Initial Experience with the First Long-Section, Inter-Urban, Concrete Road in Israel

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Synopsis

Although concrete-pavement-construction technology has been improved, its use is still rare in Israel because of the lower initial cost of asphalt pavement. In addition, the lack of local experience in placing concrete with a slipform paver has made paving authorities in Israel reluctant to specify concrete-pavement alternatives in their construction projects. Since competition serves as a major factor in the modern economy, competition between the two paving technologies (i.e., concrete paving technology versus asphalt paving technology) needs to be fostered in order to encourage continuous improvements in both technologies

These arguments led the Israeli Public Works Department (IPWD) to assign for its first long-section, inter-urban, concrete road (Route No. 3) a joint venture between a local asphalt-paving contractor and a well-experienced concrete-paving contractor from abroad (Germany). The concrete road whose 4 lanes ran for 6 kilometers, was opened to the public in 2001. Obviously, IPWD considered this new concrete road a case-study project in order to determine both its deterioration characteristics and its maintenance and repair expenditures over time. These determinations are necessary in order (a) to improve future local design and construction of concrete pavements and (b) to conduct reliable life-cycle cost analyses for selecting the appropriate pavement type for future major inter-urban projects.

This determination consisted of (a) evaluating the pavement-surface conditions by utilizing the PAVER system developed by the U.S. Army Corps of Engineers to provide PCI (Pavement Condition Index) scores and (b) measuring the surface roughness by utilizing a Road Surface Profiler (RSP) to provide IRI (International Roughness Index) scores. The PCI and IRI scores for the road were determined after one service year. In addition, the IRI was recorded again after two service years.

In light of these measurements, the major conclusions derived were as follows: (a) For the regular concrete slab-segments, the average rates of change in IRI_{100} values were extremely small (maximum of only 2.5%). (b) The rates of change in IRI_{100} values were far below the AASHTO-calculated rates of change in IRI_{100} values (about 5% minimum). (c) The new roughness-criteria limits that IPWD recently assigned to future concrete-road projects indicate that substantial portions of the IRI_{100} results exceed these limits. Thus, if the same roughness pattern also existed on the opening day of the concrete road under discussion, further improvements in the concrete paving technique would be required in Israel. (d) The 2002 PCI measurements indicate that the PCI values obtained for one of the two carriageways lie in the very high rating-region, starting from a very good rating and ending with an excellent rating, whereas the PCI values obtained for the other carriageway lie in an inferior rating-region compared to the first carriageway, starting with a good rating (and not with a very good rating) and ending with an excellent rating. This means that the paving-material properties and the accompanying construction operations were more stringent for the execution of the first carriageway than for the other carriageway. (e) The comparative analysis shows that the better (higher) PCI scores are associated with better (lower) IRI scores and vice versa. (f) The use of the Local Roughness Deviation (LRD) criterion, as suggested by the AASHTO procedure, cannot be replaced by the IRI_{10} criterion, as suggested by some Israeli agencies.

Finally, initial measurements described in the present paper suggest that the actual observed PSI-deterioration curve (under one and two years of service) may be considered adequate for the concrete pavement starting period, thus promising a high standard in-situ pavement performance of in years to come. In contrast to this finding however, it is highly recommended that the local paving technology for concrete roads should be further developed and modified for future projects.

INITIAL EXPERIENCE WITH THE FIRST LONG-SECTION, INTER-URBAN, CONCRETE ROAD IN ISRAEL

INTRODUCTION

Although concrete-pavement-construction technology has been improved, its use is still rare in Israel because of the lower initial cost of asphalt pavement. In addition, the lack of local experience in placing concrete with a slipform paver has made paving authorities in Israel reluctant to specify concrete-pavement alternatives in their construction projects. It is well known that competition serves as a key factor in the modern economy. Thus, competition between the two paving technologies (i.e., concrete paving technology versus asphalt paving technology) should be in order to encourage continuous technical improvements in both of them.

Such arguments led the Israeli Public Works Department (IPWD) to assign for its first long-section, inter-urban, concrete road (Route No. 3) a joint venture between a local asphalt-paving contractor and a well-experienced concrete-paving contractor from abroad (Germany). This concrete road opened to the public in 2001, was a 4-lane divided highway, 6-kilometer in length. Obviously, IPWD considered the new road a case-study project in order to determine both its deterioration characteristics and its maintenance and repair expenditures over time. This determination was required in order (a) to improve the local design and construction of concrete pavements in the future and (b) to conduct reliable life-cycle cost analyses for selecting the appropriate pavement type in future major inter-urban projects [see, Livneh, 2004].

To determine these factors, the IPWD laid out a full detection program, consisting of (a) a periodic evaluation of the pavement-surface conditions utilizing the PAVER system developed by the U.S. Army Corps of Engineers to provide PCI (Pavement Condition Index) scores [see ASTM D6433, 2001], and (b) a periodic measuring of the surface roughness with a Road Surface Profiler (RSP) to provide IRI (International Roughness Index) scores. Indeed both PCI and IRI scores for the 6 km stretch of Route No. 3 were calculated after one service year. The IRI scores were determined again after two service years.

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

(a) To describe and evaluate the outputs obtained for the two IRI measurements and to detect the changes that occurred in these two measurements.

(b) To describe and evaluate the outputs obtained for the PCI measurements and to compare them with the two IRI measurements.

(c) To evaluate outputs obtained for the localized roughness measurements and to find the possible relationship of these measurements to the calculated IRI_{10} values.

(d) To derive tentative conclusions concerning a determination of the deterioration behavior of the concrete-pavement construction on Israel's Route No. 3.

The processes of reaching the above-mentioned four objectives are detailed in the following sections of the present paper.

DESIGN DATA

The technical data concerning the pavement design of Israel's first long-section, inter-urban, concrete road are given in the next two paragraphs. This road (Route No. 3) is of the divided-highway type and has two lanes in each direction, and its rigid pavement design was carried out by a professional consultant with well known technical experience in Europe.

A check of the rigid pavement design was performed by the author according to the AASHTO design method, utilizing the AASHTOWare Darwin 3.01 software (AASHTO, 1997) for (a) JPCP Pavement Type, (b) Initial Performance Period of 30 Years, (c) 80-kN over Initial Performance Period of 85,000,000, (d) Initial Serviceability of 4.5, (e) Terminal Serviceability of 2.5, (f) 28-day Mean PCC Modulus of Rupture of 5,500 kPa, (g) 28-day Mean Elastic Modulus of Slab of 27,600,000 kPa, (h) Mean Effective k-value (stabilized base) of 172 kPa/mm, (i) Reliability Level of 80%, (j) Overall Standard Deviation of 0.35, (k) Load Transfer Coefficient, J-value of 2.7, and (l) Overall Drainage Coefficient, Cd-value of 1.1. Finally, the calculated design thickness of the concrete slab was 240 mm (see Table 1).

For comparison purposes, the flexible pavement design was carried out according to the IPWD design method (Uzan, 1996; Divinsky et al., 1998; Divinsky et al., 1999) for (a) Subgrade CBR of 5%, (b) Initial Daily Traffic of 20,000 (in both directions), (c) Percentage of Trucks of 14%, (d) Percentage of Buses of 4%, (e)

Percentage of Annual Traffic Growth of 4%, and (d) Initial Performance Periods of 20, and 30 Years. The calculated design layer-thicknesses of the flexible pavement were as given in Table 1.

Table 1. Details of the rigid pavement, compared to the flexible structures of Route No. 3

Pavement Type	**JPCP**	**Flexible**	
Total Design Period (years)	**30**	**20**	**30**
Number of ESALs (million)	85	44	67
Thickness of Subbase Layer (mm)	200	200	200
Thickness of Granular Base (mm)	---	240	240
Thickness of Cement Stabilized Base (mm)	150	---	---
Thickness of Upper Asphaltic Layers (mm)	---	200	220
Thickness of Concrete Slab (mm)	240	---	---
Equivalent All-Asphaltic Structure (mm)	---	456	475

Finally, a point that should be raised concerning Table 1 is the variation in the thickness of an all-asphaltic structure over varying lengths of the total design period. For an annual traffic growth of 4%, the all-asphaltic thickness for 30 years of a design period is only about 105% of that associated with 20 years of a design period (i.e., the conventional design period). Thus, the thickness variation is not so remarkable.

IRI MEASUREMENTS

After more than one year following the completion of the concrete pavement section of Route No. 3, road-roughness measurements were conducted with a Road Surface Profiler (RSP). All of the four lanes of a total length of about 20 km were monitored 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. These filtered data were then used to calculate the IRI values for each 10-meter (IRI_{10}) and 100-meter segment (IRI_{100}). The pattern and characteristics of the IRI_{100} results are dealt with below; those of the IRI_{10} results are dealt with in Appendix A.

Figure 1 shows the variation in the IRI_{100} values along the center of each lane of the concrete road as recorded in both the 2002 and 2003 measurements. In this figure lane No. 5 and lane No. 6 denote the inner two lanes (lane No. 5 for carriageway No. 1 and lane No. 6 for carriageway No. 2; see Table 2) and lanes No. 7 and No. 8 denote the outer two lanes (lane No. 7 for carriageway No. 1 and lane No. 8 for carriageway No. 2; see Table 2). It should be noted that the stretch of the concrete pavement under discussion contains three overpasses covered with an asphalt layer. These overpasses do not represent the conventional concrete-pavement structure, and their behavior is entirely different. The roughness values obtained for these three overpasses were substantially higher than the rest of the concrete-pavement stretch.

The IRI_{100} results obtained in the 2002 and 2003 measurements are also displayed in Figure 2. Specifically, this figure shows the cumulative percentage distribution (the cumulative frequency) of the IRI_{100} values measured along the center of each lane of the concrete road, but excluding the odd values obtained for the three overpasses. For comparison purposes, Figure 2 also includes the FHWA 2008 smoothness goal values [see Perera et al., 2002], which are IRI_{100} values of less than 2.65 m/km on 95 percent of the National Highway System and will be less than 1.35 m/km on 60 percent of the system by 2008.

In this respect, the roughness measurements of Route No. 3 indicate the non-correspondence of the IRI results with the FHWA goal, except for the outer lane of carriageway No. 2 (i.e., lane No. 8) for which the roughness values obtained are reasonable. In this regard, it is also worth noting a study carried out in Quebec [see Thébau, 2002]. Eight sections of the freeway network of this province, exhibited IRI_{100} values of 1.6 m/km and less after several years of service. Some of these sections even exhibited IRI_{100} values of 1.2 m/km and less. Al these IRI_{100} values can be compared to the IPWD tentative roughness criteria for concrete pavements; namely, a maximum allowable IRI_{100} value of 1.7 m/km, beyond which correction actions are required, and a nominal allowable IRI_{100} value of 1.3 m/km, beyond which reduced pay-adjustments take place.

The criteria limits are also displayed in Figure 2, which shows that substantial portions of the IRI_{100} results exceed the proposed criteria limits. Thus, it can be concluded that if the same roughness pattern also existed on the opening day of Route No. 3 (i.e., the construction-termination day), further improvements in concrete-paving technique are advisable in the future.

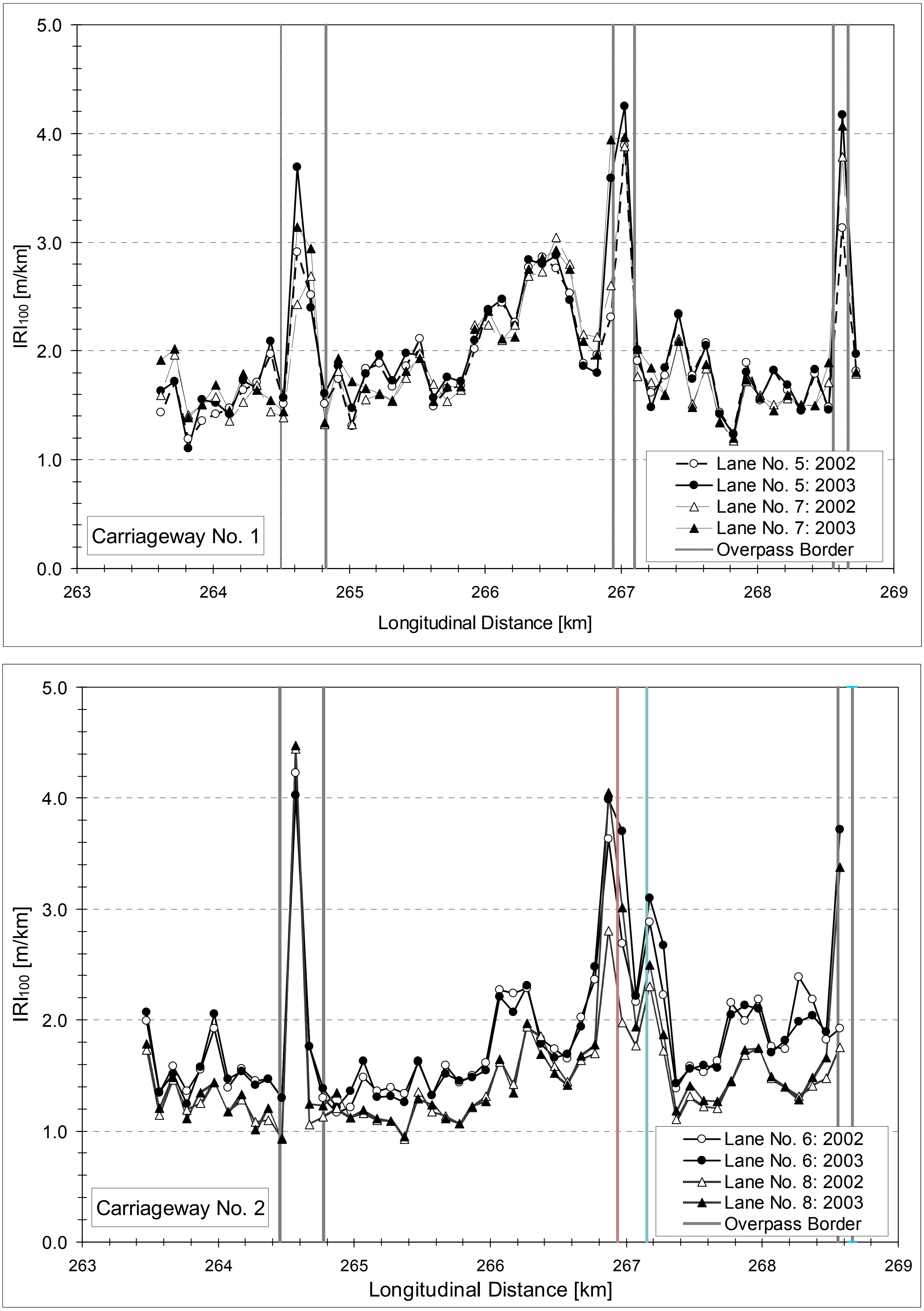


Figure 1. Longitudinal variation in IRI_{100} values along the center of each lane of the concrete pavement of Route No. 3 as recorded in 2002 and in 2003

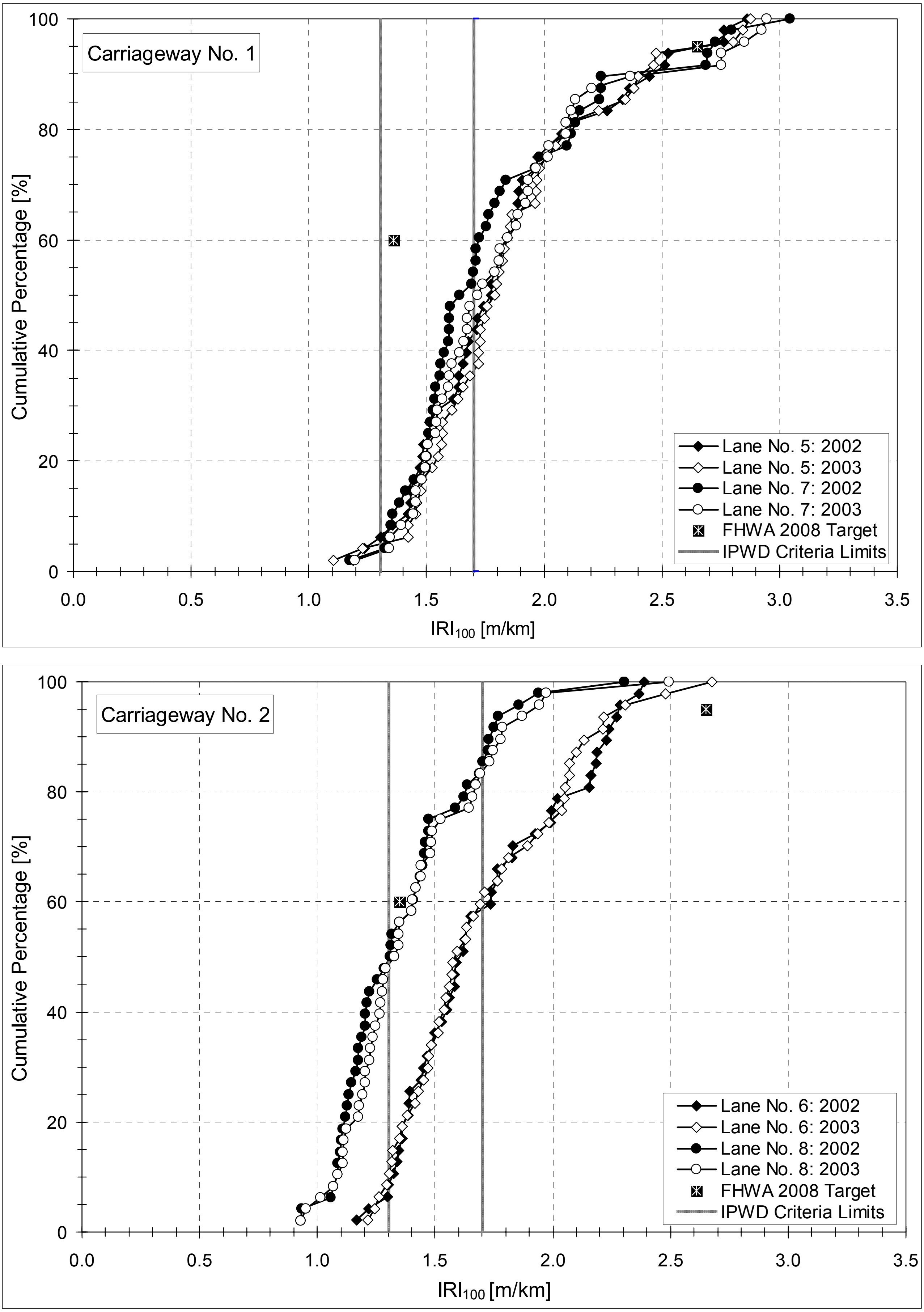


Figure 2. Cumulative frequency distribution of the regular values of IRI_{100} for the concrete pavement of Route No. 3 obtained in 2002 and in 2003

The range of change in the IRI_{100} results obtained in the 2003 measurements compared to the 2002 measurements is presented best in Figure 3. In this figure, the irregular points denote the IRI_{100} values obtained for the three overpasses, and the regular points denote the IRI_{100} values for the rest of the concrete-pavement stretch. Table 2 contains the data obtained from the restrained regression analysis conducted on the 2002 and 2003 IRI_{100} data; the analysis covers a regression that is forced to obtain a constant value of zero (i.e., a=0).

Table 2. Details of the restrained regression analysis (forced to obtain a constant value of zero) performed on the IRI_{100} regular data for 2002 and 2003

C'y 2		C'y 1	
Lane 8	Lane 6	Lane 5	Lane 7

Carriageway No.	Lane No.	The Regression-Multiplier Variable 'b'			R^2 Value	No. of IRI_{100} Points
		Mean Value	Lower 95%	Upper 95%		
1	5	1.011	0.997	1.025	0.951	48
	7	1.022	1.003	1.040	0.902	48
2	6	0.997	0.977	1.017	0.997	47
	8	1.024	1.009	1.040	0.970	48

It should be pointed out that the data in Table 2 relate only to the regular points of Figure 3 (i.e., they exclude the three overpass segments). In general terms, this table indicates that the change in IRI_{100} values over one year of service is practically zero. Moreover, from a statistical point of view, the zero hypnosis for which the two IRI_{100} populations are the same cannot be rejected for the inner lane of carriageway No. 1 (lane No. 5) and the inner lane of carriageway No. 2 (lane No. 6). This statement derives from the fact that the true-multiplier variable 'b' lies in the range of below and above the value of identity, (i.e., the value of 1) for a probability of 95%. This conclusion does not hold, however, for the regression results associated with the outer lane of carriageway No. 1 (lane No. 7) and the outer lane of carriageway No. 2 (lane No. 8). For these two lanes, the zero hypnosis, for which, as mentioned the two IRI_{100} populations are the same, can be rejected, as the true-multiplier variable 'b' lies in the range above the value of 1. Even so, the average rate of change in the IRI_{100} values of lane No 8, which is the least rough lane of the four measured lanes, was extremely small, only 2.5%. Here, it is worthwhile noting that for the lane adjacent to lane No. 8 (i.e., lane No. 6) there was even an average reduction in the 2003 roughness values compared with the 2002 values. In the same manner, the average rate of change in the IRI_{100} values of lane No 7 was even smaller, only 2.2%. Finally, for a probability of 95% the maximum obtained value of the true rate of change in IRI_{100} values was relatively small, 4%.

As for the three overpass segments, the data in Figure 3 show a different roughness behavior. In other words, the roughness values of the 2003 measurements for almost all of the data obtained were significantly higher than for the 2002 measurements. The ratio of the average IRI_{100} values for the 2003 measurements to the average IRI_{100} values for the 2002 measurements for each lane was as follows: lane No.5 - 1.28, lane No.7 - 1.19, lane No.6 - 1.21, and lane No.8 - 1.36. Furthermore, the statistical t-test showed that the zero hypnosis, for which the two IRI_{100} populations are the same, can be rejected for each of the all four lane measurements. This roughness behavior indicates that the three overpass segments were improperly designed (or constructed) to take into account all the necessary site conditions.

COMPARISON OF IRI CHANGES OVER TIME

The technical literature contains several in-situ studies that evaluate the change in concrete-pavement roughness over time [see, for example, Perera et al., 2002; Siddique et al., 2002; Chatti and Iftikhar, 2003; and Vongchusiri et al., 2003]. These studies have suggested several expressions characterizing the pavement-performance curve. A well known expression is the one derived from the AASHTO basic-design equations. The required expression for the design data given in Table 1 was calculated from these design equations, utilizing the AASHTOWare Darwin 3.01 software (AASHTO, 1997). The output of this calculation led to the variation in pavement serviceability, from an initial value of 4.5 down to a terminal value of 2.5, with accumulated 80-kN ESALs. As the traffic composition and the traffic growth are known, the accumulated 80-kN ESALs variable can be replaced by the number of years that have elapsed from the opening day of the concrete pavement, leading to the following expression:

[1] $$PSI=4.5-0.051\times A-0.0005\times A^2$$

where PSI is the Present Serviceability Index of the pavement surface at any given time; and A is the number of years elapsed from the opening day of the road (termination day of construction).

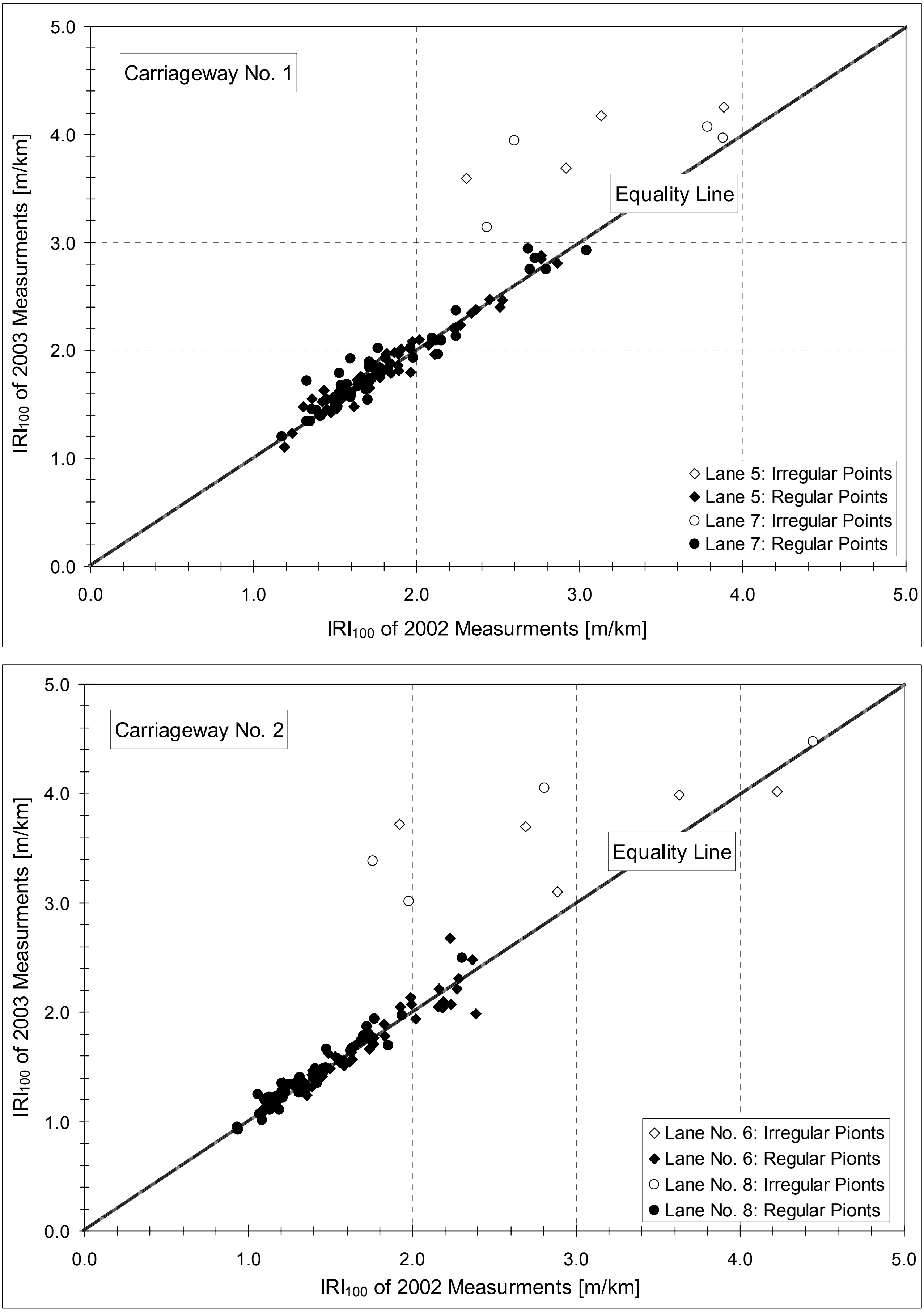


Figure 3. IRI_{100} values obtained in the 2003 measurements versus IRI_{100} values obtained in the 2002 measurements

For the purposes of this paper, PSI variable has to be replaced by the IRI variable. Prior to this replacement, the relationships that exist between the IRI variable and the PSI variable should be summarized. Figure 4 displays a graphical representation of available expressions for these relationships, whose formulation is as the follows:

[2] $PSI=\alpha\times\exp[-\beta\times IRI]$

where α and β are the regression coefficients given in Table 3 for IRI units of m/km.

Table 3. The α and β values of Equation 2 according to several sources

Curve No.	Source	α	β
1	World Bank (Paterson,1986)	5.000	0.182
2	AC Pavements (Al-Omari & Darter, 1994)	5.000	0.240
3	PCC Pavements (Al-Omari & Darter, 1994)	5.000	0.272
4	Interpretation of $PI_{5\text{-}mm}$ (Livneh et al.,2003)	4.577	0.191
5	S. Carolina, U.S.A. (Baladi et al., 1992)	5.000	0.180
6	Maine, U.S.A. (Baladi et al., 1992)	5.793	0.210
7	Appendix J (FHWA, 1993)	5.000	0.260

Figure 4 indicates that the mean PSI score can be predicted from the IRI values. It should be taken into account, however, that an error in the range of about ±0.5 exists in the PSI prediction. To illustrate the PSI conversion, an IRI value of 1.0 m/km corresponds to a PSI value of 3.8 to 4.8. In the same manner, an IRI value of 1.5 m/km corresponds to a PSI value of 3.3 to 4.3.

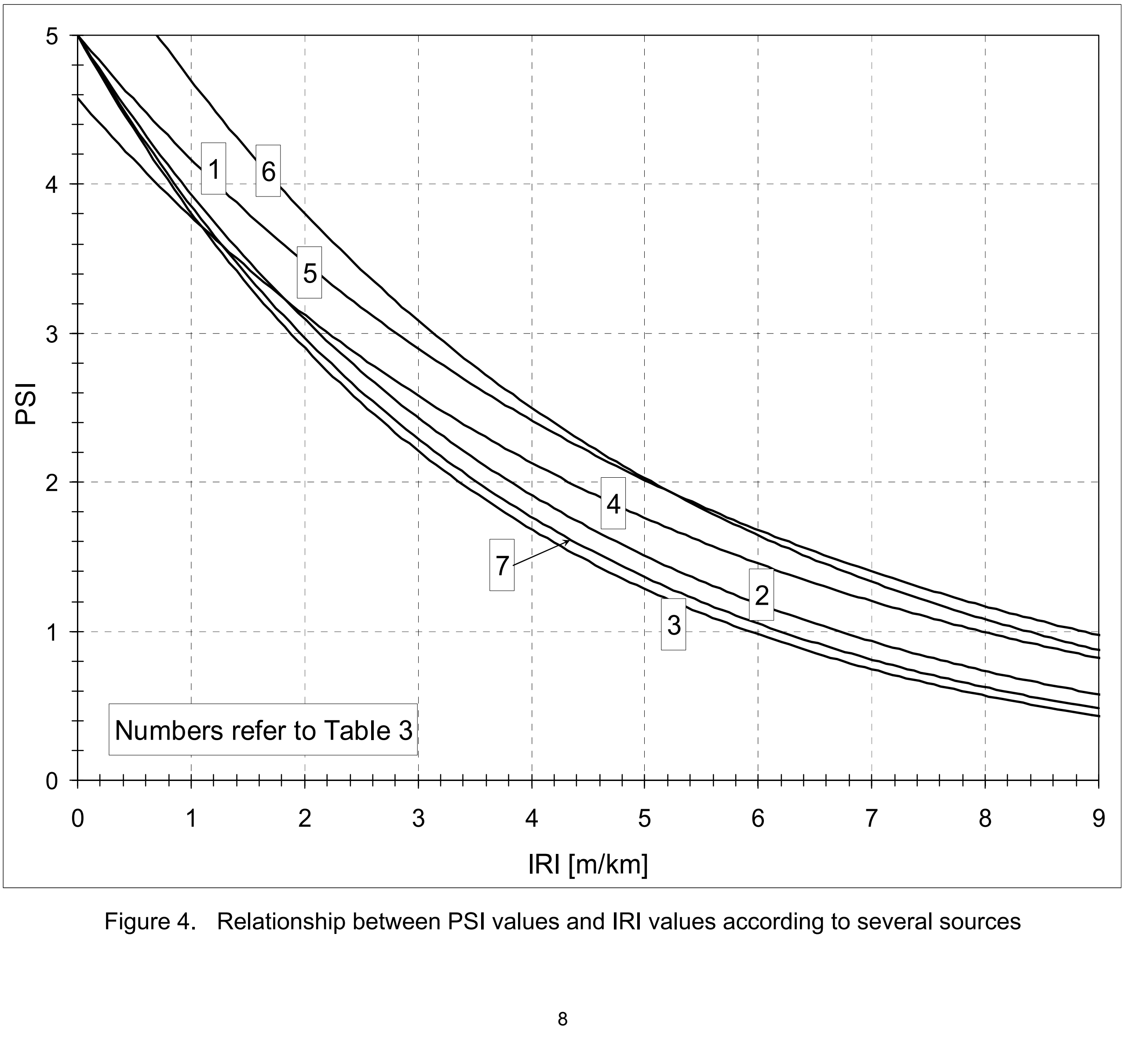


Figure 4. Relationship between PSI values and IRI values according to several sources

Now, combing Equation 1 with Equation 2 leads to the following equation:

[3] $RIR=IRI_A/IRI_{A-1}= a\times A^4+b\times A^3+c\times A^2+d\times A+e$

where RIR is the Roughness Increase Ratio; IRI_A is the IRI value for a given elapsed year, A; IRI_{A-1} is the IRI value for the preceding given elapsed year, A-1; a, b, c, d, and e are the polynomial coefficients given in Table 4 for two α values of Equation 2 (5.000 and 5.793).

A graphical display of Equation 3 is given in Figure 5. The figure indicates that the variation in Roughness Increase Ratio (RIR) over time depends on the α value of Equation 2. For the first year of service (A=1), RIR varies from 1.05 to 1.11; for the second year of service (A=2), RIR varies almost the same, 1.05 to 1.10.

Table 4. Polynomial coefficients of Equation 3 for calculating the Roughness Increase Ratio (RIR)

α of Eq. 2	**a of Eq. 3**	**b of Eq. 3**	**c of Eq. 3**	**d of Eq. 3**	**e of Eq. 3**
5.000	1.66452×10^{-7}	-1.39602×10^{-5}	4.70850×10^{-4}	-8.32778×10^{-3}	$1.11657\times10^{+0}$
5.793	5.05632×10^{-9}	-3.04337×10^{-7}	1.93250×10^{-5}	-6.74831×10^{-4}	$1.04623\times10^{+0}$

The regression-multiplier 'b' values of Table 2 actually express the RIR values measured for A=2. Comparng these values with the above-calculated RIR values leads to this conclusion: for two years of service, the measured deterioration pattern in terms of roughness characteristics of the concrete pavement under discussion is less severe than, or at least coincides with, the pattern calculated from the AASHTO equations for the lower rate of change conditions (i.e., for an α value of Equation 2 equals 5793). In this respect, it is a promising start for the concrete road being discussed.

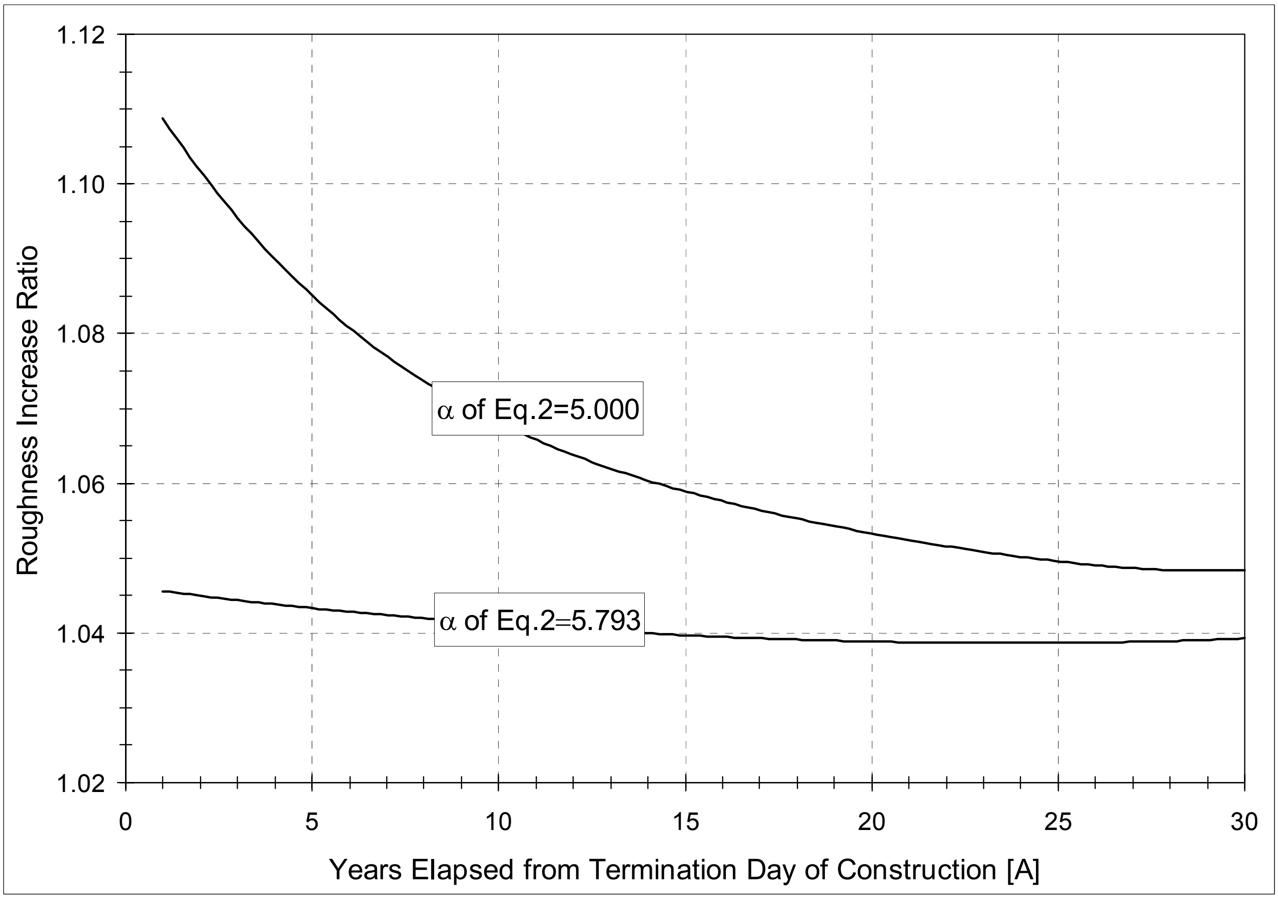


Figure 5. Variation in Roughness Increase Ratio (RIR) over years elapsed from opening day of the concrete pavement under discussion, as derived from the AASHTO design equations

DISTRESS SURVEY

An evaluation of the pavement-surface conditions was also performed after one year of service, utilizing the PAVER system developed by the U.S. Army Corps of Engineers [see, ASTM D6433, 2001]. This method provided PCI (Pavement Condition Index) scores for all the existing slabs. These scores were calculated on each lane for a defined lane-segment of 24 slabs; i.e., for a lane-segment of 108 meters in length. The present paper terms the scores the PCI_{108} scores.

Figure 6 shows the variation in PCI_{108} scores along the slabs of each lane of the concrete road as recorded in the 2002 measurement. Again, lanes No. 5 and No. 6 in this figure denote the inner two lanes (lane No. 5 for carriageway No. 1 and lane No. 6 for carriageway No. 2) and lanes No. 7 and No. 8 denote the outer two lanes (lane No. 7 for carriageway No. 1 and lane No. 8 for carriageway No. 2).

Here it should be noted, again, that the stretch of the concrete pavement being discussed contains three overpasses covered with an asphalt layer. As these overpasses do not represent the conventional concrete pavement structure, their PC I scores were not recorded.

According to the PAVER procedure [see ASTM D6433, 2001], the PC_{108} scores signify the following pavement states: (a) the 100-85 rating is termed excellent; (b) the 85-70 rating is termed very good; (c) the 70-55 rating is termed good; (d) the 55-40 rating is termed fair; (e) the 40-25 rating is termed poor; (f) the 25-10 rating is termed very poor, and (g) the 10-0 rating is termed failed. Thus the majority of the recorded PCI_{108} results were found to be in the region of the good to excellent ratings. More elaborations can refine the borders of this range, as will be given below.

The PCI_{108} results obtained in the 2002 measurement are also displayed in Figure 7. More specifically, this figure shows the cumulative percentage distribution (the cumulative frequency) of the PCI_{108} results measured as described above (i.e., excluding the values obtained for the three overpasses). This figure indicates that the pavement condition of Carriageway No. 2 lie in the very high rating-region from a very good rating to an excellent rating, whereas the pavement condition of Carriageway No. 1 lie in an inferior rating-region to that of Carriageway No. 2, starting with good rating (and not with very good rating) and ending with excellent rating. This means that the paving material properties and the accompanying construction operations were more stringent in the execution of Carriageway No. 2 than in Carriageway No. 1.

PCI VERSUS IRI

Table 5 tries to compare the measured IRI_{100} values with the measured PCI_{108} values. The values given in the table correspond (a) to the 50 percentile of both the IRI_{100} and PCI_{108} measured values, (b) to the 15 percentile of only the PCI_{108} measured values, and (c) to the 85 percentile of only the IRI_{100} measured values. The table indicates that the better (higher) PCI scores are associated with the better (lower) IRI scores (see Carriageway No. 2 in Table 5) and vice versa (see Carriageway No. 1 in Table 5). This finding strengthens the above-mentioned conclusion concerning the execution stringency of Carriageway No. 2 compared to that of Carriageway No. 1.

Table 5 The 50-percentile and 85-percentile, or 15-percentile, of IRI_{100} and PCI_{108} values obtained in the 2002 measurement

Carriageway No.	Lane No.	IRI_{100}		PCI_{108}	
		50-Percentile	85-Percentile	50-Percentile	15-Percentile
1	5	1.79	2.35	78.3	68.0
	7	1.64	2.24	77.3	68.0
2	6	1.60	2.18	88.2	82.7
	8	1.31	1.70	89.3	81.4

Moreover, visual comparison of the IRI data in Figure 1 with the PCI data in Figure 6 indicates that for almost equal locations, a reasonable correspondence exists between these two variables.

Interactions between pavement roughness and distress growth over time are dealt with in the technical literature. Recently, a comprehensive study was performed on data taken from the Michigan Department of Transportation Pavement Management System [see Chatti and Iftikhar, 2003]. Pavements with lower initial roughness and distress levels (newer pavements) were observed to exhibit higher increases in roughness than in distress; whereas pavements with higher initial roughness and distress levels (older pavements) exhibited a higher increase in distress than in roughness during the same period of time. Based on this finding, it can be concluded that an increase in pavement roughness tends to precede and, hence, to contribute to pavement distress initiation and growth. This trend, however, was most clearly visible in rigid pavements, followed by composite pavements. In this issue, flexible pavements exhibited more of an increase in pavement distress, in comparison with rigid and composite pavements, at an earlier stage.

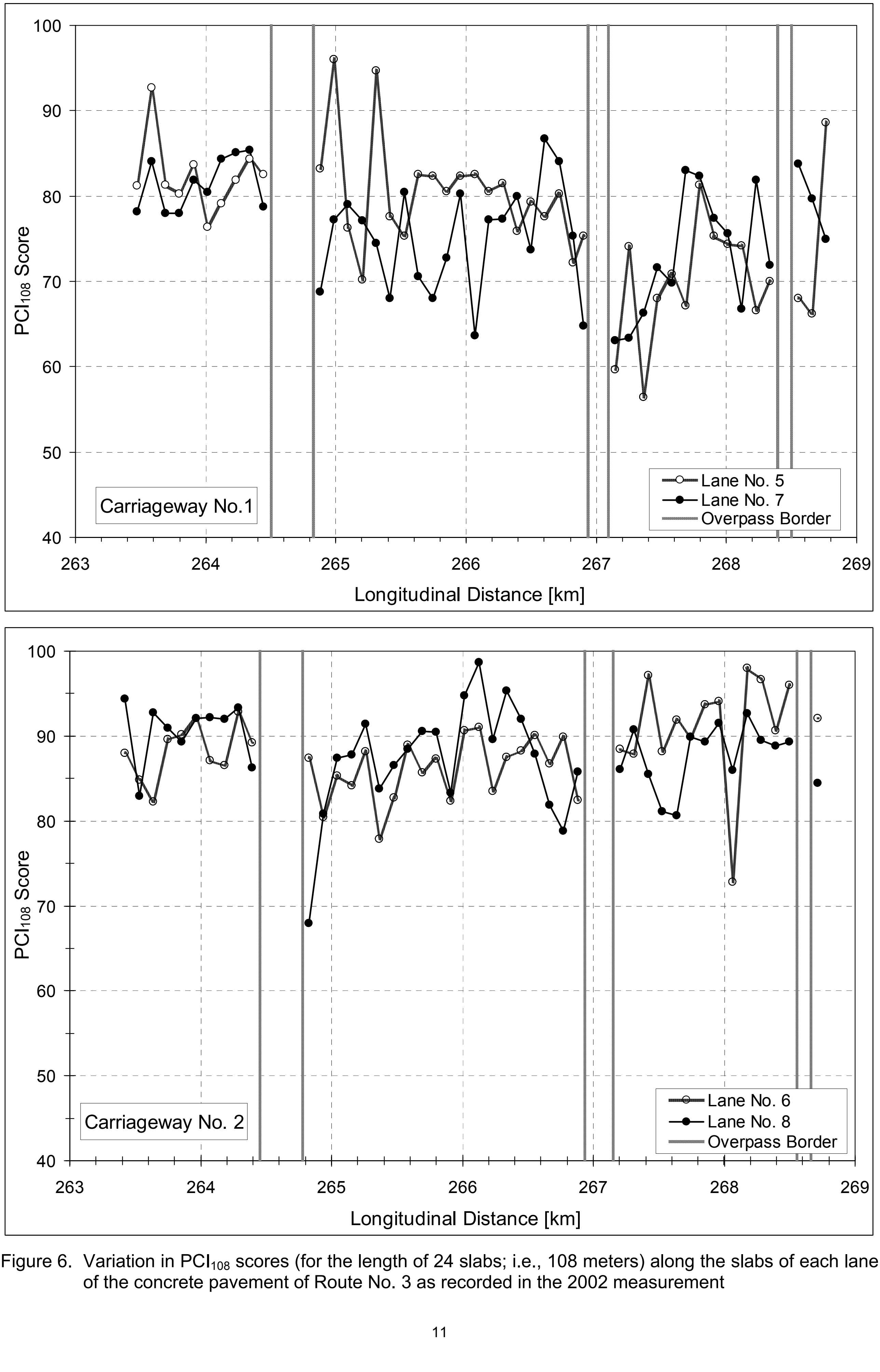
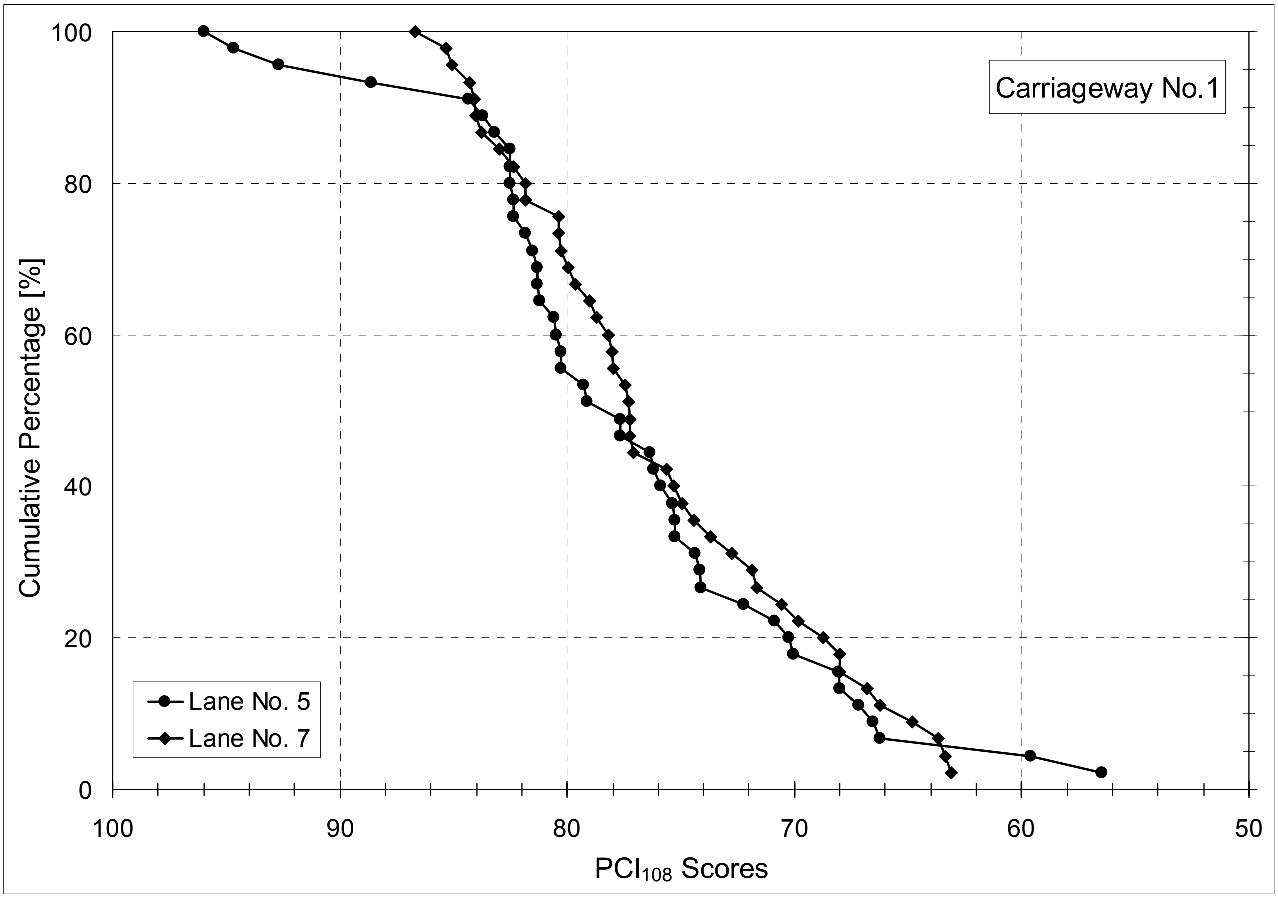


Figure 6. Variation in PCI_{108} scores (for the length of 24 slabs; i.e., 108 meters) along the slabs of each lane of the concrete pavement of Route No. 3 as recorded in the 2002 measurement



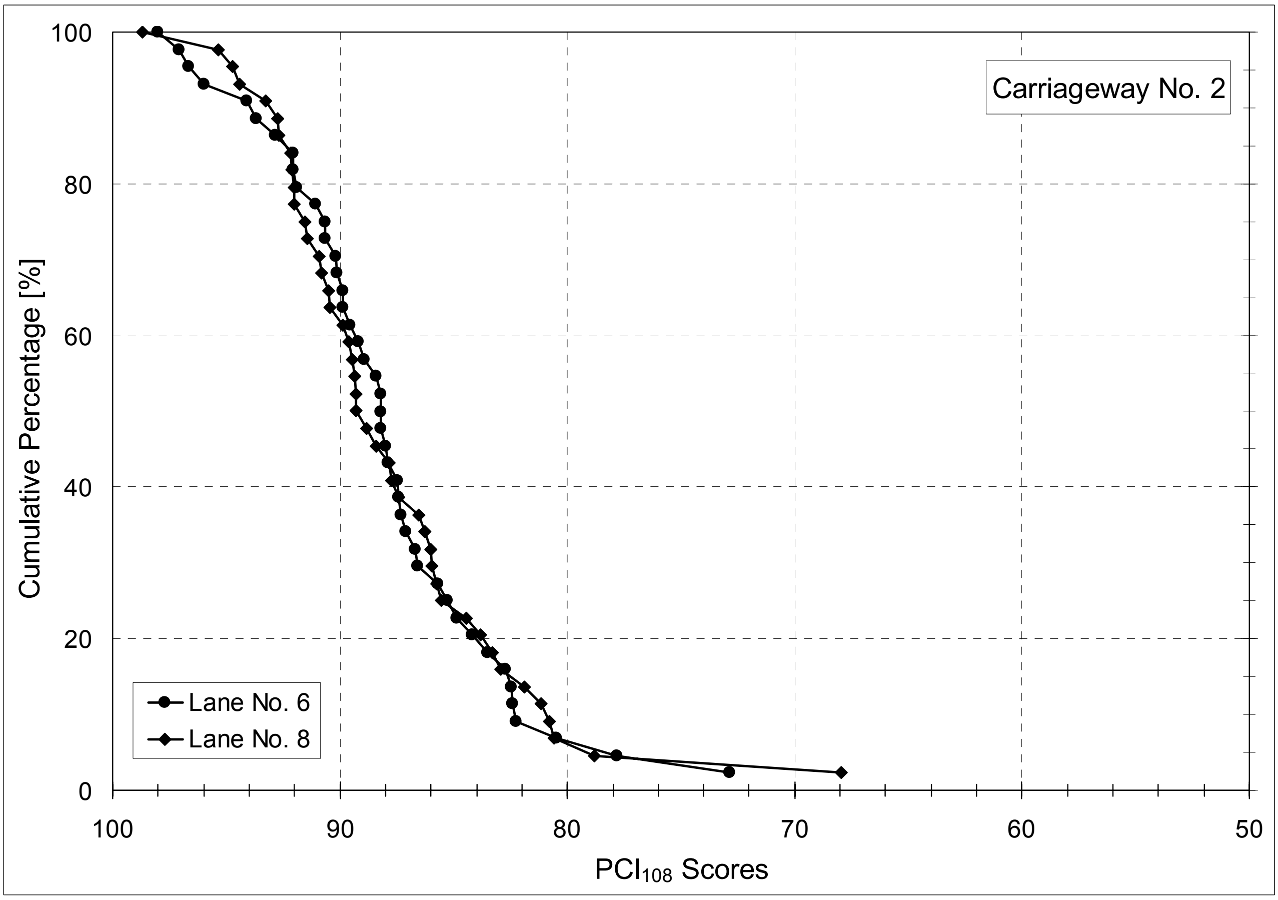


Figure 7. Cumulative frequency distribution of the PCI_{108} scores for the concrete pavement of Route No. 3 as obtained in the 2002 measurement

The implementation of the conclusions of the Michigan study in the present paper may yield a possible higher increase in distress (PCI) than in roughness (IRI) for Carriageway No.1 during the same (future) period of time.

LOCALIZED ROUGHNESS

Recently, AASHTO (2002) introduced engineering requirements to limit localized roughness values. 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 illustrated example, see Figure 8) with the difference determined between it and the reported relative elevation for every profile point. These differences (deviations) were later termed LRD (Localized Roughness Deviation). 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 (again, for an illustrated example, see Figure 9).

In Israel, another method is sometimes suggested for detecting the areas of localized roughness: the calculation of IRI_{10}; i.e., the average IRI value for a 10-meter long segment. Thus, for the 2002 measurements, Table 6 and Figure 10 display the statistical characteristics of the calculated LRD and IRI_{10} values that were obtained for the concrete-pavement section of Route No. 3.

Table 6 Statistical characteristics of the localized roughness of the concrete-pavement section of Route No. 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 Only			IRI_{10} for All Measured Points without Excessive LRD Values		
		Mean	St. Deviation	15 Percentile	Mean	St. Deviation	15 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

Table 6 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 2002 roughness measurements contained areas of localized roughness. Thus, it can again be concluded that if the same localized roughness pattern already existed on the opening day (i.e., the construction-termination day) of the present concrete pavement of Route No. 3, further improvements in concrete-paving technique in the future are advisable.

Additionally, Table 6 shows that the two IRI_{10} populations (i.e., one of all measured points with excessive LRD values only, 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 the IRI_{10} and the 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 rejected although only about 10% of the area (see Table 6) contains unacceptable results in terms of LRD values.

Obviously, If a higher maximum limiting value is assigned for 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 for the IRI_{10} results is assigned to be 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 should not be replaced by the IRI_{10} criterion.

CONCLUSIONS

Recently, the IPWD accomplished the construction of its first long-section, inter-urban, concrete road (Route No. 3). This road, a 4-lane highway that ran for 6 kilometers, was opened to the public in 2001. This new road is considered to be a case-study for determining both its deterioration characteristics and its maintenance and repair expenditures over time. This determination is required in order (a) to improve local design and construction of concrete pavements and (b) to conduct reliable life-cycle cost analyses for selecting the appropriate pavement in the future type for future major inter-urban projects.

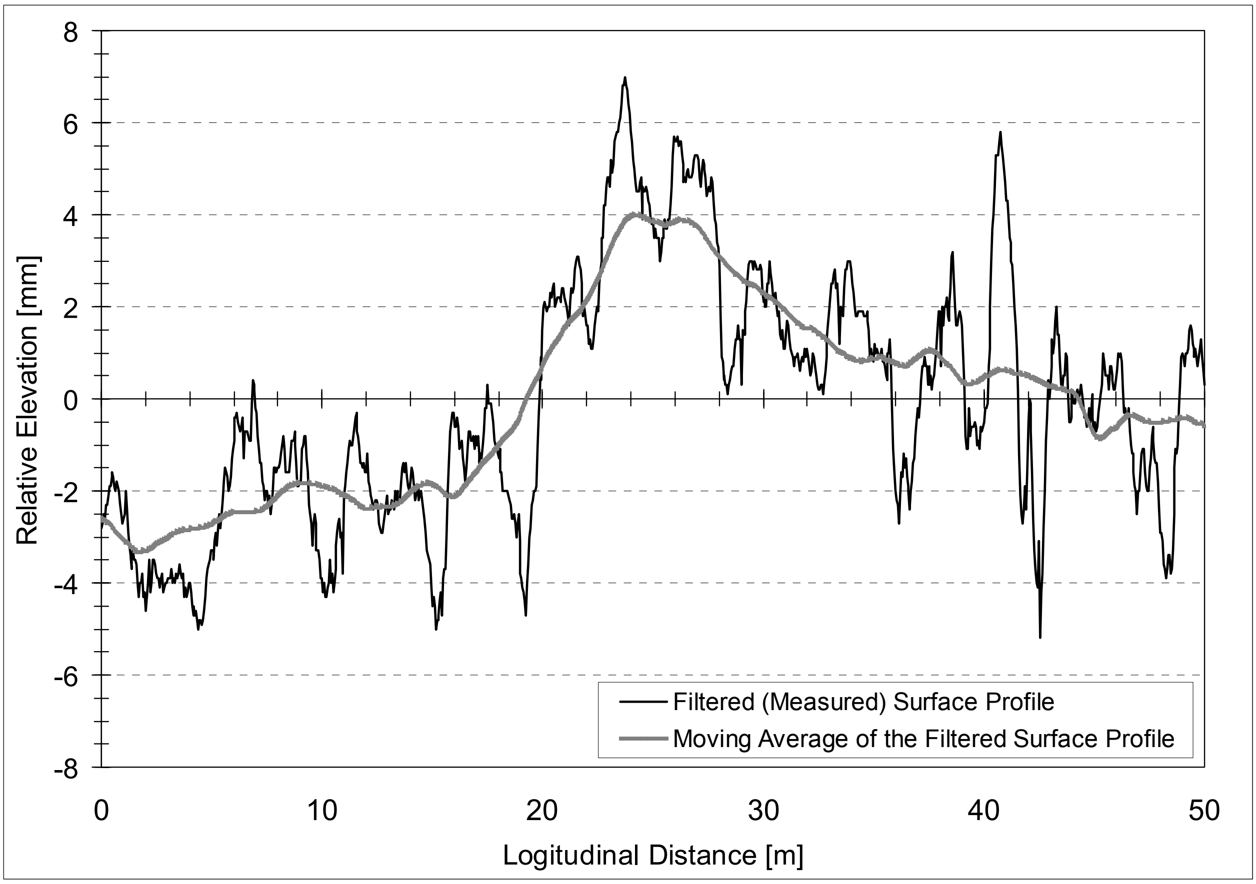


Figure 8. Illustrated example of measured and 7.6-meter moving average profiles

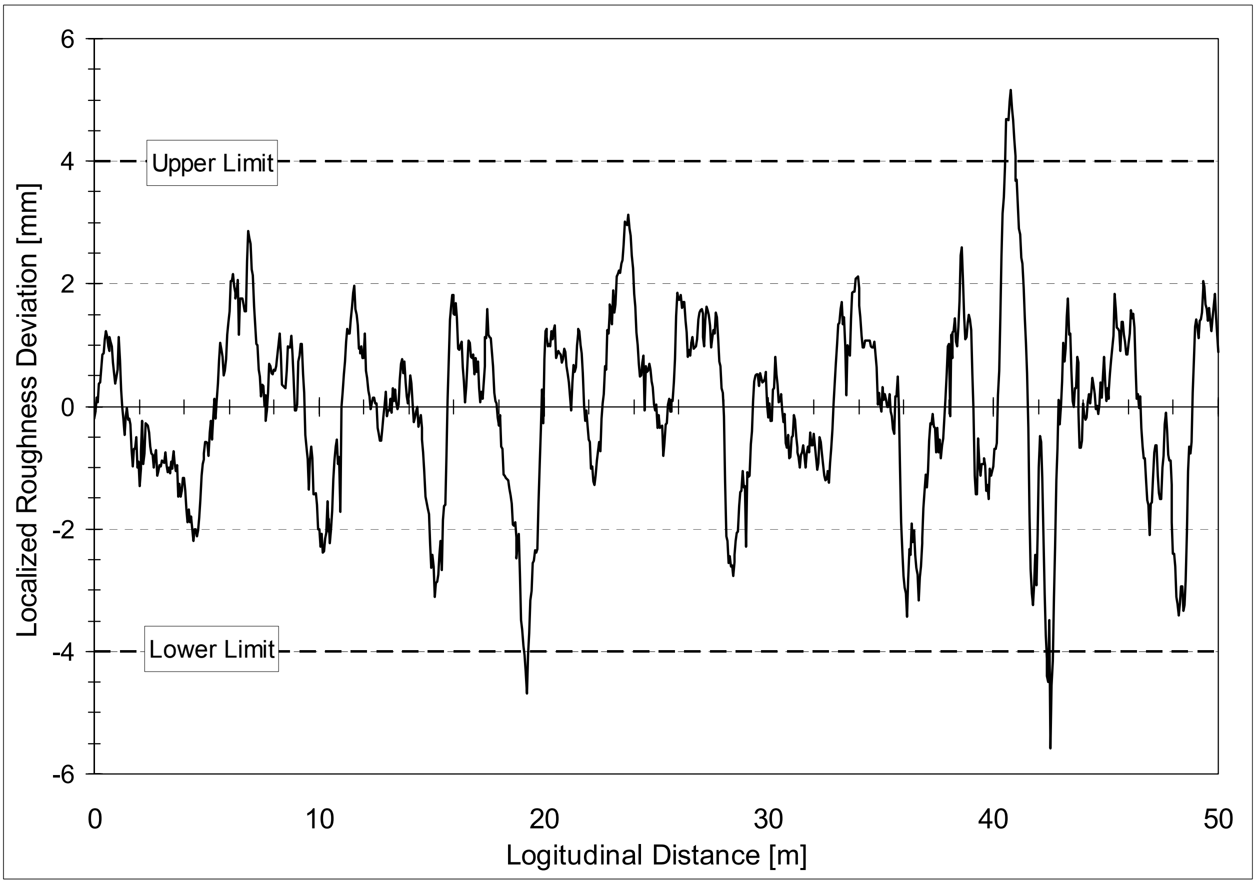
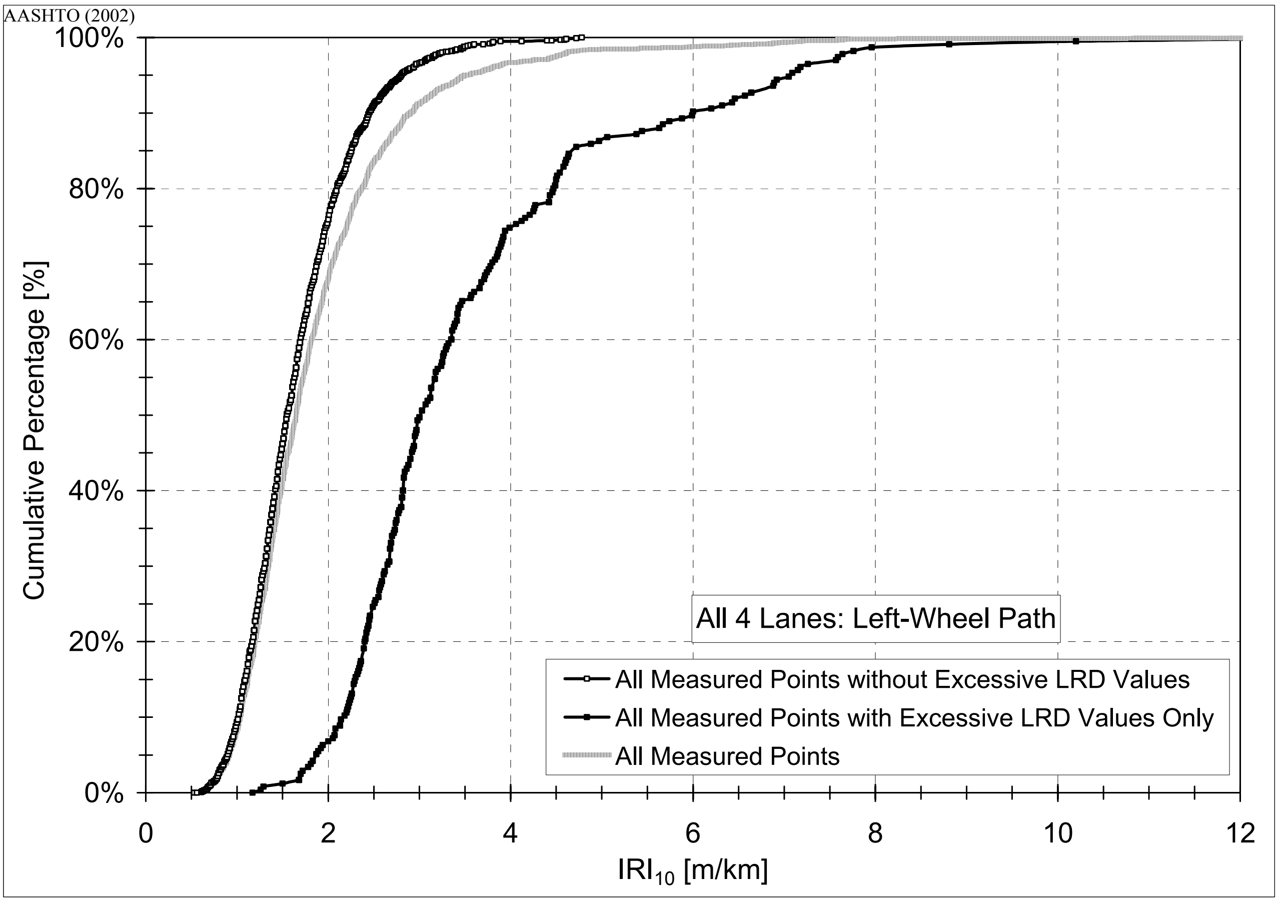


Figure 9. Illustrated example of the height deviation (LRD) of the measured and moving average profiles of Figure 8



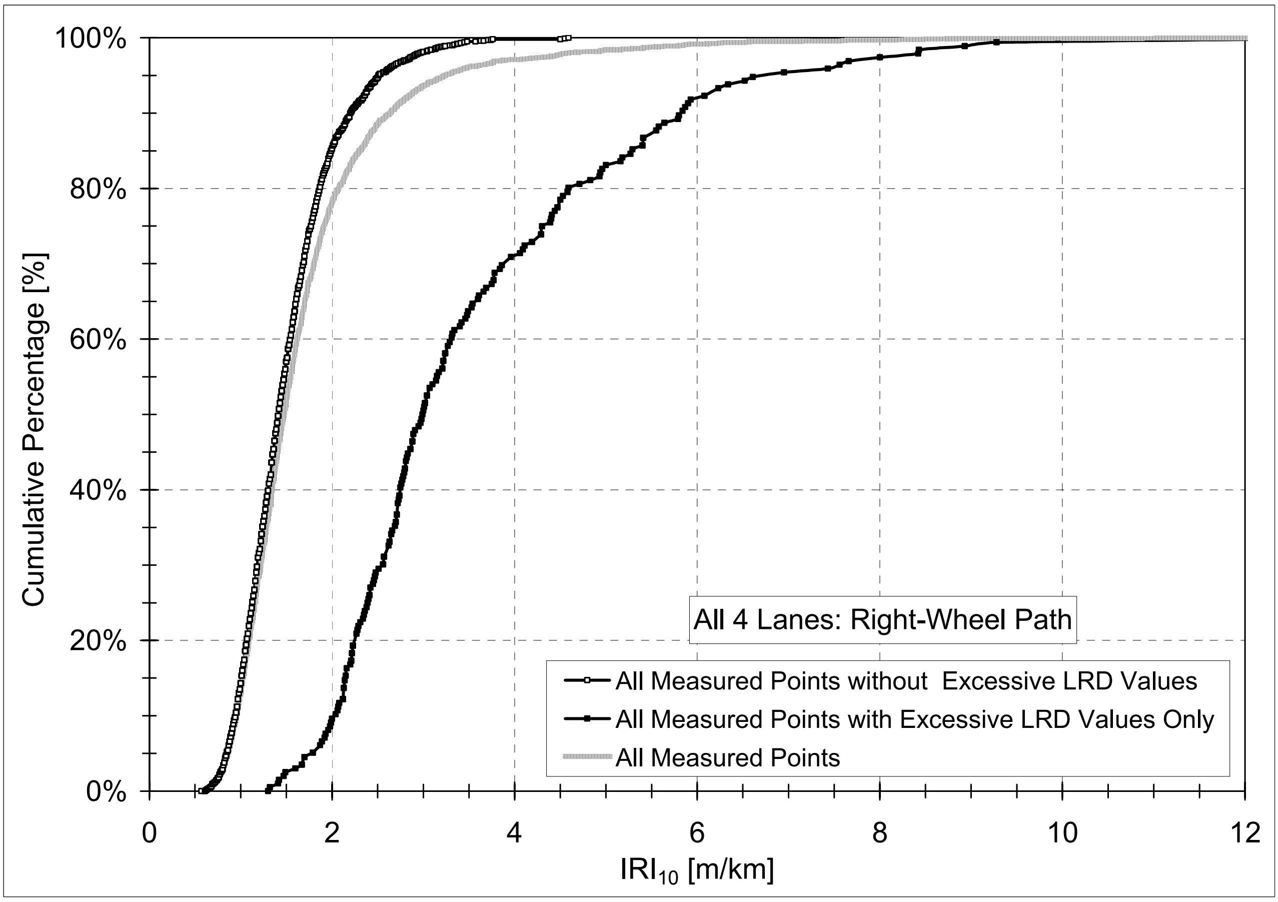


Figure 10. Cumulative frequency distribution of the IRI_{10} values obtained in the 2002 measurement for all four of the concrete pavement of Route No. 3

Till now, determination involved (a) evaluating the pavement surface conditions by utilizing the PAVER system developed by the U.S. Army Corps of Engineers to provide PCI (Pavement Condition Index) scores and (b) measuring the surface roughness by utilizing a Road Surface Profiler (RSP) to provide IRI (International Roughness Index) scores. Both the PCI and the IRI scores were measured after one service year. In addition, the IRI scores were measured again after two service years. In light of these measurements, the conclusions derived were as follows:

(a) For the regular concrete-slab segments, the average rate of change in the IRI_{100} values of lane No 8, which is the least rough lane of the four lanes measured, was extremely small, only 2.5%. It is worth noting that for the adjacent lane (i.e., lane No. 6), there was even an average reduction in the 2003 roughness values compared with the 2002 measurements. In the same manner, the average rate of change in the IRI_{100} values of lanes No 5 and No. 7 were even smaller, 1.1% and 2.2%, respectively. Finally, for a probability of 95% the maximum obtained value of the true rate of change in the IRI_{100} values was relatively small, 4%.

(b) These rates of change in the IRI_{100} values were far below the calculated rates of change in the IRI_{100} values (about 5% minimum). In other words, the measured deterioration pattern for two years of service of the concrete pavement under discussion in terms of roughness characteristics was found to be less severe than, or at least coinciding with, the pattern calculated from the AASHTO equations for the lower rate-of-change conditions. In this respect, there is a promising start for the concrete road.

(c) For the three overpass segments, the roughness values of the 2003 measurements were significantly higher than those of the 2002 measurements. The ratio of the average of IRI_{100} values of the 2003 measurements to the average of IRI_{100} values of the 2002 measurements for each lane was as follows: lane No.5 - 1.28, lane No.7 - 1.19, lane No.6 - 1.21, and lane No.8 - 1.36. This roughness behavior indicates that the three overpass segments were improperly designed to take into account all the necessary site conditions.

(d) The new roughness criteria limits that were recently assigned by IPWD to future concrete-roads projects indicate that substantial portions of the IRI_{100} results exceed these limits. Thus, if the same roughness pattern also existed on the opening day of the concrete road being discussed, further improvements in the concrete-paving technique are required in Israel.

(e) The 2002 PCI measurements indicate that PCI values obtained for Carriageway No. 2 lie in the very high rating-region, from very good to excellent, whereas the PCI values obtained for Carriageway No. 1 lie in an inferior rating-region to Carriageway No. 2, or from good (and not very good) to excellent rating. This means that the paving-material properties and the accompanying construction operations were more stringent for the execution of Carriageway No. 2 than for Carriageway No. 1.

(f) The comparative analysis shows that the better (higher) PCI scores are associated with the better (lower) IRI scores (see PCI and IRI values obtained for Carriageway No. 2), and vice versa (see PCI and IRI values obtained for Carriageway No. 1). This finding strengthens the conclusion concerning the stringency in the execution of Carriageway No. 2 as compared with the execution of Carriageway No. 1.

(g) The Implementation of the conclusions of the Michigan study to the findings of the present paper may yield a possible higher increase in distress (PCI) for Carriageway No.1 compared to roughness (IRI) during the same period of time in the future.

(h) The use of the Local Roughness Deviation (LRD) criterion suggested by the AASHTO procedure cannot be replaced by the IRI_{10} criterion as suggested by some Israeli agencies.

In summing up, the initial measurements described in the present paper suggest that the actual observed PSI-deterioration curve may be considered adequate for the concrete pavement starting period, thus promising an in-situ pavement performance of a high standard in the years to come. Contrary to this finding, however, it is highly recommended that the local paving technology for concrete roads should be further developed and modified for future projects.

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APPENDIX A: IRI_{10} RESULTS

In Israel, some agencies use the IRI_{10} results in order to detect areas of localized roughness. These IRI_{10} results denote the average IRI value for a 10-meter long segment. After more than one year following the completion of the concrete pavement section of Route 3, road-roughness measurements were conducted with a Road Surface Profiler (RSP). The profile elevations obtained were then used to calculate the IRI values for each 10-meter-segment (IRI_{10}) along with the IRI values for each 100-meter-segment (IRI_{100}). The pattern and characteristics of the IRI_{10} results are dealt with below.

Figure A-1 shows the variation of the ratio (the ratio of 2003 measurements to the 2002 measurements) along the center of each lane of the concrete road as recorded in both measurements. In this figure, lanes No. 5 and No. 6 denote the inner two lanes (lane No. 5 for carriageway No. 1 and lane No. 6 for carriageway No. 2) and lanes No. 7 and No. 8 denote the outer two lanes (lane No. 7 for carriageway No. 1 and lane No. 8 for carriageway No. 2). Figure A-1 also shows the odd results from the three overpasses covered with an asphalt layer.

Figure A-1 indicates that the ratio of the 2003 IRI_{10} values to the 2002 IRI_{10} values varies in a changeable manner within a wide range of lower and higher values than 1. The fact that there are many points containing ratios having lower values than 1 and even lower than 0.5 (i.e., exhibiting proof of roughness improvements over time) indicates that the use of the IRI_{10} outputs in repetitive measurements may lead to a significant scatter of the results, as there is no full guarantee that the repetitive measurements are made without (a) any lateral deviations (i.e., not on the same wheel paths throughout all the repetitive measurements), and (b) a longitudinal deviation (i.e., not exactly on the location of the starting point). Thus, the use of IRI_{100} values is preferable in determining roughness variations over time, as they indicate the average of 10 successive values of IRI_{10} for each 100-meter segment, thus reducing the effect of the above-mentioned scatter. In contrast to the regular concrete-slab stretches, Figure A-1 also indicates that the ratio of 2003 IRI_{10} values to 2002 IRI_{10} values along the existing three overpasses are extremely high, up to a value of almost 5. This finding demonstrates, again, the inferiority in design and construction of these three overpasses.

The IRI_{10} results obtained in the 2002 and 2003 measurements are also displayed in Figure A-2. More specifically, this figure shows the dependency of the IRI_{10} results obtained in the 2003 measurements on the IRI_{10} results obtained in 2002. In the same manner of Figure 3, the irregular points in this figure denote the IRI_{10} values obtained for the three overpasses, and the regular points denote the IRI_{10} values obtained for the rest of the concrete-pavement stretch under discussion. Table A-1 contains the data obtained from the restrained regression analysis conducted on the 2002 and 2003 IRI_{10} data. In the present case, the restrained regression analysis denotes a regression that is forced in order to obtain a constant value of zero (i.e., a=0). The comparison of the data of Table A-1 to Table 2 indicates that the present R^2 values are substantially smaller. Again, this finding is a result of the possible scatter that exists in the repetitive measurements as mentioned earlier.

Table A-1. Details of the restrained regression analysis (forced to obtain a constant value of zero) performed on the 2002 and 2003 IRI_{10} regular data

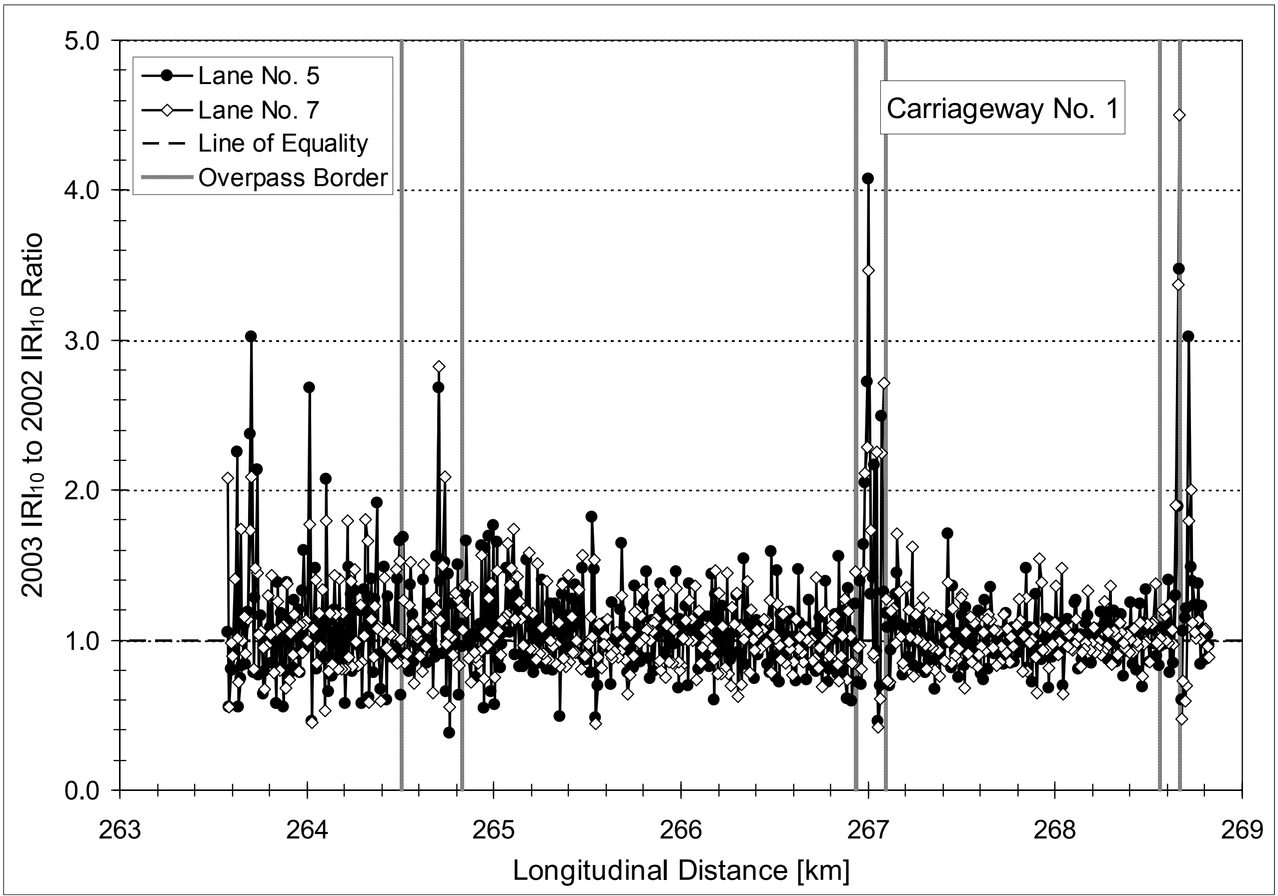
Carriageway No.	Lane No.	The Regression-Multiplier Variable 'b'			R^2 Value	Number of IRI_{10} Points
		Mean Value	Lower 95%	Upper 95%		
1	5	0.982	0.957	1.007	0.450	462
	7	0.958	0.935	0.981	0.498	462
2	6	0.927	0.896	0.957	0.425	457
	8	1.102	1.019	1.185	0.594	469

Because of the very low R^2 values in Table A-1, t-tests of the Paired-Two-Sample-for-Means type were conducted on the paired 2003 IRI_{10} and 2002 IRI_{10} data. The main results of these tests are given in Table A-2, which shows that the null hypothesis of the equality of the true mean of the two populations cannot be rejected. Thus, the IRI_{10} measurements support the findings associated with the IRI_{100} measurements.

Table A-2. Details of the Paired-Two-Sample-for-Means t-tests for the IRI_{10} data

Carriageway No.	Lane No.	All Values of IRI_{10}				All Regular Values of IRI_{10}			
		Mean 2002 IRI_{10}	Ratio of Means	Alpha [%]	No. of Data Points	Mean 2002 IRI_{10}	Ratio of Means	Alpha [%]	No. of Data Points
1	5	1.933	1.045	1.1	526	1.867	1.018	18.3	462
	7	1.903	1.047	0.9	526	1.838	1.011	38.3	462
2	6	1.849	1.028	15.5	526	1.791	0.999	94.9	457
	8	1.479	1.069	0.0	526	1.419	1.046	1.6	469

Note: Alpha [%] denotes the level of significance; i.e., the maximum probability of rejecting a true null hypothesis. In order to justify rejection, this calculated alpha should be lower than or equal to the one that is considered to be "beyond all reasonable doubt," generally 5%.



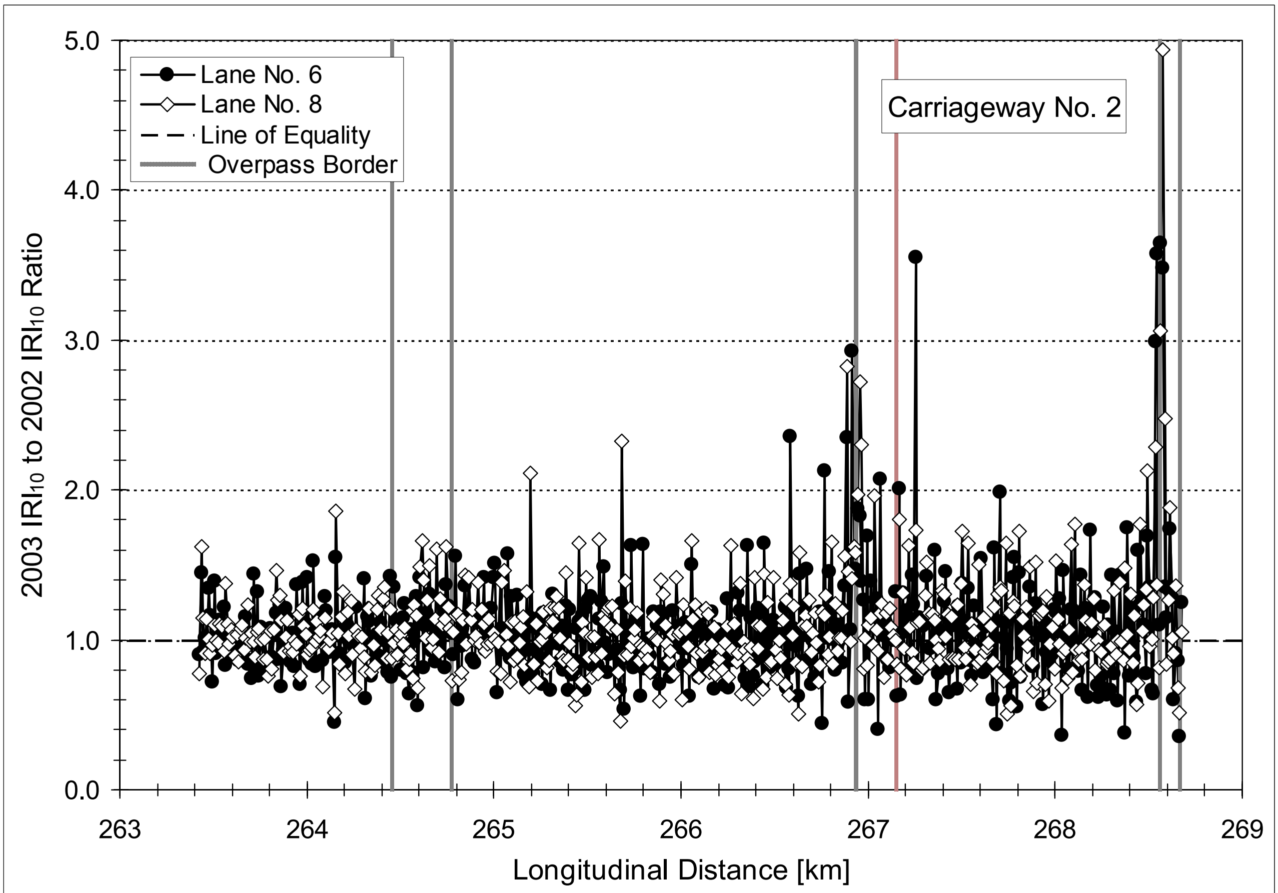
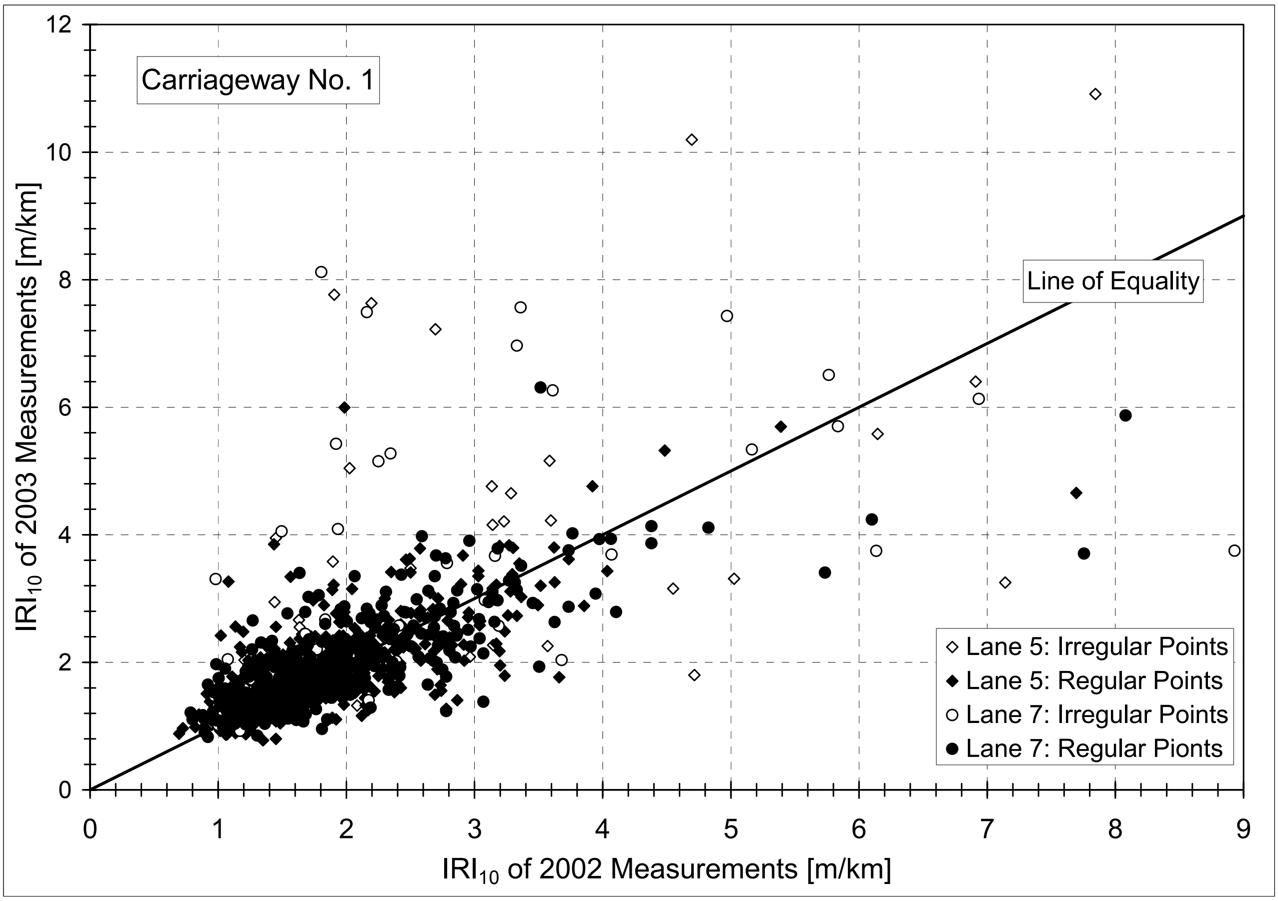


Figure A-1. Longitudinal variation of the 2003 IRI_{10} to 2002 IRI_{10} ratio-values along the center of each lane of the concrete pavement of Route No. 3



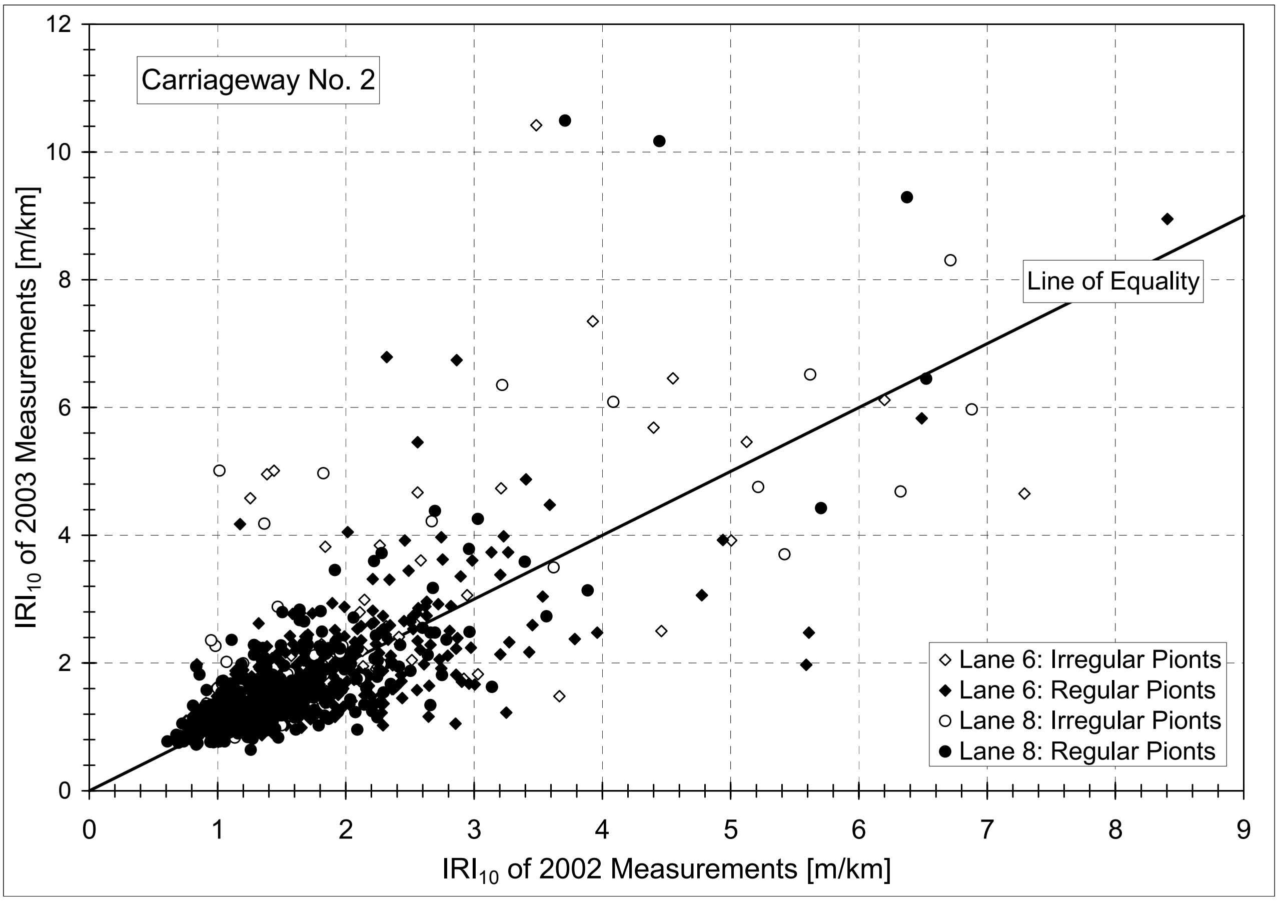


Figure A-2. IRI_{10} values obtained in the 2003 measurements versus IRI_{10} values obtained in the 2002 measurements