SMOOTHNESS OF PAVEMENTS IN CONNECTICUT
Phase 2-Report
DATA ANALYSES and TRENDS

June, 2001

Prepared by
Dr. Charles E. Dougan

Report Number 2226-F-2001-1

This project was sponsored by the Connecticut Department of Transportation in Cooperation with the U.S. Department of Transportation, Federal Highway Administration.

Technical Report Documentation Page

1. Report No. 2226-F-2001-1	2. Government Accession No. N/A	3. Recepient's Catalog No. N/A
4. Title and Subtitle Smoothness of Pavements in Connecticut, Phase 2 - Report, Data Analyses and Trends		5. Report Date June, 2001
		6. Performing Organization Code N/A
7. Author(s) Dr. Charles E. Dougan		8. Performing Organization Report No. 2226-F-2001- 1
9. Performing Organization Name and Address University of Connecticut Connecticut Transportation Institute 179 Middle Turnpike, U-202 Storrs, CT 06269-5202		10 Work Unit No. (TRAIS) N/A
		11. Contract or Grant No. N/A
12. Sponsoring Agency Name and Address Connecticut Department of Transportation Office of Research & Materials 280 West Street Rocky Hill, CT 06067-0207		13. Type of Report and Period Covered Final 6/1/00-6/30/2001
		14. Sponsoring Agency Code Research Project SPR-2226

15 Supplementary Notes

In cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The Connecticut Department of Transportation annually collects roughness data for the entire state highway system. The data are obtained via an ARAN system and are provided in the form of IRI units processed through a quarter-car-algorithm. Research was undertaken to determine the smoothness of various functional classes of highways and to determine factors affecting IRI values.

This report presents a series of analyses designed to document trends in IRI data and to quantify the effects of various factors on IRI data. The data universe is comprised of four years of IRI data, obtained from the state highway system in Connecticut. Analysis samples were selected based on input from the Connecticut Department of Transportation staff to document factors affecting IRI of direct importance to the Department.

17. Key Words Pavement smoothness, International Roughness Index - IRI	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	21. Price N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Table of Contents

List of Tables

List of Figures

Page

Smoothness of Pavements in Connecticut
Phase 2 - Report
Data Analyses and Trends

INTRODUCTION:

During the early to mid-1990's several national surveys of highway user satisfaction were conducted. The results of these surveys dramatically demonstrated that highway users wanted a smooth riding surface. They perceived and judged the success or failure of a highway in terms of a smooth, unencumbered ride.

State Departments of Transportation and the Federal Highway Administration (FHWA) have been measuring and reporting road smoothness for decades /1/. The currently accepted statistic for this purpose is the International Roughness Index (IRI), a value obtained from a quarter-car algorithm /2/. Currently, this parameter is measured and obtained in Connecticut annually by conducting field surveys of the state highway system with the Connecticut Department of Transportation's (ConnDOT) Automatic Road Analyzer (ARAN) system. The criteria for acquiring IRI data are set forth by the American Association of State Highway and Transportation Officials (AASHTO) /3/ and the American Society for Testing and Materials (ASTM)/4,5/. The recent national focus on IRI data has prompted AASHTO to review and subsequently improve the technology affecting the acquisition of IRI data /6,7/. Similar efforts are being addressed by individual states /10,11,13,14/ FHWA/9/, and other affected agencies /8/.

In Connecticut, to better understand and document the smoothness of the state highway system, ConnDOT a project to seek out and quantify the smoothness characteristics of roadways in this State. The initial phase of this work focused on the process of developing an IRI database and a log which would present the overall IRI of the various roadways in the state. The second phase centers on quantifying various data trends and factors which affect the IRI data obtained. The study is projected to produce data trends for various pavement surfaces and operations. It will aid in defining pavement smoothness issues for pavements and overlays which are part of the National Quality Initiative (NQI). In turn, the data will provide constructive insights into the application of incentive/disincentive payments for hot-mix asphalt (HMA) pavements placed in Connecticut.

The Data Analyzed in this study were field data obtained via ConnDOT's photolog surveys of the state highway system. The data were obtained using a single pass of the ARAN. Details on this process are presented in Reference 12. For this report, the data analyzed are the average IRI of the left and right wheel path which were sampled and processed by the ARAN. Only the log direction data were studied, although ConnDOT staff conduct a bi-directional survey annually. All data were processed using: 1-ARAN software to obtain an IRI from the longitudinal profile; and, 2-ConnDOT software to compute IRI mean and standard deviation statistics for a given length of roadway.

The Analyses Performed were designed to address major issues and concerns confronting ConnDOT staff in their efforts to construct and maintain longlasting smooth roadway surfaces. The project Advisory Panel was very helpful in focusing attention on ConnDOT's needs. Their assistance is gratefully appreciated.

For the purpose of this Report, the author has grouped the analyses into five major categories. They are: pavement type; construction practices; roadway characteristics; traffic levels; and the National Highway System (NHS). The results of these analyses are presented after a brief discussion of factors affecting IRI. As each category is developed the rationale for the analysis conducted and the process followed for each analysis are discussed.

Factors Affecting IRI are summarily depicted schematically in Figure 1. The Figure demonstrates that there are many factors which affect the value of IRI. They begin with the contractor, his equipment and personnel, who place the surface material. No attempt has been made to factor out the impact of individual contractors or paving crews on the surface placed.

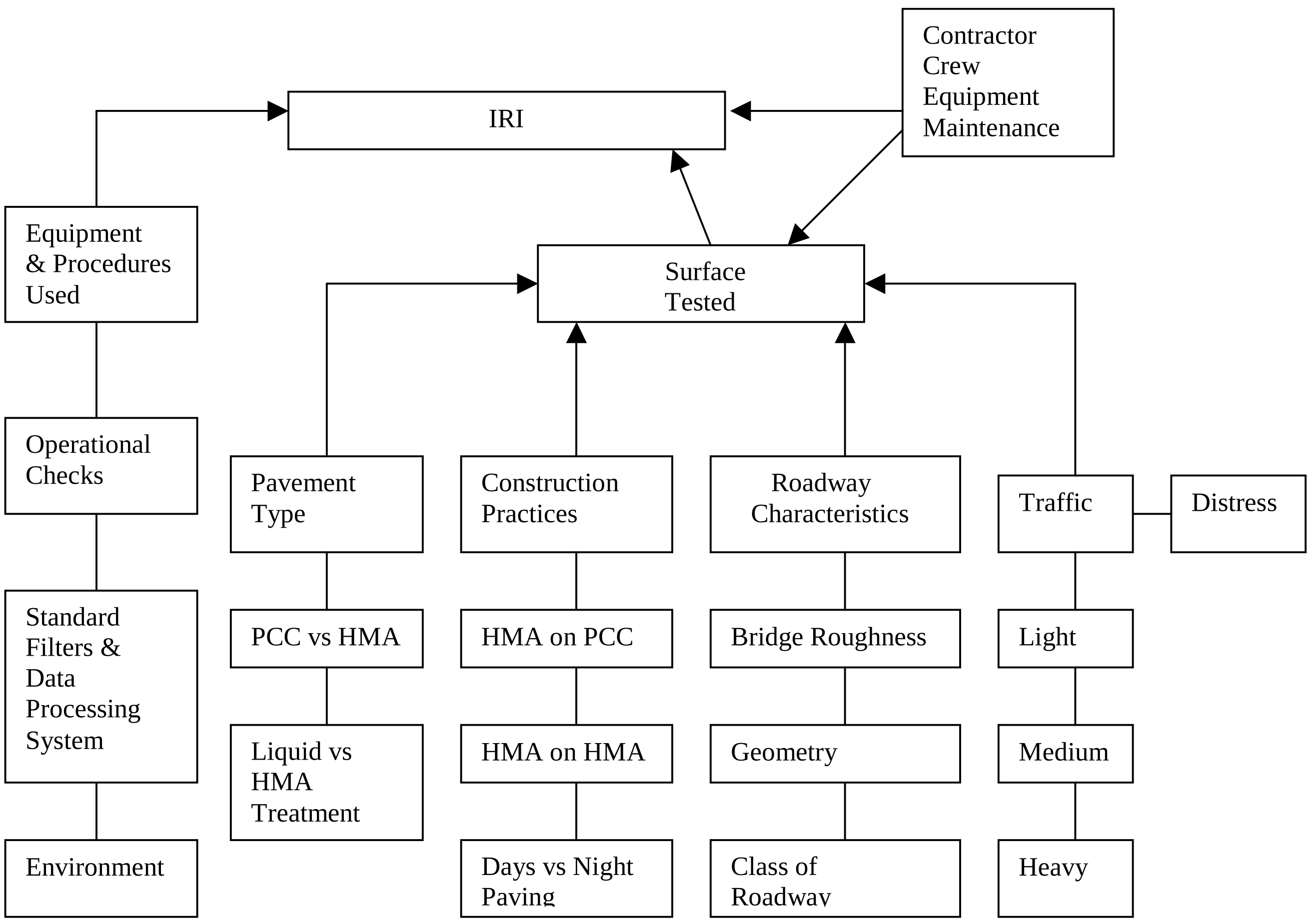
The ARAN equipment ConnDOT staff employ, and related data handling systems, etc. are not analyzed. ConnDOT staff adheres to pertinent ASTM and AASHTO test protocols and employs a series of daily equipment checks to assure that the systems are functioning correctly. This study accepts the fact that ConnDOT field staff oversee the roadway surfacing operation to assure the material is placed in accordance with ConnDOT specification requirements and that the data are obtained using properly calibrated and operated systems. However, the IRI value of the surface tested is affected by several physical roadway characteristics, surface type, construction practices and traffic considerations. These are outlined in Figure 1. Roadway distresses are greatly influenced by the environment and the amount and weight of traffic borne by the surface. For this report, the magnitude of the IRI value obtained is considered to be a measure of distress; i.e. the higher the IRI the greater the roadway distress, irrespective of its causative factors.

To minimize the effect of seasonal environmental factors, ConnDOT staff obtain photolog and IRI data approximately at the same time each year. Studies conducted by FHWA on Long-Term Pavement Performance (LTPP) test sections/14/ suggest temperature and support conditions influence IRI values. These data are sparse and further research is recommended to establish firm relationships. Based on this research, the author concludes that ConnDOT staff conduct photolog and data surveys in a reasonable manner thereby reducing seasonal effects on IRI data.

Not shown in Figure 1 is an analysis of the IRI data for the NHS in Connecticut. This activity focuses exclusively on the NHS because of its importance in providing financial resources to upgrade and maintain the highway system in Connecticut. Issues related to the IRI-valuation of the NHS will be discussed later.

ANALYSES PERFORMED:

Figure 1 – Factors Affecting IRI



As stated previously, the analyses performed were selected to provide descriptive insights into the IRI data obtained by ConnDOT. They are designed to address commonly asked questions about IRI and the factors which affect the data obtained. The following discussion will follow from left to right those factors affecting IRI shown in Figure 1 (Pavement Type to Traffic). The final analysis focuses on the IRI of the NHS in Connecticut. Substantial time and effort was expended on the NHS analysis because of the significance of the NHS in the allocation of federal-aid monies. It is the author's opinion that recommendations based on the NHS analysis will greatly improve the current method of determining the IRI for the NHS.

ANALYSIS OF PAVEMENT TYPE:

Portland Cement Concrete (PCC) and Hot-Mix Asphalt (HMA) are the two major classes of pavement surface. In the past three decades the existing PCC surfaces have been overlain with HMA in Connecticut, which limited the data from PCC pavement. Table 1 presents the PCC and HMA sites analyzed. Table 2 shows the IRI data for four years for both cases with and without bridges. In most cases the HMA sections selected were adjacent to the PCC sections, where adjacent sections could not be found, nearby areas of comparable traffic and geometric characteristics were employed. In all cases, the traffic volume was high (greater than 12,000 adt).

For the data shown the HMA surface has a lower IRI, reflecting a smoother surface, than adjacent PCC pavements. The reader is cautioned that in all cases the data for the PCC reflect a much older existing surface than the HMA. The variability in the data, as measured by the standard deviation, in some cases is marginally larger for PCC vs HMA. This is to be expected based on the age factor cited previously.

The IRI values for both PCC and HMA have remained constant over the four-year period 1997-2000. This is consistent with the findings from the LTPP field data which were analyzed by FHWA/15/.

Liquid Surface Treatment vs HMA - In Connecticut liquid surface treatments have been employed to maintain lower functionally classed routes particularly in the more rural areas such as ConnDOT’s Districts 2 and 4. Recently, ConnDOT is moving towards using more HMA overlays to improve the structural characteristics of these roadways. This analysis compares the IRI of a liquid treatment dusted with a chip or grit cover sand to 50-mm HMA overlay.

Tables 3 and 4 show the route, location, IRI with and without bridges, and the standard deviation for each liquid surface treatment and HMA overlays for each data set, respectively. The routes were selected from the 1996 maintenance program. Each treatment was shown to be completed in 1996, was tested in 1997 - 2000, and was at least 1-km in length. A short length at the beginning and ending termini of the treatment was dropped to avoid potential problem areas encountered in starting and stopping project activities. Candidate HMA overlays were secured in each of the four maintenance districts in the state. Liquid applications were only placed in two of the four districts, District 2, eastern Connecticut and District 4, northwestern Connecticut. Districts 1 and 3 serve urban Connecticut and employ overlay treatments only.

Table 1- **IRI - PCC vs HMA Pavement Summary of Locations Sampled**

PCC				HMA			
Route	Start	End	Length(km)	Route	Start	End	Length(km)
I-84	108.50	112.38	3.88	I-84	112.94	116.85	3.91
9	57.84	60.19	2.35	9	61.07	63.87	2.80
I-691	0.00	12.07	12.07	I-84	59.98	64.97	4.99
25	7.63	10.91	3.28	111	0.00	11.73	11.73
I-95[1]	149.00	150.30	1.30	I-95	154.00	179.00	25.00

[1] No bridges in section shown.

Table 2 - **Comparison of IRI Values for PCC and HMA Surfaces**

Log Directions Only

Bridges Included

Route	IRI_97[1]	Stdev97[2]	IRI_98	Stdev98	IRI_99	Stdev99	IRI_00	Stdev00
				PCC				
I-84	1.960	0.750	2.000	0.750	2.090	1.160	1.920	0.735
9	2.360	1.090	2.390	1.070	2.410	1.130	2.329	1.150
25	2.390	0.980	2.400	1.080	2.530	1.140	2.290	0.997
I-691	2.080	1.020	2.080	1.030	2.090	1.050	1.810	1.121
I-95[3]	2.650	0.690	2.240	1.230	2.650	0.630	2.782	1.080
				HMA				
I-84	1.630	0.760	1.640	0.720	1.630	0.700	1.610	0.750
9	1.730	0.880	1.740	0.920	1.750	0.780	1.672	0.824
111	2.570	1.310	2.550	1.440	2.490	1.260	2.270	1.370
I-84	2.57[4]	1.010	1.55[4]	0.580	1.600	0.600	1.548	0.600
I-95	1.820	1.090	1.980	1.030	1.540	0.730	1.440	0.790

Bridges Excluded

Route	IRI_97[1]	Stdev97[2]	IRI_98	Stdev98	IRI_99	Stdev99	IRI_00	Stdev00
				PCC				
I-84	1.900	0.540	1.940	0.660	2.030	0.820	1.890	0.730
9	2.360	1.100	2.410	1.070	2.410	1.050	2.410	1.163
25	2.250	0.740	2.260	0.800	2.350	0.820	2.300	0.900
I-691	2.010	0.930	1.990	0.880	2.000	0.940	1.710	0.970
I-95[3]	2.650	0.690	2.220	1.170	2.650	0.630	2.782	1.080
				HMA				
I-84	1.600	0.720	1.610	0.690	1.640	0.710	1.600	0.730
9	1.720	0.880	1.730	0.930	1.760	0.790	1.687	0.833
111	2.560	1.290	2.550	1.440	2.490	1.260	2.260	1.360
I-84	2.59[4]	1.020	1.51[4]	0.510	1.570	0.540	1.508	0.537
I-95	1.750	0.970	1.980	1.030	1.520	0.700	1.450	0.790

[1] IRI for year indicated

[2] Standard deviation of data set for year indicated

[3] No bridges in section shown

[4] 97-98, 1 inch HMA surface applied by maintenance forces

Table 3 - **IRI - Maintenance - Liquid Program**

Route	St_km	End_km	IRI_97_w	IRI_97_o	Std_97_w	Std_97_o	IRI_98_w	IRI_98_o	Std_98_w	Std_98_o
14	32.3	39.1	4.148	4.178	1.567	1.564	4.371	4.390	1.706	1.697
14A	11.25	16.6	4.978	4.237	1.350	1.332	4.573	4.526	1.498	1.456
138	0.45	6.5	4.647	4.664	1.702	1.706	4.867	4.882	1.880	1.880
109	0.24	9.2	3.790	3.790	1.613	1.613	3.701	3.701	1.663	1.663
199	0	3.03	4.144	4.194	1.778	1.769	3.260	3.289	1.361	1.364
341	5.49	17.3	4.271	4.259	1.559	1.548	4.251	4.246	1.591	1.593
$\bar{X}$			4.330	4.220	1.595	1.589	4.171	4.172	1.617	1.609

Route	St_km	End_km	IRI_99_w	IRI_99_o	Std_99_w	Std_99_o	IRI_00_w	IRI_00_o	Std_00_w	Std_00_o
14	32.3	39.1	4.263	4.274	1.434	1.405	2.270	2.260	1.360	1.350
14A(2)	11.25	16.6	4.500	4.480	1.440	1.430	2.360	2.360	1.470	1.470
138(2)	0.45	6.5	1.718[1]	1.708[1]	0.776	0.774	1.710	1.700	1.110	1.110
109(2)	0.24	9.2	3.691	3.691	1.495	1.495	3.850	3.850	1.680	1.680
199	0	3.03	3.285	3.319	1.423	1.429	2.110	2.130	1.400	1.410
341	5.49	17.3	3.653	3.647	1.551	1.551	3.670	3.660	1.630	1.630
$\bar{X}$			3.878	3.882	1.353	1.347	2.662	2.660	1.442	1.442

[1] Section resurfaced with HMA

(2) No Bridges in Section

Table 4 - IRI - Maintenance Overlay Treatment(50mm Overlay)[1]

Route	Start_km	End_km	iri_97_w	iri_97_o	std_97_w	std_97_o	iri_98_w	iri_98_o	std_98_w	std_98_o
159	0.50	6.26	2.082	2.066	1.141	1.108	2.123	2.116	1.174	1.166
190	25.40	29.37	2.295	2.295	0.835	0.841	2.385	2.379	0.919	0.921
191	0.50	6.12	1.88	1.808	0.867	0.716	1.912	1.835	0.818	0.647
372	2.09	4.46	2.304	2.304	1.12	1.12	2.215	2.215	1.118	1.118
44	133.17	137.60	1.507	1.504	0.646	0.645	1.6	1.599	0.694	0.696
1	125.50	127.90	1.924	1.904	0.664	0.652	1.96	1.971	0.719	0.722
1	80.87	84.00	1.974	1.955	1.027	1.04	1.9	1.905	0.903	0.918
243	3.80	8.30	2.457	2.428	1.04	0.986	2.444	2.416	1.026	0.98
41	21.79	28.74	1.226	1.226	0.404	0.404	1.233	1.233	0.411	0.412
187	26.60	31.70	1.631	1.631	0.665	0.665	1.609	1.609	0.555	0.555
$\bar{X}$			1.928	1.912	0.841	0.818	1.938	1.928	0.834	0.814

Route	Start_km	End_km	iri_99_w	iri_99_o	std_99_w	std_99_o	iri_00_w	iri_00_o	std_00_w	std_00_o
159	0.50	6.26	2.133	2.115	1.087	1.055	2.140	2.120	1.250	1.230
190	25.40	29.37	2.382	2.383	0.946	0.954	2.380	2.360	0.950	0.950
191	0.50	6.12	1.942	1.869	0.951	0.838	1.940	1.880	1.170	1.220
372(2)	2.09	4.46	2.906	2.906	1.759	1.759	3.200	3.200	2.540	2.540
44(2)	133.17	137.60	1.623	1.623	0.765	0.765	1.510	1.510	0.640	0.640
1	125.50	127.90	2.044	2.044	0.82	0.82	2.000	1.970	0.860	0.840
1(2)	80.87	84.00	2.058	2.057	1.154	1.177	2.180	2.100	2.160	2.170
243	3.80	8.30	2.56	2.532	1.147	1.108	2.540	2.510	1.240	1.210
41	21.79	28.74	1.316	1.307	0.451	0.447	1.280	1.270	0.450	0.4400
187(2)	26.60	31.70	1.675	1.675	0.545	0.545	1.690	1.690	1.240	1.240
$\bar{X}$			2.064	2.051	0.963	0.947	2.058	2.035	0.932	1.074

[1] Daylight operations only.
(2) No Bridges in Section

Figure 2 graphically presents the average IRI data and its corresponding standard deviation for overlay and liquid treatments. The liquid application's IRI is substantially higher than that of an HMA (greater than 2.0). The standard deviation is higher by a corresponding value (2.0). The value of IRI remains essentially constant for the overlay, but decreases with time for the liquid application. It appears that the HMA will provide a more substantial surface, in terms of IRI, for a greater time span than the liquid treatment.

CONSTRUCTION PRACTICES:

ConnDOT staff were very interested in the IRI of various construction operations such as milling, leveling courses, etc., which, when ongoing, affect the motoring public. To address this issue special ARAN runs were conducted by ConnDOT staff during the rehabilitation of an overlain PCC pavement and the overlay of an HMA pavement. Both of these treatments and their component operations are typical of ConnDOT rehabilitation activities.

For the HMA Overlay on PCC, a 13-km project on Rt 8 (State Project 144-171) was selected. It is a 4-lane divided highway which had been previously overlain in part. The existing pavement was deteriorating and required rehabilitation. This activity required: removal of any existing overlay work on the pavement or bridge decks, repair of the PCC pavement and resurfacing with a two-course 12.5mm SuperPave designed HMA overlay placed on an HMA leveling course. ConnDOT's ARAN was run over the right hand lane to provide IRI data on the existing surface and after each major construction operation. Figure 3 presents the data obtained. The IRI shown is the mean value over the total length. Figure 4 shows the corresponding standard deviation of each operation. Figure 5 was prepared to compare the corresponding IRI and standard deviation of each operation.

The reader should note the substantial improvement in ride after the motorist suffers through the needed PCC repairs. The influence of bridge roughness is noted at this project site and it contributes additional value to the IRI measured for each operation.

It is interesting to note that the improvement (lowering) of IRI with succeeding operations is accompanied by a corresponding decrease in the standard deviation. This reflects added process control at each succeeding step of the overlay construction process. In other words, the data suggest that more care is being exercised to achieve a smooth riding surface during each succeeding process.

An assessment of an HMA overlay on an HMA pavement was performed on data provided for a 5.2-km resurfacing of I-395 (State Project 85-131). I-395 at the location is a 4-lane divided highway. It was rehabilitated by removing the existing the surface at bridges to preserve required truck clearances, and then placing a two-course 12.5 mm SuperPave designed overlay on a HMA leveling course throughout the project limits. Construction was accomplished during 1999.

Again, it was planned to conduct ARAN runs over the project after each major construction operation but slight deviations occurred. Initially, because I-395 had been surveyed just prior to construction, it was determined that previously available IRI data would be used to define the existing surface. This eliminated the need for an initial run. Any existing surface

Figure 2 **- IRI - Maintenance Treatments**

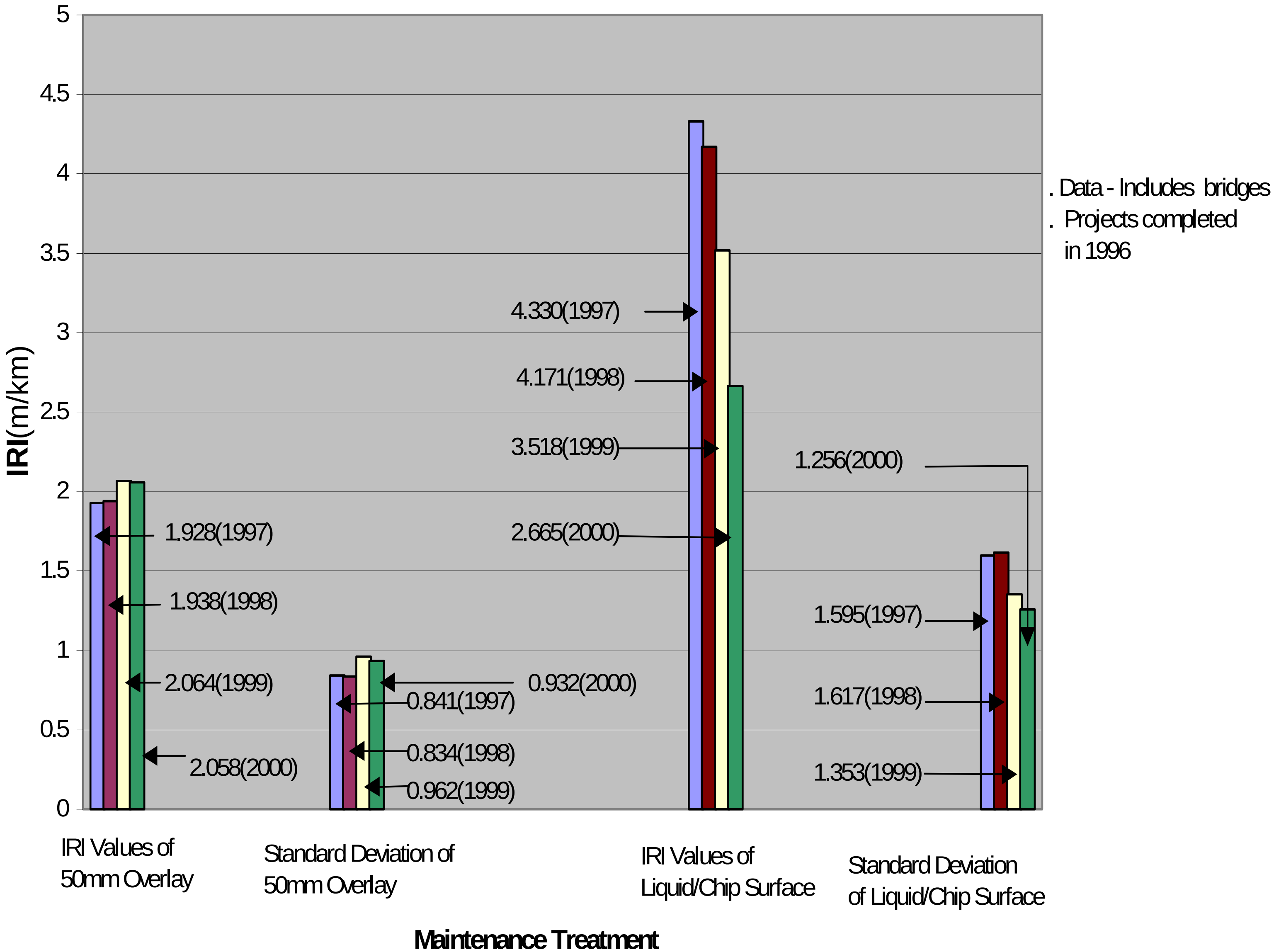


Figure 3- **IRI - Construction Operations**
HMA Overlay on PCC
Route 8 Project 144-171

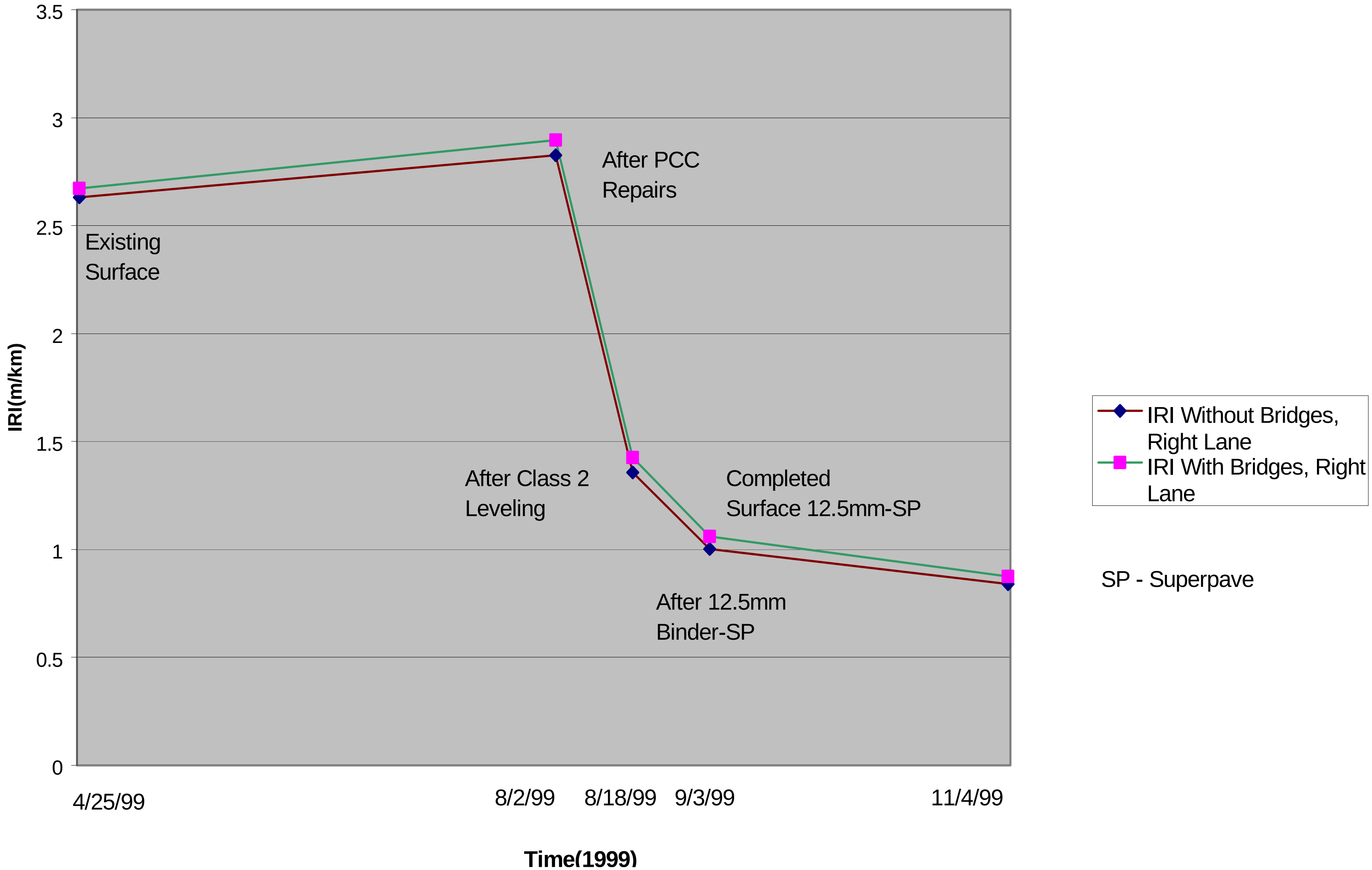


Figure 4 -**Standard Deviation of IRI by Construction Operation**

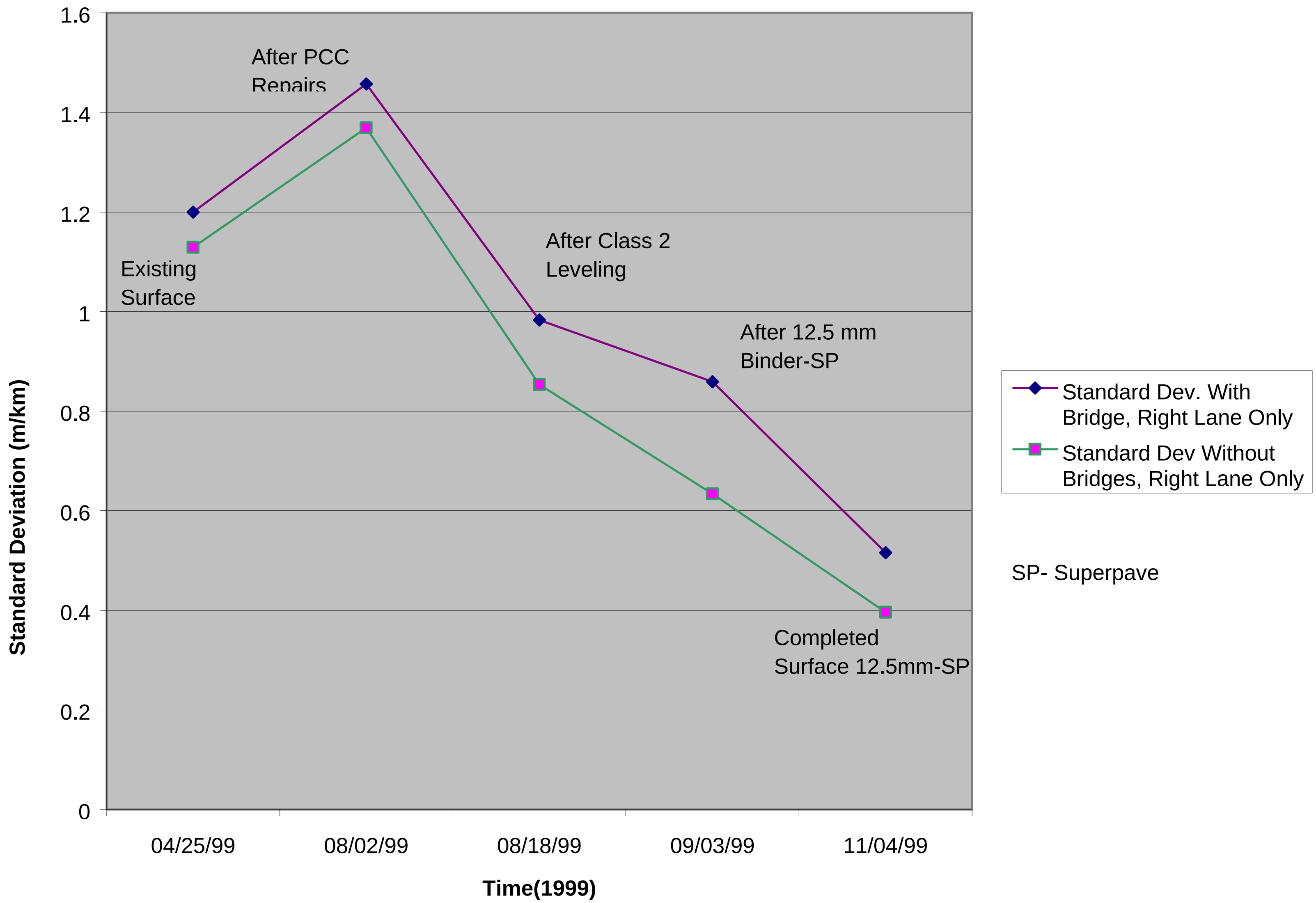
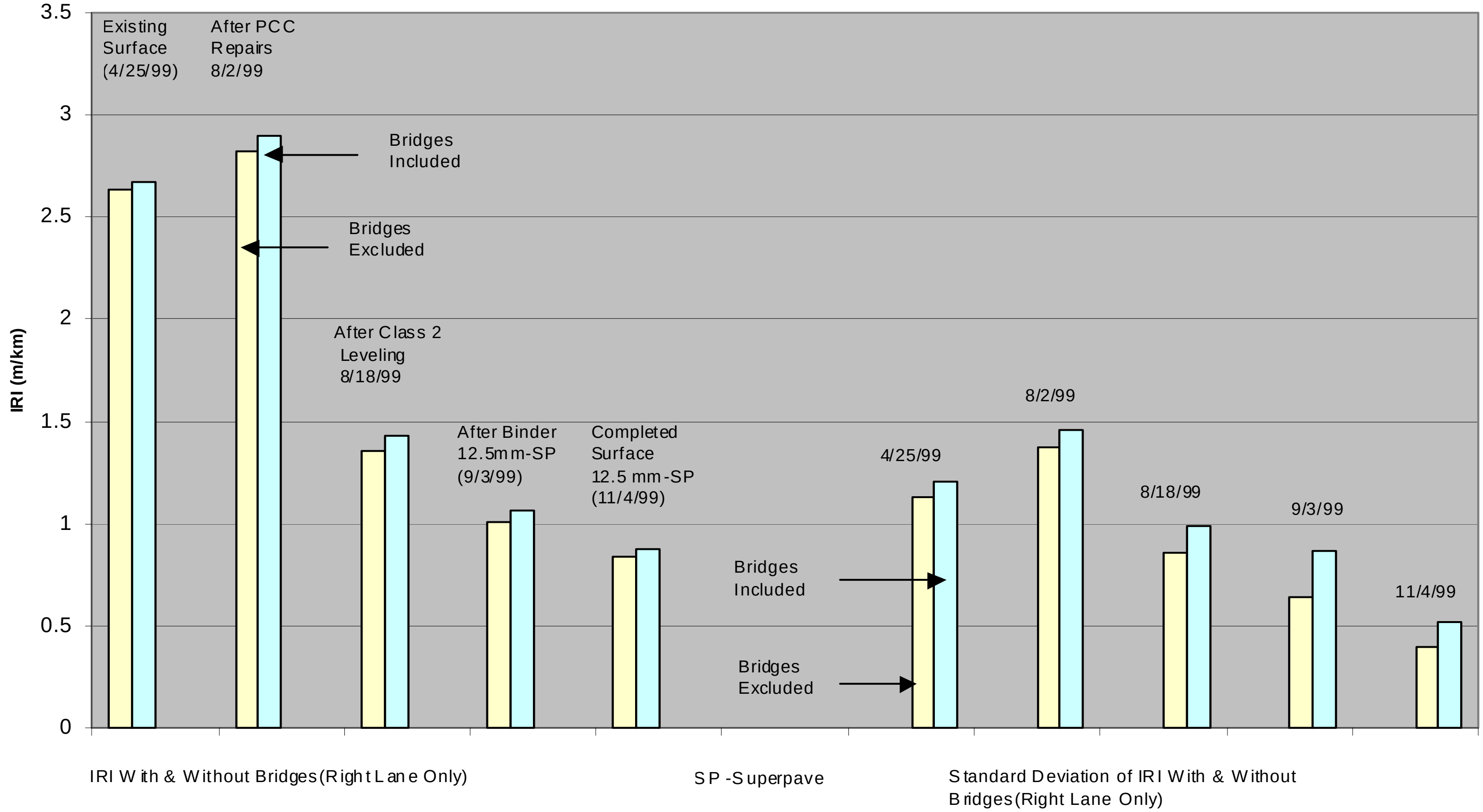


Figure 5 - **Construction Operations- Comparison of IRI&Corresponding Standard Deviations**
(With & Without Bridge Roughness)



removed via milling was followed almost immediately by an application of a leveling course. Limited data were obtained to define the IRI of the milled HMA surface and are not included in this report. Succeeding operations, placement of the binder and surface layers, were better coordinated and the IRI trends obtained are shown in Figures 6-8, inclusive. Separate data were developed and plotted for the northbound roadway but are not included. The northbound roadway shows similar data trends of the same magnitude.

The trend is improved IRI as construction proceeds. The standard deviation is fairly constant until the final course is placed. This is slightly different than the above HMA overlay on PCC, but here again better process control is indicated by the data when the finished course is placed.

To look at trends in night vs day HMA paving, members of the advisory panel provided data on paving conducted in 1996 for both maintenance and construction projects. In each area, the projects were at least 2-km long. The exception is Rt 34, a night maintenance project. It is included because of the limited data available.

Table 5 presents the IRI data for night maintenance paving operations. These data can be compared to the data in Table 4 for maintenance paving during daylight hours. Table 6 shows both night and day IRI values for several construction projects. In each case (maintenance or construction operations) the data analyzed were selected to provide four years of field IRI data. This resulted in only two night paving projects for maintenance and two day time paving projects for construction. Additional data sets will be needed to precisely define performance trends using IRI values. It is thought, however, that there are reasonable trends exhibited in these data.

Table 7 summarizes the IRI data shown in Tables 4, 5 and 6. These are the arithmetic means of the IRI and standard deviation of each route. The data are plotted in Figures 9 and 10, for maintenance and construction paving operations, respectively.

Daytime maintenance operations show a fairly consistent IRI and corresponding standard deviation. Nighttime paving is somewhat more inconsistent. The difference is attributed to limited experience with night paving and the small data set analyzed. It is projected that the IRI values will remain fairly constant over a 1-5 year time frame but will increase thereafter, based on IRI trends in published literature.

Figure 10 presents the construction paving IRI and its standard deviation. The data shows a consistent IRI and standard deviation, with the night paving being slightly better than daytime operations, based solely on IRI. Here again there were limited data analyzed (two projects) in the case of day paving.

HMA paving is performed in two operational areas of ConnDOT, Maintenance or Construction. The fact that Connecticut employs both construction and maintenance forces for HMA paving is fairly unique but has a proven track record of success in the state. A further outline of the separate processes undertaken follows.

Figure 6 **IRI - Construction Operations Overlay on HMA**
I-395, South Bound

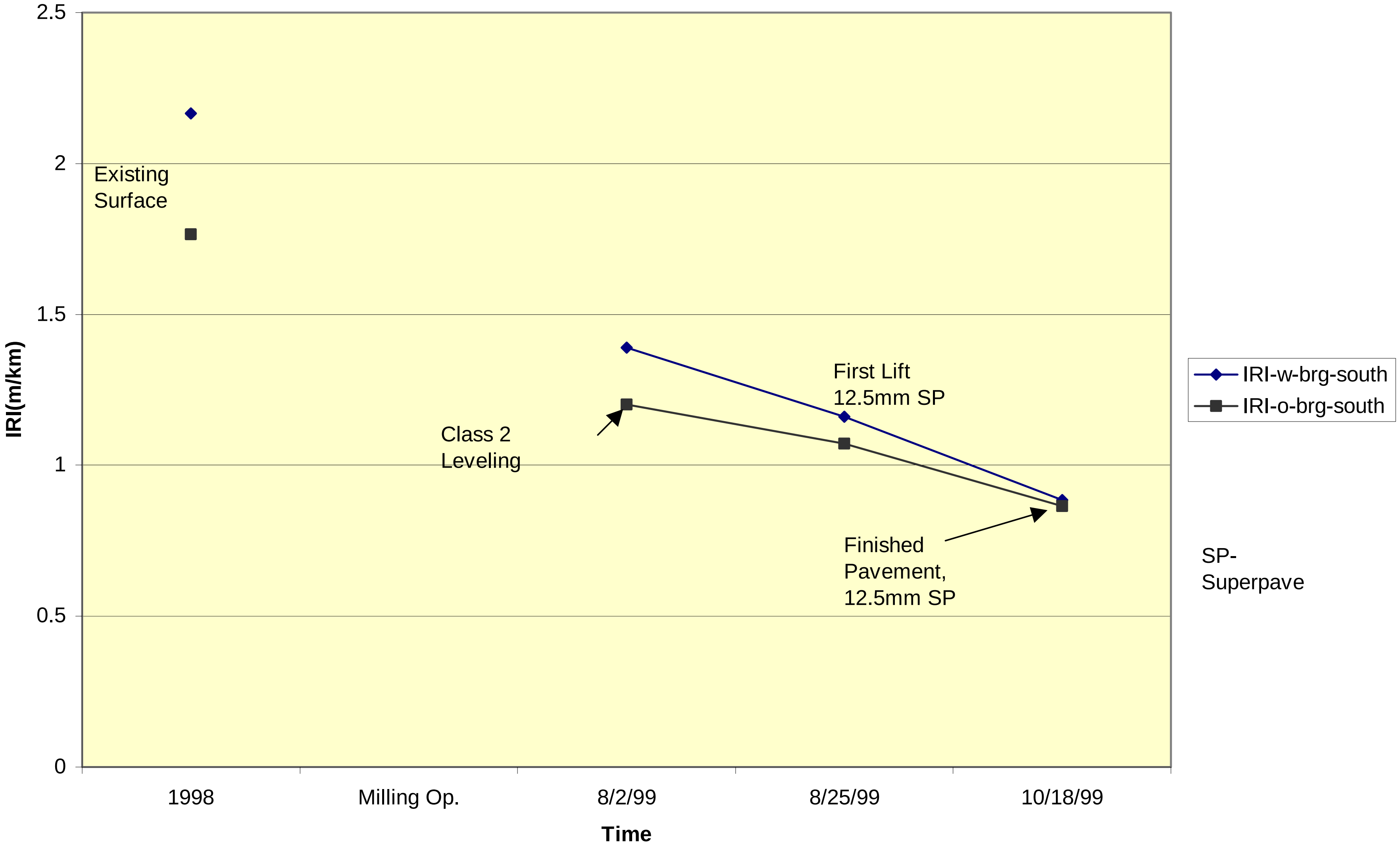


Figure 7 **- Standard Deviation of IRI by Construction Operation I-395 South Bound, With and Without Bridges**

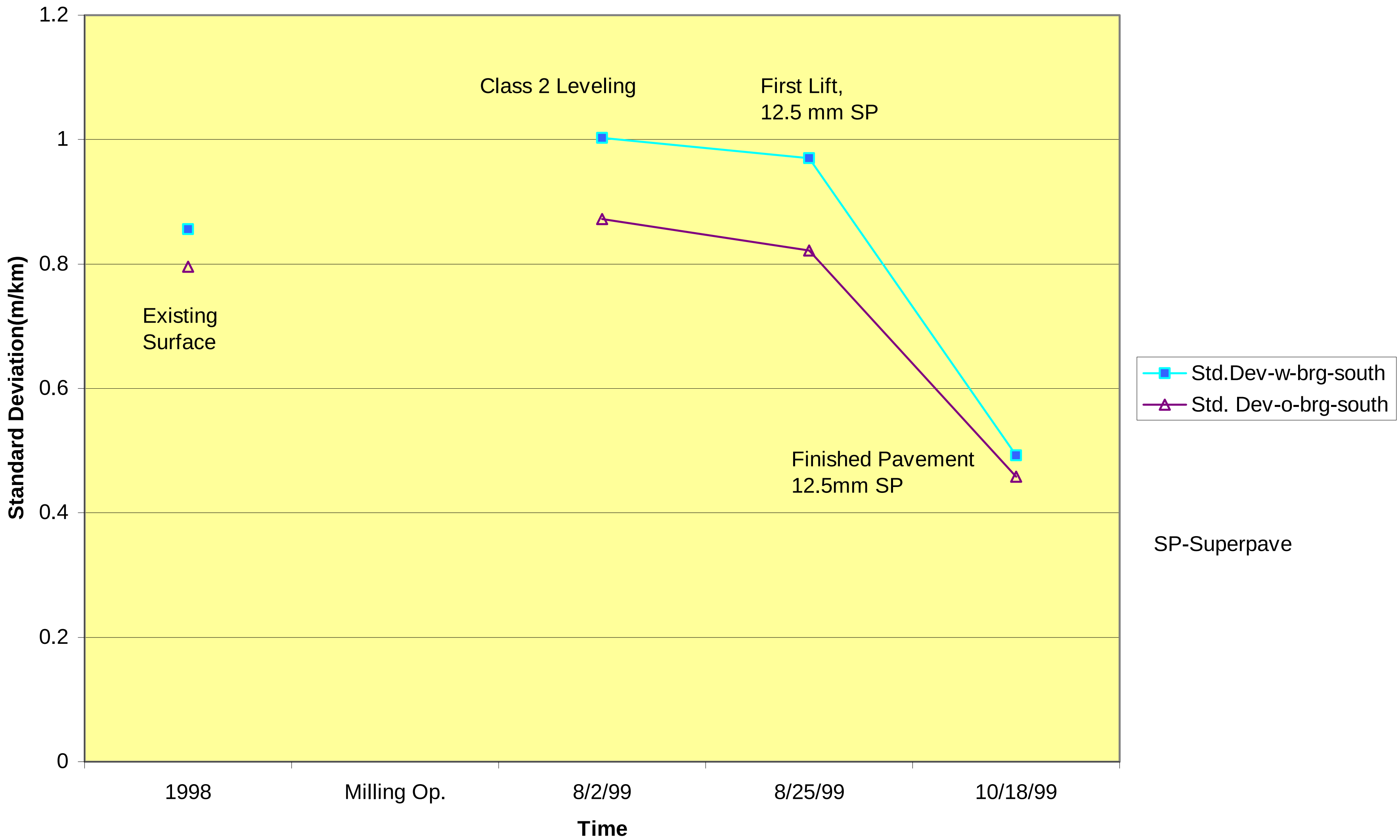


Figure 8- **Construction Operations I-395 South Bound-Comparison of IRI& Corresponding Standard Deviation**
(With & Without Bridges)

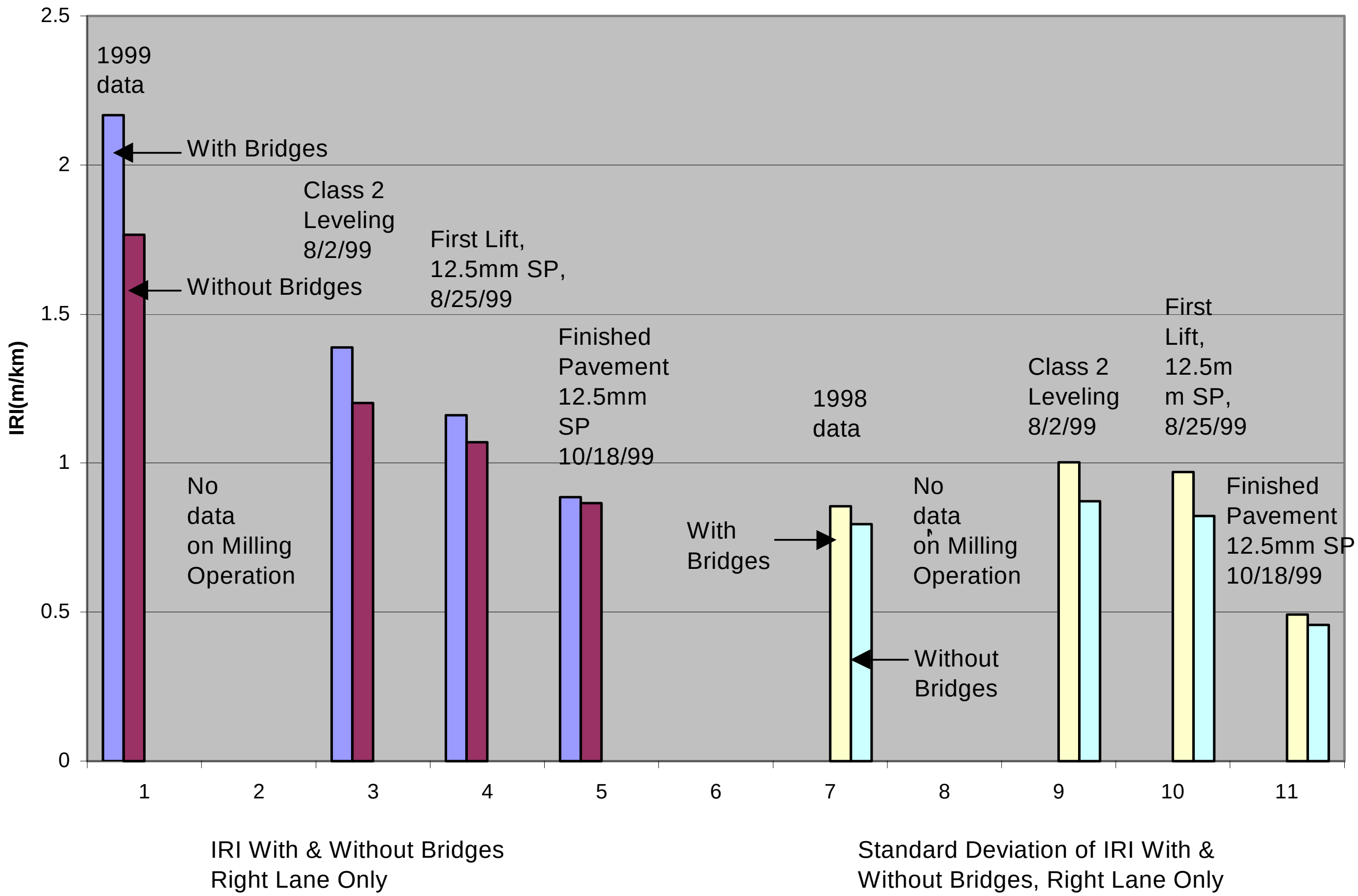


Table 5 - **IRI of Night Maintenance Paving Operations***

			1997				1998				1999				2000			
Route	Start	End	IRI		Std. Dev.		IRI		Std. Dev.		IRI		Std. Dev.		IRI		Std. Dev.	
	(km)	(km)	w**	w/o***	w	w/o	w	w/o	w	w/o	w	w/o	w	w/o	w	w/o	w	w/o
15(N)	76.23	80.5	1.936	1.908	0.812	0.801	1.955	1.920	0.815	0.783	2.030	1.960	0.850	0.790	1.810	1.750	0.770	0.700
34(N)	22.14	22.73	3.524	3.001	2.276	1.588	2.975	2.892	1.334	1.355	3.470	3.470	1.680	1.680***	3.190	3.280	2.490	2.550

Table 6 **- IRI-Day and Night Construction Paving Operations**

			1997.000				1998.000				1999.000				2000.000			
Route	Start	End	IRI		Std. Dev.		IRI		Std. Dev.		IRI		Std. Dev.		IRI		Std. Dev	
	(km)	(km)	w	w/o	w	w/o	w	w/o	w	w/o	w	w/o	w	w/o	w	w/o	w	w/o
9(N)	51.90	56.50	1.299	1.272	0.516	0.496	1.310	1.289	0.562	0.560	1.384	1.374	0.579	0.589	1.340	1.340	0.580	0.582
I-84(D)	113.88	117.50	1.512	1.412	0.743	0.571	1.533	1.445	0.744	0.609	1.526	1.531	0.719	0.742	1.511	1.486	0.940	0.741
72(D)	7.31	10.19	1.598	1.401	0.833	0.488	1.571	1.438	0.816	0.555	1.638	1.489	0.669	0.524	1.640	1.460	0.840	0.576
I-84(N)	42.58	48.22	1.523	1.368	0.750	0.486	1.502	1.367	0.727	0.495	1.552	1.502	0.727	0.679	1.470	1.408	0.750	0.679
I-95(N)	0.13	3.77	1.338	1.262	0.690	0.581	1.360	1.291	0.702	0.624	1.456	1.396	0.776	0.685	1.370	1.280	0.740	0.630
I-95(N)	29.23	36.10	1.402	1.329	0.660	0.548	1.432	1.367	0.716	0.577	1.452	1.424	0.667	0.640	1.400	1.370	0.690	0.643
25(N)	3.43	7.82	1.492	1.469	0.725	0.690	1.494	1.476	0.741	0.709	1.532	1.520	0.742	0.740	1.450	1.460	0.680	0.681

* Data from 1996 Vendor-in-Place(VIP)
** Bridges included
*** Bridges excluded
**** No data on bridges
(N) = Night Paving Completed in Calendar 1996
(D) = Daylight Paving Completed in Calendar 1996

Table 7 - **Summary of Data for Day vs Night Paving**

Maintenance Operations

(With Bridges)

# of Data Points		1997		1998		1999		2000	
		IRI	Std. Dev.	IRI	Std. Dev.	IRI	Std. Dev.	IRI	Std.Dev.
4423	Day(10)	1.875	0.804	1.883	0.791	2.064	0.962	2.086	1.250
486	Night(2)	2.730	1.544	2.465	1.076	2.750	1.265	2.500	1.620

Construction Operations

(With Bridges)

# of Data Points		1997		1998		1999		2000	
		IRI	Std. Dev.	IRI	Std. Dev.	IRI	Std. Dev.	IRI	Std. Dev.
630	Day(2)	1.555	0.788	1.552	0.780	1.582	0.694	1.570	0.890
2514	Night(5)	1.411	0.668	1.420	0.690	1.474	0.698	1.410	0.690

(#) Number of Projects

Figure 9**-Day vs Night IRI Values for Maintenance Paving**

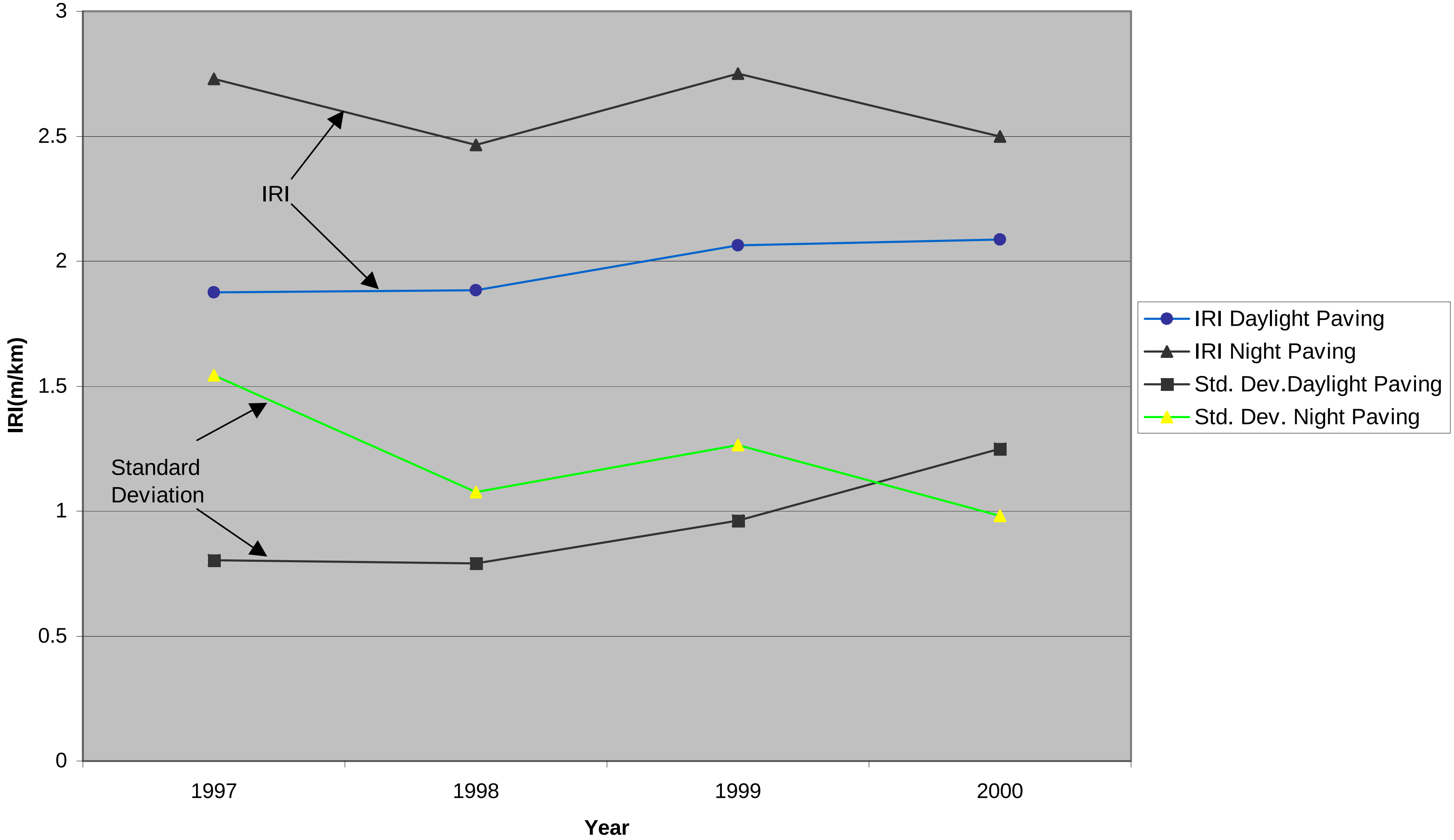
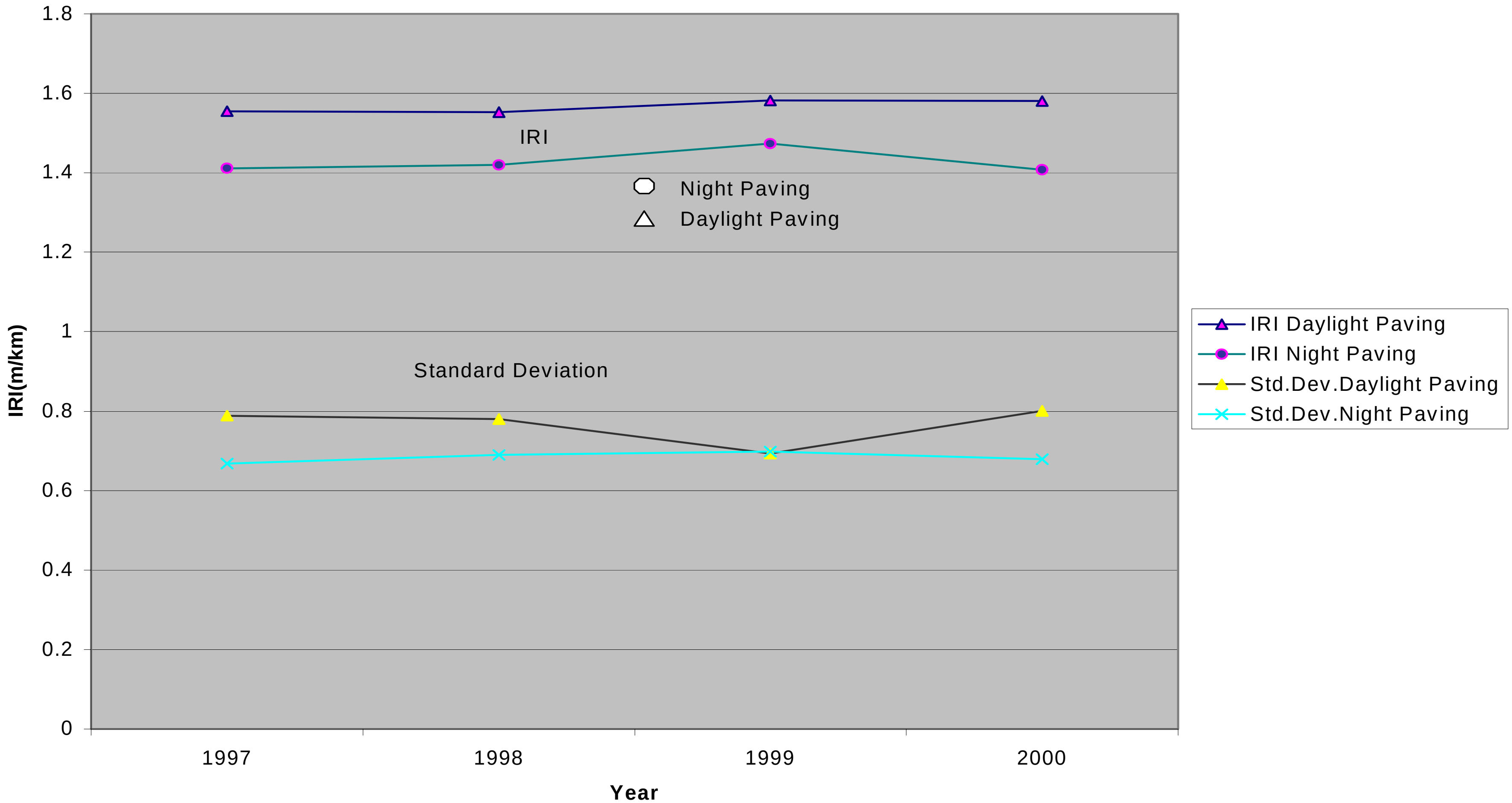


Figure 10 **- Day vs Night IRI Values for Construction Paving**



Maintenance paving is conducted under the Vendor-In-Place (VIP) Program. In this program statewide bids for HMA tonnage in set classes are obtained. Maintenance staff then program and manage HMA resurfacing. Maintenance staff also provide inspection of the operation for quality assurance (QA) purposes. Maintenance activities are primarily focused on the lower functionally classified roadways.

The Office of Construction manages individual paving and rehabilitation projects prepared by the Department's design group. Each project is competitively bid. The construction inspection force, supplemented by consultants as needed, provide QA for the pavement placed.

Both Construction and Maintenance follow departmental specifications for HMA placement. Recently, night paving has been employed to reduce traffic delays and to minimize lane closures during peak traffic hours. These night projects occur on major highways. Maintenance paving at night began around 1995-96, while construction staff have been into night paving since the 1980's.

The data shown reflect slightly better IRI for construction vs maintenance. The reader is cautioned that the maintenance activities were performed mainly on lower functionally classified roads where geometry, curve and grade, adjacent access and the existence of underground utilities influence the paving operation. Few of these problems are encountered in the construction projects, particularly when they are conducted on limited access expressways. Further, construction projects generally reconstruct or improve base conditions and add to the structural capability of the roadway section. This is not the case with maintenance paving operations. For these reasons the author would expect to find generally higher IRI for maintenance paving than that of construction paving.

In 1999, ConnDOT undertook a contract to diamond grind an existing PCC surface to smooth the pavement on a 4-km section of I-691 in the Meriden-Cheshire area. Both roadways of a 4-lane divided highway were ground. The IRI data prior to grinding in 1999 and follow-up measurements in 2000 are show in Table 8, and graphically presented in Figure 11. The grinding process did lower the mean IRI about 20 percent (1999 to 2000). The standard deviation (1999 to 2000) shows an increase of approximately 10-15 percent. Why this is occurring is unknown. The research team believes that additional data are required to establish any performance trends for the diamond grinding process. In any event this methodology appears to be a viable technique to improve the IRI of PCC pavements.

ANALYSIS OF ROADWAY CHARACTERISTICS:

These primary factors are included in this category: bridge roughness, roadway geometry; and class of roadway. The project advisory panel believes that each of these factors affect the IRI values obtained. The analyses conducted are designed to build upon the analytical work begun in Phase 1 of this project.

Bridge Roughness - The methodology used to remove bridge roughness is described in Reference 12. Figure 12 presents this system in graphic form. Briefly, the system removed the

Table 8

Comparison of IRI Mean and Standard Deviation Before and After Milling PCC Surface

(Sections on I-691E and I-691W)

Year	Rt. #	Start Location	Start Km	End Location	End Km	IRI_R	IRI_L	IRI_B	Standard Deviation
1999	691E	Wb Bgn Op Ten Mile Rv	11.87	Up Rt. 322	7.75	2.140	2.290	2.210	1.010
1999	691W	Up Rt. 322	7.8	Wb Bgn Op Ten Mile Rv.	11.93	2.420	2.550	2.480	1.060
2000	691E	Wb Bgn Op Ten Mile Rv	11.77	Up Rt. 322	7.63	1.900	1.760	1.830	1.120
2000	691W	Up Rt. 322	7.83	Wb Bgn Op Ten Mile Rv.	11.97	1.800	1.840	1.820	1.300

Figure 11
Before and After Milling PCC Surface
Comparison of Mean IRI and Standard Deviation
(I-691E and I-691W, 1999 and 2000 Data)

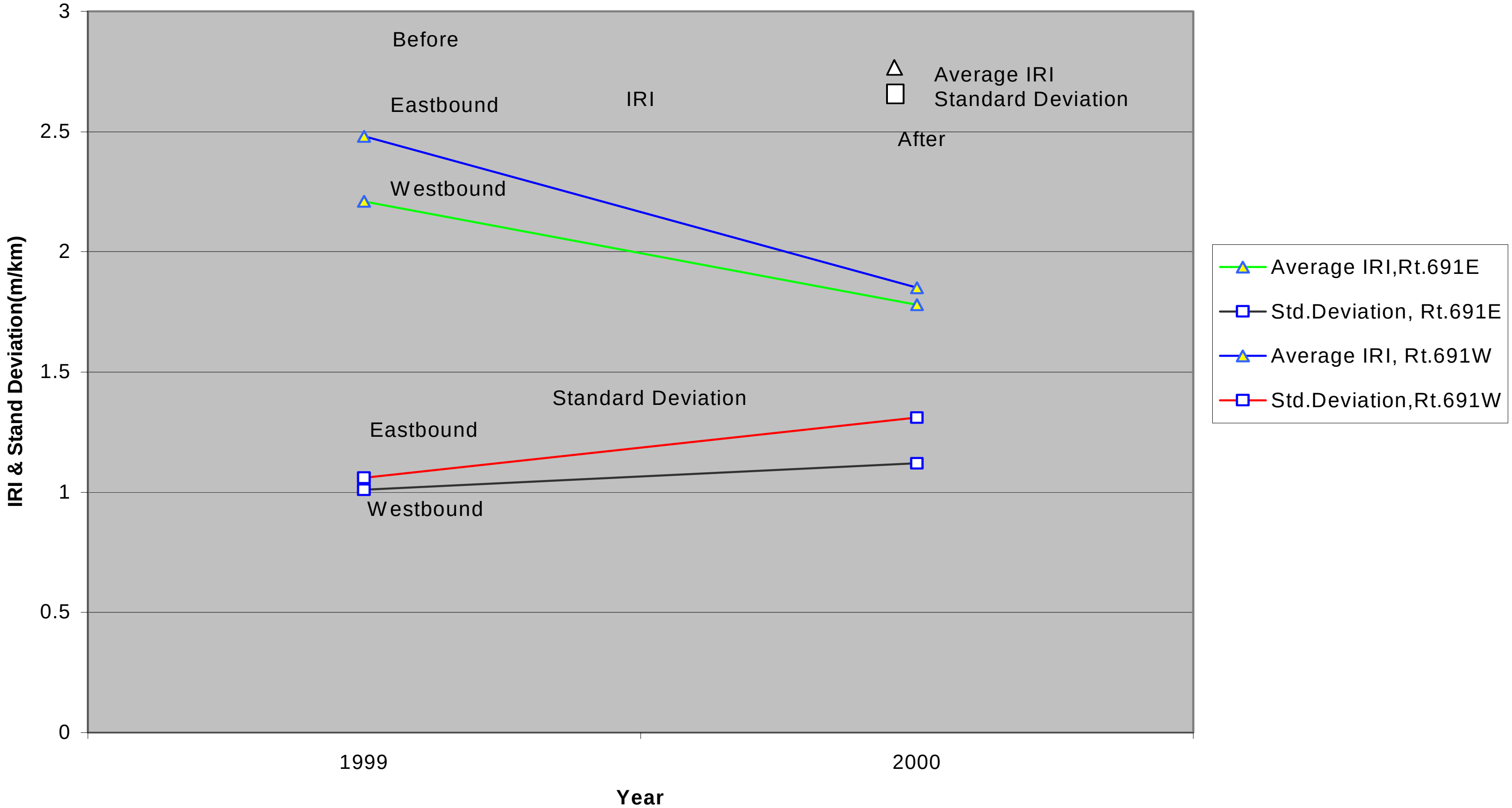
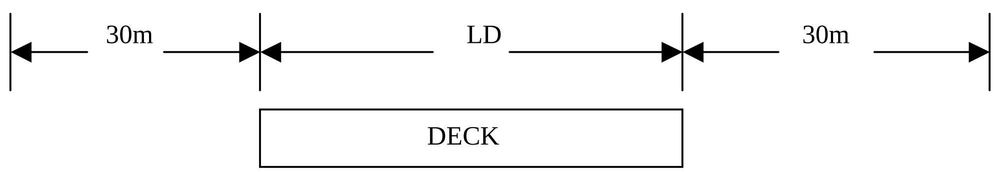


Figure 12

Schematic Representation of Length of Roughness Removed Associated with Bridges

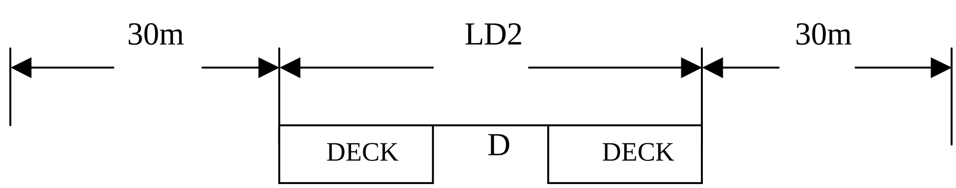
Traffic in Log Direction



Length Removed = 30 m + LD + 30m, where LD = Length of Bridge in ConnDot Bridge Log in SI Units.

Two Bridges Apart in Same Roadway

Traffic in Log Direction



Length Removed = 30 m + LD2 + 30 m,

where LD2 = Length of Deck (in SI units) from Bridge Log

D = Length in meters <60 m

length of the bridge deck plus 30m on each end of the deck to eliminate roughness associated with the leading and trailing ends of the bridge. When there are two bridges separated by less than 60m of pavement the two decks plus the intermediate pavement are considered as one and removed. All bridge information was obtained from the Connecticut State Highway Bridge Log /16/. The data were then converted to SI units. For this analysis, 2066 sections were removed from the total state highway system.

Prior results of work done in Connecticut /12/ show that the IRI value, when bridge roughness is included, is not significantly different than the overall roughness of a given roadway. In other words, bridge roughness is localized and does not detract from the overall rideability of a roadway. Working on this premise, the bridge lengths removed were grouped according to length in three classes: <100m; 100-300m; and, >300m. Table 9 presents the mean weighted IRI, Standard Deviation of the IRI and number of areas in each length group. The mean IRI is essentially the same for each length group, however the standard deviation of the IRI decreases as length increases. This implies greater process control on longer bridges, which is very reasonable.

Inspection of a tabulation of all routes with an IRI greater than 2.68 m/km, led the author to look at the influence of route length on IRI. Table 10 presents a summary of routes with IRI greater than 2.68 m/km and less than 2.68 m/km and the corresponding average length of each route for 1997 and 1999. Although correlations performed showed no significant statistical relation between route length and IRI value, the Table clearly shows that routes with greater length have a greater chance to have an IRI value less than 2.68 m/km. This is true for each year, 1997 and 1999.

<u>To assess the effect of roadway geometry</u> on IRI, two parameters were examined, roadway curvature and the grade of the route. Curve data were computed using ConnDOT software developed for this purpose. Grade data were obtained from the output of the ARAN data system.

For <u>curvature analysis</u> a sample of two interstate routes and eight lower functionally classified routes were selected. The curvature was classed in one degree/100 ft increments; i.e. 0 through 12 degrees/100 ft. Tables 11 and 12 present data for the interstate and lower functionally classified routes, respectively. Figures 13 - 15 show the data for interstate roads in graphic form.
Similarly, lower functionally classed road data are shown in Figures 16 -18. The data were then grouped by curvature: for the interstates there were two groups; <1 degree/100 ft and more than 1 degree/100 ft; (Figure 15) the lower functionally classed roads were placed in two groups; 0-3, and >3 degree100 ft (Figure 18).

One-way Analysis of Variance was performed on these data. The results are shown in Tables 13 and 14, for interstate and lower functional roads, respectively. In both cases, for interstate routes and lower functionally classified secondary roads, the analysis shows that sharper curves have significantly higher IRI values.

Table 9 **- IRI - Bridges by Length of Bridge**
1998 data, log direction only

Length(m)	Mean IRI*	Standard Deviation	# of Brg Areas
<100	2.645	1.218	1533
100 - 300	2.694	1.17	483
>300	2.654	0.721	50

* IRI-Weighted = Sum(IRI*Length of Sections)/sum(Length of Sections)

Table 10 **- Influence of Route Length on IRI Value**

	Number of Routes	Average Length of Route	Correlation	Significance
1997 Data, Without Bridges				
Routes With IRI Greater Than 2.68	174	6.69	-0.116	0.129
Routes With IRI Less Than 2.68	269	19.02	-0.128	0.036
1999 Data, Without Bridges				
Routes With IRI Greater Than 2.68	185	6.19	-0.07	0.339
Routes With IRI Less Than 2.68	257	20	-0.094	0.134

Table 11 **- Average IRI - Sections of Interstate Routes With Different Curvature**

(1999 Data Only, Including Bridges)

Curvature (degree/100ft)	**Route 84 Number of Sections**	**Average IRI**	**Route 91 Number of Sections**	**Average IRI**
1	77	2.1	67	2.12
2	31	2.14	15	2.39
3	32	2.64	8	2.69
4	17	3.21	3	2.67
5	9	2.84	4	3.04
6	3	3.2	2	3.34
7	2	2.54	1	3.89
8	2	3.82		
9	1	3.69		
10	1	3.24		
11	2	3.71		
12	1	5.17		

Note:

1= curvature with 0 - 1 degree/100 ft
2= curvature with 1 - 2 degree/100 ft
3= curvature with 2 - 3 degree/100 ft
4= curvature with 3 - 4 degree/100 ft
5= curvature with 4 - 5 degree/100 ft
6= curvature with 5 - 6 degree/100 ft
7= curvature with 6 - 7 degree/100 ft
8= curvature with 7 - 8 degree/100 ft
9= curvature with 8 - 9 degree/100 ft
10= curvature with 9 - 10 degree/100 ft
11= curvature with 10 - 11 degree/100 ft
12= curvature with 11 - 12 degree/100 ft
13=curvature with greater than 12 degree/100 ft

Table 12- **Average IRI of Sections of Lower Functional Classification Roads With Different Curvature**

(1999 Data, Bridges included)

Curvature		Route 3		Route 89		Route 99		Route 109		Route 116		Route 132		Route 149		Route 275	
(degree/100ft)		IRI	# of	IRI	# of	IRI	# of	IRI	# of	IRI	# of	IRI	# of	IRI	# of	IRI	# of
		(m/km)	Secs.	(m/km)	Secs.	(m/km)	Secs.	(m/km)	Secs.	(m/km)	Secs.	(m/km)	Secs.	(m/km)	Secs.	(m/km)	Secs.
1		2.269	10	2.337	37	2.562	15	2.626	29	1.719	11	3.258	33	1.828	43	2.137	10
2		2.404	8	2.325	9	2.73	8	3.207	11	1.839	4	3.172	12	2.034	8	3.047	6
3		2.123	5	2.309	5	2.874	5	2.854	10	1.934	5	3.858	6	1.99	8	3.235	5
4		2.572	10	2.989	18	3.438	3	2.409	15			4.059	7	2.344	3	2.701	4
5		3.191	3	3.462	3			2.373	6	2.356	1	3.503	3	2.185	5	3.693	1
6		3.883	1	3.108	5			3.174	7	1.96	1	4.379	5	1.71	6		
7		2.386	1	3.487	4			3.462	7			3.709	1	2.23	3	4.34	3
8		3.335	1	4.087	4			2.728	6	2.068	3	4.436	5	2.131	5	2.522	1
9				2.912	2			2.879	7	1.726	3	3.9	2	2.358	4	3.401	3
10				3.445	2			3.191	4	2.096	2			1.85	1		
11				5.277	2			4.246	1			3.919	3	1.881	1		
12								2.187	3	2.704	1			2.634	1		
13				4.516	8			3.392	19	1.959	2	3.588	9	2.078	19	3.251	4

1= curvature of 0 - 1 degree/100 ft
2= curvature of 1 - 2 degree/100 ft
3= curvature of 2 - 3 degree/100 ft
4= curvature of 3 - 4 degree/100 ft
5= curvature of 4 - 5 degree/100 ft
6= curvature of 5 - 6 degree/100 ft
7= curvature of 6 - 7 degree/100 ft
8= curvature of 7 - 8 degree/100 ft
9= curvature of 8 - 9 degree/100 ft
10= curvature of 9 - 10 degree/100 ft
11= curvature of 10 - 11 degree/100 ft
12= curvature of 11 - 12 degree/100 ft
13=curvature is greater than 12 degree/100ft

Figure 13 - **Average IRI vs Curvature on Interstate Roads**
(1999 Data, Rt.84, Rt.91,Bridges Included)

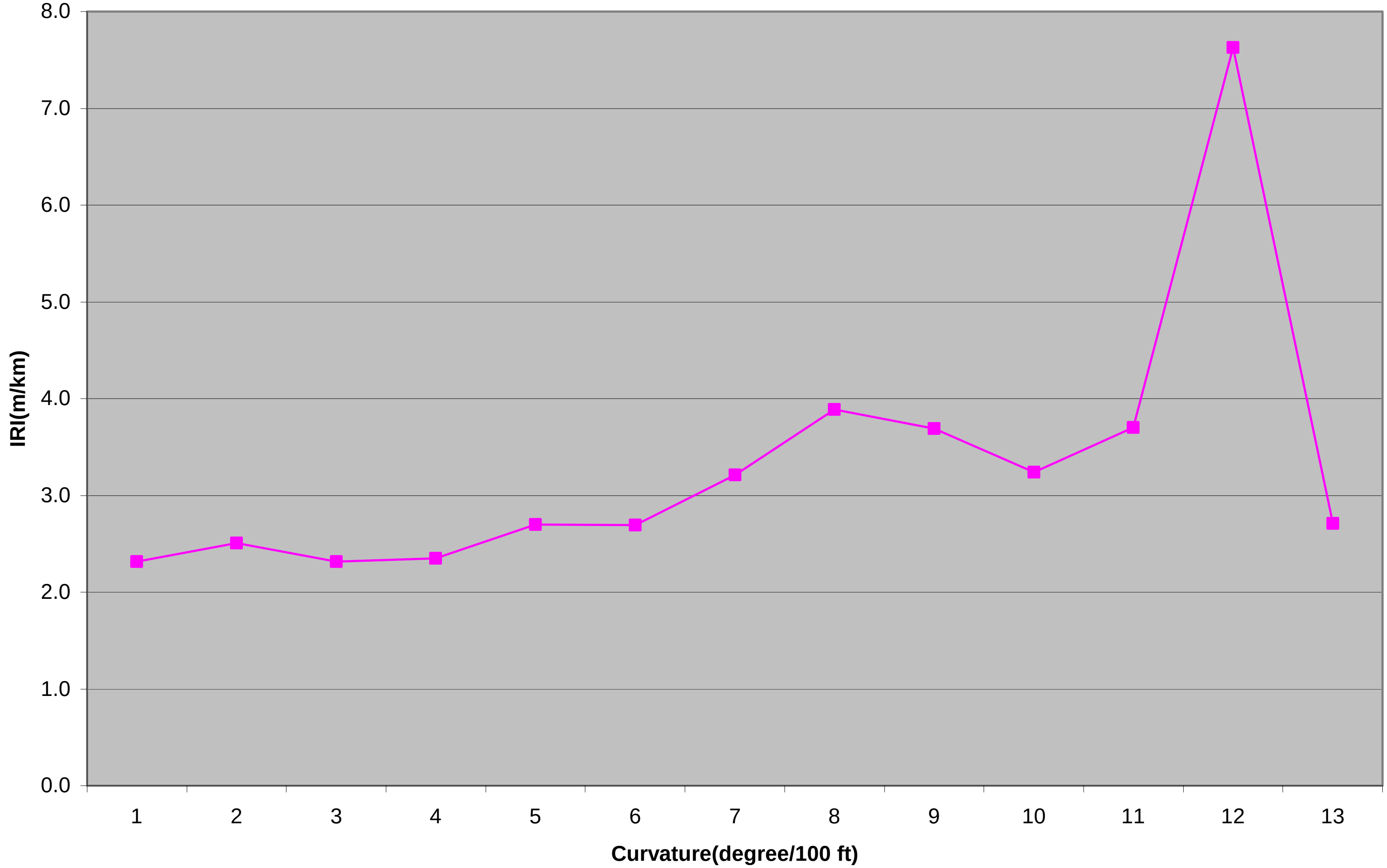


Figure 14 - **Grouping of Average IRI vs Curvature on Interstate Routes**
(1999 Data, With Bridges, Route 84 and Route 91**)**

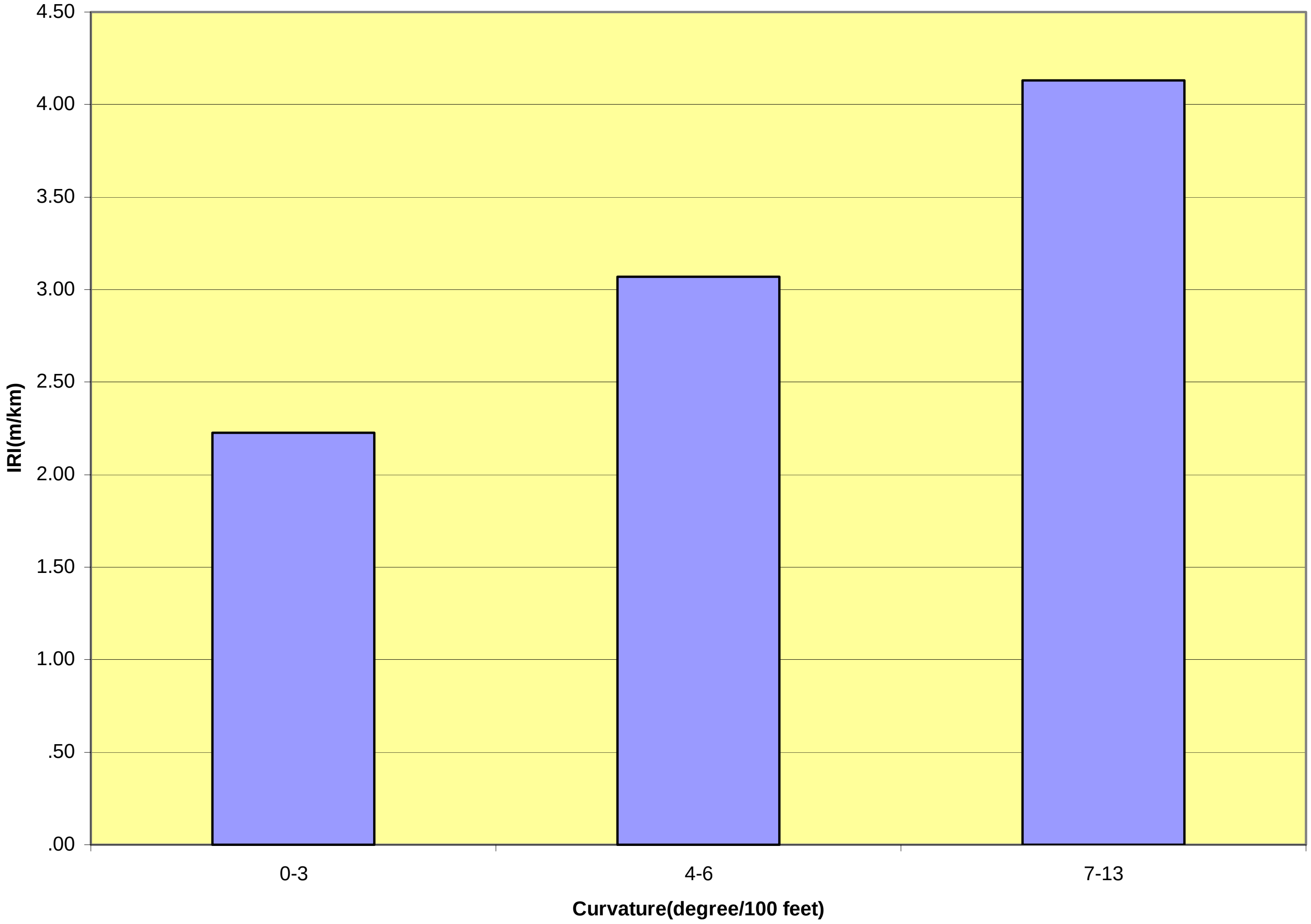


Figure 15 - **Average IRI for Curvature<= 1 Degree/ft and Curvature >1 Degree/ft on Interstate Routes**
(1999 Data, Rt. 84, Rt. 91, With Bridges)

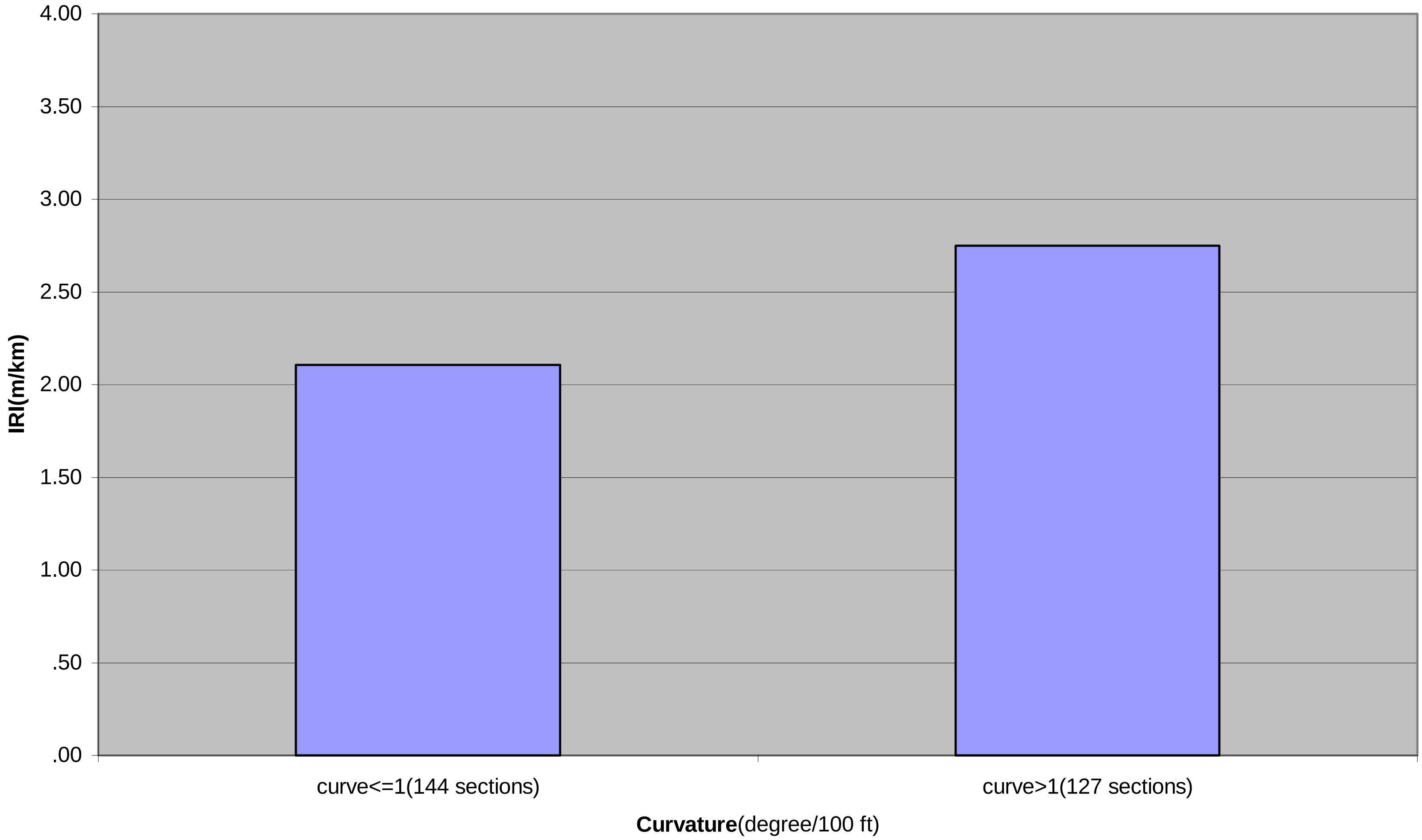


Figure 16 - **Average IRI vs Curvature for Lower Functionally Classified Roads**

(1999 Data, Rt. 3, Rt. 89, Rt. 109, Rt. 116, Rt. 132, Rt. 149, Rt. 275, Bridges Included)

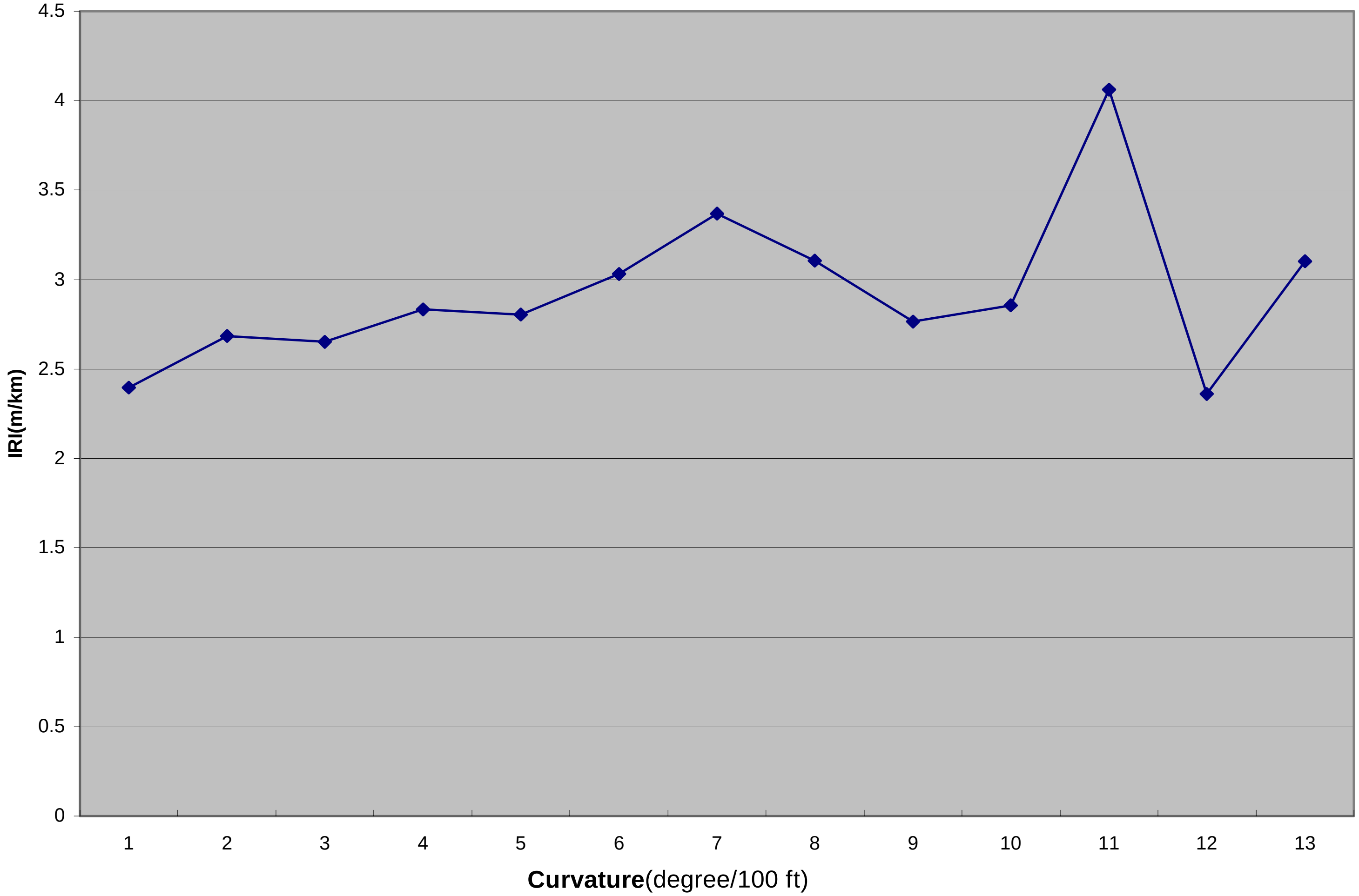


Figure 17 - **Grouping of Average IRI vs Curvature for Lower Functional Classification Roads**
(1999 Data, With Bridges, Route 3,89,99,109,116,132,149,275)

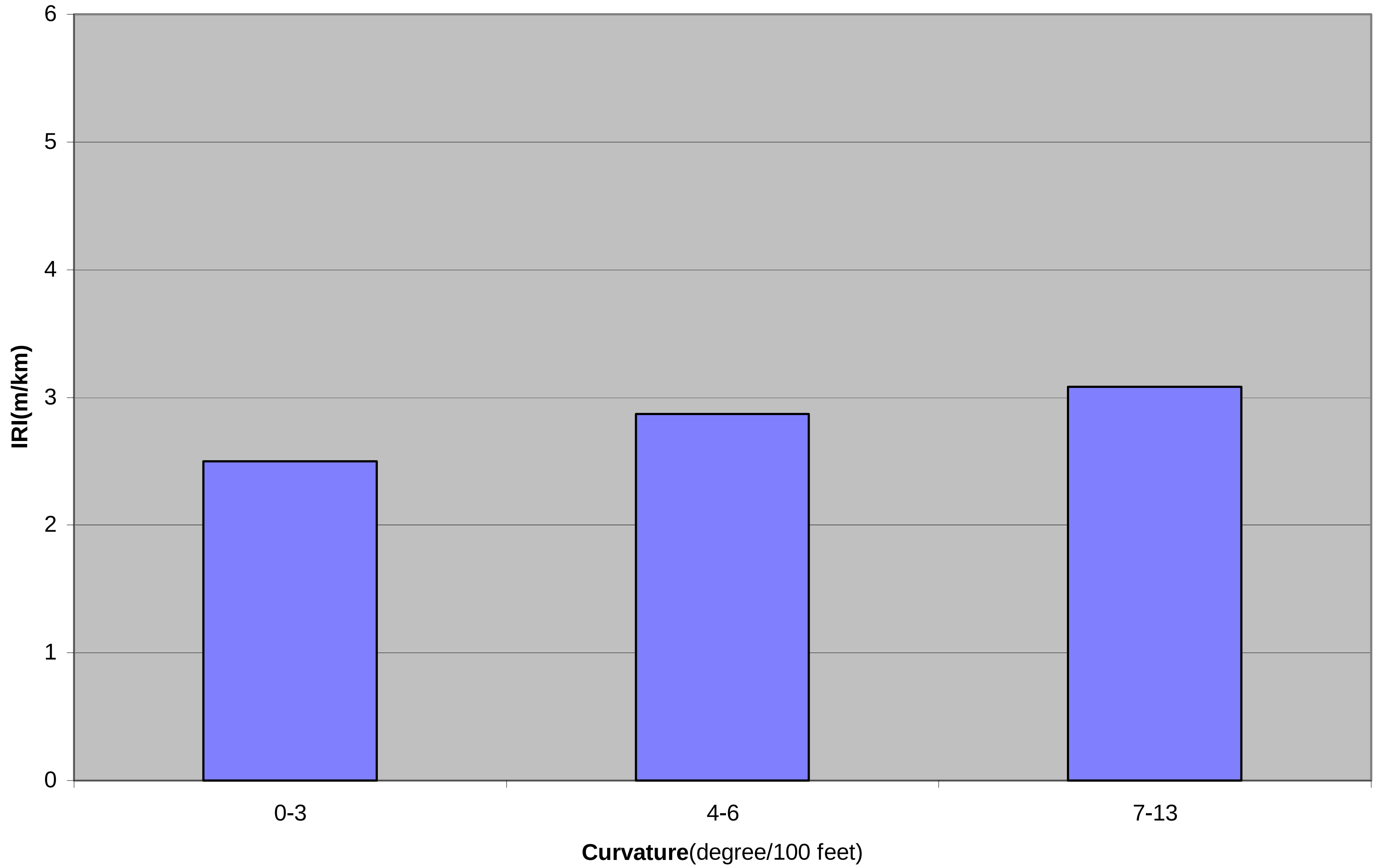


Figure 18 - **Average IRI of Lower Functional Classification Roads With Different Curvature**

(1999 Data, Route 3,Route 89, Route 99, Route 109, Route 116, Route 132, Route 149,Route 275,Bridges Included)

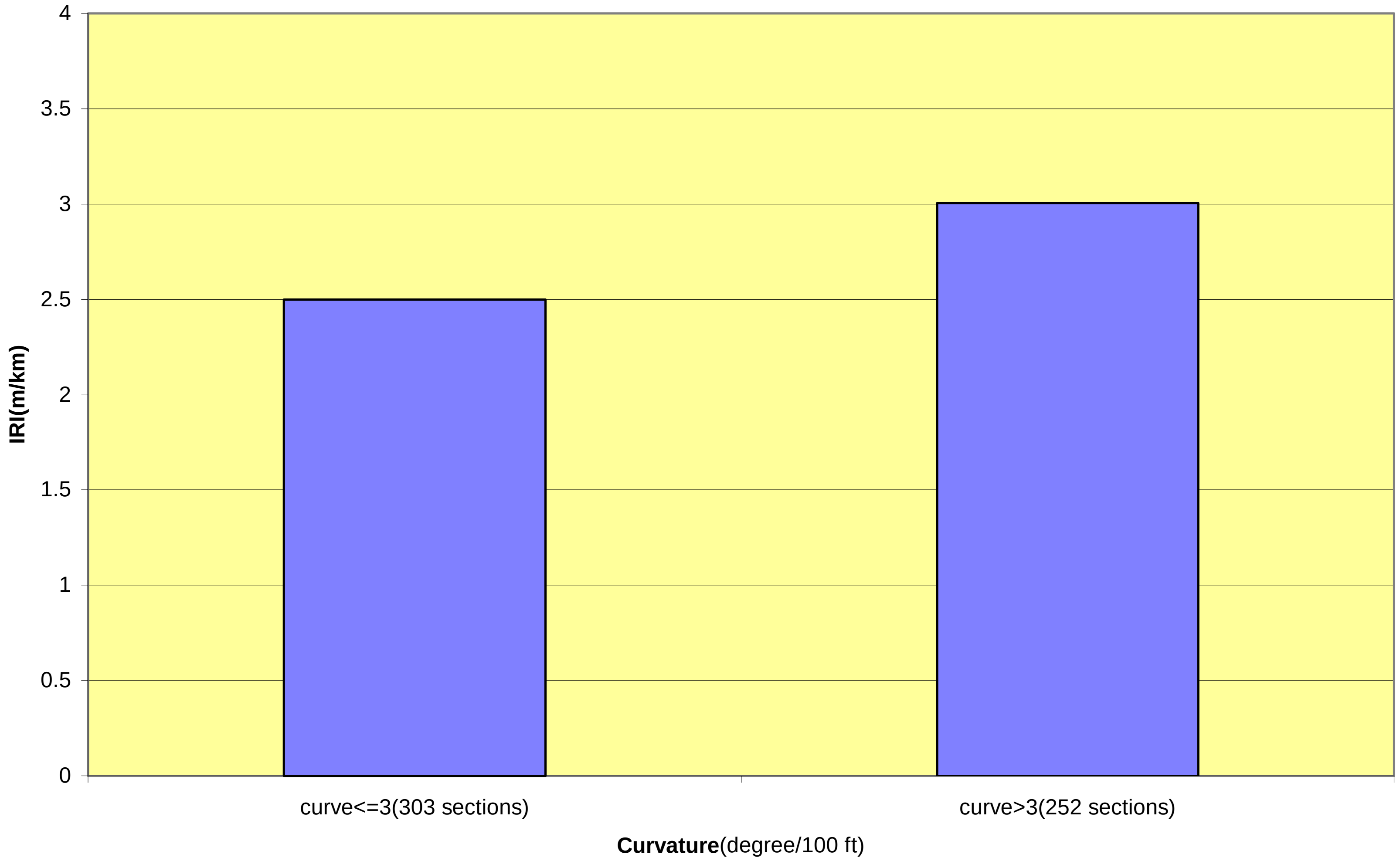


Table 13 - **One-Way ANOVA (Unequal Cell Number)-Curvature and IRI on Interstate Routes**

		Group 1: Curvature<=1 (144 sections in total)		Group 2: Curvature>1 (127 sections in total)
Mean	$\bar{X}1$	2.11	$\bar{X}2$	2.75

Hypothesis(H0): X1 = X2

ANOVA Table

Source	d.f	Sum of Square	Mean of Square	F	F Critical*	P
Curvature	1	25.11	25.11	24.38	11.2	0.10%
Error	270	279.87	1.035			

Conclusion: Mean IRI of Group 1 is different from Mean IRI of Group 2. That is, for interstate roads, sections with sharper curves tend to have higher IRI values.

Note

* F Value with degree of freedom (1, 270) at 0.1% significance level.

Table 14- **One Way ANOVA(Unequal Cell Number) for Curvature and IRI on Secondary Roads**

	Group 1: Curvature <=3		Group 2: Curvature >3	
	(303 sections in total)		(252 sections in total)	
Mean	$\bar{X}1$	2.499	$\bar{X}2$	3.005

Hypothesis(H0): X1=X2

ANOVA Table

Source	d.f	Sum of Square	Mean of Square	F	F Critical*	P
Curvature	1	35.08	35.08	29.2	11	0.10%
Error	554	673.687	1.216			

Conclusion : Mean IRI of Group 1 is different from Mean IRI of Group 2. That is, for secondary roads, sections with sharper curves tend to have higher IRI values.

* F value with degree of freedom(1, 554) at 0.1% significance level.

The ANOVA technique was applied to four routes, two interstate and two lower functional routes . The Null Hypothesis in this case is to determine if curvature affected IRI on the individual route. The same data groups were used as stated previously. In all cases, sharper curves had significantly higher IRI values. The results of these analyses are shown in Appendix 2.

The effect of grade was analyzed in a like manner. Appendix 3 summarizes the methodology details and results of the analysis conducted. The data analyzed clearly shows that grade affects IRI, the greater the road gradient the higher the value of IRI.

Roadway classification reflects different levels of design and roadway function. It was thought that various factors in the original design of the roadway might influence the relative magnitude of the measured IRI. The current classification scheme used in Connecticut is shown as Table15. The Federal classes are also presented in the Table.

In previous analyses, length of route was found to affect the measured IRI. To assess any influence of functional classification it was decided to evaluate each functional class using the number of profile points greater than or less than 2.68 m/km (170 in/mi). This value was selected to agree with the FHWA's proposed breakpoint between acceptable and unacceptable smoothness. Table 16 tabulates the results of this analysis for the state functional classification system. The reader is reminded that the profile points reflect an 8-inch length over which the vertical height variation is measured throughout the entire route.

Table 17 presents the same data for the FHWA functional classes. It is interesting to note that for both classification schemes, the higher type roads, which generally are long, have less of the route with an IRI greater than 2.68 m/km. The short collector- type routes have the highest percent of their length greater than 2.68 m/km. Appendix 1 is a tabulation of all routes with an average IRI greater than 2.68 m/km. It is for the 1999 data only and includes bridge roughness. Each route was reviewed on the Photolog to determine if there were construction activities ongoing which would affect the IRI value recorded. These data are shown in the Appendix.

The construction areas were found by inspection of ConnDOT's 1999 Photolog. The termini were estimated by finding sign locations which advise the motorist of construction or maintenance activities on the roadway. Corresponding IRI values were determined for the area under construction. No attempt was made to assess the stage of construction. Inspection of Appendix 1 shows that the IRI value in construction areas is sometimes greater than the IRI of the route but it can also be less than the IRI of the route depending on the type of work being done and the percent of completed work.

Of interest to highway administrators and engineers is the change in IRI with time. Figure 19 shows the four-year trend of each of the nine FHWA roadway classifications. The data are presented in Table 18. The same data for the Connecticut state functional classes are shown in Table 19. State data were not plotted for clarity. These data support the trend that IRI is reasonably constant with time. The greatest variation in mean IRI occurs on the collectors of unclassified routes.

Table - 15
Functional Classifications of Routes in Connecticut

Rural Code	Urban Code 5-10(1)	10-25	25-50	>50	Federal Classification
01	11	21	31	41	Interstate
---	12	22	32	42	Other Freeway or Expressway
02	13	23	33	43	Other Principal Arterial
03	14	24	34	44	Minor Arterial
---	15	25	35	45	Major Collector(Urban)
04					Major Collector(Rural)
05					Minor Collector(Rural)
06	16	26	36	46	Unclassified(Local Usage)

(1) Population in thousands

Table 16
State Functional Class vs Number of IRI Profiling Points
All Routes, 1997 Data

Functional Class	Profiling Points IRI<2.68	Profiling Points IRI>2.68	%Class>2.68
01	14011	1114	7
02	13567	2877	17
03	69192	15864	19
04	92587	50023	35
05	2945	4045	58
06	344	1064	76
11	293	6	2
13	613	137	18
14	615	600	49
15	11	6	35
23	854	378	31
24	124	31	20
25	602	307	34
33	1096	514	32
34	484	465	49
35	1076	304	22
36	21	61	74
41	30184	3290	10
42	17018	3134	16
43	48745	20578	30
44	77513	32347	29
45	6965	3129	31
46	1463	989	40

Table 17

FHWA Functional Classification

Federal Class	State Class	Profiling Points IRI<=2.68	IRI>2.68	% Class >2.68
Interstate	01,11,21,31,41	44488	4410	9
Other Expressway	12,22,32,42	17018	3134	16
Other Principal Arterial	02,13,23,33,43	64875	24484	27
Minor Arterial	03,14,24,34,44	120500	37471	24
Major Collector(Urban)	15,25,35,45	8654	3746	30
Major Collector(Rural)	04	92587	50023	35
Minor Collector (Rural Only)	05	2945	4045	58
Unclassified (Local Usage)	06	344	1064	76

[1] All Roads Included

Figure 19
Change in Average IRI with Time for FHWA Functional Classes

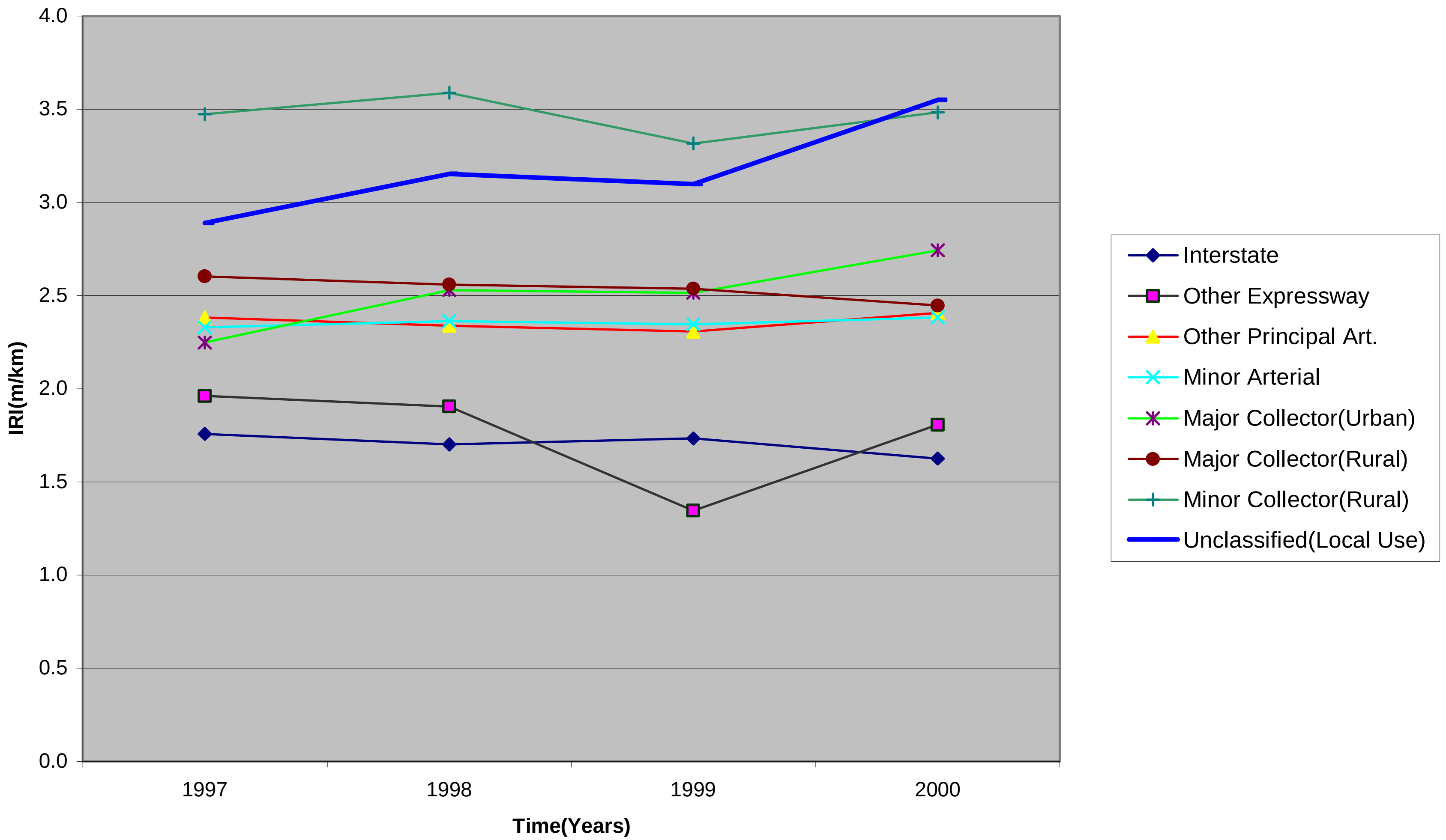


Table 18

Mean IRI and Standard Deviation of FHWA Functional Classes

(Bridges Included)

Class	Profiling Points	iri97	std97	iri98	std98	iri99	std99	iri00	std00
Interstate	55538	1.758	0.91	1.702	0.869	1.733	0.905	1.513	0.713
Other Expressway	33091	1.96	0.732	1.904	0.718	1.346	0.741	1.845	1.055
Other Principal Art.	98291	2.382	0.959	2.338	1.078	2.306	1.099	2.175	1.450
Minor Arterial	190138	2.329	1.024	2.362	1.034	2.345	1.057	2.306	1.189
Major Collector(Urban)	13219	2.247	1.084	2.529	1.09	2.514	1.155	2.282	1.195
Major Collector(Rural)	155027	2.604	1.126	2.558	1.103	2.536	1.112	2.437	1.123
Minor Collector(Rural)	7113	3.474	1.289	3.588	1.309	3.315	1.357	2.814	1.297
Unclassified(Local Use)	6243	2.889	1.21	3.153	1.25	3.099	1.246	3.392	1.471

Total Length: 5586.6km

Year	**1997**	**1998**	**1999**	**2000**
Mean IRI	2.455	2.517	2.399	2.345
Standard Deviation	1.041	1.056	1.084	1.188

Table 19

Mean IRI and Standard Deviation of State Functional Classified Roadways

(Bridges Included)

Class	Profiling Points	Profiling Points-00	iri97	Std97	iri98	std98	iri99	std99	Iri00	std00
01	16089	16089	1.612	0.730	1.530	0.663	1.586	0.688	1.447	0.630
02	20411	16156	2.057	0.860	1.933	0.843	2.061	0.876	2.080	0.970
03	80196	57274	2.112	0.867	2.108	0.853	2.125	0.898	2.037	0.937
04	155027	105127	2.652	1.126	2.558	1.103	2.536	1.112	2.437	1.133
05	7113	3807	3.474	1.289	3.588	1.309	3.315	1.357	2.814	1.297
06	1791	850	3.823	1.317	3.925	1.375	3.998	1.403	3.392	1.471
11	304	304	1.417	0.510	1.442	0.530	1.460	0.540	1.390	0.540
13	775	0	2.095	1.066	2.149	1.059	2.546	1.413	2.010	1.736
14	1246	499	3.388	1.404	3.532	1.428	2.917	1.401	2.570	1.449
15	25	25	2.897	1.400	3.000	1.310	2.240	1.180	2.110	0.955
23	1271	939	2.521	1.098	2.601	1.181	2.511	1.146	2.108	1.599
24	246	246	2.579	1.033	2.252	0.861	2.369	1.065	2.227	1.132
25	863	409	2.572	1.176	2.622	1.170	2.489	1.323	2.138	1.238
33	1657	726	2.594	1.138	2.405	1.173	2.460	1.146	2.385	1.551
34	1771	956	3.062	1.249	2.875	1.249	3.196	1.391	2.210	1.041
35	1409	1409	2.268	1.010	2.242	0.964	1.999	0.994	2.365	1.211
36	83	80	4.093	1.727	3.875	1.780	3.807	1.793	2.545	1.643
41	39145	39145	1.819	0.987	1.775	0.956	1.795	0.997	1.701	0.968
42	33091	20316	1.960	0.732	1.904	0.718	1.346	0.741	1.845	1.055
43	74177	54634	2.478	0.979	2.446	1.139	2.364	1.156	2.290	1.396
44	106679	77874	2.489	1.133	2.531	1.163	2.490	1.167	2.487	1.390
45	10922	7266	2.509	1.085	2.557	1.100	2.583	1.163	2.516	1.379
46	4369	1530	2.728	1.156	2.823	1.188	2.717	1.172	2.599	1.386

Total Length- 5586.6km

	Year	1997	1998	1999	2000
	Mean IRI	2.381	2.348	2.296	2.293
Standard	Deviation	1.019	1.033	1.054	1.132

To estimate the effect of traffic on IRI, the Panel determined that three traffic levels would be employed: 0-3,000 vpd; 3-12,000 vpd; and, greater than, 12,000 vpd. These are the grouping used by maintenance staff as criteria for roadway surface treatments. The traffic is total traffic in both directions.

Figure 20 shows the IRI, and corresponding standard deviation values for daytime HMA paving operations for the above traffic levels. The IRI is fairly constant over the four-year data period within the individual traffic levels analyzed. For the 3-12,000 vpd range the IRI is approximately thirty percent higher in the 1997-99 period, increasing in 2000 to a value greater than that for 12,000 vpd. This is unexplainable at this time.

For construction activities, the data presented in Table 7 and plotted in Figure 10 show the four-year IRI trend for HMA paving. The data reflect paving on high volumes (<12,000 vpd) roadway only. Data for low and intermediate traffic volume were not readily available. Figure 10 clearly shows the stable IRI value and corresponding standard deviation for the period 1997-2000, inclusive.

IRI of the NHS

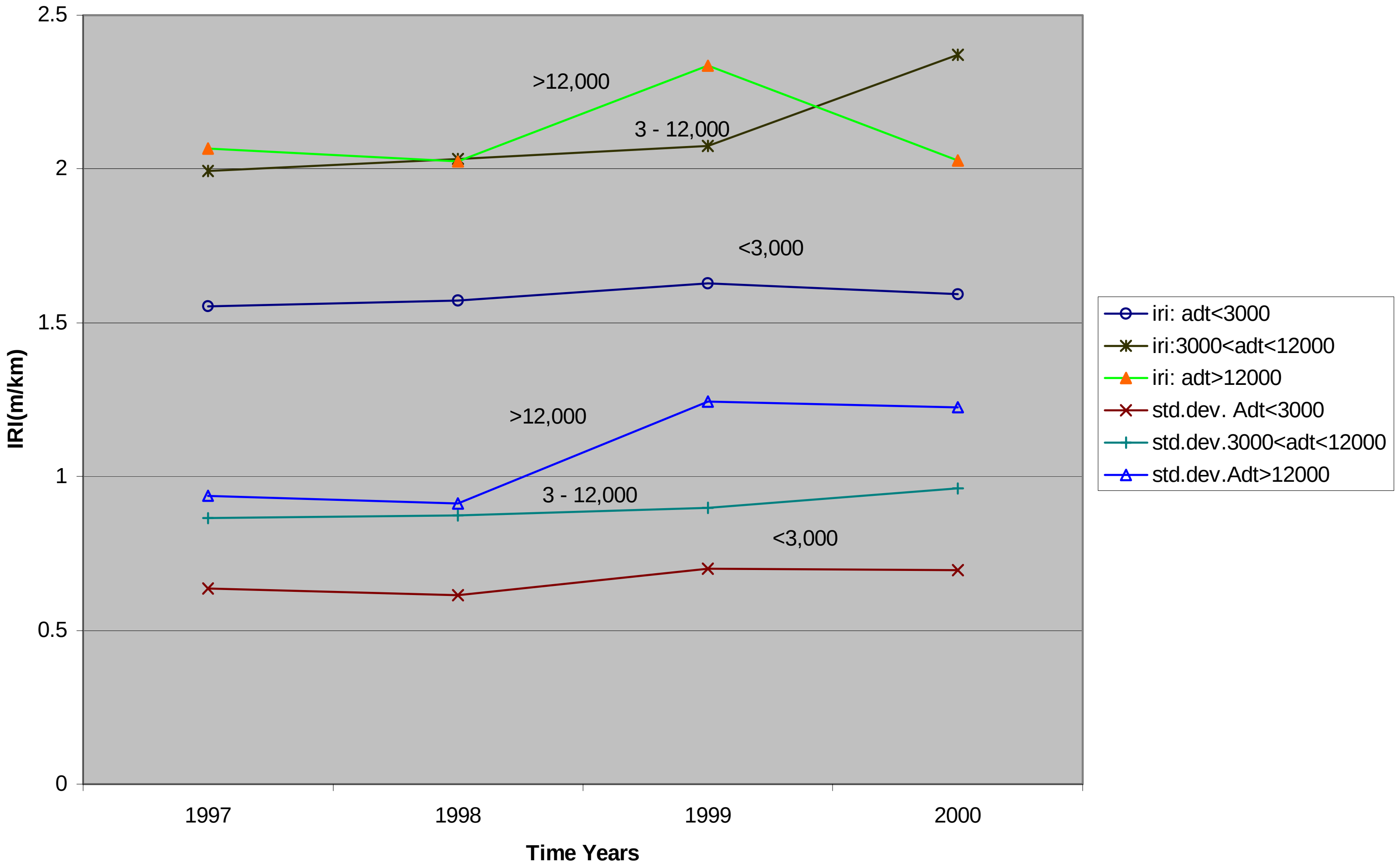
The NHS is a series of routes which are accepted by FHWA as the federal system of roadways. They purport to be the “backbone” of the total roadway network in the United States. Based on the importance of federal financing, a substantial effort was undertaken to examine the NHS in CT. Current emphasis by FHWA on quality service have prompted FHWA staff to consider setting roadway performance standards. These standards would be measured in terms of IRI measured on the NHS.

The FHWA method of computing the IRI is based on the use of IRI data supplied by the states for the FHWA Highway Performance Monitoring System (HPMS). HPMS is a statistical sample of sections on the total highway system in the United States. It includes both state and local roads. The sections vary in length and character (design and function) and are thought to be a representative sample of roads in a given state. Each state is required to provide IRI data on all NHS sections regardless of functional classification. IRI is also required for all sections functionally classified as Urban Interstate, Urban Other Freeways and Expressways, Urban Other Principal Arterial, Rural Interstate and Rural Other Principal Arterial, as well as HPMS standard sample sections classified as Rural Minor Arterial

To estimate the IRI of the NHS, FHWA staff compute an arithmetic average of the IRI data for all roads on the NHS which are included in the HPMS data set. The data used excludes bridges as the IRI is used to judge pavement rideability only.

Some interesting facts about the CT NHS System evolved. In CT, the NHS is comprised on 43 routes; the shortest is 0.27 km (Rt. 753); the longest 179.55 km (I-95). The HPMS sections thus comprise approximately a ten percent sample of the 448 routes on the CT State Highway system. Eight of the NHS routes have no HPMS standard sample sections (3,78,82,184,601,I-684,706 and 753). The data for I-684 is supplied by the New York State Department of Transportation in accordance with an

Figure 20 **- Maintenance Daytime HMA Resurfacing at Various Traffic Levels**



agreement with ConnDOT. A review of the 35 highways with HPMS standard sample sections shows that nearly half of these routes (17) have 10 or less PMS sections, of these four have only one section per route. The remaining 18 have more than 10 sections, the highest number of sections due on the two major interstate routes in CT (I-95, 84 in 1999 and I-84, 74 in 1999).

It is apparent that the FHWA method of determining the arithmetic average IRI of the NHS will be greatly influenced by the large number of HPMS sections on the high-design-type interstate and major collector routes. Prior analyses have shown that length affects the measured IRI value. To address this issue the mean IRI of a section was weighted by the length of the section. Appendix 4 contains Tables 4.1 - 4.5 which were prepared to address the issue of arithmetic versus weighted IRI. Some interesting yet somewhat inconsistent observations evolved.

Based on previous work, bridge roughness is a localized condition. There is no significant change in IRI with and without bridges if the total length of roadway is considered. Tables 4.1 and 4.2, which contain bridge roughness, show that for the same year, the arithmetic IRI is greater than the comparable weighted mean when the entire set of HPMS sections is considered.

The arithmetic IRI were the same (Table 4.3), when succeeding years were compared. If the weighted mean was used the 1997 average was slightly greater than that in 1998 (Table 4.4). Including bridge roughness, the arithmetic mean for 1998 is greater than the same value in 1997. The reverse is true when the weighted average is used, 1997 IRI is greater than the 1998 IRI (Tables 4.1 and 4.2). Table 4.5 shows the difference between the arithmetic and weighted IRI values for 1997 and 1998.

Table 20 presents the IRI data for a four year period for the NHS routes, non-NHS routes and all routes on the state highway system. Data for this table were obtained from the IRI distributions, samples of which are shown in Appendix 4, plotted for each route system. The individual IRI data per 10m of road length form these distributions. Year to year there is little difference in the data and the distribution of the data. The cumulative distributions for 1997 through 1999, inclusive, support this observation (See Appendix 4).

The most striking observation is when the reader views Table 20 vertically. The percentage of IRI data >2.68 for the NHS is approximately 10 percent, while the non-NHS routes has an IRI percentage greater than 2.68 of roughly 28 percent. Again, these values exhibit the same trend for each year shown. It is interesting to note that the only NHS routes which have an average IRI of greater than 2.68 m/km are lower functionally classed routes (see Table 21). The 1997 and 1999 data both show this trend. These data also reflect the influence of route length, the shorter routes having the highest average IRI - the 1997 data more so than the 1999 data. Route 20 for 1997 and Routes 20 and 12 in 1999 are exceptions to this trend. The trend is demonstrated dramatically in Table 22 which shows the average length and corresponding IRI for the interstate and lower functionally classified routes on the NHS.

Table 20

Percentage of Roads with IRI>2.68m/km

System		1997 With Brg	1997 Without Brg	1998 With Brg	1998 Without Brg	1999 With Brg	1999 Without Brg	2000 With Brg	2000 Without Brg
	%>2.68	10.100	10.200	9.900	8.100	10.800	9.000	13.330	11.620
NHS[1]	DIST.Mean[4]	2.060	2.020	1.700	1.610	2.640	2.280	1.830	1.800
	STD. Dev.	1.480	1.100	0.950	0.790	1.070	1.340	1.170	1.130
	%>2.68	28.400	28.000	27.900	27.700	28.400	28.200	28.170	27.310
Non-NHS[2]	DIST.Mean	2.420	2.410	2.400	2.390	3.410	2.700	2.430	2.420
	STD. Dev.	1.340	1.320	1.530	1.340	1.260	1.570	1.530	1.520
	%>2.68	31.500	31.100	30.900	30.700	28.800	28.500	24.210	23.110
All Roads[3]	DIST.Mean	2.330	2.320	2.310	2.300	2.330	2.320	2.270	2.260
	STD. Dev.	1.220	1.200	1.220	1.200	1.230	1.220	1.470	1.450

[1] % of Roads on NHS System
[2] % of Roads not on NHS
[3] % of All Roads
[4] DIST Mean- Mean of IRI Distribution

Table - 21

NHS Routes With IRI Greater Than 2.68

1997 Data, Without Bridges

Route	Functional Class	Length(km)	IRI
20	Secondary	50.78	3.021
437	Secondary	0.71	3.600
601	Secondary	0.24	8.369
753	Secondary	0.28	2.952

NHS Routes With IRI Greater Than 2.68

1999 Data, Without Bridges

Route	Functional Class	Length(km)	IRI
12	Secondary	87.78	2.755
20	Secondary	50.78	3.089
437	Secondary	0.71	3.936
753	Secondary	0.28	2.753

Table - 22

Average Length of Interstate and Secondary Roads

Functional Class	Average Length	Average IRI
Interstate	79.33	1.76
Secondary	12.97	2.56

[1] L.F.C = Lower Functional Classification

Summary of Major Findings and Conclusions

1 - Night paving operations can be performed with good or better IRI than conventional daytime operations. It is the author's opinion that experience with night operations appears to have a major influence on the smoothness of the resurfacing pavement.
2 - Bridge roughness is localized. When the total length of a route is considered, bridge roughness does not significantly affect the overall roughness of a given roadway.
3 - Roadway length affects IRI. The routes with greater lengths have lower IRI values. For bridges, length of bridges does not affect IRI significantly.
4 - Curve and grade of a roadway affect the IRI. The more curvature and grade the higher the IRI of the roadway. Both interstate and lower functionally classified routes show their trend although the interstate routes do not exhibit the same amount of increased IRI.
5 - Class of roadway does not appear to affect IRI. Rather, as stated in 4 above the length of route greatly influences the value of IRI.
6 - When considering traffic volumes selected for this project, the IRI is fairly constant over the three year period of this study. The corresponding standard deviations of the data, also reflect this trend.
7 - The FHWA process to compute the IRI of the NHS does not reflect the IRI of the total roadway system in Connecticut. The IRI of the NHS, with bridges included is approximately 90% <2.68 m/km while only 72% of all roads have an IRI <2.68 m/km.

Recommendations

The major findings and conclusions are directed at a better understanding of the IRI measurement. IRI can be employed to document the overall performance of various pavement surfaces and treatments, as long as specific pavement selections are properly located by route and cumulative mileage.

Concerning the proposed method of estimating smoothness of roadways by FHWA:

1- Bridge roughness should be included in any reported IRI data for a roadway.
2- FHWA should review their proposed method of computing the IRI of NHS. Included in their analysis should be: bridge roughness and the length of route.

REFERENCES:

1. "Highway Performance Monitoring System Reassessment," FHWA Publication No. FHWA-PL-99-001.
2. Sayers, M.W., et al., "The International Road Roughness Experiment," World Bank Technical Paper Number 45, World Bank, 1986.
3. AASHTO PP37-99, "Standard Practice for Quantifying Roughness of Pavements".
4. ASTM E867-97, "Terminology Relating to Vehicle-Pavement System".
5. ASTM E950-98, "Standard Method of Test for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference".
6. Gillespie, T.D., et al., "Calibration of Response Type Road Roughness Measuring Systems," NCHRP Report 228.
7. Gillespie, T.D. et al., "Operational Guidelines for Longitudinal Pavement Profile Measurement-FINAL REPORT" NCHRP Report 434.
8. Sayers, M.W., et al., "Guidelines for Conducting and Calibrating Road Roughness Measurements," World Bank Technical Paper Number 46, World Bank, 1996.
9. Perera, R.W., et al., "Investigation of Development of Pavement Roughness," FHWA Report No. FHWA-RD-97-147, May 1998.
10. El-Korchi, T., "Correlation Study of Ride Quality Assessment Using Pavement Profiling Devices," unpublished, June,2000.
11. Larsen, D.A., "Evaluation of Lightweight Non-Contact Profiles for Use in Quality Assurance Specifications on Pavement Smoothness," ConnDOT Report No. 2225-1-99-8, December 1999.
12. Dougan, C.E., "Smoothness of Pavements in Connecticut -Phase 1 Report, Initial Data Presentations," ConnDOT Report No. 2226-1-2000-1, June 2000.
13. McGhee, K.K., "Factors Affecting Overlay Ride Quality - 1996. Rideability Status", Virginia Transportation Research Council, Report No. VTRC98-IRI, November 1997.
14. McGhee, K.K., "Measuring, Achieving and Promoting Smoothness of Virginia's Asphalt Overlays," Virginia Transportation Research Council, Report No. VTRC 99-R19, April 1999.
15. Perara, R.W., et al., "Investigation of Development of Pavement Roughness," Report No.-FHWA-RD-97-147, May 1998.
16. "Connecticut State Highway Bridge Log" 8/22/94
17. Kleinbaum, D. G., et al, “Applied Regression Analysis and other Multivariable Methods”, Third Edition, Duxbury Press, 1997.
18. “SPSS Base 9.0 User’s Guide”, SPSS Inc., 1999.

APPENDIX 1

Tabulation of Routes
With IRI Greater Than 2.68 m/km

Routes With IRI Greater Than 2.68

1999 Data, With Bridges

Route	Length(km)	IRI		IRI of Construction Area
1A	3.11	2.708	No Construction	
12	87.78	2.783	2.8-4.6	2.13
14A	16.64	4.165	3.65-3.72	999*
14A	16.64	4.165	4.21-4.71	3.214
20	50.78	3.082	No Construction	
42	21.96	2.924	3.16-3.69	999*
43	8.15	4.675	No Construction	
45	16.57	3.151	No Construction	
74	35.78	2.743	No Construction	
89	26.18	2.902	No Construction	
102	5.56	2.699	No Construction	
103	8.52	2.770	3.38-4.03	2.359
106	22.76	2.996	1.669-2.269	3.648
108	17.79	2.832	5.0-5.15	3.645
108	17.79	2.832	12.26-12.80	3.255
113	13.07	2.755	No Construction	
124	15.37	2.813	0.39-1.39	2.298
125	2.01	5.430	No Construction	
126	9.78	4.066	No Construction	
127	10.95	2.795	0.86-0.9	999*
130	13.23	3.206	No Construction	
132	17.64	3.587	No Construction	
136	32.82	2.867	No Construction	
137	15.01	2.688	0.35-0.47	4.078
140	36.27	2.740	3.68-4.05	2.398
150	14.55	2.857	No Construction	
152	5.38	2.772	No Construction	
155	3.57	2.889	No Construction	
156	36.58	3.223	No Construction	
162	16.72	2.911	No Construction	
171	33.40	2.972	No Construction	
174	5.13	2.782	No Construction	
178	11.20	2.973	No Construction	
181	12.63	3.957	No Construction	
182	6.12	4.265	No Construction	
182A	3.36	4.164	No Construction	
183	30.74	3.256	No Construction	
192	5.63	2.936	No Construction	
197	17.68	2.741	No Construction	
199	7.44	3.937	0.29-2.79	3.175
200	3.04	2.884	No Construction	
214	11.73	2.797	No Construction	

216	4.50	3.460	No Construction	
220	9.29	3.003	No Construction	
222	13.01	4.095	No Construction	
234	11.19	3.682	No Construction	
243	10.85	2.786	No Construction	
263	10.07	3.887	No Construction	
272	28.90	3.204	1.93-8.9	3.641
275	6.69	2.961	No Construction	
316	9.74	2.705	No Construction	
319	4.55	3.600	2.89-3.00	3.023
320	11.36	3.598	No Construction	
337	7.94	2.695	No Construction	
341	25.76	2.952	No Construction	
361	5.72	3.880	No Construction	
364	7.35	3.263	No Construction	
404	1.33	2.917	No Construction	
405	0.73	2.937	No Construction	
422	0.51	3.086	No Construction	
423	0.49	3.049	No Construction	
424	1.38	3.485	No Construction	
429	1.06	3.304	No Construction	
431	3.84	4.832	No Construction	
432	0.88	4.936	No Construction	
433	2.10	3.001	No Construction	
434	16.32	4.001	No Construction	
435	0.33	6.078	No Construction	
437	0.71	3.739	0.13-0.58	3.899
438	4.66	4.808	No Construction	
439	0.91	4.751	No Construction	
449	1.75	2.896	No Construction	
453	0.52	3.168	No Construction	
454	3.06	4.678	No Construction	
478	9.84	4.160	No Construction	
479	0.40	3.962	No Construction	
480	1.26	5.982	No Construction	
481	0.44	3.701	No Construction	
482	6.59	5.052	No Construction	
483	0.79	3.994	No Construction	
485	1.90	2.887	No Construction	
486	1.73	2.978	No Construction	
487	6.85	3.035	0.19-0.23	999*
488	1.45	5.119	No Construction	
489	0.29	4.838	No Construction	
493	0.57	5.821	No Construction	
500	0.86	2.953	No Construction	
502	10.16	3.065	No Construction	
503	1.04	3.316	No Construction	
505	0.84	2.952	No Construction	
510	4.12	2.705	No Construction	

511	0.63	2.799	No Construction	
516	0.31	3.808	No Construction	
517	2.02	2.916	No Construction	
518	0.74	2.807	No Construction	
524	0.50	2.741	No Construction	
527	3.30	2.759	No Construction	
528	4.32	3.394	No Construction	
529	2.13	3.338	0.44-0.48	5.043
530	0.93	3.404	0.02-0.4	3.101
531	2.35	3.048	No Construction	
532	0.70	2.783	No Information	*
533	6.52	3.339	No Construction	
534	7.25	2.863	No Construction	
535	0.36	5.293	No Construction	
536	2.47	2.792	2.07-2.12	3.148
536	2.47	2.792	2.35-2.46	999*
540	2.32	2.763	No Construction	
542	0.48	3.410	No Construction	
545	0.25	3.927	No Construction	
549	1.93	3.182	No Construction	
555	2.10	3.435	No Construction	
565	2.75	3.007	No Construction	
598	1.21	3.476	No Construction	
600	1.08	3.756	No Construction	
603	5.70	2.699	No Construction	
607	4.08	3.031	No Construction	
608	6.99	2.773	No Construction	
609	1.57	3.567	No Construction	
610	3.46	3.070	No Construction	
617	1.36	3.159	No Construction	
618	1.11	3.865	No Construction	
620	0.49	2.794	No Construction	
626	0.42	3.238	No Construction	
628	0.56	2.852	No Construction	
629	0.41	2.898	No Construction	
630	0.58	3.668	No Construction	
631	0.30	3.085	No Construction	
640	0.27	4.328	No Construction	
642	3.56	2.906	0.05-0.329	3.541
660	2.64	3.608	No Construction	
664	9.17	3.350	No Construction	
700	2.81	6.637	No Construction	
703	0.31	3.406	No Construction	
705	4.31	2.839	No Construction	
706	1.30	2.963	No Construction	
708	0.53	4.648	No Information	*
709	0.48	3.874	No Construction	
710	0.51	3.347	No Construction	
711	1.30	3.024	No Construction	

712	0.38	3.879	No Construction	
713	0.45	2.916	No Construction	
714	8.17	2.698	No Construction	
718	0.45	2.815	No Construction	
719	3.27	3.706	No Information	*
723	0.26	3.745	No Construction	
725	0.13	4.456	No Construction	
726	0.20	2.826	No Construction	
728	1.40	2.916	No Construction	
729	0.94	2.994	No Construction	
731	0.53	3.954	No Construction	
734	0.94	3.225	No Construction	
735	0.35	3.172	No Construction	
736	5.84	2.894	No Construction	
737	2.43	3.827	No Construction	
740	5.26	2.767	No Information	*
741	0.17	2.698	No Construction	
742	1.15	4.291	No Construction	
745	1.94	3.708	No Construction	
749	0.33	4.110	No Construction	
753	0.28	2.753	No Construction	
811	0.18	4.096	No Construction	
812	0.20	3.685	No Construction	
813	1.12	3.585	No Construction	
819	5.09	3.908	No Information	*
820	0.60	5.782	No Construction	
821	0.59	5.705	No Construction	
822	5.82	3.218	No Construction	
824	0.48	2.894	No Construction	
827	5.56	4.576	No Construction	
832	0.52	3.292	No Construction	
833	2.01	3.570	No Construction	
834	0.23	4.930	No Construction	
835	1.63	2.929	No Construction	
836	0.20	3.210	No Construction	
839	1.36	2.760	No Construction	
841	0.25	3.376	No Construction	
849	0.34	3.197	No Construction	
850	0.33	3.395	No Construction	
853	0.64	5.550	No Construction	
855	2.44	2.736	No Construction	
860	1.70	2.816	No Information	*
867	1.93	2.997	No Construction	
907	0.18	2.870	No Construction	
910	0.05	3.539	No Construction	
914	0.12	3.190	No Construction	
918	0.26	3.494	No Construction	

* 999: Data are not available.

APPENDIX 2

For Curvature, Methodology Employed and
Summary of Analysis of Variance (ANOVA) Conducted
On Individual Interstate and
Lower Functionally Classified Roads

Method of Analyzing The Relationship Between Curvature and IRI on Interstate and Lower Functionally Classified Routes

For Individual Roads

1) For Rt. 44, Rt. 89, I-84 and I-91, the average IRI value was calculated every 160 meters, and total curvature in each 160m section was computed using ConnDOT software.

2) For Rt. 44, the first 100 sections were used as a sample. For Rt. 89 and I-91, 100 sections were randomly sampled. For Rt. 84, 178 sections were sampled at random. (Note that for observational studies, a sample size of 100 is appropriate to ensure the power.) Extremely large IRI values were deleted from the sample by inspection from the data sets.

3) Curvature was divided into 13 categories, and the IRI values of each road plotted as a function of curvature. By observation, the trend of IRI values plotted has similar pattern on all of the four routes.

4) From the samples it was determined that for lower functionally classed roads, the median curvature is 3, but for interstate roads, the median value is 1. Therefore, for interstate roads, curvature values are classified into two groups: the group in which curvatures are not greater than 1, and the group in which curvatures are greater than 1. For lower functionally classified, curvature values are classified into two groups also: the group in which curvatures are not greater than 3, and the group in which curvatures are greater than 3.

5) The mean of these two groups for each road were analyzed using One-Way

ANOVA.

Null Hypothesis:

H01:For Rt. 44, the mean IRI value of the group with sharper curves is not different from that of the group with flatter curves.

H02: For Rt. 89, the mean IRI value of the group with sharper curves is not different from that of the group with flatter curves.

H03: For I-84, the mean IRI value of the group with sharper curves is not different from that of the group with flatter curves.

H04: For I-91, the mean IRI value of the group with sharper curves is not different from that of the group with flatter curves.

Finding: For individual roads, Rt. 44, Rt. 89, I-84, and I-91, respectively, sharper curves have higher IRI values than flatter curves.

For Interstate and Lower Functionally Classified Roads Using Combined Samples

Interstate Roads

1) The samples derived from I-84 and I-91 were combined and then plotted vs. curvature. The pattern is similar with individual Interstate routes.

2) The combined sample was then divided into two groups: a group in which curvature is not greater than 1, and a group in which curvature is greater than 1.

3) The mean of these two groups was analyzed using One-Way ANOVA.

Null Hypothesis:

HO: For interstate roads, the mean IRI value of the group with sharper curves is not different from that of the group with flatter curves.

Finding: For interstate roads (sample composed of data from I-91 and I-84), sharper curves have higher IRI values than flatter curves.

Lower Functionally Classified Roads

1) Eight lower class routes which have a substantial number of curves and are relatively short (the range of length is from 6.7 km to 33.6 km) were selected. They are Rt 3, Rt 89, Rt 99, Rt 109, Rt 116, Rt 132, Rt 149, Rt 275. For each road the average IRI value was calculated every 160 meters, and total curvature calculated in each 160m section.

2) The sections from all of the roads were combined to form a sample of 555.

3) The combined sample was divided into two groups: a group in which curvature is not greater than 3, and a group in which curvature is greater than 3.

4) The mean of these two groups was analyzed using One-Way ANOVA.

Null Hypothesis:

HO: For lower functionally classified roads, the mean IRI value of the group with sharper curves is not different from that of the group with flatter curves.

Finding:

For Lower Functionally Classified roads, sharper curves have higher IRI values than flatter curves.

Table 2.1

Average IRI of Sections of Lower Functionally Classified Roads With Different Curvature

(1999 Data, Combined Sample, Bridges Included)

Curvature (degree/100ft)	IRI(m/km)	# of Sections.
1	2.395	188
2	2.686	66
3	2.653	49
4	2.835	59
5	2.804	22
6	3.030	24
7	3.369	19
8	3.104	25
9	2.791	21
10	2.855	9
11	4.063	7
12	2.380	5
13	3.103	61

1= curvature of 0 - 1 degree/100 ft
2= curvature of 1 - 2 degree/100 ft
3= curvature of 2 - 3 degree/100 ft
4= curvature of 3 - 4 degree/100 ft
5= curvature of 4 - 5 degree/100 ft
6= curvature of 5 - 6 degree/100 ft
7= curvature of 6 - 7 degree/100 ft
8= curvature of 7 - 8 degree/100 ft
9= curvature of 8 - 9 degree/100 ft
10= curvature of 9 - 10 degree/100 ft
11= curvature of 10 - 11 degree/100 ft
12= curvature of 11 - 12 degree/100 ft
13=curvature is greater than 12 degree/100ft

Table 2.2- **One Way ANOVA(Unequal Cell Number) for Curvature and IRI on Rt. 91**

Group 1: Curvature <=1 (67 sections in total)

Group 2: Curvature >1 (33 sections in total)

Mean $\bar{X}1$ 2.091 $\bar{X}2$ 2.67

Hypothesis(H0): $\bar{X}1 = \bar{X}2$

ANOVA Table

Source	d.f	Sum of Square	Mean of Square	F	F critical*	P
Curvature	1	6.737	6.737	9.89	8.24	0.50%
Error	99	67.42	0.681			

Conclusion: Mean IRI of Group 1 is different from Mean IRI of Group 2. That is, on Rt. 91, sections with sharper curves tend to have higher IRI values.

* F critical: F value with degree of freedom (1,99) at 0.1% significant value.

Figure 2.1-**Average IRI vs Curvature on Interstate Roads**
(1999 Data, Route 91, With Bridges)

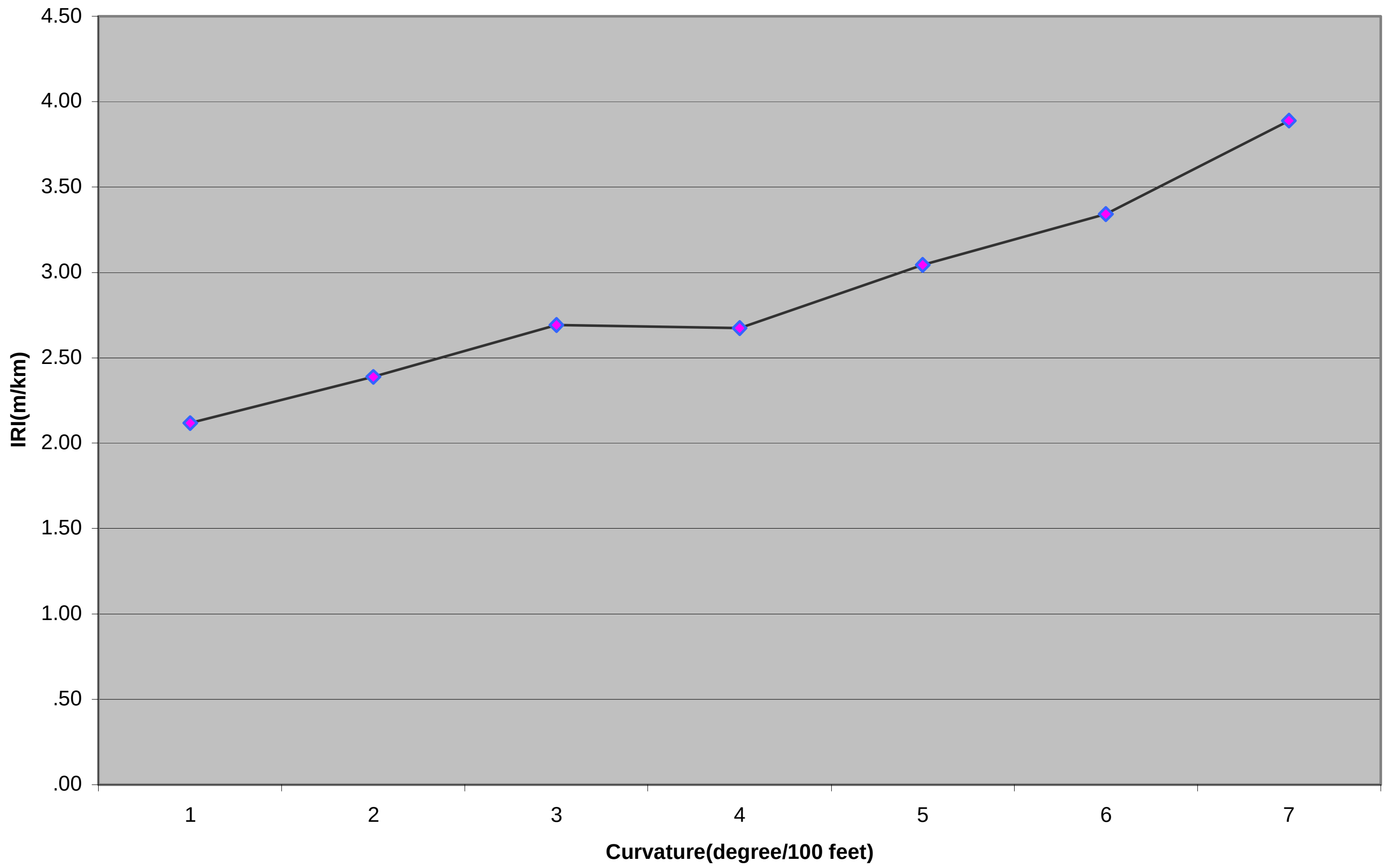


Figure 2.2-**Average IRI vs Curvature on Interstate Roads**
(1999 Data, Rt. 91, With Bridges)

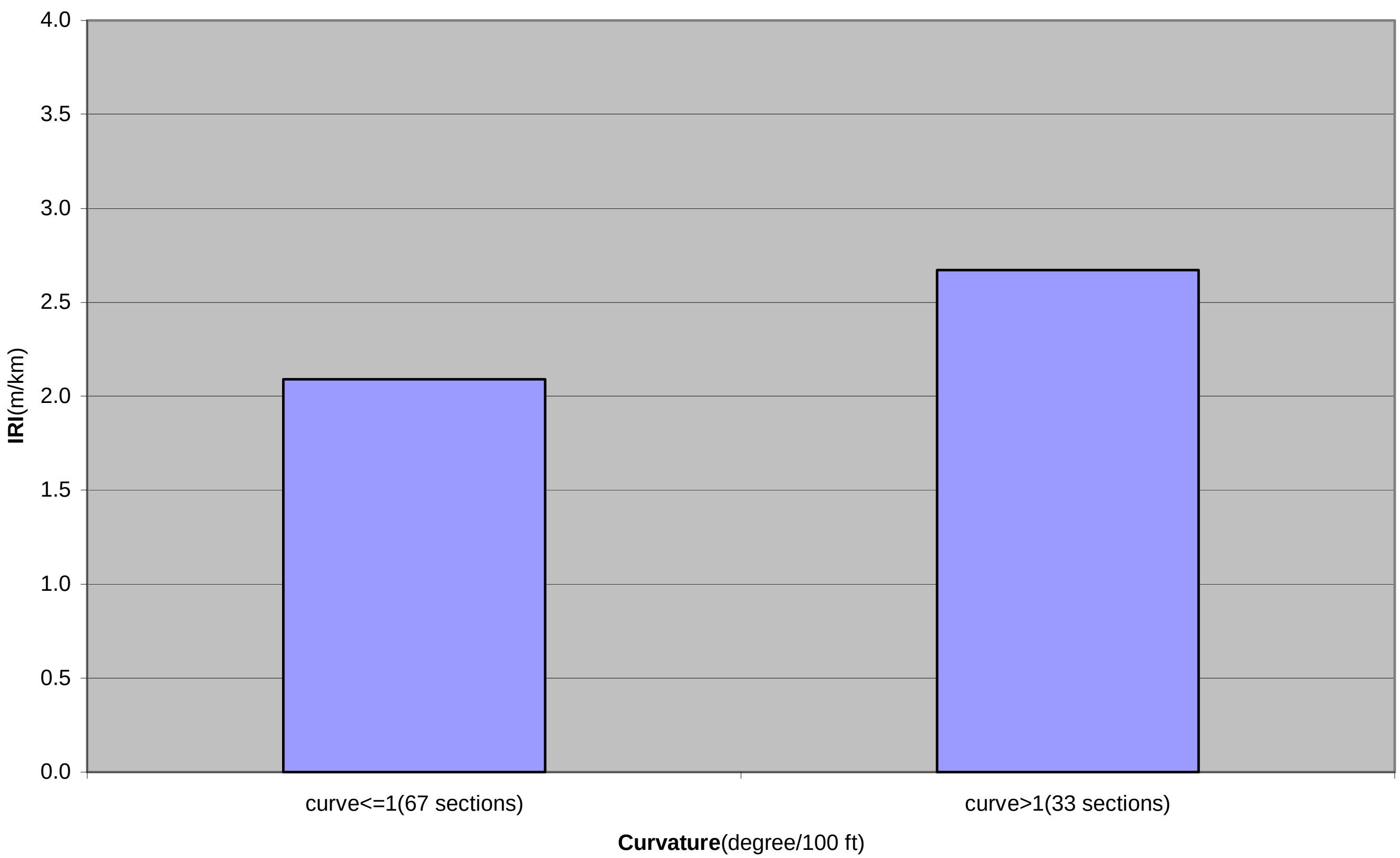


Table 2.3**-One Way ANOVA (Unequal Cell Number) for Curvature and IRI on Rt. 84**

		Group 1: Curvature <=1 (77 sections in total)		Group 2: Curvature >1 (94 sections in total)
Mean	$\bar{X}1$	2.101	$\bar{X}2$	2.753

Hypothesis(H0): X1=X2

ANOVA Table

Source	d.f	Sum of Square	Mean of Square	F	F Critical*	P
Curvature	1	17.02	17.02	14.29	11.2	0.10%
Error	170	202.34	1.19			

Conclusion: Mean IRI of Group 1 is different from Mean IRI of Group 2. That is, on Rt. 84, sections with sharper curves tend to have higher IRI values.

* F Critical: F value with degree of freedom(1,200) at 0.1% significant level.

Figure 2.3 - **Average IRI vs Curvature on Interstate Roads**
(1999 Data, Route 84, With Bridges)

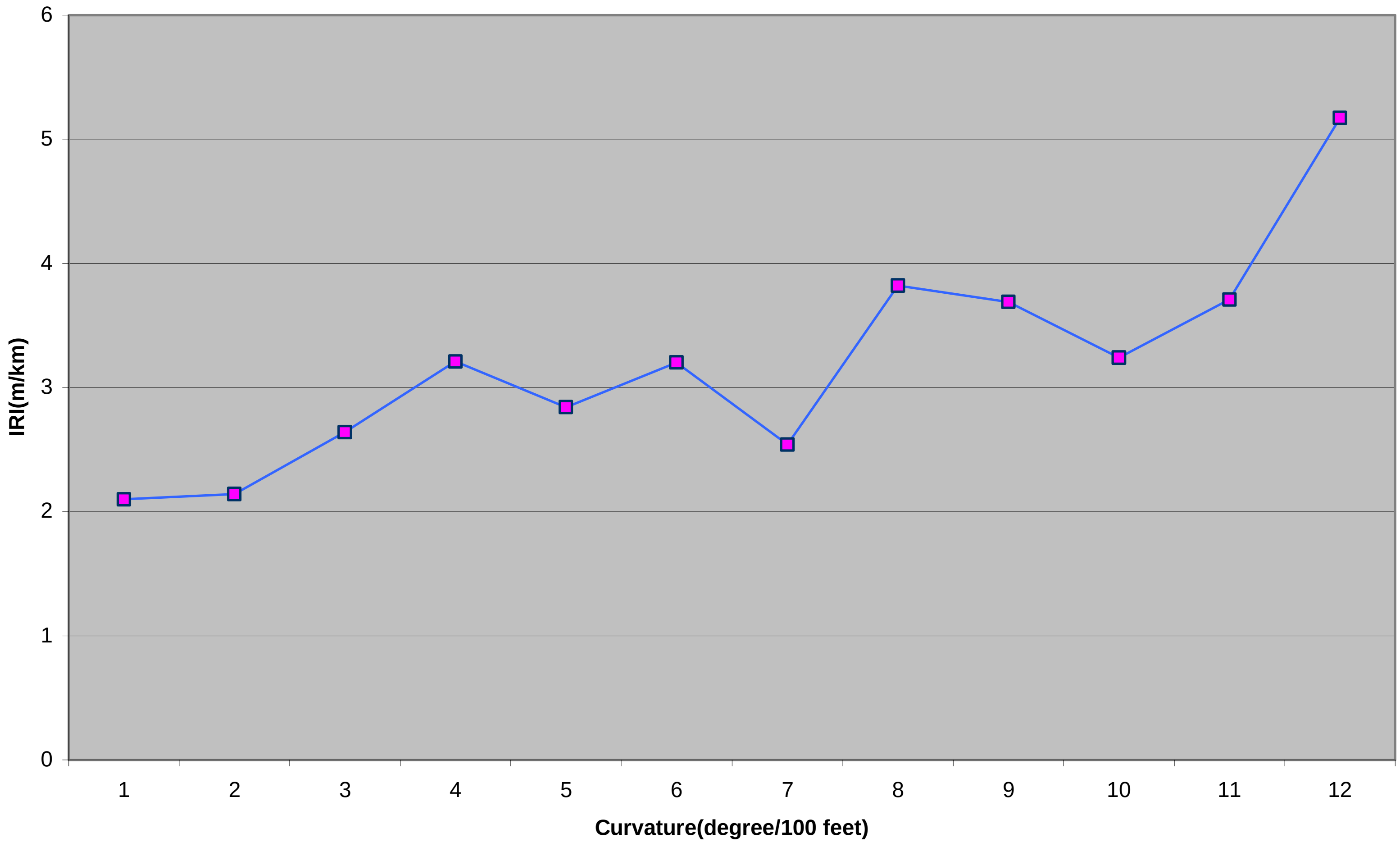


Figure 2.4-**Average IRI vs Curvature on Interstate Roads**
(1999 Data, Rt.84, With Bridges)

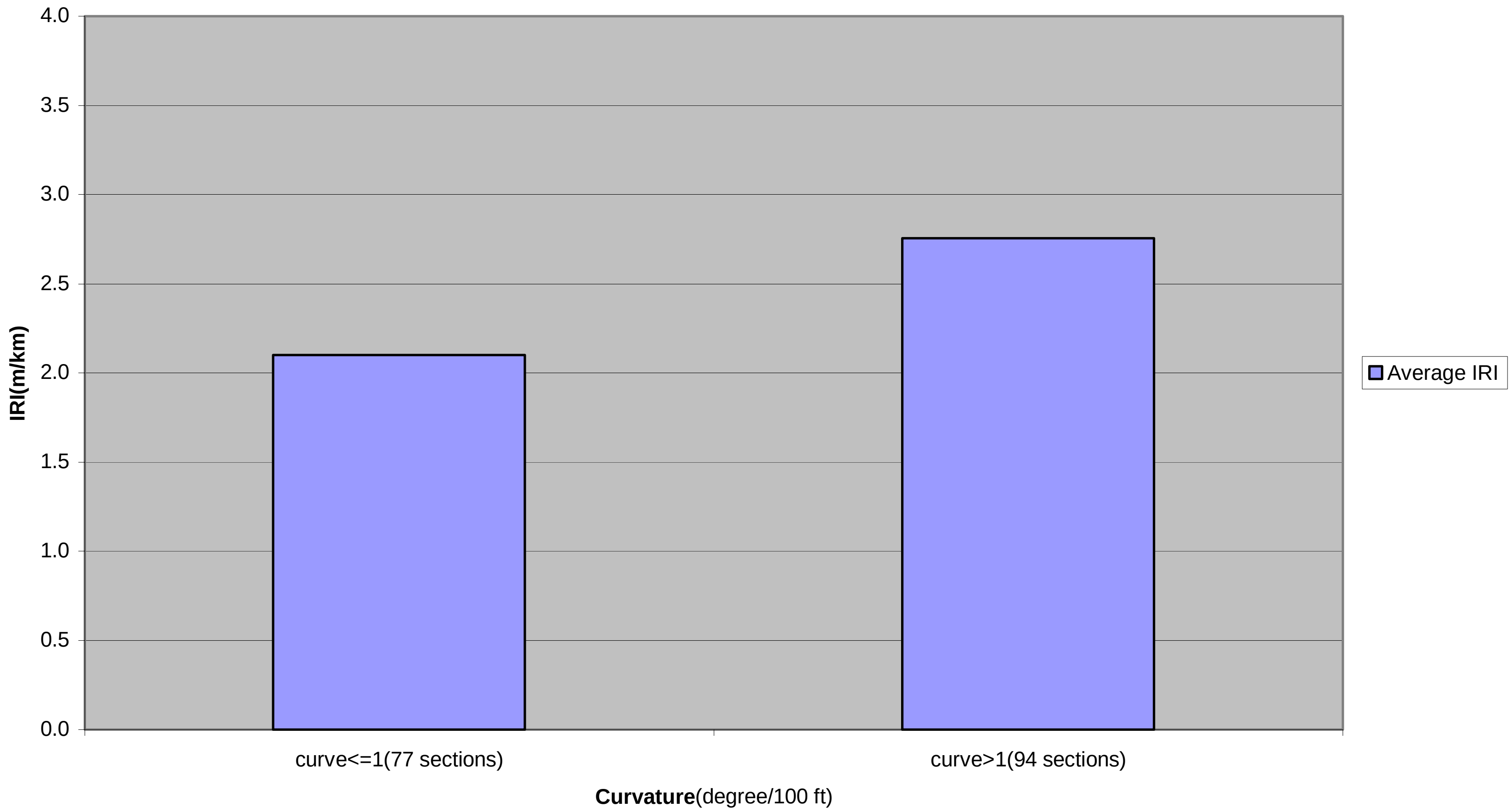


Table 2.4 **- One Way ANOVA(Unequal Cell Number) for Curvature and IRI on Rt. 89**

	Group 1: Curvature <=3 (51 sections in total)		Group 2: Curvature>3 (44 sections in total)	
Mean	$\bar{X}1$	2.332	$\bar{X}2$	3.487

Hypothesis(H0): $\bar{X}1 = \bar{X}2$

ANOVA Table

Source	d.f	Sum of Square	Mean of Square	F	P
Curvature	1	30.51	30.51	36.06	0.10%
Error	94	79.51	0.846		

Conclusion: Mean IRI of Group 1 is different from Mean IRI of Group 2. That is, on Rt. 89, sections with sharper curves tend to have higher IRI values.

Figure 2.5-**Average IRI vs Curvature on Lower Functionally Classified Roads**
(1999 Data, Route 89, With Bridges)

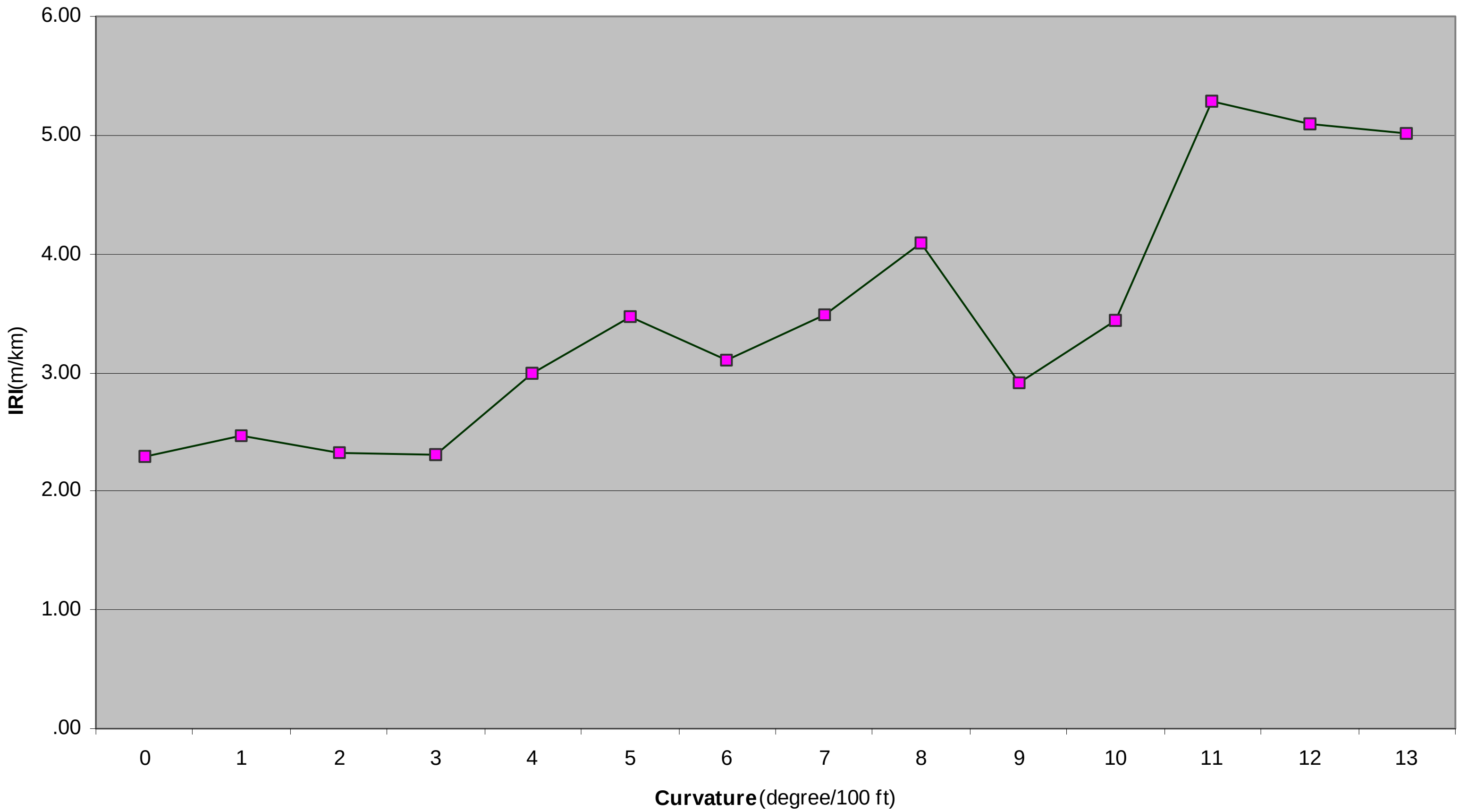


Figure 2.6 - **Average IRI vs Curvature on Lower Functionally Classified Roads**
(1999 Data, Route 89, With Bridges)

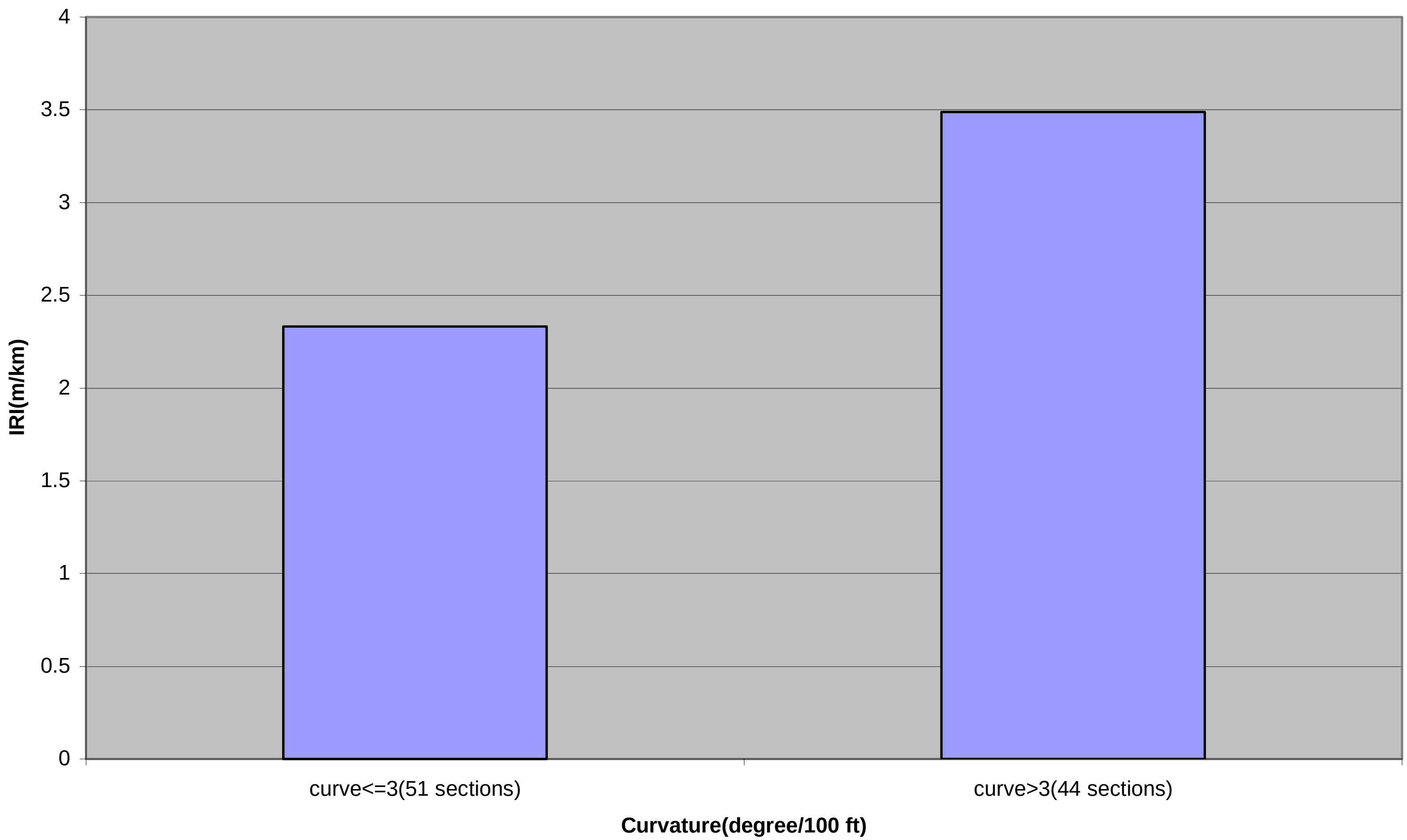


Table 2.5 **One Way ANOVA(Unequal Cell Number) for Curvature and IRI on Rt. 44.**

	Group 1: Curvature<=3		Group 2: Curvature>3	
	(50 sections in total)		(49 sections in total)	
Mean	$\bar{X}1$	1.966	$\bar{X}2$	2.259

Hypothesis(H0): $\bar{X}1 = \bar{X}2$

ANOVA Table

Source	d.f	Sum of Square	Mean of Square	F	P
Curvature	1	2.083	2.083	5.92	2.50%
Error	98	34.58	0.353		

Conclusion: Mean IRI of Group 1 is different from Mean IRI of Group 2. That is, on Rt. 44, sections with sharper curves tend to have higher IRI values.

Figure 2.7 - **Average IRI vs Curvature on Lower Functionally Classified Roads**
(1999 Data, Route 44,With Bridges)

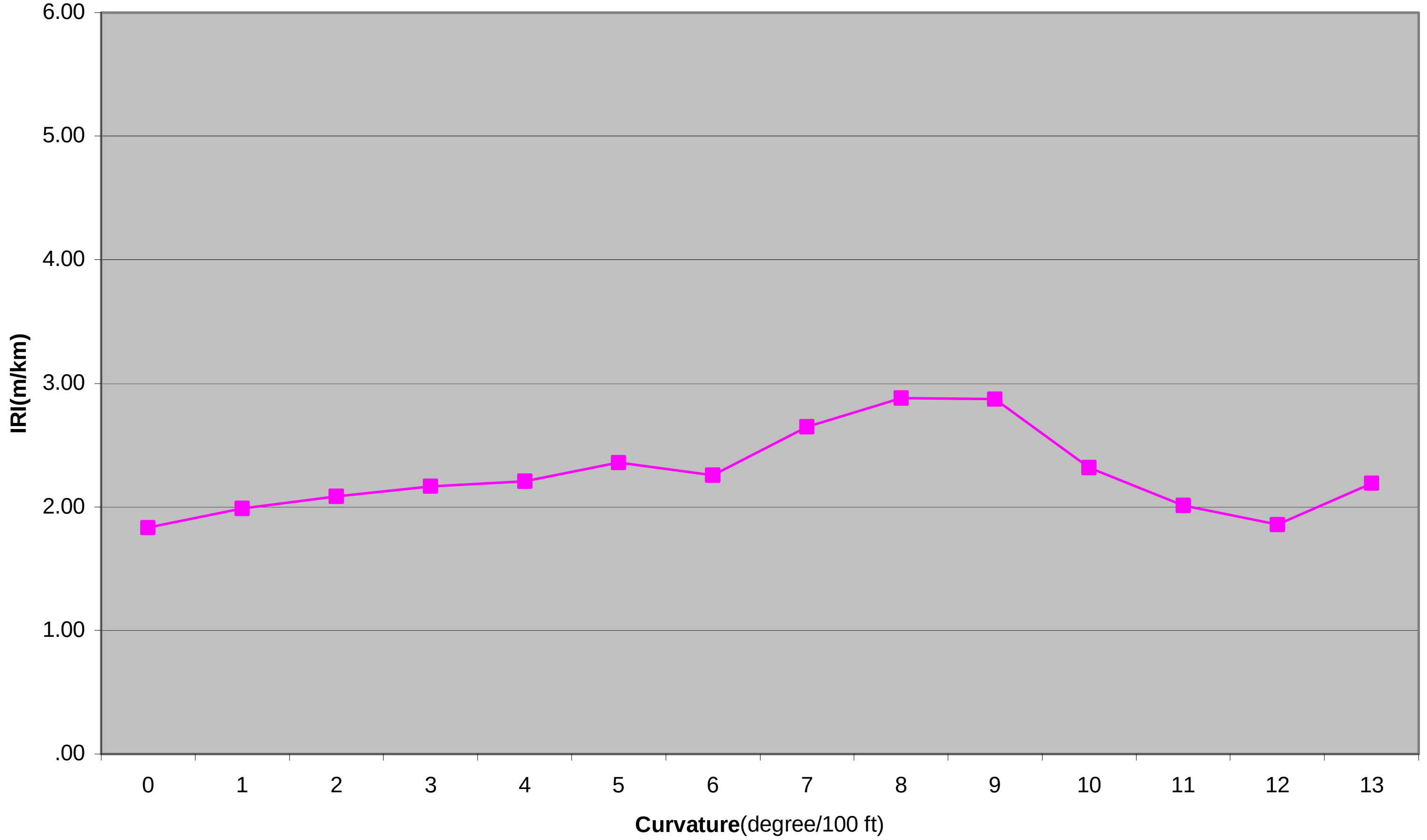
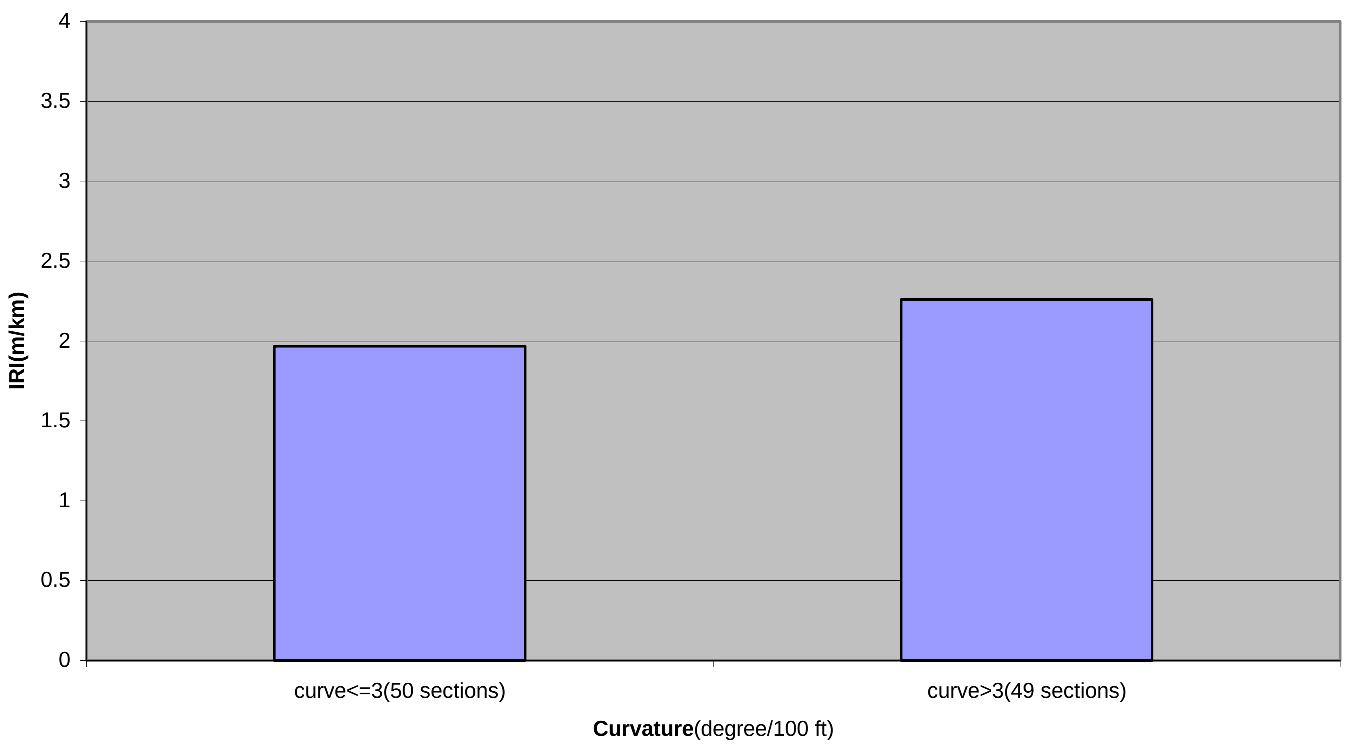


Figure 2.8 - **Average IRI vs Curvature on Lower Functionally Classified Roads**
(1999 Data, Route 44, With Bridges)



Appendix 3

For Grade Methodology Employed and
Summary of Analysis of Variance (ANOVA)
Conducted on Interstate Routes and
Lower Functionally Classified Roads

Method of Analyzing the Effect on IRI and of Roadway Grade

Objective:

1) To determine the effect of Grade on IRI measurements.

2) To define any trend or pattern of IRI vs Roadway gradient.

Hypothesis

For a given road section, the Mean IRI value of this section is related to its grade value.

Methodology

1) Study unit

Gradient values and IRI values are collected at 10m intervals; therefore, 10m road sections are used as the basic study unit. The IRI values on each 10m section, together with corresponding grade values are studied as dependent and independent variables, respectively.

2) Sampling method and sample size

Stratified sampling method is used - several lower functionally classified roads were selected from which samples are drawn and combined together to represent the lower design standard for these roads. Separately, samples are drawn from I-84 and I-91 to represent each route. These two samples are combined to represent both interstate roads. SPSS [187] was employed to assure random samples for each road.

As a check on sample size, the Pearson Correlation Method was employed on three samples (500, 1000, and 1500 units) from I-84 and I-91. The following table presents the results of three draws from the total data set. For Pearson, the smaller r-value (correlation between IRI and grade) and the lower P (significance) the higher the confidence that the sample elected represents a reasonable correlation for the data set analyzed.

Sample Size	**First Draw**	**Second Draw**	**Third Draw**
500	r=0.03	r=0.07	r=0.025
	P=0.95	P=0.138	P=0.583
1000	r=0.033	r=0.033	r=0.034
	P=0.29	P=0.29	P=0.27
1500	r=0.061	r=0.055	r=0.063
	P=0.018	P=0.032	P=0.014

Based on the results of the Pearson analysis, it is concluded that when the sample size is 1500, P value is consistent and significant at 5% level. Therefore we decided to use a sample size of 1500-1000 units. **Note that this sample size of grade study is consistent with Curvature study, in which the minimum sample size is 100 units (each unit is 160 meter long road sections). In both studies, minimum sample size totals up to 15 km to 20 km long.**

3) Statistical tools

For each sample, the sample was divided into 2 groups: group 1, units lower than the sample median, and group 2, using units greater than the sample median. The mean IRI value of the two

groups are evaluated using One-Way ANOVA (Unequal Cell Number) to test if these two mean IRI values are different.

Conclusion:

1) For I-84 and I-91 combined, road sections with higher absolute grade values tend to have higher IRI values.

2) For I-84 and I-91, respectively, road sections with higher absolute grade values tend to have higher IRI values.

3) Routes 3, 116, 275, and 268 combined, road sections with higher absolute grade values tend to have higher IRI values.

Table 3.1 - **One Way ANOVA(Unequal Cell Number) for Grade and IRI on Interstate Roads**

(1999 Data, Rt. 84, Rt. 91, With Bridges)

Group 1: -1<grade<1			Group 2: -3.5<=grade<=-1, or 1<=grade<=3.5		
1.57	1.49	2.33	2.25	0.95	1.46
1.76	2.12	1.49	1.04	1.24	3
1.86	1.31	1.53	1.3	1.14	1.95
1.16	1.54	2.41	0.88	0.7	2.03
1.09	1.01	2.02	1.79	1.65	0.91
1.57	1.57	2.04	1.39	1.59	1.21
1.61	2.09	1.85	1.78	1.01	2.93
1.79	2.35	1.37	1.32	0.9	3.62
	…			…	
(835 sample sections in total)			(1165 sample sections in total)		

Mean $\bar{X}1$ 1.84 $\bar{X}2$ 2.07

Hypothesis(H0): $\bar{X}1 = \bar{X}2$

ANOVA Table

Source	d.f	Sum of Square	Mean of Sqaure	F	F Critical	P
Grade	1	25.76	25.76	18.19	11.2	0.10%
Error	1999	2831.45	1.416			

Conclusion: The mean IRI value of Group 2, which has greater grade values, is significantly greater than that of Group 1, which has lower grade values. This means that roads sections with high grades tend to have higher IRI values.

Table 3.2

Grade and IRI on Interstate Roads

(1999 Data, 2000 Points, With Bridges)

Grade	IRI(m/km)	# of Points
0	1.94	295
1	1.86	855
2	2.15	300
3	2.05	550

0 - -0.5<=grade<0.5
1 - 0.5<=grade<1.5, or -1.5<=grade<-0.5
2 - 1.5<=grade<2.5, or -2.5<=grade<-1.5
3 - 2.5<=grade<3.5, or -3.5<=grade<-2.5

Correlations

		Grade	IRI
Grade	Corr.	1	0.061
	Sig. (2-tailed)	.	0.006
	N	2000	2000
IRI	Corr.	0.061	1
	Sig. (2-tailed)	0.006	.
	N	2000	2000

The correlation between IRI and Grade is 0.061, which is significant at 0.01 level.

Figure 3.1 - **Average IRI vs Grade on Interstate Roads**
(1999 Data, Rt. 84 and Rt.91, With Bridges)

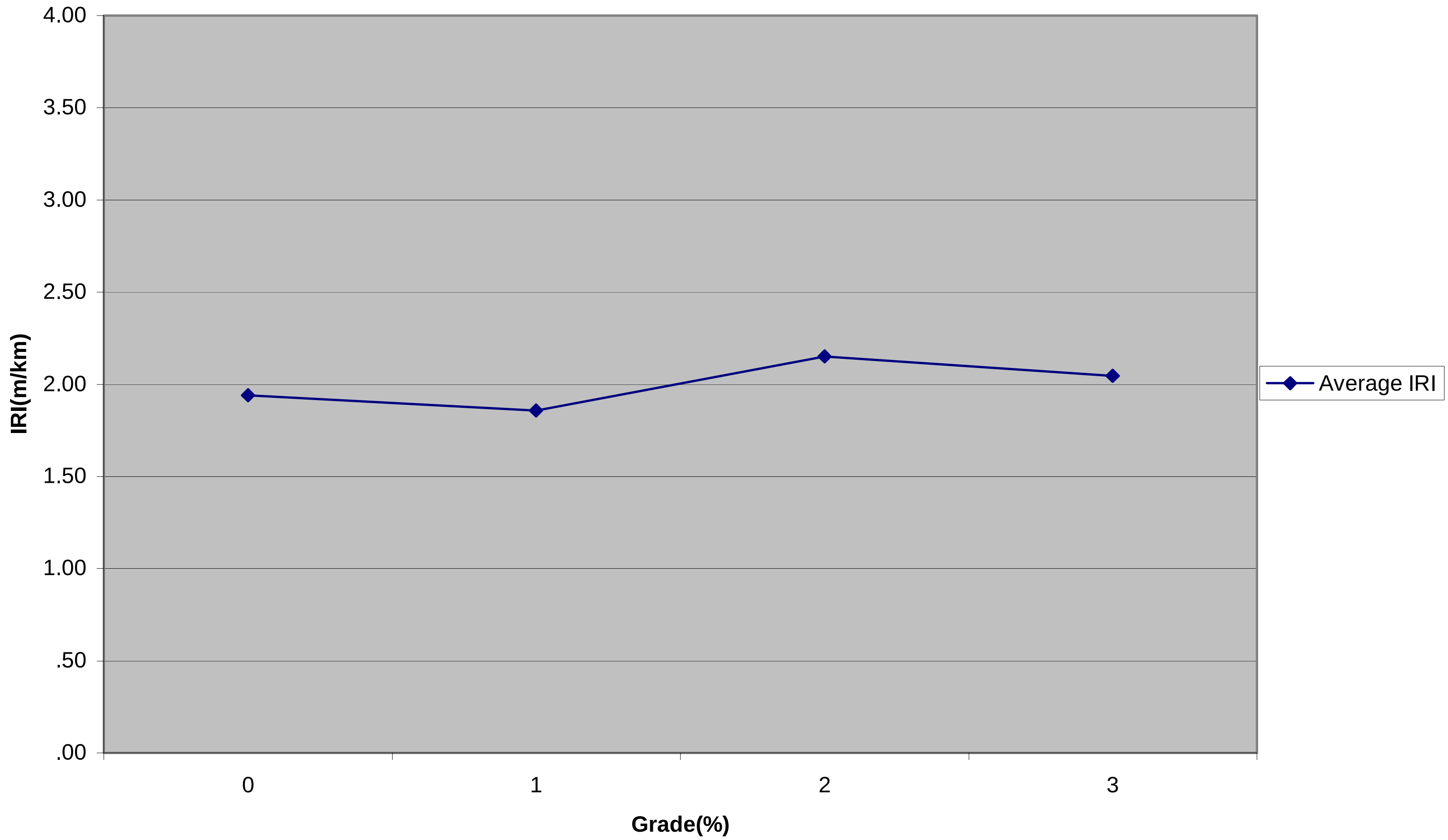


Figure 3.2 - **Average IRI vs Grade on Interstate Roads**
(1999 Data, Rt. 84, Rt. 91, 2000 Sample Sections, With Bridges)

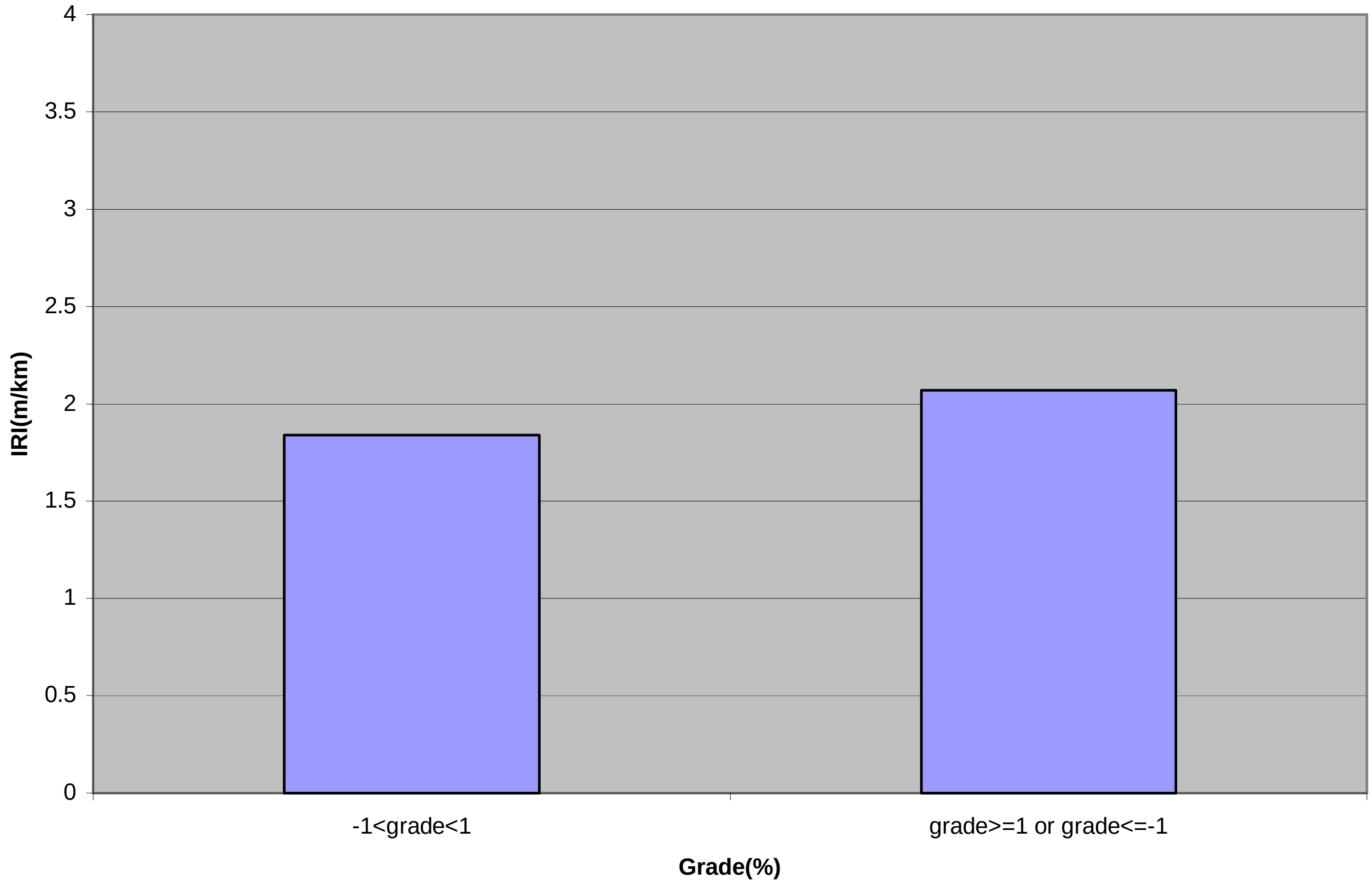


Table 3.3 – One Way ANOVA(Unequal Cell Number) for Grade and IRI on Lower Functionally Classified Roads
(1999 Data, Rt. 3, Rt. 116, Rt. 275, Rt. 268, With Bridges)

	Group 1: -1.5<=Grade <1.5 (1795 points in total)		Group 2: Grade<-1.5 or Grade>=1.5 (1760 points in total)	
Mean	$\bar{X}1$	2.31	$\bar{X}2$	2.64

Hypothesis(H0): $\bar{X}1 = \bar{X}2$

ANOVA Table

Source	d.f	Sum of Square	Mean of Square	F	F Critical*	P
Grade	1	96.78	96.78	60.52	11.2	0.10%
Error	3554	5686.32	1.599			

Conclusion: Mean IRI of Group 2 is significantly greater than Mean IRI of Group 1. That is, section with greater grades tend to have higher IRI values. Therefore, H0 is rejected.

* F value with degree of freedom(1,200), at 0.5% significant level

Table 3.4 - **Correlation Analysis of Grade and IRI**

		IRI	GRADE
IRI	Pearson Correlation	1	0.202
	Sig.(2-tailed)		0
	N	3570	3570
GRADE	Pearson Correlation	0.202	1
	Sig.(2-tailed)	0	
	N	3570	3570

N is the sample size which is 3570. The correlation between GRADE and IRI is 0.202, which is significant at 0.01 level. This suggests that for the whole population of lower functionally classified roads in Connecticut, IRI is significantly related to grade, which is true at 99% confidence.

Table 3.5

Grade and IRI on Lower Functionally Classified Roads

(1999 Data,Rt.3, Rt.116, Rt.275, Rt.268, With Brides)

Grade(%)	IRI(m/km)	# of Points
0	2.35	608
1	2.29	1152
2	2.33	559
3	2.59	550
4	2.83	228
5	2.86	192
6	2.74	151
7	2.92	46
8	4.47	14
9	3.91	21
10	3.76	34

Grade		
0	-	-0.5<=grade<0.5
1	-	0.5<=grade<1.5, or -1.5<=grade<-0.5
2	-	1.5<=grade<2.5, or -2.5<=grade<-1.5
3	-	2.5<=grade<3.5, or -3.5<=grade<-2.5
4	-	3.5<=grade<4.5, or -4.5<=grade<-3.5
5	-	4.5<=grade<5.5, or -5.5<=grade<-4.5
6	-	5.5<=grade<6.5, or -6.5<=grade<-5.5
7	-	6.5<=grade<7.5, or -7.5<=grade<-6.5
8	-	7.5<=grade<8.5, or -8.5<=grade<-7.5
9	-	8.5<=grade<9.5, or -9.5<=grade<-8.5
10	-	9.5<=grade, or grade <-9.5

Figure 3.3 - **Average IRI vs Grade on Lower Functionally Classified Roads**
(1999 Data, Rt.3,Rt.116, Rt. 275,Rt. 268, With Bridges)

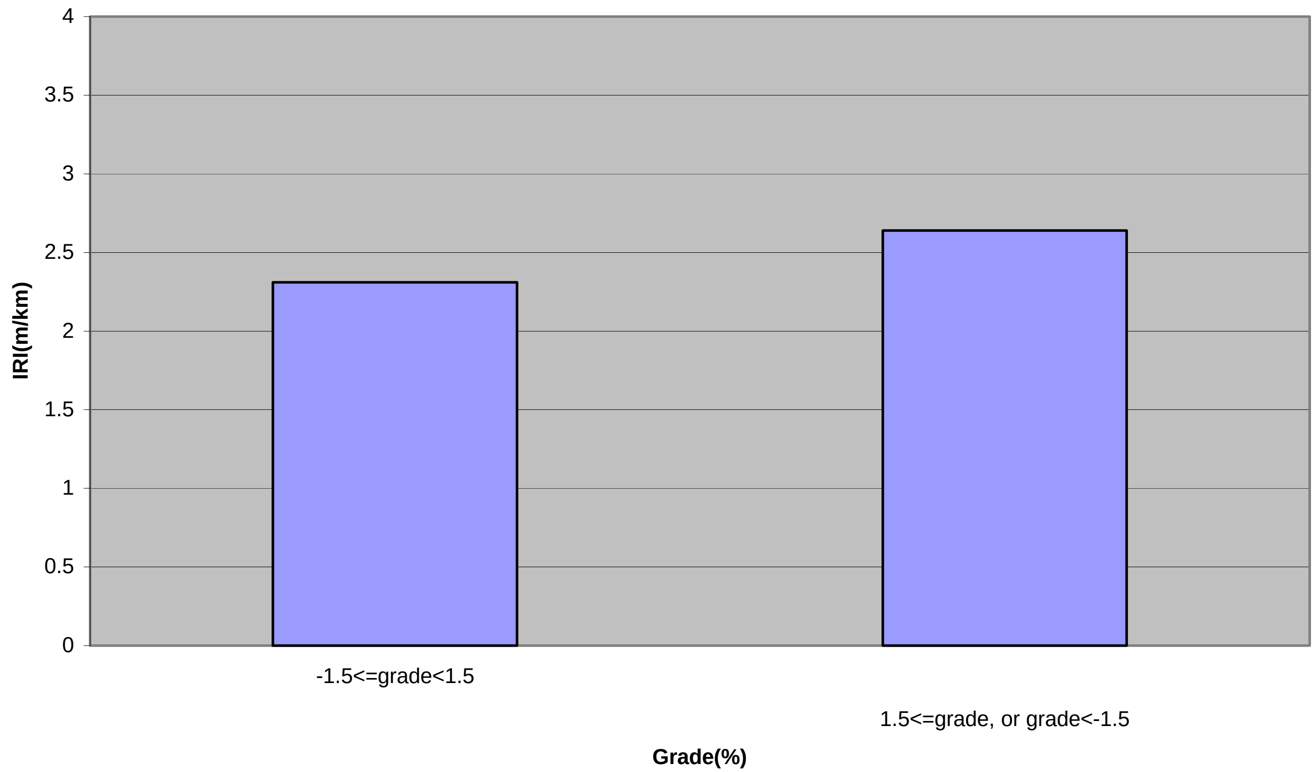
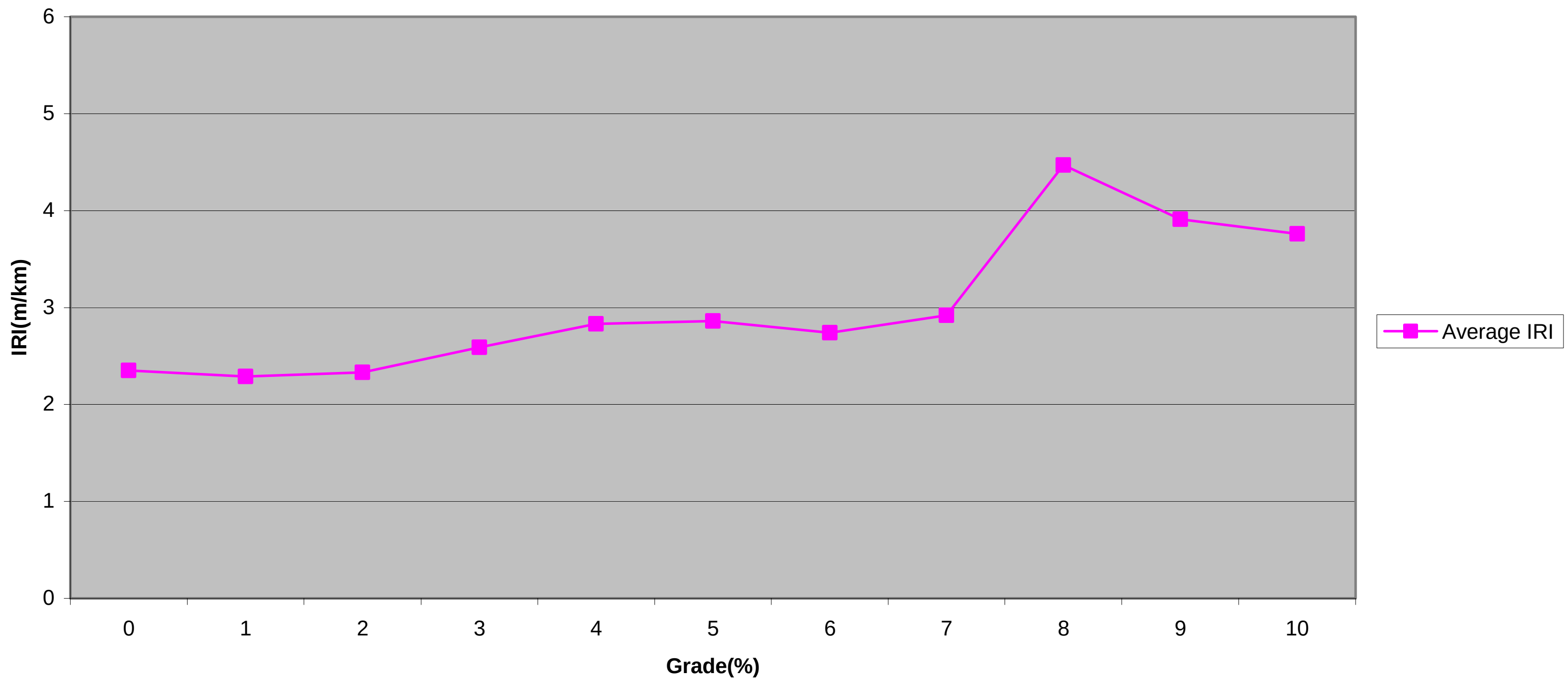


Figure 3.4 - **Average IRI vs Grade on Secondary Roads**
(1999 Data, Rt.3, Rt.116, Rt. 275, Rt. 268, With Bridges)



APPENDIX 4

IRI of NHS in Connecticut
Sample Data Weighted and Not Weighted
Tables 4.1-4.5

Sample Plots of IRI for:
NHS Routes
Non-NHS Routes
All Routes in Connecticut

Sample Cumulative Distributions of IRI

route	iri_97	iri_98	num of sections
2	2.064	2.191	44
2A	2.097	2.294	2
3	1.852	1.957	1
4	3.707	3.555	1
5	2.433	2.255	7
6	2.051	2.073	33
7	2.176	2.142	56
8	1.887	1.774	68
9	1.705	1.781	26
10	2.399	2.918	36
11	1.335	1.423	8
12	2.808	3.502	8
15	2.042	2.072	68
20	1.675	1.601	5
25	2.136	2.147	3
32	2.296	2.149	7
34	2.602	3.007	11
40	1.59	1.594	7
44	2.247	2.158	42
66	2.45	2.534	17
72	2.273	1.929	24
84	1.857	1.782	113
85	2.535	2.866	1
91	1.845	1.731	42
95	1.79	1.811	111
202	2.329	2.324	31
291	1.822	1.858	8
384	1.516	1.624	18
395	1.58	1.604	43
401	1.678	1.729	4
437	1.78	999	1
597	2.45	2.156	4
691	2.116	2.144	20
693	1.403	1.623	5
695	2.1	1.213	3
796	2.031	2.137	3
	2.074	2.104	

Average IRI = IRI*(num of sections)/Sum(num of sections)
Arithmetic Means IRI of HPMS Sections in Connecticut
Includes Bridge Roughness

Table 4.1

route	iri_97_wt	iri_98_wt	Num of Sections
2	1.837	1.878	44
3	1.852	1.957	1
4	3.707	3.555	1
5	2.206	2.077	7
6	2.185	2.124	33
7	2.094	2.082	56
8	1.876	1.701	68
9	1.518	1.54	26
10	2.28	2.432	36
11	1.329	1.406	8
12	2.201	2.081	8
15	1.907	1.894	68
20	1.676	1.604	5
25	2.137	2.147	3
32	2.078	1.851	7
34	2.129	2.298	11
40	1.372	1.381	7
44	2.022	1.893	42
66	2.51	2.335	17
72	2.036	1.924	24
84	1.751	1.633	113
85	2.535	2.866	1
91	1.728	1.651	42
95	1.663	1.617	111
202	2.337	2.213	31
291	1.811	1.846	8
384	1.504	1.592	18
395	1.531	1.565	43
401	1.674	1.712	4
437	1.78	0	1
597	2.523	2.188	4
691	2.057	2.112	20
693	1.272	1.475	5
695	2.259	1.316	3
796	1.841	1.94	3
	1.99	1.96	

Average IRI = Sum(IRI*Length)/Sum(Length)

Weighted IRI of HPMs, Sections in Connecticut

Includes Bridges Roughness

Table 4.2

Route	Iri_97_o	Iri_98_o	Num of Sections	IRI Difference
2	2.055	2.155	44	0.100
2A	1.820	2.189	2	0.369
3	2.250	2.224	1	-0.026
4	2.819	2.617	1	-0.202
5	2.415	2.353	7	-0.062
6	2.222	2.190	33	-0.032
7	2.124	2.099	56	-0.025
8	1.890	1.820	68	-0.070
9	1.756	1.828	26	0.072
10	2.439	2.911	36	0.472
11	1.335	1.417	8	0.082
12	2.579	2.863	8	0.284
15	2.055	2.065	68	0.010
20	2.200	1.822	5	-0.378
25	2.063	2.065	3	0.002
32	2.454	2.444	7	-0.010
34	2.599	2.847	11	0.248
40	1.687	1.592	7	-0.095
44	2.248	2.240	42	-0.008
66	2.420	2.500	17	0.080
72	2.200	1.930	24	-0.270
84	1.890	1.836	113	-0.054
85	2.588	2.586	1	-0.002
91	1.942	1.839	42	-0.103
95	1.789	1.810	111	0.021
202	2.307	2.307	31	0.000
291	1.822	1.858	8	0.036
384	1.516	1.623	18	0.107
395	1.579	1.604	43	0.025
401	1.859	1.994	4	0.135
437	1.780	999	1	999
597	2.437	2.137	4	-0.300
691	2.136	2.140	20	0.004
693	1.403	1.623	5	0.220
695	2.100	1.213	3	-0.887
796	2.202	2.163	3	-0.039
	2.083	2.083		-0.008

Average IRI=Sum(IRI of section)/Num of Sections

Arithmetic Mean - Without Bridges

Table 4.3

route	iri97_o_wt	iri98_o_wt	num
2	1.835	1.869	44
2A	2.024	2.569	2
3	2.003	2.105	1
4	3.707	3.555	1
5	2.206	2.077	7
6	2.185	2.124	33
7	2.090	2.077	56
8	1.874	1.707	68
9	1.518	1.540	26
10	2.280	2.432	36
11	1.094	1.395	8
12	2.201	2.081	8
15	1.908	1.893	68
20	1.626	1.556	5
25	2.140	2.150	3
32	2.078	1.851	7
34	1.984	2.142	10
40	1.430	1.380	7
44	1.925	1.893	42
66	2.464	2.335	17
72	2.028	1.917	24
84	1.750	1.633	113
85	2.535	2.866	1
91	1.727	1.652	42
95	1.663	1.616	111
202	2.336	2.213	31
291	1.811	1.846	8
384	1.504	1.592	18
395	1.531	1.564	43
401	1.674	1.712	4
437	1.780	999	1
597	2.515	2.176	4
691	2.058	2.112	20
693	1.272	1.475	5
695	2.259	1.316	3
796	1.840	1.938	3
	1.968	1.953	

Weighted IRI - Without Bridges
IRI = Sum (IRI * length tested)/Sum(length tested)

Table 4.4

		1997 data				1998 data	
route	num	iri_97_o	iri97_o_wt	ArithIRI-WtIRI	iri_98_o	iri98_o_wt	ArithIRI-WtIRI
2	44	2.055	1.835	0.220	2.155	1.869	0.286
2A	2	1.820	2.024	-0.204	2.189	2.569	-0.380
3	1	2.250	2.003	0.247	2.224	2.105	0.119
4	1	2.819	3.707	-0.888	2.617	3.555	-0.938
5	7	2.415	2.206	0.209	2.353	2.077	0.276
6	33	2.222	2.185	0.037	2.190	2.124	0.066
7	56	2.124	2.090	0.034	2.099	2.077	0.022
8	68	1.890	1.874	0.016	1.820	1.707	0.113
9	26	1.756	1.518	0.238	1.828	1.540	0.288
10	36	2.439	2.280	0.159	2.911	2.432	0.479
11	8	1.335	1.094	0.241	1.417	1.395	0.022
12	8	2.579	2.201	0.378	2.863	2.081	0.782
15	68	2.055	1.908	0.147	2.065	1.893	0.172
20	5	2.200	1.626	0.574	1.822	1.556	0.266
25	3	2.063	2.140	-0.077	2.065	2.150	-0.085
32	7	2.454	2.078	0.376	2.444	1.851	0.593
34	10	2.599	1.984	0.615	2.847	2.142	0.705
40	7	1.687	1.430	0.257	1.592	1.380	0.212
44	42	2.248	1.925	0.323	2.240	1.893	0.347
66	17	2.420	2.464	-0.044	2.500	2.335	0.165
72	24	2.200	2.028	0.172	1.930	1.917	0.013
84	113	1.890	1.750	0.140	1.836	1.633	0.203
85	1	2.588	2.535	0.053	2.586	2.866	-0.280
91	42	1.942	1.727	0.215	1.839	1.652	0.187
95	111	1.789	1.663	0.126	1.810	1.616	0.194
202	31	2.307	2.336	-0.029	2.307	2.213	0.094
291	8	1.822	1.811	0.011	1.858	1.846	0.012
384	18	1.516	1.504	0.012	1.623	1.592	0.031
395	43	1.579	1.531	0.048	1.604	1.564	0.040
401	4	1.859	1.674	0.185	1.994	1.712	0.282
437	1	1.780	1.780	0.000	999	999	999
597	4	2.437	2.515	-0.078	2.137	2.176	-0.039
691	20	2.136	2.058	0.078	2.140	2.112	0.028
693	5	1.403	1.272	0.131	1.623	1.475	0.148
695	3	2.100	2.259	-0.159	1.213	1.316	-0.103
796	3	2.202	1.840	0.362	2.163	1.938	0.225
				0.115			0.130

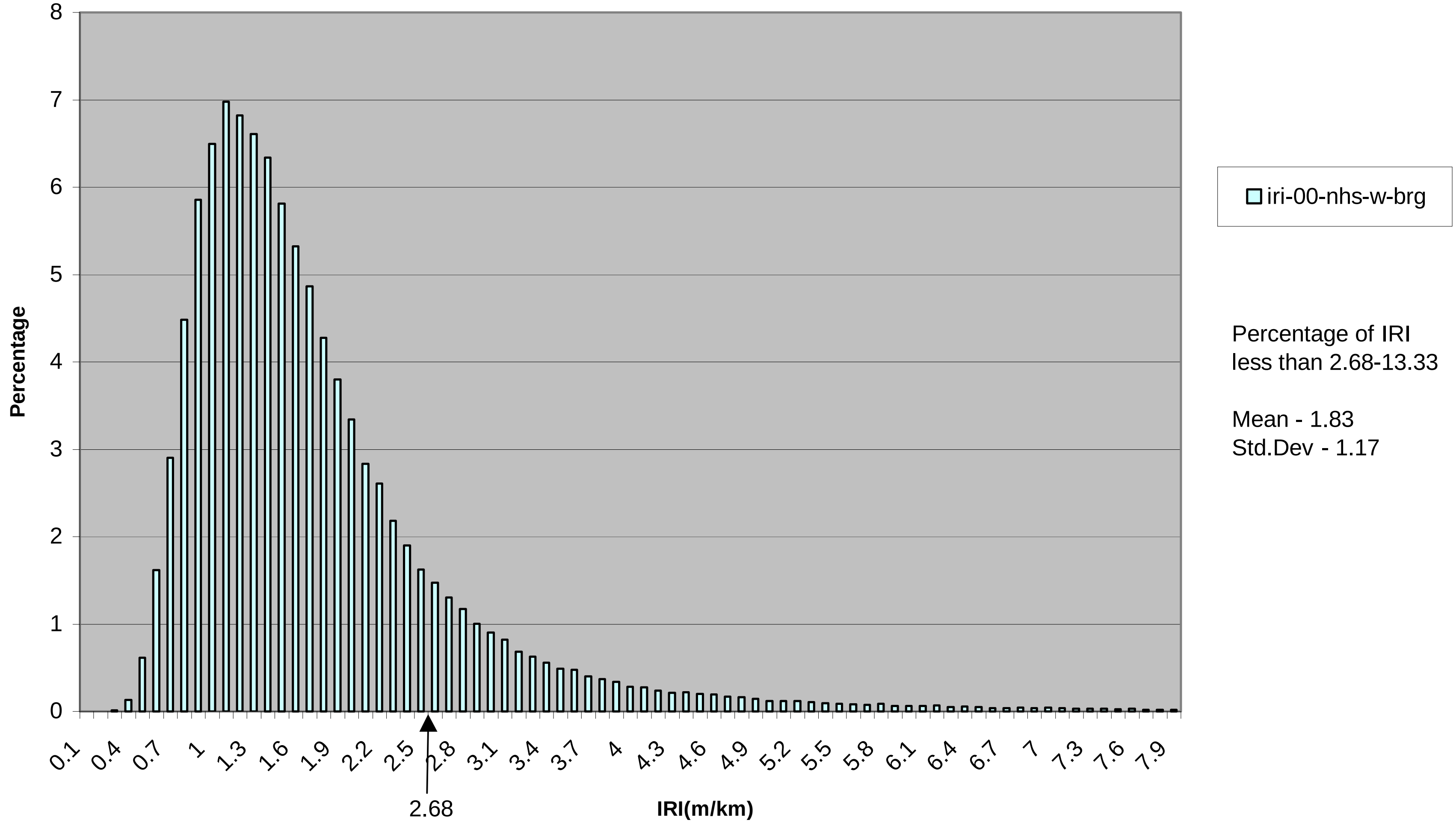
Difference in IRI(Arithmetic - Weighted)
[Weighing factor = length of section]
Without Bridges

Table 4.5

IRI DISTRIBUTIONS

Including Bridge Roughness

Figure 4.1 **IRI Distribution of NHS Roads**
(2000 Data, With Bridges)



Percentage of IRI
less than 2.68-13.33

Mean - 1.83
Std.Dev - 1.17

Figure 4.2 **Cumulative Distribution of IRI Values of NHS Roads**
(1997,1998,1999,2000 data, with bridges)

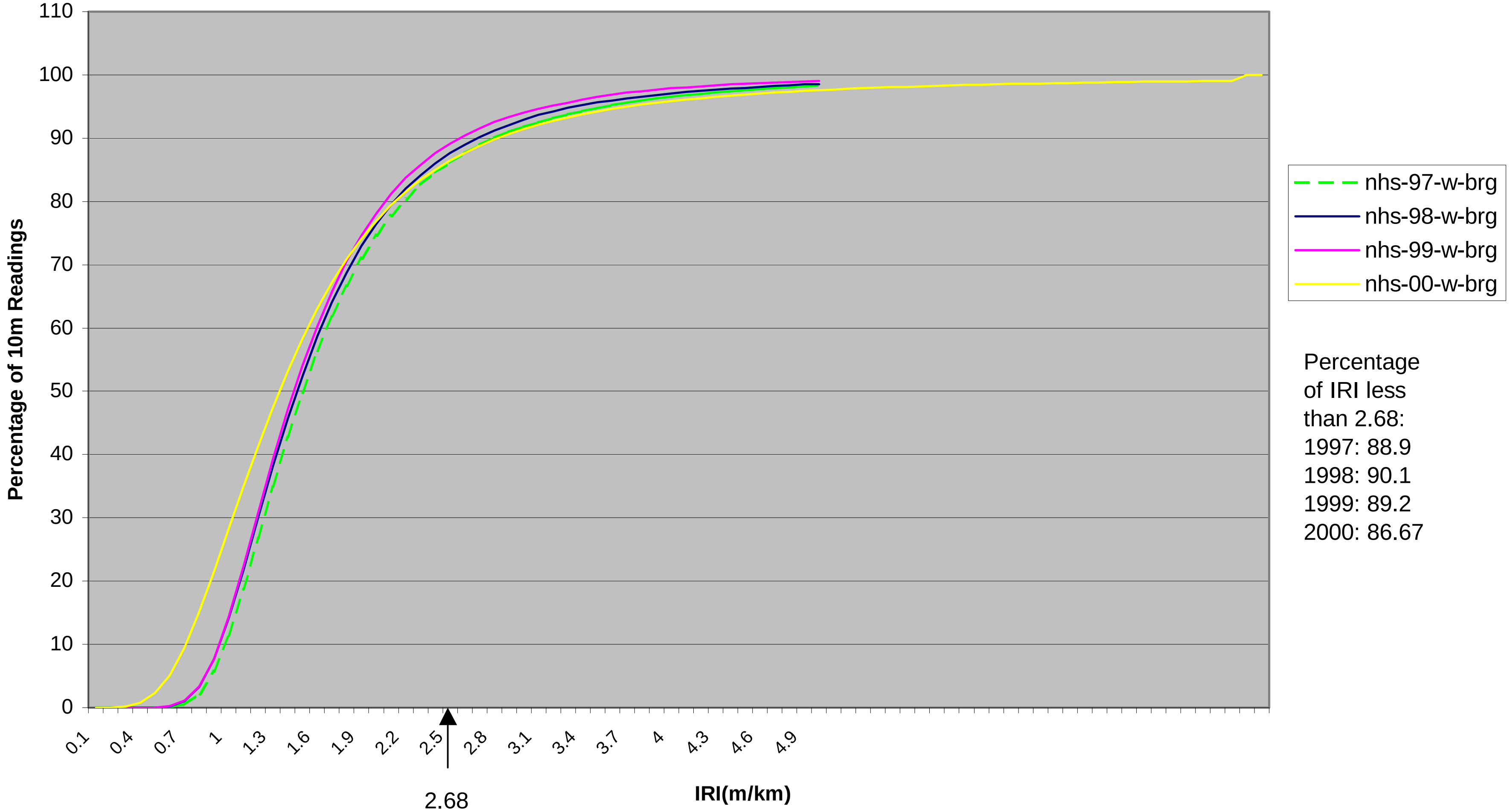


Figure 4.3 **IRI Distribution of Non NHS Roads**

(2000 Data, With Bridges)

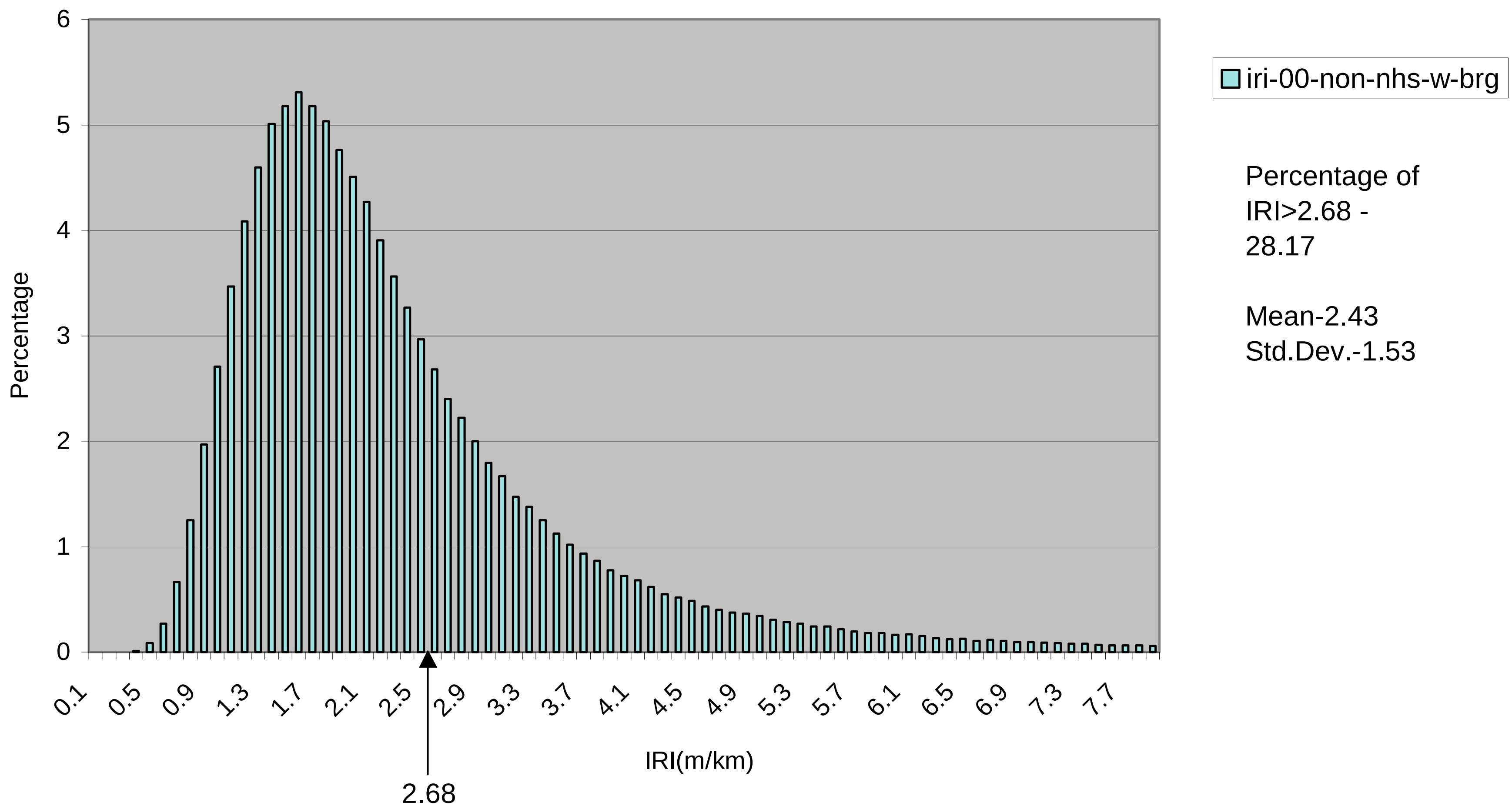


Figure 4.4 **Cumulative Distribution of IRI Values of Non NHS Roads**
(1997,1998,1999,2000 data,with bridges)

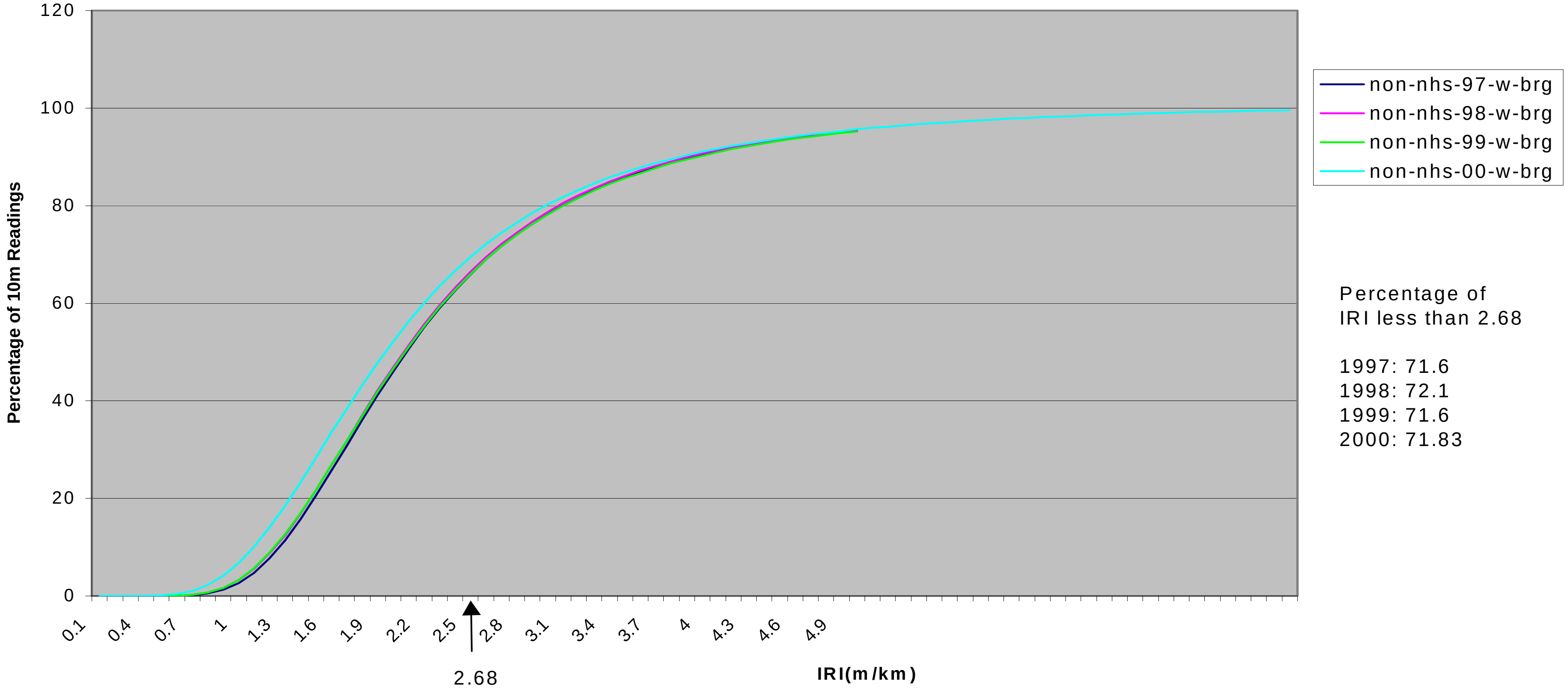
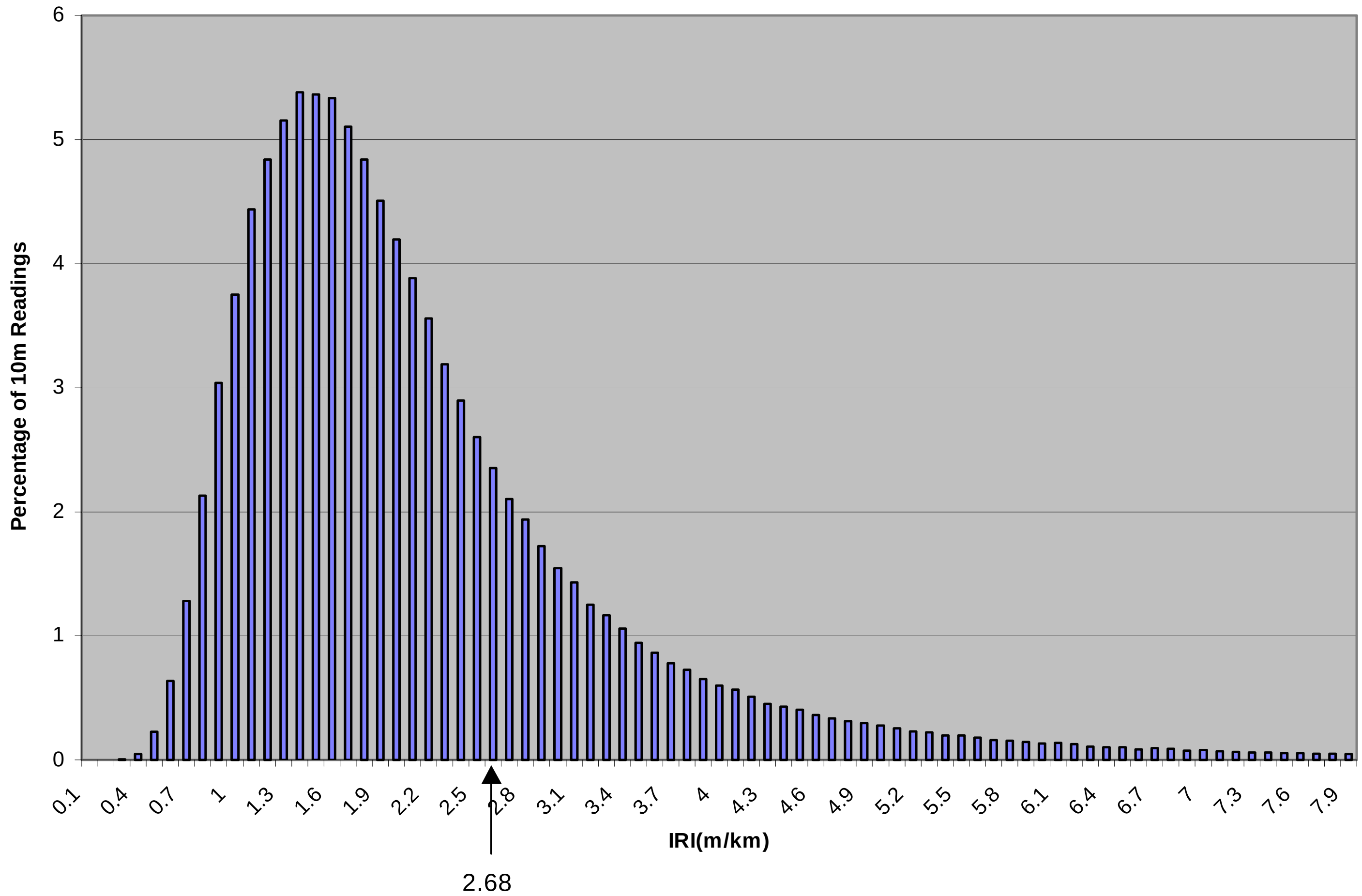


Figure 4.5 **IRI Distribution of All Roads**
(2000 Data, With Bridges)

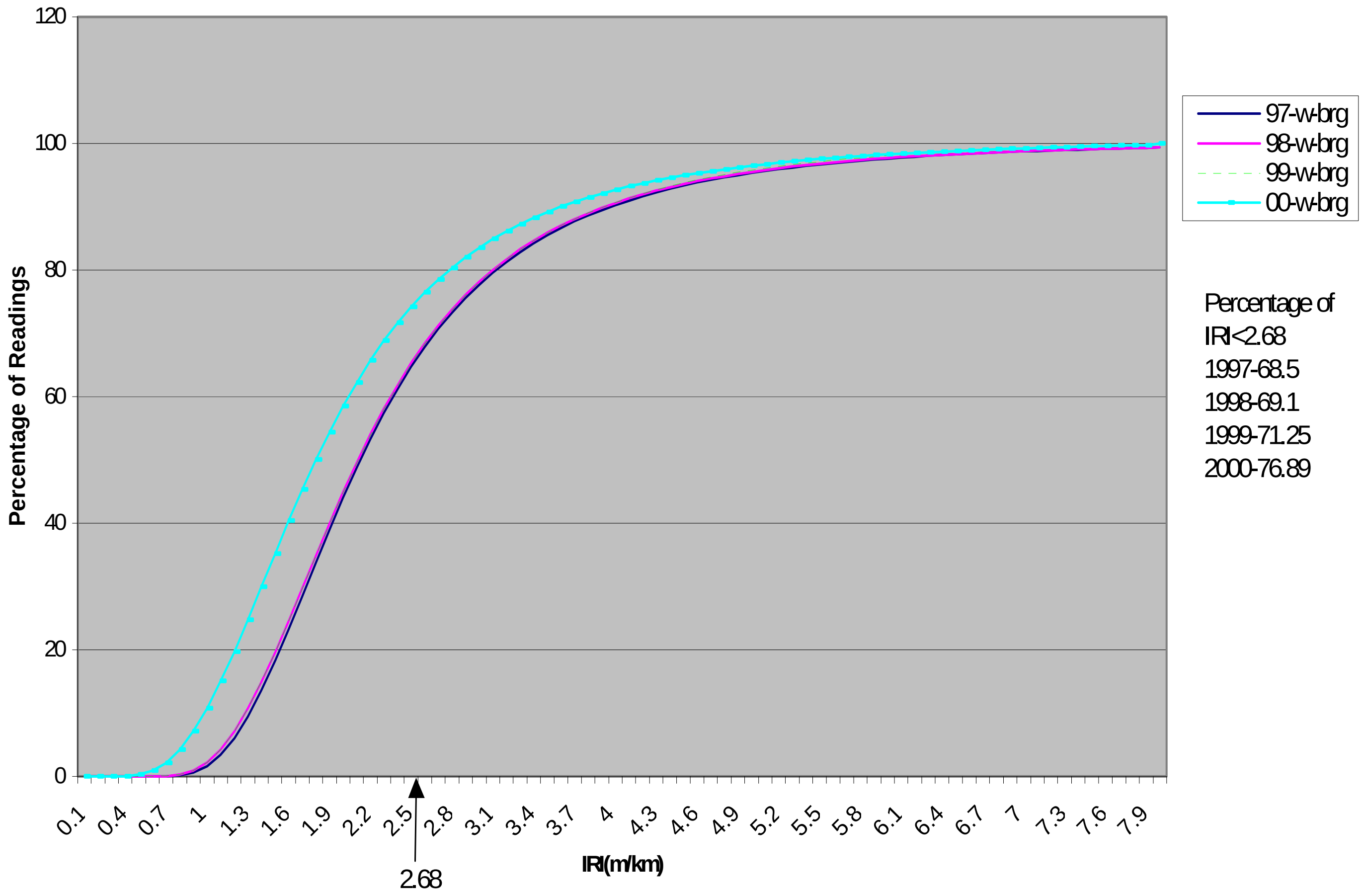


Percentage of
IRI>2.68-24.2

Mean - 2.27
Std. Dev.- 1.47

Figure 4.6 **Cumulative Distribution of IRI Values of All Roads**

1997,1998,1999,2000 Data,With Bridges



IRI DISTRIBUTIONS

Excluding Bridge Roughness

Figure 4.7 **IRI Distribution of NHS Roads**
(2000 Data, Without Bridges)

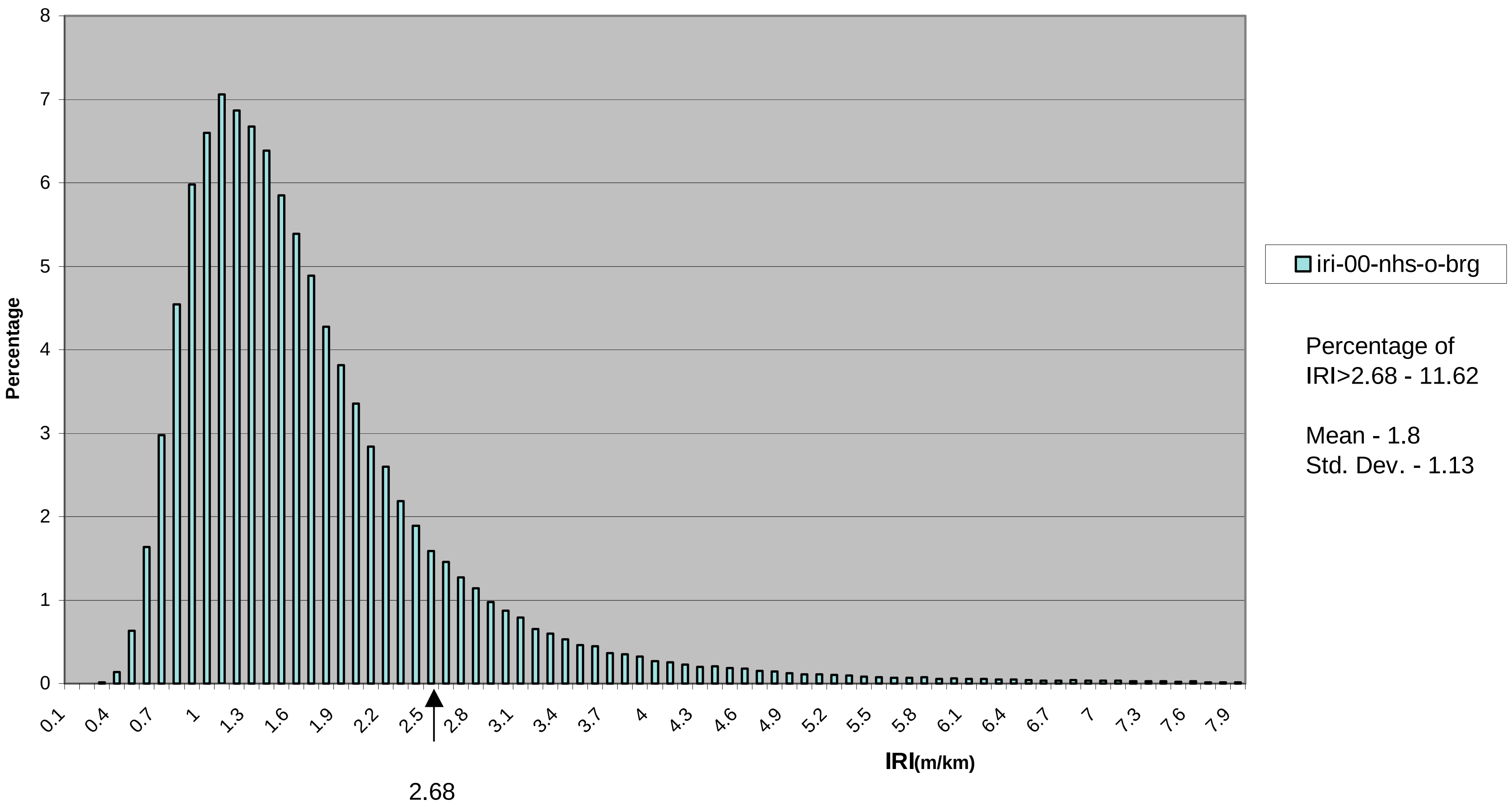


Figure 4.8 **Cumulative Distribution of IRI Values of NHS Roads**
(1997, 1998, 1999,2000 data, without bridges)

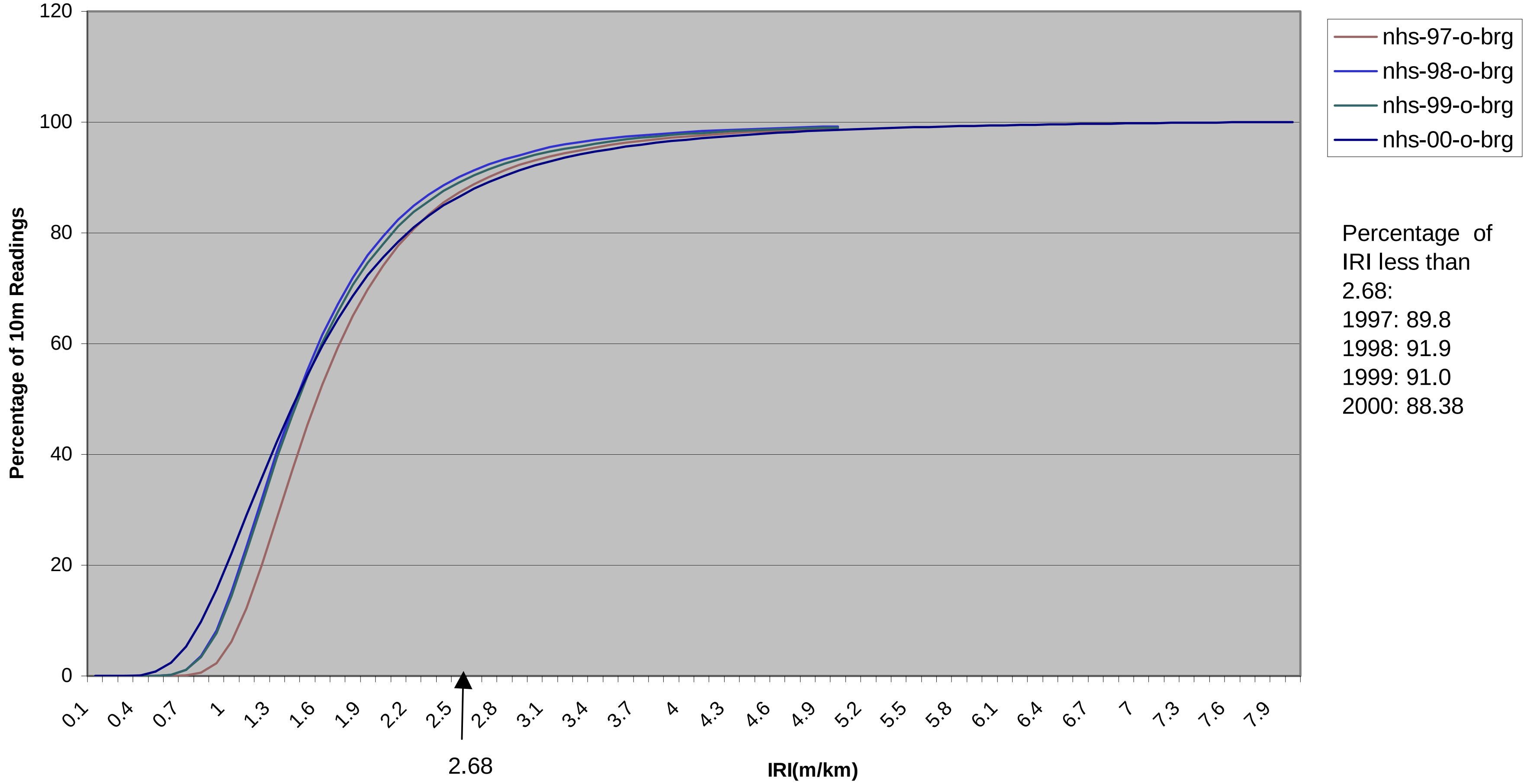


Figure 4.9 **IRI Distribution of Non NHS Roads**
(2000 Data, Without Bridges)

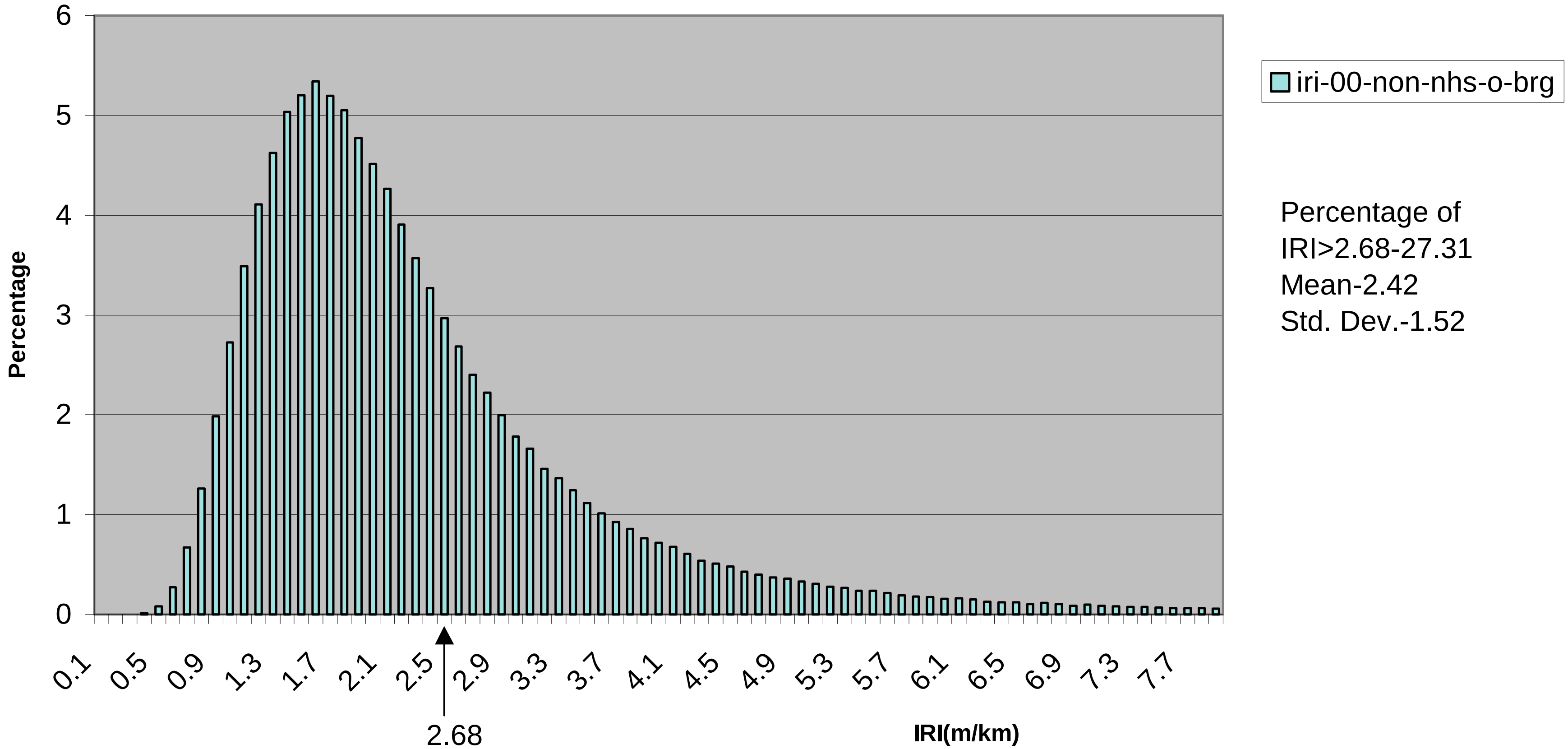


Figure 4.10 **Cumulative Distribution of IRI Values of Non NHS Roads**
(1997, 1998, 1999,2000 data, without bridges)

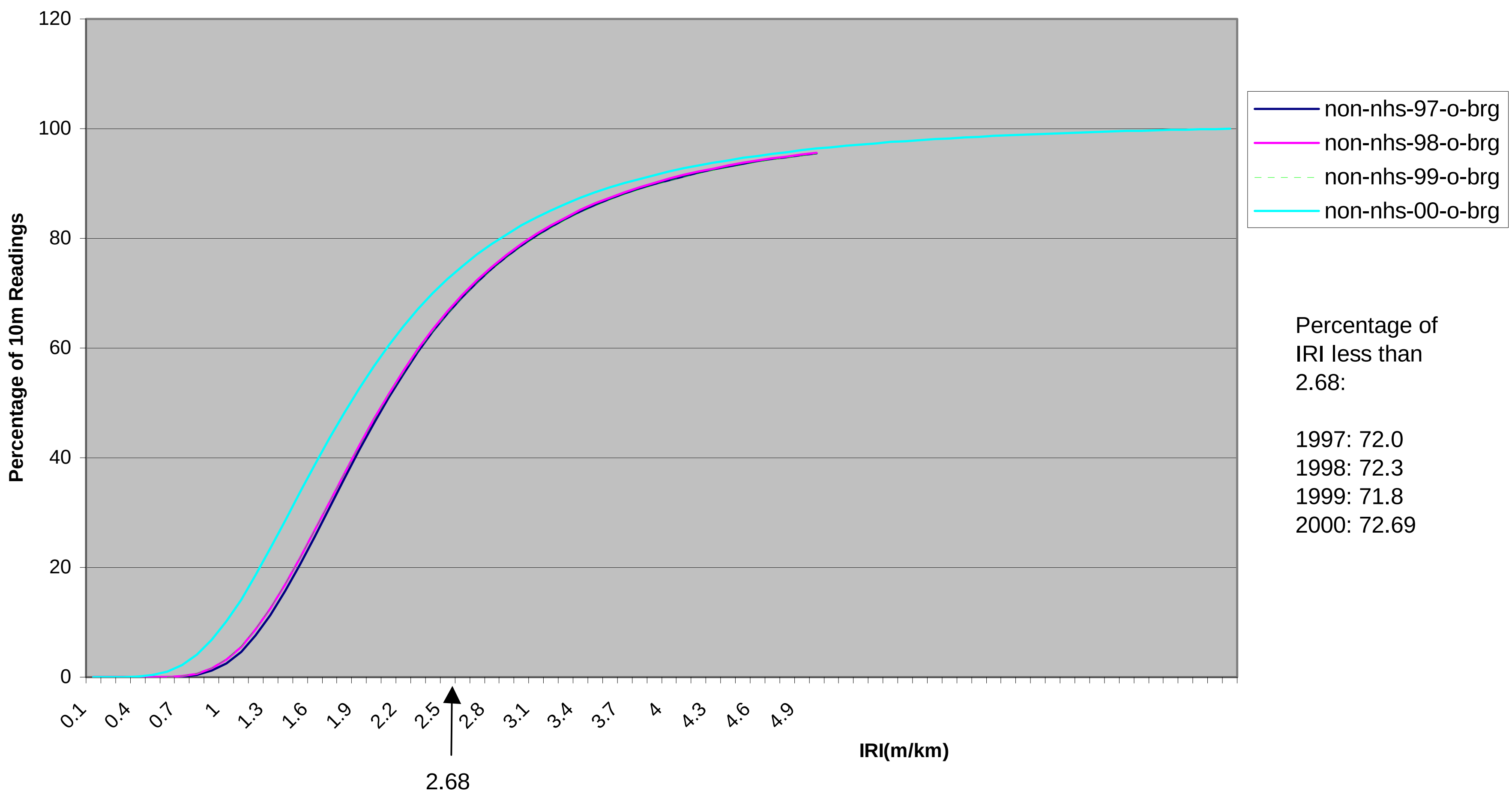


Figure 4.11 **IRI Distribution of All Roads**
(2000 Data, Without Bridges)

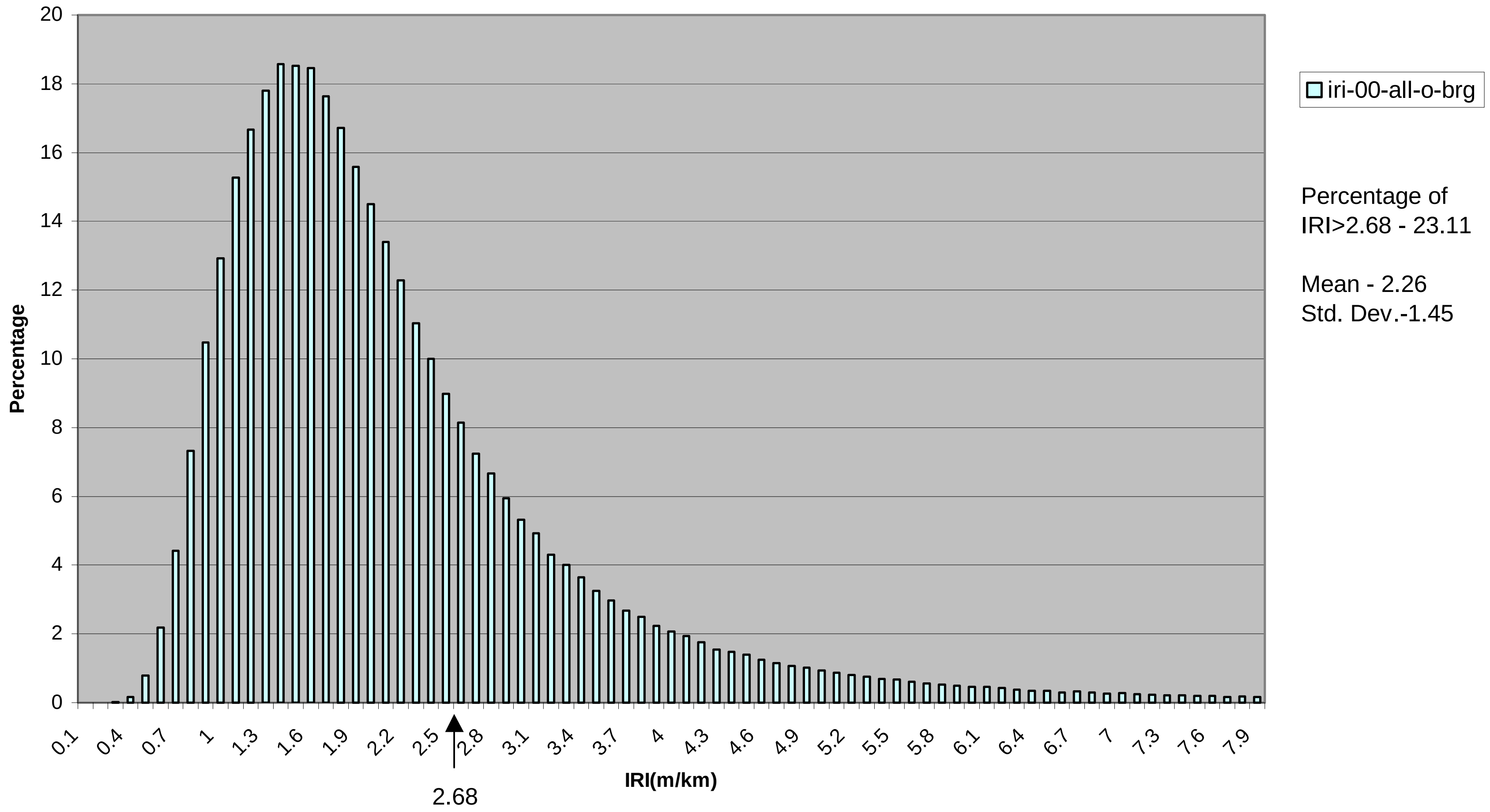


Figure 4.12 **Cumulative Distribution of IRI Values of All Roads**
1997, 1998, 1999,2000 Data, Without Bridges