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Effects of Milling and Other Repairs on Smoothness of Overlays: Additional Testing on Construction Under Profiler-Based Smoothness Specifications

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Effects of Milling and Other Repairs on Smoothness of Overlays: Additional Testing on Construction Under Profiler-Based Smoothness Specifications

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Partnered Pavement Research Center (PPRC) Project Numbers 4.42 and 2.7 (DRISI Tasks 2363 and 2684): Effects of Milling and Other Repairs on Smoothness of Overlays and Provide Advice to State Government on Pavement Technology

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16. ABSTRACT

This technical memorandum provides additional information regarding smoothness on several thin asphalt overlay projects constructed soon after changes in Caltrans specifications for constructed pavement surfaces using the International Roughness Index (IRI) as the quality metric. The IRI data were collecting using inertial profilers, before and after construction, on overlaid surfaces employing one of three repairs—digouts, cold in-place recycling (CIR), mill and filling—or none. Because the data were collected after the close of the construction contract, they include the effects of any grinding that Caltrans required the contractor to perform prior to that close. However, the data provide a preliminary look at whether changes in the construction smoothness specification necessitate changes to any of the recommendations in a previous report regarding repairs before overlay. The results indicate that the recommendations in the previous report are generally being followed. The results also indicate that the previous recommendation to not include milling before overlay when IRI is less than 120 inches/mile or below 95 inches/mile may need to be revised under the new specification. However, additional data are needed, since only two projects with milling were included in this data set. A survey of district practices conducted in September 2017 indicated that decisions regarding the inclusion of digouts, milling, and CIR prior to overlay were based on addressing load-related cracking, not roughness. It was observed that decisions regarding pre-overlay repairs for the small set of projects reviewed have generally resulted in smoother existing pavements not being subjected to pre-overlay repairs, and digouts, milling, and CIR being used on successively rougher existing pavements.

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5. CALTRANS TECHNICAL LEAD AND REVIEWER Sri Balasubramanian	6. FHWA NUMBER CA182363A

7. PROPOSALS FOR IMPLEMENTATION
Review guidance regarding milling as part of pre-overlay repairs after collection and analysis of more data.

8. RELATED DOCUMENTS
Effects of Milling and Other Repairs on the Smoothness of Overlays on Asphalt Pavements from 2000 to 2009, UCPRC-RR-2013-09 *(www.ucprc.ucdavis.edu/PDF/UCPRC-RR-2013-09.pdf)*

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The UCPRC laboratory is accredited by AASHTO re:source for the tests listed in this report

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PROJECT OBJECTIVES

The goal of this project, SPE 4.42, titled “Effects of Milling and Other Repairs on Smoothness of Overlays,” is to investigate the effect of various repairs on the ride quality performance of asphalt concrete overlays. This technical memorandum provides additional information regarding smoothness on several projects constructed soon after Caltrans changed to construction smoothness specifications based on measurement using International Roughness Index (IRI) as the quality assurance metric. It is intended to provide a preliminary check on results presented in a separate report on constructed smoothness using the previous specification. This memorandum completes all of the additional work of this project completed under SPE 2.7, titled “Provide Advice to State Government on Pavement Technology.”

LIST OF ABBREVIATIONS

CIR	Cold In-place Recycling
HMA	Hot Mix Asphalt
IRI	International Roughness Index
LTPP	Long Term Pavement Performance
MnF	Mill and Fill
PCS	Pavement Condition Survey
SPS	Specific Pavement Studies

TEST METHODS AND SPECIFICATIONS USED IN THE MEMORANDUM

ASTM E1926	Computing International Roughness Index of Roads from Longitudinal Profile Measurements
ASTM E950	Measuring the Longitudinal Profiles of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003).

1 INTRODUCTION

1.1 Background

Smoothness measured according to the International Roughness Index (IRI) is increasingly used as a construction quality parameter for both new construction and rehabilitation and maintenance treatments. Smoothness as measured by IRI is of interest because rough pavements cause increased vehicle maintenance costs, increased vehicle fuel use, and increased freight damage. Pavements that are built rougher also tend to have shorter lives because of the dynamic interactions between vehicle suspensions and the pavement surface that result in heavier loading.

Caltrans has historically used the California Profilograph, which is a moving straight-edge, to identify localized rough areas in newly paved surfaces that require attention before a project is accepted from a contractor. In September 2013, Caltrans implemented a new Standard Special Provision (SSP) 39-1.12 for asphalt pavement, to replace Standard Specifications Section 39-1.12, and revised SSP 40-1 for concrete pavement, both of which require a contractor to collect pavement smoothness profiles in both the left and right wheelpaths using an inertial profiler and to average the left and right wheelpaths to determine the Mean Roughness Index (MRI) as the roughness parameter for overlay construction smoothness.

A study was begun in 2012 to evaluate the benefits of pre-overlay repairs on the constructed smoothness of asphalt overlays. Using data mining, construction projects appropriate for data analysis were selected from databases provided by the Caltrans Pavement Program. Statistical analysis was then used to determine the effects of different explanatory variables, and the results were used to make recommendations for the design of overlays based on existing pavement condition.

The data used in this study were taken from the Caltrans Pavement Condition Survey (PCS) between the years 2000 and 2009, a period during which as-built overlay smoothness was controlled with a specification based on the California Profilograph. The study analyzed the following factors in order to determine their effects on constructed overlay smoothness: initial pavement smoothness prior to overlay; overlay thickness; overlay mix type (dense-graded or gap-graded versus open-graded); binder type (rubberized versus conventional or polymer-modified); and the pre-overlay repairs milling (milling of entire lane width) and digouts (milling and patching of wheelpaths only).

The results of the study were published in 2017 *(1)* and its conclusions were as follows:

- Regardless of other factors, applying an overlay on a pavement with a low pre-overlay IRI can further reduce the post-overlay IRI.
- Increasing the thickness of an overlay has no additional benefit when the pre-overlay IRI is less than 120 in./mile (1.90 m/km). When the pre-overlay IRI is greater than 120 in./mile, thicker dense- and rubberized gap-graded overlays reduce post-overlay IRI more than thinner overlays do. Given that some of the medium overlays (0.25 ft to 0.40 ft thick) and all of the thick overlays (thicker than 0.45 ft) required two or sometimes more lifts, it is considered likely that multiple passes of the paver contributed to the improved smoothness. With open-graded mixes, overlay thickness does not show any significant effect on post-overlay IRI, reflecting the narrower range of thicknesses for open-graded overlays.
- Milling prior to overlay and using rubberized binder alone do not provide any additional benefits for achieving lower post-overlay IRI.
- Using rubberized binder in open-graded overlays may help achieve lower post-overlay IRI compared with conventional open-graded mixes. (The reason why this might be is not certain.)
- Milling prior to overlay on pavements with existing IRI of less than 120 in./mile (1.90 m/km) is disadvantageous and will likely result in a rougher pavement than if milling had not been done.
- Digouts, which should be done to correct cracking in the wheelpath prior to overlay, provide a benefit regardless of pre-overlay IRI, but have the greatest benefit in reducing post-overlay IRI when the pre-overlay IRI is greater than 120 in./mile (1.90 m/km).
- Analysis of the Caltrans PCS database indicates that projects with digouts in the wheelpath have better post-overlay IRI than those that were milled across the entire width of the pavement prior to overlay.
- Although, in general, overlay mix type alone (open-graded versus dense- and gap-graded) has no effect on post-overlay IRI, milling or digouts prior to placing open-graded overlays may help to achieve lower post-overlay IRI.
- Sparse data indicate that milling of existing open-graded surfaces prior to overlay may result in rougher overlays than if milling was not done.

A similar analysis of the Long-Term Pavement Performance Specific Pavement Study *(2)* sections from 120 subsections collected from the SPS-5 data—from 15 states and provinces across the United States and Canada—resulted in the following conclusions:

- Overall, pre-overlay condition has a significant effect on both post-overlay IRI and IRI reduction. Post-overlay IRI was higher in the groups with poor pre-overlay condition yet IRI reduction was also higher in the groups with poor pre-overlay condition.
- Overlay thickness was shown to have little influence on post-overlay IRI and IRI reduction for all mixes included in those sections.

- Overlay thickness was shown to have little influence on post-overlay IRI and IRI reduction for all mixes included in those sections.
- No specific trends could be found for pre-overlay repairs and mix types based on the descriptive statistics and boxplots.
- The following recommendations were based on the conclusions of this study:
  - Caltrans should use the results of this study to provide guidance to designers regarding use of milling and not use milling to try and improve the smoothness of an overlay when the IRI of the existing pavement is less than 120 in./mile (1.9 m/km). Digouts are to be used as pre-overlay repairs in situations where it is necessary to remove cracking in the wheelpaths but the nonwheelpath pavement is in satisfactory condition. The selection of digouts is to be based on the severity and extent of cracking and no additional guidance on this process is needed. However, consideration should be given to considering digouts in IRI performance equations in the PaveM pavement management system.
  - Caltrans should compare the results from this study, which is based on data collected prior to implementation of an IRI-based construction smoothness specification in 2013, with smoothness values obtained since implementation of the new smoothness specification to see if it has resulted in improvements, and whether adjustments to the specification are needed or desired.

In late 2015 Caltrans requested additional testing on a limited number of construction projects built with the new IRI-based smoothness specification. Cold in-place recycling (CIR) was not included in the initial report *(1)* because very few sections with that pre-overlay treatment had been built at the time of that study. CIR was considered in this follow-up study.

1.2 Purpose of Project

The purpose of the project, Partnered Pavement Research Center (PPRC) Strategic Plan Element (SPE) 4.42, "Effects of Milling and Other Repairs on Smoothness of Overlays," is to measure the IRI before and after construction on pavements that received an asphalt overlay, compare sections that have milling or other repairs to sections that do not, and to evaluate the smoothness benefits of pre-overlay activities. A list of open contracts was used to select field projects where an overlay had not yet been placed. The UCPRC tested the IRI of these sections both before and after construction. The data collected were used to determine if there is any benefit of pre-overlay repairs on pavement smoothness.

The purpose of the additional testing on sections built under the IRI-based construction smoothness specification is to determine if there are indications that the recommendations of the original study should be changed. This technical memorandum documents the results of the testing and evaluation of the recommendations.

2 EXPERIMENT DESIGN FOR IRI TESTING

The list of overlay projects constructed under the IRI-based construction specification and tested in this project is provided in Table 2.1, along with the contract number, project location, and description of work provided by the Caltrans database of ongoing projects *(3)*. Most of these projects generated two test sections, with different sections for different directions or lanes. The list of sections used for comparison is provided in Table 2.2. The IRI was measured before construction and after the close of the construction contract, and therefore the postconstruction data include the effects of any grinding that Caltrans required the contractor to perform prior to close.

Table 2.1: List of Overlay Projects

Contract Number	Project Location (District-County-Route-Post Mile)	Nearest Town	Work Description*
02-4G1104	02-Tehama-32-PM10.0/16.0	Forest Ranch	RHMA Overlay with digouts
02-4G1904	02-Shasta-299-PM60.0/67.8	Montgomery Creek	Replace HMA surface, place HMA
03-3M9204	03-El Dorado-193-PM6.0/12.7	Georgetown	CIR and place HMA
03-4M8204	03-Sacramento-99-PM32.1/36.9	Sutter County Line	RHMA-O overlay
03-4M8504	03-Sacramento-50-PMR12.9/R5.8	Rancho Cordova	RHMA-O overlay
04-3E3604	04-Solano-37-PM0.1/7.4	Vallejo	Cold plane and place RHMA
10-381514	10-Merced-165-PM26.7/30	Turlock	Pavement rehab; shoulder widening
10-0X3804	10-San Joaquin-4-PM14.2/15.9	Stockton	Repair failed areas and place HMA
10-0X4004	10-Calaveras-4-PM30.0/49.6	Murphys	RHMA overlay with digouts
10-0Y1204	10-Merced-59-PM7.9/14.1	Merced	CIR and place HMA
10-0Y2604	10-Stanislaus-33-PM14.5/17.9	Patterson	CIR and place HMA

* RHMA(–O): rubberized hot mix asphalt (–open-graded); HMA: hot mix asphalt; CIR: cold in-place recycling

2.1 Test Sections

For this analysis, each lane and direction is treated as a separate section. Generally, the leftmost lane (Lane 1) in both directions was sampled, except for the Sacramento-area projects. On Sacramento 99 the two leftmost lanes (Lane 1 and Lane 2) in both directions were sampled, and on Sacramento 50 only westbound Lane 4 was sampled.

2.2 Test Protocol

Roughness measurements were calculated following ASTM E1926 *(4)*: "Computing International Roughness Index of Roads from Longitudinal Profile Measurements." The UCPRC test vehicle carries equipment for measuring the inertial profile in accordance with ASTM E950 *(4)*: "Measuring the Longitudinal Profiles of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference."

IRI was measured in the left wheelpath with a standard spot laser measuring at 16 kHz and in the right wheelpath with a wide-spot (Roline™) laser measuring at 3 kHz, both of which were attached to the rear of the test vehicle in a Dynatest Mark III bumper-mounted inertial profiler. While both laser types satisfy the requirements of the ASTM standard, the 2015 Caltrans specification requires a wide-spot type laser in both wheelpaths, and this test vehicle was only equipped with a wide-spot laser in the right wheelpath. However, since these data are being compared to data collected earlier using the same test vehicle and laser arrangement, and since this study is only a preliminary check on the new specification, the test vehicle equipment was considered acceptable. Any more comprehensive testing in the future should include a change to the current Caltrans-specified laser arrangement.

Table 2.2: List of Twenty-Three Test Sections Used for Comparison

Project Location (County-Route-Direction-Lane-Post Mile)	Section Length	Lane Number/ Total Lanes	Section Identification	Repair or Treatment*
Sacramento-50-West-Lane 4-PMR12.9/R5.8	7.1 miles	4/4	Sac50W4	None
Sacramento-99-North-Lane 1-PM32.1/36.9	4.8 miles	1/2	Sac99N1	None
Sacramento-99-South-Lane 1-PM32.1/36.9	4.8 miles	1/2	Sac99S1	None
Sacramento-99-North-Lane 2-PM32.1/36.9	4.8 miles	2/2	Sac99N2	None
Sacramento-99-South-Lane 2-PM32.1/36.9	4.8 miles	2/2	Sac99S2	None
Merced-165-North-Lane 1-PM26.7/30	3.3 miles	1/1	Mer165N1	None
Merced-165-South-Lane 1-PM26.7/30	3.3 miles	1/1	Mer165S1	None
San Joaquin-4-East-Lane 1-PM14.2/15.9	1.7 miles	1/1	SJ4E1	Digouts
San Joaquin-4-West-Lane 1-PM14.2/15.9	1.7 miles	1/1	SJW1	Digouts
Calaveras-4-East-Lane 1-PM30.0/49.6	19.6 miles	1/1	Cal4E1	Digouts
Calaveras-4-West-Lane 1-PM30.0/49.6	19.6 miles	1/1	Cal4W1	Digouts
Tehama-32-East-Lane 1-PM10.0/16.0	6.0 miles	1/1	Teh32E1	Digouts
Tehama-32-West-Lane 1-PM10.0/16.0	6.0 miles	1/1	Teh32W1	Digouts
Shasta-299-East-Lane 1-PM60.0/67.8	7.8 miles	1/1	Sha299E1	Digouts
Shasta-299-West-Lane 1-PM60.0/67.8	7.8 miles	1/1	Sha299W1	Digouts
El Dorado-193-East-Lane 1-PM6.0/12.7	6.7 miles	1/1	ED193E1	CIR
El Dorado-193-West-Lane 1-PM6.0/12.7	6.7 miles	1/1	ED193W1	CIR
Merced-59-North-Lane 1 -PM7.9/14.1	6.2 miles	1/1	Mer59N1	CIR
Merced-59-South-Lane 1-PM7.9/14.1	6.2 miles	1/1	Mer59S1	CIR
Stanislaus-33-North-Lane 1-PM14.5/17.9	3.4 miles	1/1	Sta33N1	CIR
Stanislaus-33-South-Lane 1-PM14.5/17.9	3.4 miles	1/1	Sta33S1	CIR
Solano-37-East-Lane 1-PM0.1/7.4	7.3 miles	1/1	Sol37E1	MnF
Solano-37-West-Lane 1-PM0.1/7.4	7.3 miles	1/1	Sol37W1	MnF

* CIR: cold in-place recycling; MnF: mill and fill (cold plane and place RHMA); None: no repairs

As shown in Table 2.2, the length of these projects varied from 1.7 miles to 19.6 miles. Because the protocol test length is 0.1 miles, each section produced several 0.1 mile-long protocol sections. For instance, Section Sac99N1 produced 48 protocol sections over the 4.8 miles of section length. The 0.1 mile-long test section is the data analyzed and presented here.

3 DATA AND ANALYSIS

The raw data were processed using *ProVAL (5)* according to the 0.1 mile protocol length and then aggregated for each section. In this chapter, a summary of the aggregated section data is presented and then followed by a look at the 0.1 mile-long data collected within each section. Throughout the memo the projects are grouped according to the four repair types listed in Table 2.2: none, digouts, cold in-place recycling (CIR), and mill and fill (MnF).

3.1 Summary of Section Data

A summary of the IRI data collected on each section before and after construction is shown in Table 3.1, along with the calculated reduction in IRI resulting from the overlay. Again, note that the IRI measurements presented after the close of each construction contract include the effects of any grinding that Caltrans required the contractor to perform prior to that close. The table includes the overlay thickness and the depth of cold in-place recycling or milling, where applicable. The sections are grouped according to the kind of repair work and ranked by the absolute reduction in IRI. The average, shown in bold, and the standard deviation are also presented according to the type of repair. Figure 3.1 displays the data from Table 3.1.

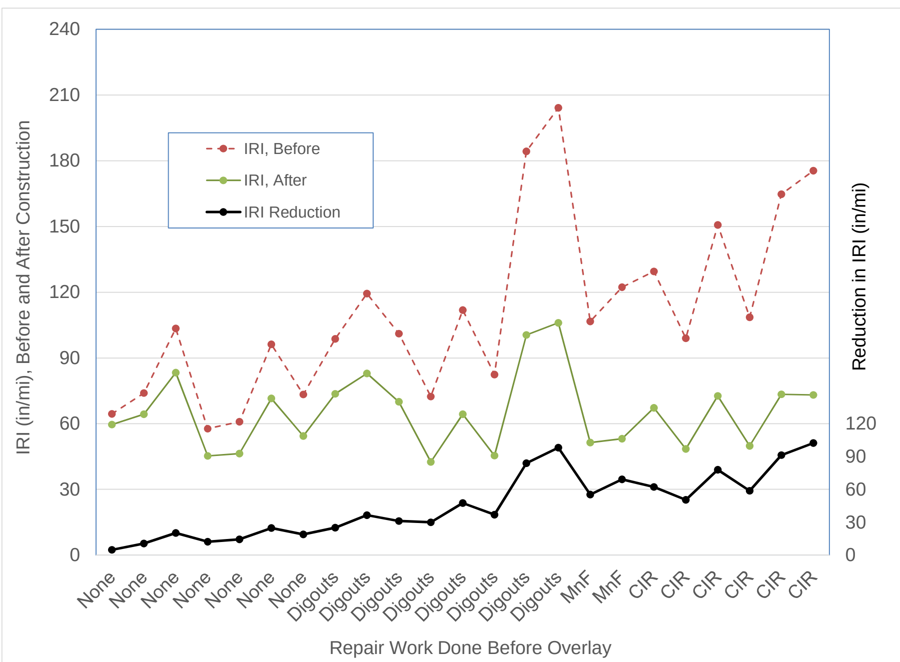

Figure 3.1: Average section IRI reduction for the repair options considered.

Table 3.1: Sections, Grouped by Repair Work, Ranked by IRI Reduction

Section ID	IRI (inch/mile)				IRI Reduction (inch/mile)		Repair Work	Overlay Material	Overlay Thickness	CIR or Milling Depth
	Before		After							
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.				
Sac99S1	64.5	20.9	59.6	24.5	4.9	11.9	None	RHMA-O	0.10 ft	-
Sac50W4	74.0	18.7	64.3	12.8	10.6	17.3	None	RHMA-O	0.10 ft	-
Sac99N2	57.7	12.0	45.3	13.9	12.3	11.9	None	RHMA-O	0.10 ft	-
Sac99N1	60.9	14.2	46.4	12.7	14.4	13.8	None	RHMA-O	0.10 ft	-
Sac99S2	73.3	23.8	54.4	20.9	18.9	16.8	None	RHMA-O	0.10 ft	-
Mer165N1	103.5	18.3	83.3	9.2	20.2	16.8	None	RHMA-G	0.20 ft	-
Mer165S1	96.2	17.1	71.5	9.6	24.7	15.5	None	RHMA-G	0.20 ft	-
Average	**75.7**	**17.9**	**60.7**	**14.8**	**15.1**	**14.9**	**None**	**7 sections**	**3 projects**	
Std. Dev.	17.7	4.0	13.7	5.8	6.6	2.3				
Cal4W1	98.7	33.2	73.6	13.8	25.1	28.0	Digouts	RHMA-G	0.10 ft	-
Sha299W1	72.4	11.2	42.5	5.5	30.0	9.8	Digouts	HMA	0.15 ft	-
Cal4E1	101.1	32.9	70.0	14.4	31.1	27.8	Digouts	RHMA-G	0.10 ft	-
SJ4E1	119.4	43.4	82.9	27.8	36.5	29.7	Digouts	HMA	0.10 ft	-
Sha299E1	82.4	18.7	45.4	9.2	37.0	18.9	Digouts	HMA	0.15 ft	-
SJ4W1	111.8	57.0	64.3	28.6	47.5	42.2	Digouts	HMA	0.10 ft	-
Teh32W1	184.3	48.2	100.5	23.7	83.9	46.8	Digouts	RHMA-G	0.10 ft	-
Teh32E1	204.2	36.9	106.0	22.4	98.1	32.5	Digouts	RHMA-G	0.10 ft	-
Average	**121.8**	**35.2**	**73.2**	**18.2**	**48.7**	**29.5**	**Digouts**	**8 sections**	**4 projects**	
Std. Dev.	47.4	15.0	23.1	8.7	27.2	11.8				
Average	***97.6***	*32.7*	***63.1***	*16.6*	***34.5***	*26.1*	***Digouts***	***6 sections***	***3 projects***	
Std. Dev.	*17.6*	*16.5*	*16.1*	*9.6*	*7.7*	*10.9*	*Digout sections excluding Tehama 32*			
Sol37E1	106.7	23.2	51.4	11.9	55.3	17.0	MnF	RHMA-G	0.10 ft	0.10 ft
Sol37W1	122.3	35.6	53.1	11.6	69.2	31.2	MnF	RHMA-G	0.10 ft	0.10 ft
Average	**114.5**	**29.4**	**52.3**	**11.8**	**62.3**	**24.1**	**MnF**	**2 sections**	**1 project**	
Std. Dev.	11.0	8.8	1.2	0.2	9.8	10.0				
Sta33S1	99.0	40.6	48.5	27.1	50.5	21.1	CIR	HMA	0.15 ft	0.25 ft
Sta33N1	108.6	41.2	49.9	29.0	58.7	23.0	CIR	HMA	0.15 ft	0.25 ft
Mer59S1	129.5	34.0	67.2	17.0	62.3	33.1	CIR	HMA	0.15 ft	0.33 ft
Mer59N1	150.7	37.2	72.7	23.5	78.0	36.7	CIR	HMA	0.15 ft	0.33 ft
ED193E1	164.7	42.2	73.4	18.4	91.3	41.8	CIR	HMA	0.15 ft	0.25 ft
ED193W1	175.5	52.3	73.1	15.9	102.4	48.7	CIR	HMA	0.15 ft	0.25 ft
Average	**138.0**	**41.3**	**64.1**	**21.8**	**73.9**	**34.1**	**CIR**	**6 sections**	**3 projects**	
Std. Dev.	30.8	6.2	11.8	5.5	20.2	10.7				
Average	***155.1***	*41.4*	***71.6***	18.7	***83.5***	*40.1*	***CIR***	***4 sections***	***2 projects***	
Std. Dev.	*19.9*	*8.0*	*2.9*	*3.4*	*17.3*	*6.8*	*CIR sections excluding Stanislaus 33*			

RHMA(–O): rubberized hot mix asphalt (–open-graded); RHMA(–G): rubberized hot mix asphalt (–gap-graded); HMA: hot mix asphalt; CIR: cold in-place recycling; MnF: mill and fill

3.1.1 *Projects with No Repairs*

Looking at the average data from each section, which range in length from about 1.7 to nearly 20 miles, and the averages across the repair types across the sections, it can be seen that the seven sections with no repair work had an average IRI over the seven sections of 76 in./mile before construction and 61 in./mile after, resulting in an average reduction of 15 in./mile. Understandably, the sections with no repair work preceding the overlay had lower average sections IRI values before construction—ranging between 58 and 104 in./mile—than the sections that had digouts, CIR, or milling. However, with less room for improvement, these sections also showed the smallest IRI reduction from the overlay project.

3.1.2 *Projects with Digouts*

The eight sections with digouts had an average IRI of 122 in./mile before construction and 73 in./mile afterward: a reduction of 49 in./mile. Two of those sections, both of which are on Teh32, had initial average section IRI values of 184 and 204 in./mile and average section IRI reductions of 84 and 98 in./mile, respectively. The other six sections with digouts had initial average section IRI values of 73 to 119 in./mile and 43 to 83 in./mile afterward, an average IRI reduction across the six of 35 in./mile.

The IRI reduction on projects with digouts was significantly better than projects with no repairs. At the project level, the IRI measured after construction between sections with digouts, excluding Teh32 (63 in./mile), compares well to those with no repairs (61 in./mile).

Typically, CIR was the selected treatment on the other projects with initial IRI values above 150 in./mile (Mer33 and ED193). However, a different repair approach may have been taken with Teh32 because this section of pavement is part of a narrow, winding mountain road where vehicle speeds typically range between 10 and 40 miles per hour due to frequent, sharp vertical and horizontal curves. It is also likely that in some places the pavement structural section is thin and highly variable. Under these circumstances milling would have been difficult.

3.1.3 *Projects with Mill and Fill*

The two mill-and-fill sections, the two directions of Sol37, had an average IRI of 114 in./mile before construction and 52 in./mile afterward: a reduction of 62 in./mile. The IRI after construction was the lowest of the considered treatments, and ranked second in IRI reduction overall, although this observation should be qualified by the fact that there were only two sections with milling.

The recommendation from the initial report in this project *(1)*—that milling generally should not be used for sections with initial IRI values less than 95 in./mile—could not be tested with the one project available for this follow-up study. However, the IRI data from these two sections in this study, which showed moderate initial IRI values and large IRI reductions, contradict the recommendation that milling might not provide much value for sections with initial IRI values of 95 to 120 in./mile. The milling performance shown by this data compared with that in the initial report may be due to improvements in milling technology, including the introduction of micromilling or overall better attention to smoothness because of the new specification.

3.1.4 Projects with Cold In-Place Recycling

The six sections with CIR had an average IRI of 138 in./mile before construction and 64 in./mile afterward: an average reduction of 74 in./mile over all of the sections. Two of those sections, both on Sta33, had initial average section IRI values (99 and 109 in./mile) and average section IRI reductions (51 and 59 in./mile) that were not consistent with the other four sections. Those other sections with CIR had initial average section IRI values of 130 to 176 in./mile and 67 to 73 in./mile afterward, resulting in an average IRI reduction of 84 in./mile.

The CIR sections and the six digout sections (those other than Teh32) that did not have average initial IRI values over 170 in./mile had similar postconstruction IRI values of 64 in./mile for the CIR sections and 63 in./mile for the six digout sections. In addition to complete milling and replacement of 0.25 to 0.33 ft with CIR, the CIR sections all had an overlay of 0.15 ft compared with four out of six of the digout sections having overlays of 0.10 ft. Both CIR and digouts appear to be able to deliver similar final IRI values when the initial IRI values are below about 170 in./mile before CIR treatment and below about 120 in./mile for the digout treatment.

3.1.5 Pre-Paving Repairs before an Overlay

In general, it appears from this small set of projects that Caltrans has been using no pre-overlay repairs when initial IRI values are in the range of about 60 to 105 in./mile, digouts when the initial IRI values are between 75 and 120 in./mile—except for the two low-speed Teh32 sections with high initial IRI values over 175—and CIR when initial IRI values are between about 100 and 175 in./mile.

In order to check the apparent correlation of decisions on whether or not to use pre-overlay repairs, and the pre-overlay type selections made with different levels of roughness, a phone survey was conducted with a sample of four district maintenance engineers in different parts of the state. The district engineers were asked if they used any IRI criteria when deciding whether or not to use pre-overlay repairs; if they did use these criteria, they were also asked if these were considered in the decision regarding whether or not digouts, milling, or CIR were chosen.

All four engineers said that roughness is not considered when programming pre-overlay repairs for maintenance overlays. And while some district engineers requested IRI testing for informational or estimating purposes, the data were not used as a construction quality control metric. All four said that digouts are specifically used prior to overlay to repair localized failures that are load related. It was mentioned that the distinction between milling and digouts primarily depended on the width of the pavement and the lateral location and width of load-related cracking. Because of wander, wheelpaths may extend to the edge of a pavement where there is often an unimproved shoulder, particularly on rural and winding roads. One engineer stated that “digouts can extend from 4 feet wide to 12 feet wide and 10 feet to 500 feet long.” Thus, the distinction between milling and digouts is just a question of width.

Disagreement exists among the district maintenance engineers as to the effectiveness of milling or cold planing. One engineer stated that it is hard to quantify the benefit of milling. Specifically, the engineer noted that “testing whether the IRI on a road that is in poor condition is high enough to warrant milling is difficult, and it is likely the testing would lead to erroneous data.” Further, the testing would have limited value since the performance of the overlay is heavily determined by the material that remains under the milled surface. In contrast, another engineer stated that “there is no need to worry about smoothness, the cold planes we have these days are pretty phenomenal.”

There was no disagreement among the engineers about the need for the smoothness specification for overlays. However, they all pointed to the lack of funding needed to enforce the smoothness requirement. Repeated in several different ways was the following statement by one engineer: “you can’t afford rehab work with maintenance money.” Another engineer in the Central Valley noted that “there are a lot of places where you cannot do the right project, and you never will” because of other limitations.

The survey results indicate that the apparent pattern of selecting treatments based on IRI is an unintended outcome of the pre-overlay treatments selected by district engineers to deal with load-related cracking. The apparent pattern likely appears because badly cracked pavement typically has higher pre-overlay IRI values.

Regardless, the average IRI values after construction are 61, 63, 64, and 52 in./mile for the no repair, digout (excluding the initially very rough Teh32 sections), CIR, and mill-and-fill sections, respectively. This may indicate that the use of these treatments for projects with these ranges of initial roughness is producing similar final IRI results under the new smoothness specification, even though the choice of treatment is largely determined by the extent of wheelpath cracking and other cracking rather than roughness. Data from a larger number of projects will provide a better indication.

3.2 Summary of Repair Options

In this section, the repair or treatment options are discussed using the 0.1 mile-long subsection data that were used to generate IRI section averages in Section 3.1. Some example figures are shown here, and Appendix A displays the IRI graphs from each section. The plots display the IRI trace before and after and the IRI reduction over the project length, as well as the summary values shown in Table 3.1.

3.2.1 Projects with No Repairs

Figure 3.2 shows the IRI trace from Sac99S1, a section with no repairs. This particular section demonstrated the lowest IRI reduction of the study. However, like some other projects with no repairs, this section contains areas where the IRI after construction was higher than before construction; this can be seen in the figure where the IRI reduction is negative. It can be seen that locations in the section with the highest IRI (i.e., the rough spots) have not been eliminated with the thin 0.1 ft (30 mm) thick overlay when no repairs were made before the overlay. This is unsurprising and was also observed on the Sacramento 99 and 50 projects.

The cumulative distribution chart shown in Figure 3.3 illustrates that IRI increased after the overlay in 17 percent of the subsections tested that did not have pre-overlay repairs. By looking at this further with Figure 3.4, it can be seen that most of the subsections that showed an increase in IRI after the overlay had an initial IRI below 70 in./mile. This small dataset, collected from only three projects, casts some doubt on whether an overlay will always reduce IRI when pre-overlay the IRI is already low.

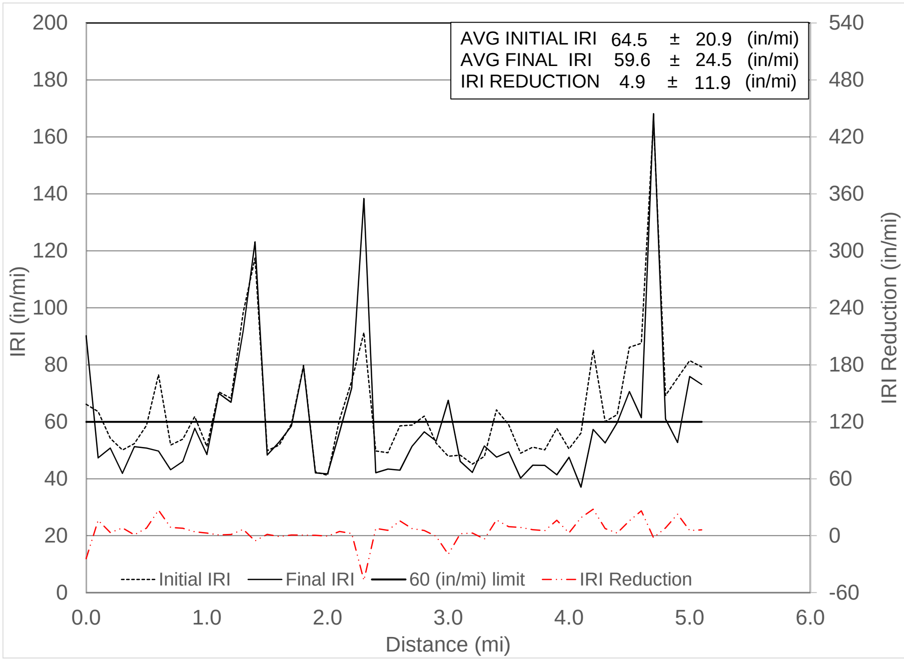

Figure 3.2: IRI section trace from project with no repair, Sac99S1.

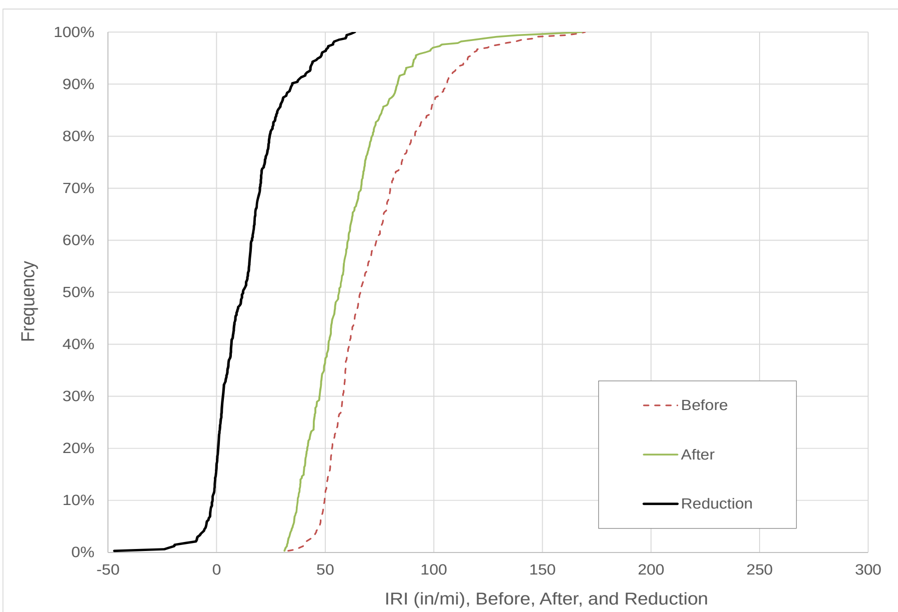

Figure 3.3: Cumulative distribution of IRI data from projects with no repairs.

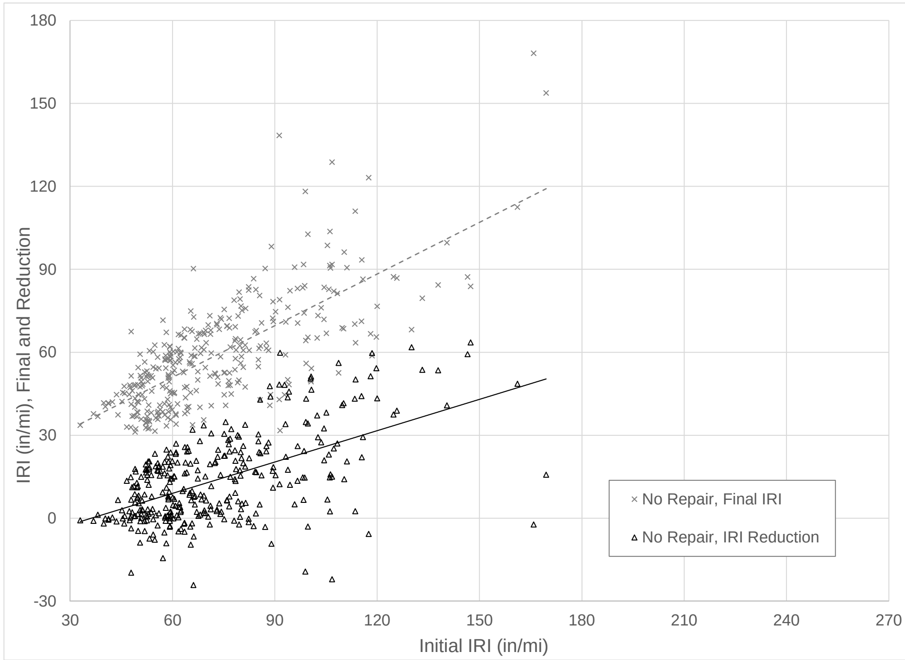

Figure 3.4: Scatterplot of IRI data from projects with no repairs.

3.2.2 Projects with Digouts

Figure 3.5 shows the IRI trace from Cal4W1, a 20 mile-long project with digouts. This particular section demonstrated the lowest IRI reduction of the projects with digouts. Like the other projects with digouts, the IRI graphs show that digouts can eliminate high local rough spots, unlike the overlay with no repairs. Unlike the other projects with digouts, the Cal4 project contains a six-mile length where the IRI before construction (approximately 60 in./mile) was not improved with construction.

The cumulative distribution chart shown in Figure 3.6 illustrates that IRI increased after the overlay in 10 percent of the subsections tested that had digout repairs. The project produced 65 of the 68 data points with an increase in IRI, all in the six-mile length between PM43 and PM49.6. The scatterplot in Figure 3.7 shows that if the IRI before construction is below 50 or 60 in./mile, IRI will often increase after overlay with digouts.

As noted in the discussion of average section results, the low-speed, mountainous Teh32 project had much higher initial IRI than the rest of the sections with digouts, and the results in Figure 3.6 are shown with and without those data.

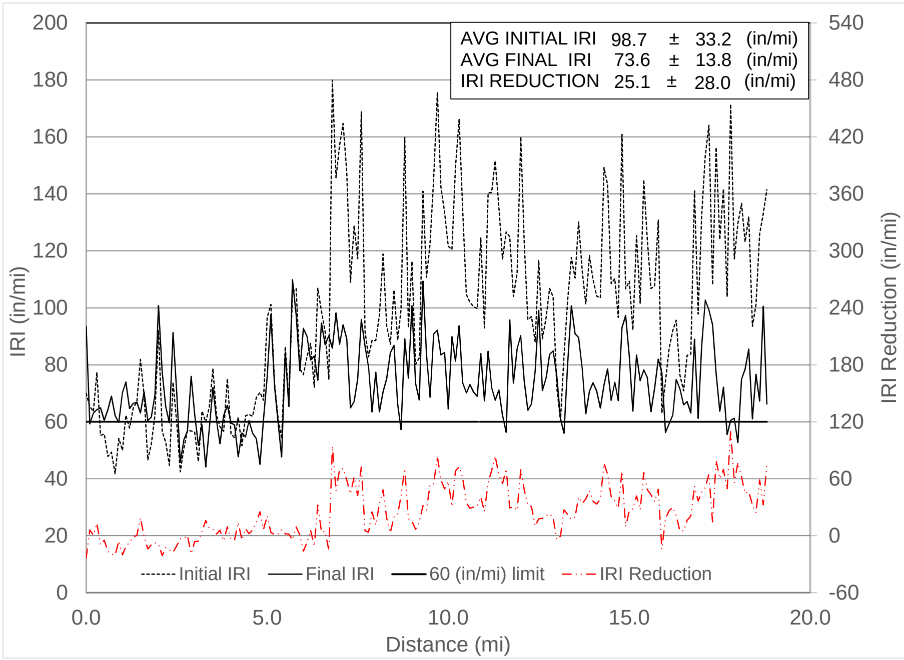

Figure 3.5: IRI section trace from project with digouts, Cal4W1.

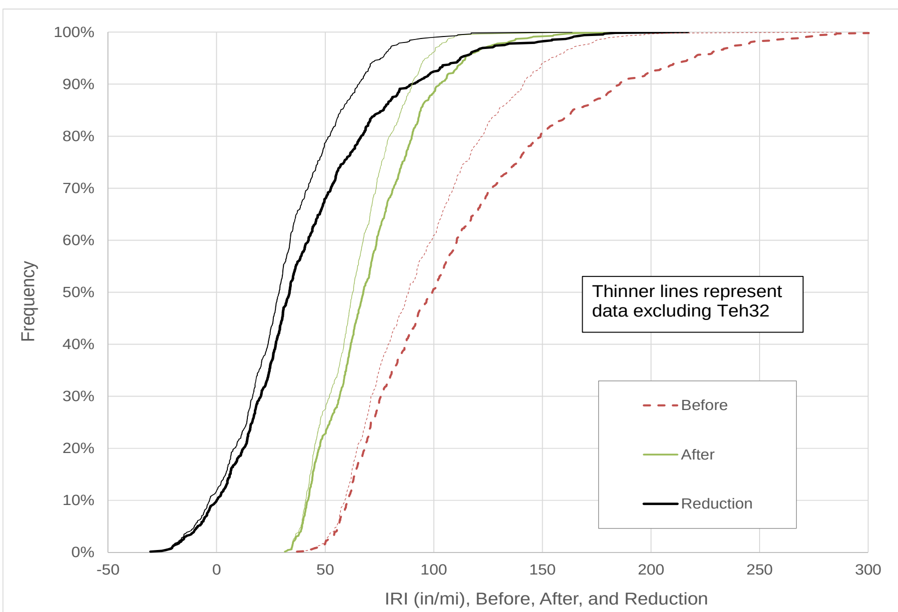

Figure 3.6: Cumulative distribution of IRI data from projects with digouts.

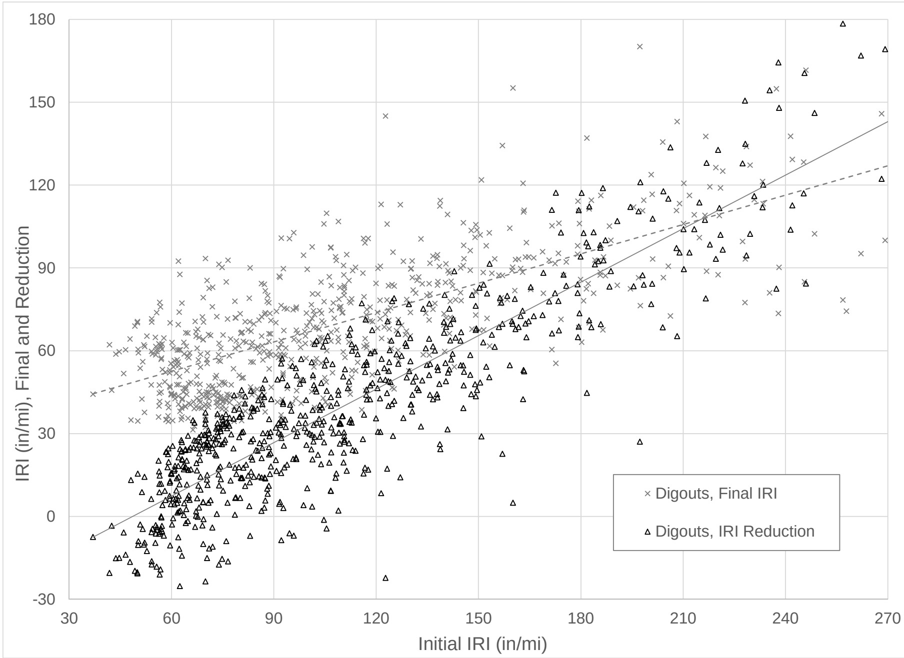

Figure 3.7: Scatterplot of IRI data from projects with digouts.

3.2.3 Projects with Mill and Fill

Figure 3.8 shows the IRI trace from Sol37E1, a seven-mile long mill-and-fill section. The Sol37 project, with two sections, was the only MnF sample in this study and so the conclusions regarding this treatment are limited. However, this project demonstrated a large IRI reduction, 62 in./mile, with an average IRI before construction of 115 in./mile. More MnF samples would help with a comparison to other treatments. A comprehensive study of the MnF options might include data such as mill depth, fill thickness, overlay material, and the age of the underlying material.

Like the projects with digouts, the IRI graphs show that MnF can eliminate high local rough spots. However, some subsections with peak IRI values still had elevated IRI values after construction. Figure 3.9 presents the cumulative distribution of the MnF data, and Figure 3.10 presents a scatterplot of the data. As noted earlier, subsections with initial IRI values as low as 105 in./mile experienced IRI reductions above 60 in./mile with milling and filling.

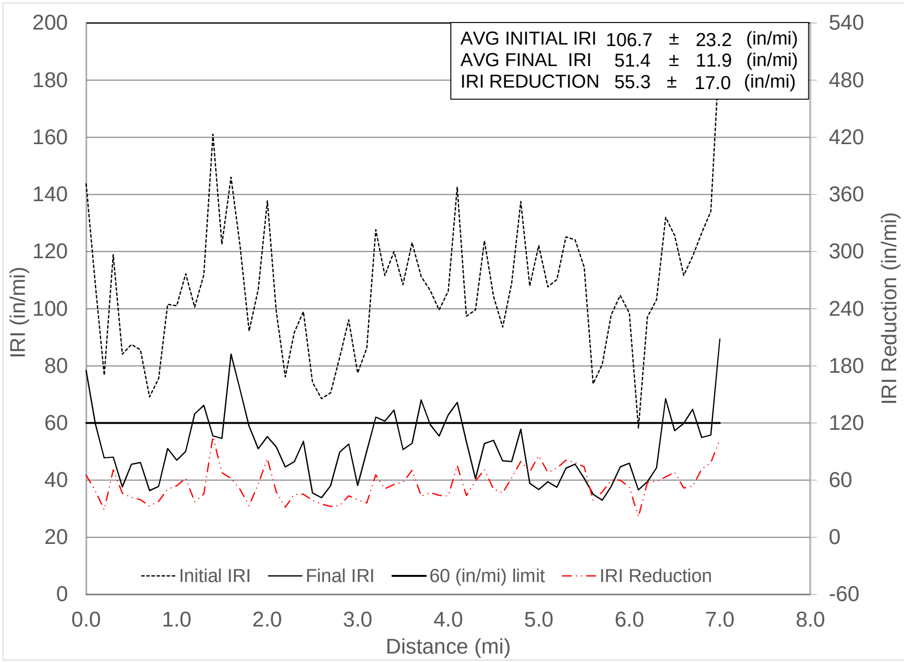

Figure 3.8: IRI section trace from project with mill and fill, Sol37E1.

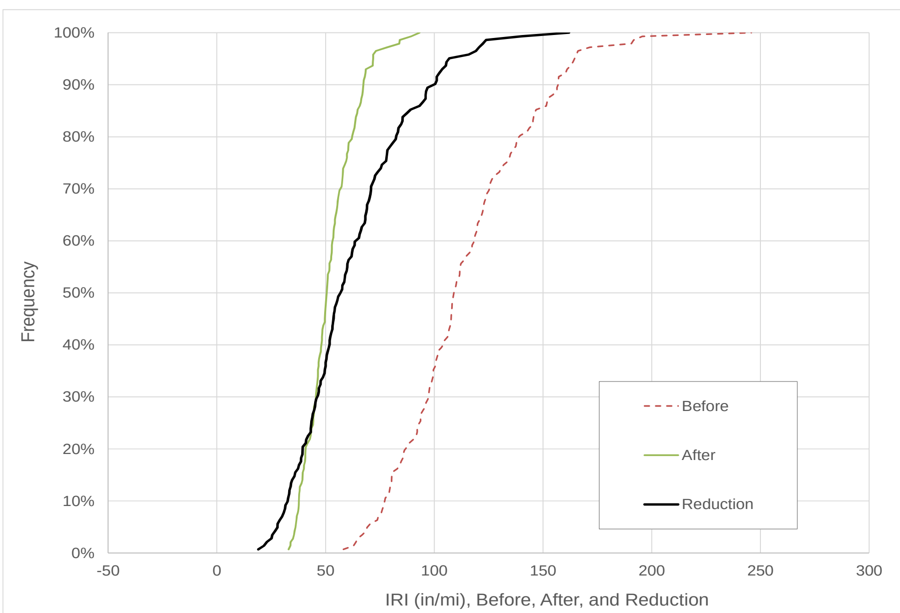

Figure 3.9: Cumulative distribution of IRI data from mill-and-fill projects.

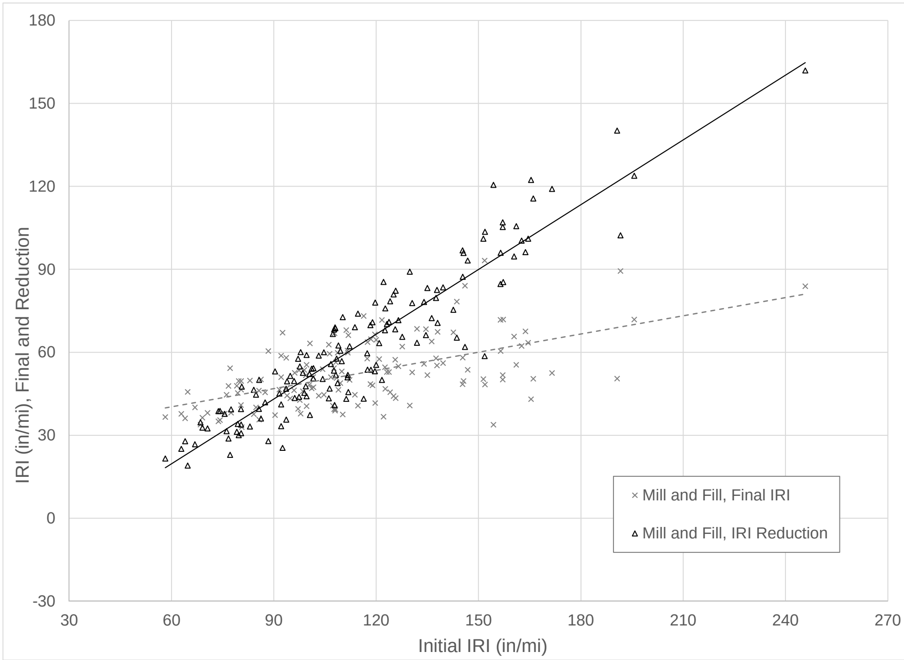

Figure 3.10: Scatterplot of IRI data from mill-and-fill projects.

3.2.4 Projects with Cold In-Place Recycling

Figure 3.11 shows the IRI trace from Mer59N1, a six-mile–long CIR section. All the section graphs show the significant IRI reduction that resulted from this treatment. When the two sections from the Sta33 project were excluded from the subsection data, the average IRI reduction was 77 in./mile and 84 in./mile. In all likelihood these large reductions resulted in part from the distressed initial condition of the surface, i.e., a condition with cracking significant enough to warrant CIR.

The CIR process appears to have removed rough spots but it did not produce as smooth a surface as those on the limited number of subsections in this study subjected to the MnF process. As seen in Figure 3.12, only 45 percent of the subsections had IRI values below 60 in./mile after construction, and 7 percent of the subsections maintained IRI values above 100 in./mile. The limited MnF data show that 75 percent of those subsections had postconstruction IRI values below 60 in./mile, with no subsections measuring above 95 in./mile.

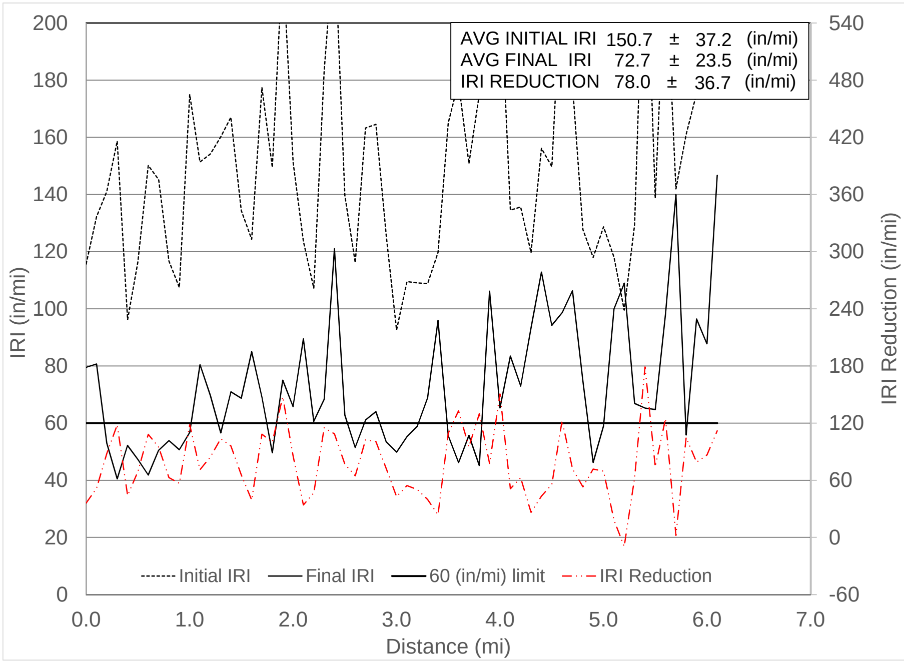

Figure 3.11: IRI section trace from project with cold in-place recycling, Mer59N1.

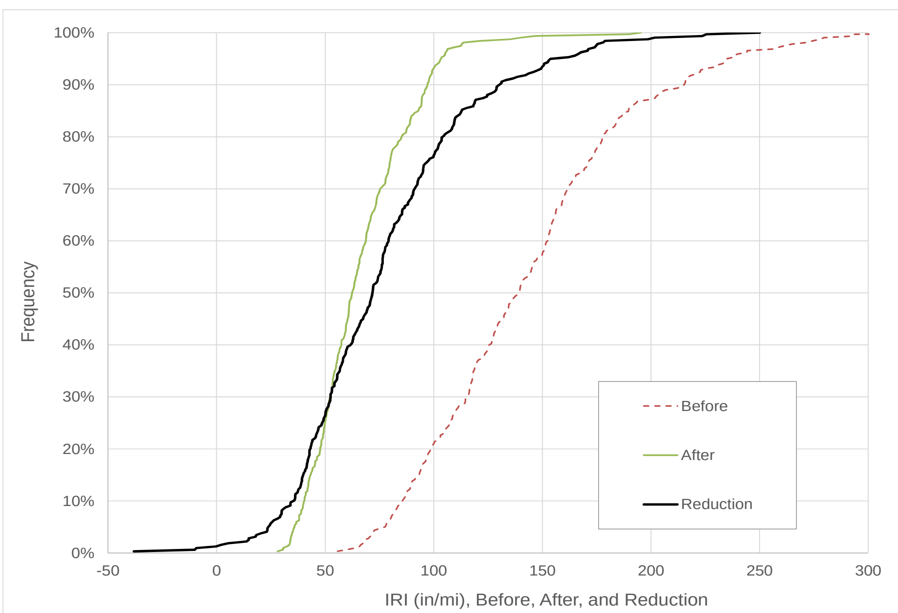

Figure 3.12: Cumulative distribution of IRI data from cold in-place recycling projects.

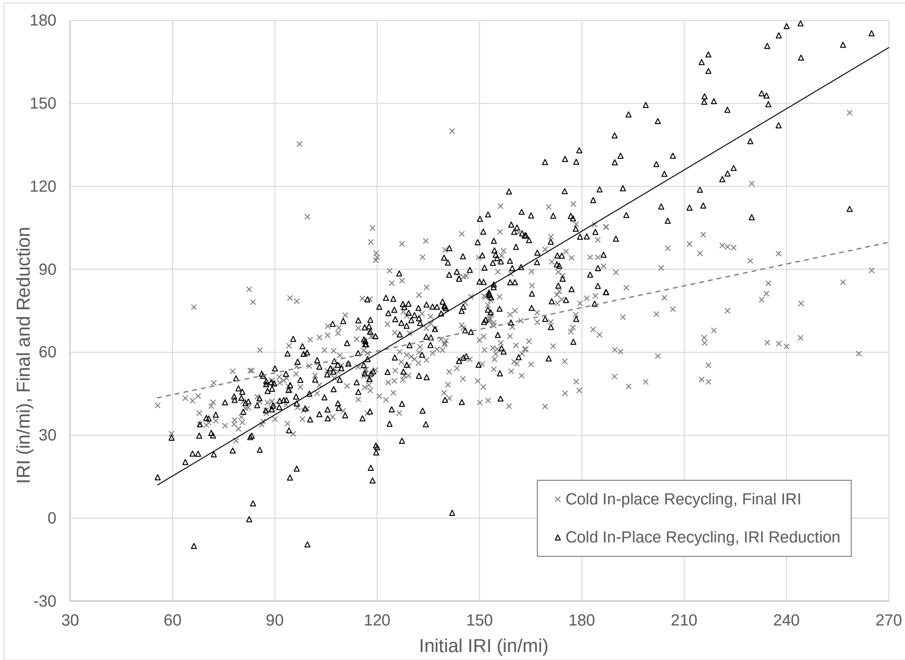

Figure 3.13: Scatterplot of IRI data from cold in-place recycling projects.

3.3 Summary of Overlay Material and Thickness

Table 3.2 presents the section summary data sorted by overlay material type: open-graded, rubberized hot mix (RHMA-O); gap-graded, rubberized hot mix (RHMA-G); or dense-graded, non-rubberized hot mix (HMA); and material thickness. The averages, which are shown in bold, and standard deviation are ordered by overlay material. Because of the limited dataset, no conclusions have been drawn with regard to the effects of overlay material or thickness. Figure 3.14 illustrates the data from Table 3.2.

3.3.1 Projects with an RHMA-O Overlay

The five sections that used the RHMA-O material come from two projects, both of which had 0.10 ft overlays with no preconstruction repairs. Looking at the section averages, the IRI before construction, 66 in./mile, was half that of the IRI of the RHMA-G and HMA overlay materials, 127 in./mile and 121 in./mile, respectively. And because the condition of these sections before construction was good, the IRI reduction was very low, 14 in./mile, less than one-third of the other materials.

Table 3.2: Sections, Grouped by Overlay Material and Thickness, and Ranked by IRI Reduction

Section ID	IRI (inch/mile)				IRI Reduction (inch/mile)		Overlay Material*	Repair Label	Overlay Thickness	CIR or Milling Thickness*
	Before		After							
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.				
Sac99S1	64.5	20.9	59.5	24.5	4.9	11.9	RHMA-O	None	0.10 ft	
Sac50W4	74.0	18.7	64.3	12.8	10.6	17.3	RHMA-O	None	0.10 ft	
Sac99N2	57.7	12.0	45.3	13.9	12.3	11.9	RHMA-O	None	0.10 ft	
Sac99N1	60.9	14.2	46.4	12.7	14.4	13.8	RHMA-O	None	0.10 ft	
Sac99S2	73.3	23.8	54.4	20.9	18.9	16.8	RHMA-O	None	0.10 ft	
Average	**66.1**	**17.9**	**54.0**	**17.0**	**14.1**	**14.3**	**RHMA-O**	**5 sections**	**2 projects**	
Std. Dev.	7.4	4.8	8.2	5.4	3.6	2.6				
Mer165N1	103.5	18.3	83.3	9.2	20.2	16.8	RHMA-G	None	0.20 ft	
Mer165S1	96.2	17.1	71.5	9.6	24.7	15.5	RHMA-G	None	0.20 ft	
Sol37E1	106.7	23.2	51.4	11.9	55.3	17.0	RHMA-G	MnF	0.10 ft	0.10 ft
Sol37W1	122.3	35.6	53.1	11.6	69.2	31.2	RHMA-G	MnF	0.10 ft	0.10 ft
Cal4W1	98.7	33.2	73.6	13.8	25.1	28.0	RHMA-G	Digouts	0.10 ft	
Cal4E1	101.1	32.9	70.0	14.4	31.1	27.8	RHMA-G	Digouts	0.10 ft	
Teh32W1	184.3	48.2	100.5	23.7	83.9	46.8	RHMA-G	Digouts	0.10 ft	
Teh32E1	204.2	36.9	106.0	22.4	98.1	32.5	RHMA-G	Digouts	0.10 ft	
Average	**127.1**	**30.7**	**76.2**	**14.6**	**51.0**	**27.0**	**RHMA-G**	**8 sections**	**4 projects**	
Std. Dev.	42.5	10.5	19.8	5.5	30.1	10.5				
Average	**104.8**	**26.7**	**67.2**	**11.8**	**37.6**	**22.7**	***RHMA-G***	***6 sections***	***3 projects***	
Std. Dev.	9.3	8.2	12.4	2.1	19.9	7.0	*RHMA-G Sections excluding Tehama 32*			
SJ4E1	119.4	43.4	82.9	27.8	36.5	29.7	HMA	Digouts	0.10 ft	-
SJ4W1	111.8	57.0	64.3	28.6	47.5	42.2	HMA	Digouts	0.10 ft	-
Sha299W1	72.4	11.2	42.5	5.5	30.0	9.8	HMA	Digouts	0.15 ft	-
Sha299E1	82.4	18.7	45.4	9.2	37.0	18.9	HMA	Digouts	0.15 ft	-
Sta33S1	99.0	40.6	48.5	27.1	50.5	21.1	HMA	CIR	0.15 ft	0.25 ft
Sta33N1	108.6	41.2	49.9	29.0	58.7	23.0	HMA	CIR	0.15 ft	0.25 ft
ED193E1	164.7	42.2	73.4	18.4	91.3	41.8	HMA	CIR	0.15 ft	0.25 ft
ED193W1	175.5	52.3	73.1	15.9	102.4	48.7	HMA	CIR	0.15 ft	0.25 ft
Mer59S1	129.5	34.0	67.2	17.0	62.3	33.	HMA	CIR	0.15 ft	0.33 ft
Mer59N1	150.7	37.2	72.7	23.5	78.0	36.7	HMA	CIR	0.15 ft	0.33 ft
Average	**121.4**	**37.8**	**62.0**	**20.2**	**59.4**	**30.5**	**HMA**	**10 sections**	**5 projects**	
Std. Dev.	34.0	13.9	14.2	8.4	24.3	12.2				

* RHMA(–O): rubberized hot mix asphalt (–open-graded); RHMA(–G): rubberized hot mix asphalt (–gap-graded); HMA: hot mix asphalt; CIR: cold in-place recycling; MnF: mill and fill

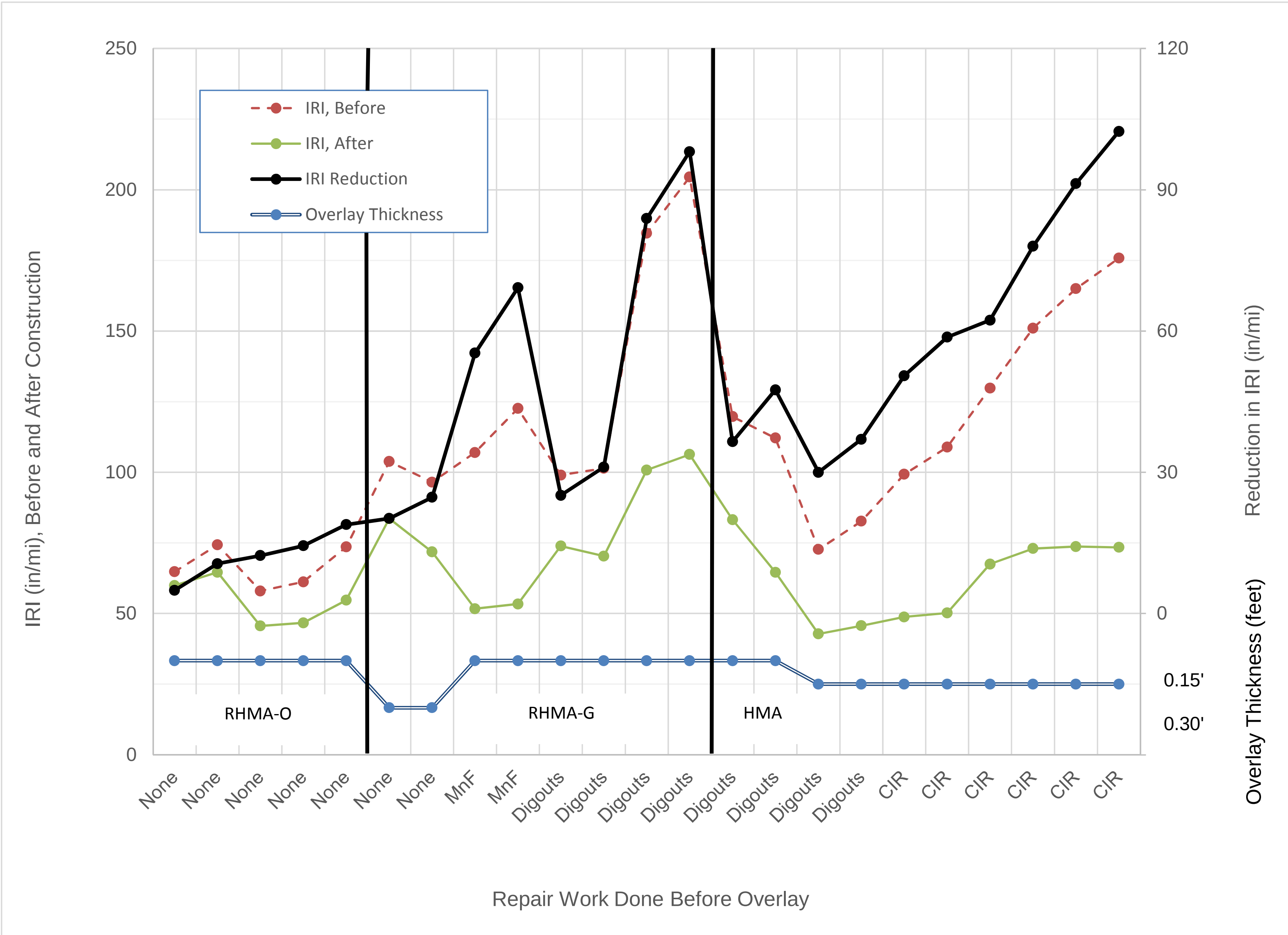

Figure 3.14: IRI reduction of repair options, shown with overlay material type.

3.3.2 Projects with an RHMA-G Overlay

The eight sections that were overlaid with RHMA-G material came from four projects, and represent three of the four treatments (not CIR). Of these repairs, the one MnF project produced the only sections to have an average IRI below 60 in./mile after construction.

Despite different treatment and overlay thicknesses, the Mer165 and Cal4 projects had similar test results when averaged over their projects. The IRI values were similar before construction and after construction: between 96 and 104 in./mile and between 20 and 31 in./mile, respectively. Along with Teh32, three of the four projects raised questions of whether there are clear directives or guidance provided to maintenance engineers designing overlays.

3.3.3 Projects with an HMA Overlay

Ten sections from five projects were overlaid with HMA. Three of the projects had CIR and the other two had digouts. In terms of preconstruction IRI, the sections with RHMA-G and HMA overlays were statistically similar at the 95 percent confidence interval. And in terms of postconstruction IRI, the sections with RHMA-G and HMA overlays were statistically different at the 95 percent confidence interval. The HMA sections were on average smoother than the RHMA-G sections, at 60 in./mile and at 74 in./mile respectively, even without the Teh32 data (68 in./mile).

Looking at the effect of mixture type, both the Cal4 and SJ4 projects had digouts and 0.10 ft overlay; however, Cal4 was overlaid with RHMA-O and SJ4 was overlaid with HMA. The IRI after construction (72 in./mile and 74 in./mile, respectively) was statistically similar at the 95 percent confidence interval.

Of the digout projects with HMA, the one with the higher IRI before construction (SJ4, 116 in./mile) received a 0.10 ft overlay while the other project (Sha299, 77 in./mile) received a 0.15 ft overlay. And SJ4 showed the greater IRI reduction, even though this was likely caused by its much higher initial IRI. The three CIR projects ranked the same for highest initial IRI, highest IRI reduction, and highest IRI after construction: ED193, Mer59, then Sta33. Although ED193 showed the greatest IRI reduction, Mer59 recycled 0.33 ft whereas the other two recycled 0.25 ft.

Unfortunately there are not enough data to draw stronger conclusions about the different material types or overlay thicknesses.

It is interesting to note that none of the CIR sections had rubberized surfaces. It is unknown whether RHMA-G can be used atop CIR, and it is not known why RHMA-G is not being used as an overlay for CIR, although it may have to do with the perception that RHMA-G has greater permeability than HMA and might allow water to reach the CIR.

4 SUMMARY AND RECOMMENDATIONS

4.1 Summary

Two important observations can be made from the data set collected from the 11 projects after the change to the smoothness specification and from data set in the initial study that included 110 projects with 0.1 ft overlays:

- In the initial report, one-quarter (25 percent) of the projects with thin overlays showed an increase in IRI after placement of the overlay, while none of the very thin overlays in this follow-up study showed an increase in IRI. Specifically, the average reduction for sections in this current study was about 20 in./mile both with and without the two sections of Teh32 that were very rough initially. This provides an initial indication that overall the ability to obtain good smoothness has improved for thin overlays under the new specification.
- The average IRI after placement of overlays of 0.2 ft on pavement and initial IRI values of less than 120 in./mile in the initial study was 74 in./mile; in this follow-up data set for the eight sections in the same category, the average IRI after overlay was 68 in./mile. This is also an initial indication of better results under the new specification.

Based on results collected from the sections built under the new IRI-based smoothness specification and included in this follow-up study, and on the small input sample from district maintenance engineers, it generally appears that the current practice of selecting pre-overlay repairs to deal with different amounts of load-related cracking is also excluding pre-overlay repairs on sections that are already generally smooth, and including digouts, milling, and CIR for successively rougher sections. These unintentional (with respect to roughness) practices follow the general recommendations from the initial report and appear to produce similar final IRI values around 60 in./mile. Overall, the IRI values for overlays less than 0.2 ft thick and with initial IRI values of 120 in./mile or less appear to have fallen from about 74 in./mile—under the earlier profilograph-based Caltrans specification—to about 60 in./mile on average—under the new Caltrans IRI-based smoothness specification. It is not certain how much grinding is being done that might be at last partially responsible for that drop.

Contrary to the findings in the initial study, this study found that the use of milling on the two sections with initial IRI values between 95 and 104 in./mile did not prevent a large improvement in smoothness after overlay. In this follow-up study no sections with initial IRI values less than 95 in./mile were found that had milling prior to overlay, which follows the recommendation made in the initial study.

Digouts did not show IRI values after overlay quite as low as those on the MnF sections after construction. More data (projects) would aid the comparison of projects with and without repair work, as would the addition of comparisons of different repair types, overlay materials, and the effect of overlay thickness.

The IRI measurements presented were made after the close of each construction contract, and therefore they include the effects of any grinding that Caltrans required the contractor to perform prior to that close.

4.2 Recommendations

Based on results from this study, the preliminary recommendation from the initial study should be changed to consider inclusion of milling for overlays on sections with IRI values between 95 and 120 in./mile. It is also recommended that additional data be obtained regarding the usefulness of milling on sections with this range of smoothness prior to overlay under the new specification and that any differences between different types of milling also be investigated. Consideration of special circumstances—such as conditions on narrow, winding highways where it would be difficult to mill—are also be recommended.

A comprehensive study of the MnF options might include data such as mill depth, fill thickness, overlay material, and the age of the underlying material. Further studies to quantify the benefits of construction activities should collect data *before* corrective grinding takes place as well as after close of the contract, and the percentage of the surface area that needed grinding should also be quantified. Finally, any further studies of smoothness in California should be conducted with equipment with a wide-spot laser installed in each wheelpath in order to match changes in the Caltrans requirements for profiler equipment that have occurred since the study presented in this report was completed.

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3. Caltrans Statement of Ongoing Contracts: *www.dot.ca.gov/hq/construc/statement.html* (Accessed July 2014).
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5. *ProVAL,* version 3.61.21. The Transtec Group, Inc. Copyright 2000-2016.

APPENDIX A: IRI GRAPHS FROM INDIVIDUAL SECTIONS

The graphs in Appendix A are grouped according to projects with no repairs (A.1), with digouts (A.2), with cold in-place recycling (A.3), and milling (A.4).

Appendix A.1: Projects with No Repairs

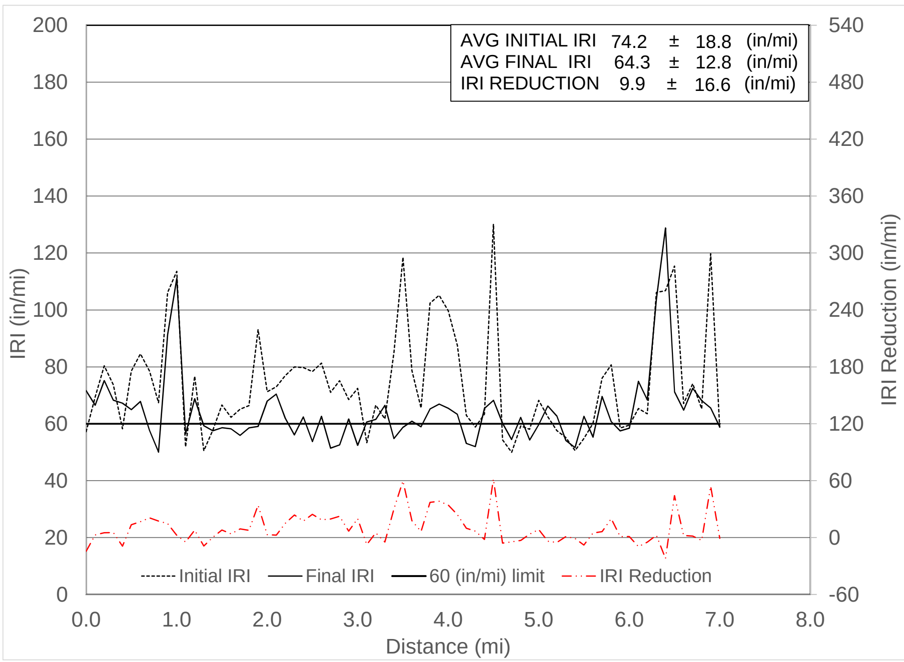

Figure A.1: Sacramento-50-West-Lane 4-PMR12.9/R5.8.

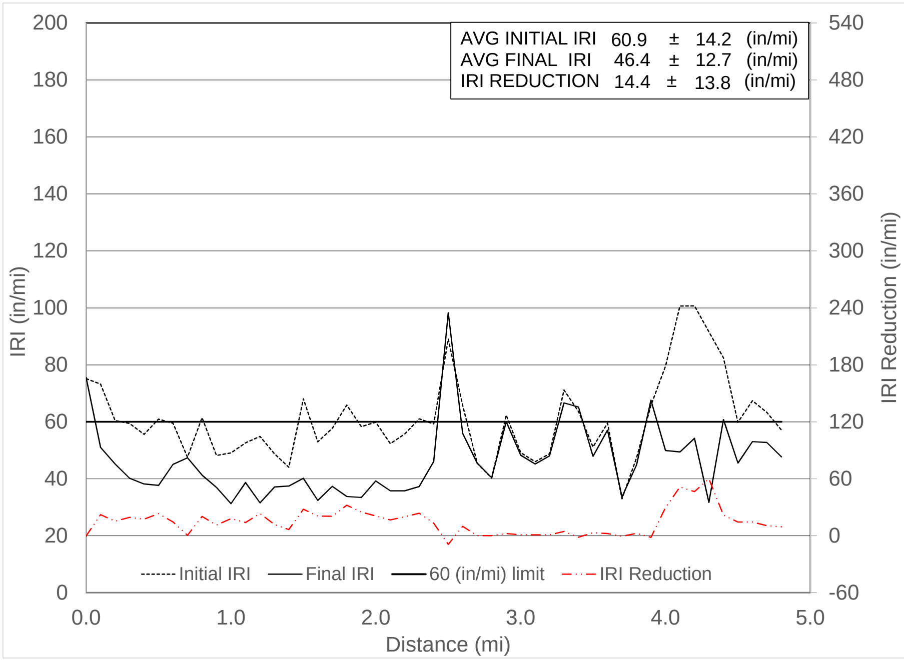

Figure A.2: Sacramento-99-North-Lane 1-PM32.1/36.9.

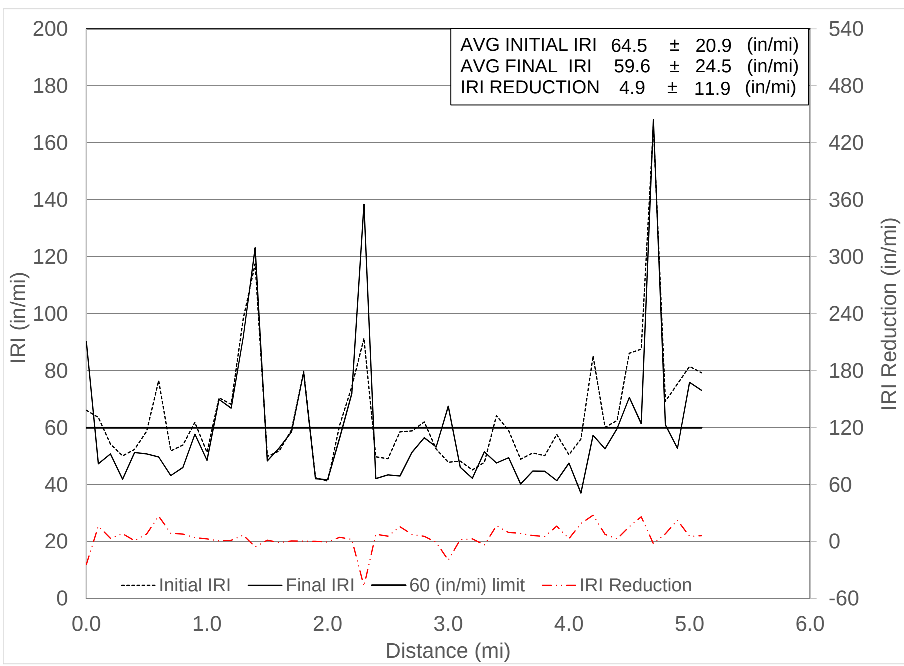

Figure A.3: Sacramento-99-South-Lane 1-PM32.1/36.9.

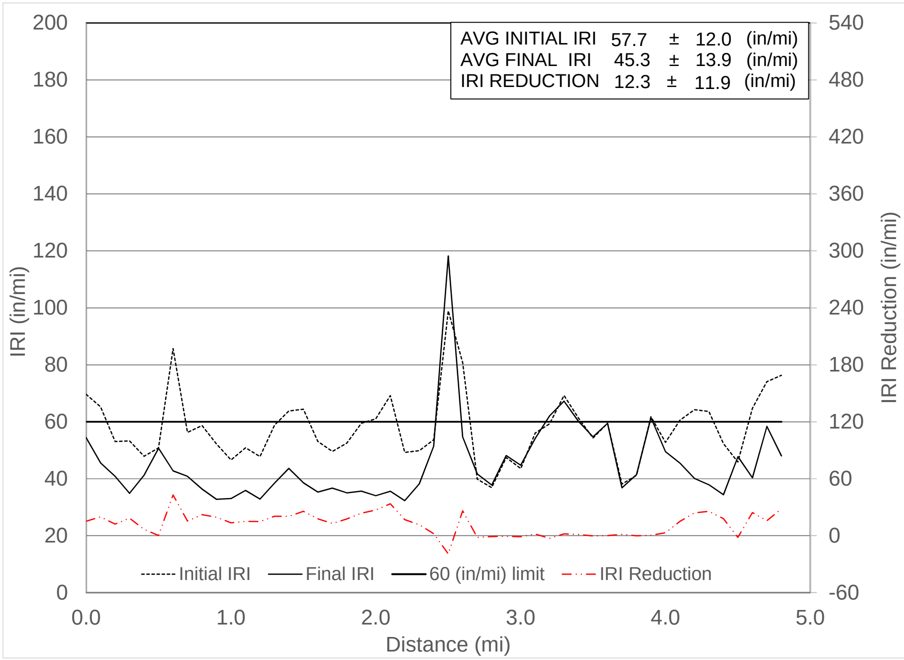

Figure A.4: Sacramento-99-North-Lane 2-PM32.1/36.9.

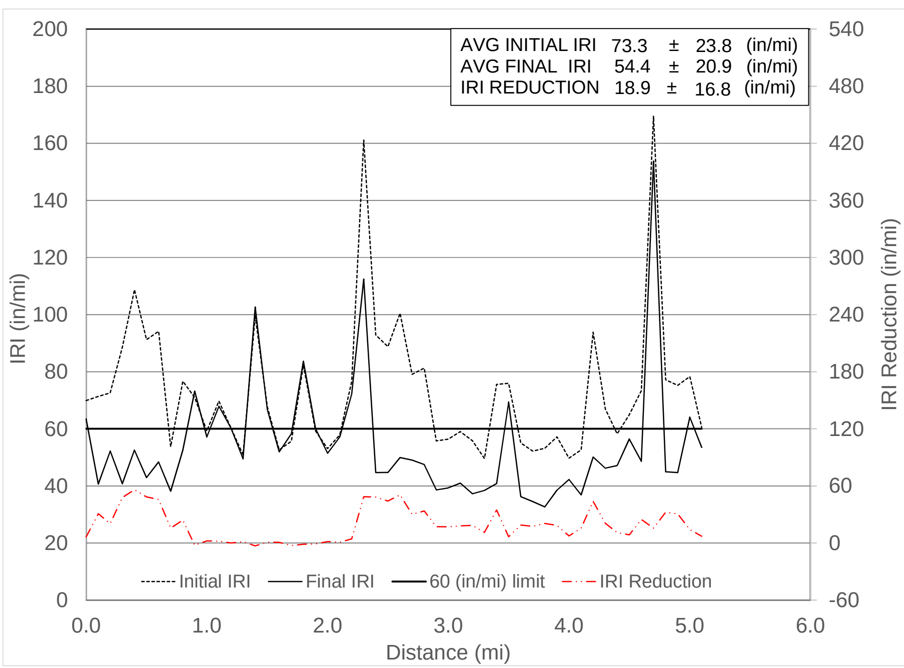

Figure A.5: Sacramento-99-South-Lane 2-PM32.1/36.9.

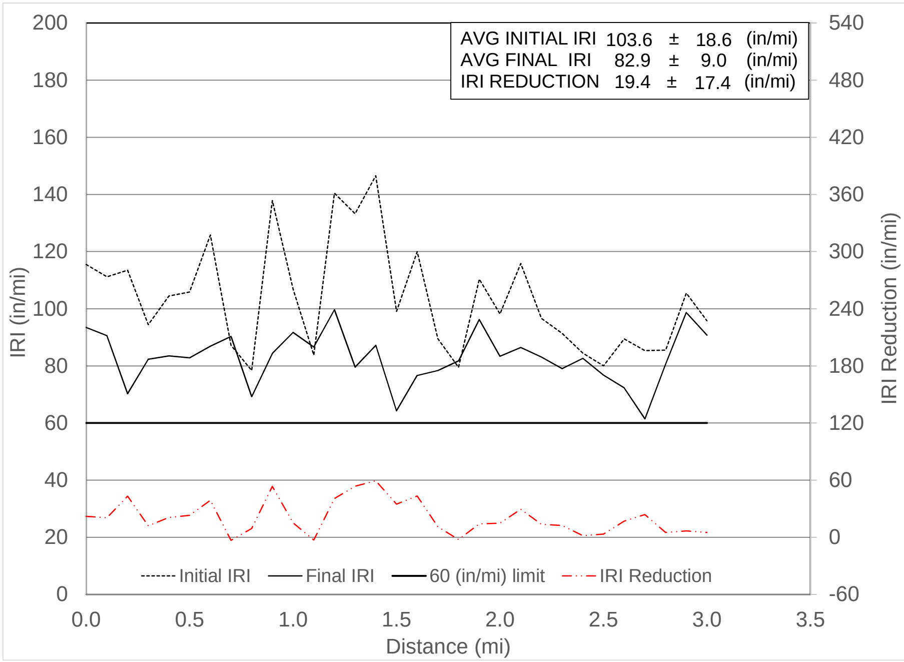

Figure A.6: Merced-165-North-Lane 1-PM26.7/30.

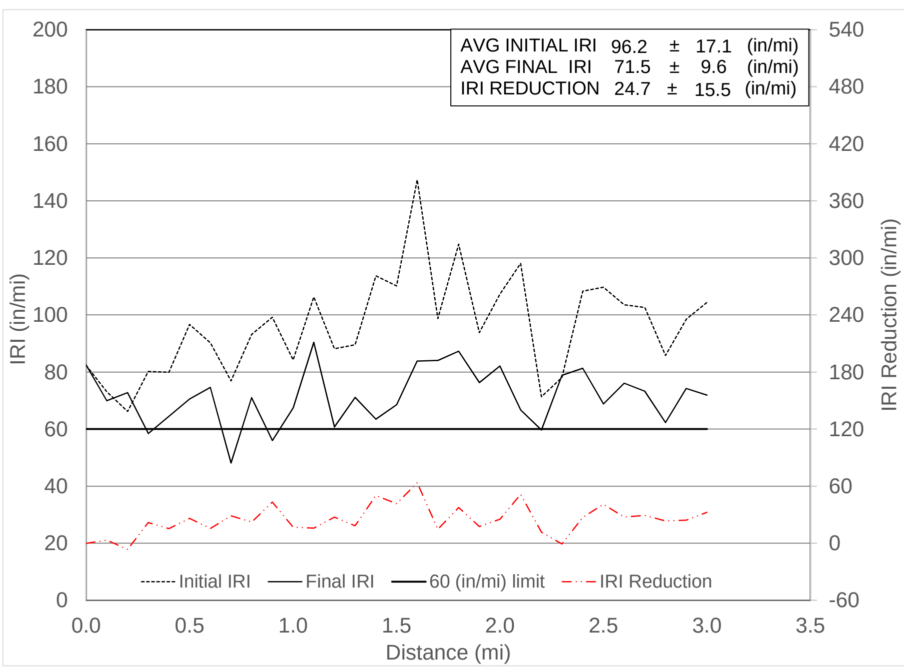

Figure A.7: Merced-165-South-Lane 1-PM26.7/30.

Appendix A.2: Projects with Digouts

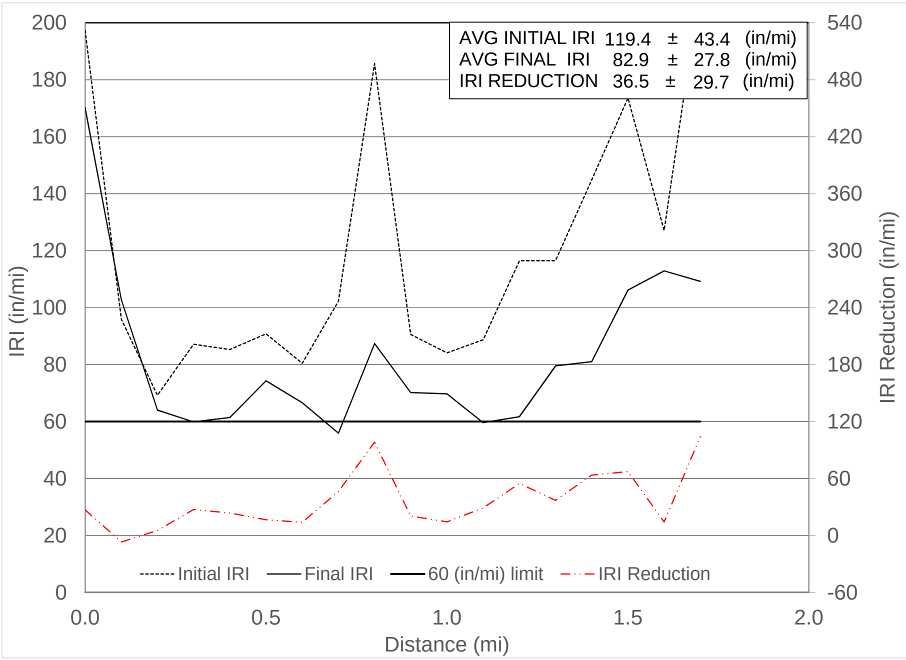

Figure A.8: San Joaquin-4-East-Lane 1-PM14.2/15.9.

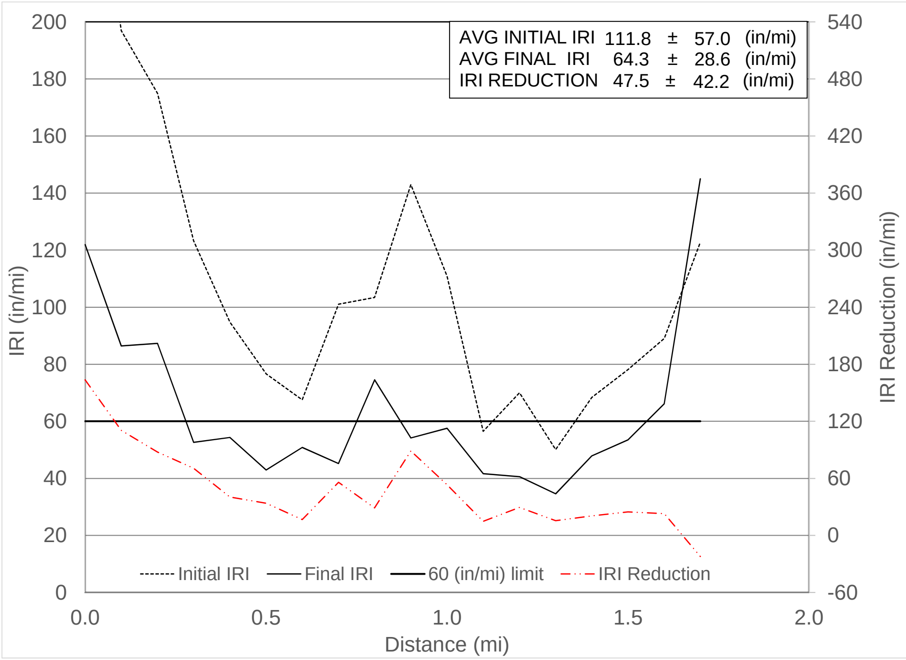

Figure A.9: San Joaquin-4-West-Lane 1-PM14.2/15.9.

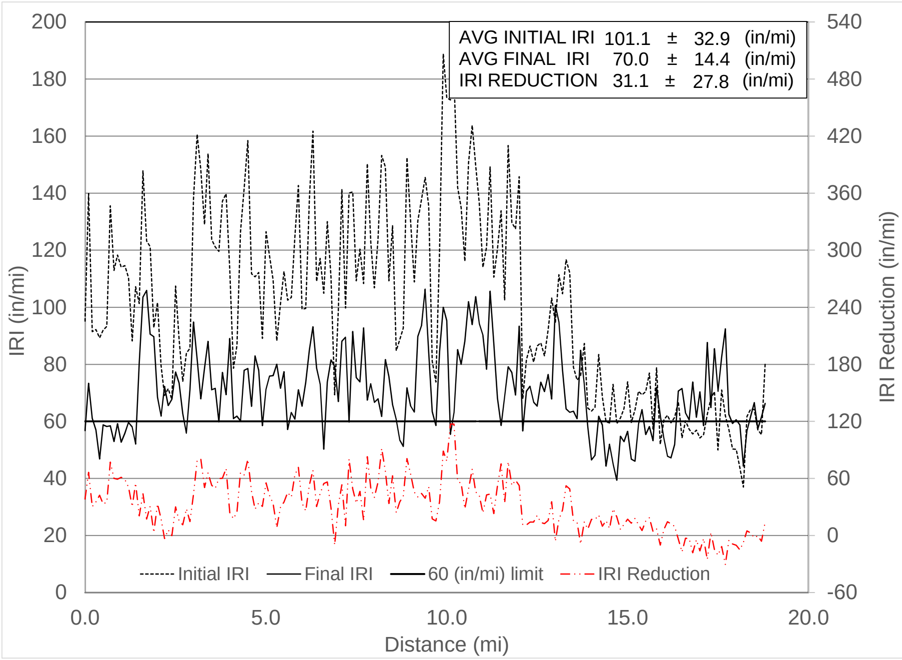

Figure A.10: Calaveras-4-East-Lane 1-PM30.0/49.6.

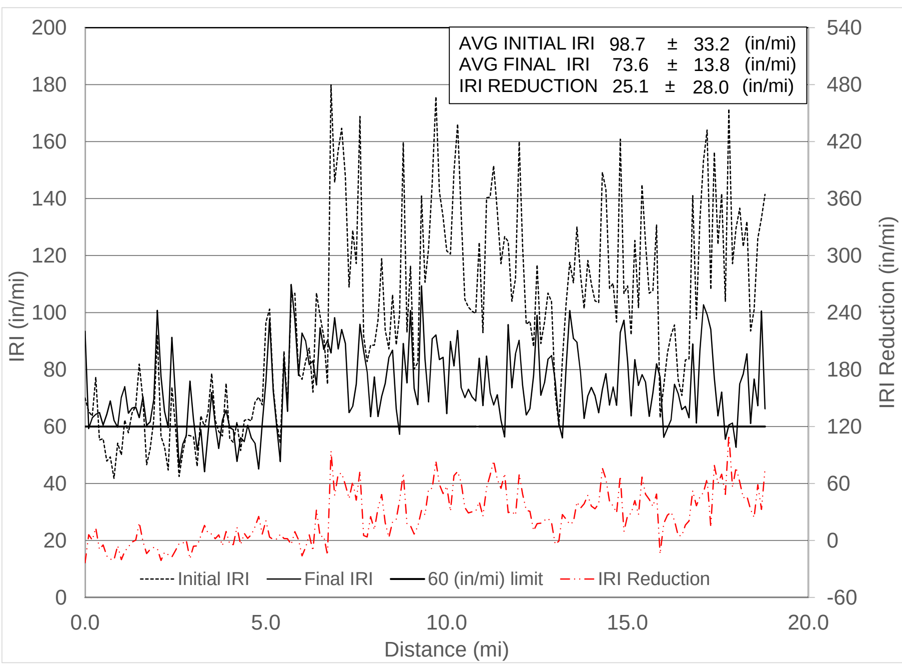

Figure A.11: Calaveras-4-West-Lane 1-PM30.0/49.6.

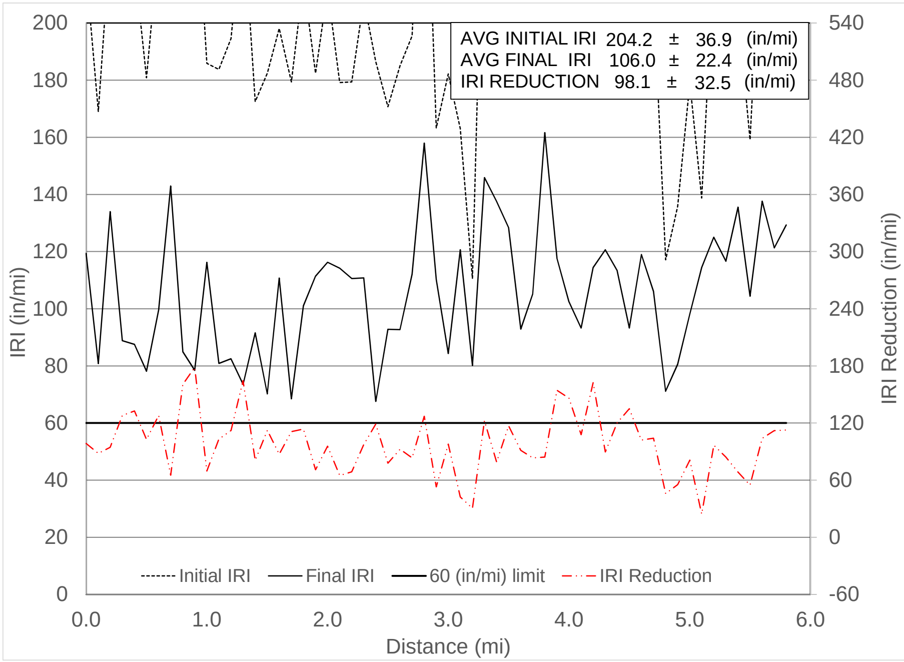

Figure A.12: Tehama-32-East-Lane 1-PM10.0/16.0.

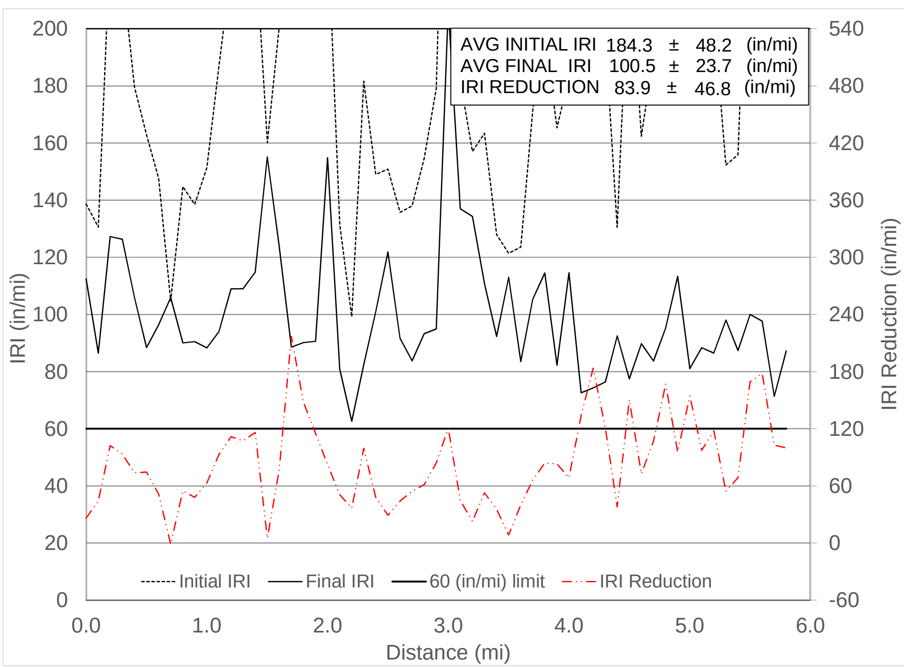

Figure A.13: Tehama-32-West-Lane 1-PM10.0/16.0.

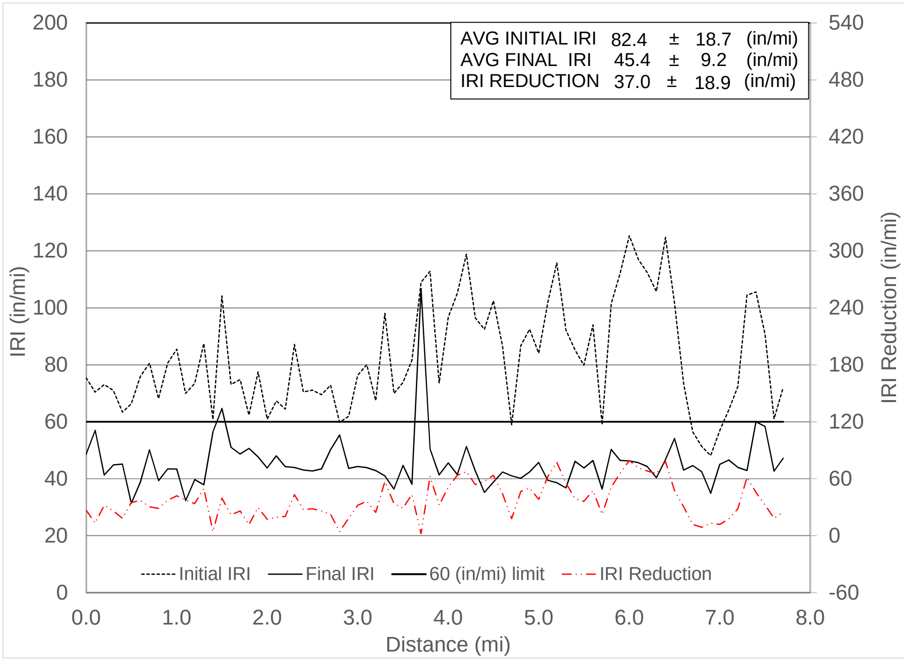

Figure A.14: Shasta-299-East-Lane 1-PM60.0/67.8.

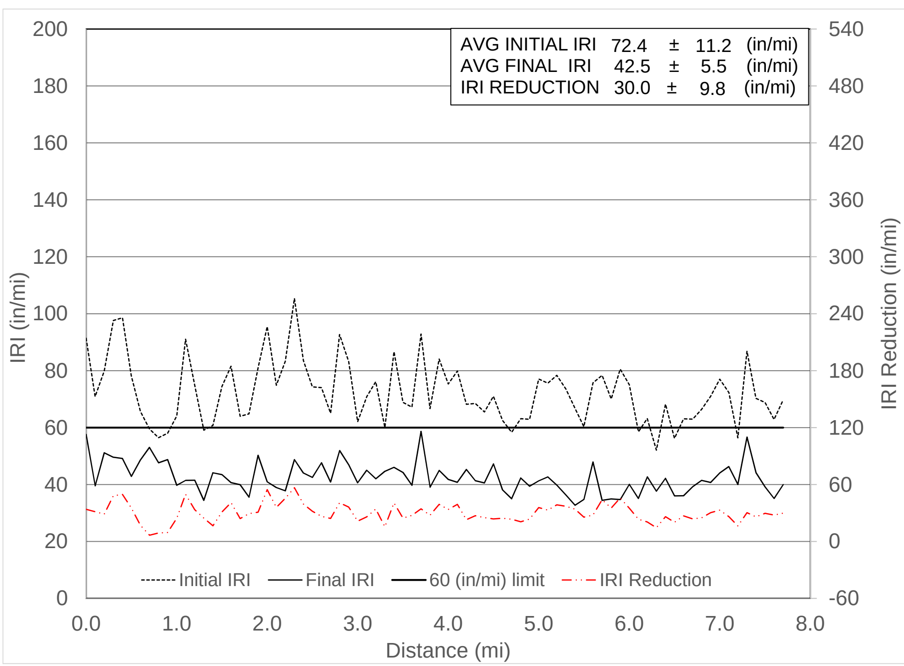

Figure A.15: Shasta-299-West-Lane 1-PM60.0/67.8.

Appendix A.3: Projects with CIR (Cold In-Place Recycling)

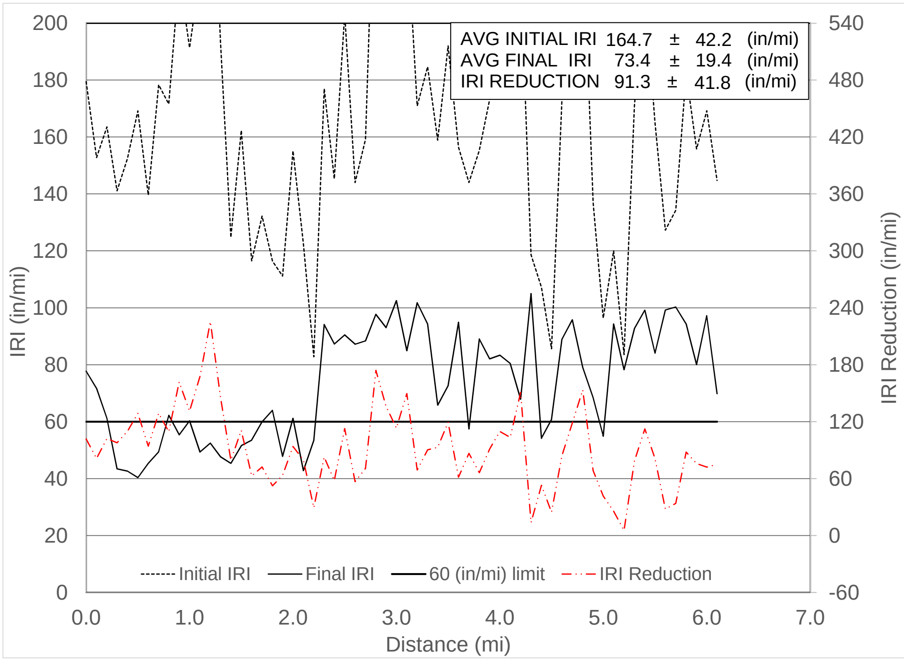

Figure A.16: El Dorado-193-East-Lane 1-PM6.0/12.7.

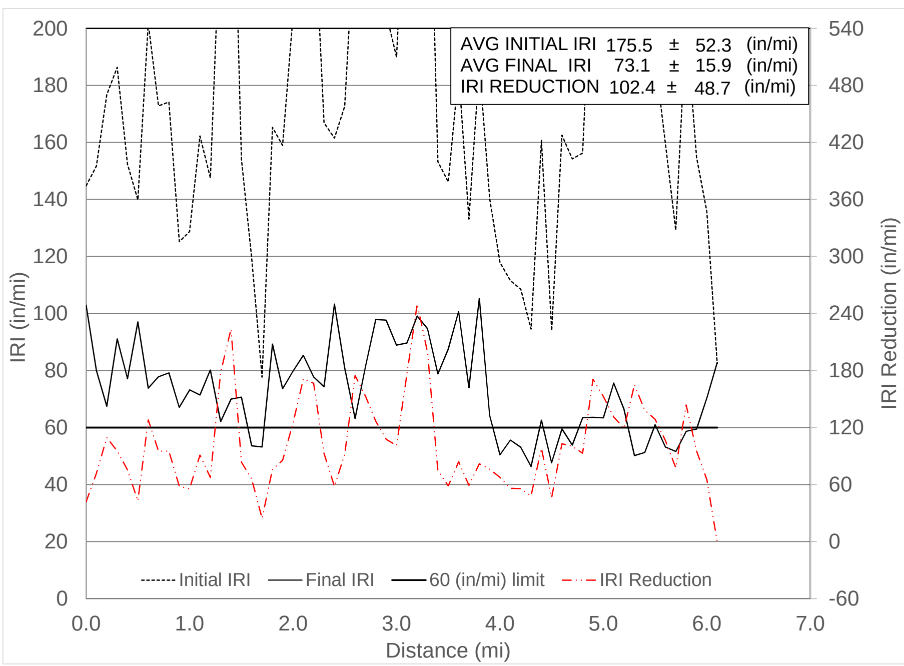

Figure A.17: El Dorado-193-West-Lane 1-PM6.0/12.7.

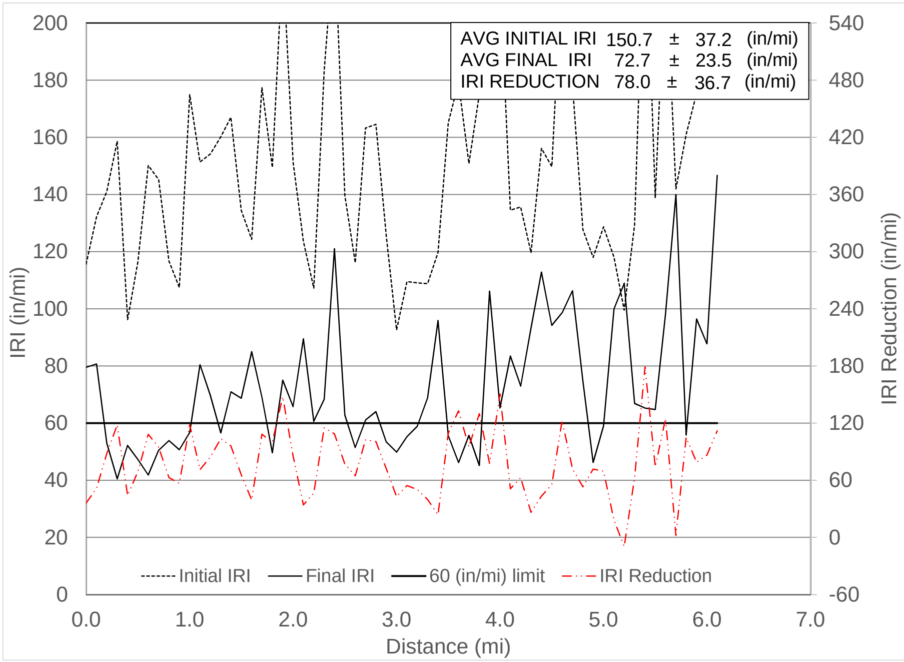

Figure A.18: Merced-59-North-Lane 1 -PM7.9/14.1.

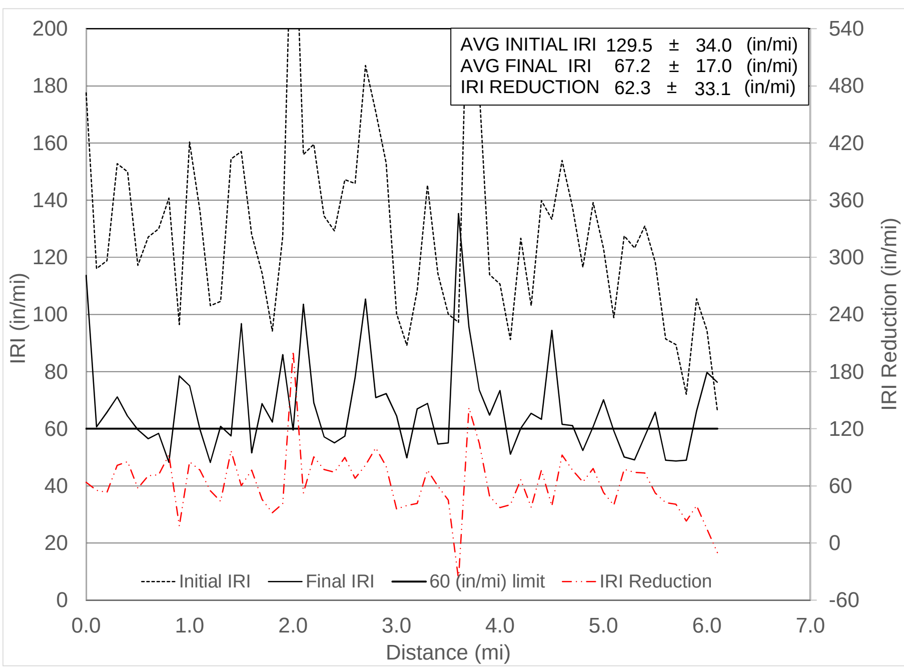

Figure A.19: Merced-59-South-Lane 1-PM7.9/14.1.

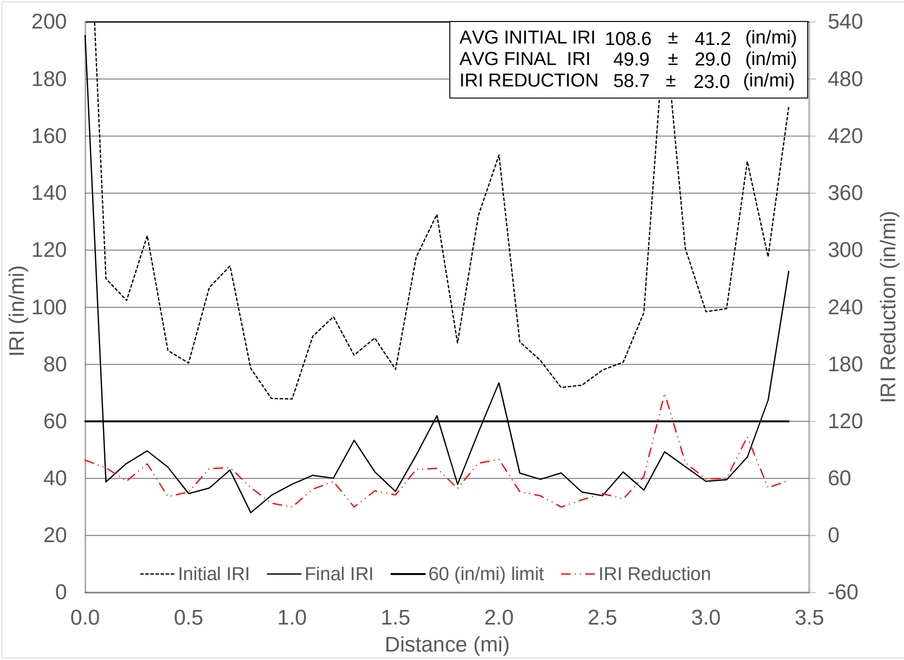

Figure A.20: Stanislaus-33-North-Lane 1-PM14.5/17.9.

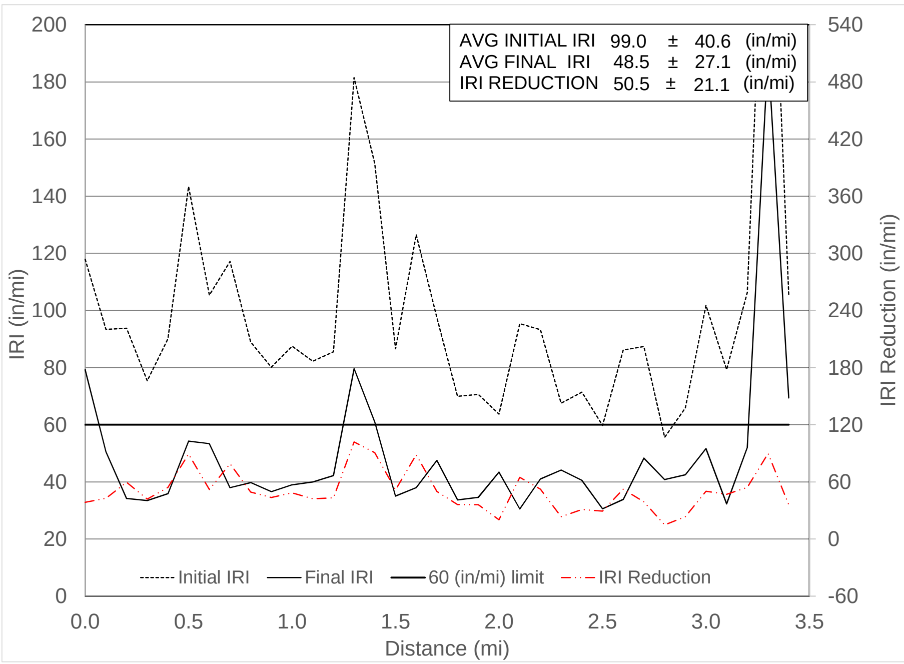

Figure A.21: Stanislaus-33-South-Lane 1-PM14.5/17.9.

Appendix A.4: Projects with Mill and Fill

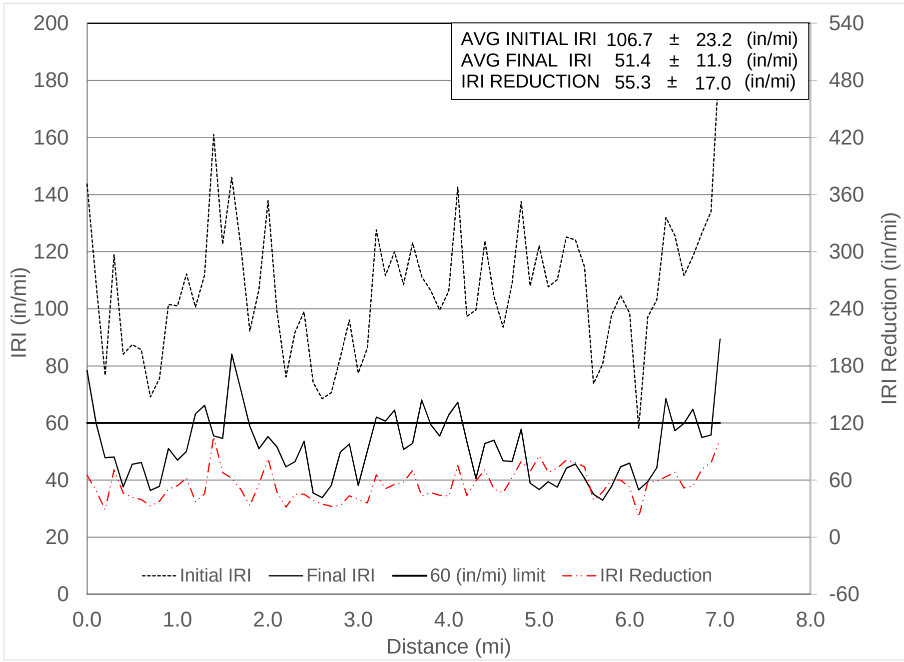

Figure A.22: Solano-37-East-Lane 1-PM0.1/7.4.

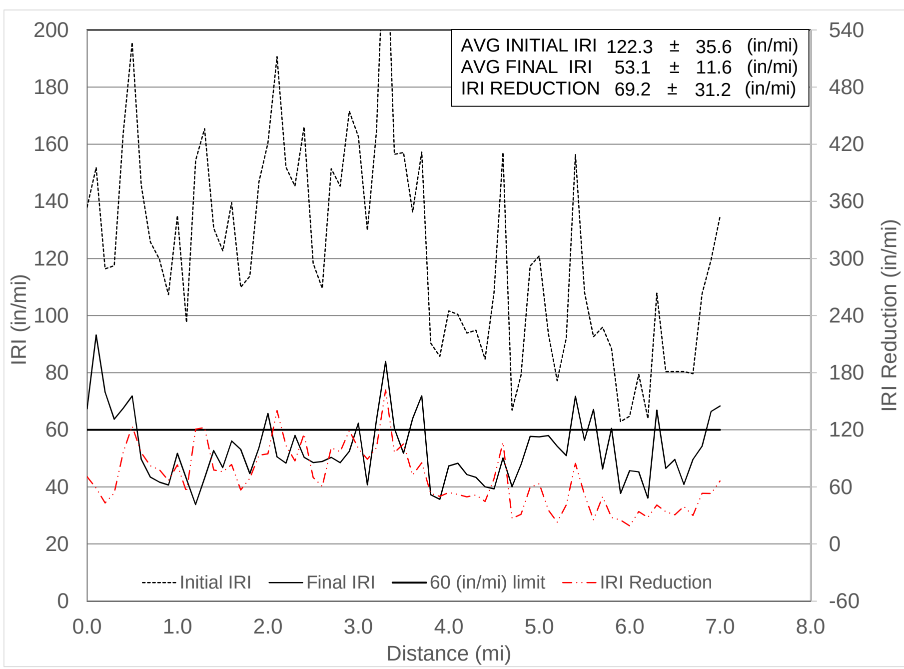

Figure A.23: Solano-37-West-Lane 1-PM0.1/7.4.