24 x 24 (in.)	24 x 24 (in.)	36 x 36 (in.)
Elevation data in wheelpath	No	Yes	Yes	Yes	No	Yes	Yes
Maximum water film thickness (in.)	0.998	0.968	0.956	0.965	0.277	0.834	0.990
Total depression storage (ft^3)	2.4424	2.9839	2.5091	2.4345	0.9711	2.1555	2.6142
Percent of wheelpath below 55 mph	52.9	67.1	65.3	65.3	11.1	58.0	55.6
Minimum hydroplaning speed at a single point (mph)	43	43	43	43	46	43	43
Minimum hydroplaning speed, average of three consecutive points (mph)	43	43	43	43	46	43	43
Continuity error (% of total)	3.075	0.823	2.333	1.833	4.333	1.667	5.469
Computer run time (sec)	1,333	1,593	200	37	13	11	6

TABLE 2 Sensitivity of the Prediction of Runoff Depths and Hydroplaning Potential for Different Elevation Precisions (grid point spacing = 12 in. x 12 in., rainfall intensity = 1 in. per hr)

	Elevation Precision					
	0.0003 (ft)	0.0005 (ft)	0.0010 (ft)	0.0050 (ft)	0.0100 (ft)	0.0500 (ft)
Maximum water film thickness (in.)	0.956	0.967	0.965	0.948	0.946	1.166
Total depression storage (ft^3)	2.5091	2.4861	2.4895	2.5642	2.4581	2.6375
Percent of wheelpath below 55 mph	65.3	66.3	66.7	64.6	66.3	29.3
Minimum hydroplaning speed at a single point (mph)	43	43	43	43	43	43
Minimum hydroplaning speed, average of three consecutive points (mph)	43	43	43	43	43	43
Continuity error (% of total)	2.333	2.333	1.916	1.499	0.999	8.334
Computer run time (sec)	199	197	182	164	166	76

are presented in Table 2. These cases were all run at a grid point spacing of 12 in., in both the lateral and longitudinal directions. The various levels of elevation precision were established by rounding off the original elevation data (collected at a least count of 0.1 mm = 0.0003 ft) to the precision level indicated. It is noted that the minimum hydroplaning speed, averaged over three consecutive elevation data points, is 43 mph, for elevation precision ranging from 0.0003 ft to 0.0500 ft. The maximum water film thickness and total depression storage vary up to only 2 percent for elevation precision ranging from 0.0003 ft to 0.01 ft. At the elevation precision level of 0.05 ft, however, the variation in maximum water film thickness is 22 percent.

It is concluded from this evaluation that, for the state-of-the-art prediction of runoff depths and hydroplaning potential, it is adequate to collect elevation data points at a precision of 0.01 ft, with a grid spacing up to 36 in., being sure to include elevation points in the wheelpaths.

It is noted that these results have been obtained from the analysis of a single test site that was severely rutted, where the maximum water film thickness was approximately 1 in. The relative insensitivity of the minimum hydroplaning speed to large grid point spacings and elevation precision is largely due to the relative insensitivity of Equation 1 to water film thickness and to changes in water film thickness obtained for the given test site. Preliminary results from the analysis of a second test site, with maximum water film thickness approximately 0.06 in. and with maximum uniform pavement slope of 1.8 percent, appear to confirm these elevation precision and grid spacing requirements. However, it is recommended that additional test sites be observed and analyzed for further understanding of the relationships described, especially under conditions where maximum water film thickness ranges between 0.01 and 0.1 in. In this range, a more refined elevation precision and grid spacing may be required under certain circumstances.

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