LATERAL VARIATION in PAVEMENT SMOOTHNESS

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16. Abstract

Current performance-based contracting specifications employ International Roughness Index (IRI) to measure the smoothness of a pavement as perceived by the motorist. This parameter is measured in the outer or right-hand traffic lane and requires an understanding of how smoothness, as measured by IRI, varies spatially, with time and other design factors. Recently the change in traffic flow characteristics where heavy volumes of traffic travel in the left-hand lane or lanes of multi-lane highways has raised issues as to whether or not measurements in the outer lane represents an "worst case" condition for the assessment of pavement performance and design considerations. To assess these variables a large field data set of IRI data across all lanes of four multi-lane highways was collected during field photolog operations by ConnDOT staff. These data were analyzed to determine if there were statistical differences laterally on the test routes. It was concluded that there are smoothness differences in adjacent lanes of multi-lane freeways, which are consistent, random and small in value (0.2m/km). No strong causal relationships were found in the variables studied, age, pavement design and type, or traffic load. Rut was found to have more influence on IRI than cracking. Large values recorded, outliers, are associated with construction and maintenance activities.

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Executive Summary

Lateral Variation in Pavement Smoothness

The International Roughness Index (IRI) is used routinely to measure the smoothness of a pavement as perceived by the motorist and current performance-based contracting agreements employ IRI to apply incentive disincentive payments to work performed. Any further use of the IRI concept requires an understanding of how smoothness varies spatially, with time and with other design and environmental factors. In Connecticut there was a concern that due to recent changes in traffic flow patterns there could be significantly higher IRI values in the left-hand lane or lanes of expressways. This project employed a large data set of IRI field data together with traffic and pavement design/age data to analyze IRI variations across the lanes of four multi-lane highways/freeways in the State of Connecticut (368 highway kilometers or 1,790 lane kilometers). Data obtained during routine field photolog operations, that was measured in the right-hand lane only, were used and additional IRI data for the adjacent lane or lanes were obtained in separate field operations.

These data were analyzed to determine to what extent IRI varies over all lanes as a function of time and to determine if there were statistically significant differences laterally on the test routes. Specific project objectives were:

(1) To determine representative values for one or more lanes adjacent to the outer lane on selected multi-lane roadways;
(2) To determine if IRI varies systematically with pavement design, age, or traffic levels; and,
(3) To determine any distress in the adjacent lane or lanes and delineate any causative factors for this distress.

<u>SUMMARY of STUDY CONCLUSIONS</u> - Analyses performed show that, based on IRI, small average roughness differences exist between adjacent lanes. This difference is consistent at 0.1-0.2 m/km (the right lane is highest)when averaged over long roadway sections. The IRI values are highest 50.9 percent of the time in the outer lane, 38.6 percent of the time projects analyzed show no significant difference between lanes, and in 10.5 percent of the projects the IRI of the left-hand lane or lanes were greater than the outer lane. No strong causal relationships were found for variables such as: pavement age; design of the pavement structure; type of riding surface or traffic loading. This lack of a relationship could be because of limited data. Most large IRI values (outliers) were found at construction and maintenance activities encountered at the time the IRI measurements were made. Lastly, rutting had a greater correlation with IRI than pavement cracking. The variation in IRI measurements is relatively small but unpredictable, especially over small spatial areas.

<u>RECOMMENDATION</u> – ConnDOT should not measure, annually, the IRI of adjacent traffic lanes on multi-lane roadways. Routine data collection in the right-hand lane is sufficient.

LATERAL VARIATION IN PAVEMENT SMOOTHNESS

BACKGROUND AND INTRODUCTION A vehicle's response to the road surface is a function of the combination of a vehicle's weight, the condition and configuration of its chassis and suspension, the size and inflation pressure of its tires, and a number of other factors (not to mention the condition of the road surface, itself). As vehicles (as well as their operators) come in all shapes and sizes, rarely do two users experience the identical ride over the same section of road. The accepted solution is to measure and analyze the road surface profile, rather than measuring the response of any single instrumented vehicle. An accurate measurement of the surface profile is necessary in order to make a repeatable, objective assessment of ride quality. In turn, these measurements can then be converted into a statistic which can quantify the smoothness of the pavement. The currently accepted statistic in the United States and elsewhere in the world is the International Roughness Index (IRI).

Technically, the IRI is a mathematical representation of the accumulated suspension stroke of a vehicle, divided by the distance traveled by the vehicle. The IRI is calculated mathematically from the measured longitudinal profile with use of a quarter-car simulation along a single wheel path. The quarter car includes: one tire represented with a vertical spring, the axle mass supported by the tire, a suspension spring and a damper, and the mass of the body supported by the suspension for the tire. A simulation speed of 80 km/h (50mi/h) is used for the quarter car, and the simulated suspension motion is linearly accumulated and divided by the length of the profile to yield the IRI. The coefficients used in the mathematical equations are those that have provided the maximum correlation to the output of the response-type roughness measuring systems. As inertial profilers typically measure longitudinal profiles along the two wheel paths, the IRI for the section can be obtained by computing the IRI for each wheel path, and then averaging the two values.

ASTM Standard E1170, "Practices for Simulating Vehicular Response to Longitudinal Profiles of a Vehicular Traveled Surface," describes the method for conducting a quarter-car simulation that produces an IRI. Using a fairly sophisticated algorithm, a model of a quarter vehicle traveling at a specified speed is applied to a profile, and its reaction is measured and reported. This reference vehicle is complete with all the basic parameters necessary to describe an actual automobile (or at least the portion of interest here). These parameters include: 1) the mass of the vehicle body, suspension, wheels and tires; 2) stiffness coefficients for the vehicle springs, shocks and/or struts; and 3) damping coefficients indicative of a conventional shock-absorbing system. The simulated suspension motion is accumulated and divided by the distance traveled to yield the IRI. Lower values represent a smoother ride; higher values indicate a rougher one.

Since 1996, Connecticut Department of Transportation (ConnDOT) staff have obtained IRI data as part of their annual roadway image-and data acquisition activities. An Automatic Roadway Analyzer (ARAN) vehicle is used for this purpose. Studies of the data obtained/14, 15/, were undertaken to better understand the IRI data obtained from normal ARAN image-and-data-acquisition activities. These studies also illustrate the effective use of IRI data to predict pavement performance trends and factors affecting these data.

A possible shortcoming of these traditional analyses is the fact that IRI data were obtained only in the outer or right hand lane of multi-lane expressways or roadways. The positioning of the ARAN in the outer lane is based on the assumption that the majority of traffic-induced distress on a roadway would occur in this lane. This assumption may no longer be valid, as evidenced by the large volume of trucks traveling in the left or middle lane of Connecticut's multi-lane roadways. Moreover, as is being reported and addressed by ConnDOT's maintenance forces, there appears to be substantial pavement distress in all lanes. In effect, this means that analysis of images and data obtained from and within the outer lane may not accurately estimate the service life of pavement surfaces placed in the left or middle lane of a multi-lane roadway.

<u>PROJECT OBJECTIVES</u> To address the need to determine representative IRI values for a lane or lanes adjacent to the outer lane a two-part study was undertaken: Part A – to test adjacent traffic lanes; and, Part B - to evaluate all multi-lane roadways in Connecticut based on the IRI values obtained. This report presents the results of Part A, which has the following two objectives:

(1) To determine representative IRI values for one or more lanes adjacent to the outer lane on selected multi-lane roadways; and,
(2) To determine the distress in the adjacent lane or lanes and delineate any causative factors uncovered for this distress.

<u>PROJECT METHODOLOGY</u> In Connecticut there are many configurations of multi-lane roadways, ranging from Interstate expressways, collector roads for commercial and industrial areas, to multi-lane roads in rural areas. Each roadway and class of roadway carries with it its own set of problems and limitations. To address these situations and finalize a sound basis for evaluation of lateral difference in IRI and distress, an Advisory Team was formed to oversee and direct all phases of the project. At the beginning of the project this Team helped determine:

(1) the variables that would be considered, i.e. class of roadways, traffic volume, percent of trucks, age of pavement, etc.; and,
(2) the routes which were to be evaluated and the data used to finalize a plan to evaluate the entire Connecticut Highway system.

Four routes were selected for this study: I-91, a 6-lane divided urban highway; I-395, a 4-lane divided rural facility; CT Route 8, a 4-lane divided rural and urban freeway;

and two sections of CT Route 15; a 4-lane divided older parkway and a 4-lane divided unlimited access urban roadway. Each of the above routes nominally contain the number of lanes listed, however, there are limited areas containing additional lanes due to operational requirements. In these cases, only through lanes were included in this study. The location of the test sites is shown in Figure 1 while descriptive details are presented in Table 1. Each route was reviewed on the photolog. Limited sections within the routes which were being rehabilitated or reconstructed are deleted from the analysis set.

After completing the route selection process, initial IRI and related images and data were obtained from ConnDOT's 2001 annual network survey (right-hand lane only). Additional data for the adjacent lane or lanes were obtained by follow-up photolog runs on the same test routes. All of the data were provided to CTI staff, who conducted standard statistical analyses to determine the average IRI, standard deviations, and outliers in the data set.

Distress analyses were performed by ConnDOT staff using the WISECRAX® software and work station. This software automates the distress definition process, and is currently in use in the Pavement Management Section of ConnDOT. It is used to define distress type in the form of cracks, and their extent and severity. WISECRAX® does not account for other types of distress such as potholes, patching, sealed cracks or rutting. These data were related to any change in IRI as part of the overall data analysis by CTI staff. Field notes obtained during field photolog operations were used to complement the WISECRAX® analysis of the test sections.

Traffic data, both total volumes and lane distributions, were provided by ConnDOT. These data included the number of trucks by lane at various locations or projects but not the entire route. Additional data and information on the type of surface mix placed, age of pavement - which is defined as the date of project acceptance by ConnDOT, and structural thickness were secured from existing records in ConnDOT. Table 2 lists the various factors analyzed during this project. It presents an outline of the flow of work performed during the study. Figure 2 shows the lane codes used by ConnDOT staff to obtain data for this study. L2 and L3 designate the inner lane for 4-lane roadways, while L2 and L5 are the middle and L3 and L4 are the inner lanes for 6-lane roadways, respectively. Data for short sections of roadways with four or more lanes per direction and/or short operational lanes are not included in this study. Any high occupancy vehicle lane (HOV) is included and is defined by its direction.

RESULTS Project activities were accomplished in three major phases. Initially, a five-year history of each route was prepared to define any trends in the IRI data over time. Secondly, the IRI for adjacent lane/s for the entire route was determined. Route 15 was separated into two study sections, a 101km section of parkway and a 15km section of unlimited access divided highways, in order to address the influence of truck traffic on IRI. These data were then subdivided into projects and the IRI by lane determined. In addition, on a project basis, IRI trends by type and age of surface material were developed. Lastly, any relation or data trend of IRI as a function of distress was examined. For this effort, WISECRAX® data, rut data and photolog images were studied. Spatial representations and regression techniques provided notable data relationships. The following pages present our findings for this project.

Figure 1 – Study Areas

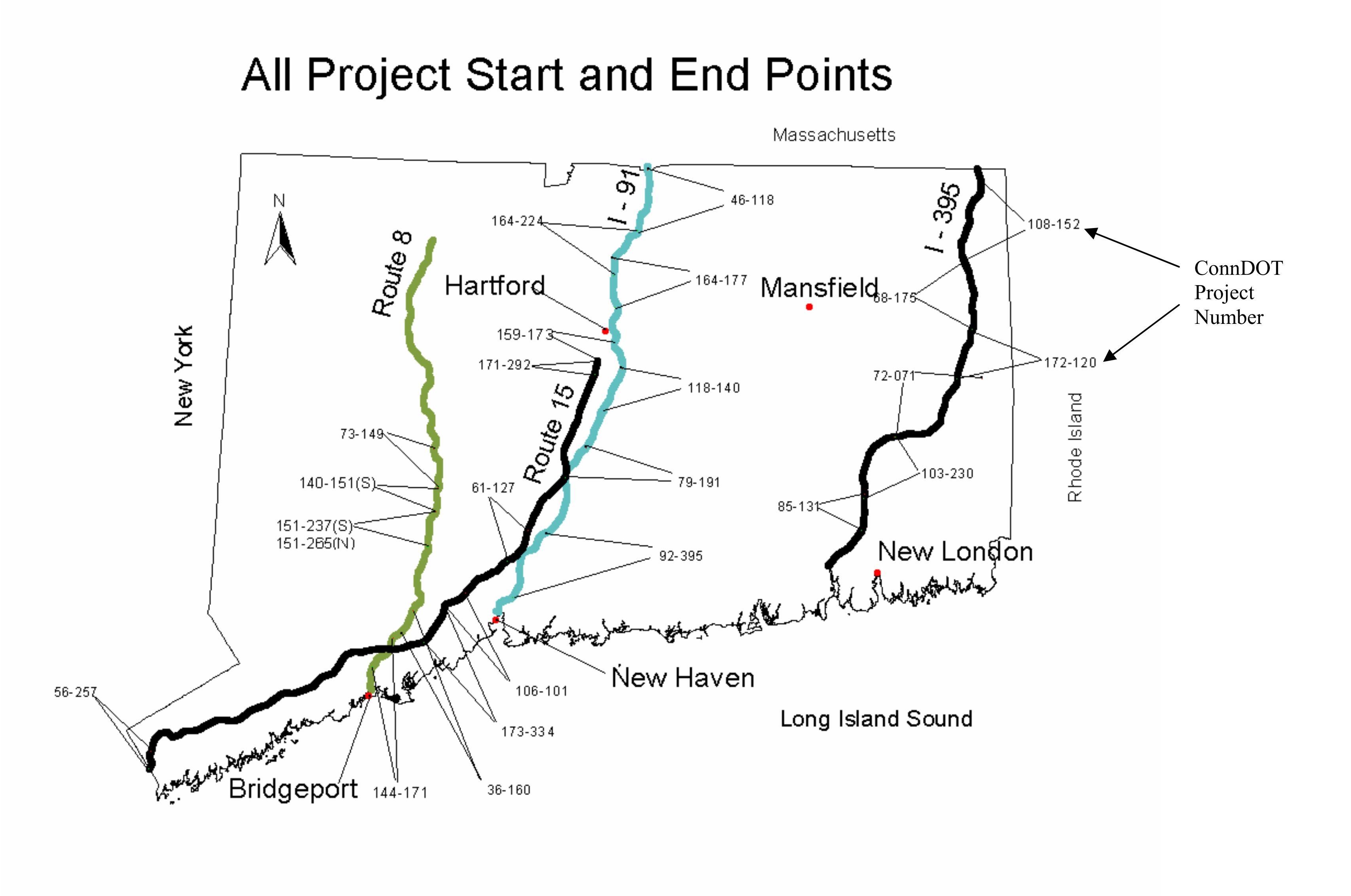


Table 1 - Description of Test Areas

Route	Location	# of Lanes	Year of latest Paving	Pavement Type	AADT	No. of Trucks	Traffic by Lane		
							L3	L2	L1
8	Bridgeport(0.0) – Torrington(58.29)	2/Dir.	1990-2000	HMA[4] on PCC[5] & HMA	H 86,500 L 12,900	H: 3,432 L: 1,250		H: 1,441 L: 13	H: 1,601 L: 336
15[1]	New York SL(0.0) – Hartford(79.94)	2/Dir.	1998-2001	HMA on PCC	H 78,200 L 17,500	H: 1,663 L: [2]		157	617
I – 91	New Haven(0.0) - Enfield(58.0)	3/Dir.	1992-2001	HMA on PCC & HMA	H 145,500 L 67,200	H: 13,646 L: 9,841	H: 4,228 L:177 [3]	H: 7,068 L: 3,853	H: 6,387 L: 2,415
I - 395	Waterford(0.0) – Putnam(54.69)	2/Dir.	1986-2000	HMA & PCC on HMA	H 57,800 L 17,100	H: 3,270 L: 2,678		H: 991 L: 360	H:3,279 L: 2,318

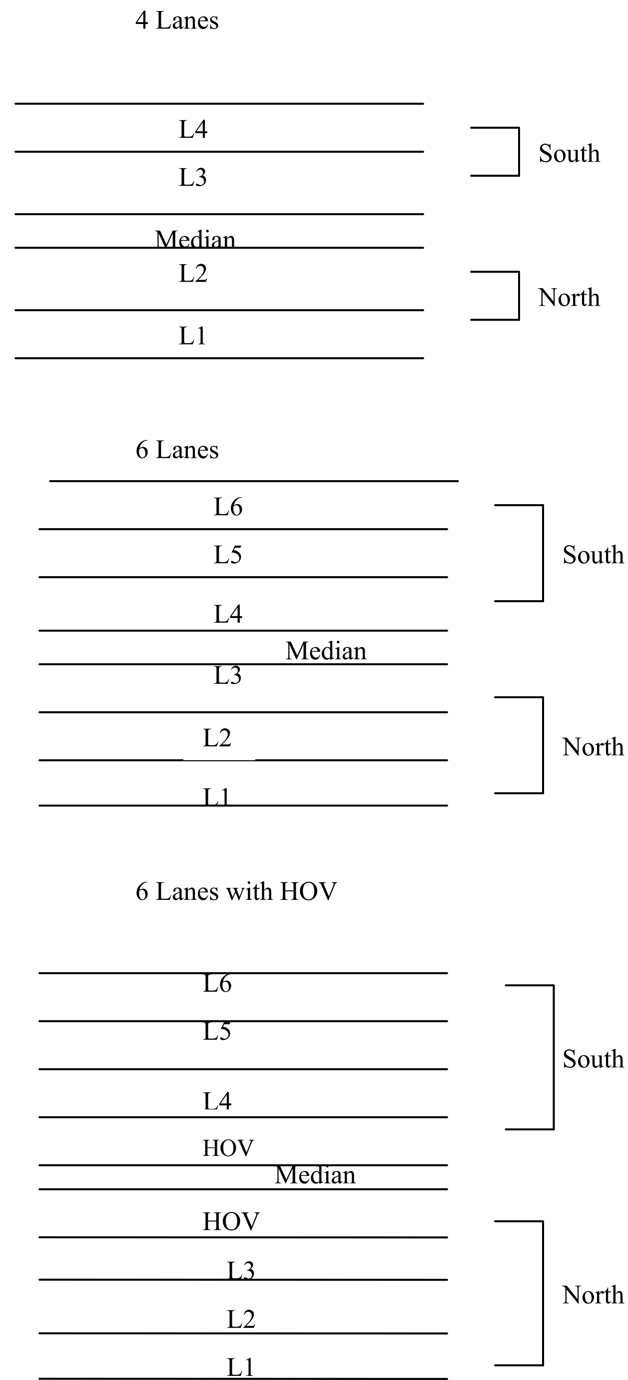
(1) Route 15 New York SL (0 km) north to Meriden (101km) – Parkway with controlled access.
Route 15 Meriden (110km) north to Hartford (125km) – 4-lane divided highway with unlimited access.
(xx km) Chainage from 2000 Highway Log /7/.
(2) Route 15 Truck Traffic- One Location Only
(3) Left lane truck exclusion for selected sections of I-91
(4) HMA - Hot-Mix Asphalt
(5) PCC - Portland Cement Concrete

Table 2 – Listing of Factors Analyzed

- Determine 5-year trend (1997-2001) in IRI for the test routes.
- Sub-divide the test routes into individual paving projects and determine the 2001 IRI values for these projects.

Lane	Outside	Middle	Inner	HOV
Traffic Level (ADT by lane)				
Number of Heavy Vehicles (Trucks)				
Number of Trucks with 4+ axles				
Access	Limited	Unlimited		
Type of Surface	Class1	Class114	Superpave	
Structure	HMA on HMA	HMA on PCC		
Age of Surface				
Distresses				
Design Thickness				

Figure 2 - Lane Codes



Temporal Patterns in Shoulder Lane IRI

5-year IRI Trend - Table 3 summarizes the mean and standard deviation of IRI data for each route. The data were obtained from ConnDOT files and represent the outer or right-hand lane only. The data includes the IRI contributed by bridges as well. Figures 3 shows the 5-year time histories of the IRI and Figure 4 the standard deviation of the data, respectively. The IRI plot generally reflects improvement in IRI with time, as Connecticut has accelerated its program of pavement rehabilitation during the timeframe of this research. The graph of IRI for I-395 reflects this ongoing effort and its results. The plot of standard deviation is fairly constant with time. The exception is Route 15, which had several large resurfacing projects ongoing in the 1997-98 time period and the standard deviation of the IRI data is exceptionally high in 1998.

Average Lateral Difference in IRI by Route

Initially, the lateral difference between the IRI values for adjacent lanes were calculated on the whole route level. Table 4 illustrates the average IRI by lane for each of the four study routes and Figure 5 presents these data graphically. This figure shows that on an average level the IRI does not vary significantly except for the HOV lanes on I-91.

In preparing Table 4, the mean and standard deviation of all IRI data were initially calculated. Outliers, IRI values greater than three standard deviations, were removed and the mean and standard deviation recomputed (see data in bold in Table 4). The data removed was attributed to construction and maintenance (C&M) operations and/or rough bridge decks or joints. To verify this premise, the data points removed were located using GIS and the areas scanned using the photolog images. In an estimated 95 percent plus of the areas viewed, bridges or C&M was documented. Appendix 1 presents photos typical of areas that were excluded as outliers. The revised data, outliers excluded, was used in subsequent analyses.

As stated previously, additional photolog runs were performed to obtain IRI and other information on the adjacent lane/s. At the same time, limited additional data were obtained in the outer lanes for I-91 and I-395 to compare to the L1 and L4 data obtained during the regular photolog survey conducted on 6/9/01 (See Table 4A). For I-395 there was no significant change in these data and we concluded from this exercise that all outer lane data from the regular photolog surveys could be included in this study.

In the case of I-91, sections of the outer lanes were retested because of two large resurfacing projects on-going in the area north of Hartford. Both projects employ the SuperPave design process with the surface being placed in two lifts. Due to the uncertainty of the construction activities initially encountered, a limited survey of the outer lanes (L1 and L6) was conducted. The data showed significant changes from the initial survey, performed 4/30/01, to the December retests. We believe these differences are attributable to the ongoing construction operations.

Table 3 - IRI Trend for All Test Routes
(Data with outliers from Outer Lanes Only)

Route	Direction	IRI(m/km)-1997		IRI(m/km)-1998		IRI(m/km)-1999		IRI(m/km)-2000		IRI(m/km)-2001	
		Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.
8	North	1.85	1.00	1.87	1.02	1.87	1.14	1.60	1.15	1.59	1.15
	South	1.91	1.04	1.85	1.07	1.66	0.96	1.60	1.04	1.58	0.95
	Both	1.88	1.02	1.86	1.05	1.76	1.05	1.60	1.10	1.59	1.05
15	North	2.16	3.75	2.23	5.26	1.90	1.10	1.89	1.40	1.87	1.39
	South	2.15	3.00	2.18	4.58	1.89	1.06	1.84	1.07	1.86	1.39
	Both	2.16	3.38	2.20	4.92	1.89	1.08	1.87	1.24	1.87	1.39
I-91	North	1.99	1.10	1.72	0.99	1.74	1.05	1.70	1.11	1.64	1.11
	South	1.92	1.12	1.74	0.98	1.74	1.11	1.68	1.20	1.66	1.24
	Both	1.95	1.11	1.73	0.99	1.74	1.08	1.69	1.16	1.65	1.18
I-395	North	1.55	0.74	1.54	0.73	1.73	0.93	1.25	0.63	1.21	0.69
	South	1.60	0.76	1.64	0.78	1.63	0.90	1.28	0.77	1.22	0.70
	Both	1.57	0.75	1.59	0.76	1.68	0.92	1.27	0.70	1.22	0.70

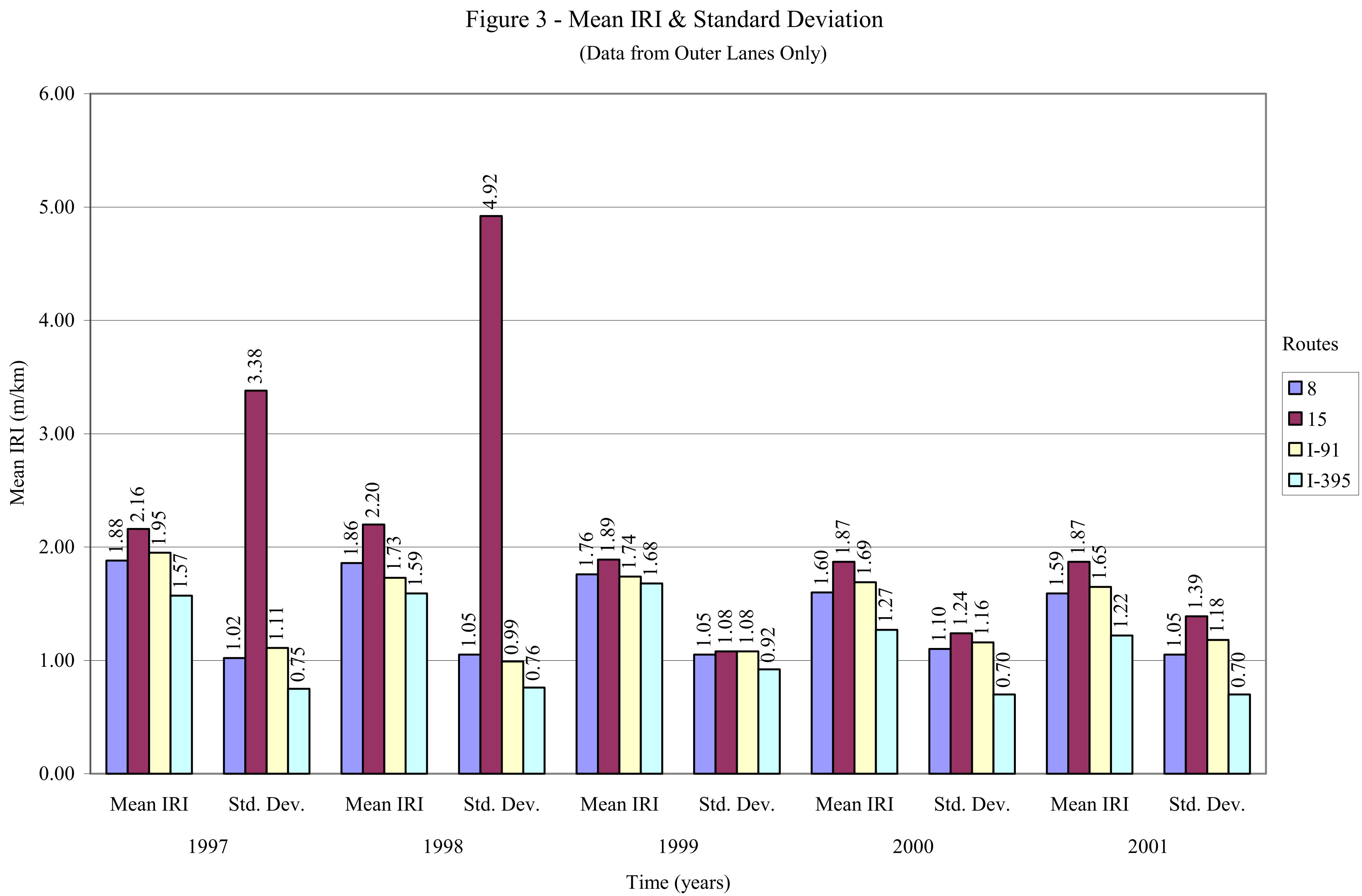


Figure 3 - Mean IRI & Standard Deviation
(Data from Outer Lanes Only)
Mean IRI (m/km)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1.88
2.16
1.95
1.57
1.02
3.38
1.11
0.75
1.86
2.20
1.73
1.59
1.05
4.92
0.99
0.76
1.76
1.89
1.74
1.68
1.05
1.08
1.08
0.92
1.60
1.87
1.69
1.27
1.10
1.24
1.16
0.70
1.59
1.87
1.65
1.22
1.05
1.39
1.18
0.70
Mean IRI
Std. Dev.
Mean IRI
Std. Dev.
Mean IRI
Std. Dev.
Mean IRI
Std. Dev.
Mean IRI
Std. Dev.
1997
1998
1999
2000
2001
Time (years)
Routes
8
15
I-91
I-395

Figure 4 - Standard Deviation for All Test Routes (Average of Both Roadways)

(Data from Outer Lanes Only)

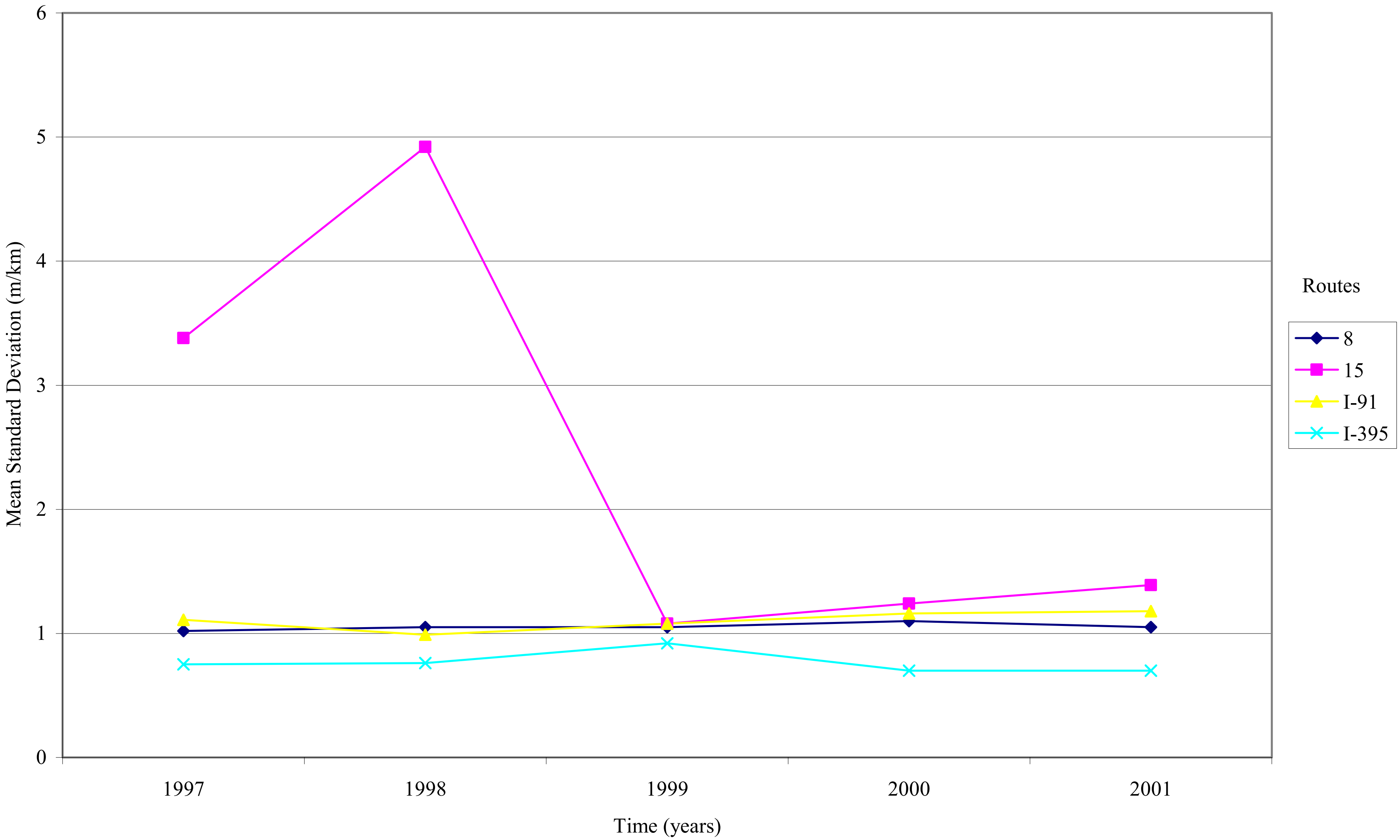


Table 4- Summary of 2001 IRI by Lane

Route	Direction	Lane	Mean	Std Dev.	Max/Min iri	Records	# of Outliers
8	N	1	1.59	1.07	20.64/0.34	10846	
	N(1)		**1.50**	**0.75**	**4.80/0.34**	**10666**	**180**
	N	2	1.42	0.95	18.89/0.30	9282	
	N(1)		**1.34**	**0.71**	**4.25/0.30**	**9119**	**163**
	S	3	1.40	0.88	11.87/0.29	9266	
	S(1)		**1.34**	**0.68**	**4.05/0.29**	**9119**	**147**
	S	4	1.58	0.89	15.29/0.33	10820	
	S(1)		**1.51**	**0.71**	**4.25/0.33**	**10631**	**189**
15 0-101 km(3)	N	1	1.84	1.36	21.85/0.48	10101	
	N(1)		**1.74**	**0.78**	**5.91/0.48**	**9997**	**104**
	N	2	1.71	1.37	27.61/0.41	10089	
	N(1)		**1.61**	**0.76**	**5.82/0.41**	**9987**	**102**
	S	3	1.72	1.53	30.87/0.48	10101	
	S(1)		**1.61**	**0.76**	**6.24/0.48**	**1009**	**92**
	S	4	1.85	1.44	23.60/0.49	10101	
	S(1)		**1.74**	**0.79**	**6.08/0.49**	**9996**	**105**
15 110-125 km(4)	N	1	2.06	1.13	13.62/0.69	1489	
	N(1)		**1.97**	**0.82**	**5.37/0.69**	**1464**	**25**
	N	2	3.10	1.59	31.25/0.69	1478	
	N(1)		**3.00**	**1.02**	**7.75/0.69**	**1467**	**11**
	S	3	1.91	1.21	16.81/0.53	1454	
	S(1)		**1.82**	**0.83**	**5.48/0.53**	**1435**	**19**
	S	4	1.96	1.02	12.57/0.60	1484	
	S(1)		**1.86**	**0.74**	**4.99/0.60**	**1452**	**32**
I-91	N	1	1.64	1.05	14.25/0.34	9351	
	N(1)		**1.54**	**0.73**	**4.78/0.34**	**9159**	**192**
	N	2	1.45	0.83	12.00/0.37	10461	
	N(1)		**1.38**	**0.61**	**3.94/0.37**	**10282**	**179**
	N	3	1.39	0.81	9.77/0.36	9329	
	N(1)		**1.33**	**0.61**	**3.81/0.36**	**9175**	**154**
	S	4	1.38	0.85	15.79/0.40	9341	
	S(1)		**1.30**	**0.60**	**3.93/0.40**	**9152**	**189**
	S	5	1.35	0.85	11.86/0.36	9290	
	S(1)		**1.26**	**0.59**	**3.89/0.36**	**9106**	**184**
	S	6	1.66	1.17	14.69/0.36	9347	
	S(1)		**1.53**	**0.80**	**5.16/0.36**	**9131**	**216**
	(2)HOV(N)	0	1.64	1.06	12.29/0.36	1129	
	HOV(N)(1)		**1.56**	**0.83**	**4.81/0.36**	**1111**	**18**
	HOV(S)	0	1.78	1.22	11.55/0.47	1065	
	HOV(S)(1)		**1.65**	**0.84**	**5.40/0.47**	**1041**	**24**
I-395	N	1	1.21	0.63	16.19/0.33	8863	
	N(1)		**1.17**	**0.45**	**3.09/0.33**	**8735**	**128**
	N	2	1.21	0.54	7.18/0.31	8875	
	N(1)		**1.17**	**0.45**	**2.84/0.31**	**8734**	**141**
	S	3	1.18	0.55	6.06/0.32	8864	
	S(1)		**1.15**	**0.47**	**2.83/0.32**	**8737**	**127**
	S	4	1.22	0.64	10.99/0.31	8855	
	S(1)		**1.17**	**0.47**	**3.13/0.31**	**8716**	**139**

(1) - Outliers, values> Mean+ (Std.Dev.X 3), removed and mean & Std.Dev. recalculated.
(2) - HOV: High Occupancy Vehicle Lane
(3) - 0-101 km: Parkway (4) -110-125 km: Unlimited Access

Figure 5 - 2001 Mean IRI by Lane (Average for Both Directions)

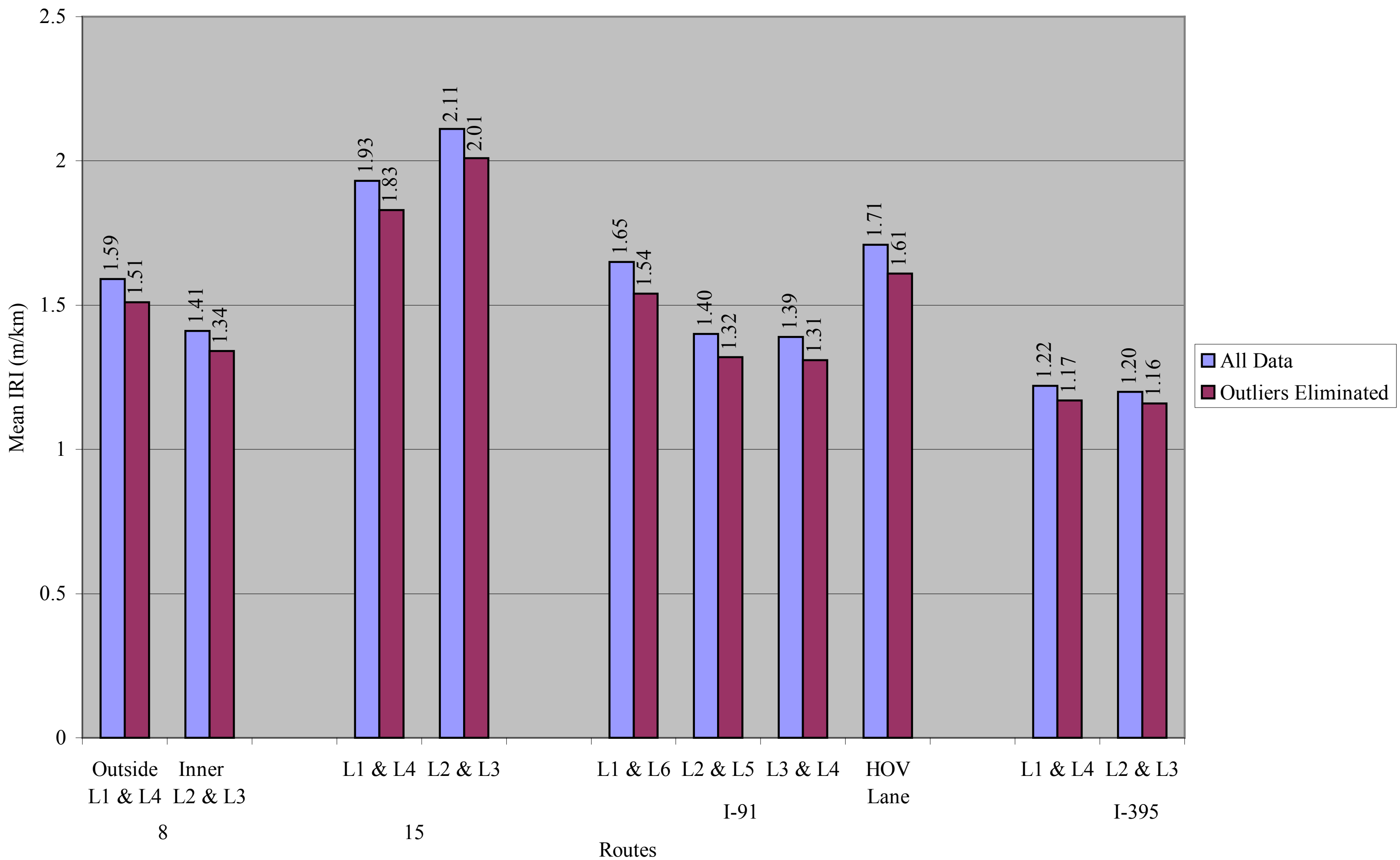


Table 4A – Recheck of 2001 IRI Data (Right Lane Only)

Route	Data	Location (ARAN)		IRI (m/km)			# of Records	# of Outliers
	of Test	Start (km)	End (km)	Mean	Std Dev.	Max/Min		
I-91	North-(4/01)	79.71	93.28	1.88	1.45	12.49/0.43	1358	
	North-(4/01)*			**1.76**	**1.16**	**6.13/0.43**	**1330**	**28**
	North-(12/01)	79.71	93.28	1.09	0.66	8.54/0.40	1358	
	North-(12/01)*			**1.03**	**0.44**	**3.07/0.40**	**1336**	**22**
I-395	North-(06/01)	0	21.16	1.17	0.70	16.19/0.33	2118	
	North-(06/01)*			**1.13**	**0.47**	**3.27/0.33**	**2097**	**21**
	North-(11/01)	0	21.16	1.15	0.53	6.32/0.29	2118	
	North-(11/01)*			**1.11**	**0.44**	**2.75/0.29**	**2083**	**35**
	South-(06/01)	22.06	0.08	1.15	0.61	10.99/0.31	2199	
	South-(06/01)*			**1.11**	**0.44**	**2.95/0.31**	**2170**	**29**
	South-(11/01)	22.06	0	1.13	0.5	5.28/0.29	2232	
	South-(11/01)*			**1.10**	**0.42**	**2.64/0.29**	**2198**	**34**

* - Outliers, values> Mean+ (Std.Dev.X 3), removed and mean & Std.Dev. recalculated.

IRI by Project – To further refine our analysis, each roadway was broken down into 27 paving projects along these routes representing 418 one-direction km of highway. The data were obtained from ConnDOT records. Only projects greater than one mile in length were analyzed and all bridge projects were excluded. Table 5 presents these data and Table 6 summarizes pertinent statistics and the results of significance tests for the projects. In this analysis we sought to determine if the IRI of the outer lane was significantly different from the adjacent lane or lanes. Each roadway was treated separately, i.e. L1 was compared to L2 and L3 and L6 was compared to L5 and L4. In Table 6, any lane shown greater than (>) there is a statistical significance at the 95% confidence level. When lanes are shown as equal (=) no significant difference was detected.

Table 7 shows a breakdown of the statistical results by test route. In 50.9 percent of projects analyzed the IRI in the outer lane was higher than the adjacent lane or lanes; in 38.6 percent of the projects there is no significant difference between the outer and adjacent lane or lanes. 10.5 percent of the projects had significantly higher IRI in the left-hand or middle lanes than the corresponding outer lane.

IRI by Lane – Figure 5 presents the IRI data by lane for each route tested. In each route there is little or no difference between the left-hand lane, and the right-hand lane or lanes. The exceptions are the HOV lanes on I-91, where the IRI is approximately 0.30 m/km higher than the IRI of the adjacent lanes (L3 and L4).

As stated above all outliers were removed and the mean and standard deviation were then recomputed. These data are shown in BOLD in Table 4. The number of outliers removed is tabulated in the right-hand column of the Table. It is interesting to note that the percentage of outliers/lane that was dropped is fairly uniform (1.0 – 2.3 percent). All tests for significance were performed using the t-test in EXCEL at a 95 percent confidence level. Unequal variance of the IRI data was assumed.

The results for Route 8 show that IRI data in the right-hand lanes, north and southbound, are not significantly different. When the right lane is compared to the adjacent lane in each roadway, it has a significantly higher IRI.

Route 15 was analyzed in two ways: (1) using the total length of highway, and (2) separating the parkway and the uncontrolled access sections of the highway. In (1) above no significant differences were found between the right-hand lanes, north and southbound. The right lanes north and southbound have significantly higher IRI than the left lanes north and southbound. In (2) above, corresponding lanes for the parkway and uncontrolled access sections were analyzed, i.e., L1 for the parkway to L1 for the uncontrolled access section. In all lanes, outside north and southbound, and both left-hand lanes have significantly lower IRI in the parkway section than in the uncontrolled access section. This difference is most likely related to the lack of truck traffic on the parkway.

In the case of I-91, the results of significance testing were different than those previously stated. When the outside lanes north and southbound were compared, and when the HOV lane north versus to the outside lane north were analyzed, no

Table 5 – Listing of Individual Project Data (Without Outliers)

Route #	Project #	Year Accepted	Start Mile (chainage)	End Mile (chainage)	Start Lat.	Start Long.	End Lat.	End Long.	Pavement Type	Surface Tested[1]	Depth of Surface(in.)	2001 IRI (m/km)-all lanes		
												Mean	Std. Dev.	Max/Min
	144-171	00	4.80 (7.71)	11.75 (18.89)	41.225919	73.166236	41.307635	73.097898	Comp [2]	SP[4] 12.5mm	3	0.79	0.36	3.94/0.33
	36-160	90	13.41(21.56)	18.11 (29.13)	41.324260	73.084922	41.389576	73.076892	Comp	cl-1[5]	1.5	2.02	0.82	4.77/0.57
	151-237(S)	93	31.38 (50.49)	38.31 (61.64)	41.566236	73.058358	41.655693	73.078952	Comp	cl-114[6]	1.5	1.43	0.66	4.23/0.41
8	140-151(S)	93	38.33 (61.67)	43.00 (69.20)	41.655963	73.078983	41.712561	73.088508	Comp	cl-1	1.5	1.39	0.65	4.23/0.40
	151-265(N)	98	31.37 (53.08)	38.31 (63.89)	41.587499	73.056928	41.672621	73.066499	Comp	cl-1	1.5	1.15	0.50	4.75/0.43
	73-149	90	43.10 (69.35)	50.67 (83.14)	41.713294	73.088888	41.827636	73.107263	Comp	cl-114	1.5	1.28	0.67	4.70/0.30
	56-257	98	0.08 (0.13)	2.24 (3.61)	41.037696	73.674835	41.066309	73.670553	Comp	cl-1	1.5	1.68	0.72	5.93/0.60
	173-279(N)	98	16.08 (25.88)	23.54 (37.88)	41.134904	73.454245	41.173358	73.324543	Comp	cl-1	2	1.58	0.80	5.77/0.41
Parkway	173-279(S)	95	23.56 (37.92)	34.11 (54.89)	41.173747	73.323511	41.237558	73.155913	Comp	cl-1	2	1.68	0.73	5.84/0.52
	173-334	2001	38.22 (61.40)	43.05 (69.29)	41.248450	73.08035	41.307200	73.033370	Comp	SP 12.5mm	11/2-2	1.51	0.64	5.68/0.48
15	106-101	88	43.09 (69.34)	45.87 (73.81)	41.307617	73.033175	41.328250	72.989386	Comp	cl-114	2	1.37	0.58	5.16/0.56
	61-127	94	52.14 (83.91)	56.54 (90.99)	41.382662	72.897594	41.431633	72.851856	Comp	cl-114	3/4	1.50	0.62	5.56/0.51
Unlimited	171-292	2001	76.35 (122.87)	77.92 (125.41)	41.686073	72.708019	41.708014	72.700327	Comp	SP 12.5mm	3	1.85	1.01	6.04/0.38
Access	159-173	97	77.95 (125.46)	80.93 (130.25)	41.708435	72.700112	41.737643	72.662667	Comp	cl-1	2 NB, 1.5 SB	1.65	0.81	5.72/0.50
	92-395	95	2.78 (4.48)	11.60 (18.66)	41.324081	72.882766	41.428264	72.813951	Comp	cl-114 on 1" of cl-1	3	1.45	0.63	5.01/0.44
	79-191	95	18.85 (30.34)	23.15 (37.26)	41.520960	72.771214	41.569618	72.724764	Comp	cl-114 on 2" of cl-2	4	1.31	0.50	4.78/0.40
	118-140	99	27.73 (44.63)	33.07 (53.22)	41.629004	72.686906	41.698311	72.643930	Comp	cl-1on 2" cl-2	4	1.16	0.45	4.51/0.41
I-91	164-177	92	41.40 (66.63)	46.32 (74.55)	41.806978	72.660558	41.877419	72.661971	Flex [3]	cl-1	41/2	1.51	0.68	4.91/0.39
	164-224	Under Const.	44.49 (76.61)	50.77 (81.71)	41.891625	72.647128	41.924612	72.609581	Comp&Flex	SP 12.5mm	3	1.42	0.69	5.14/0.37
	46-118	2001	50.75 (81.67)	57.98 (93.31)	41.924258	72.609668	42.023465	72.589154	Comp&Flex	SP 12.5mm	4	1.16	0.69	5.08/0.39
	85-131	2000	5.61 (9.02)	9.80 (15.77)	41.430273	72.121977	41.489728	72.114365	Flex	SP 12.5mm	3	0.89	0.41	3.05/0.31
	103-230	95	9.80 (15.77)	11.05 (17.78)	41.489728	72.114365	41.507553	72.115001	Comp&Flex	cl-1on 1" of cl-2	3-4	1.27	0.44	3.02/0.45
I-395	72-071	86	18.33(29.50)	29.28 (47.13)	41.585200	72.047825	41.675824	71.908716	Flex	cl-1	2	1.09	0.40	3.13/0.36
	172-120	86	29.30 (47.16)	35.00 (56.33)	41.676091	71.908686	41.753540	71.878067	Flex	cl-1	2	0.93	0.41	3.07/0.33
	68-175	93	35.20 (56.66)	43.28 (69.65)	41.756241	71.876469	41.867530	71.888812	Flex	cl-114 on 1" of cl-2	1.5	1.27	0.47	3.09/0.45
	108-152	93	43.37 (69.80)	54.53 (87.76)	41.868765	71.889479	42.016866	71.857953	Flex	cl-114 on 1" of cl-2	1.5	1.32	0.47	3.12/0.45

(1) Specification for the surface materials are shown in the Appendix 2.
(2) Comp = Composite structure, HMA overlay on existing PCC pavement.
(3) Flex = Flexible pavement, full-depth HMA pavement.
(4) SP = Super Pave - See Appendix 2.
(5) Cl-1 = Class 1 - See Appendix 2.
(6) Cl-114 = Class 114 - See Appendix 2.

Table 6 – Summary of Significance Tests by Project

Route #	Project #	Year Accepted	Mean IRI L1	L2	L3	L4	L5	L6	Results of Significance Tests
	144-171	00	0.78	0.86	0.78	0.76			L2 > L1; L3=L4
	36-160	90	2.16	1.99	1.86	2.07			L1 > L2; L4>L3
	151-237(S)	93			1.41	1.46			L3 =L4
8	140-151(S)	93			1.26	1.53			L4 >L3
	151-265(N)	98	1.09	1.21					L2 > L1
	73-149	90	1.73	0.86	0.91	1.6			L1 >L2; L4>L3
	56-257	98	1.39	1.55	1.8	2.0			L2>L1; L4>L3
	173-279(N)	98	1.73	1.43					L1 > L2
Parkway	173-279(S)	95			1.6	1.76			L4>L3
	173-334	2001	1.64	1.37	1.41	1.62			L1>L2; L4>L3
15	106-101	88	1.39	1.3	1.33	1.47			L1=L2; L4>L3
	61-127	94	1.54	1.53	1.44	1.51			L1=L2; L4=L3
Unlimited	171-292	2001	2.29	No data		2.43			No analysis performed
Access	159-173	97	1.66	No data		1.63			No analysis performed
	92-395	95	1.56	1.49	1.37	1.31	1.42	1.53	L1>L2;L1>3; L6>L5, L6>L4
	79-191	95	1.59	1.52	1.3	1.18	1.14	1.15	L1>L2; L1>L3; L6=L5; L6=L4
	118-140	99	1.18	1.2	1.19	1.14	1.1	1.14	L1=L2; L1=L3; L6=L5; L6=L4
I-91	164-177	92	1.82	1.37	1.38	1.34	1.33	1.80	L1>L2; L1>3; L6>L5; L6>L4
	HOV	Under Const.	1.82(1)	1.56(North)		1.65(South)		1.80(2)	L1>HOVN; L6>HOVS
	164-224	Under Const.	1.47	1.48	1.53	1.33	1.15	1.58	L1=L2; L1=L3; L6>L5; L6>L4
	46-118	2001	1.62	0.91	0.91	0.96	0.97	1.64	L1>L2; L1>3; L6>L5; L6>L4
	85-131	2000	0.84	0.91	0.94	0.88			L2>L1; L3>L4
	103-230	95	1.34	1.28	1.25	1.22			L1 =L2; L4=L3
I-395	72-071	86	1.07	1.15	1.04	1.07			L2>L1; L4=L3
	172-120	86	0.99	0.94	0.87	0.91			L1=L2; L4=L3
	68-175	93	1.24	1.26	1.27	1.28			L1=L2; L4=L3
	108-152	93	1.29	1.31	1.34	1.36			L1=L2; L4=L3

(1) L1 data from project 164-177
(2) L6 data from project 164-177

Red: Inner Lane > Outer Lane
Blue: Outer Lane = Inner Lane
Black: Outer Lane > Inner Lane

Table 7 - Tabulation of Tests for Significance by Projects

Route	Outer Lanes > Inner Lanes	Inner Lanes > Outer Lanes	No Significant Difference (Inner Lanes = Outer Lanes)
8	5*	2	2
15	6	1	3
I-91	18	0	8
I-395	0	3	9
Total	24	6	22
% totals	50.9%	10.5%	38.6%

* Number of Lane Comparisons

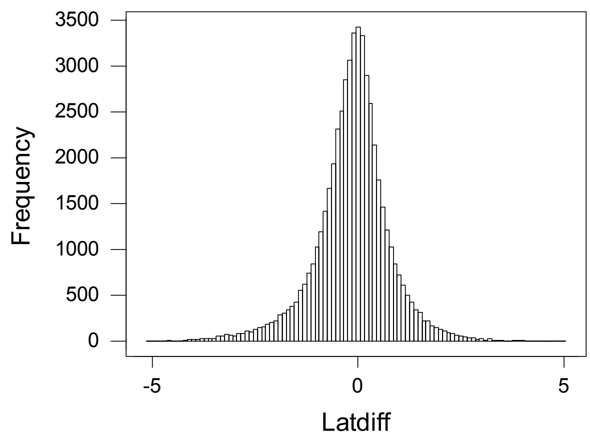
significant differences were found. The HOV lane southbound had significantly higher IRI than both the HOV lane northbound and the outside lane southbound. In some cases, however, outside lane vs. middle and inner lane northbound, and outside vs. middle lane southbound, the outer lane had a significantly higher IRI than the other lanes.

For I-395, the analysis performed showed no significant difference when the outside lanes were compared and when the outer and inner lanes northbound were analyzed. The outside lane southbound had slightly higher IRI than the inner lane southbound. Data for I-395 were very uniform and consistent.

IRI by Surface Paving Material - In order to assess pavement type and age as factors responsible for in variation in IRI or lateral difference in IRI, the pavement-surface-mix design and age data were obtained on specific projects and are shown in Table 5. The Table presents information on pavement type (flexible or composite), the in-place type or classification of bituminous concrete surfacing tested in 2001, and design depths of the surface course. Several projects involved the construction of a composite or overlaid pavement and the new construction of a flexible pavement on adjacent new alignment. Pertinent specifications for the materials are shown in Appendix 1. For this research, shorter projects, usually involving bridges only, were excluded from the analysis. The tabulated data were used to judge the influence of material type and age of the surface course on IRI. Figures 7 and 8 show the mean IRI for the three bituminous surface courses tested and the mean IRI as a function of time for the corresponding mixes. The average IRI for the SuperPave design, Class 1, and Class 114 materials, are 1.17, 1.36 and 1.38 m/km, respectively. The reader is cautioned that ConnDOT is currently implementing the SuperPave design process. The materials designated as Classes 1 and 114 are being phased out which create a confounding effect between age and surface type and it is impossible to separate these effects. Figure 9 depicts IRI vs. Age for flexible and composite construction.

Local Lateral IRI Differences Using Spatial Analysis – In order to analyze lateral IRI deviations on a smaller spatial scale, and to plot differences for visual inspection, the GIS program ArcView was used. Instead of averaging the IRI by lane along an entire route or project, this section of the analysis included the calculation of local differences between proximate individual measurements in adjacent lanes. For every IRI point location, the spatial join feature of the ArcView GIS was used to compute the difference in IRI in the middle center or median left lane relative to the closest outer right lane point. The spatial join feature of the ArcView GIS allowed each middle center lane or median left lane IRI observation to be automatically linked with the physically closest IRI point in the outer right lane. Once linked a difference could be calculated. Because the IRI data in adjacent lanes was not collected simultaneously this GIS spatial join tool was needed to link the IRI points based on latitude and longitude. The distribution of lateral IRI differences is shown in Figure 6. In this case, all IRI values in the middle or leftmost lanes are considered relative to the outer right lane so the average lateral difference of –0.14 is consistent with the aggregate results above, indicating that the outer right lane is slightly rougher (the standard deviation was 0.90). Use of a normal distribution probability plot revealed that the lower 5% of observations and the upper 1% of observations are further from the mean than would be predicted for a normal distribution. This suggests some extreme outliers but for the most part the lateral difference varies randomly in a slightly skewed near normal distribution. Therefore, the average results presented above are corroborated by the detailed lateral difference analysis; lateral difference is relatively consistent and random, but small in magnitude.

Figure 6: Proximate Lateral IRI Differences



Lateral Difference (m/km)

IRI and DISTRESS

Assessment of Distress at Outlier Locations – As stated previously, the entire dataset was analyzed and IRI values greater than three standard deviations from the mean for each roadway were eliminated. The data set was reanalyzed and a new standard deviation calculated.

All outliers were also located using ArcView and photolog images of the locations reviewed manually to define the source of the high IRI values. For this process, the color photolog images at the approximate location of the IRI data were examined in the outer lane only. A sample of typical photolog images is enclosed in Appendix 2. In over 95 percent of the images reviewed, the higher IRI values are directly related to construction or maintenance activities conducted by ConnDOT or were rough bridge decks or approaches. The remaining locations could not be adequately examined due to poor lighting conditions.

Cracking data were provided by ConnDOT Pavement Management staff, who used the WISECRAX® software to detect cracking oriented longitudinally or transversely; assign a severity of low, medium or high based on crack width; and output a summary of the distress in an excel spreadsheet. These data were compared to the IRI data at the locations indicated and, in turn, the corresponding photolog images were examined to visually assess the type of distress present at the location of high IRI values.

Figure 7 - Mean IRI for Various Surface Course Mixes

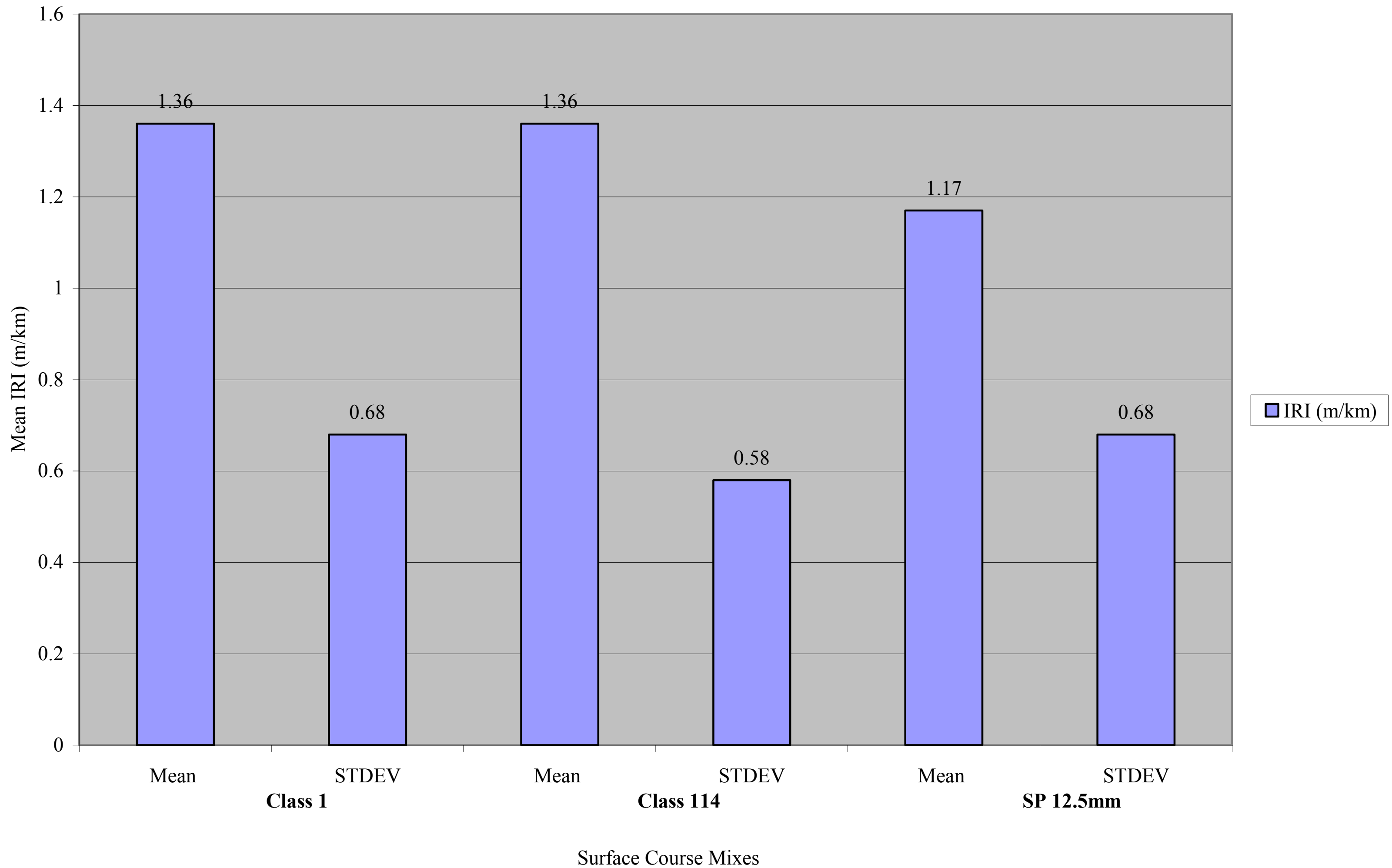


Figure 8 - IRI vs Age for Surface Mixes Tested

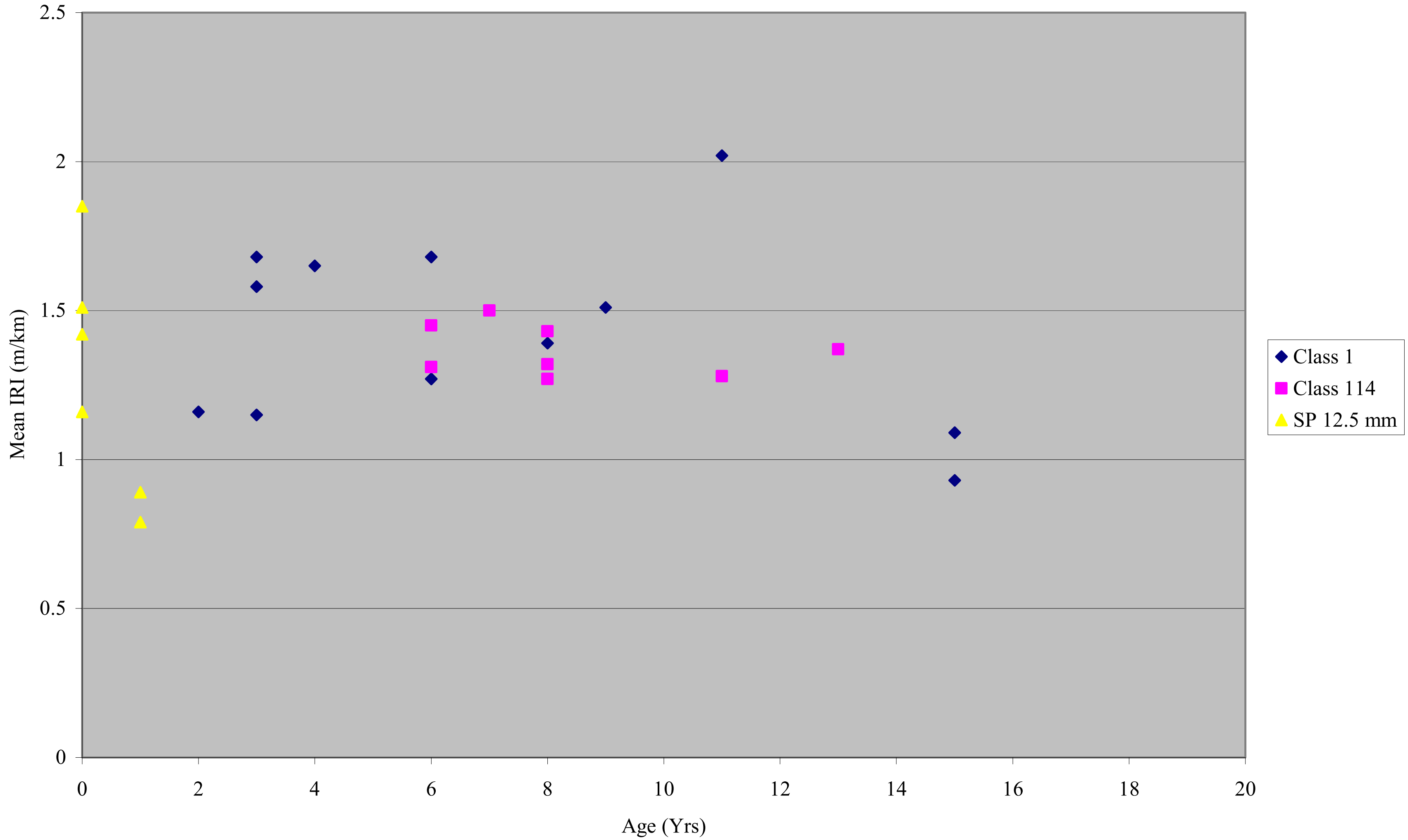
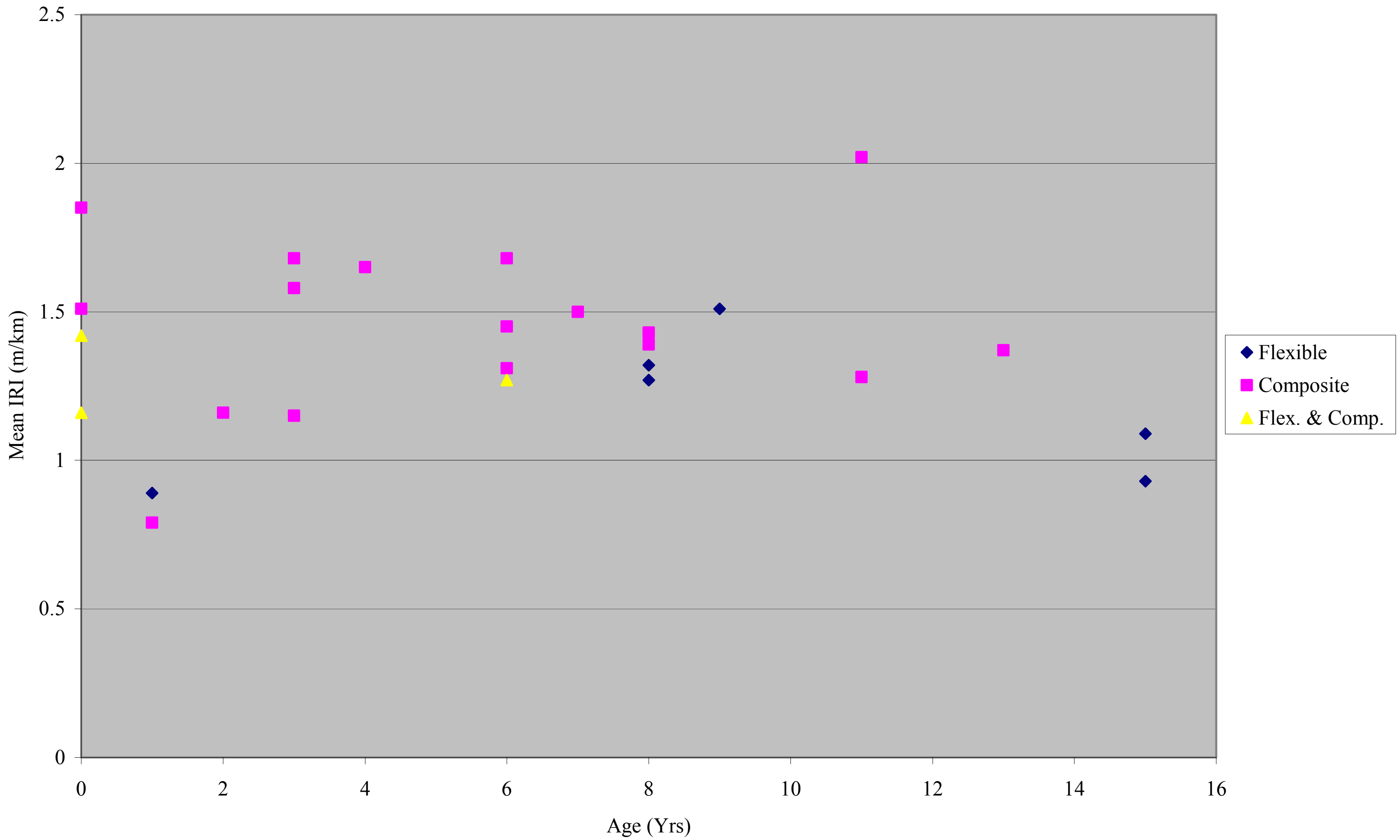


Figure 9 - Mean Project IRI vs Age for Flexible & Composite Pavement



Statistical Analysis of Rutting and Cracking Data – ANOVA and Regression techniques were employed to determine the effect of cracking and rutting on IRI. Both rut and cracking data were provided by ConnDOT staff. The systems employed to obtain and process these data are described briefly below.

Rutting is measured by ultrasonic sensors positioned at 100mm intervals on an expandable rut bar mounted on the front bumper of the ARAN vehicle. The sensors measure the height to the road surface every 5m and report the maximum depth of rut in the left and right wheel paths. For this project, the rut bar width was set at eight Feet (2.4m). The rut bar can be expanded to 12 feet, however, following traffic protection is required when the bar is extended to 12 feet.

Cracking data were obtained using two down-facing cameras mounted on the rear of the ARAN vehicle. The cameras are synchronized with high intensity strobes to illuminate the pavement surface. The pavement images currently are stored on S-VHS tape. To determine the distresses recorded and validate route sections the S-VHS tape is: digitized, and the image lighting normalized. These operations produce a 10-m long by 4-m wide section of pavement in each wheel path that is automatically analyzed using the proprietary software WISECRAX®. Sensitivity of the film analysis is determined by ConnDOT staff. The WISECRAX® software then measures the length of cracking and classifies the cracks based on orientation (longitudinal or transverse), location of cracking within the lane, and the width of crack. These data are summarized at 10-m intervals and placed on an excel spreadsheet. In this project, total cracking per 10-m was used to characterize this form of distress.

Only data from the outer lanes were analyzed. All outliers had been removed and the data smoothed to 100m intervals. Appendix 3 presents the detailed results of this effort for each route. Tables 8 and 9 are summaries of the results obtained and Figures 9 and 10 are plots of the regression equations for rutting and cracking, respectively.

There is a statistically significant relationship between each of cracking and rutting and the IRI (see t-tests). However, the low R^2 values indicate many other factors are at play in the complex relationships between surface quality measures. Based on the analyses performed, rut has the greatest influence on IRI and cracking affects IRI to a lesser extent.

CONCLUSIONS

1. There are smoothness differences in adjacent lanes of a multiple-lane freeway. 50.9 percent of time, the outer lanes had greater IRI than that of the adjacent lanes. 10.5 percent of the time, the inner lanes had a higher IRI than the outer lane, and 38.6 percent of the comparisons showed no significant difference between the IRI in the outer and adjacent lanes. The lateral differences are relatively consistent, random and small in magnitude (on average the right lane is 0.25 m/km higher).
2. No strong causal relationships were found among pavement age, surface design, type of surfacing material, or traffic loading, and IRI. However, if more

controlled systematic experiments were undertaken relationships among these variables might be found.

3. Using the ConnDOT photolog tool, IRI outliers, were found to be associated with various construction, maintenance activities and bridge decks.
4. Cracking was also analyzed and found to have a limited relationship with IRI. Rutting has by far a much greater correlation with IRI.

RECOMMENDATION

ConnDOT should not measure IRI in adjacent traffic lanes as part of its annual photolog surveys. The data obtained in the outer lanes are adequate for the assessment of Connecticut highways. This does not preclude, as special circumstances warrant, the IRI assessment of left-hand lane or lanes in the future.

Table 8 - Summary of Regression Equations for Rutting (Lane 1 Only)

Route	Equations for Rutting	R^2	P>|t|
8	IRI = 0.589+(0.29*Rut)	0.231	0.000
15-Parkway	IRI = 1.243+(0.193*Rut)	0.146	0.000
15-Unlimited Access	IRI = 0.87+(0.336*Rut)	0.286	0.000
I-91	IRI =0.491 + (0.305*Rut)	0.279	0.000
I-395	IRI = 0.82+(0.143*Rut)	0.246	0.000

Figure 10 - Equations for Rutting

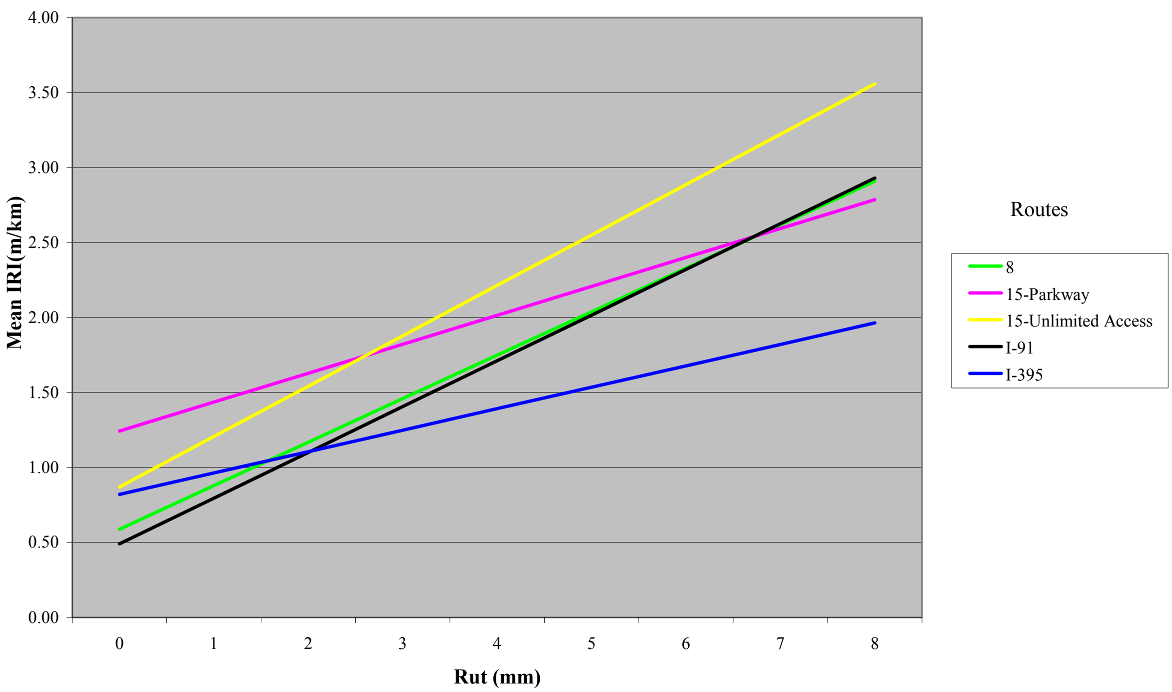
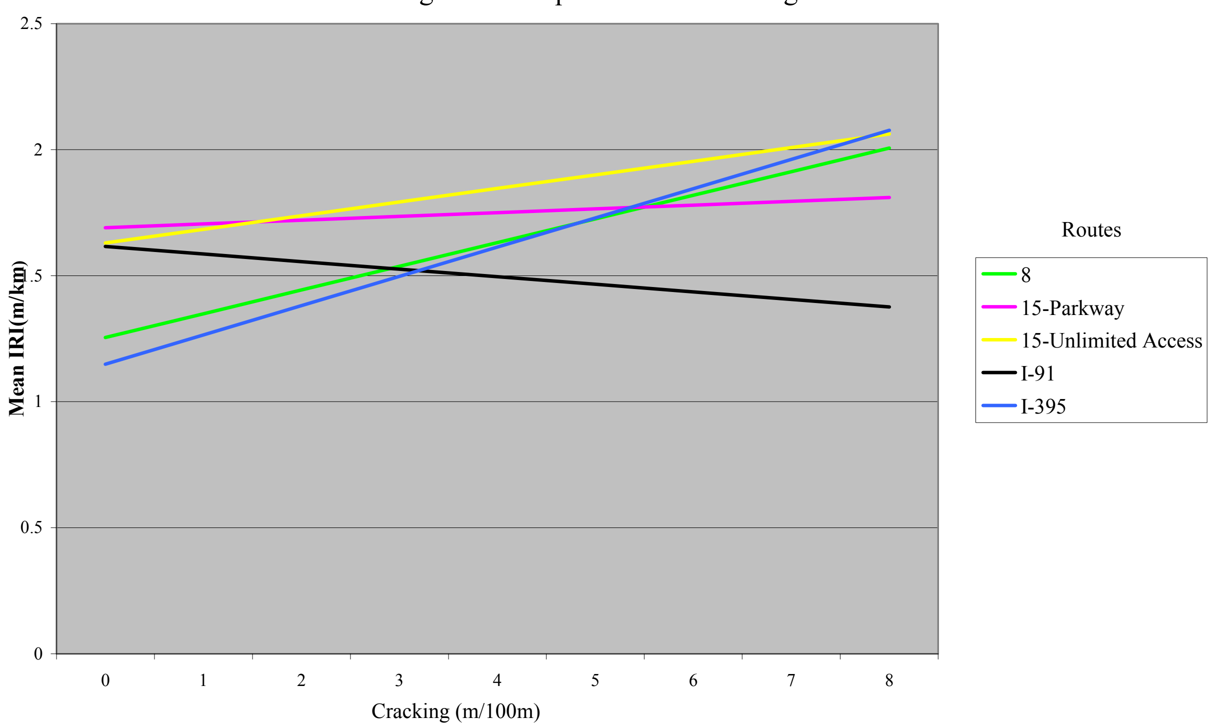


Table 9 - Summary of Regression Equations for Cracking (Lane 1 Only)

Route	Equations for Cracking	R^2	P>|t|
8	IRI = 1.255+(0.094*Crack)	0.12	0.000
15-Parkway	IRI = 1.690+(0.015*Crack)	0.005	0.023
15-Unlimited Access	IRI = 1.63+(0.054*Crack)	0.12	0.000
I-91	IRI =1.616 + (-0.03*Crack)	0.014	0.000
I-395	IRI = 1.149+(0.116*Crack)	0.03	0.000

Figure 11 - Equations for Cracking



SELECTED REFERENCES

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Appendix 1

Summary of HMA Mix Properties

Subarticle M.04.01 – 3(a): TABLE 1: Mixture criteria and Job Mix Formula tolerances

	9.5 mm Superpave				**12.5 mm Superpave**				**19.0 mm Superpave**				**25.0 mm Superpave**				**37.5 mm Superpave**				
Sieve	CONTROL POINTS		RESTRICTED ZONE		CONTROL POINTS		RESTRICTED ZONE		CONTROL POINTS		RESTRICTED ZONE		CONTROL POINTS		RESTRICTED ZONE		CONTROL POINTS		RESTRICTED ZONE		**TOL.**
Mm	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	**± (%)**
50.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	**6**
37.5	-	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	90	100	-	-	**6**
25.0	-	-	-	-	-	-	-	-	100	-	-	-	90	100	-	-	-	90	-	-	**6**
19.0	-	-	-	-	100	-	-	-	90	100	-	-	-	90	-	-	-	-	-	-	**6**
12.5	100	-	-	-	90	100	-	-	-	90	-	-	-	-	-	-	-	-	-	-	**6**
9.5	90	100	-	-	-	90	-	-	-	-	-	-	-	-	-	-	-	-			**6**
4.75	-	90	-	-	-	-	-	-	-	-	-	-	-	-	39.5	39.5	-	-	34.7	34.7	**6**
2.36	32	67	47.2	47.2	28.0	58.0	39.1	39.1	23.0	49.0	34.6	34.6	19.0	45.0	26.8	30.8	15.0	41.0	23.3	27.3	**6**
1.18	-	-	31.6	37.6	-	-	25.6	31.6	-	-	22.3	28.3	-	-	18.1	24.1	-	-	15.5	21.5	**4**
0.600	-	-	23.5	27.5	-	-	19.1	23.1	-	-	16.7	20.7	-	-	13.6	17.6	-	-	11.7	15.7	**4**
0.300	-	-	18.7	18.7	-	-	15.5	15.5	-	-	13.7	13.7	-	-	11.4	11.4	-	-	10.0	10.0	**3**
0.150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**3**
0.075	2.0	10.0	-	-	2.0	10.0	-	-	2	8	-	-	1	7	-	-	0	6	-	-	**2**
Binder	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**0.4**
VMA(%)	**15 – 17**				**14 – 16**				**13 – 15**				**12 – 14**				**11 – 13**				**- - - -**

G_{mm}	**G_{se}**	**Air Voids at N_d**	**Dust [1] to Asphalt ratio:**	**Tensile Strength Ratio[2]:**
± 0.030	**± 0.040**	**4 ± 1.0 (%)**	**0.6 to 1.2**	**80 % MIN.**

Note 1: - Dust is considered to be the percent of material passing the 0.075 mm sieve. The calculated effective asphalt content (Pbe) shall be used for this calculation.
Note 2: - Tensile Strength Ratio: AASHTO T 283 (Modified) performed during mix design.

Subarticle M.04.01-3(a): TABLE 2: Consensus Properties of Combined Aggregate Structure for Superpave Mixtures.

Traffic Level	Design ESALs (80 kN)	Coarse Aggregate Angularity [3] ASTM D5821		Fine Aggregate Angularity [3] AASHTO T-304		Flat or Elongated Particles ASTM D-4791	Sand Equivalent AASHTO T-176
-----	(million)	(Depth from final surface) ≤ 100 mm	(Depth from final surface) > 100 mm	(Depth from final surface) ≤ 100 mm	(Depth from final surface) > 100 mm	> 4.75 mm	-----
1	< 0.3	55/- -	- -/- -	- -	40	- - -	40
2	0.3 to < 3.0	75/- -	50/- -	40	40	10	40
3	3.0 to < 30.0	95/90[4]	80/75[4]	45	40	10	45
4	≥ 30.0	100/100	100/100	45	45	10	50
	Design ESALs are the anticipated project traffic level expected on the design lane, projected over a 20 year period, regardless of the actual expected design life of the roadway.	Criteria presented as minimum values. 95/90 denotes that a minimum of 95% of the coarse aggregate, by mass, shall have one fractured face and that a minimum of 90% shall have two fractured faces.		Criteria presented as minimum percent air voids in loosely compacted fine aggregate passing the 2.36 mm sieve.		Criteria presented as maximum Percent by mass of flat or elongated particles of materials retained on the 4.75 mm sieve, determined at 3:1 ratio.	Criteria presented as minimum values for fine aggregate passing the 2.36 mm sieve.

<u>**Note 3:**</u> If less than 25 % of a given layer is within 100 mm of the anticipated top surface, the layer may be considered to be below 100 mm for mixture design purposes.
<u>**Note 4:**</u> For Superpave mixtures with design ESALs between **3.0 and 10.0 million**, the coarse aggregate angularity criteria shall be <u>**85/80**</u> for layers < 100 mm depth from final surface and a criteria of <u>**60/- -**</u> for layers >100 mm from final surface.

Subarticle M.04.01-3(a): TABLE 3: Hot Mix Asphalt and Volumetric Properties for Superpave Mixtures.

Traffic Level	Design ESALs (million)	Number of Gyrations by Superpave Gyratory Compactor			Percent Density of Gmm from HMA specimen			Voids Filled with Asphalt (VFA) Based on Nominal mix size				
		Nini	Ndes	Nmax	Nini	Ndes	Nmax	9.5 mm	12.5 mm	19.0 mm	25.0 mm	37.5 mm
1	< 0.3	6	50	75	≤ 91.5	95 - 97	≤ 98.0	70 - 80	70 - 80	70 - 80	67 – 80	64 – 80
2	0.3 to < 3.0	7	75	115	≤ 90.5	95 - 97	≤ 98.0	65 - 78	65 - 78	65 - 78	65 - 78	64 - 78
3	3.0 to < 30	8	100	160	≤ 89.0	95 - 97	≤ 98.0	73 - 76	65 - 75	65 - 75	65 - 75	64 - 75
4	≥ 30.0	9	125	205	≤ 89.0	95 - 97	≤ 98.0	73 - 76	65 - 75	65 - 75	65 - 75	64 - 75

M.04.03 - HOT MIX ASPHALT MIXTURES
MASTER RANGE
2001

	CLASS									TOLERANCE
PASSING (%)	**1** PG 64-28 (k)	**2** PG 64-28 (k)	**3** PG 64-28 (k)	**4** PG 64-28 (k)	**12** PG 64-28 (k)	**5**(f) MC-250(e)	**5A**(f) MC-250(e)	**5B**(f) MC-250(e)		± Percent
75 µm	3-8(h)	3-8(h)	3-8(h)	0-5(h)	3-10(h)	0-2.5	0-2.5	0-2.5		2
300 µm	6-26	8-26	10-30	5-18	10-40					4
600 µm	10-32	16-36	20-40		20-60	2-15	2-15	2-15		5
2.36 mm	28-50	40-64	40-70	20-40	60-95	10-45	10-45	10-45		6
4.75 mm	40-65	55-80	65-87	30-55	80-95	40-100	40-100	40-100		7
6.3 mm										
9.5 mm	60-82	90-100	95-100	42-66	98-100	100	100	100		8
12.5 mm	70-100	100	100		100					8
19.0 mm	90-100			60-80						8
25.0 mm	100									
50.0 mm				100						
ASPHALT CEMENT -% (g)	5.0-6.5	5.0-8.0	6.5-9.0	4.0-6.0	7.5-10.0	6.0-7.5	6.0-7.5(i)	6.0-7.5(j)		0.4
TEMPERATURES--°C										
ASPHALT CEMENT	163 max	163 max	163 max		163 max	60-85	60-85	60-85		
MIXTURES	129-163	129-163	129-163		129-163 (a)	49-79	49-79	49-79		
AGGREGATE	138-177	138-177	138-177		138-177	38-79	38-79	38-79		
VOIDS - %	3-6(b)	2-5(c)	0-4		0-5(b)					
STAB. - N - min.	5300(d)	4500	4500		4500					
FLOW - mm	2-4	2-4	2-5		2-4					
VMA - % - min.	15(1):16(2)									

(1) Mixture with 5% or more aggregate retained on 19mm sieve.
(2) Mixture finer than condition (1) above.

(a) 300ºF minimum after October 1.
(b) 75 blows (Marshall criteria).
(c) 3-6% when used for a roadway wearing surface.
(d) For divided roadways with 4 or more lanes, a stability of 6600N. is required.
(e) Contains an approved nonstripping compound.
(f) To help prevent stripping, the mixed material will be stockpiled on a paved surface and at a height not greater than 1.5 m during the first 48 hours.
(g) All producers shall add at least the minimum allowable percentage of asphalt cement to the mixes.
(h) The percentage of -75 µm mesh material shall not exceed the percentage of asphalt cement determined by extraction tests (AASHTO T 164, Modified; see Note 1).
(i) Polypropylene fibers, 9.5mm to 12.5mm inch, added at the minimum rate of 3 kg of fiber per ton of mix. Fibers shall be approved by the Director of Research and Materials.
(j) Polyester Fibers, 6.3mm, added at the rate of 1.25kg of fiber per ton of mix. Fibers shall be approved by the Director of Research and Materials.
(k) Or as specified.

M.04.03 – BITUMINOUS CONCRETE MIXTURES
MASTER RANGE
1 9 9 4

	CLASS											TOLERANCE
PASSING (%)	**1 AC-20**	**114 AC-20**	2 AC-20	3 AC-20	4 AC-20	12 AC-20	14 AC-20	5(f) MC-250(e)	5A(f) MC-250(e)	5B(f) MC-250(e)	8 MC-3000	± Percent
#200	**3-8(h)**	**2-5**	3-8(h)	3-8(h)	0-5(h)	3-10(h)	1-5	0-2.5	0-2.5	0-2.5	3-10(h)	2
#50	**6-26**	**8-18**	8-26	10-30	5-18	10-40					15-40	4
#30	**10-32**	**13-22**	16-36	20-40		20-60		2-15	2-15	2-15	20-60	5
#8	**28-50**	**22-32**	40-64	40-70	20-40	60-95	5-19	10-45	10-45	10-45	65-95	6
#4	**40-65**	**26-40**	55-80	65-87	30-55	80-95	20-45	40-100	40-100	40-100		7
1/4”											95-100	
3/8”	**60-82**	**55-70**	90-100	95-100	42-66	98-100	80-100	100	100	100	100	8
1/2”	**70-100**	**90-100**	100	100		100	95-100					8
3/4”	**90-100**	**95-100**			60-80		100					8
1”	**100**	**100**										
1 1/2”					100							
BITUMEN % (g)	**5-8**	**4.8-6.5**	5-8	6.5-9	4-6	7.5-10	5.5-7.5	6.0-7.5	6.0-7.5(i)	6.0-7.5(j)	7-10	0.4
TEMPERATURES (°F)												
BITUMEN	**325 max**	**325 max**	325 max	325 max	325 max.	325 max	325 max.	140-185	140-185	140-185	150-200	
MIXTURES	**265-325**	**265-325**	265-325	265-325	256-325	265-325(a)*	225-250	120-175	120-175	120-175	275-325*	
AGGREGATE	**280-350**	**280-350**	280-350	280-350	250-350	280-350		100-175	100-175	100-175	280-350	
VOIDS %	**3-6(b)**	**3-6(b)**	2-5(c)	0-4		0-5(b)						
STAB. (lbs – min)	**1200(d)**	**1200**	1000	1000		1000						
FLOW (inches)	**.08-.15**	**.08-.15**	.08-.15	.08-.18		.08-.15						
VMA (% - min)	**15(1):16(2)**	**16**										

* 300ºF minimum after OCTOBER 1

(1)	Mixture with 5% or more aggregate retained on 3/4” sieve.
(2)	Mixture finer than condition (1) above.
(a)	Or recommended by membrane manufacturer
(b)	75 blows (Marshall criteria).
(c)	3-6% when used for a roadway wearing surface.
(d)	For divided roadways with 4 or more lanes, a s tability of 1500 lb. is required.
(e)	Contains an approved nonstripping compound.
(f)	To help prevent stripping, the mixed material will be stockpiled on a paved surface and at a height not greater than 4 feet during the first 48 hours.
(g)	All producers shall add at least the minimum allowable percentage of asphalt cement to the mixes.
(h)	The percentage of -200 mesh material shall not exceed the percentage of bitumen determined by extraction tests (AASHTO T 164, Modified).
(i)	Polypropylene fibers, 3/8 to 1/2 inch, added at the minimum rate of 6 pounds of fiber per ton of mix. Fibers shall be approved by the Director of Research and Materials.
(j)	Polyester Fibers, 1/4 inch, added at the rate of 2 1/2 pounds of fiber per ton of mix. Fibers shall be approved by the Director of Research and Materials.

Appendix 2

Typical Images of Existing Pavement Conditions

@Outlier Locations and
@ Areas Containing "Good" IRI Data

Typical Images of Route 8 N - Lane 1

Outliers

Location 2.08 km
Mean IRI -7.27 m/km
Rough Bridge Deck and Joints

Location 20.46 km
Mean IRI - 6.59 m/km
Rough Bridge Deck and Joints

Route 8

Location 27.41 km
Mean IRI - 4.32 m/km
Edge Cracking and Sealed Crack

Location 89.79 km
Mean IRI - 2.35 m/km
Longitudinal Cracks in Wheelpaths

Typical Images of Route 15 N - Lane 1 (Parkway)

Outliers

Location 60.22 km
Mean IRI - 18.28 m/km
Open-Grid Bridge Deck

Location 28.64 km
Mean IRI – 10.26 m/km
Underlying Joint Distress

Route 15 N - Lane 1 (Parkway)

Location 16.93 km
Mean IRI -4.11 m/km
Longitudinal Cracking at Slab Edges

Location 45.93 km
Mean IRI - 3.45 m/km
Longitudinal and Transverse Reflective Cracks

Route 15 N - Lane 1 (Unlimited Access)

Outliers

Location 118.37 km
Mean IRI –11.05 m/km
Transverse Reflection Cracking

Location 112.19 km
Mean IRI –8.28 m/km
Rutted Pavement at Traffic Light

Route 15 N - Lane 1 (Unlimited Access)

Location 120.48 km
Mean IRI – 1.96 m/km
Transverse and Longitudinal Reflection Cracking

Location 124.40 km
Mean IRI – 1.63 m/km
Sealed Transverse and Longitudinal Reflection Cracks

Typical Images of I-91 N - Lane 1

Outliers

Location 59.53 km
Mean IRI - 10.40 m/km
Rough Skewed Bridge Joint

Location 84.66 km
Mean IRI - 12.76 m/km
Construction Project –Milling of Existing Bituminous Pavement

Typical Images of I-91 N - Lane 1

Location 17.21 km
Mean IRI - 3.66 m/km
Transverse Reflection Crack

Location 20.36 km
Mean IRI - 3.61 m/km
Pavement Cracking

Typical Images of I-395 N - Lane 1

Outliers

Location 46.37 km
Mean IRI - 8.19 m/km
Bridge Reconstruction

Location 48.08 km
Mean IRI - 5.33 m/km
Bridge Reconstruction

Typical Images of I-395 N - Lane 1

Location 22.43 km
Mean IRI - 2.61 m/km
Longitudinal Edge Cracking

Location 15.90 km
Mean IRI - 2.38 m/km
Cracking at Acceleration Lane

Appendix 3

Results of Regression Analysis for Each Test Route

Result of Regression Analysis for Rt 8-Lane1: IRI & Rut

Number of Obs =1057
F (1, 1056) =316.336
Prob > F =0.000
R-squared =.231
Adj R-squard =.230

Source	SS	df	MS
Model	68.386	1	68.386
Residual	228.071	1055	0.216
Total	296.457	1056	

IRI(Rt 8 L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Rut	0.291	0.016	17.786	0.000	0.259	0.323
Constant	0.589	0.053	11.155	0.000	0.486	0.693

IRI =0.589 + (0.291*Rut)

Result of Regression Analysis for Rt 8-Lane1: IRI & Cracking

Number of Obs =1057
F (1, 1056) =143.942
Prob > F =0.000
R-squared =.120
Adj R-squard =.119

Source	SS	df	MS
Model	35.592	1	35.592
Residual	260.865	1055	0.247
Total	296.457	1056	

IRI(Rt 8 L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Crack	0.094	0.008	11.998	0.000	0.079	0.11
Constant	1.255	0.025	50.055	0.000	1.206	1.305

IRI =1.255 + (0.094*Crack)

Results of Regression Analysis for Rt 15-Parkway-Lane1: IRI & Rut

Number of Obs =998
F (1, 998) =169.946
Prob > F =0.000
R-squared =.146
Adj R-squard =.145

Source	SS	df	MS
Model	34.093	1	34.093
Residual	200.008	997	0.201
Total	234.101	998	

IRI(Rt 15-Parkway L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Rut	0.193	0.015	13.036	0.000	0.164	0.222
Constant	1.243	0.04	30.831	0.000	1.164	1.322

IRI =1.243 + (0.193*Rut)

Results of Regression Analysis for Rt 15-Parkway-Lane1: IRI & Cracking

Number of Obs =999
F (1, 998) =5.196
Prob > F =0.023
R-squared =.005
Adj R-squard =.004

Source	SS	df	MS
Model	1.214	1	1.214
Residual	232.887	997	0.234
Total	234.101	998	

IRI(Rt 15-Parkway L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Crack	0.018	0.008	2.28	0.023	0.003	0.035
Constant	1.69	0.025	67.624	0.000	1.641	1.739

IRI =1.69 + (0.018*Crack)

Results of Regression Analysis for Rt 15-Unlimited Access-Lane1: IRI & Rut

Number of Obs =309
F (1, 308) =122.925
Prob > F =0.000
R-squared =.286
Adj R-squard =.284

Source	SS	df	MS
Model	23.946	1	23.946
Residual	59.805	307	0.195
Total	83.752	308	

IRI(Rt 15-Unlimited Access L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Rut	0.336	0.03	11.087	0.000	0.276	0.395
Constant	0.87	0.089	9.736	0.000	0.694	1.046

IRI =0.87 + (0.336*Rut)

Results of Regression Analysis for Rt 15-Unlimited Access-Lane1: IRI & Cracking

Number of Obs =309
F (1, 308) =41.694
Prob > F =0.000
R-squared =.120
Adj R-squard =.117

Source	SS	df	MS
Model	10.014	1	10.014
Residual	73.747	307	0.24
Total	83.752	308	

IRI(Rt 15-Unlimited Access L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Crack	0.054	0.008	6.457	0.000	0.038	0.071
Constant	1.633	0.04	40.555	0.000	1.554	1.713

IRI =1.63 + (0.054*Crack)

Results of Regression Analysis for I-91-Lane1: IRI & Rut

Number of Obs =895
F (1, 894) =345.977
Prob > F =0.000
R-squared =.279
Adj R-squard =.278

Source	SS	df	MS
Model	59.411	1	59.411
Residual	153.345	893	0.172
Total	212.756	894	

IRI(I-395 L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Rut	0.305	0.016	18.6	0.000	0.273	0.337
Constant	0.491	0.057	8.585	0.000	0.379	0.603

IRI =0.491 + (0.305*Rut)

Results of Regression Analysis for I-91-Lane1: IRI & Cracking

Number of Obs =895
F (1, 894) =12.748
Prob > F =0.000
R-squared =.014
Adj R-squard =.013

Source	SS	df	MS
Model	2.994	1	2.994
Residual	209.762	893	0.235
Total	212.756	894	

IRI(I-395 L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Crack	-0.03	0.008	-3.57	0.000	-0.047	-0.014
Constant	1.616	0.03	53.019	0.000	1.556	1.675

IRI =1.616 + (-0.03*Crack)

Results of Regression Analysis for I-395-Lane1: IRI & Rut

Number of Obs =853
F (1, 852) =278.361
Prob > F =0.000
R-squared =.246
Adj R-squard =.246

Source	SS	df	MS
Model	13.889	1	34.093
Residual	42.461	851	0.201
Total	56.35	852	

IRI(I-395 L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Rut	0.143	0.009	16.684	0.000	0.126	0.159
Constant	0.82	0.022	37.699	0.000	0.778	0.863

IRI =0.82 + (0.143*Rut)

Results of Regression Analysis for I-395-Lane1: IRI & Cracking

Number of Obs =853
F (1, 852) =26.043
Prob > F =0.000
R-squared =.030
Adj R-squard =.029

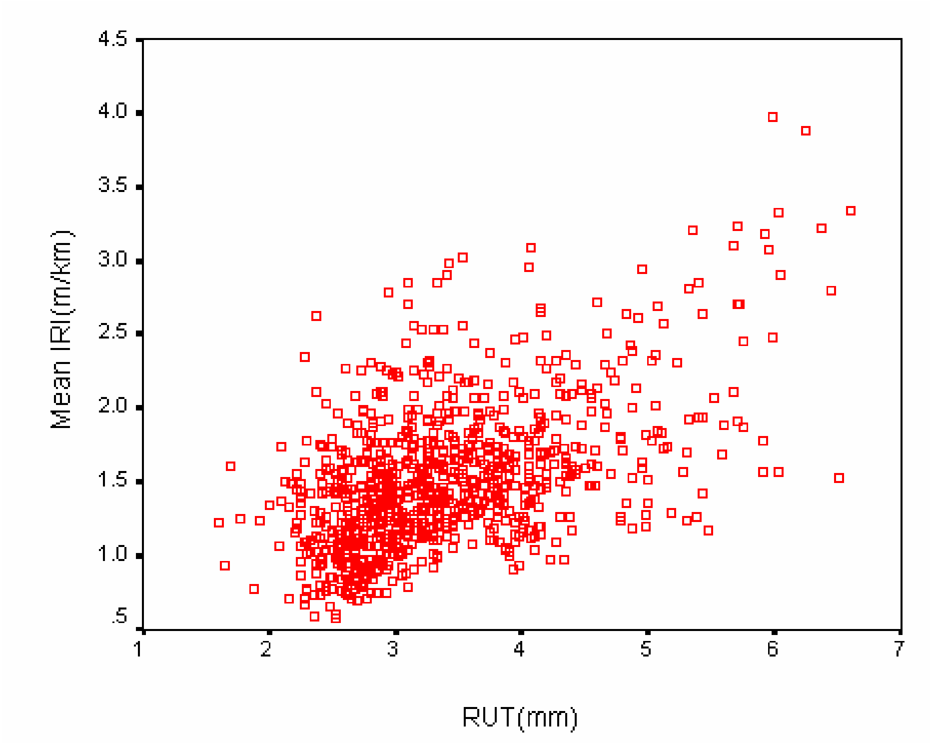
Source	SS	df	MS
Model	1.673	1	1.673
Residual	54.677	851	0.064
Total	56.35	852	

IRI(I-395 L1)	Coef.	Std. Err.	t	P> |t|	[95% Conf. Interval]	
Crack	0.116	0.023	5.103	0.000	0.072	0.161
Constant	1.149	0.009	128.004	0.000	1.131	1.166

IRI =1.149 + (0.116*Crack)

A Sample of Scatter Graphs (I-91 L1)

Mean IRI vs. Rut



Mean IRI vs. Crack