Using IRI Measurements for Calculating German Planograph Outputs

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Synopsis

Smoothness has become the primary measure by which the traveling public determines and evaluates the quality of both newly constructed and rehabilitated pavements. Thus, striving for improved initial smoothness is becoming a worldwide endeavor. Numerous investigations have conclusively shown that even small improvements in initial smoothness provide significant increases in the long-term performance of the pavement surface with respect to roughness progression and long-term cracking. For these reasons, the Israeli Public Works Department (IPWD) has included strict roughness specifications in its recent, first, long-section, inter-urban, concrete road, consisting of a 4-lane stretch over a 7-kilometer length (on Route 3). This project was undertaken as a joint venture between a local asphalt-paving contractor and a well-experienced concrete-paving contractor from abroad (Germany). The IPWD utilized California-type profilograph outputs to serve the new roughness specifications. The reason for using this particular profile-measuring device stemmed from the rich experience acquired with it across the U.S. and Canada. For practical reasons, however, the German contractor on this project substituted the California-type profilograph with a German planograph of the Riedhofer Messtechnik V. 0.12 type.

In addition to the use of this German planograph, IPWD initiated its own roughness measurement by utilizing the Road Surface Profiler (RSP), a modern measuring machine equipped with optical distance-measurement devices (laser sensors) and accelerometers. The RSP machine is capable of measuring, calculating in real-time, displaying, and storing on a computer hard disk longitudinal road profiles and roughness data in terms of IRI (International Roughness Index). Thus, the output of this machine also enables virtual runs of the California-type profilograph and the German planograph on the measured longitudinal road profiles in order to calculate two key values: (a) the Profile Index (PI) (i.e., the roughness measures associated with the California-type profilograph) and (b) the vertical deviation (VD) (i.e., the roughness measures associated with the German planograph).

This paper shows the complete method of these virtual runs and their relevant equations. It also includes statistical studies comparing the IRI outputs obtained from the RSP machine measurements with the California-type profilograph and the German planograph outputs obtained from the virtual runs of these two measuring devices. Finally, a comparison of these outputs enables an evaluation of the German requirements for roughness in terms of the American and Canadian requirements. Conclusions and tentative recommendations on this matter are given.

In essence, the conclusions derived are as follows: (a) the model developed for calculating the VD (associated with the use of a German planograph) from the longitudinal road profiles that were measured with the RSP (associated with the use of IRI outputs) seems to be adequate; (b) the IPWD roughness criteria associated with the PI or IRI measurements are stricter than the German roughness criteria, which are associated with the VD measurements, even without taking into account the replacement actions that are compulsory in the PI and IRI criteria, but not in the VD criteria; (c) the German planograph, given its present German requirements, is capable of detecting localized roughness only, not of detecting continuous roughness along a pre-defined, substantial longitudinal distance; (d) the use of IRI outputs (both IRI_{100} and IRI_{10}) to characterize the roughness pattern of a given road is most appropriate when the use of the German planograph can substitute for the use of the American straightedge; (e) the use of the Local Roughness Deviation (LRD) criterion, suggested by the AASHTO procedure, cannot be replaced by the IRI_{10} criterion as some Israeli agencies suggested by and the use of the VD criterion (associated with the use of the German panograph) cannot replace the suggested AASHTO procedure. To sum up: the German planograph may be used as a substitute for the American straightedge. When the German planograph is applied, the roughness criteria associated with the American straightedge (such as those described by USACE) should also be applied.

Using IRI Measurements for Calculating German Planograph Outputs

Roughness is widely regarded as the most important measure of pavement performance because it is the measure most evident to the traveling public. In other words, it is by this measure that the traveling public determines and evaluates the quality of both newly constructed and rehabilitated pavements. Roughness greatly affects ride quality, safety, and vehicle-operating costs. Thus, striving for improved initial smoothness is becoming a worldwide endeavor. Numerous investigations have conclusively shown that even small improvements in initial smoothness provide significant increases in the long-term performance of the pavement surface because of delayed roughness progression and long-term cracking.

For example, some studies (see Smith et al., 1997a and 1997b), using both roughness-model and pavement-failure-analysis techniques, revealed that initial pavement smoothness had a significant effect on pavement life. Sensitivity analyses, in which the percentage change in pavement life as a percentage change in smoothness was determined, indicated sizeable increases in pavement life for most pavement groups, corresponding to nominal increases in smoothness. At least a 9 percent increase in life, corresponding to a 25 percent increase in smoothness, was observed for the majority of pavement groups, both asphalt and concrete. Table 1 shows partial data taken from the above two references for illustrative purposes.

Table 1. Smoothness Sensitivity Analysis for Kentucky and Wisconsin (Smith et al., 1997a and 1997b)

State (USA)	Pavement Type	Mean Percentage Increase in Life Corresponding to a Serviceability Increase of:		
		10%	20%	25%
Kentucky	Interstate: AC	3	7	---
	Parkway: AC	38	75	---
	Interstate: PCC	13	26	33
	Parkway: PCC	11	22	28
	Interstate: AC/AC	17	35	---
	Parkway: AC/AC	35	70	---
Wisconsin	AC on Rigid Base	10	20	---
	AC on Flex. Base	20	39	---

Additionally, cost-effectiveness analyses conducted by Smith et al. (1997a) on several pavement families showed that the most cost-effective smoothness levels are considerably higher than what is typically used as the 1997 target in the U.S. Moreover, theoretical pay-adjustment functions conducted by Smith et al. (1997a) for the above-mentioned pavement families showed greater maximum incentive amounts and more punitive disincentive amounts than the U.S. 1997 pay-adjustment functions. In support of these findings, Hein et al. (2000) have shown that compliance with the strict roughness requirements that have been posted in the Province of Ontario, Canada, since 1996 has led to an increase in pavement initial life by a full two years.

For these reasons, the Israeli Public Works Department (IPWD) has included strict roughness specifications in its recent, first, long-section, inter-urban, concrete road, consisting of a 4-lane stretch over a 7-kilometer length (on Route 3). This project was undertaken as a joint venture between a local asphalt-paving contractor and a well-experienced concrete-paving contractor from Germany as already described elsewhere (see Livneh, 2004). The experience gained from this project with the implementation of the new roughness-specifications is the subject of the present paper.

OBJECTIVES

In the above Route 3 project, the IPWD utilized California-type profilograph outputs to serve the specified roughness specifications. The reason for using this particular profile-measuring device stemmed from the rich experience acquired with it across the U.S. and Canada. For practical reasons, however, the German contractor on this project substituted the California-type profilograph with the German planograph of the Riedhofer

Messtechnik V. 0.12 type.

In addition to the use of this German planograph, IPWD initiated its own roughness measurement by utilizing a modern measuring machine equipped with optical distance-measurement devices (laser sensors) and accelerometers: the Road Surface Profiler (RSP). At this point, it should be mentioned that the RSP is capable of measuring, calculating in real-time, displaying, and storing on a computer hard disk longitudinal road profiles and roughness data in terms of IRI (International Roughness Index). Thus, the output of this machine also enables virtual runs of the California-type profilograph and the German planograph on the longitudinal road profiles measured in order to calculate two key values: (a) the Profile Index (PI) (i.e., the roughness measures associated with the California-type profilograph) and (b) the vertical deviation (VD) (i.e., the roughness measures associated with the German planograph).

Given this background, the objectives of the present paper were formulated as follows:

(a) To describe the German planograph of the Riedhofer Messtechnik V. 0.12 type and the German specifications associated with this measuring device,
(b) To develop the required equations for calculating the roughness outputs of a virtual German planograph (i.e., the VD outputs) from the profile measurements executed for the IRI measurements by a RSP machine,
(c) To compare the various roughness outputs and to evaluate the various roughness requirements associated with these outputs,
(d) To derive tentative conclusions concerning the most appropriate roughness index and the most appropriate use for the German planograph.

The processes of reaching these four objectives are detailed in the following sections of the present paper.

THE GERMAN PLANOGRAPH

The German planograph of the Riedhofer Messtechnik V. 0.12 type consists, as shown in Figure 1, of frame sections, wheel assemblies, steering mechanism, and a recorder. As shown in Figure 2, the beam length of the planograph is 4.0 meters, while the overall length is 4.3 meters. There are ten wheel-system supports at the bottom of the beam at the following distances from its center on both sides: 280 mm (wheels No. 5L and 5R, see Figure 2), 760 mm, (wheels No. 4L and 4R) 1,240 (wheels No. 3L and 3R), 1,720 mm (wheels No. 2L and 2R), 2000 mm (wheels No. 1L and 1R). The wheel located at the center of the unit is linked to a recorder, which records the gap between the height of the center of the beam with respect to the datum established by the two support wheels and the height of the profile at the same point. This vertical deviation (VD) is derived from the set of the following expressions:

$$Z_{1R:1L}=Z_{1R}\times[1-(L_{1R}/(L_{1R}+L_{1L})]+Z_{1L}\times L_{1R}/(L_{1R}+L_{1L}) \quad (1a)$$
$$Z_{1R:2L}=Z_{1R}\times[1-(L_{1R}/(L_{1R}+L_{2L})]+Z_{2L}\times L_{1R}/(L_{1R}+L_{2L}) \quad (1b)$$
$$Z_{1R:3L}=Z_{1R}\times[1-(L_{1R}/(L_{1R}+L_{3L})]+Z_{3L}\times L_{1R}/(L_{1R}+L_{3L}) \quad (1c)$$
$$Z_{1R:4L}=Z_{1R}\times[1-(L_{1R}/(L_{1R}+L_{4L})]+Z_{4L}\times L_{1R}/(L_{1R}+L_{4L}) \quad (1d)$$
$$Z_{1R:5L}=Z_{1R}\times[1-(L_{1R}/(L_{1R}+L_{5L})]+Z_{5L}\times L_{1R}/(L_{1R}+L_{5L}) \quad (1e)$$
$$Z_{2R:1L}=Z_{2R}\times[1-(L_{2R}/(L_{2R}+L_{1L})]+Z_{1L}\times L_{2R}/(L_{2R}+L_{1L}) \quad (2a)$$
$$Z_{2R:2L}=Z_{2R}\times[1-(L_{2R}/(L_{2R}+L_{2L})]+Z_{2L}\times L_{2R}/(L_{2R}+L_{2L}) \quad (2b)$$
$$Z_{2R:3L}=Z_{2R}\times[1-(L_{2R}/(L_{2R}+L_{3L})]+Z_{3L}\times L_{2R}/(L_{2R}+L_{3L}) \quad (2c)$$
$$Z_{2R:4L}=Z_{2R}\times[1-(L_{2R}/(L_{2R}+L_{4L})]+Z_{4L}\times L_{2R}/(L_{2R}+L_{4L}) \quad (2d)$$
$$Z_{2R:5L}=Z_{2R}\times[1-(L_{2R}/(L_{2R}+L_{5L})]+Z_{5L}\times L_{2R}/(L_{2R}+L_{5L}) \quad (2e)$$
$$Z_{3R:1L}=Z_{3R}\times[1-(L_{3R}/(L_{3R}+L_{1L})]+Z_{1L}\times L_{3R}/(L_{3R}+L_{1L}) \quad (3a)$$
$$Z_{3R:2L}=Z_{3R}\times[1-(L_{3R}/(L_{3R}+L_{2L})]+Z_{2L}\times L_{3R}/(L_{3R}+L_{2L}) \quad (3b)$$
$$Z_{3R:3L}=Z_{3R}\times[1-(L_{3R}/(L_{3R}+L_{3L})]+Z_{3L}\times L_{3R}/(L_{3R}+L_{3L}) \quad (3c)$$
$$Z_{3R:4L}=Z_{3R}\times[1-(L_{3R}/(L_{3R}+L_{4L})]+Z_{4L}\times L_{3R}/(L_{3R}+L_{4L}) \quad (3d)$$
$$Z_{3R:5L}=Z_{3R}\times[1-(L_{3R}/(L_{3R}+L_{5L})]+Z_{5L}\times L_{3R}/(L_{3R}+L_{5L}) \quad (3e)$$
$$Z_{4R:1L}=Z_{4R}\times[1-(L_{4R}/(L_{4R}+L_{1L})]+Z_{1L}\times L_{4R}/(L_{4R}+L_{1L}) \quad (4a)$$

$$Z_{4R:2L}=Z_{4R}\times[1-(L_{4R}/(L_{4R}+L_{2L})]+Z_{2L}\times L_{4R}/(L_{4R}+L_{2L}) \tag{4b}$$
$$Z_{4R:3L}=Z_{4R}\times[1-(L_{4R}/(L_{4R}+L_{3L})]+Z_{3L}\times L_{4R}/(L_{4R}+L_{3L}) \tag{4c}$$
$$Z_{4R:4L}=Z_{4R}\times[1-(L_{4R}/(L_{4R}+L_{4L})]+Z_{4L}\times L_{4R}/(L_{4R}+L_{4L}) \tag{4d}$$
$$Z_{4R:5L}=Z_{4R}\times[1-(L_{4R}/(L_{4R}+L_{5L})]+Z_{5L}\times L_{4R}/(L_{4R}+L_{5L}) \tag{4e}$$
$$Z_{5R:1L}=Z_{5R}\times[1-(L_{5R}/(L_{5R}+L_{1L})]+Z_{1L}\times L_{5R}/(L_{5R}+L_{1L}) \tag{5a}$$
$$Z_{5R:2L}=Z_{5R}\times[1-(L_{5R}/(L_{5R}+L_{2L})]+Z_{2L}\times L_{5R}/(L_{5R}+L_{2L}) \tag{5b}$$
$$Z_{5R:3L}=Z_{5R}\times[1-(L_{5R}/(L_{5R}+L_{3L})]+Z_{3L}\times L_{5R}/(L_{5R}+L_{3L}) \tag{5c}$$
$$Z_{4R:4L}=Z_{5R}\times[1-(L_{5R}/(L_{5R}+L_{4L})]+Z_{4L}\times L_{5R}/(L_{5R}+L_{4L}) \tag{5d}$$
$$Z_{5R:5L}=Z_{5R}\times[1-(L_{5R}/(L_{5R}+L_{5L})]+Z_{5L}\times L_{5R}/(L_{5R}+L_{5L}) \tag{5e}$$
$$\begin{aligned}VD=\mathrm{Max}(&Z_{1R:1L}, Z_{2R:2L},\ldots, Z_{2R:1L}, Z_{2R:2L},\ldots, Z_{3R:1L}, Z_{3R:2L},\ldots,\\ &Z_{4R:1L}, Z_{4R:2L},\ldots, Z_{5R:1L}, Z_{5R:2L},\ldots, Z_{5R:5L})-Z_C\end{aligned} \tag{6}$$

Figure 1. The German Planograph of the Riedhofer Messtechnik V. 0.12 type: (a) a side elevation view; (b) as utilized on Route 3

In the above equations (see Figure 2), Z_{1R} denotes the height of the profile at a point located at wheel No. 1R for a given location of the center of the beam; Z_{2R} denotes the height of the profile at a point located at wheel No. 2R for the same location of the center of the beam, etc.; Z_{1L} denotes the height of the profile at a point located at wheel No. 1L for the same location of the center of the beam; Z_{2L} denotes the height of the profile at a point located at wheel No. 2L for the same location of the center of the beam, etc.; Z_C denotes the height of the profile at a point located at the center of the beam for the same given location of the beam; L_{1R} denotes the longitudinal distance between the center of the beam and a point located at wheel No. 1R; L_{2R} denotes the longitudinal distance between the center of the beam and a point located at wheel No. 2R, etc.; L_{1L} denotes the longitudinal distance between the center of the beam and a point located at wheel No. 1L; L_{2L} denotes the longitudinal distance between the center of the beam and a point located at wheel No. 2L, etc.

Also, in the above equations, $Z_{1R:1L}$ denotes the height of the center of the beam when the heights of the beam at wheel No. 1R and wheel No. 1L coincide with the heights of the given profile; $Z_{1R:2L}$ denotes the height of the center of the beam when the heights of the beam at wheel No. 1R and wheel No. 2L coincide with the heights of the given profile, etc. VD denotes the vertical deviation between (a) the center of the beam when it rests on two of its ten wheels, one at the right side of the beam and the other at the left side of the beam, according to the profile-configuration directive, and (b) the height of the profile itself.

The first 25 equations are illustrated in Figure 2 by the 25 straight lines, which each time connect one wheel of the left side of the beam to the other wheel of the right side of the beam. The outputs from using these equations will be shown later on in the paper.

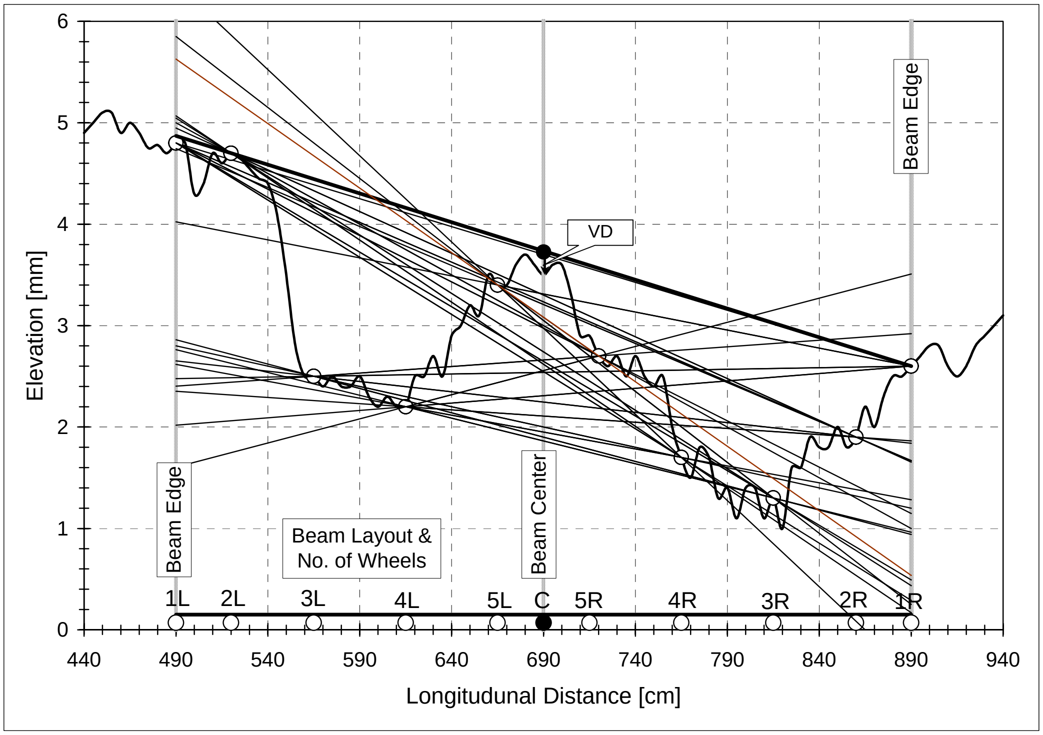

Figure 2. A schematic description of (a) the German Planograph of the Riedhoter V. 0.12 type and (b) the virtual calculation of the vertical deviation

Finally, the corresponding calculations of the PI values from the virtual runs of the California-type profilograph on the longitudinal road profiles measured are shown elsewhere (Livneh et al., 2003). In that reference, the complete method and its relevant equations are detailed.

ROUGHNESS CRITERIA

The German specifications (DIN 18316, Paragraph 3.3.4.10) call for the following smoothness requirements for any given finished surface: (a) the maximum tolerable VD value, as measured by the German planograph, shouldl not exceed the 4 mm value for all primary highways and the 6 mm for all secondary highways; (b) reduced pay-adjustments will take place when the VD values measured exceed the values specified above; more details on this issue are given later on. Note: No absolute maximum VD value is specified, beyond which replacement actions are required.

The IPWD tentative roughness criteria for concrete pavements are as follows: (a) a maximum allowable IRI_{100} value of 1.7 m/km, beyond which replacement actions are required; (b) a nominal allowable IRI_{100} value of 1.3 m/km, beyond which reduced pay-adjustments take place; and (c) a nominal allowable IRI_{100} value of 1.0 m/km, up to which bonus pay-adjustments occur. Furthermore, the IPWD tentative roughness criteria call for a maximum allowable IRI_{10} value of 2.3 m/km. Note: These IRI_{100} values are calculated for consecutive 100-meter segments; in the same manner, the IRI_{10} values are calculated for consecutive 10-meter segments.

Finally, as mentioned before, the IPWD roughness criteria specified for the construction of concrete slabs on Route 3 call for the use of the California-type profilograph. For this profilograph, the roughness requirements are the following: (a) a maximum allowable $PI_{0.0}$ value of 0.790 m/km, beyond which replacement actions are required; (b) a nominal allowable $PI_{0.0}$ value of 0.475 m/km, beyond which reduced pay-adjustments take place; and (c) a nominal allowable $PI_{0.0}$ value of 0.235 m/km, up to which bonus pay-adjustments occur. Note: These $PI_{0.0}$ values are measured for consecutive 100-meter segments. It should be remembered that the 0.0 notation in $PI_{0.0}$ denotes the use of a zero blanking band in calculating PI; for more details, see Livneh et al. (2003).

ROUGHNESS MEASUREMENTS

Immediately after the completion of the concrete pavement section of Route 3, road-roughness measurements were conducted only with the German planograph of the Riedhofer Messtechnik V. 0.12 type. All of four lanes were monitored along a total length of about 20 km by this planograph. The VD results obtained in these measurements are displayed in Figure 3. Specifically, this figure shows the cumulative percentage distribution (the cumulative frequency) only of the defect VD values (i.e., only vertical deviation values exceeding the 4-mm criterion) of all the values measured along the center line of two given sample stretches, one 3,567 meters long and the other 3,540 meters long. The figure shows that the VD values vary up to more than 10 mm. Moreover, this figure indicates that the percentage defect of all VD values measured is 3.6% for one sample stretch and 6.0% for the other sample stretch.

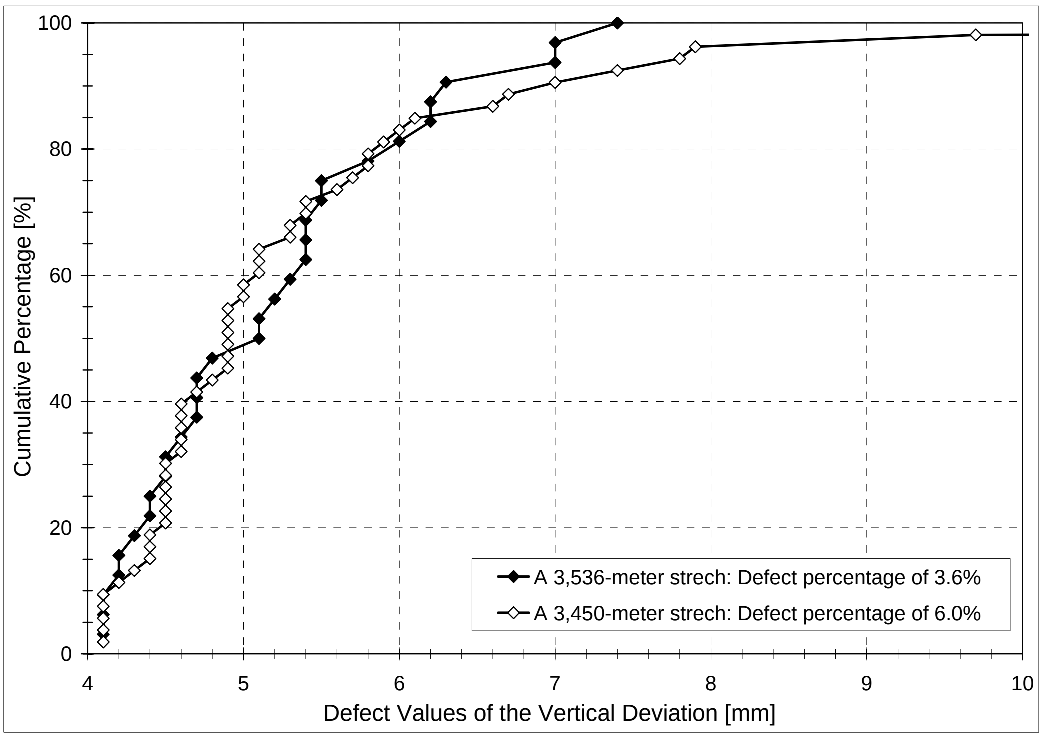

Figure 3. Cumulative frequency distribution of the defect VD (the vertical deviation) values measured by the German planograph for two sample stretches along Route 3

After more than one year following the completion of the concrete-pavement portion of Route 3, road-roughness measurements were conducted only with a Road Surface Profiler (RSP). All four lanes were monitored along a total length of about 20 km by this inertial profiler, which measured and stored longitudinal road profiles at 50 mm intervals on its computer hard disk. Note that the reported profile data in this RSP system are the filtered ones, according to the H.P. Butterworth method.

The filtered data were then used to calculate the IRI values for each 10-meter (IRI_{10}) and 100-meter segment (IRI_{100}). The cumulative frequency distributions of the IRI_{100} and IRI_{10} values measured along Lane 5 of Route 3 (excluding the odd values measured along its three existing overpass sections) are shown in Figure 4. The criteria limits for absolute rejection are also displayed in this figure, which shows that substantial portions of the IRI_{100} results (about 55%) exceed the proposed criteria limit. This figure also shows that substantial portions, though a lesser amount, of the IRI_{10} results (about 20%) exceed the proposed criteria limit.

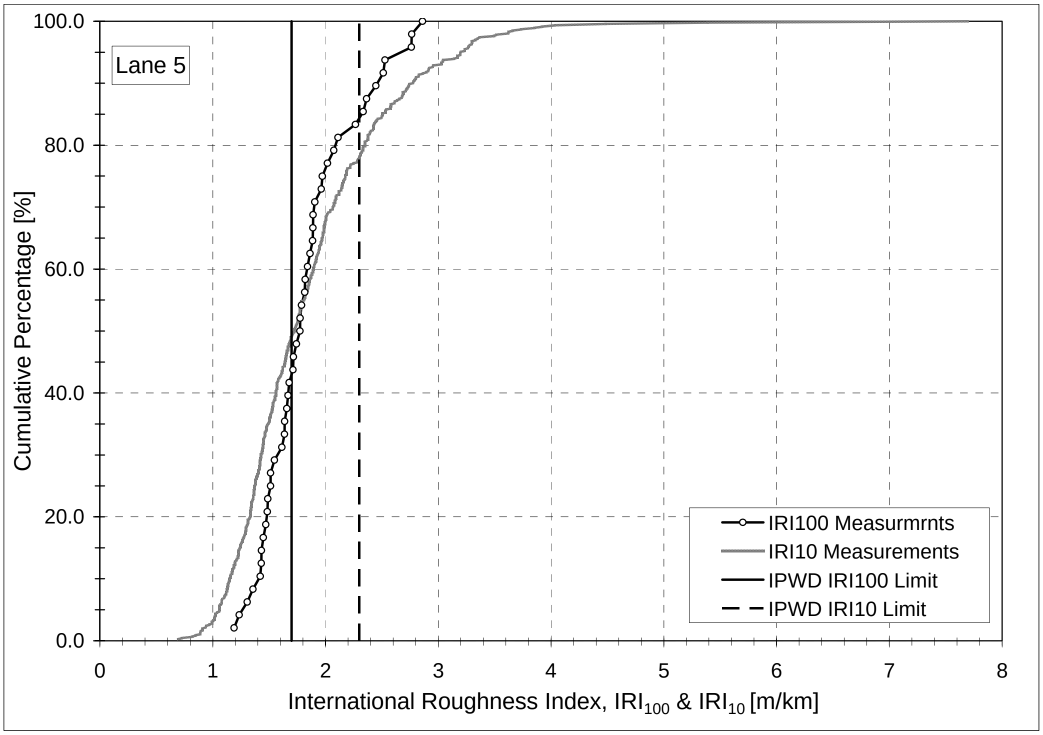

Figure 4. Cumulative frequency distribution of the IRI_{100} and IRI_{10} values measured along Lane 5 of Route 3, excluding the odd values measured along its three overpass sections

Now, the average rate of change that was measured for the IRI_{100} values of Lane 5 was only 1.1% (see Livneh, 2004). For a probability of 95%, the value of the true rate of change in the IRI_{100} values obtained for this lane was only 2.5%. Thus, the roughness pattern that existed more than one year after the completion of the concrete-pavement portion of Route 3 (as shown in Figure 4) was almost the same as at its opening day. For this observed roughness behavior, the data of Figure 4 can be compared with the data of Figure 3. This leads to the conclusion that the IPWD tentative roughness criteria associated with the IRI measurements are stricter than the German roughness criteria associated with the VD measurements, even without taking into account the replacement actions that are compulsory in the IRI criteria and not in the VD criteria.

SIMULATED-ROUGHNESS CALCULATIONS

As indicated, the IRI measurements also enable calculations of simulated PI and VD roughness indexes by making virtual runs of the California-type profilograph and the German planograph on the longitudinal road profiles measured. These calculations were conducted for Lane 5 of Route 3, using the first 1,500 meters of its measured longitudinal road profile. The outcome of these calculations is shown in Figure 5. It displays the cumulative percentage of the simulated VD values (associated with the German planograph) and the simulated $PI_{0.0}$ values (associated with the California-type profilograph) calculated for the above section. This figure indicates that the defect percentage of the VD values is 3%, whereas the defect percentage of the $PI_{0.0}$ values is 18%. This finding leads once again, to the conclusion that the IPWD roughness criteria associated with the $PI_{0.0}$ measurements are stricter than the German roughness criteria associated with the VD measurements, even without taking into account the replacement actions that are compulsory in the PI criteria and not in the VD criteria.

Here it should be noted that the defect percentage of the IRI_{100} values as shown in Figure 4 is much higher than the defect percentage of the $PI_{0.0}$ values shown in Figure 5 (55% against 18%). If the upper limit for the $PI_{0.0}$ values (0.790 m/km) is transformed into an equivalent IRI_{100} value by the regression equation derived for Route 3 roughness measurements (see Equation 7), a higher value is obtained for the upper limit, 2.0 m/km compared to 1.7 m/km for the IRI_{100} values. For this higher value of 2.0 m/km, the defect percentage of the IRI_{100} values of Figure 4 is about 23%, close to the 18% of Figure 5. The expression for the regression equation utilized for this transformation, obtained by Livneh et al. (2003), is:

$$IRI_{100}=2.1492\times PI_{0.0}+0.2968 \quad N=208 \quad R2=0.84 \qquad (7)$$

In this context, it should be noted that another regression equation was recently derived by Smith et al. (2002) for the U.S. Department of Transportation's Federal Highway Administration (FHWA):

$$IRI_{100}=2.3582\times PI_{0.0}+03172 \quad N=2888 \quad R^2=0.84 \qquad (8)$$

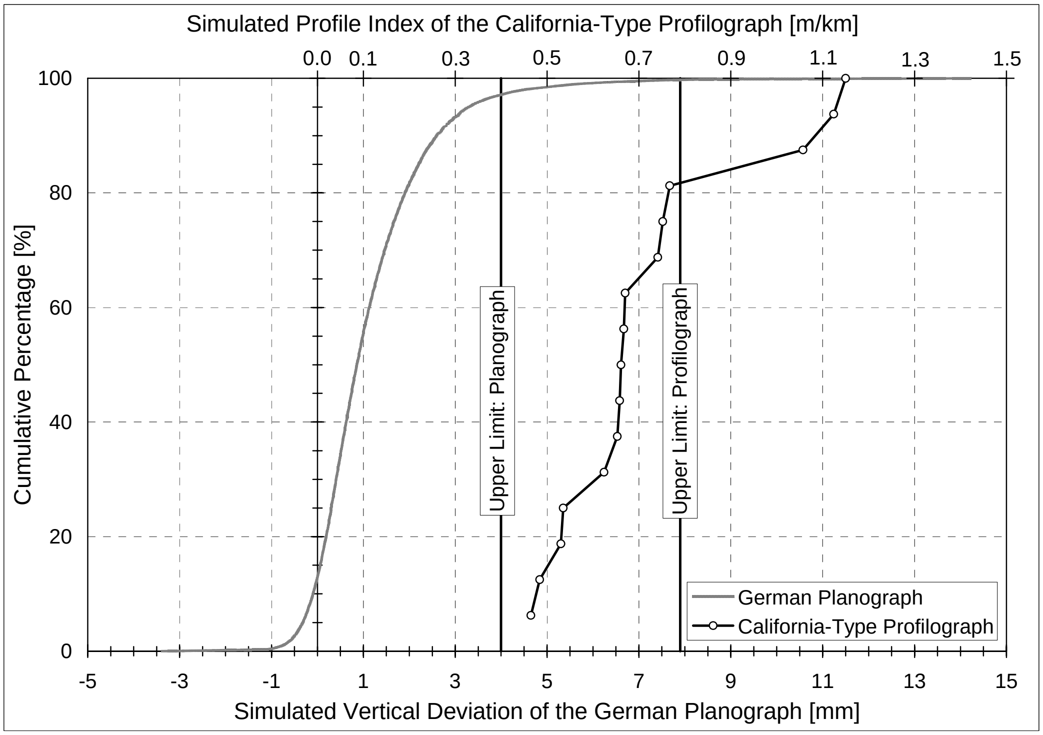

Figure 5. Cumulative frequency distribution of the simulated VD and simulated $PI_{0.0}$ values along Lane 5 of Route 3 (first 1,500 meters only along the left-wheel path)

The alternative regression equation (Equation 8) leads to higher IRI_{100} values than those of Equation 7. For example, the 2.0 m/km value derived from Equation 7 is equivalent to the 2.2 m/km value derived from Equation 8. This latter value leads from Figure 4 to a defect percentage of the IRI_{100} value of the same 18% of Figure 5.

Figure 6, which displays the same roughness results of Figure 5, describes the longitudinal variation of the defect values of the simulated VD values (associated with the German planograph) and all values of the simulated $PI_{0.0}$ values (associated with the California-type profilograph) calculated for the first 1,500 meters of Lane 5 of Route 3. Figure 6 indicates that the German planograph is capable of detecting only localized roughness. The defect VD values are concentrated each time along a very short longitudinal distance (4.0 meters), whereas the defect $PI_{0.0}$ values are associated each time with a longitudinal distance of 100 meters. Thus, the German planograph, given the present German requirements, is not capable of detecting continuous roughness along a substantial pre-defined longitudinal distance (100 meters).

Finally it should be stated that the defect percentage of the VD values obtained from real roughness measurements (see Figure 3) was found to be in the same range of the defect percentages of the simulated VD values obtained from the IRI roughness measurements (see Figure 5): 3.6% to 6.0% as against 3%. This finding supports the model calculations of the simulated VD values (associated with the German planograph) from IRI roughness measurements as described in this paper.

STRAIGHTEDGE VERSUS GERMAN PLANOGRAPH

Here, mention should be made of the USACE (2003) smoothness criteria associated with 4-meter straightedge testing: "When between 5.0 and 10.0 percent of all measurements made with a lot exceed the tolerance specified in paragraph Smoothness Requirements above, after any reduction of high spots or removal and replacement, the computed pay factor for that lot based on surface smoothness, will be 95 percent. When more than 10.0 percent of all measurements exceed the tolerance, the computed pay factor will be 90 percent. When between 15.0 and 20.0 percent of all measurements exceed the tolerance, the computed pay factor will be 75 percent. When 20.0 percent or more of the measurements exceed the tolerance, the lot shall be removed and replaced at no additional cost to the Government-Owner."

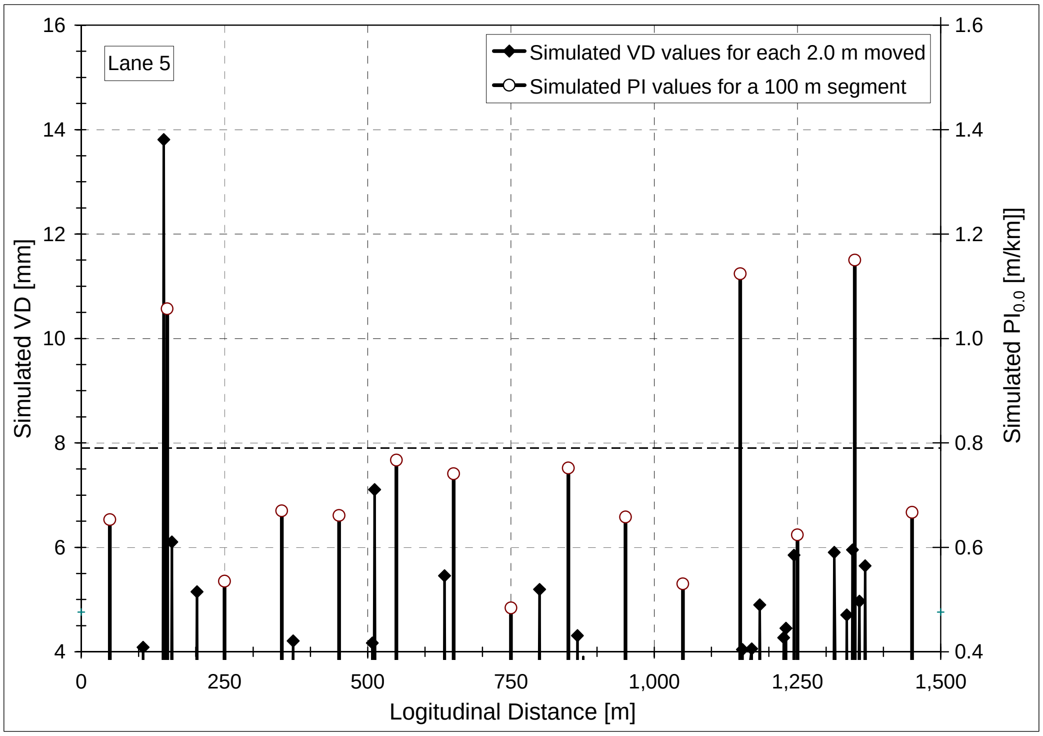

Figure 6. Variation of Figure 5 in simulated VD and simulated $PI_{0.0}$ values along Lane 5 of Route 3 (first 1,500 meters along the left-wheel path)

As for the German planograph, the reduced pay-adjustment is proportional to the following VDS_{100} parameter:

$$VDS_{100}=\Sigma(VD_i-4)^2 \qquad (9)$$

where VD_i denotes the defect VD value at the middle of the beam at point i, where the planograph is moved ahead one-half of the length of the beam (2.0 meters) for each successive measurement along a 100-meter segment; VDS_{100} denotes the sum of the square values of the difference between the above defect VD values and the maximum allowable value of 4 mm along the 100-meter segment.

Thus, the reduced pay-adjustment associated with the straightedge testing is not a function of the amount of maximum gap measured between the straightedge and the pavement surface, but of the percentage occurrence of measured defect values at any level along a given lot. This requirement makes straightedge testing capable also of detecting continuous roughness along a substantial pre-defined longitudinal distance (100 meters).

On the other hand, the reduced pay adjustment associated with German planograph testing is a function of the amount of gap measured between the center of the beam and the pavement surface, not of the percentage occurrence of measured defect values at any level along a given lot. As mentioned before, this requirement does not make the German planograph testing capable of detecting continuous roughness along a substantial pre-defined longitudinal distance (100 meters).

Finally, it is worthwhile noting that the VDS_{100} parameter of Equation 9 (associated with the German planograph) is equivalent to the $PI_{0.0}$ parameter. Thus it is interesting to calculate these VDS_{100} values of Equation 9 for the roughness data of Figure 6. The output of these calculations is shown in Figure 7 which describes the longitudinal variation of the defect values of the simulated VDS_{100} values of Equation 9 (associated with the German planograph) and all values of the simulated $PI_{0.0}$ values (associated with the California-type profilograph) calculated along the first 1,500 meters of Lane 5 of Route 3. Figure 7 indicates that there is no correlation between the VDS_{100} and the $PI_{0.0}$ values, both calculated for the same 100-meter segment. This finding stems from the difference in beams length: 4.0 meter for the German planograph and 7.6 for the California-type profilograph (see Livneh et al., 2003).

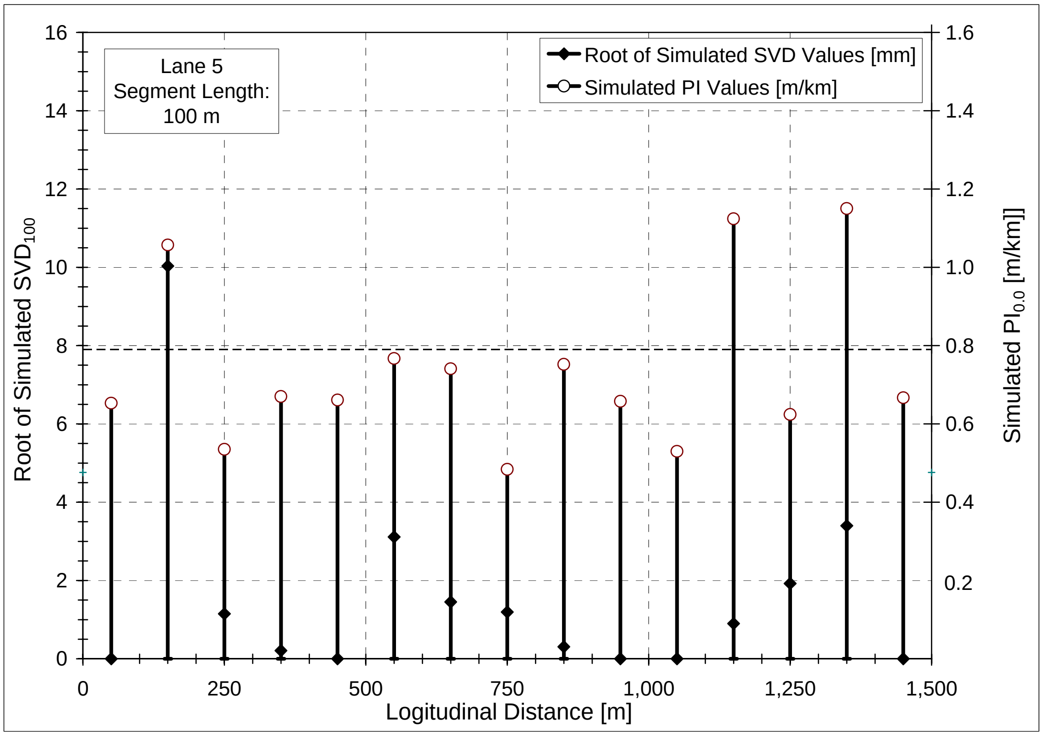

Figure 7. Variation of Figures 5 and 6 in simulated SVD_{100} and simulated $PI_{0.0}$ values along Lane 5 of Route 3 (first 1,500 meters along the left-wheel path)

LOCALIZED ROUGHNESS

Since the German planograph is capable of detecting localized roughness, it is worthwhile bringing some comparative results concerning this issue. First, though, it should be mentioned that, according to several sources (see, for example, Giammaria, 2004; Kokot and Leben, 2004), localized roughness also serves as an important indicator of ride-comfort. Thus, it should be detected along the continuous roughness. In the above-mentioned sources and in USACE (2003) the American straightedge serves to detect locations of localized roughness. The latter source states, for example, that "any small individual area with surface deviation which exceeds the tolerance given earlier by more than 50 percent, shall be corrected by diamond grinding to meet the specification requirements or shall be removed and replaced at no additional cost to the Government."

AASHTO (2002) introduced new engineering requirements to limit localized roughness values (see, also, Fernando and Bertrand, 2002). These values are now determined from the same filtered profiles collected longitudinally for the IRI determinations. In more detail, areas of localized roughness are identified through a 7.6-meter moving-average filter (for an example, see Figure 8, taken from Livneh, 2004), with the difference determined between it and the reported relative elevation for every profile point. These differences (deviations) were later termed LRD (Localized Roughness Deviations). According to AASHTO (2002), positive LRD values are considered "bumps" and negative LRD values are considered "dips," while absolute LRD values greater than 4 mm are considered a detected area of localized roughness. (See Figure 9, again taken from Livneh, 2004, for example).

Several agencies In Israel and around the world suggest sometimes another method for detecting areas of localized roughness: the calculation of IRI_{10}; i.e., the average IRI value for a 10-meter-long segment (see, for example, Ningyuan et al., 2002), or for a 16-meter-long segment (see, for example, McGhee, 2000). Thus, for the described roughness measurements, Table 2 and Figure 10 (taken from Livneh, 2004) display the statistical characteristics of the calculated LRD and IRI_{10} values that were obtained for the concrete-pavement section of Route 3.

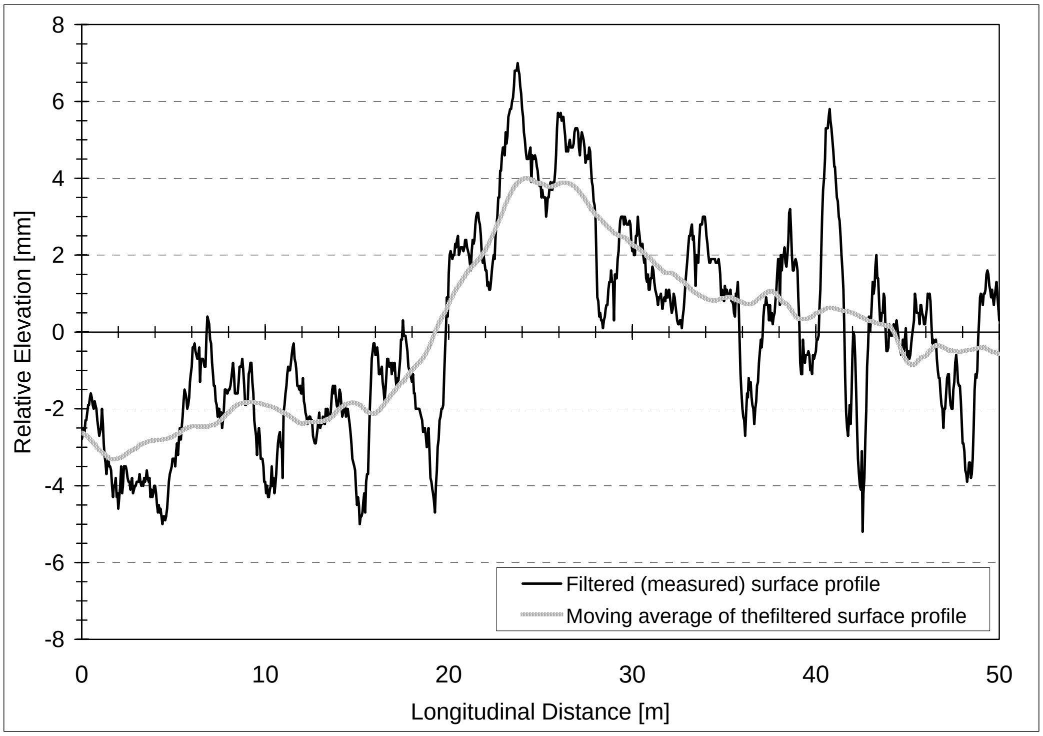

Figure 8. Example of a measured and a 7.6-meter moving-average profile

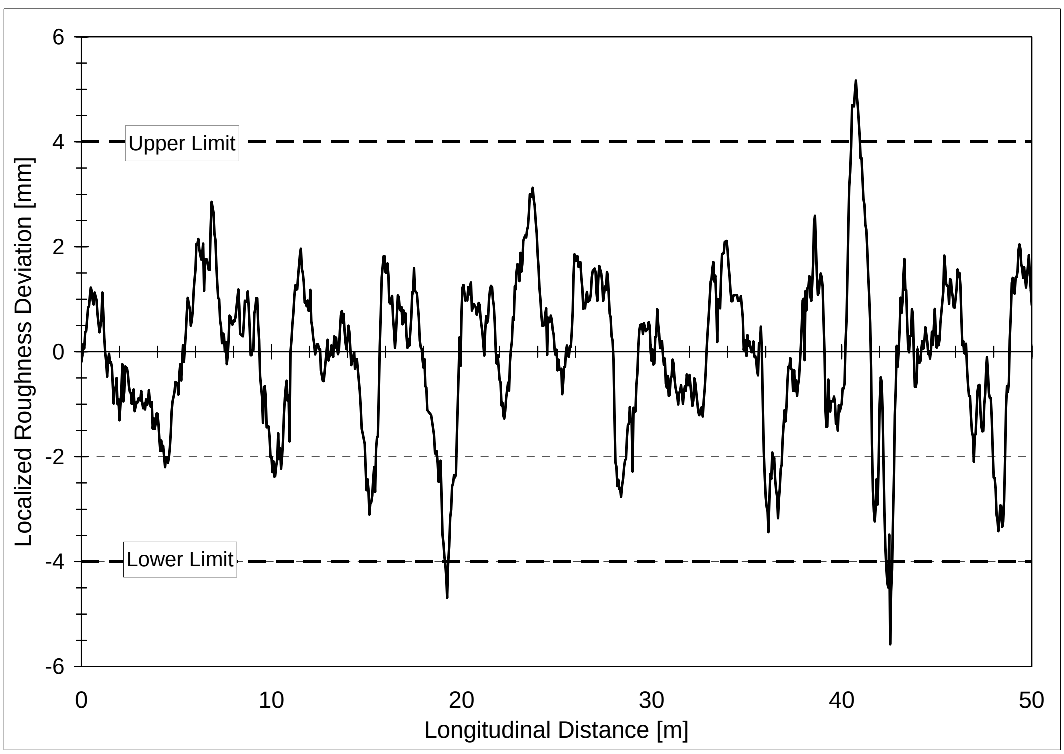

Figure 9. Example of the height deviation (LRD) of the measured and moving-average profiles of Figure 8

Table 2 refers to the measurement of all four lanes along both the inner wheel path (left path) and the outer wheel path (right path) of the measuring vehicle. This table indicates that about 10% of the road stretch (including the three overpass segments) in the roughness measurements described contained areas of localized roughness. Again, it can be concluded that the same localized roughness pattern already existed on the opening day (i.e., the construction-termination day) of the present concrete pavement of Route 3. Thus, this LRD method leads to a higher percentage of excessive localized roughness (9.5-11.3%) than that associated with the VD method (3.6-6.0%).

Table 2. Statistical characteristics of the localized roughness of the concrete-pavement section of Route 3, in terms of LRD and IRI_{10} values

Wheel Path	Percentage of Excessive LRD Points	IRI_{10} for All Measured Points with Excessive LRD Values			IRI_{10} for All Measured Points without Excessive LRD Values		
		Mean	Standard Deviation	15th Percentile	Mean	Standard Deviation	15th Percentile
Left	11.3%	3.55	1.67	2.29	1.66	0.61	1. 09
Right	9.5%	3.54	1.75	2.15	1.50	0.54	1.01

Additionally, Table 2 shows that the two IRI_{10} populations (i.e., one of all measured points with excessive LRD values, and the other of all measured points without excessive LRD values) are entirely different. This means that there is no one-to-one correlation between IRI_{10} and LRD values. Therefore, in order totally to ensure the required limitation of the LRD values (to a maximum of 4 mm), the IRI_{10} values should be limited to a maximum allowable value of about 1.2 m/km (see Figure 10). This limitation, however, would mean that more than about 80% of the area (see, again, Figure 10) should be rejected although only about 10% of the area (see Table 2) contains unacceptable results in terms of LRD values.

Obviously, if a higher maximum limiting value is assigned to the IRI_{10} results, the unnecessary rejection in terms of LRD values would be reduced; at the same time, however, not all areas with excessive LRD values would be rejected. For example, if the limiting value assigned to the IRI_{10} results is 2.5 m/km, then more than 25% of the unacceptable area in terms of LRD values would not be rejected (see Figure 10). At the same time, less than 15% of all results for the above-mentioned IRI_{10} limitation would be rejected, still allowing for acceptable results in terms of LRD values to be included in this 15% rejection region. Thus, it may be concluded that the use of the LRD criterion suggested by the AASHTO procedure should not be replaced by the IRI_{10} criterion. In the same manner, it can be concluded that the use of the VD criterion (associated with the use of the German panograph) cannot replace the suggested AASHTO procedure.

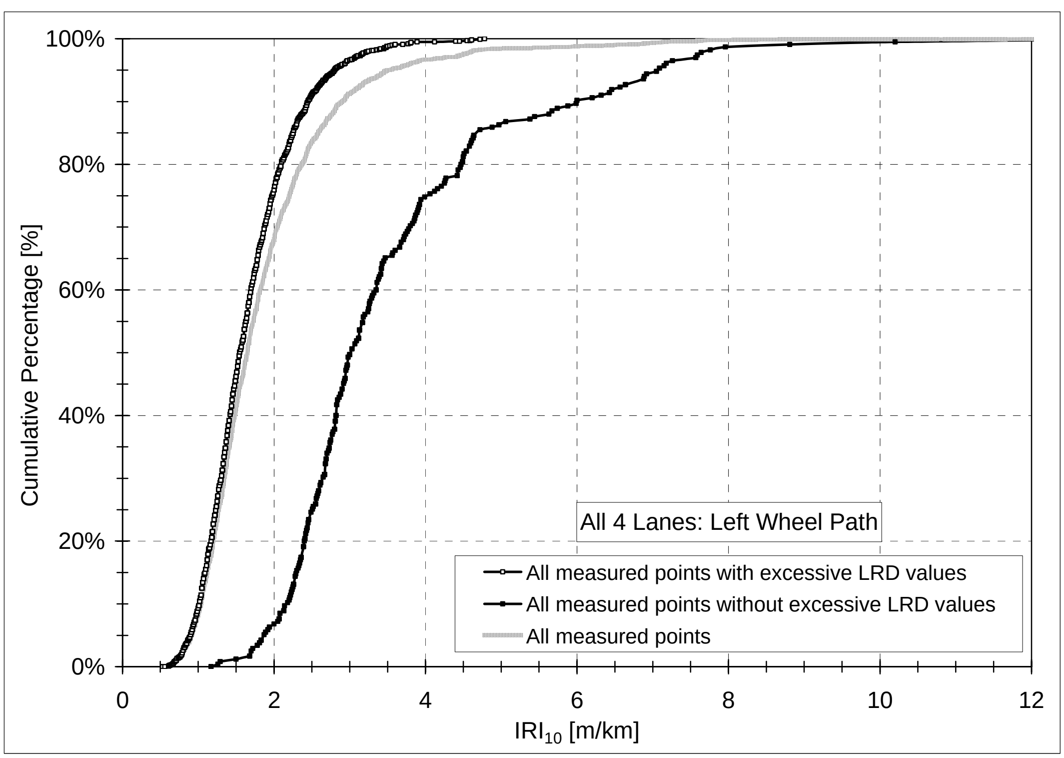

Figure 10a. Cumulative frequency distribution of the IRI_{10} values obtained from the measurement of all four concrete pavements of Route 3: Left-wheel path

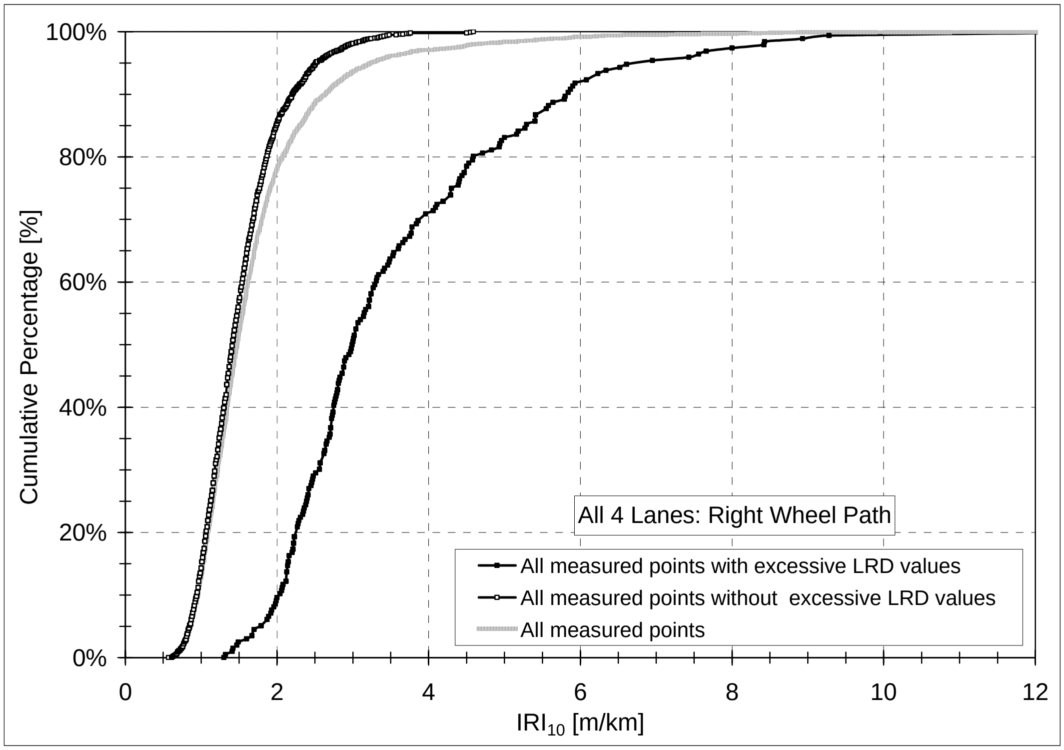

Figure 10b. Cumulative frequency distribution of the IRI_{10} values obtained from the measurement of all four concrete pavements of Route 3: Right-wheel path

In addition to the use of this German planograph, IPWD initiated its own roughness measurement by utilizing one of the modern measuring machines that are equipped with optical distance measurement devices (laser sensors) and accelerometers: a Road Surface Profiler (RSP), which is capable of measuring, calculating in real-time, displaying, and storing on a computer hard disk longitudinal road profiles and roughness data in terms of IRI (International Roughness Index). Thus, the output of this machine also enables virtual runs of the California-type profilograph and the German planograph on the longitudinal road profiles measured in order to calculate (a) the Profile Index (PI) values (i.e., the roughness measures associated with the California-type profilograph) and (b) the vertical deviation (VD) values (i.e., the roughness measures associated with the German planograph).

The roughness testing of Route 3 -- i.e., roughness testing with the German planograph device and the RSP machine -- led to the analyses described in the present paper. These analyses led to the following conclusions:

(a) The model developed for calculating the VD values (associated with the use of a German planograph) from the longitudinal road profiles measured with the RSP machine (associated with the use of IRI outputs) seems to be adequate,

(b) The IPWD roughness criteria associated with the $PI_{0.0}$ measurements, or the IPWD tentative roughness criteria associated with the IRI measurements, are stricter than the German roughness criteria associated with the VD measurements, even without taking into account the replacement actions that are compulsory in the $PI_{0.0}$ or IRI criteria, but not in the VD criteria,

(c) The German planograph with its present German requirements, is capable of detecting localized roughness only; it cannot detect continuous roughness along a substantial pre-defined longitudinal distance (100 meters),

(d) The use of IRI outputs (both IRI_{100} and IRI_{10}) to characterize the roughness pattern of a given road is most appropriate when the German planograph can substitute for the use of the American straightedge,

(e) The use of the Local Roughness Deviation (LRD) criterion suggested by the AASHTO procedure cannot be replaced by the IRI_{10} criterion as some Israeli agencies have suggested and the use of the VD criterion (associated with the use of the German panograph) cannot replace the suggested AASHTO procedure.

To sum up: the roughness measurements described in the present paper suggest that the use of the German planograph can substitute only for the use of the American straightedge, not for the use of an RSP machine. Thus, when the German planograph is applied, the roughness criteria associated with the American straightedge (such as those described by USACE) should also be applied.

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