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Effects of Milling and Other Repairs on the Smoothness of Overlays on Asphalt Pavements from 2000 to 2009

August 2014

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Effects of Milling and Other Repairs on Smoothness of Overlays on Asphalt Pavements

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16. ABSTRACT

The application of asphalt overlays comprises a significant percentage of the maintenance activities undertaken to improve the condition of existing asphalt pavements, and greater attention is now being paid to improving surface smoothness by constructing smoother overlays. The expected benefits of smoother overlays include longer service life due to decreased dynamic loading, improved fuel economy, and greater road-user comfort.

In this study, data from the California Department of Transportation (Caltrans) Pavement Condition Survey (PCS) for projects built between 2000 and 2009 were used to investigate the effects of repairs, pavement pre-overlay smoothness (in terms of International Roughness Index, IRI), overlay mix type (dense-graded, gap-graded, open-graded), and binder type (rubberized versus conventional or polymer-modified) on initial post-construction overlay smoothness. The results are based on overlays constructed prior to implementation of the Caltrans smoothness specification for overlay construction. Linear mixed effects models were used in the analysis to take into account the variation across random effect variables. In this study, overlay smoothness was measured in terms of IRI. The analysis results indicated that the pavement pre-overlay IRI was the most important variable affecting overlay smoothness: pavements with lower pre-overlay IRI were smoother than those with higher pre-overlay IRI. When the pre-overlay condition was poor, increasing overlay thickness was also found to have a significant effect on post-overlay smoothness. In terms of pre-overlay repairs, analysis of Caltrans PCS data showed that overlays were smoother when digouts (milling and patching in the wheelpaths) were performed compared with milling of the entire surface prior to the overlay. The effects of overlay mix type and binder type were dependent on the pre-existing pavement condition and/or other factors.

Note: This report (version 1.1) was revised in December 2017 to clarify that 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. The revisions appear in the executive summary (introduction, conclusions and recommendations), Chapter 1, Section 3.1.1, Section 4.1, and Section 4.2.

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Smoothness, pre-overlay surface, milling, thickness, rubberized binder

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S. Balasubramanian and P. Vacura

PROPOSALS FOR IMPLEMENTATION

It is recommended that milling (cold planning) not be used as a means to improve smoothness prior to overlays when the pre-overlay IRI is less than 120 in./mile. Changes in Caltrans milling practice since 2009 may have made this recommendation unnecessary for pavements constructed since that time, but this should be investigated using projects built after the change to Caltrans smoothness specifications in 2013. Second, consider separate PaveM performance equations for overlays with and without digouts. Third, compare the results obtained in this study with smoothness values obtained since implementation of the Caltrans smoothness specification to see if improvements were made, and if adjustments to the specification are needed or desired.

RELATED DOCUMENTS

SIGNATURES

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PROJECT OBJECTIVES

The goal of this project, Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.42, "Effects of Milling and Other Repairs on Smoothness of Overlays," was to provide up-to-date information and technical assistance that will support the development of guidelines and specifications for pre-overlay treatments and the smoothness of overlays for the California Department of Transportation (Caltrans) based on the results of measurements, the analysis of construction projects, and the benefits/costs that are based on them.

The objectives of this study were achieved through the following tasks:

1. Review the existing literature to identify potential smoothness levels achievable with different initial surface profiles and different pre-overlay treatments.
2. Develop a factorial for the selection of construction projects that considers the explanatory variables, including pre-overlay pavement condition, overlay thickness, pre-overlay repairs, overlay mix type, and material used. Other variables were considered but discarded based on initial statistical review or lack of information, including underlying pavement type (except for certain cases which were considered) and structural thickness, paving sequence, paving season, climate region, and existing distresses.
3. Work with Caltrans district offices and headquarters to identify planned overlay projects and make arrangements for testing on them to include several types of pre-overlay treatments. Characterize pavement surfaces before overlay projects begin and after they are completed.
4. Analyze the data collected to determine the effects of the explanatory variables on overlay smoothness and the benefit-to-cost ratio of different pre-overlay treatment strategies.
5. Monitor the performance of the overlays in order to quantify the functional performance of the different strategies over time.
6. Prepare annual construction summaries and analysis reports, and a summary report that details the research and findings.

This report completes the work of Tasks 1, 2, and 4, except that benefit-to-cost was not evaluated because it was found that a number of the pre-overlay strategies had no benefit.

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EXECUTIVE SUMMARY

The primary purpose of the study presented in this report was to investigate the effects that pre-overlay pavement condition, overlay thickness, pre-overlay repairs, mix type (based on aggregate gradation), and binder type have on the smoothness of overlays. Previous studies were reviewed to determine the possible factors that might affect overlay smoothness. 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 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- or gap-graded versus open-graded); binder type (rubberized versus conventional or polymer-modified); and pre-overlay repairs, which consist of milling (milling of entire lane width) and digouts (milling and patching of wheelpaths only).

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. 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 PCC pavement, both of which require the contractor to determine pavement smoothness profiles using an inertial profiler and to use the International Roughness Index (IRI) as the roughness parameter for overlay construction smoothness. However, even though the asphalt overlay results in this study are based on overlays constructed prior to implementation of these new Caltrans smoothness specifications based on IRI, IRI was still used as the roughness parameter. 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.

The scope of this study only includes asphalt overlays on existing asphalt surfaces built by contractors for both the Caltrans maintenance (HM) and rehabilitation (HA22) programs, including the Capital Preventive Maintenance (CAPM) overlays that are part of the latter. This report does not include asphalt overlays on PCC surfaces.

Along with the data obtained from the Caltrans PCS, this study also extracted data from other Caltrans sources that contained information not included in the PCS. Construction as-built information (as-built thicknesses, materials, and construction dates) was obtained from the Caltrans Division of Construction through the Caltrans document retrieval system. However, the construction information available did not include pavement maintenance performed directly by Caltrans maintenance personnel.

In order to provide the level of detail needed for analysis, the data from the as-built documents were combined with the Caltrans PCS data to obtain details of overlay construction contracts, such as information about overlay thicknesses, pre-overlay repairs, and the materials used. Some difficulties and limitations arose when this data was used, primarily due to changes in PCS segment boundaries and to issues with data collection equipment.

Due to these limitations and the need to relate construction information to condition information, a comprehensive data mining exercise was carried out to prepare an adequate dataset for the study. The initial part of the data-mining process yielded 193 contracts that met the requirements of the study. Applying this process further, different pre-overlay repairs, overlay thicknesses, or overlay materials within the same contract were each treated as independent projects, and thus 228 projects were identified among the 193 contracts. Each overlay project included one or more PCS data collection subsections in the longitudinal direction, and, moreover, sections in multiple lanes—with their associated IRI values—were considered as separate subsections. The length of the subsections varied from project to project, most with lengths between 0.1 and 1.5 miles (0.16 and 2.4 km). The total number of subsections in the final data set was 4,475.

Data were also analyzed from 120 subsections in the Specific Pavement Studies (SPS-5) experiment portion of the Long-Term Pavement Performance (LTPP) program database operated by the U.S. Federal Highway Administration (FHWA). These SPS-5 sections included data from 15 states and provinces across the United States and Canada.

In addition to the data analysis, this report also includes a number of models that were developed as part of the statistical analysis. The aim of this analysis was to find what level of smoothness can be achieved with a new overlay and to recommend best practices for overlay repairs based on the existing pavement condition. Multiple regression analysis was used to develop these models in order to conduct a further analysis of the effects of the explanatory variables on overlay smoothness. In the multiple regression models, post-overlay IRI and IRI reduction were the dependent variables. The independent variables in the regression models were pre-overlay condition, overlay thickness, pre-overlay repairs (two types: *milling,* which is referred to as *cold planing* in Caltrans contract cost items and consists of the removal of 0.1 to 0.2 ft [30 to 60 mm] of material, often across the entire lane; and *digouts*, which consists of the removal of 0.25 to 0.4 ft [75 to 120 mm] in the wheelpaths), overlay type (open-graded or non-open-graded [including rubberized hot mix asphalt mixes, and dense-graded conventional and modified mixes]), and type of binder (asphalt rubber binder versus conventional or modified).

Based on the results of the analysis of the available data, the following conclusions were drawn:

- 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. Considering 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) would have been paved in two or sometimes more lifts, the multiple passes of the paver would have 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. The thickness effect could not be separated for different kinds of open-graded overlays (conventional, polymer-modified, rubberized, bonded wearing course).
- Milling prior to overlay and using rubberized binder (grouping gap-graded and open-graded mixes together in the statistical analysis) alone do not provide any additional benefits for achieving lower post-overlay IRI. However, using rubberized binder in open-graded overlays may help achieve lower post-overlay IRI.
- Milling prior to overlay on pavements with existing IRI less than 120 in./mile, and particularly when the existing IRI is less than 95 in./mile, is disadvantageous and will likely result in a rougher pavement than if milling had not been done, based on the data used for this study. As with all of the results in this study, changes in specifications and quality assurance practice may change this conclusion.
- Digouts, which should be done to correct cracking in the wheelpath prior to overlay, generally provide a benefit when the pre-overlay IRI is greater than 95 in./mile, but have the greatest benefit in reducing post-overlay IRI when the pre-overlay IRI is greater than 120 in./mile.
- 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. This result may be because relatively shallow milling (see definition above) may not address underlying structural problems in the wheelpaths, while digouts are generally only used where there are evident structural problems in the wheelpaths and, as defined for this study (see above), result in deeper removal of material in those locations.
- 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.

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.

A similar analysis of the LTPP SPS-5 sections from 120 subsections collected from the SPS-5 data—from fifteen 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, although 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. There was no information available regarding lift thicknesses used for different overlay total thicknesses. This finding is somewhat different from that found using the Caltrans data which showed that overlay thickness had no benefit on post-overlay IRI when the pre-overlay IRI was below 120 in./mile, but showed a benefit of thicker overlays when the pre-overlay IRI was greater than 120 in./mile.
- No specific trends could be found for pre-overlay repairs and mix types based on the descriptive statistics and boxplots.

Recommendations

The following recommendations are 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 recommend against using milling as a means to improve the smoothness of an overlay when the IRI of the existing pavement is less than 120 in./mile (1.9 m/km). Changes in milling practice since 2009 may change this recommendation, but this should be investigated using projects built since the change in the Caltrans smoothness specification in 2013.
- Digouts are used for pre-overlay repair to remove cracking only in the wheelpaths and only when the nonwheelpath pavement is in satisfactory condition; a decision to use digouts is based solely on the severity and extent of cracking. However, consideration should be given to using separate IRI performance equations in the *PaveM* pavement management system for overlays with and without digouts since their use on rough pavements helps improve overlay smoothness.
- 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 any changes in the findings of this study and whether adjustments to the specification are needed or desired. These new measurements should be taken by the UCPRC prior to any grinding for smoothness that Caltrans

requires the contractor to do prior to closing the construction contract, and if possible the UCPRC should also collect information regarding the amount of grinding that was required to pass the specification.

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
AIC	Akaike Information Criterion
Caltrans	California Department of Transportation
CCA	Construction Contract Acceptance
FHWA	Federal Highway Administration
FDOT	Florida Department of Transportation
GPS	General Pavement Studies
IRI	International Roughness Index
ITRD	International Transport Research Documentation
LTPP	Long-Term Pavement Performance
M&R	Maintenance and Rehabilitation
MTD	Material Transfer Device
OECD	Organization for Economic Co-operation and Development
PCC	Portland cement concrete
PCS	Pavement Condition Survey
PPRC SPE	Partnered Pavement Research Center Strategic Plan Element
RAP	Reclaimed Asphalt Pavement
TRID	Transport Research International Documentation
TRIS	Transportation Research Information Services
TWM	Total Weight of Mixture
VDOT	Virginia Department of Transportation
UCPRC	University of California Pavement Research Center

LIST OF TEST METHODS AND SPECIFICATIONS

ASTM E1926-08	Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements
CT 526	Method of Test for Operation of California Highway Profilograph and Evaluation of Profiles

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

The pavement structures in state highway and local road networks represent significant assets that have been built and are maintained with public funds. To make the most of this funding while preserving these assets requires highway agencies to select maintenance strategies that will maximize the network's serviceability while remaining within budget. One prominent strategy used by Caltrans to manage its network is the application of asphalt overlays on existing pavements to preserve or restore pavement condition and pavement smoothness in particular.

Maintaining pavement smoothness is important because it has been identified as a significant factor in drivers' perception of pavement condition [*1*], and because smooth pavements also reduce vehicle operating costs, including vehicle maintenance and fuel consumption [*2*], and reduce carbon dioxide emissions and energy use [*3*].

The primary purpose of the study presented in this report was to investigate the effects that pre-overlay pavement condition, overlay thickness, type of pre-overlay repairs, mix type (based on aggregate gradation), and binder type have on the smoothness of overlays using data from 2000 to 2009. Accomplishing this involved reviewing earlier studies to determine what factors might affect overlay smoothness, mining databases provided by the Caltrans Pavement Program to select construction projects appropriate for data analysis, and conducting a statistical analysis to determine the effects of different explanatory variables. The results obtained were then used to make recommendations for the design of overlays based on existing pavement condition.

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 the contractor to determine pavement smoothness profiles using an inertial profiler and to use the International Roughness Index (IRI) as the roughness parameter for overlay construction smoothness. However, even though the asphalt overlay results in this study are based on overlays constructed prior to implementation of these new Caltrans smoothness specifications, IRI was still used as the roughness parameter.

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 (open-graded, gap-graded, or dense-graded); binder type (rubberized versus conventional or polymer-modified); and two types of pre-overlay repairs (*milling*, which is referred to as *cold planing* in Caltrans contract cost items and consists of the removal of 0.1 to 0.2 ft [30 to 60 mm] of material, often across the entire lane; and *digouts,* which consists of the removal of 0.25 to 0.4 ft [75 to 120 mm] in the wheelpaths), overlay type (open-graded or non-open-graded [including rubberized hot mix asphalt mixes, and dense-graded conventional and modified mixes]), and type of binder (asphalt rubber binder versus conventional or modified).

As noted, this study used IRI as the measure of smoothness (ride quality). IRI is defined as the accumulated vertical movement of the sprung mass of one quarter of a standard vehicle divided by the distance traveled, as calculated by a computer simulation of the quarter-car operating in the wheelpath on the longitudinal profile of the measured pavement per ASTM E1926-08 ("Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements"). Von Quintus et al. [*4*] pointed out that IRI is significantly affected not only by the initial pavement smoothness but also by pavement distresses such as fatigue cracking, transverse cracking, block cracking, and rutting, particularly when they are severe and widespread. IRI is typically expressed in the units inches per mile (in./mile) or meters per kilometer (m/km) [*5*].

The objectives of this study were achieved through the following tasks:

1. Review the existing literature to identify potential smoothness levels achievable with different initial surface profiles and different pre-overlay treatments.
2. Develop a factorial for the selection of construction projects that considers the explanatory variables, including pre-overlay pavement condition, overlay thickness, pre-overlay repairs, overlay type, and material used. Other variables were considered but discarded based on initial statistical review or lack of information, including underlying pavement type (except for certain cases which were considered) and structural thickness, paving sequence, paving season, climate region, and existing distresses.
3. Work with Caltrans district offices and headquarters to identify planned overlay projects and make arrangements for testing on them to include several types of pre-overlay treatment. Characterize pavement surfaces before overlay projects begin and after they are completed.
4. Analyze the data collected to determine the effects of the explanatory variables on overlay smoothness and the benefit-to-cost ratio of different pre-overlay treatment strategies.
5. Monitor the performance of the overlays in order to quantify the functional performance of the different strategies over time.
6. Prepare annual construction summaries and analysis reports, and a summary report that details the research and findings.

This report completes the work of Tasks 1, 2, and 4, except that benefit-to-cost was not evaluated because it was found that a number of the pre-overlay strategies had no benefit.

The data used in this study were taken from the Caltrans 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

(California Test 526, “Method of Test for Operation of California Highway Profilograph and Evaluation of Profiles”) (Note: In 2013, Caltrans implemented a new construction smoothness specification based on measurement of IRI: CPB13-2, “Inertial Profiler Construction Inspection Guidance and Evaluation of Profiles.”) The scope of this study only includes asphalt overlays on existing asphalt surfaces built by contractors for both the Caltrans maintenance (HM) and rehabilitation (HA22) programs, including the Capital Preventive Maintenance (CAPM) overlays that are part of the latter. This report does not include hot mix asphalt (HMA) overlays on PCC surfaces. *Note:* 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.

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2 LITERATURE REVIEW

The primary source for this literature review was TRID, an integrated database that combines records from the Transportation Research Board's (TRB) Transportation Research Information Services (TRIS) database and the Joint Transport Research Centre's (JTRC) International Transport Research Documentation (ITRD) database of the Organization for Economic Co-operation and Development (OECD). In this report, the information collected from the databases regarding overlay smoothness was synthesized to identify the factors that affect overlay smoothness and to determine their significance levels.

2.1 Factors that Affect Overlay Smoothness

Earlier studies that addressed the factors affecting overlay smoothness were found in the literature review. Some of these studies used pavement performance data collected from across the U.S. and Canada for the LTPP program database operated by FHWA, while others used state- or province-specific data. As part of the LTPP program, General Pavement Studies (GPS) were conducted to evaluate the performance of in-service pavement sections either after the original construction or after an overlay (that is, after an HMA overlay of an existing HMA pavement or PCC pavement). Additional Specific Pavement Studies (SPS) were conducted to evaluate the performance of specific design features of pavements [*6*].

2.1.1 Pre-Overlay Repairs

The results of earlier studies on the effects of pre-overlay repairs on overlay smoothness are inconsistent as to whether or not milling is significant. For example, using the LTPP data, West et al. [*7*] found that milling prior to overlay significantly decreased IRI and future cracking. Using that same LTPP data, Raymond et al. [*8*] also found that the extent of surface preparation (milling) had a significant effect on overlay roughness when the pre-overlay IRI was over 95 in./mile (1.5 m/km). On the other hand, when Perera and Kohn [*9*] investigated the influence of milling on overlay smoothness, also by analyzing the LTPP data, they found that milling did not result in any statistically significant effect on post-overlay IRI when the measurements were compared to results collected from unmilled sections. Based on these results, it appears that the effect of pre-overlay repairs may have a certain level of interaction with post-overlay smoothness, but there was no consensus among the studies as to whether or not milling prior to overlay has a significant effect.

2.1.2 Overlay Thickness

Studies that analyzed the LTPP data for the effect of overlay thickness on post-overlay IRI found varying and sometimes contradictory results. For example, Raymond et al. [*8*] and Perera and Kohn [*9*] found that overlays between 2 inches (50 mm) and 5 inches (125 mm) had no significant effect on post-overlay IRI regardless of the pre-overlay condition. However, West et al. [*7*] found that 5 inch (125 mm) thick overlays yielded better performance than 2 inch (50 mm) thick overlays in terms of smoothness—and in delaying the onset of cracking and raveling—thus showing that overlay thickness significantly affects pavement roughness.

The effects of overlay thickness on long-term condition were also investigated using the LTPP data. In one study, Hall et al. [*10*] found that 5 inch thick overlays outperformed 2 inch thick overlays in terms of smoothness and fatigue cracking over an average analysis period of 7.8 years. In another study, Wen et al. [*11*] found that a small increase of overlay thickness can effectively reduce the development rate of transverse cracking. These results showed that increased thickness has some positive effects on slowing the increase of IRI over time.

2.1.3 Pavement Smoothness Prior to Overlay

As with the preceding factors discussed, inconsistent results among earlier studies have not clarified the role of pavement smoothness prior to overlay as a key factor affecting overlay smoothness. A study by Hall et al. [*10*] found that original surface roughness had a significant effect on the smoothness of overlays and work by McGhee [*12*] found a correlation between pre-overlay IRI and post-overlay IRI. However, Perera and Kohn [*9*] found a contradictory result that showed no correlation between the IRI before and after the overlay.

2.1.4 Overlay Materials

The effects of materials used for overlays were evaluated by McGhee [*12*] and the results showed that the asphalt mix type had no significant effect on pavement smoothness. However, that evaluation was limited to gap-graded mixes with different stiffness values and asphalt contents. The types of mixes considered in the data analysis in this current study are broader than those included in the study by McGhee partly because Caltrans has increased its use of rubberized gap-graded overlays, and rubberized, polymer-modified, and conventional open-graded overlays. It is still to be determined whether and how these materials affect pavement smoothness after overlay.

In recent years, the use of Reclaimed Asphalt Pavement (RAP) in overlays has also gradually increased, and the performance of overlays with increased RAP contents is a concern for some state highway agencies. Research results from two studies indicated that there was no significant effect on post-overlay IRI or on the long-term development of roughness, rutting, block cracking, or raveling introduced by mixes with either virgin aggregate or with 30 percent RAP [*10, 11*]. It should be noted that during the period covered by this current study, Caltrans did not allow RAP in rubberized gap-graded mixes or in any type of open-graded mix, and limited RAP content to a maximum of 15 percent in dense-graded mixes.

2.1.5 Other Factors

Smith and Tighe [*13*] investigated the effects of freeze-thaw cycles and trapped water on the performance of overlays and found that they accelerated pavement roughness progression. The study also found that if the water does not freeze, it does not affect roughness progression.

The effects on overlay smoothness of adding supplemental structural layers and the time of day when the paving was performed (daytime or nighttime) were also evaluated in earlier studies. Study results published by the Virginia Department of Transportation (VDOT) [*12*] showed that an added intermediate or base layer in a pavement structure had little positive effect on reducing post-overlay IRI. That report, as well as another one by the Florida Department of Transportation (FDOT) [*14*], showed that daytime versus nighttime paving also had no significant effect on post-overlay IRI.

In addition, Holzschuher et al. [*14*] found that adding a Material Transfer Device (MTD, referred to as a Material Transfer Vehicle [MTV] by Caltrans) to the paving process significantly reduced the post-overlay IRI of pavements. This is because the use of the device helped achieve continuous movement of the paver and a uniform flow of consistent mix, thus eliminating the need to stop the paver to connect it with haul trucks. MTD use also improved the consistency of the asphalt mix temperature and gradation when the mixes were delivered to the paver. The study's results showed that the use of an MTD can improve IRI by about 15 to 25 percent compared to IRI values measured on overlays performed without the use of an MTD.

2.2 Summary of the Factors Affecting Overlay Smoothness Found in Previous Studies

A summary of the factors discussed above that might affect the smoothness of overlays are listed below and are shown in Table 2.1. Among the factors that were considered to possibly affect overlay smoothness, the most common ones investigated in the literature were found to be pre-overlay IRI, overlay thickness, and pre-overlay repairs. Inconsistencies among the results of those studies leave it unclear whether or not these factors have significant effects on overlay smoothness.

- In several of the studies, overlay thickness and milling did not have a significant effect on post-overlay IRI regardless of the pre-overlay condition, but some of the studies pointed out that overlay thickness or milling *might* influence long-term overlay smoothness.
- Differences in the materials used in overlays, such as binder type, aggregate gradation, and mix type (virgin or containing RAP [referred to as "recycled" in modeling performed for this study]), do not have a significant influence on overlay smoothness.

- In the VDOT [*12*] and FDOT [*14*] reports, the time of paving (daytime versus nighttime) did not affect overlay smoothness.
- The use of an MTD in paving has a significant positive effect on post-overlay IRI values.
- Overlay age and traffic conditions are considered to have a significant effect on the progression of IRI.

Table 2.1: Potential Factors Affecting Overlay Smoothness Included in Earlier Studies

Factors	**Reference**							
	Perera and Kohn [*9*]	**West et al. [*7*]**	**Raymond et al. [*8*]**	**Hall et al. [*10*]**	**Wen et al. [*11*]**	**McGhee [*12*]**	**Smith and Tighe [*13*]**	**Holzschuher et al. [*14*]**
Pre-overlay repairs	0	2	1	0	2	0		
Overlay thickness	0	2	0	0, 2	2	0	2	
Pavement smoothness prior to overlay	0			1		1		
Materials (virgin vs. recycled mixes)				0	0			
Subgrade type (coarse vs. fine)							0	
Overlay mix type (open-graded vs. dense-graded)								0
Binder type (polymer-modified vs. others)								0
Paving time						0		0
Provision for smoothness						1		
Use of a Material Transfer Device (MTD)								1

Notes:
0: The factor does not have a significant effect on overlay smoothness (initial or long-term).
1: The factor has a significant effect on post-overlay smoothness.
2: The factor has a significant effect on long-term pavement smoothness.

3 INVESTIGATION OF FACTORS AFFECTING OVERLAY SMOOTHNESS

As noted in the literature review, it is currently unknown whether or to what extent overlay smoothness is affected by overlay thickness, pre-overlay pavement condition, pre-overlay repairs, materials, or other factors. In order to better understand which factors significantly affect overlay smoothness and what potential levels of smoothness can be achieved after placement of overlays, two different datasets—the Caltrans PCS and the LTPP SPS-5—were used to conduct a more precise analysis.

3.1 Data Extraction and Data Mining

3.1.1 Caltrans PCS Data

Data for this study were extracted from the Caltrans PCS and from other Caltrans sources that contained information not included in the PCS. All the data were then combined to perform the analysis. Data from the Caltrans PCS included information on IRI, wheelpath cracking, and other distresses, which is collected on a regular basis.

Construction as-built information (as-built thicknesses, materials, and construction dates) was obtained from the Caltrans Division of Construction through the Caltrans document retrieval system. This construction information did not include data regarding pavement maintenance performed directly by Caltrans maintenance personnel, and did not include data regarding the amount of grinding that Caltrans required the contractor to perform based on the profilograph measurements prior to closing the contract. The data from the as-built documents provided the details of overlay construction contracts, such as overlay thicknesses, pre-overlay repairs, and materials used. Some difficulties and limitations arose when putting together the PCS IRI data with the as-built data, primarily due to changes in the PCS segment boundaries from year to year and issues with IRI data collection equipment.

Due to these limitations and the need to relate construction information to condition information, a comprehensive data mining exercise was carried out to prepare an adequate dataset for the study. The initial part of the data-mining process yielded 193 contracts that met the requirements of the study. Applying this process further, different pre-overlay repairs, overlay thicknesses, or overlay materials within the same contract were each treated as an independent project, and thus 228 projects were identified among the 193 contracts. Each overlay project included one or more PCS data collection subsections in the longitudinal direction; moreover, sections in multiple lanes—with their associated IRI values—were considered as separate subsections. The length of the subsections varied from project to project, most with lengths between 0.1 and 1.5 mi. The total number of subsections in the final dataset was 4,475.

The cumulative distribution of the length of the subsections is shown in Figure 3.1. The figure is a cumulative distribution plot which shows the subsection lengths on the x-axis and the cumulative percentage of subsections on the y-axis. From the plot it can be seen that the median (50th percentile) subsection length is a little less than 0.3 miles, that about 20 percent of the sections were less than 0.1 miles, and that the longest subsection was 5 miles, which was the maximum length introduced into the data set.

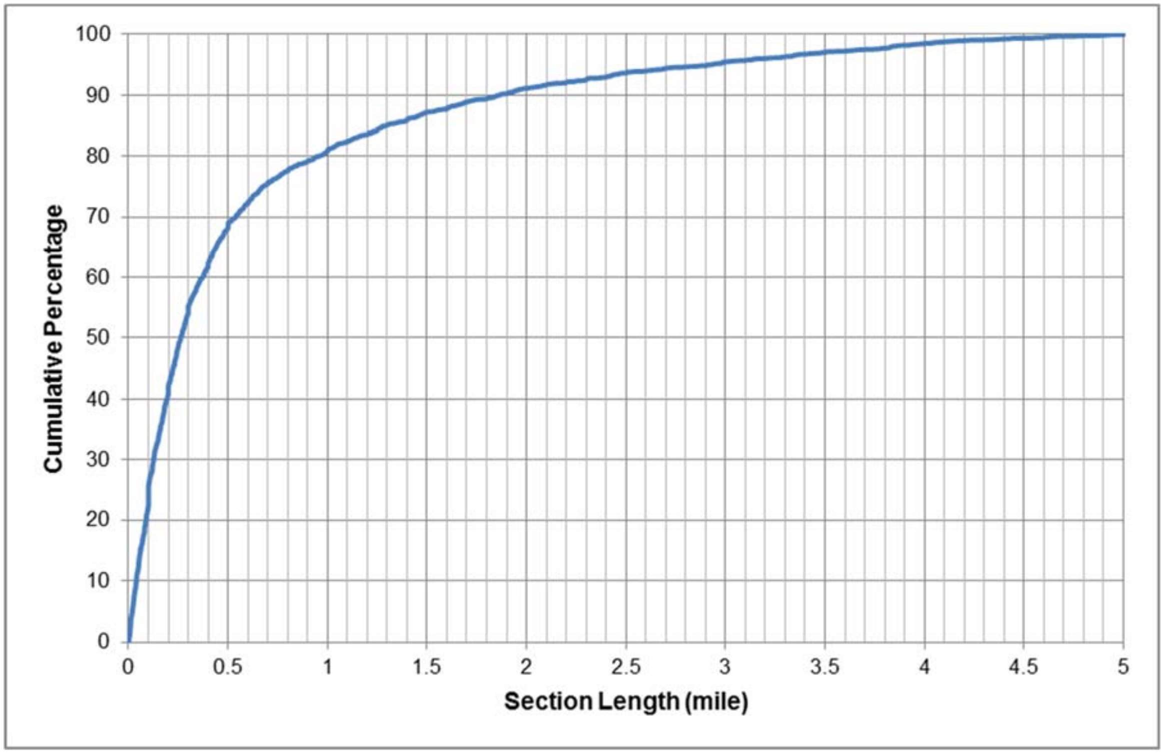


Figure 3.1: Cumulative distribution of the length of subsections.

The data-mining process is summarized in the following steps and shown as part of the flow chart in Figure 3.2 (starting at Step 3).

1. Projects with more than two years' worth of reasonable data (IRI variation with time is considered reasonable) after completion of their overlay projects were selected.
2. The actual construction date of each project was identified by a drop in its IRI. Subsections within each project were also checked for a drop in IRI, and the date of construction assigned to them was defined as the time when most of the subsections showed a drop in IRI.
3. Because the construction contract acceptance (CCA) date (as-built) was used rather than the construction completion date (which is not recorded), two assumptions were made when selecting subsections. First, projects showing a drop in IRI in the year preceding the CCA date or in the two years following it were selected. Second, projects that had more than one IRI drop within the period were eliminated because the extra IRI might have been caused by other unknown maintenance activities.

4. The latest IRI measurement taken before applying the overlay was defined as the *pre-overlay IRI;* and the earliest IRI measurement taken after applying the overlay was defined as the *post-overlay IRI.*
5. Projects with an interval longer than three years between IRI measurements were eliminated in order to reduce the effects from traffic or aging.
6. Altogether, 228 overlay projects were identified for data analysis in this study.

After a number of variables were considered, the following were selected for data analysis: pre-overlay IRI, post-overlay IRI, overlay thickness, the application of milling, the application of digouts, overlay mix type (dense- or gap-graded versus open-graded), and binder type (rubberized versus conventional or polymer-modified).

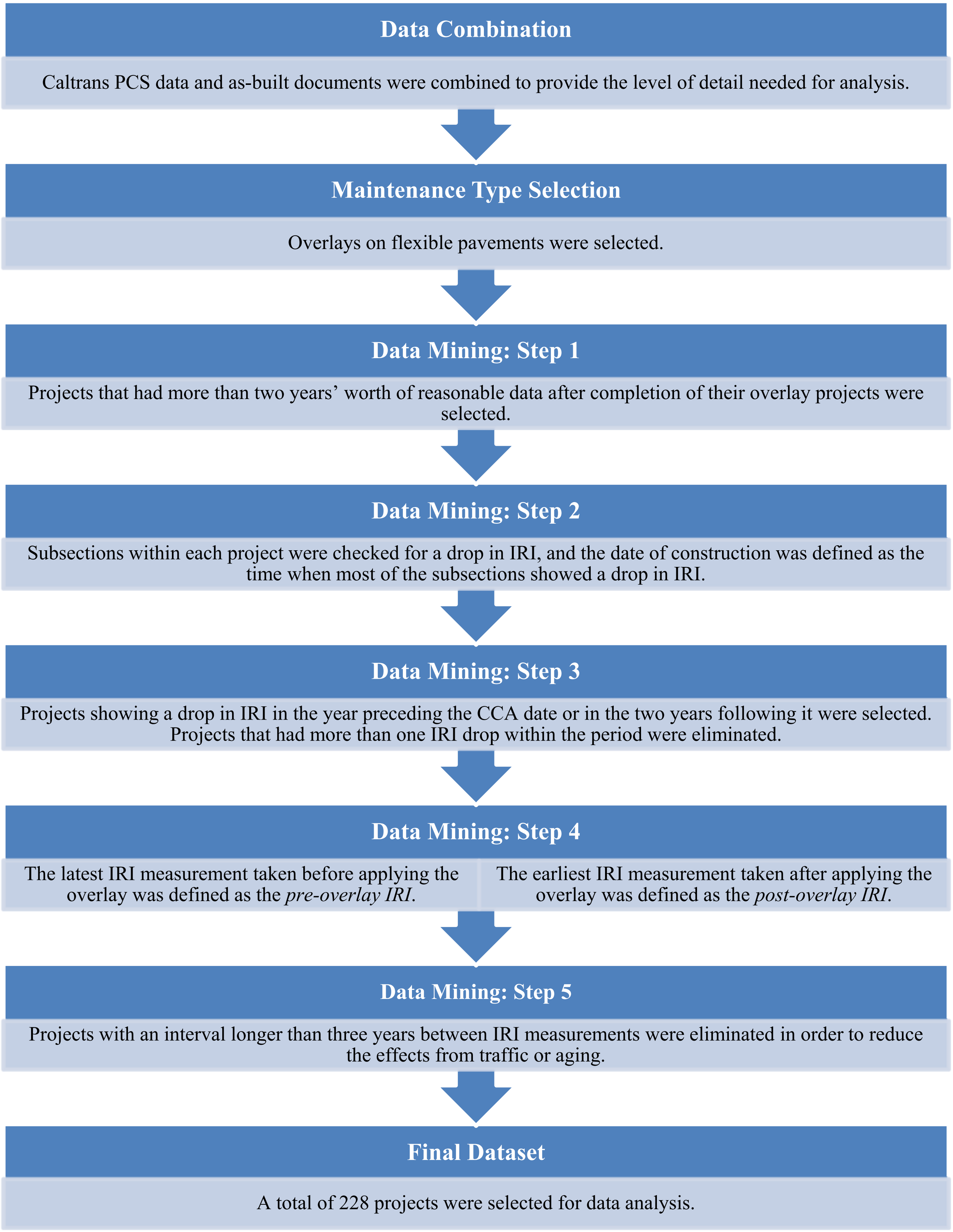
3.1.2 LTPP SPS-5 Data

The LTPP SPS-5 experiment data was extracted from the LTPP program's online database *(www.infopave.com).* (Note: accessing the database requires registration at the LTPP InfoPave website.) All the extracted data were raw data, so the program *ProVAL (www.roadprofile.com)* was used to obtain the IRI value for the specified sections. After this was done, the extracted data were compared to that of an earlier study [*9*] to ensure their accuracy.

3.2 Data Analysis

3.2.1 Caltrans PCS Data

Figure 3.3 shows the cumulative distributions of pre-overlay and post-overlay IRI for all the subsections and projects. About 90 percent of the pre-overlay IRI values are below 170 in./mile (2.70 m/km), while 90 percent of the post-overlay IRI values are below 120 in./mile (1.90 m/km). The post-overlay IRI reduction is proportional to the pre-overlay IRI. Figure 3.4 shows the IRI reduction cumulative distributions for the subsections and the projects. The average IRI reduction values for the projects were obtained using the average IRI reduction for all the subsections within the same project. A negative IRI reduction value indicates that the post-overlay IRI value exceeded those of the pre-overlay. About 20 percent of the subsections showed higher IRI values due to overlay construction. This increase in the IRI values of the subsections can be attributed to construction quality or, in a few cases, to measurement errors or errors in the location referencing of the pre- and post-overlay IRI measurements. In general, nearly all the overlays improved pavement smoothness in terms of project averages.



Data Combination

Caltrans PCS data and as-built documents were combined to provide the level of detail needed for analysis.

Maintenance Type Selection

Overlays on flexible pavements were selected.

Data Mining: Step 1

Projects that had more than two years' worth of reasonable data after completion of their overlay projects were selected.

Data Mining: Step 2

Subsections within each project were checked for a drop in IRI, and the date of construction was defined as the time when most of the subsections showed a drop in IRI.

Data Mining: Step 3

Projects showing a drop in IRI in the year preceding the CCA date or in the two years following it were selected. Projects that had more than one IRI drop within the period were eliminated.

Data Mining: Step 4

The latest IRI measurement taken before applying the overlay was defined as the *pre-overlay IRI*.

The earliest IRI measurement taken after applying the overlay was defined as the *post-overlay IRI*.

Data Mining: Step 5

Projects with an interval longer than three years between IRI measurements were eliminated in order to reduce the effects from traffic or aging.

Final Dataset

A total of 228 projects were selected for data analysis.

Figure 3.2: Flow chart of steps to establish the dataset.

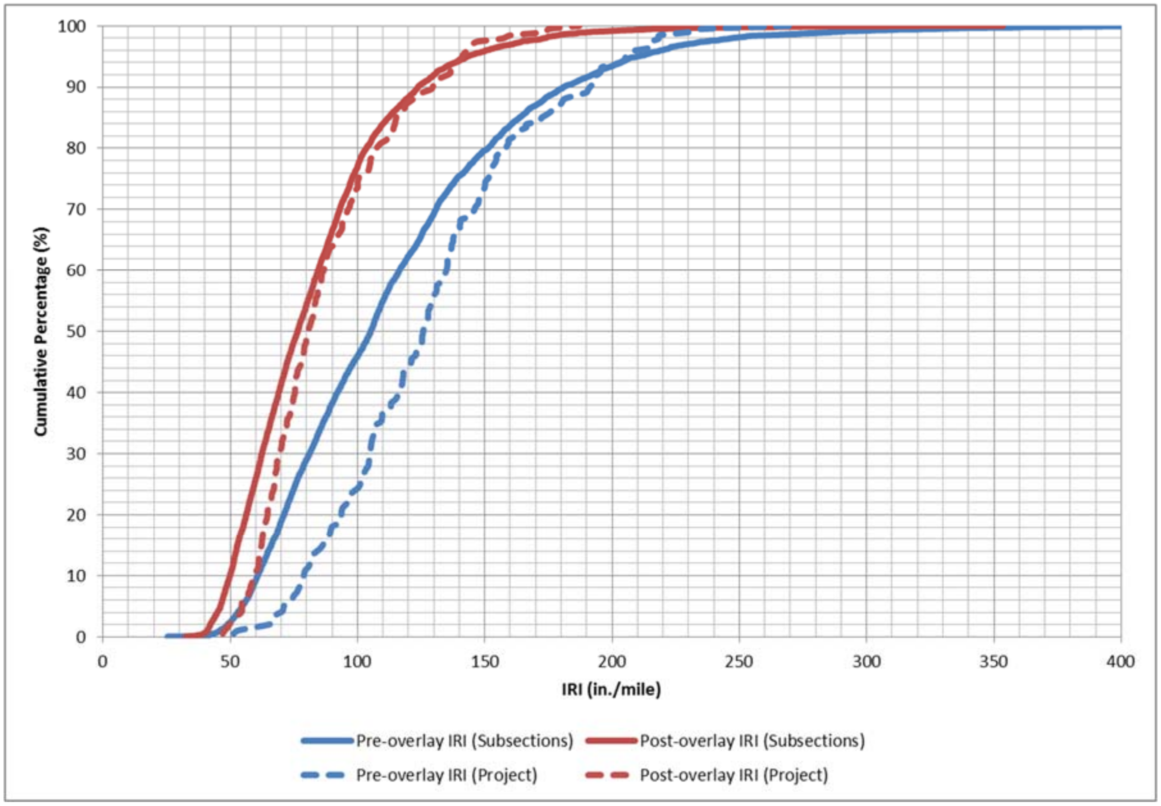


Figure 3.3: Cumulative distribution of pre-overlay and post-overlay IRI for projects and subsections.

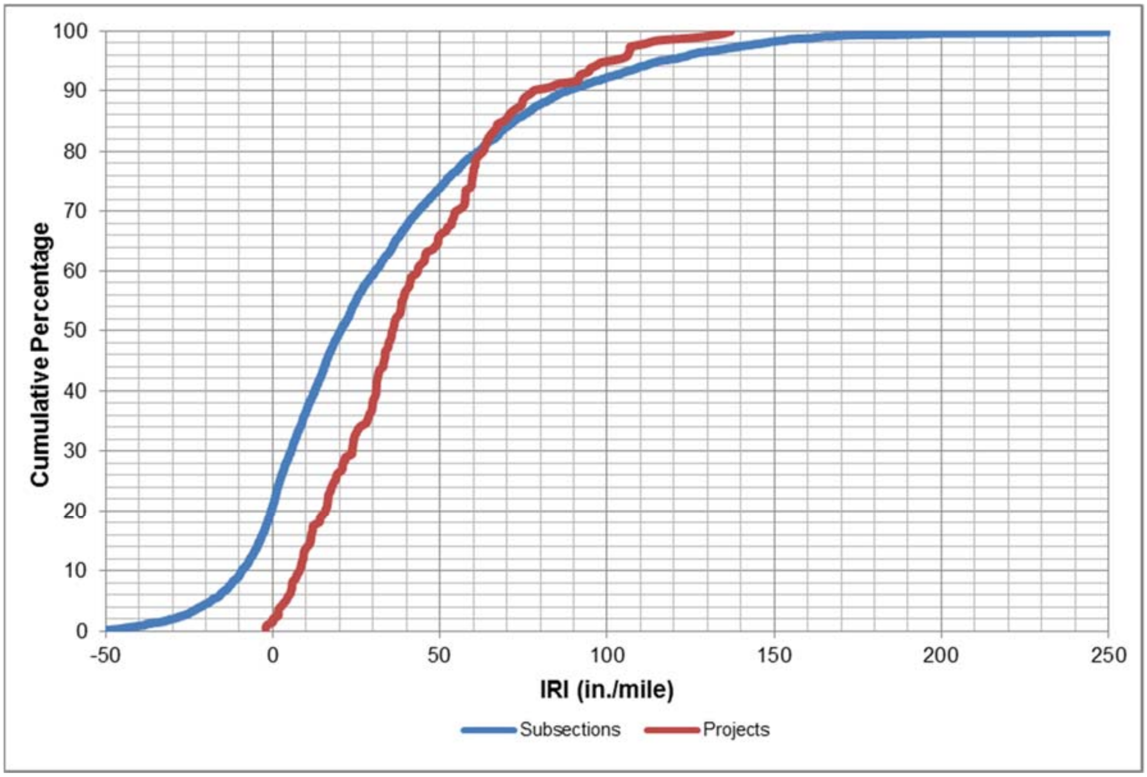


Figure 3.4: Cumulative distribution of IRI reduction for projects and subsections.

Four categories of overlay thickness were defined in the dataset: *Very Thin* (≤0.098 ft [30 mm]), *Thin* (0.099 to 0.197 ft [31 to 60 mm]), *Medium* (0.198 to 0.410 ft [61 to 125 mm]), and *Thick* (≥0.411 ft [125 mm]).These categories of thickness were based on thickness definitions in the Caltrans pavement management system at the time the analysis was done. The Caltrans PMS also used metric units at the time the statistical analysis was performed. The number of projects and subsections for the different overlay thicknesses in the dataset are shown in Table 3.1. A histogram of the overlay thicknesses in the dataset is shown in Figure 3.5. Figure 3.6 shows a cumulative distribution plot of overlay thicknesses of the subsections. Based on the information in these two figures, it can be seen that about half of the subsections have "very thin" overlays, about 80 percent of the projects have overlays of 0.197 ft (50 mm) or less thickness—which fit in the "thin" and "very thin" categories—and less than eight percent were thicker than 0.4 ft.

The majority of the subsections have overlays less than or equal to 0.197 ft (60 mm). The cumulative distribution of pre-overlay IRI and post-overlay IRI with and without milling for each category of overlay thickness is shown in Figure 3.7 for all subsections. The cumulative distribution for all subsections of pre-overlay IRI and post-overlay IRI with and without digouts for each category of overlay thickness is shown in Figure 3.8. Based on the figures, for the "very thin" and "thin" categories, overlays with milling or digouts had little effect on the post-overlay IRI. For the "medium" and "thick" categories, overlays with milling had little effect on post-overlay IRI, but overlays with digouts showed lower post-overlay IRI. The cumulative distribution of IRI reduction for each category of overlay thickness is shown in Figure 3.9. In general, thicker overlays reduce IRI more and provide a smoother pavement compared to thinner overlays.

Caltrans Standard specifications (2006 shown here as an example) for asphalt lift thicknesses are shown in Table 3.2. These specifications indicate that the "very thin" overlays (≤0.098 ft [30 mm]) would have been compacted in one lift, the "thin" overlays (0.1 to 0.2 ft [30 to 60 mm]) would have been compacted in one lift, the "medium" overlays (0.2 to 0.4 ft [61 to 125 mm]) would have been compacted in one lift if less than 0.25 ft and two lifts if between 0.25 and 0.40 ft, and the "thick" overlays (≥0.4 ft [125 mm]) would have been compacted in two or more lifts.

Table 3.1: Number of Projects and Subsections for Different Overlay Thickness

Overlay Thickness	Very Thin (≤0.098 ft [30 mm])	Thin (0.099 – 0.197 ft [31 – 60 mm])	Medium (0.198 – 0.410 ft [61 – 125 mm])	Thick (≥0.411 ft [125 mm])
Projects	112	46	46	24
Subsections	2,284	1,260	604	327

Table 3.2: Caltrans 2006 Standard Specifications for Asphalt Lift Thickness

Total Thickness Shown on Plans[a]	No. of Layers	Top Layer Thickness (foot)		Next Lower Layer Thickness (foot)		All Other Lower Layer Thickness (foot)	
		Min.	Max.	Min.	Max.	Min.	Max.
0.20-foot or less	1	—	—	—	—	—	—
0.25-foot	2[b]	0.12	0.13	0.12	0.13	—	—
0.30 – 0.40 foot	2	0.15	0.20	0.15	0.25	—	—
0.45-foot or more	c	0.15	0.20	0.15	0.25	0.15	0.40

a When pavement reinforcing fabric is shown to be placed between layers of, the thickness of asphalt concrete above the pavement reinforcing fabric shall be considered to be the "Total Thickness Shown on Plans" for the purpose of spreading and compacting the asphalt concrete above the pavement reinforcing fabric.

b At the option of the Contractor, one layer 0.25-foot thick may be placed.

c At least two layers shall be placed if total thickness is 0.45-foot. At least three layers shall be placed if total thickness is more than 0.45-foot and less than 0.90-foot. At least four layers shall be placed if total thickness is 0.90-foot or more.

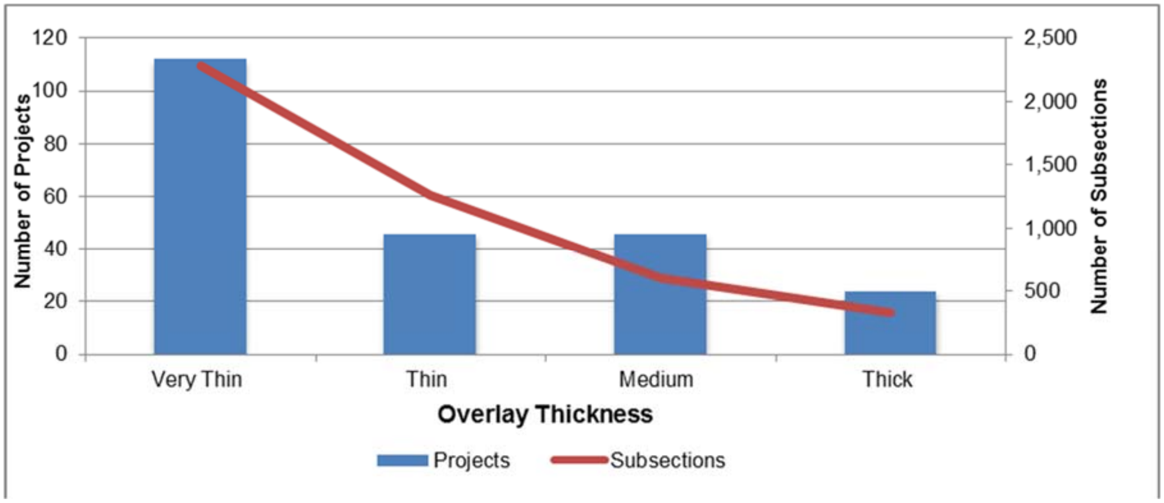


Figure 3.5: Histogram of the number of projects and subsections for the different overlay thicknesses.

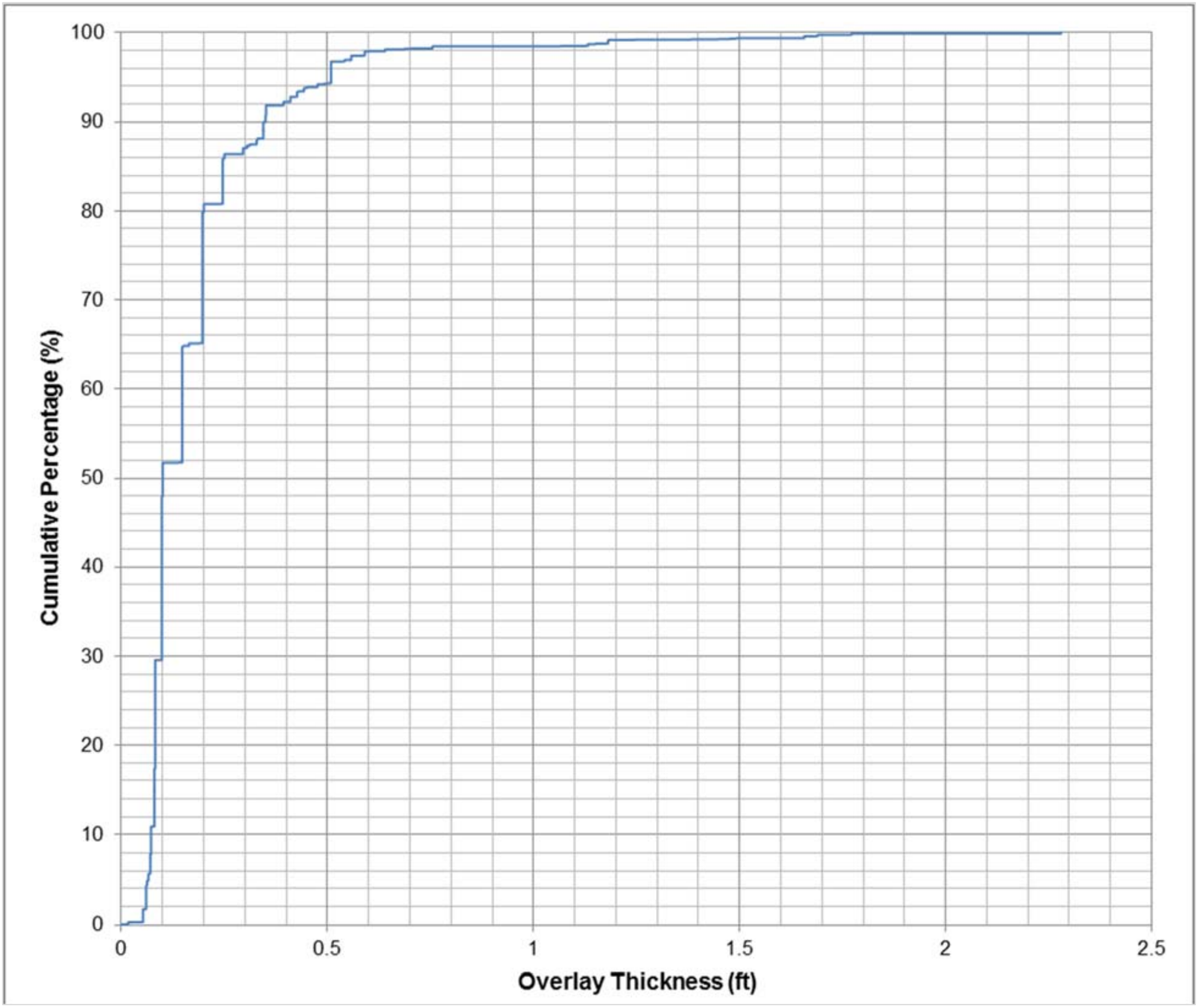


Figure 3.6: Cumulative distribution of overlay thicknesses for subsections.

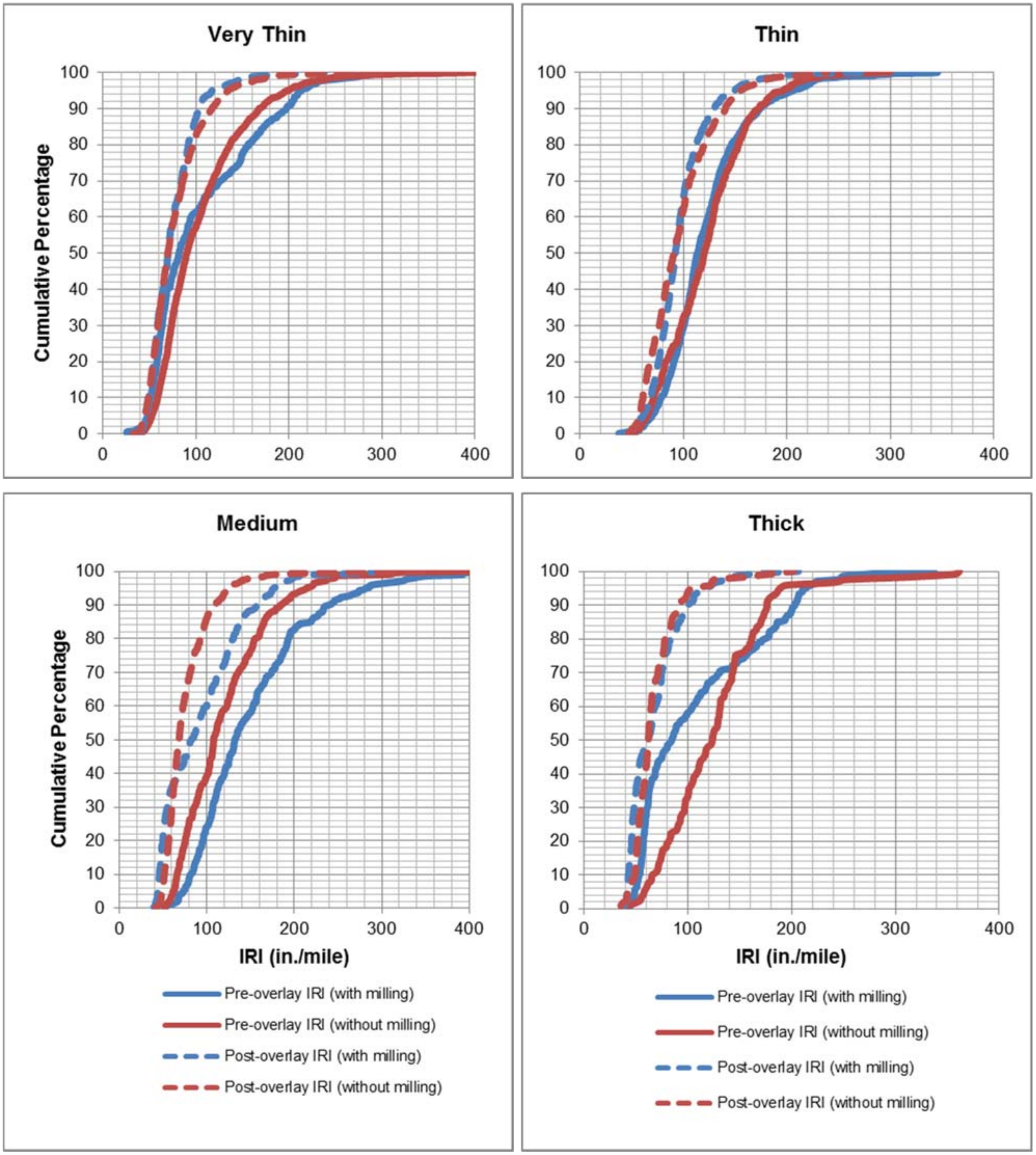


Figure 3.7: Cumulative distribution for subsections of pre-overlay and post-overlay IRI with and without milling for different thickness categories.

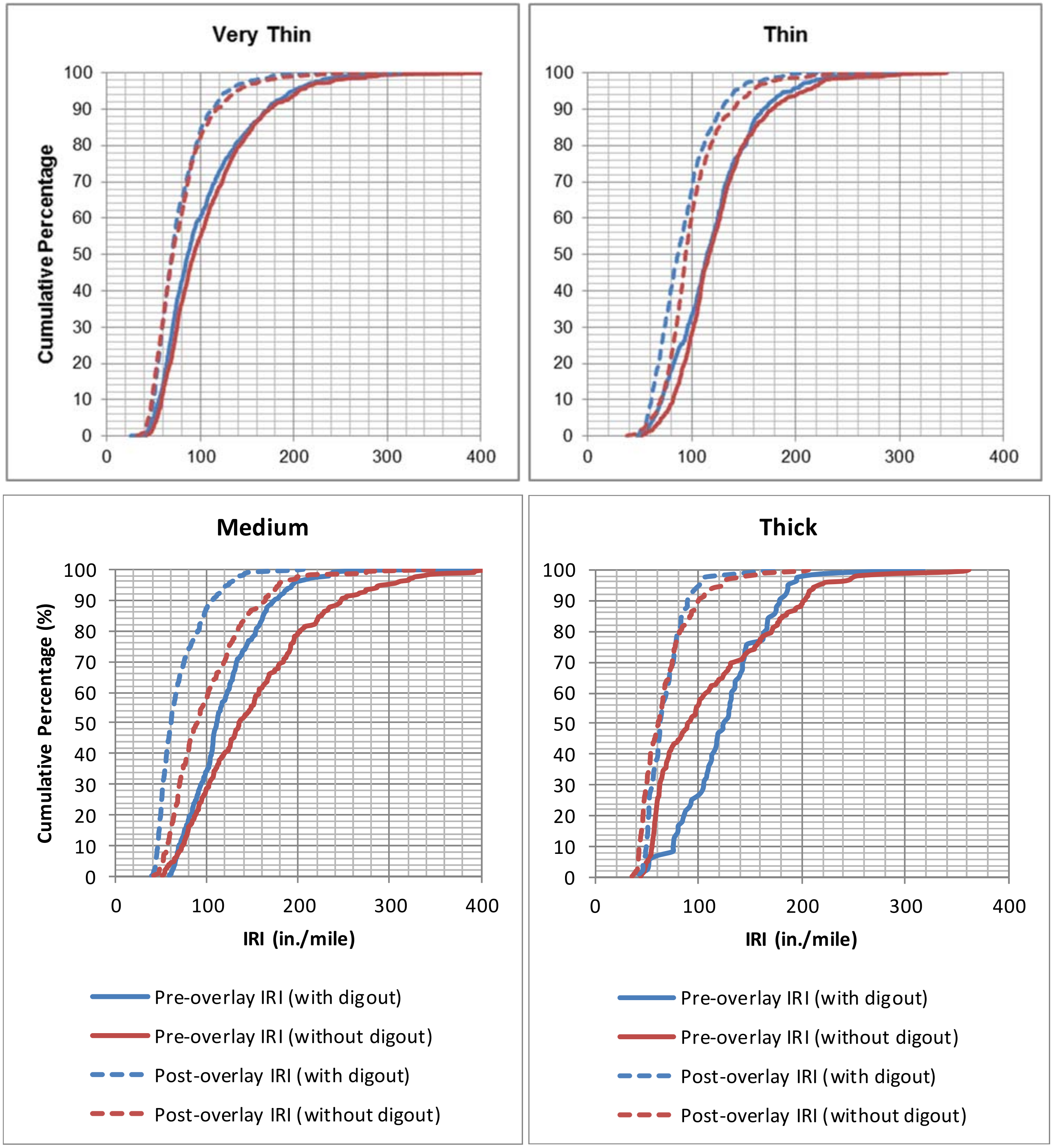


Figure 3.8: Cumulative distribution for subsections of pre-overlay and post-overlay IRI with and without digouts for different thickness categories.

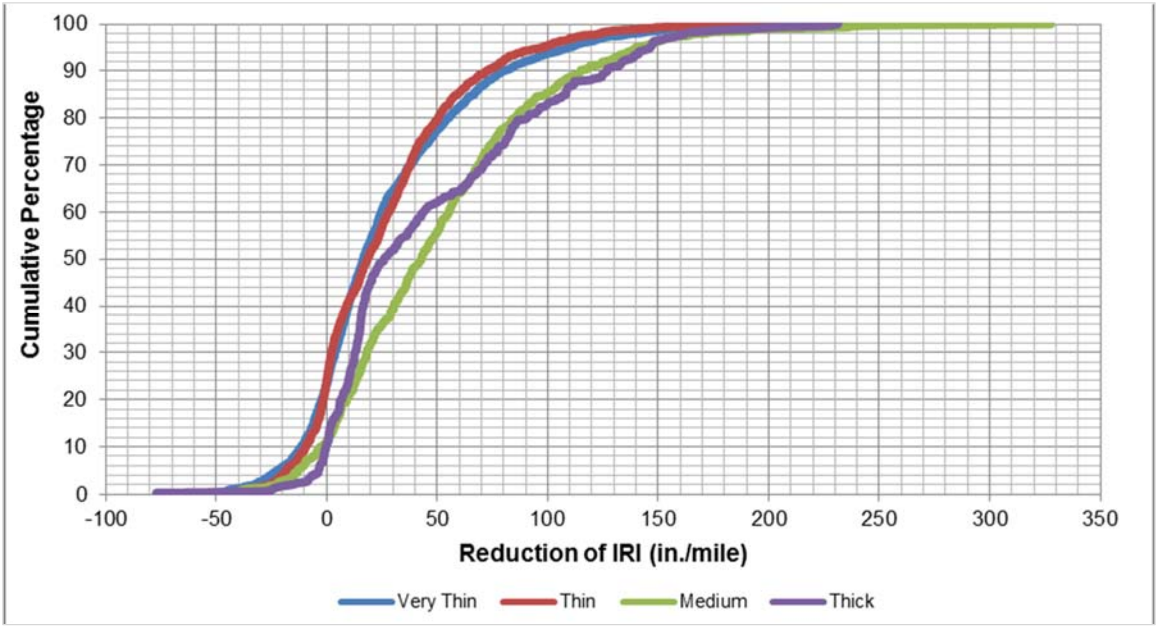


Figure 3.9: Cumulative distribution of IRI reduction for the different thickness categories, by subsection.

In order to better understand the effects of factors that might influence post-overlay IRI, the data were divided into four categories: pre-overlay condition, overlay thickness, the application of milling, and the application of digouts, as shown in Table 3.3. In order to have a large enough sample size for each experimental block, pre-overlay condition was also classified into two categories, with *Good* being IRI lower than 120 in./mile (1.90 m/km) and *Poor* being IRI greater than 120 in./mile (1.90 m/km). Overlay thickness was also divided into two categories, with *Thin* defined as thickness ≤ 0.197 ft (60 mm) and *Thick* defined as > 0.197 ft (60 mm). Two categories of thickness were used instead of four in order to reduce the complexity of the analysis results, and because there were small sample sizes in the thicker categories for the number of independent variables considered. Table 3.3 shows the descriptive statistics (averages and standard deviations) for pre-overlay IRI, post-overlay IRI, and reduction of IRI for all the data groups, before they were further divided into mix and binder type. The descriptive statistics for all subdivisions of the data including mix and binder type are shown in the Appendix.

Figure 3.10 to Figure 3.12 show boxplots of pre-overlay IRI, post-overlay IRI, and IRI reduction for each group shown in Table 3.3. It can be seen in Figure 3.10 that the pre-overlay IRI values within the Good Condition group (Groups 1 through 8 in Table 3.3, IRI less than 120 in./mile [(1.90 m/km)]) were similar regardless of the overlay thickness or pre-overlay repairs, except for Group 7 (thick overlay, milling, no digouts) which had lower IRI on average. The Poor Condition group (Groups 9 through 16, greater IRI values) also had generally consistent pre-overlay IRI values, except for Group 15 (thick overlay, milling, no digouts), which tended to have somewhat greater pre-overlay IRI values than the rest of the Poor Condition group data set.

Among the post-overlay IRI value group distributions shown in Figure 3.11, the average values of the overlays placed on the originally Good pavements (Groups 1 through 8 in Table 3.3, low pre-overlay IRI), Group 8 (thick overlays, digouts, milling, but note small sample size) had the lowest post-overlay IRI values, while Groups 3 and 4 (thin overlays, milling, with and without digouts) had the worst post-overlay IRIs. The average post-overlay IRIs of the thin overlays with milling on Good pavement (Groups 3 and 4) were higher than those of the thin overlays without milling on Good pavement (Groups 1 and 2). The post-overlay IRI values for the overlays placed on originally Poor pavement show that the lowest post-overlay values were for Group 16 (thick overlays, milling, digouts) and the highest were for Group 15 (thick overlays, milling, no digouts).

From the IRI reduction group distributions shown in Figure 3.12, the average values of the overlays placed on the originally Good pavements (Groups 1 through 8 in Table 3.3, lower pre-overlay IRI) were all much lower than those of the overlays placed on originally Poor pavements (Groups 9 through 16, higher pre-overlay IRI), as expected. The average IRI reductions for the thinner overlays on Good pavement were all less than 13 in./mile, although with standard deviations of about 20 in./mile. The average IRI reductions for thin overlays on Good pavement with milling were less than those without milling. The thicker overlays on Good pavement reduced IRI more than thinner overlays, as expected, but with similar standard deviations. The IRI reductions for the overlays placed on originally Poor pavement show that on average the thicker overlays reduced IRI more than the thinner overlays, as expected, but the standard deviations of IRI reduction for overlays on Poor pavements ranged from 30 to 60 in./mile for the different groups. Average IRI reductions for overlays on Poor pavements were greater with digouts than without digouts, except for thick overlays that also had milling where the results were similar. Average IRI reductions for overlays on Poor pavements with and without milling were generally similar and had similar standard deviations.

Table 3.3: Descriptive Statistics of Dataset Prior to Further Division by Binder and Mix Type

Group	Pre-Overlay Condition	Overlay Thickness	Milling	Digouts	Number of Projects	Number of Subsections	Average Pre-Overlay IRI (in./mile)	Std. Dev. of Pre-Overlay IRI (in./mile)	Average Post-Overlay IRI (in./mile)	Std. Dev. of Post-Overlay IRI (in./mile)	Average Reduction IRI (in./mile)	Std. Dev. of Reduction IRI (in./mile)
1	Good	Thin	No	No	51	650	82	19	70	21	13	19
2				Yes	56	979	81	20	72	22	9	22
3			Yes	No	23	422	91	20	82	20	8	20
4				Yes	15	248	81	22	78	18	2	21
5		Thick	No	No	17	97	83	19	70	18	14	19
6				Yes	20	142	89	19	70	20	19	22
7			Yes	No	20	175	76	21	65	23	11	18
8				Yes	7	81	94	17	57	18	37	23
9	Poor	Thin	No	No	45	327	163	44	110	41	53	42
10				Yes	53	467	161	39	98	37	63	46
11			Yes	No	24	319	162	42	106	36	56	46
12				Yes	18	132	163	35	100	31	63	39
13		Thick	No	No	14	73	177	54	85	51	93	49
14				Yes	20	116	161	39	98	28	63	39
15			Yes	No	22	184	197	60	115	45	82	60
16				Yes	11	63	159	34	70	33	89	30

Notes:

1. *Good* pre-overlay condition: pre-overlay IRI < 120 in./mile (1.9 m/km); *poor* pre-overlay condition: pre-overlay IRI ≥ 120 in./mile.
2. *Thin* overlay: overlay thickness ≤ 0.197 ft (60 mm); *thick* overlay: overlay thickness > 0.197 ft (60 mm)
3. The average standard deviation of post-overlay IRI for *good* pre-overlay condition among all subsections: 21.7.
4. The average standard deviation of post-overlay IRI for *poor* pre-overlay condition among all subsections: 39.6.

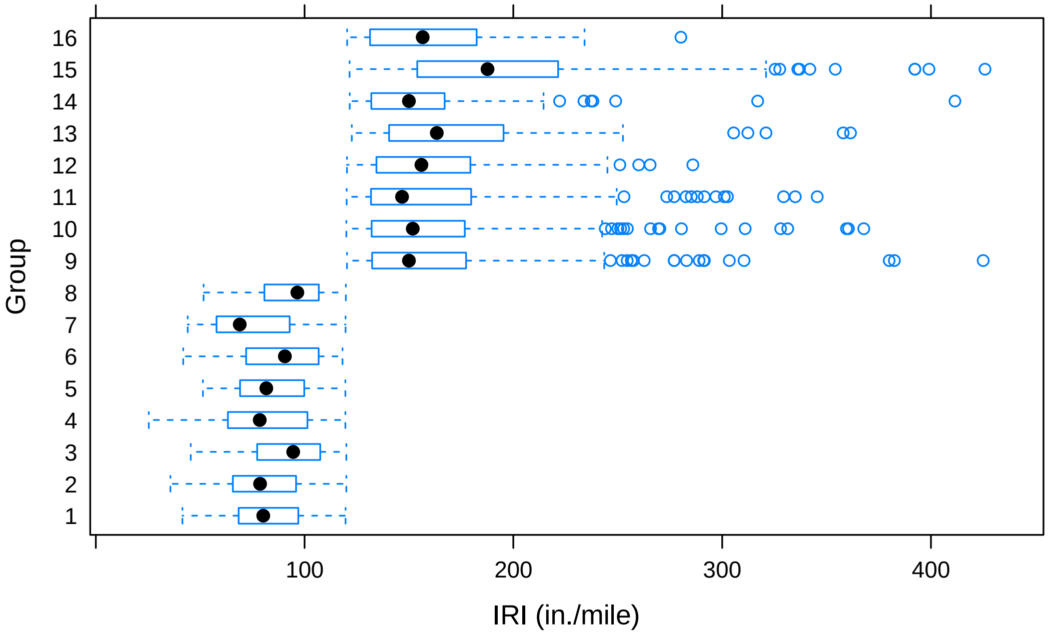


Figure 3.10: Boxplots showing variability of pre-overlay IRI for each group (pre-overlay condition [greater or less than IRI of 120 in./mile], overlay thickness, and pre-overlay repairs by groups) listed in Table 3.3.

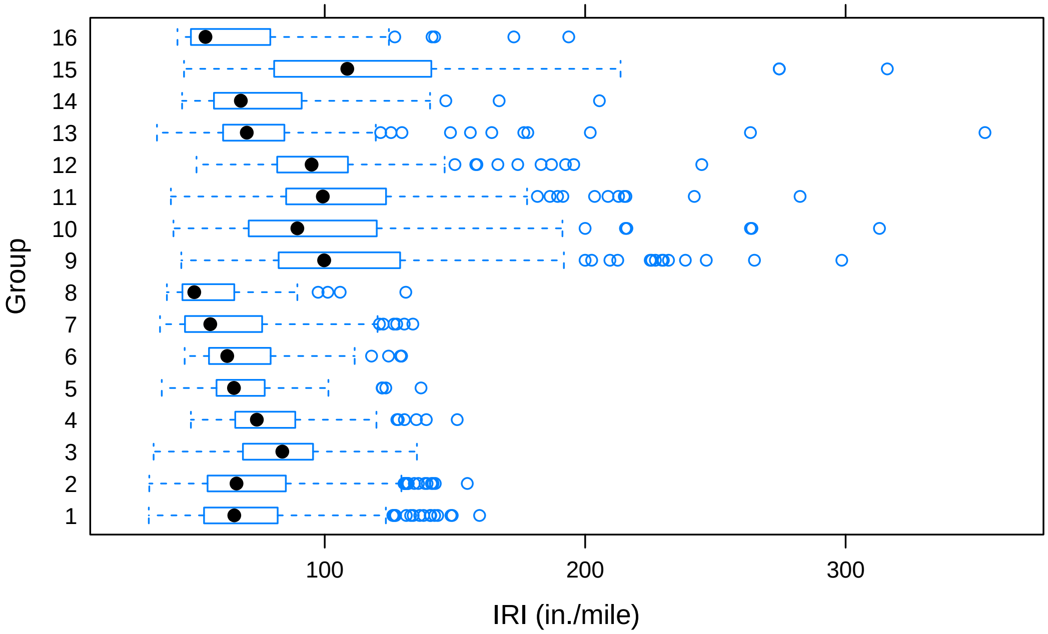


Figure 3.11: Boxplots showing variability of post-overlay IRI for each group (pre-overlay condition [greater or less than IRI of 120 in./mile], overlay thickness and pre-overlay repairs by groups) listed in Table 3.3.

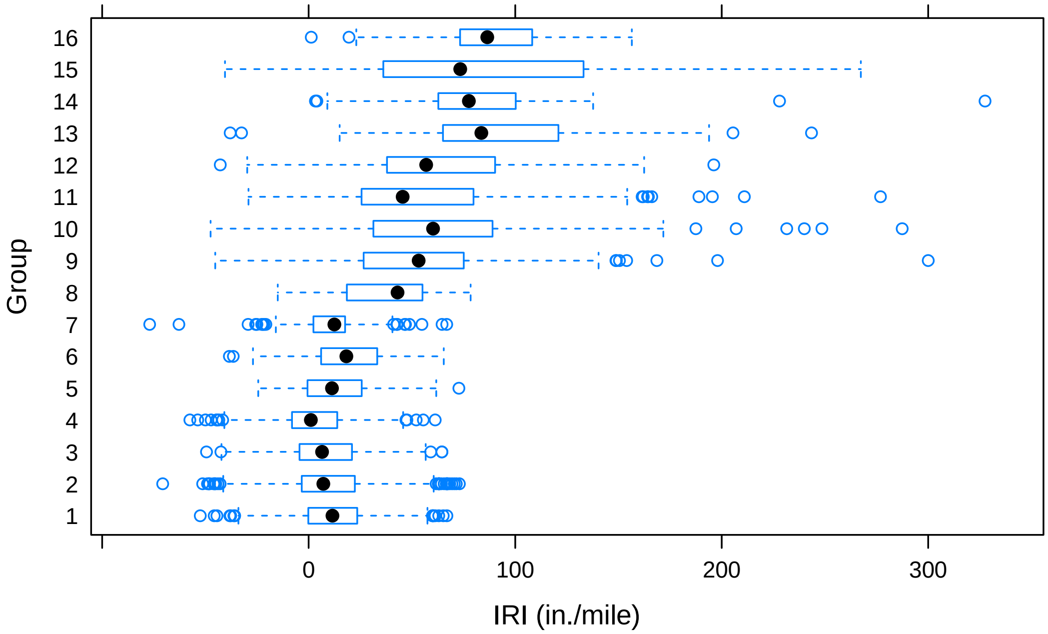


Figure 3.12: Boxplots showing variability of IRI reduction for each group (pre-overlay condition [greater or less than IRI of 120 in./mile], overlay thickness, and pre-overlay repairs by groups) listed in Table 3.3.

The "thin" overlay data were further stratified in plots by pre-overlay IRI level (Figure 3.13), the combination of pre-overlay IRI and milling or no milling (Figure 3.14), the combination of pre-overlay IRI and digouts or no digouts (Figure 3.15), and the combination of pre-overlay IRI and milling or no milling when the existing asphalt under the overlay was dense-graded (Figure 3.16) or open-graded (Figure 3.17). In each figure the post-overlay IRI is shown on the y-axis and the condition of the underlying asphalt is shown on the x-axis.

In Figure 3.13 the sections were divided by pre-overlay IRI as follows:

- Group 1: Pre-overlay IRI < 120 in./mile (1.93 m/km)
- Group 2: 120 in./mile <= Pre-overlay IRI < 160 in./mile (2.57 m/km)
- Group 3: 160 in./mile <= Pre-overlay IRI < 200 in./mile (3.21 m/km)
- Group 4: Pre-overlay IRI > 200 in./mile (most sections had pre-overlay IRI < 250 in./mile [4.01 m/km])

From the figure it can be seen that the pre-overlay IRI had an important effect on the post-overlay IRI for the "thin" overlays.

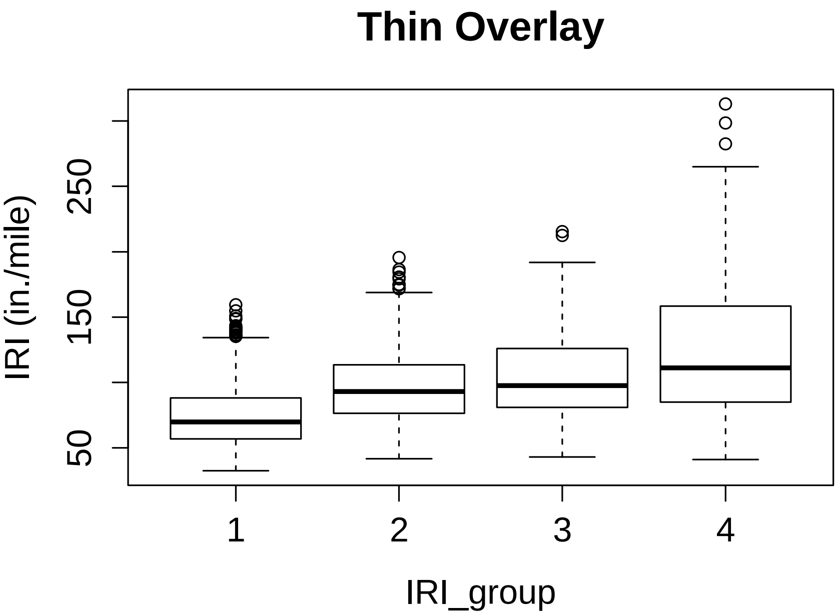


Figure 3.13: Boxplot of post-overlay IRI (y-axis) versus pre-overlay IRI group (x-axis) for thin overlay (<= 0.197 ft [60 mm]).

Figure 3.14 shows that milling had different effects on thin overlays that were placed on existing smooth pavements (IRI Groups 1 and 2) and on rougher pavements (IRI Groups 3 and especially 4). It can be seen that milling on the existing less rough pavements with pre-overlay IRI values up to 200 in./mile (the Yes 1, Yes 2, and Yes 3 groups [with milling] versus groups No 1 and , No 2, and No 3 [without milling]) resulted in the overlays being rougher than when there was no milling, while milling on the existing very rough pavements with pre-overlay IRI values greater than 200 in./mile (the Yes 4 group) resulted in the overlays being smoother than when there was no milling. On the other hand, digouts had a beneficial effect on overlays for all existing roughness categories, with the benefit increasing as the roughness of the existing pavement increased, as can be seen in Figure 3.15. Comparison of both figures indicates that digouts had a greater benefit than did milling on thin overlays placed over existing rough pavements.

Figure 3.16 and Figure 3.17 show the effects of existing pavement roughness and milling or no milling on thin overlays placed on existing dense-graded asphalt (also referred to as hot mix asphalt [HMA]) and open-graded asphalt, respectively. There were relatively few data for thin overlays on existing open-graded asphalt, which limits the ability to compare the results. However, the results for thin overlays on existing dense-graded HMA indicates that milling, in general, results in rougher overlays for pre-overlay IRI values up to 200 in./mile (3.21 m/km). The sparse data for overlays on existing open-graded asphalt indicate that milling generally made them rougher.

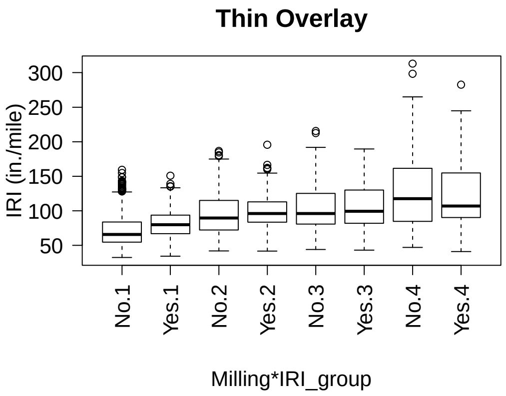


Figure 3.14: Boxplot of post-overlay IRI (y-axis) versus pre-overlay IRI group (x-axis) for thin overlay (<= 0.2 ft [60 mm]) without (No) and with (Yes) milling.

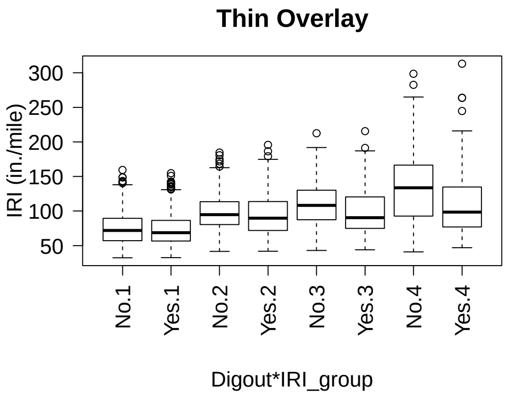


Figure 3.15: Boxplot of post-overlay IRI (y-axis) versus pre-overlay IRI group (x-axis) for thin overlay (<= 0.2 ft [60 mm]) without (No) and with (Yes) digouts.

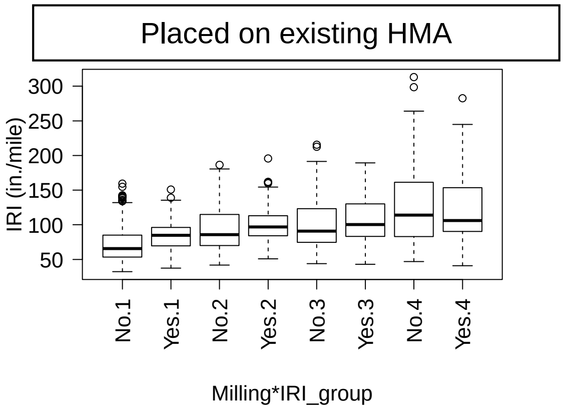


Figure 3.16 Boxplot of post-overlay IRI (y-axis) versus pre-overlay IRI group (x-axis) for thin overlay (<= 0.2 ft (60 mm) without (No) and with (Yes) milling and placed on existing HMA.

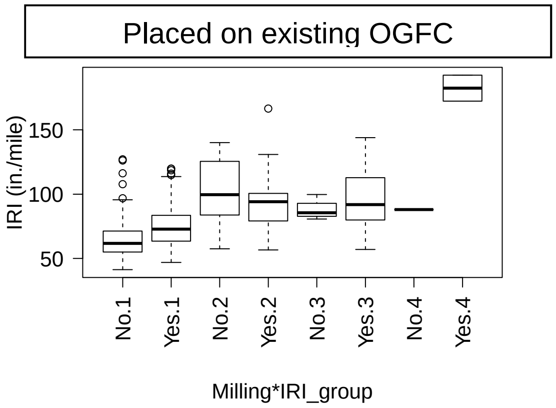


Figure 3.17: Boxplot of post-overlay IRI (y-axis) versus pre-overlay IRI group (x-axis) for thin overlay (<= 0.2 ft [60 mm]) without (No) and with (Yes) milling and placed on existing OGFC.

A decision was also made to analyze the data using two different dependent variables: post-overlay IRI and IRI reduction. The following conclusions were drawn from the table and figures:

- 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. IRI reduction was also higher in the groups with poor pre-overlay condition. In other words, an overlay will have a more pronounced effect on IRI reduction on a pavement with a poor pre-overlay condition than it will on a pavement with a good pre-overlay condition.
- Although overlay thickness shows some influence on post-overlay IRI and IRI reduction, it is hard to recognize the difference on the boxplots, especially for the groups with poor pre-overlay condition.

- The effects of pre-overlay repairs (milling and digouts) indicate, based on the table and boxplots, that milling makes post-overlay IRI worse when the existing pavement is smoother while it improves the post-overlay IRI when the existing pavement is rough. On the other hand, digouts, which should only be done when there is cracking in the wheelpaths, appeared to improve the post-overlay IRI regardless of the pre-overlay IRI and had the most benefit when the existing pavement was rough. Groups with poor pre-overlay condition had greater post-overlay IRI variance than did groups with good pre-overlay condition, but no specific trends can be found for other factors.

Multiple regression analysis was used to conduct a further analysis of the effects of the explanatory variables on overlay smoothness. Post-overlay IRI and IRI reduction were the dependent variables in the multiple regression models. The aim of this analysis was to find what level of smoothness can be achieved with a new overlay and to recommend best practices for overlay repairs based on the condition of the existing pavement. The independent variables in the regression models were pre-overlay condition, overlay thickness, pre-overlay repairs (milling [removal of 0.1 to 0.2 ft (30 to 60 mm) of material often across the entire lane] and digouts [removal of 0.25 to 0.4 ft (75 to 120 mm) in the wheelpaths]), overlay mix type (open-graded or non-open-graded [including gap-graded rubberized mixes, and dense-graded conventional and polymer-modified mixes]), and binder type (rubberized versus conventional or polymer-modified). Pre-overlay IRI and overlay thickness were considered as both continuous variables and categorical variables, with the category-based models set up for comparison with the observations from Table 3.3. Milling, digouts, overlay mix type, and binder type were treated as categorical variables.

In order to take into account the variation across random effect variables, mixed effects models were employed. With this approach, the accuracy of the regression models is improved and the heterogeneity bias is avoided. Identification of the individual projects, defined as the work completed in a unique construction contract, and climate zone (per Caltrans performance-graded asphalt (PG) climate zones), were considered as random effects variables in the mixed effect models. Individual project, which could also be defined as a specific contractor working on a specific project, was not identified because it was desired to look across all projects and contractors in the data set without separating them. Climate zone was not included because the goal of this research was to look at IRI immediately before and after construction and not at longer-term IRI performance. Climate, which consists primarily of rainfall and temperature effects, should not affect the smoothness obtained during construction, except for any potential effects of temperature on late-season paving and these were not considered. It was assumed that Caltrans specifications for minimum temperatures for paving and incentives for compaction would limit the effects of climate zones on the results.

Some projects were further divided into subsections if there were different thicknesses or pre-overlay treatments within the contract, with each subsection carrying its project identification for consideration of random effects. The random effects between projects might come from different equipment, material sources, and contractors' construction techniques; and the random effects between climates might come from different temperatures, moisture, and amounts of rainfall. The general form of the mixed effect models used in this study can be represented as:

$$y = AX + BY + \epsilon$$

where:

y is a vector of observations (post-overlay IRI or IRI reduction),

X is a vector of fixed effects,

Y is a vector of random effects,

ϵ is a vector of random error terms, and

A and B are matrices of regressors.

Table 3.4 shows all the regression models developed to analyze the effect of each variable in this study. With each pair of models, for example Models 1 and 2, the first model considers the independent variables of pre-overlay repair and overlay thickness as a continuous variable and the second model considers them as category variables. Category variables are groups of values of the continuous variable. When the explanatory variable is treated as a continuous variable the purpose is to model the effects of the explanatory variables on the dependent variable. When the explanatory variable is treated as a category variable the purpose of the model is to primarily look at the differences between different categories (groups) of the explanatory variable. Models 1 and 2 are the regression models with post-overlay IRI as the dependent variable; pre-overlay IRI, overlay thickness, milling, digouts, overlay mix type, and binder type as independent variables; and project as the random effect variable. Models 3 and 4 are the regression models with post-overlay IRI as the dependent variable; pre-overlay IRI, overlay thickness, milling, digouts, overlay mix type, and binder type as independent variables; and project and climate as the random effect variables. Models 5 and 6 are regression models with IRI reduction as the dependent variable; pre-overlay IRI, overlay thickness, milling, digouts, overlay mix type, and binder type as independent variables; and project as the random effect variable. Models 7 and 8 are regression models with IRI reduction as the dependent variable; pre-overlay IRI, overlay thickness, milling, digouts, overlay mix type, and binder type as independent variables; and project and climate as the random effect variables.

The significance of the independent variables and the Akaike Information Criterion (AIC) are shown in Table 3.5. AIC is a statistical index that represents the loss of information as the model's approximate reality. The model with the least information lost (the lowest AIC) is the preferred one because it is closest to reality (a good model can minimize loss of information).

The analysis results show that Models 6 and 8, which are the regressions of IRI reduction with categorical variables, have statistically different results than the other models. Generally, overlays with good pre-overlay condition, digouts, and an open-graded mix as the final overlay mix type have significant positive effects; namely, they result in a smoother overlay. Inexplicably, milling is also a significant factor but it is a negative one that causes rougher overlays—although the further analysis discussed later indicates that this is not a general conclusion. Based on the analysis of the available data, overlay thickness and binder type (rubberized versus conventional or polymer-modified) were found to have no significant effect on overlay smoothness. A comparison of the AIC values reveals that models with continuous variables have lower AIC values than those with categorical variables because categorized variables might increase the loss of information in the regression models. The relatively high AIC values indicate problems with Models 6 and 8. All the regression results of the different models used in this study are shown in the Appendix.

A study conducted by Raymond et al. [*8*] pointed out that the extent of surface preparation (milling) has a significant effect on overlay roughness when the pre-overlay IRI is greater than 95 in./mile (1.5 m/km) but that it has no effect when the pre-overlay IRI is less than 95 in./mile (1.5 m/km). In other words, whether or not pre-overlay repairs significantly affect post-overlay IRI is related to the pre-overlay condition. Thus, based on the sample size of each group and the FHWA categories of pavement conditions [*1*]**,** 120 in./mile (1.90 m/km) was selected as the threshold for subdividing pre-overlay condition into two categories, after which additional regression analysis was performed. Since the differences (values of AIC) between models with project and models with project and climate as random variables are relatively small, models with only project as a random variable were selected for further analysis to reduce the complexity of the models.

The results of the regression analysis for Models 9 and 10 are shown in Table 3.6. Different sets of analyses were conducted for different pre-overlay conditions. The results of the analyses indicate that the effects of overlay thickness, mix type (open-graded or not), and binder type (rubberized or not) were not statistically significant within each of the two sets of pre-overlay conditions. The results of the analyses indicate that the effects of milling and digouts were different for the two levels of pre-overlay IRI. Milling had a significantly negative effect when there was a good pre-overlay condition and had no effect when there was a poor pre-overlay condition. Digouts had a significant positive effect on post-overlay IRI when the pre-overlay condition was poor (as defined by IRI greater than 120 in./mile [1.90 m/km]). Overlay mix type had no effect on the smoothness of overlays. Comparing the results from previous studies and the results summarized in Table 3.6, it appears that pre-overlay repairs have either no effect or a negative effect on post-overlay smoothness when the pre-overlay pavement condition is good, and have either a positive effect or no effect when the pre-overlay condition is poor.

Table 3.7 goes into further detail regarding the effects of the explanatory variables, breaking the two categories of pre-overlay IRI in Table 3.6 into four categories. The regression results are similar to those for the pre-overlay repairs in Table 3.6. Changes in the models with the more detailed breakdown of pre-overlay condition indicate that overlay thickness now becomes significant and positive for existing pavement with IRI values of 170 in./mile and higher, milling remains significant and negative for pre-overlay IRI values less than 120 in./mile, digouts remain significant and negative for pre-overlay IRI values greater than 120 in./mile, and digouts are not significant when the pre-overlay IRI is between 95 and 120 in./mile. In addition, rubberized binder becomes significant and positive when pre-overlay IRI is less than 95 in./mile or greater than 170 in./mile. Although the results for overlay thickness, overlay mix type, and binder type were different for the four categories of pre-overlay condition, it is also noteworthy that breaking down the pavement condition into four categories reduced the reliability of the statistics of the models.

Table 3.4: List of Regression Models

Regression Model	Dependent Variable	Independent Variable				
		Fixed Effect	**(Type)**	**Fixed Effect**	**(Type)**	**Random Effect**
Model 1	Post-overlay IRI	Pre-overlay IRI Overlay Thickness	(Continuous) (Continuous)	Milling Digouts Overlay mix type Binder ype	(Categorical)	Project
Model 2	Post-overlay IRI	Pre-overlay IRI Overlay Thickness	(Categorical) (Categorical)	Milling Digouts Overlay mix type Binder ype	(Categorical)	Project
Model 3	Post-overlay IRI	Pre-overlay IRI Overlay Thickness	(Continuous) (Continuous)	Milling Digouts Overlay mix type Binder ype	(Categorical)	Project Climate
Model 4	Post-overlay IRI	Pre-overlay IRI Overlay Thickness	(Categorical) (Categorical)	Milling Digouts Overlay mix type Binder ype	(Categorical)	Project Climate
Model 5	IRI reduction	Pre-overlay IRI Overlay Thickness	(Continuous) (Continuous)	Milling Digouts Overlay mix type Binder ype	(Categorical)	Project
Model 6	IRI reduction	Pre-overlay IRI Overlay Thickness	(Categorical) (Categorical)	Milling Digouts Overlay mix type Binder ype	(Categorical)	Project
Model 7	IRI reduction	Pre-overlay IRI Overlay Thickness	(Continuous) (Continuous)	Milling Digouts Overlay mix type Binder ype	(Categorical)	Project Climate
Model 8	IRI reduction	Pre-overlay IRI Overlay Thickness	(Categorical) (Categorical)	Milling Digouts Overlay mix type Binder type	(Categorical)	Project Climate

Table 3.5: Significance of Independent Variables and Akaike Information Criterion for Regression Models (α=0.05)

Models	Significance						
	Pre-Overlay IRI	Overlay Thickness	Milling	Digouts	Overlay Mix Type (OG)	Material Used (Rubberized)	AIC
Model 1	Yes	No	Yes	Yes	Yes	No	40115
Model 2	Yes	No	Yes	Yes	Yes	No	40882
Model 3	Yes	No	Yes	Yes	Yes	No	40087
Model 4	Yes	No	Yes	Yes	Yes	No	40843
Model 5	Yes	No	Yes	Yes	Yes	No	40115
Model 6	Yes	Yes	No	No	No	No	42861
Model 7	Yes	No	Yes	Yes	Yes	No	40087
Model 8	Yes	Yes	No	No	No	No	42861

Notes:
1. Green cells represent a positive effect on improving pavement smoothness.
2. Red cells represent a negative effect on improving pavement smoothness.

In order to better determine the effect of pre-overlay repairs, the combination of all the factors had to be considered. Therefore, further analysis was conducted by adding ten interaction terms into the regression models to account for the different interactions among the contributing factors. The results of the analysis with two-factor interaction terms added are shown in Table 3.8. The table shows that sections with thicker overlays had lower post-overlay IRI than sections with thinner overlays when the pre-overlay IRI was greater than 120 in./mile (1.90 m/km); sections with milling prior to overlay had higher post-overlay IRI than sections without milling, regardless of their pre-overlay condition; sections with rubberized binder had higher post-overlay IRI than sections with conventional/polymer-modified binder when the pre-overlay IRI was less than 120 in./mile (1.90 m/km), and rubberized open-graded mixes had lower post-overlay IRI than did other types of mixes.

Generally, sections with lower pre-overlay IRI had lower post-overlay IRI regardless of other factors. Thicker overlays had lower post-overlay IRI when the pre-overlay IRI was greater than 120 in./mile and especially when greater than 170 in./mile, with the exception of milled or open-graded surfaces. Milling did not provide any benefits for achieving a smoother overlay except on open-graded surfaces. Digouts proved to be an efficient pre-overlay repair for reducing the post-overlay IRI in all the models, except that a more detailed breakdown indicated that they are not beneficial when the pre-overlay IRI is less than 95 in./mile.

It should be remembered that these results are from projects built between 2000 and 2009 and pertain to practices used during that period. These results may change if any of the practices considered in this study are changed.

Table 3.6: Significance of Variables in Different Pre-Overlay Conditions (α=0.05) for Models 9 and 10 with Pre-Overlay IRI Divided at 120 in./mile

Regression Models on Post-Overlay IRI	Significance						
	Pre-Overlay IRI	**Overlay Thickness**	**Milling**	**Digouts**	**Overlay Mix Type (OG)**	**Binder Type (Rubberized)**	**Random Effect**
Model 9 *Pre-overlay IRI* *< 120 in./mile*	Yes	No	Yes	No	No	No	Project
Model 10 *Pre-overlay IRI* *≥ 120 in./mile*	Yes	No	No	Yes	No	No	Project

Notes:
1. Green cells represent a positive effect on improving pavement smoothness.
2. Red cells represent a negative effect on improving pavement smoothness.

Table 3.7: Significance of Variables in Different Pre-Overlay Conditions (α=0.05) for Models 11 through 14 with Pre-Overlay IRI Divided at 95, 120, and 170 in./mile

Regression Models on Post-Overlay IRI	Significance						
	Pre-Overlay IRI	**Overlay Thickness**	**Milling**	**Digouts**	**Overlay Mix Type (OG)**	**Binder Type (Rubberized)**	**Random Effect**
Model 11 *Pre-overlay IRI* *< 95 in./mile*	Yes	No	Yes	Yes	No	Yes	Project
Model 12 *Pre-overlay IRI* *≥ 95 & < 120 in./mile*	Yes	No	Yes	No	No	No	Project
Model 13 *Pre-overlay IRI* *≥ 120 & < 170 in./mile)*	Yes	No	No	Yes	No	No	Project
Model 14 *Pre-overlay IRI* *≥ 170 in./mile*	Yes	Yes	No	Yes	No	Yes	Project

Notes:
1. Green cells represent a positive effect on improving pavement smoothness.
2. Red cells represent a negative effect on improving pavement smoothness.
3. 95 in./mile = 1.5 m/km, 120 in./mile = 1.9 m/km, 170 in./mile = 1.9 m/km,

Table 3.8: Significance of Variables in Different Pre-Overlay Conditions (α=0.05) for Models 15 and 16

Linear Mixed Effects Models on Post-Overlay IRI with Project as a Random Effects Variable		
Coefficients	**Model 15** *Pre-overlay IRI < 120 in./mile (< 1.90 m/km)*	**Model 16** *Pre-overlay IRI ≥ 120 in./mile (≥ 1.90 m/km)*
(Intercept)	Yes	Yes
Pre-overlay IRI	🟩 Yes	🟩 Yes
Thickness	No	🟩 Yes
Milling (Yes)	🟥 Yes	🟥 Yes
Digouts (Yes)	No	🟩 Yes
Overlay mix type (OG)	No	No
Binder Type (Rubberized)	🟥 Yes	No
Thickness*Milling (Yes)	No	🟥 Yes
Thickness*Digouts (Yes)	🟩 Yes	No
Thickness*Overlay mix type (OG)	No	🟥 Yes
Thickness*Binder Type (Rubberized)	No	No
Milling (Yes)*Digouts (Yes)	No	No
Milling (Yes)*Overlay mix type (OG)	🟩 Yes	🟩 Yes
Milling (Yes)* Binder Type (Rubberized)	No	🟩 Yes
Digouts (Yes)*Overlay mix type (OG)	🟩 Yes	No
Digouts (Yes)* Binder Type (Rubberized)	🟩 Yes	No
Overlay mix type (OG)* Binder Type (Rubberized)	🟩 Yes	🟩 Yes

Notes:

1. **Green cells represent a positive effect on pavement smoothness.**
2. **Red cells represent a negative effect on pavement smoothness.**

3.2.2 Re-Analysis of the LTPP SPS-5 Data

The LTPP SPS-5 data were originally used in studies for investigating the effects of pre-overlay repairs, overlay thickness, and material type of overlay on flexible pavements. Those studies used specially designed experimental pavements. Since the independent variables in the LTPP SPS-5 data were considered to be very similar to the independent variables collected in the Caltrans PCS data, a selection of SPS-5 data was made for this project and re-analyzed. Once the analyses were completed, the results from the LTPP SPS-5 data were compared to the actual field construction results from the Caltrans PCS data.

Data from 120 subsections were collected from the SPS-5 data, from 15 states and provinces across United States and Canada. Each state had one overlay project including eight subsections. The dataset included pre-overlay IRI, post-overlay IRI, overlay thickness (0.167 ft [50 mm] and 0.410 ft [125 mm]), pre-overlay repairs (intense and minimal), and material used (virgin mixes and 30 percent recycled mixes). Figure 3.18 shows a cumulative distribution of pre-overlay IRI and post-overlay IRI from the LTPP SPS-5 data. The distribution of the pre-overlay

IRI from the LTPP SPS-5 data is quite similar to that from the Caltrans PCS data, but the distribution of post-overlay IRI has much lower values than the Caltrans PCS data. It can be seen in Figure 3.18 that the 50th percentile post-overlay IRI is 56 in./mile, while in the Caltrans PCS data from 2000 to 2009 the 50th percentile value is 76 in./mile (for subsections, Figure 3.3). The cumulative distribution of IRI reduction is shown in Figure 3.19. Only 5 percent of IRI reduction is negative, a much smaller value than 20 percent from the Caltrans PCS data. Overall, the overlay projects in the LTPP SPS-5 data showed better performance in post-overlay IRI than the overlay projects in the Caltrans PCS data.

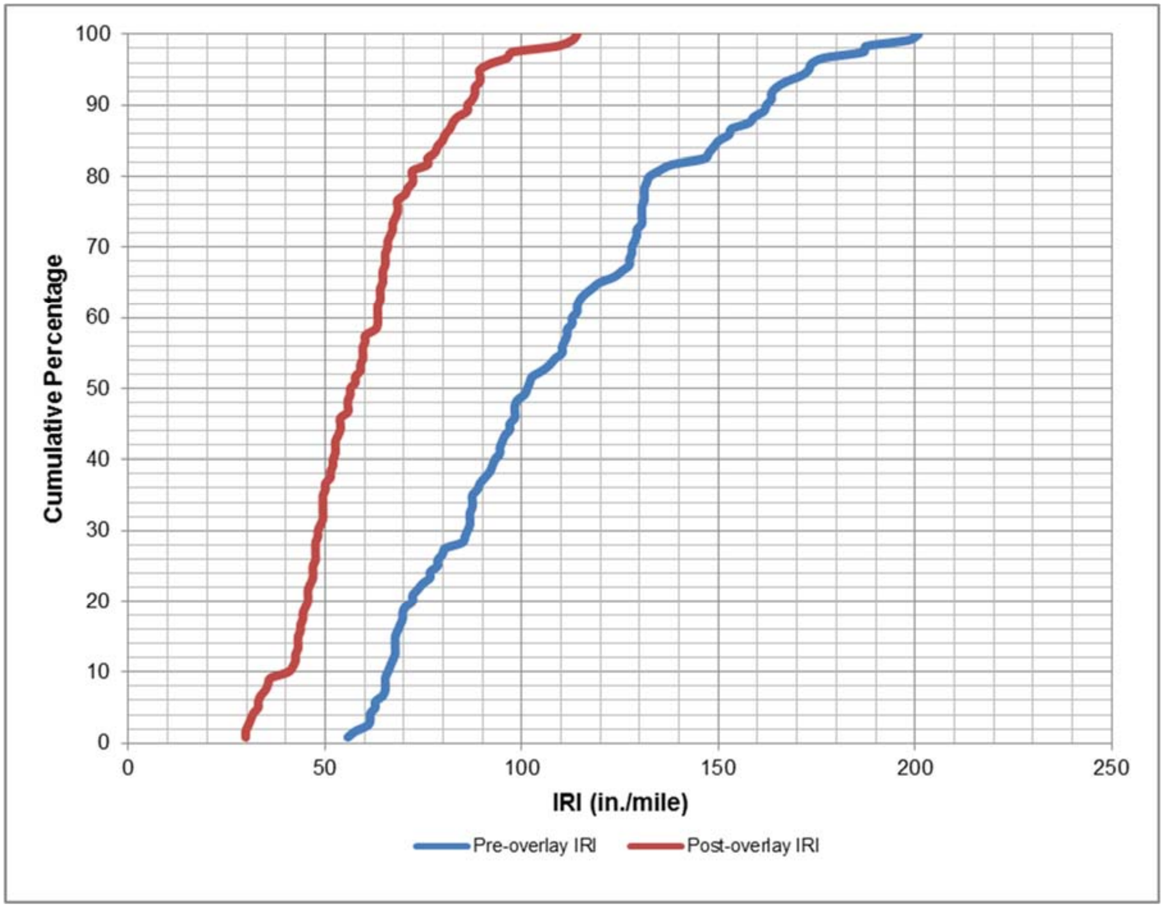


Figure 3.18: Cumulative distributions of pre-overlay and post-overlay IRI (SPS-5).

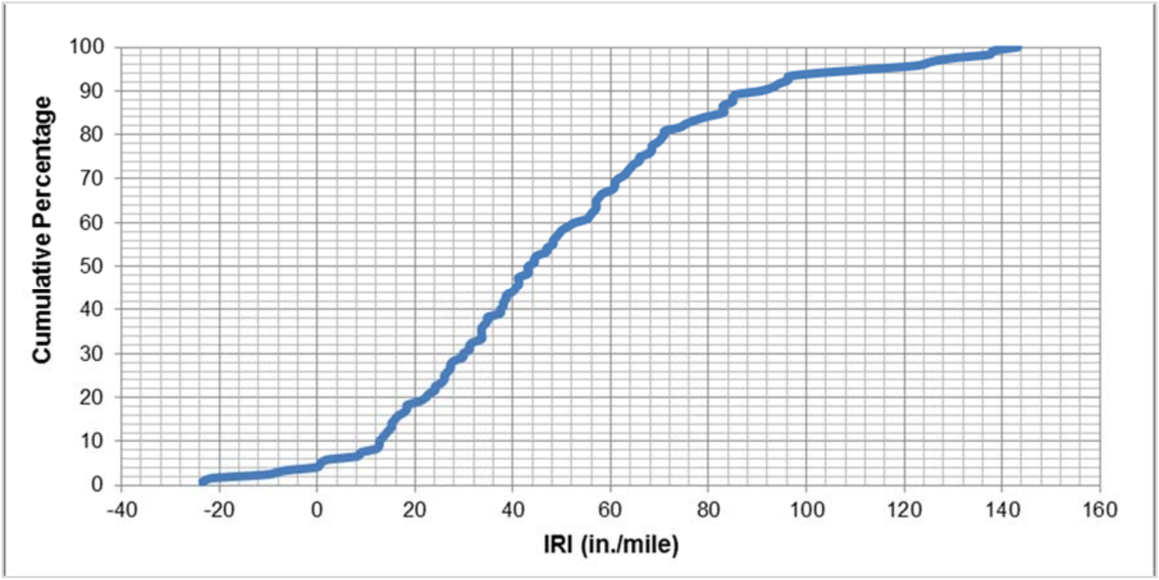


Figure 3.19: Cumulative distribution of IRI reduction (SPS-5).

Table 3.9 shows the average pre-overlay IRI, post-overlay IRI, and IRI reduction for each group based on the LTPP SPS-5 data. As with the PCS data, pre-overlay condition was reclassified into two categories, with *Good* being IRI less than 120 in./mile (1.90 m/km) and *Poor* being IRI greater than 120 in./mile (1.90 m/km). Two overlay thickness categories were identified in the LTPP SPS-5 data: 0.167 ft (50 mm) and 0.410 ft (125 mm). Pre-overlay repairs consisted of minimal repairs that included patching and leveling without milling, and intense repairs that included patching, crack sealing, and milling. Materials included virgin and reclaimed asphalt (referred to as "recycled" in models) that were used in overlay projects. Boxplots for pre-overlay IRI, post-overlay IRI, and IRI reduction are shown in Figure 3.20 to Figure 3.22. Based on Table 3.9 and the boxplots, the following points were drawn from the SPS-5 data:

- Pre-overlay condition has a significant effect on both post-overlay IRI and IRI reduction. The post-overlay IRI was higher in the groups with poor pre-overlay condition. The IRI reduction was higher in the groups with poor pre-overlay condition as well.
- Overlay thickness was shown to have little influence on post-overlay IRI and IRI reduction.
- No specific trends could be found for pre-overlay repairs and mix types based on the descriptive statistics and boxplots.

Table 3.9: Descriptive Statistics of Dataset (SPS-5)

Group	Pre-Overlay Condition	Thickness	Pre-Overlay Repairs	Mix Type	Number of Projects	Pre-Overlay IRI (in./mile)	Post-Overlay IRI (in./mile)	IRI Reduction (in./mile)
1	Good	Thin	Minimal	Virgin	13	88.56	58.97	29.58
2				Recycled	8	81.81	61.78	20.04
3			Intense	Virgin	10	86.11	52.84	33.26
4				Recycled	7	79.56	48.24	31.32
5		Thick	Minimal	Virgin	10	90.16	55.95	34.21
6				Recycled	9	89.20	53.79	35.41
7			Intense	Virgin	9	84.76	60.97	23.80
8				Recycled	12	89.13	53.38	35.75
9	Poor	Thin	Minimal	Virgin	2	162.52	74.45	88.07
10				Recycled	8	155.68	71.69	84.00
11			Intense	Virgin	5	142.69	65.01	77.68
12				Recycled	8	144.94	67.40	77.54
13		Thick	Minimal	Virgin	5	153.33	70.08	83.26
14				Recycled	6	144.25	68.11	76.14
15			Intense	Virgin	6	151.75	57.24	94.51
16				Recycled	3	145.31	66.74	78.57

Notes:

1. ***Good* pre-overlay condition: pre-overlay IRI < 120 in./mile (1.90 m/km); *poor* pre-overlay condition: pre-overlay IRI ≥ 120 in./mile (1.90 m/km)**
2. ***Thin* overlay: 0.167 ft (50 mm); *thick* overlay: 0.410 ft (125 mm)**

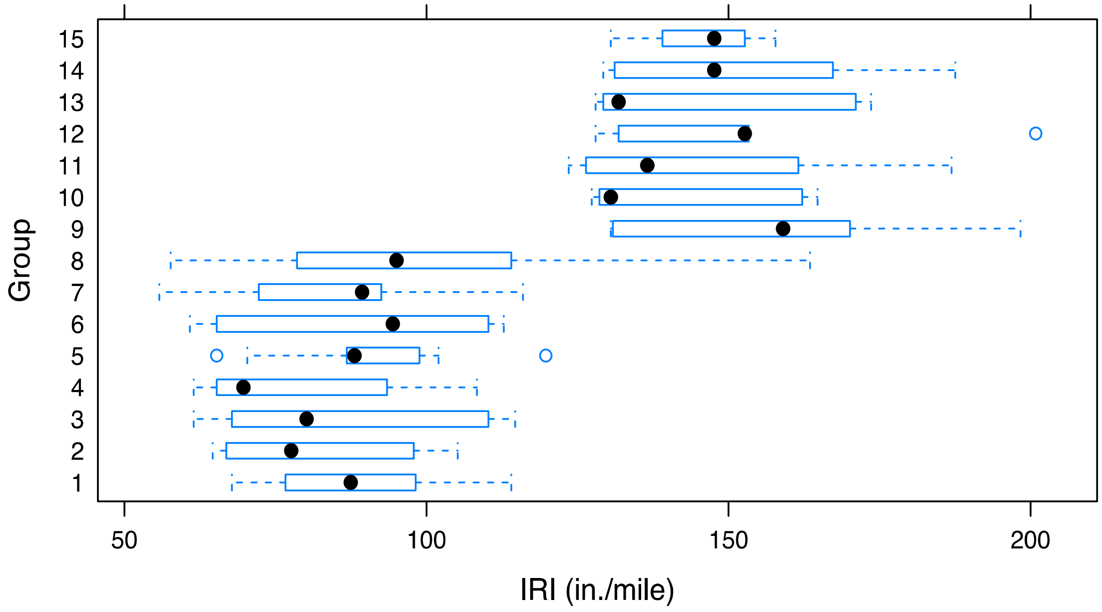


Figure 3.20: Boxplots of pre-overlay IRI for each group in LTPP SPS-5.

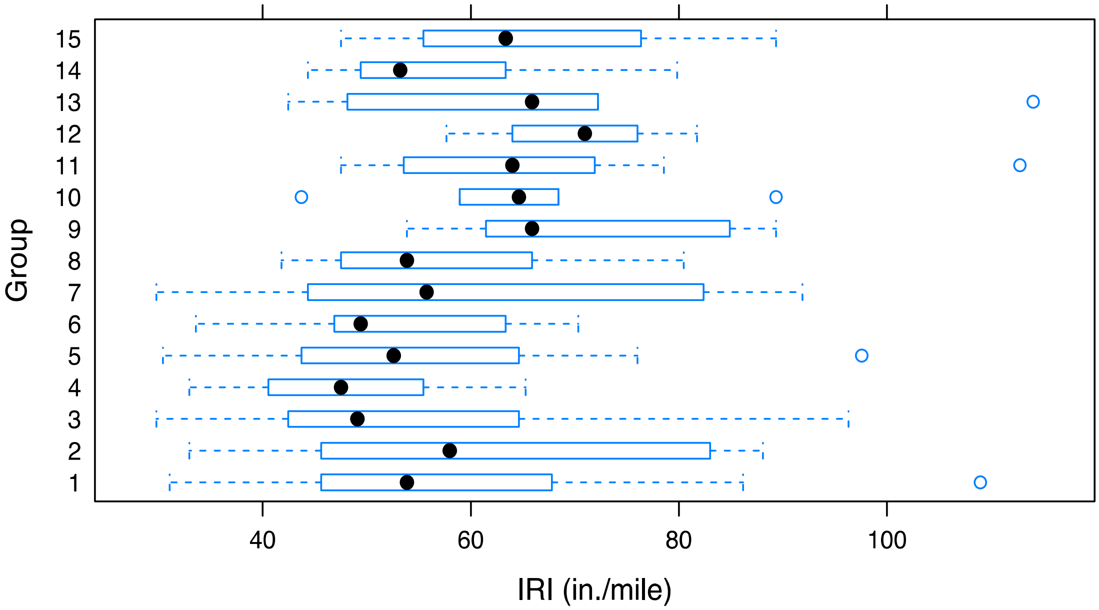


Figure 3.21: Boxplots of post-overlay IRI for each group in LTPP SPS-5.

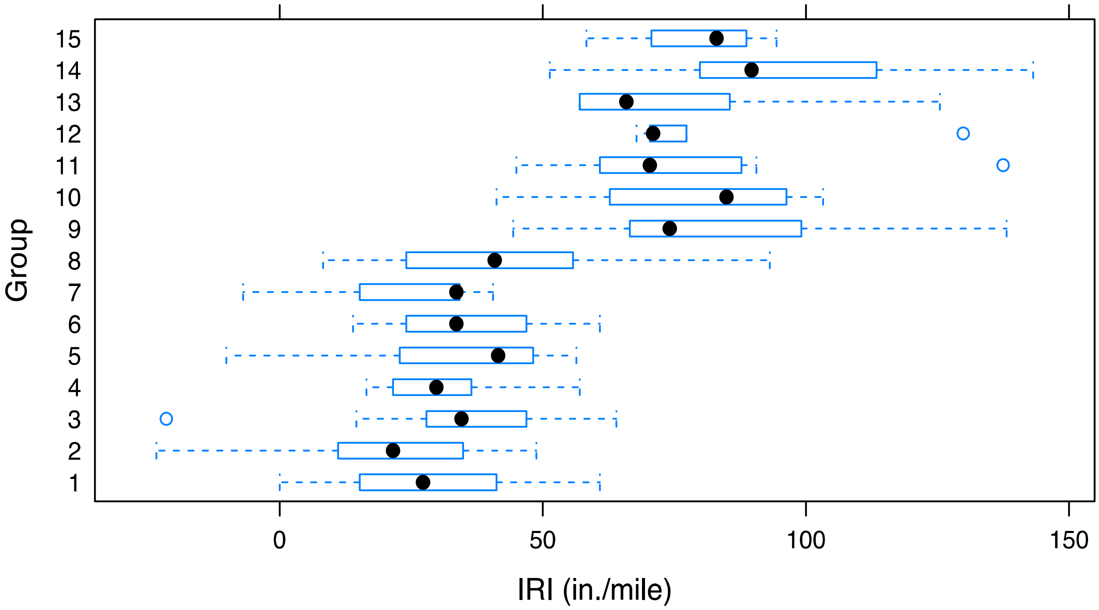


Figure 3.22: Boxplots of IRI reduction for each group in LTPP SPS-5.

As with the Caltrans PCS data, mixed effect models were used to investigate the effects of variables in the LTPP SPS-5 data. In the regression models, post-overlay IRI was the dependent variable; and pre-overlay IRI, overlay thickness, pre-overlay repair (minimal or intense), and mix type (virgin or recycled) were the independent variables. Pre-overlay IRI was analyzed as a continuous variable, and the rest of factors were analyzed as categorical variables. State was considered to be the random effect variable in the regression models.

Table 3.10 shows the results of the regression models, and indicates that pre-overlay condition and surface preparation are the only two variables that had significant effects on the smoothness of overlays in the model with all of the data. The results from this re-analysis of the regression models differ from the earlier studies. The difference might be due to the use of mixed effects models in this study. The following conclusions were drawn from the regression analysis of the LTPP SPS-5 data:

- Pre-overlay condition was a significant factor for the model that analyzed all of the LTPP SPS-5 data.
- Overlay thickness and mix type have no effect on the post-overlay IRI.
- According to the analysis of the LTPP SPS-5 data, milling has a positive effect on the post-overlay IRI.
- No significant variables were found for the models with two categories of pre-overlay condition. This result might be due to the small sample size.

Table 3.10: Significance of Variables in Different Pre-Overlay Condition (α=0.05) for Models 17 through 19

Regression Models on Post-Overlay IRI	**Significance**				
	Pre-Overlay IRI	**Overlay Thickness**	**Pre-Overlay Repairs**	**Overlay Mix Type**	**Random Effect**
Model 17 *All data*	Yes	No	Yes	No	State
Model 18 *Pre-overlay IRI < 120 in./mile (< 1.90 m/km)*	No	No	No	No	State
Model 19 *Pre-overlay IRI ≥ 120 in./mile (≥ 1.90 m/km)*	No	No	No	No	State

Notes:
1. Green cells represent a positive effect on improving pavement smoothness.
2. Red cells represent a negative effect on improving pavement smoothness.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

In this research study, California Pavement Condition Survey (PCS) data from overlays constructed based on the profilograph specification were analyzed using mixed effect models, and the effects of several factors on initial overlay smoothness were evaluated. The PCS data were collected prior to the 2013 implementation of the Caltrans smoothness specification for overlay construction based on IRI. Based on the results of the analysis of the available data, the following conclusions were drawn:

- 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. Considering 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) would have been paved in two or sometimes more lifts, the multiple passes of the paver would have 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. The thickness effect could not be separated for different kinds of open-graded overlays (conventional, polymer-modified, rubberized, bonded wearing course).
- Milling prior to overlay and using rubberized binder (grouping gap-graded and open-graded mixes together in the statistical analysis) alone do not provide any additional benefits for achieving lower post-overlay IRI based on the data used for this study from the period of 2000 to 2009. As with all of the results in this study, changes in specifications and quality assurance practice may change this conclusion. However, using rubberized binder in open-graded overlays may help achieve lower post-overlay IRI.
- Milling prior to overlay on pavements with existing IRI less than 120 in./mile, and particularly when the existing IRI is less than 95 in./mile, is disadvantageous and will likely result in a rougher pavement than if milling had not been done, based on the data used for this study. As with all of the results in this study, changes in specifications and quality assurance practice may change this conclusion.
- Digouts, which should be done to correct cracking in the wheelpath prior to overlay, generally provide a benefit when the pre-overlay IRI is greater than 95 in./mile, but they have the greatest benefit in reducing post-overlay IRI when the pre-overlay IRI is greater than 120 in./mile.
- 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. This result may be because relatively shallow milling (see definition above) may not address underlying

structural problems in the wheelpaths, while digouts are generally only used where there are evident structural problems in the wheelpaths and, as defined for this study (see above), result in deeper removal of material in those locations.
- 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.

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.

A similar analysis of the LTPP SPS-5 sections from 120 subsections collected from the SPS-5 data—from fifteen 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, although 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. There was no information available regarding lift thicknesses used for different overlay total thicknesses. This finding is somewhat different from that found using the Caltrans data which showed that overlay thickness had no benefit on post-overlay IRI when the pre-overlay IRI was below 120 in./mile, but showed a benefit of thicker overlays when the pre-overlay IRI was greater than 120 in./mile.
- No specific trends could be found for pre-overlay repairs and mix types based on the descriptive statistics and boxplots.

4.2 Recommendations

The following recommendations are 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 recommend against using milling as a means to improve the smoothness of an overlay when the IRI of the existing pavement is less than 120 in./mile (1.9 m/km). Changes in milling practice since 2009 may change this recommendation, but this should be investigated using projects built since the change in the Caltrans smoothness specification in 2013.

- Digouts are used for pre-overlay repair to remove cracking only in the wheelpaths and only when the nonwheelpath pavement is in satisfactory condition; a decision to use digouts is based solely on the severity and extent of cracking. However, consideration should be given to using separate IRI performance equations in the *PaveM* pavement management system for overlays with and without digouts since their use on rough pavements helps improve overlay smoothness.
- 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 any changes in the findings of this study and whether adjustments to the specification are needed or desired. These new measurements should be taken by the UCPRC prior to any grinding for smoothness that Caltrans requires the contractor to do prior to closing the construction contract, and if possible the UCPRC should also collect information regarding the amount of grinding that was required to pass the specification.

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APPENDIX

Table A.1: Descriptive Statistics of Dataset

Group	Pre-Overlay Condition	Overlay Thickness	Milling	Digout	Surface Type	Rubberized Material Used	Number of Projects	Number of Subsections	Avg. Pre-Overlay IRI (in./mile)	SD Pre-Overlay IRI (in./mile)	Post-Overlay IRI (in./mile)	SD Post-Overlay IRI (in./mile)	Reduction IRI (in./mile)	SD of Reduction IRI (in./mile)
1	Good	Thin	No	No	Non-OG	No	7	19	103	10	70	12	33	14
						Yes	12	128	87	22	74	24	13	18
					OG	No	17	227	80	19	73	22	7	17
						Yes	17	276	80	18	65	19	16	19
2			No	Yes	Non-OG	No	8	126	86	22	71	21	15	24
						Yes	30	366	80	20	70	20	9	20
					OG	No	11	170	95	16	96	21	-1	25
						Yes	10	317	73	17	60	13	13	19
3			Yes	No	Non-OG	No	7	58	95	16	91	16	4	18
						Yes	10	284	96	16	87	18	9	20
					OG	No	3	24	87	16	67	17	20	24
						Yes	3	56	60	10	56	11	4	14
4			Yes	Yes	Non-OG	No	4	38	102	12	91	23	11	23
						Yes	8	134	82	18	78	17	4	16
					OG	No	1	50	66	25	78	13	-13	22
						Yes	2	26	71	20	62	9	9	22
5		Thick	No	No	Non-OG	No	9	46	84	18	74	17	10	18
						Yes	3	10	82	15	70	14	12	18
					OG	No	6	31	78	22	65	21	13	19
						Yes	1	10	95	11	62	5	33	9
6			No	Yes	Non-OG	No	11	58	92	21	72	23	20	26
						Yes	4	60	83	16	63	13	20	17
					OG	No	2	4	110	5	88	14	22	18
						Yes	3	20	97	14	82	17	15	21
7			Yes	No	Non-OG	No	15	72	93	16	80	22	13	21
						Yes	2	5	84	15	97	19	-13	31
					OG	No	2	96	62	13	51	12	11	14
						Yes	1	2	107	0	106	1	1	1
8			Yes	Yes	Non-OG	No	2	7	83	24	65	18	19	21
						Yes	2	63	95	16	51	9	44	19
					OG	No	1	9	83	15	65	13	19	17
						Yes	2	2	95	2	51	36	44	33

Note: SD = Standard Deviation

Table A.1: Descriptive Statistics of Dataset *(cont.)*

Group	Pre-Overlay Condition	Overlay Thickness	Milling	Digout	Surface Type	Rubberized Material Used	Number of Projects	Number of Subsections	Avg. Pre-Overlay IRI (in./mile)	SD Pre-Overlay IRI (in./mile)	Post-Overlay IRI (in./mile)	SD of Post-Overlay IRI (in./mile)	Reduction IRI (in./mile)	SD of Reduction IRI (in./mile)
9	Poor	Thin	No	No	Non-OG	No	9	47	163	50	91	31	72	26
						Yes	14	136	155	35	112	37	44	38
					OG	No	13	82	169	43	119	41	50	47
						Yes	10	62	173	55	110	50	63	47
10			No	Yes	Non-OG	No	12	38	164	37	92	32	71	45
						Yes	26	251	161	38	85	48	76	41
					OG	No	12	160	160	38	119	36	40	37
						Yes	6	18	167	70	92	27	75	61
11			Yes	No	Non-OG	No	8	61	158	30	132	32	26	33
						Yes	12	226	160	43	105	32	55	39
					OG	No	3	12	167	56	70	22	97	62
						Yes	1	20	196	25	57	16	139	24
12			Yes	Yes	Non-OG	No	7	58	164	40	106	36	58	43
						Yes	8	47	172	34	96	30	76	39
					OG	No	2	25	147	19	95	13	52	20
						Yes	1	2	134	7	62	6	72	13
13		Thick	No	No	Non-OG	No	8	39	184	65	92	56	92	50
						Yes	2	13	175	40	92	62	84	49
					OG	No	4	21	166	39	67	26	99	49
						Yes	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
14			No	Yes	Non-OG	No	11	68	164	47	78	29	86	46
						Yes	5	30	152	26	70	28	83	26
					OG	No	2	7	157	16	85	10	72	17
						Yes	3	11	142	16	86	22	56	20
15			Yes	No	Non-OG	No	17	122	203	68	122	48	81	61
						Yes	2	23	180	31	129	25	51	41
					OG	No	2	34	197	36	78	23	119	44
						Yes	1	5	146	13	142	20	4	16
16			Yes	Yes	Non-OG	No	7	18	187	37	108	40	78	39
						Yes	2	39	145	23	51	6	93	24
					OG	No	1	5	179	29	76	10	103	34
						Yes	1	1	143	N/A	77	N/A	65	N/A

Note: SD = Standard Deviation

Table A.2: Number of Subsections for Each Group (Milling)

Pre-Overlay Condition	Number of Subsections	Thickness	Number of Subsections	Milling	Number of Subsections	Overlay Mix Type	Number of Subsections	Rubberized Overlay	Number of Subsections
Good	2,794	Thin	2,299	No	1,629	Non-OG	639	No	145
								Yes	494
						OG	990	No	397
								Yes	593
				Yes	670	Non-OG	514	No	96
								Yes	418
						OG	156	No	74
								Yes	82
		Thick	495	No	239	Non-OG	174	No	104
								Yes	70
						OG	65	No	35
								Yes	30
				Yes	256	Non-OG	147	No	79
								Yes	68
						OG	109	No	105
								Yes	4
Poor	1,681	Thin	1,245	No	794	Non-OG	472	No	85
								Yes	387
						OG	322	No	242
								Yes	80
				Yes	451	Non-OG	392	No	119
								Yes	273
						OG	59	No	37
								Yes	22
		Thick	436	No	189	Non-OG	150	No	107
								Yes	43
						OG	39	No	28
								Yes	11
				Yes	247	Non-OG	202	No	140
								Yes	62
						OG	45	No	39
								Yes	6

Table A.3: Number of Subsections for Each Group (Digouts)

Pre-Overlay Condition	Number of Subsections	Thickness	Number of Subsections	Digouts	Number of Subsections	Overlay Mix Type	Number of Subsections	Rubberized Overlay	Number of Subsections
Good	2,794	Thin	2,299	No	1,072	Non-OG	489	No	77
								Yes	412
						OG	583	No	251
								Yes	332
				Yes	1,227	Non-OG	664	No	164
								Yes	500
						OG	563	No	220
								Yes	343
		Thick	495	No	272	Non-OG	133	No	118
								Yes	15
						OG	139	No	127
								Yes	12
				Yes	223	Non-OG	188	No	65
								Yes	123
						OG	35	No	13
								Yes	22
Poor	1,681	Thin	1,245	No	646	Non-OG	470	No	108
								Yes	362
						OG	176	No	94
								Yes	82
				Yes	559	Non-OG	394	No	96
								Yes	298
						OG	205	No	185
								Yes	20
		Thick	436	No	257	Non-OG	197	No	161
								Yes	36
						OG	60	No	55
								Yes	5
				Yes	179	Non-OG	155	No	86
								Yes	69
						OG	24	No	12
								Yes	12

Table A.4: Regression Results of Model 1 (α =0.05)

Model 1					
Coefficients:	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	53.688690	2.408578	22.29	0.0001	Yes
Pre-overlay IRI	0.280152	0.007794	35.95	0.0001	Yes
Thickness	1.591108	2.559577	0.62	0.9378	No
Milling (Yes)	4.807362	1.671557	2.88	0.0008	Yes
Digouts (Yes)	-4.595220	1.180360	-3.89	0.0001	Yes
Overlay mix type (OG)	-5.409904	2.296037	-2.36	0.0142	Yes
Binder type (Rubberized)	-0.120175	1.786771	-0.07	0.4904	No

Table A.5: Regression Results of Model 2 ($\alpha = 0.05$)

Model 2					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	82.4201	2.4955	33.03	0.0001	Yes
Pre-overlay IRI	15.9924	0.8379	19.09	0.0001	Yes
Thickness	4.2779	2.4717	1.73	0.7796	No
Milling (Yes)	6.9828	1.8447	3.79	0.0001	Yes
Digouts (Yes)	-5.4406	1.2920	-4.21	0.0001	Yes
Overlay mix type (OG)	-9.0316	2.5671	-3.52	0.0002	Yes
Binder type (Rubberized)	-0.6606	1.9958	-0.33	0.1674	No

Table A.6: Regression Results of Model 3 ($\alpha = 0.05$)

Model 3					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	53.170535	4.449969	11.95	0.0001	Yes
Pre-overlay IRI	0.277631	0.007775	35.71	0.0001	Yes
Thickness	1.844065	2.553524	0.72	0.7090	No
Milling (Yes)	6.478822	1.713821	3.78	0.0002	Yes
Digouts (Yes)	-4.199970	1.181123	-3.56	0.0002	Yes
Overlay mix type (OG)	-4.866324	2.341401	-2.08	0.0234	Yes
Binder type (Rubberized)	0.874185	1.877612	0.47	0.8500	No

Table A.7: Regression Results of Model 4 ($\alpha = 0.05$)

Model 4					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	82.3025	5.6529	14.559	0.0001	Yes
Pre-overlay IRI	15.8765	0.8331	19.058	0.0001	Yes
Thickness	3.1447	2.5005	1.258	0.6780	No
Milling (Yes)	9.0695	1.8958	4.784	0.0001	Yes
Digouts (Yes)	-4.9165	1.2906	-3.810	0.0002	Yes
Overlay mix type (OG)	-9.0828	2.6086	-3.098	0.0002	Yes
Binder type (Rubberized)	0.9872	2.0889	0.473	0.8256	No

Table A.8: Regression Results of Model 5 ($\alpha = 0.05$)

Model 5

Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	-53.688690	2.408578	-22.29	0.0001	Yes
Pre-overlay IRI	0.719848	0.007794	92.36	0.0001	Yes
Thickness	-1.591108	2.559577	-0.62	0.9090	No
Milling (Yes)	-4.807362	1.671557	-2.88	0.0004	Yes
Digouts (Yes)	4.595220	1.180360	3.89	0.0001	Yes
Overlay mix type (OG)	5.409904	2.296037	2.36	0.0120	Yes
Binder type (Rubberized)	0.120175	1.786771	0.07	0.4886	No

Table A.9: Regression Results of Model 6 ($\alpha = 0.05$)

Model 6

Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	13.4966	2.6635	5.07	0.0001	Yes
Pre-overlay IRI	52.4861	1.0475	50.11	0.0001	Yes
Thickness	7.5022	2.7477	2.73	0.0018	Yes
Milling (Yes)	-0.5042	2.1524	-0.23	0.5466	No
Digouts (Yes)	2.7082	1.5516	1.75	0.0820	No
Overlay mix type (OG)	-1.6738	2.7110	-0.62	0.6180	No
Binder type (Rubberized)	-0.5942	2.2277	-0.27	0.8858	No

Table A.10: Regression Results of Model 7 ($\alpha = 0.05$)

Model 7

Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	-53.170535	4.449969	-11.95	0.0001	Yes
Pre-overlay IRI	0.722369	0.007775	92.91	0.0001	Yes
Thickness	-1.844065	2.553524	-0.72	0.6938	No
Milling (Yes)	-6.478822	1.713821	-3.78	0.0002	Yes
Digouts (Yes)	4.199970	1.181123	3.56	0.0008	Yes
Overlay mix type (OG)	4.866324	2.341401	2.08	0.0234	Yes
Binder type (Rubberized)	-0.874185	1.877612	-0.47	0.8842	No

Table A.11: Regression Results of Model 8 ($\alpha = 0.05$)

Model 8					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	14.1579	3.0809	4.60	0.0008	Yes
Pre-overlay IRI	52.4804	1.0475	50.10	0.0001	Yes
Thickness	7.3296	2.7535	2.66	0.0018	Yes
Milling (Yes)	-1.0393	2.1724	-0.48	0.3986	No
Digouts (Yes)	2.6471	1.5540	1.70	0.1012	No
Overlay mix type (OG)	-1.7841	2.7351	-0.65	0.4832	No
Binder type (Rubberized)	-0.4544	2.2962	-0.20	0.7814	No

Table A.12: Regression Results of Model 9 ($\alpha = 0.05$)

Model 9					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	42.68821	2.42809	17.581	0.0001	Yes
Pre-overlay IRI	0.34006	0.01719	19.788	0.0001	Yes
Thickness	2.43273	2.17532	1.118	0.6628	No
Milling (Yes)	5.91571	1.47985	3.998	0.0008	Yes
Digouts (Yes)	0.47711	0.94026	0.507	0.6074	No
Overlay mix type (OG)	-1.63934	1.88113	-0.871	0.2628	No
Binder type (Rubberized)	-0.25391	1.47802	-0.172	0.2718	No

Table A.13: Regression Results of Model 10 ($\alpha =0.05$)

Model 10					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	54.77480	4.92648	11.118	0.0001	Yes
Pre-overlay IRI	0.34627	0.01732	19.990	0.0001	Yes
Thickness	-0.91947	5.65146	-0.163	0.3884	No
Milling (Yes)	-1.27644	3.36150	-0.380	0.5686	No
Digouts (Yes)	-19.40115	2.86119	-6.781	0.0001	Yes
Overlay mix type (OG)	-7.71945	4.24860	-1.817	0.1258	No
Binder type (Rubberized)	-1.89548	3.62718	-0.523	0.5606	No

Table A.14: Regression Results of Model 11 (α =0.05)

Model 11					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	38.79442	2.67663	14.494	0.0001	Yes
Pre-overlay IRI	0.39447	0.02515	15.686	0.0001	Yes
Thickness	2.86763	2.28841	1.253	0.5420	No
Milling (Yes)	4.47956	1.60469	2.792	0.0072	Yes
Digouts (Yes)	2.07726	0.97273	2.136	0.0262	Yes
Overlay mix type (OG)	-0.97793	1.97046	-0.496	0.3716	No
Binder type (Rubberized)	-3.53387	1.59471	-2.216	0.0082	Yes

Table A.15: Regression Results of Model 12 (α =0.05)

Model 12					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	58.45510	9.89032	5.910	0.0001	Yes
Pre-overlay IRI	0.24064	0.08654	2.781	0.0166	Yes
Thickness	-3.79298	4.40084	-0.862	0.2074	No
Milling (Yes)	7.51982	2.82429	2.663	0.0218	Yes
Digouts (Yes)	-3.96105	2.00838	-1.972	0.0536	No
Overlay mix type (OG)	-3.25365	3.01969	-1.077	0.2764	No
Binder type (Rubberized)	-2.60385	2.55675	-1.018	0.0520	No

Table A.16: Regression Results of Model 13 (α =0.05)

Model 13					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	56.67975	7.49530	7.562	0.0001	Yes
Pre-overlay IRI	0.27535	0.04647	5.925	0.0001	Yes
Thickness	0.61029	4.63766	0.132	0.5538	No
Milling (Yes)	-2.59598	3.25736	0.797	0.0726	No
Digouts (Yes)	-15.07081	2.58210	-5.837	0.0001	Yes
Overlay mix type (OG)	-1.68049	4.28519	-0.392	0.9100	No
Binder type (Rubberized)	3.36190	3.52332	0.954	0.4446	No

Table A.17: Regression Results of Model 14 (α =0.05)

Model 14					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	56.67975	7.49530	7.562	0.0001	Yes
Pre-overlay IRI	0.27535	0.04674	5.925	0.0001	Yes
Thickness	0.61029	4.63766	0.132	0.0024	Yes
Milling (Yes)	2.59598	3.25736	0.797	0.6296	No
Digouts (Yes)	-15.07081	2.58210	-5.837	0.0001	Yes
Overlay mix type (OG)	-1.68049	4.28519	-0.392	0.0556	No
Binder type (Rubberized)	3.36190	3.52332	-0.954	0.0048	Yes

Table A.18: Regression Results of Model 15 (α =0.05)

Multiple Regression Analysis: Model 15					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	39.36153	3.40027	11.576	0.0001	Yes
Pre-overlay IRI	0.32842	0.01726	19.031	0.0001	Yes
Thickness	0.56205	4.28228	0.131	0.9790	No
Milling (Yes)	11.38524	3.55008	3.207	0.0004	Yes
Digouts (Yes)	3.22908	2.68715	1.202	0.2878	No
Overlay mix type (OG)	2.96872	3.27755	0.906	0.4342	No
Rubberized Overlay (Yes)	7.94607	3.43977	2.310	0.0414	Yes
Thickness*Milling (Yes)	-3.54927	5.59309	-0.635	0.3662	No
Thickness*Digouts (Yes)	-11.91048	5.53230	-2.153	0.0278	Yes
Thickness*Overlay mix type (OG)	3.13222	5.58884	0.560	0.5712	No
Thickness*Rubberized Overlay (Yes)	7.28784	8.00925	0.910	0.3382	No
Milling (Yes)*Digouts (Yes)	3.45917	2.07635	1.666	0.1442	No
Milling (Yes)*Overlay mix type (OG)	-10.52115	3.41884	-3.077	0.0004	Yes
Milling (Yes)*Rubberized Overlay (Yes)	-1.80557	3.57168	-0.506	0.1730	No
Digouts (Yes)*Overlay mix type (OG)	4.40895	1.96688	2.242	0.0102	Yes
Digouts (Yes)*Rubberized Overlay (Yes)	-5.84029	2.26765	-2.575	0.0086	Yes
Overlay mix type (OG)*Rubberized Overlay (Yes)	-10.78510	3.61616	-2.982	0.0018	Yes

Table A.19: Regression Results of Model 16 (α =0.05)

Multiple Regression Analysis: Model 16					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	54.80594	6.56091	8.353	0.0001	Yes
Pre-overlay IRI	0.34631	0.01706	20.298	0.0001	Yes
Thickness	-33.79657	12.66940	-2.668	0.0062	Yes
Milling (Yes)	8.23098	6.31754	1.303	0.0286	Yes
Digouts (Yes)	-27.80400	6.29974	-4.414	0.0004	Yes
Overlay mix type (OG)	2.90719	7.13799	0.407	0.5866	No
Rubberized Overlay (Yes)	6.33247	6.74535	0.939	0.1098	No
Thickness*Milling (Yes)	23.20683	10.88609	2.132	0.0406	Yes
Thickness*Digout (Yes)	6.84401	10.51592	0.651	0.8626	No
Thickness*Overlay mix type (OG)	27.61267	11.68240	2.364	0.0210	Yes
Thickness*Rubberized Overlay (Yes)	18.77007	24.93357	0.753	0.3406	No
Milling (Yes)*Digouts (Yes)	12.50828	5.66084	2.210	0.0502	No
Milling (Yes)*Overlay mix type (OG)	-44.40778	8.20404	-5.413	0.0001	Yes
Milling (Yes)*Rubberized Overlay (Yes)	-22.72801	7.40836	-3.068	0.0001	Yes
Digouts (Yes)*Overlay mix type (OG)	3.98700	6.22687	0.640	0.2326	No
Digouts (Yes)*Rubberized Overlay (Yes)	2.75788	6.02034	0.458	0.4202	No
Overlay mix type (OG)*Rubberized Overlay (Yes)	-22.45089	8.79987	-2.551	0.0144	Yes

Table A.20: Regression Results of Model 17 (α =0.05)

Model 17					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	56.6053	6.21325	9.110	0.0001	Yes
Pre-overlay IRI	0.0549	0.04253	1.291	0.0272	Yes
Thickness (Thick)	-1.7776	1.74866	-1.017	0.3690	No
Pre-overlay Repairs (Intense)	-4.1017	1.74976	-2.344	0.0426	Yes
Mix Type (Recycled)	0.3698	1.75706	0.210	0.9218	No

Table A.21: Regression Results of Model 18 (α =0.05)

Model 18					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	55.2464	10.23187	5.399	0.0002	Yes
Pre-overlay IRI	0.0674	0.10058	0.670	0.0678	No
Thickness (Thick)	-0.0620	2.35801	-0.026	0.8096	No
Pre-overlay Repairs (Intense)	-3.7837	2.36051	-1.603	0.2172	No
Mix Type (Recycled)	-0.0388	2.35281	-0.016	0.7608	No

Table A.22: Regression Results of Model 19 (α =0.05)

Model 19					
Coefficients	Estimate	Std. Error	t-value	Pr(>|t|)	Significance
(Intercept)	55.2993	16.24212	3.405	0.0030	Yes
Pre-overlay IRI	0.0949	0.09955	0.953	0.4676	No
Thickness (Thick)	-4.992	3.43048	-1.457	0.2324	No
Pre-overlay Repairs (Intense)	-4.5205	3.63013	-1.245	0.2080	No
Mix Type (Recycled)	1.4659	3.40620	0.430	0.6458	No