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Pavement Rehabilitation Analysis: A Life-Cycle Cost and Long-Term Performance Comparison of Full Depth Reclamation and Overlays

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16. Abstract

To reduce the environmental impact of transportation, Departments of Transportation (DOTs) are incorporating cold-recycling technologies such as Full-Depth Reclamation (FDR) in their rehabilitation strategies. One of the limitations hindering the deployment of FDR is the limited information available on the material properties of these mixtures and their long-term performance. The objective of this project is to analyze the long-term performance and life-cycle costs of FDR and compare this rehabilitation solution with traditional mill and overlay. For each of these alternatives, a set of reference sections built across the state of Colorado were analyzed. Historical information of costs, maintenance history and pavement conditions were characterized using statistical analyses. This information was then incorporated into a probabilistic life-cycle analysis using Monte Carlo simulations to account for the uncertainty in the model inputs. Outputs related to life-cycle costs, long-term condition, and cost-effectiveness were estimated for both FDR and overlay pavements.

Overall, FDR was found to be a more cost-effective rehabilitation solution than overlays. FDR pavements have significantly lower life-cycle costs than overlay pavements. On average, the life-cycle cost of FDR pavements is $178,243/ln-mi less expensive than overlay pavements, resulting in a potential cost saving of 30%. FDR pavements also have a better long-term performance than overlays. Over the 10 years analysis, FDR pavements have an average roughness, measured in terms of the International Roughness Index (IRI) of 104 in/mi, compared to 124 in/mi for overlays.

This study characterized these alternatives based on direct costs and long-term condition. Future research analyzing the environmental impacts of these alternatives is recommended to fully capture the differences between FDR and traditional overlays. Our analysis also found some unexpected trends and inconsistencies in the historical pavement condition data that would be worth exploring further.

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Abstract

Transportation plays a critical economic role and is now the nation's biggest emitter of greenhouse gas emissions. To reduce the environmental impact of transportation, Departments of Transportation (DOTs) are incorporating cold-recycling technologies such as Full-Depth Reclamation (FDR) as an alternative for pavement rehabilitation. FDR involves pulverizing and reusing materials from distressed pavements, producing a new base mixture. One of the limitations hindering the deployment of FDR is the limited information available on the material properties of these mixtures. The objective of this project is to analyze the long-term performance and life-cycle costs of FDR and compare this rehabilitation solution with traditional overlays. For each of these alternatives, a set of reference sections built across the state of Colorado were analyzed. Historical information of costs, maintenance history and pavement conditions were characterized using statistical analyses. This information was then incorporated into a probabilistic life-cycle analysis using Monte Carlo simulations to account for the uncertainty in the model inputs. Outputs related to life-cycle costs, long-term condition, and cost-effectiveness were estimated for both FDR and overlay pavements.

Overall, FDR was found to be a more cost-effective rehabilitation solution than overlays. FDR pavements have significantly lower life-cycle costs than overlay pavements. On average, the life-cycle cost of FDR pavements is $178,243/ln-mi less expensive than overlay pavements, resulting in a potential cost saving of 30%. FDR pavements also have a better long-term performance than overlays. Over the 10 years analysis, FDR pavements have an average roughness, measured in terms of the International Roughness Index (IRI) of 104 in/mi, compared to 124 in/mi for overlays.

This analysis is limiting the characterization of these alternatives to direct costs and long-term condition terms. Future research analyzing the environmental impacts of these alternatives is recommended to fully capture the benefits of FDR rehabilitation. Our analysis also found some unexpected trends and inconsistencies in the historical pavement condition data that would be worth exploring further. Future research is needed to propose a more accurate process to measure and characterize pavement deterioration.

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Chapter 1. Introduction

1 Motivation

In the recent years, Departments of Transportation (DOTs) are placing increasing emphasis on incorporating asphalt mixtures using cold-recycling technologies in their rehabilitation strategies. Cold-recycling technologies, such as Full-Depth Reclamation (FDR), are effective rehabilitation strategies that are proven to reduce environmental impacts, as well as construction costs and time (Schwartz et al. 2017). FDR involves pulverizing and reusing materials from distressed pavements in place, ultimately producing a new base mixture.

Unfortunately, limited information is available on the material properties of these mixtures to facilitate the structural design of FDR pavements. This information is critical in the mechanistic-empirical (ME) design of pavements using the AASHTOWare software. Several authors (May 2008; Apeagyei and Diefenderfer 2013) have noted that default values in previous AASHTOWare software versions for cold recycled materials were overly conservative and bordered on non-representative. This leads to an underestimation of the true performance capabilities of these materials resulting in a significant loss of potential cost and resource saving or even reluctance to specify these techniques (Apeagyei and Diefenderfer 2013).

To address this problem, the PI recently completed a research project sponsored by CDOT (project code R 418-02, final research report by Torres-Machi et al. (2020)) to establish standard modulus values for FDR materials for ME design. This project found that design inputs used by CDOT were conservative and led to underestimate the performance of FDR projects. Based on pavement performance data and laboratory testing, the research team derived recommendations on the ME input design parameters that should be used in future FDR design.

The current project aims to further advance our knowledge in FDR and perform a life-cycle cost analysis to compare traditional rehabilitation strategies based on mill and overlay with FDR. CDOT is a leading state in the use of sustainable solutions such as FDR. FDR has been used in Colorado for more than a decade and CDOT has been the first DOT recommending state-specific ME input parameters for FDR design. The project aims at expanding CDOT efforts in sustainable pavement management by analyzing the long-term performance and costs of FDR projects and comparing them to traditional alternatives based on mill and overlay.

2 Methods and Materials

The objective of this research is to analyze the long-term performance and life-cycle costs related to FDR and compare this rehabilitation solution with traditional overlay methods used by CDOT.

2.1 Research Method

To achieve this objective, the research plan considered six tasks:

Task 1 – Kick-Off Meeting and Detailed Work Plan: The kickoff meeting of this project was held on August 25, 2021. The research team prepared a detailed work plan that incorporated the comments received in this meeting and was submitted to the Study Panel on September 3, 2021.

Task 2 – Data Collection: CDOT provided the research team with long-term performance data of sections rehabilitated with FDR and traditional mill and overlay. This information was extracted from CDOT's Pavement Management System (PMS). The research team also collected economic data related to construction and maintenance costs of both types of projects. From this data, we developed a representative scenario of the most common solutions used by CDOT.

Task 3 – Analysis of Long-Term Performance from PMS Data: Based on data from CDOT Pavement Management System, the research team analyzed the long-term performance of the different reference sections in terms of their roughness, cracking, and rutting. From this analysis, we derived conclusions about the long-term performance and maintenance needs of FDR and overlay sections.

Task 4 – Life-Cycle Cost and Sensitivity Analysis: The objective of this task was to perform a comparative life-cycle cost analysis of FDR and traditional solutions. To account for the uncertainties of this analysis, the study considered a probabilistic approach. A probabilistic life-cycle cost analysis includes a mean, variance, and probability distribution to characterize the variables influencing the evaluation, in contrast to a more simplistic deterministic approach that incorporates a single point value. A probabilistic approach enables to better characterize the problem by accounting for the uncertainties in costs, deterioration, and performance. The results from this probabilistic life-cycle cost analysis were explored further through a sensitivity analysis to identify the most influential variables in the problem.

Task 6 – Research Report and Presentation: At the conclusion of this project, the research team produced a final report and presentation summarizing project findings and recommendations.

2.2 *Experimental Materials*

This project analyzed two rehabilitation strategies: FDR and traditional overlays (the latter including both mill and overlays and levelling and overlays). For each of these alternatives, a set of reference sections were analyzed. The FDR sections were the analyzed in the previous research project on FDR strength (R 418-02), with the exemption of a site located in Wyoming for which we did not have updated performance data and was therefore excluded from this analysis. CDOT personnel provided the research team with comparable sections of roadways that were rehabilitated using milling or leveling and overlay. Table 1 and Table 2 summarize the basic characteristics of FDR and overlayed sections, respectively. Most of the FDR sites consist of non-stabilized FDR sections (also referred as "dry sections"). Only two sites (sites 5 and 6) are emulsion-stabilized FDR. Emulsion-stabilized FDR consists of adding emulsified asphalt or foamed (expanded) asphalt to the FDR mix to enhance their performance. In a previous study (Torres-Machi et al. 2020), we found that the emulsion-stabilized FDR layers are generally stiffer than dry sections. This can be expected to increase the structural capacity of emulsion-stabilized FDR pavements and reduce their deterioration, in comparison with non-stabilized FDR. This enhanced performance and the potential differences in the construction costs and maintenance needs of emulsion-stabilized FDR, however, is not evident in our data because of the limited number of cases in the analysis (only two sites are emulsion-stabilized) and the high variability of costs and performance metrics. The variability in the dataset is larger than the one observed when comparing non-stabilized and emulsion-stabilized FDR. Given this, both emulsion-stabilized and non-stabilized FDR sites will be analyzed as a group to characterize FDR rehabilitation.

Table 1. Basic characteristics of FDR sites

ID	Location	CDOT project	Region	Hwy	BMP	EMP	Type
FDR1	SH 83 El Paso County Line North	16028	1	083A	33.1	35.5	Non-stab.
FDR2	SH 83 El Paso County Line North	16028	1	083A	36.5	41.2	Non-stab.
FDR3	US 34: Estes Pk to Rky Mtn Pk	15141	4	034A	57.9	62.4	Non-stab.
FDR4	US 34: Eckley East & West	15146	4	034B	241	249.4	Non-stab.
FDR5	US 34: Eckley East & West	15146	4	034B	231	241.0	Emulsion
FDR6	US 160 East of Aztec Creek PH	17635	5	160A	11.5	18.0	Emulsion
FDR7	SH 96 Sheridan Lake East	18434	2	096D	193.7	200.0	Non-stab.

ID	Location	CDOT project	Region	Hwy	BMP	EMP	Type
FDR8	SH 145 - Dolores Northeast	16037	5	145A	12.6	16.2	Non-stab.
FDR9	SH-131 Choke Cherry Ln South	16189B	3	131B	58.3	61.5	Non-stab.
FDR10	US 50 Blue Creek West	17735	3	050A	117.6	121.7	Non-stab.

Table 2. Basic characteristics of overlay sites

ID	Location	CDOT project	Region	Hwy	BMP	EMP	Type
OL1	SH 83 El Paso County Line North	16028	1	083A	35.5	36.5	M & O
OL2	Antelope Creek - Castlewood	18380R	1	083A	30.6	33.2	L & O
OL3	Lincoln - Cottonwood	18262	1	083A	60.9	62.7	M & O
OL4	S. Peoria St to Jewell Cir	14624	1	083A	70.8	73.2	M & O
OL5	SH83: Jewell to Mississippi	18736	1	083A	73.1	74.5	M & O
OL6	SH 83(Leetsdale): Miss. To Colorado	21208	1	083A	74.5	77.3	M & O
OL7	East and West of Parshall	15030	3	040A	223.6	224.0	M & O
OL8	SH 34, from Taft Av. To Garfield Av.	16216	4	034A	90.9	91.8	M & O
OL9	SH 34	15618	4	034A	92.3	96.1	M & O
OL10	US 160 Towaoc to Cortez	18456	5	160A	27.6	29.7	O
OL11	SH 145 Cortez to Dolores River Bridge	19702	5	145A	0.0	1.4	M & O
OL12	SH 145 Cortez to Dolores River Bridge	19702	5	145A	1.4	9.2	L & O

Where, M refers to Mill; O refers to overlay; and L refers to level

The research team collected data related to the construction, maintenance, condition, usage, and weather of the roadway sections under analysis. This information was used to derive estimates of cost and long-term performance of FDR and overlay sites and conduct the life-cycle cost analysis. Results derived from these analyses are detailed in the different chapters of this report.

3 Report Organization

The report is organized as follows: Chapter 2 characterizes the FDR and overlay solutions, including their standard unit cost and maintenance needs. Chapter 3 analyzes and compares the long-term performance of FDR and overlay pavements. Chapter 4 includes the results of the life-cycle cost analysis. Finally, chapter 5 presents the overall conclusions and recommendations of this research.

Chapter 2. Costs and Maintenance of FDR and Overlay Sites

1 Introduction

This chapter summarizes the characteristics of FDR and overlay rehabilitation solutions in terms of their location and structure, and the critical inputs for the life-cycle cost analysis. Inputs for life-cycle cost analysis include: (1) initial costs of rehabilitation (i.e., FDR and overlays), (2) cost of maintenance treatments applied over the pavement life-cycle, (3) criteria to apply the maintenance treatment, and (4) impact of these activities on pavement condition. To determine these inputs, the research team was provided with data relating to the construction, maintenance, condition, usage, and weather of the roadway sections under analysis. Statistical analysis was used to determine representative characteristics of FDR and overlay projects, as well as input parameters for life-cycle cost analysis.

2 Characteristics of Overlay and FDR Projects

The sites in our analysis are evenly spread out across all the five CDOT regions (Figure 1).

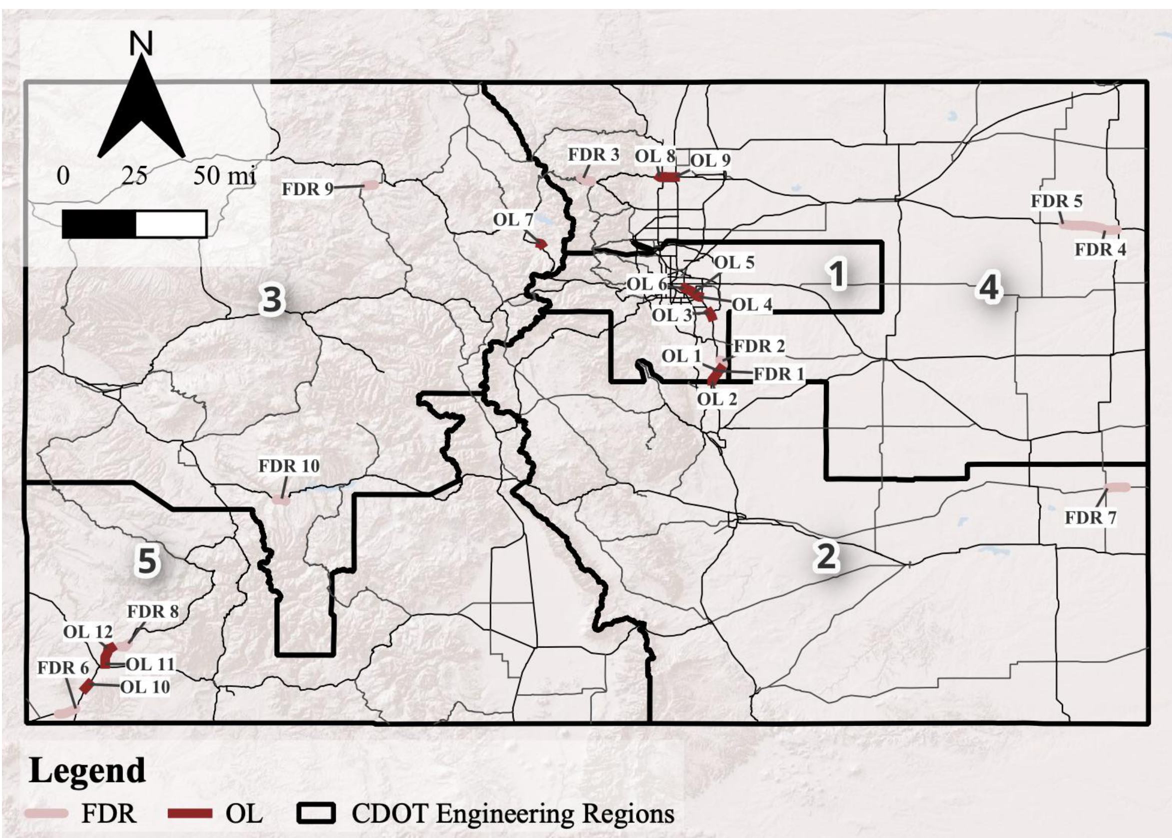


Figure 1: Site locations

Eight sites are located in region 1 (i.e., Denver metro/Central Colorado), one in region 2 (i.e., Southeast Colorado), three in region 3 (i.e., Northwest Colorado), five in region 4 (i.e., Northeast Colorado), and four in region 5 (i.e., Southwest/South Central Colorado). Many of the sites neighbor at least one other site, with the exclusions of FDR 3, 7, 9, 10, and OL 7. These sites have no close or neighboring roads with similar weather.

Typical FDR pavements are composed of 8 to 12 inches of Full-Depth Reclamation, followed by 4 to 5 inches of Hot-Mix Asphalt. Overlay roads generally consist of a 2 to 4 inch layer of Hot-Mix Asphalt that is added on top of the existing pavement (Figure 2).

Figure 2: Cross-sections of typical (a) FDR and (b) overlay sections

The sites under analysis were rehabilitated between 2005 and 2014. As of 2023, the average age for FDR roads is 14 years, whereas that for overlay roads is 12 years. Table 3 and Table 4 show more details on the ages of each of the sites and the type and thickness of the layers.

Table 3: Age, thicknesses, and layer type of FDR pavements

ID	Age [years in 2023]	HMA top depth [in]	HMA top layer type	HMA bottom depth [in]	HMA bottom layer type	FDR depth [in]
FDR 1	15	2	GR SX 75 (PG 64-28)	2	GR SX 75 (PG 64-22)	8
FDR 2	15	2	GR SX 75 (PG 64-28)	2	GR SX 75 (PG 64-22)	8
FDR 3	17	2	S 75 (PG 58-34)	2	S 75 (PG 58-34)	8
FDR 4	16	2	S75 (PG 64-28)	2	S 75 (PG 58-34)	8
FDR 5	16	2	S75 (PG 64-28)	2	S75 (PG 64-22)	8
FDR 6	12	2	GR SX 75 (PG 64-22)	2	GR SX 75 (PG 64-22)	10
FDR 7	11	2	SX75 (PG 64-28)	2	SX75 (PG 64-22)	12
FDR 8	16	2	SX 75 (PG 58-28)	3	SX 75 (PG 58-28)	10
FDR 9	15	2	SX 75 (PG 58-34)	3	SX 75 (PG 58-28)	8
FDR 10	9	2	SX75 (PG 64-28)	3	SX 75 (PG 58-28)	8

Table 4: Age, thicknesses, and layer type of OL pavements

ID	Age [years in 2023]	HMA top depth [in]	HMA top layer type	HMA bottom depth [in]	HMA top layer type	Mill depth [in]
OL 1	15	2.0	GR SX 75 (PG 64-28)	2.0	GR SX 75 (PG 64-22)	2.0
OL 2	11	1.5	GR SX 75 (PG 64-22)	1.5	GR SX 75 (PG 64-28)	0.0
OL 3	11	2.0	SMA 1/2 nom max size	2.0	GR SX 75 (PG 64-22)	4.0
OL 4	18	2.75	SX 100 (PG 76-28)			2.25
OL 5	10	2.5	SX 100 (PG 76-28)			2.0
OL 6	3	2.0	SMA Fiber Asphalt			2.0
OL 7	18	2.0	HBP Gr. SX 75			2.0
OL 8	16	2.0	GR SX 75 (PG 64-28)	1.0	GR SX 75 (PG 64-22)	3.0
OL 9	16	2.0	GR SX 75 (PG 64-28)	1.0	GR SX 75 (PG 64-22)	2.0
OL 10	10	2.0	GR SX 100 (PG 64-22)			
OL 11	9	2.0	SX 75 (PG 58-28)			2.0
OL 12	9	2.0	SX 75 (PG 58-28)			

3 Input Parameters for Life-Cycle Cost Analysis Related to Cost and Maintenance Needs

Input parameters related to cost and maintenance needs required for LCCA comprise: (1) initial costs of rehabilitation (i.e., FDR and overlays), (2) cost of maintenance treatments applied over the pavement life-cycle, (3) criteria to apply maintenance treatments, and (4) impact of these activities on pavement condition. A comprehensive life-cycle cost analysis considering the long-term performance of the pavements also require deterioration models, which are described in Chapter 3 of this report. The values recommended in this report were obtained from historical information derived from the sites analyzed in this study (i.e., 10 FDR pavements and 12 overlay projects), as well as recommendations from CDOT.

3.1 Initial Cost of Rehabilitation

For the initial rehabilitation, either FDR or overlay, the research team had information of the total final cost of the project and quantities take offs from as-builts. The unit cost of rehabilitation was estimated by adjusting the total cost by the area of the rehabilitation project. If the project included activities in other road segments (other than the rehabilitation project), the project cost was adjusted by length too. Also, to translate costs to present value, consumer price index values were collected from the Federal Reserve Bank database (U.S. Bureau of Labor Statistics 1947) and used to convert all prices to year 2021. The research team conducted statistical analyses to estimate an average rehabilitation costs per lane-mile, as well as metrics of variability (i.e., standard deviation). The average cost of FDR and overlays per lane-mile and the standard deviation of these costs are summarized in Table 5. Details of this estimate are included in the Appendix.

Table 5. Cost of FDR and overlay rehabilitation

Initial rehabilitation	Mean Cost ($/ln-mile)	Standard Deviation ($/ln-mile)
FDR	617,161	497,213
Overlay	337,778	206,182

3.2 Cost of Maintenance

For maintenance activities that occurred after the initial rehabilitation, the research team analyzed the maintenance records for each site and their associated cost. These data were categorized based on the type of maintenance activity performed and analyzed using statistical analysis to derive reference values of cost of maintenance.

Maintenance records include four different treatments: (1) pothole patching, (2) crack sealing, (3) seal coat, and (4) functional overlay. The first two maintenance treatments (i.e., pothole patching and crack sealing) are applied to both FDR and overlay sites. For the sections under analysis, seal coats have only been applied in FDR pavements. Similarly, functional overlays have exclusively been applied to overlay sites. The research team considered this historical practice to reflect the availability of maintenance treatments for FDR and overlay sites.

For each of these treatments, historical information was analyzed to define representative values of maintenance costs. In some instances (in particular, in the estimation of unit maintenance costs for seal coat and functional overlay), the unit costs obtained from the analysis of historical data resulted in unreasonable values. We hypothesize that these errors are a result of incorrect recordings of maintenance activities in the maintenance system because the recorded length in which these maintenance treatments were applied were often inconsistent with the section length. These errors resulted in unreasonable values of unit costs for maintenance. CDOT personnel provided guidance on unit costs for seal coat and functional overlay obtained from CDOT's management system. Table 6 and Table 7 summarizes average costs values, as well as the values of standard deviation, for maintenance treatments applied to FDR and overlay sites, respectively. When looking at these costs, it is important to note that, since the values of unit costs for seal coat and functional overlay were obtained from CDOT's management system (and not historical data), the number of data points used for this estimation is Not Available (NA). The standard deviation considered for these costs was estimated as the average percentage of standard deviation found in construction costs (i.e., 0.71).

Table 6. Cost of maintenance treatments for FDR sites

Treatment	Mean Cost	Standard Deviation	N (# data points)
Pothole patching	17 $/ln-mile/year	24 $/ln-mile/year	9
Crack seal	2,000 $/ln-mile	3,300 $/ln-mile	3
Seal coat	85,254 $/ln-mile	60,362 $/ln-mile	NA

Table 7. Cost of maintenance treatments for overlay sites

Treatment	Mean Cost	Standard Deviation	N (# data points)
Pothole patching	115 $/ln-mile/year	208 $/ln-mile/year	15
Crack seal	3,100 $/ln-mile	1,900 $/ln-mile	3
Functional overlay	256,256 $/ln-mile	181,436 $/ln-mile	NA

On both FDR and overlay sites, the unit cost of pothole patching is very low. Additionally, on sites that received this type of maintenance, there were instances of patching occurring nearly every year, for small segments of the site. For these reasons, it seems reasonable to assume a fixed annual cost for pothole patching. This value was obtained from average historical values. On FDR sites, pothole patching costs approximately $17/lane-mile/year. On overlay sites, the cost is estimated as $115/lane-mile/year.

For the remaining maintenance alternatives, average values were estimated per lane-mile. It is important to note that, for some of these treatments, the number of occurrences were particularly low (e.g., only three occurrences of crack seal on both FDR and overlay sites). This situation led to high variability in the average cost values and, consequently, high values of standard deviation. Because of this, the research team decided to perform a probabilistic life-cycle analysis that would account for this uncertainty.

3.3 Criteria to Apply Maintenance

To conduct an accurate life-cycle cost analysis for a roadway, it is vital that the maintenance activities assumed in the analysis are representative of the actions completed by the Department of Transportation overseeing it. This is typically done through the use of a maintenance tree, which is a decision-making matrix that determines the maintenance treatments to apply based on several variables including pavement condition or age. For this analysis, we were unable to locate a maintenance tree, and therefore used our database to deduce a de facto maintenance strategy that is representative of the practices CDOT uses on its roadways.

Our first goal of this analysis was to determine if any of the metrics of pavement condition (i.e., IRI, rutting, cracking) could be used as appropriate triggers of maintenance. However, using traditional statistical analysis and random forest methods, there was no clear trend between pavement distress values and application of maintenance. As a result, we turned our focus on analyzing maintenance strategies under a time-based criterion.

For this analysis, the research team filtered the maintenance activity history and limited the analysis to projects with a length greater than 0.25 miles and an associated cost of greater than $1,000. While there were several sites that did not receive significant maintenance since its initial construction, on the sites that received maintenance, there were consistent trends on which treatment was applied and when. This sample size is very small, but based on these significant maintenance histories, we determined that treatment should be applied in the life-cycle costs analysis based on age of the pavement.

Historical data of pavement maintenance was used to define the criteria triggering maintenance treatments. Our analysis found that pothole patching is a recurring maintenance strategy that occurs on an annual basis. Below are the estimates of maintenance application for the rest of maintenance treatments, with year 0 representing the year of initial rehabilitation.

Table 8. Criteria used to apply maintenance treatments in FDR sites

Treatment	Application criteria
Pothole patching	Annual
Seal coat	Year 5
Crack seal	Year 8

Table 9. Criteria used to apply maintenance treatments in overlay sites

Treatment	Application criteria
Pothole patching	Annual
Crack seal	Year 3
Functional overlay	Year 5 and 10

3.4 Impact of Maintenance on Condition

For rehabilitation projects, the goal of this analysis is to determine an initial level of distresses immediately following rehabilitation. This was done through dividing the condition dataset based on year of data collection. We assumed that the lowest value for each distress between the year of rehabilitation and the year following rehabilitation was representative of initial condition. This is because there is not a precise date provided with the condition data, so therefore it is not possible to know whether the pavement condition was measured before or after rehabilitation for data points labeled with the year of construction. We use the mean value of the distress for each rehabilitation activity as our baseline for initial condition.

Table 10 shows the average distress values after applying the initial rehabilitation (i.e., FDR and overlay). Values summarized in Table 10 correspond to mean values of distress measurements, with variability expressed in terms of one standard deviation. The standard deviation of initial value of cracking is somewhat high, particularly in fatigue cracking. Given this high variability, it is recommended to include a probabilistic approach in the life-cycle cost analysis.

Table 10. Impact of rehabilitation on condition – Mean values and standard deviation

Treatment	IRI [in/mile]	Rutting [in]	Trans. cracking [count]	Long. cracking [count]	Fatigue cracking [ft^2]
FDR	58 ± 10	0.1 ± 0.0	0 ± 5	0 ± 15	0 ± 448
Overlay	83 ± 20	0.1 ± 0.0	0 ± 3	0 ± 15	0 ± 15

For intermediate maintenance activities, we calculated the mean value for distresses as a percent decrease from the year prior to the activity taking place to immediately following maintenance. In this analysis, the research team considered the treatment activity and its expected impact on distresses. For example, since crack sealing consists of the application of material into open cracks (Caltrans n.d.), its application should primarily result in reduction of fatigue cracking. Chip seals, on the other hand, is an application of a thin asphalt layer which can may increase roughness (Zimmerman and Peshkin 2004), and can lead to slight reductions in cracking and rutting. Based on this, historical condition data was used to determine the actual improvement of condition associated with the maintenance activity, given the assumption that crack seal may impact fatigue cracking and roughness, and chip seal may impact all three distresses.

The mean impact of each activity was determined to be best represented as a percentage reduction in roughness, rutting, or cracking. Based on our analysis, pothole patching did not result in an observable change in pavement condition. Table 11 and Table 12 show the observed change in distress measurement associated with the application of maintenance treatments on FDR and overlay sites, respectively. Values represent average improvements, with variability expressed as one standard deviation. It should be noted that many of the percent impacts on condition have high variability, some of which are greater than the average improvement in condition. Given this high variability, the research team recommends including a probabilistic approach in the life-cycle cost analysis, in order to account for this variability in the final results.

Table 11. Impact of maintenance on FDR sites expressed as % change from previous year – Mean values and standard deviation

Treatment	ΔIRI	ΔRutting	ΔTransv. Cracking	ΔLong. Cracking	ΔFatigue Cracking
Crack seal	-3% ± 5%	-	-9% ± 10%	-11% ± 23%	-73% ± 26%
Seal coat	+14% ± 8%	-26% ± 28%	-	-14% ± 19%	-27% ± 19%

Table 12. Impact of maintenance on overlay sites expressed as % change from previous year – Mean values and standard deviation

Treatment	ΔIRI	ΔRutting	ΔTransv. Cracking	ΔLong. Cracking	ΔFatigue Cracking
Crack seal	-3% ± 5%	-	-9% ± 10%	-11% ± 23%	-51% ± 32%
Functional overlay	-15% ± 5%	-26% ± 26%	-2% ± 2%	-15% ± 15%	-34% ± 34%

4 Conclusions

This chapter summarizes the recommended input parameters for the life cycle cost analysis as it relates to: (1) initial costs of rehabilitation (i.e., FDR and overlays), (2) cost of maintenance treatments applied over the pavement life-cycle, (3) criteria to apply maintenance treatments, and (4) impact of these activities on pavement condition.

The values recommended in this report were obtained from historical information derived from 10 FDR pavements and 12 overlay projects. Recommended parameters correspond to average historical values. To account for the variability in the dataset, reference values include metrics of standard deviation. The proposed parameters show, in general, high variability. To account for this variability, the research team recommends performing a probabilistic approach in the life-cycle cost analysis.

Chapter 3. Long-Term Performance of FDR and Overlay

1 Introduction

To select the most appropriate pavement design or rehabilitation for a given situation, it is necessary to understand how the pavement properties and in-service conditions relate to performance and life cycle cost (Tighe 2001). Based on data from CDOT Pavement Management System, we analyzed the long-term performance of the FDR and overlay sections in terms of their roughness, cracking, and rutting. Our analysis found that IRI was the most reliable metric to compare condition because its continuous nature and the higher accuracy of the measurement process. Other metrics of condition were explored (e.g., rutting and cracking) but they were discarded from the analysis because the measurements were inconsistent to reflect deterioration.

2 Methods

This section discusses our data cleaning/screening procedures and provides background on probabilistic models for pavement deterioration. We start our analysis by pre-processing the raw performance data obtained from CDOT's pavement management system and performing exploratory analyses of this data. The data used in this study consists of measured international roughness index (IRI) at various overlay (OL) and full depth reclamation (FDR) pavement rehabilitation projects between 2008 and 2021. For purposes of this work, we organize the data into "sites" and "segments". A project site includes a range of mileposts on a given highway. Within each site pavement condition is measured every tenth of a mile, referred to as segments. For example, site FDR 2 contains the segments 36.5 to 36.6, 36.6 to 36.7, all the way up to 41.1 to 42.2.

The performance of FDR and overlay sites was then compared using three classes of comparison. This analysis is aimed at evaluating whether the deterioration of FDR is substantially different to overlay sites.

These analyses were used to define a deterioration model characterizing the deterioration of both FDR and overlay pavements for long-term and life-cycle cost analyses.

2.1 Data Pre-processing and Exploratory Analyses

There are several factors that require us to clean the raw data prior to subsequent analyses.

First, the IRI is not always measured in the same direction every year. Approximately 10% of the data was recorded in the direction of decreasing milepost values and were discarded from the analysis. This resulted in some segments missing a one or two years worth of data. In these cases, the missing value was linearly interpolated between the previous and next years values. In other cases, this resulted in some segments only having one data point or large gaps between recorded conditions. These were discarded from subsequent analyses.

Second, in the raw data some sites show a large decrease in IRI from age 0 to age 1 which would theoretically correspond to a large improvement in condition. An example is show in Figure 3. In these cases, we assumed that the first IRI measurement was made before the rehabilitation was completed. To remedy this, we removed the first data point and re-indexed the age accordingly.

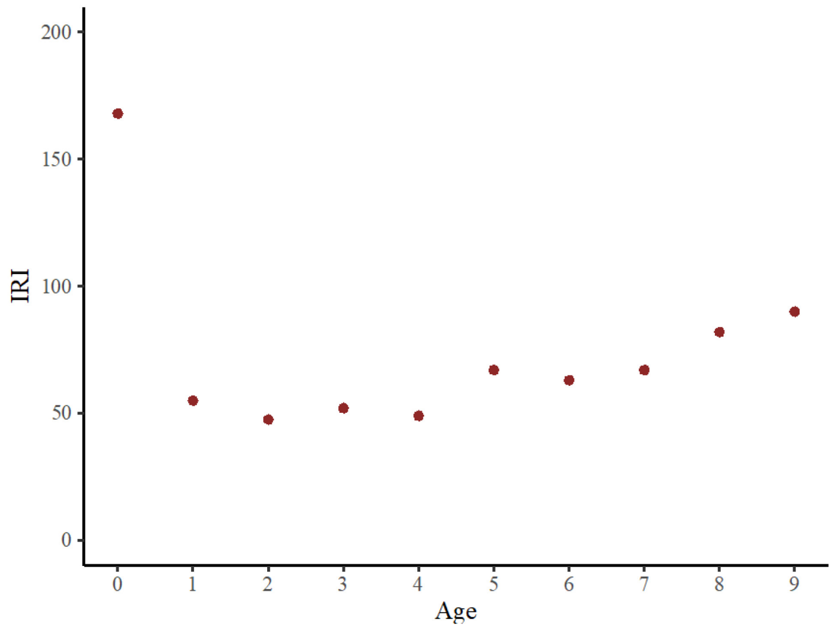


Figure 3. An example segment (site OL2, MP 33-33.1) where the first year of condition data was apparently recorded prior to rehabilitation

Third, some segments show unrealistic year-to-year changes in IRI. A sample of these is shown in Figure 4. These segments were discarded from subsequent analyses.

Finally, the IRI is not always recorded between the stated beginning and end mileposts for each site every year. For example, FDR 1 has a designated BMP of 33.1 but the recorded data actually begins at MP 33.6.

After the exclusion criteria are applied, the dataset for analysis includes pavements in 5 CDOT regions, 21 sites, 740 unique segments, and a total of 8,396 data points.

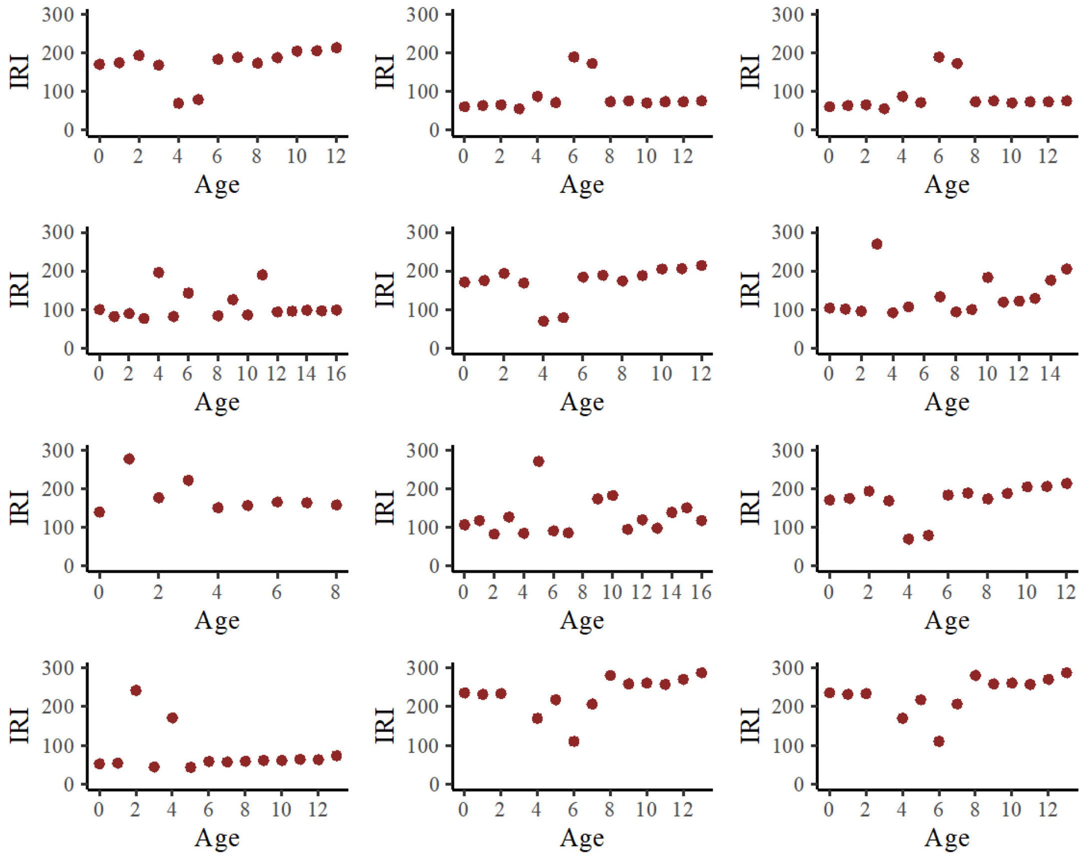


Figure 4. Segments with outlier incremental changes in IRI

2.2 *Comparison of Different Pavement Distress Metrics*

The complete dataset contains several alternative distress metrics to IRI, such as fatigue cracking (FC), transverse cracking (TC), and rutting depth (RD). We processed the alternative metric data using the same pre-processing criteria as IRI, with a slight modification to adjust the threshold for outlier incremental changes to account for different scales of measurement in the different metrics. We then compared the results of the exploratory analyses on each different metric to analyze which is the most reliable for tracking pavement condition (in the context of this dataset).

2.3 Criteria for Comparison of FDR and Overlay Sites

An overarching goal of this research is to address the question: "Is the performance of FDR sites substantially different than that of overlay sites?". Many different factors will affect the deterioration trajectory of a given road segment including the initial condition (at age 0), thickness and properties of surface course, base course, and subgrade materials, traffic, weather, and maintenance activities. To provide a fair comparison between rehabilitation strategies sites, we would ideally identify FDR and overlay sites that are matched on all of the above or develop deterioration models that explicitly adjust for the differences. The number of sites available to perform this analysis, however, is limited and make these approaches impractical. Instead, we pair sites based on a simpler proximity-based criteria that attempts to adjust for as much of the potential differences as possible. This results in three "classes" of comparison (ranked from better to worse matching) as follows:

- Class A: Adjacent sites on the same highway. Class A comparisons will have the same traffic and weather conditions (at the resolution of available data) and potentially differ only in their pavement sections and subgrade material, age 0 conditions, and maintenance activity.
- Class B: Non-adjacent sites on the same highway. Class B comparisons can still be matched on weather conditions by ensuring they are not located too far apart but will generally have different traffic.
- Class C: Sites on different highways of the same function classification within the same engineering region. Class C comparisons will have different traffic and weather conditions. However, by restricting Class C comparisons to stay within the same engineering region and functional classification, the traffic and weather conditions should at least be qualitatively similar.

Table 13 summarizes the cases of FDR and OL sites selected for pairwise comparison.

Table 13. Comparative cases of FDR and overlay long-term performance

Case	FDR Site	OL Site	Class	Comments
1	FDR 2	OL 1	A	-
2	FDR 1	OL 2	A	-
3	FDR 6	OL 10	B	Overlay site has higher traffic
4	FDR 8	OL 12	B	Similar but not equal traffic and weather
5	FDR 10	OL 7	C	Overlay traffic is higher

2.4 Deterioration Modeling of FDR and Overlay Sites

In the most general setting, a probabilistic model for the deterioration of pavement condition take the form of a stochastic process (collection of random variables):

$$\{IRI_t\}_{t\geq 0}$$

where IRI_t is the pavement condition at age t, measured at discrete ages $t = 0,1,2,\ldots$. These can be thought of as models for random functions in the sense that the (uncountable) sample space Ω

represents the possible curves of pavement deterioration in which each outcome $X(\omega)$ represents a possible sample path of deterioration and the distribution of the random variable IRI_t is the aggregation of the specific value of each possible path as they pass through a fixed time point t, as illustrated in Figure 5.

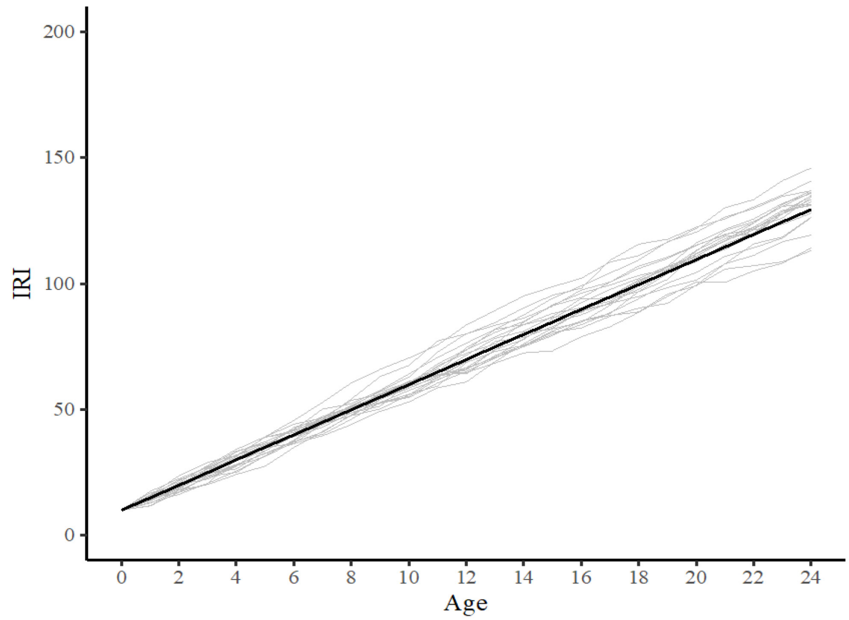


Figure 5. An example of a stochastic process model for pavement deterioration. The light gray lines illustrate possible trajectories of pavement deterioration, the solid back line indicates the overall mean trend

A homogeneous first-order Markov model, such as the one proposed in Osorio-Lird et al (2018) relaxes the conditional independence assumption to only require that the conditional distribution:

$$IRI_t | IRI_{t-1}, IRI_{t-2}, \dots, IRI_0$$

depends only on the previous value IRI_{t-1} for all ages t. That is, the process has "memory" of the previous year's condition and the length of this "memory" is increased for order Markov models. Technically, this does not mean that the condition at time t does not depend on the all the previous values – rather it means that the information conveyed by the the condition at times $t = 0,1, \dots, n-2$ is entirely contained by the condition at time $t = n-1$. The most basic Markov model typically deployed is the incremental deterioration model:

$$IRI_t | IRI_{t-1} \sim \text{Normal}(IRI_{t-1} + \alpha, \sigma)$$

where α is the average deterioration rate and σ quantifies the volatility of the deterioration process.

This incremental deterioration model could also include covariates like weather, traffic, and maintenance activities in the year prior. Higher order Markov models include data from more than the previous year (i.e., longer "memory") and can also incorporate more complicated functions for the predicted mean than the simple incremental model shown. In this project, we explored more advanced models aimed at capturing the multiple factors impacting deterioration but found that, given the high variability in the data and the limited number of cases for analysis, the added complexity of these models did not result in significantly higher prediction accuracies. Based on these results, the deterioration model we propose for this project is a first order Markov model that will estimate a single α and σ shared between all the segments. This approach significantly reduces the complexity of the inferential task at the cost of suppressing segment-to-segment variability. This simplification does not seem overly simplistic in our project because the preliminary analyses of pavement deterioration did not find significant differences in segment-to-segment variability.

Parameters for Markov models are typically estimated by least squares (or summary statistics), maximum likelihood, or Bayesian procedures. In this study we adopt a Bayesian approach because of its natural handling of both aleatory (model) and epistemic (parameter) uncertainty. Thorough introductions to Bayesian statistics can be found in Gelman et al. (2013), Kruschke (2014), or Robert (2007). Briefly, the Bayesian approach seeks to answer the question: "Given the data we observed, what values of the parameters were likely to have caused it?". Formally, this is addressed through Bayes theorem:

$$p(\theta|y) = \frac{p(\theta)p(y|\theta)}{p(y)}$$

Where y is observed data and θ is the unknown model parameters. Note that the densities $p(.)$ can be (and usually are) multidimensional, here we use vector notation for brevity. The individual components of this formulation are:

- $p(\theta|y)$ is called the posterior distribution and directly answers our posed question.
- $p(y|\theta)$ is called the data or sampling model and expresses the probability of observing different data given fixed parameters.
- $p(\theta)$ is called the prior distribution which encodes our domain expertise about the problem. Mathematically, this serves to "smooth" or "regularize" the likelihood. Commonly, the parameters are assumed independent and the prior is assembled component by component.

Once we obtain the posterior distribution, $p(\theta|y)$, we make predictions for new data (y^{est}) by averaging over the parameter uncertainty to obtain the posterior predictive distribution:

$$p(y^{est}|y) = \int p(y^{est}|\theta)p(\theta|y)d\theta$$

In a similar manner, we can also "predict" data points we have already observed (typically denoted y^{rep} instead of y^{est} to examine how well our proposed models fit.

For a Bayesian analysis, the model parameters (in our case, α and σ) require prior distributions. Throughout this work, we will generally use weakly informative priors that convey some information regarding the expected scale of the model parameters without overly influencing the estimates.

Based on these considerations, the proposed deterioration model is considered in this study is:

$$IRI_{i,t+1}|IRI_{i,t} \sim \text{Normal}\ (\alpha + IRI_{i,t}, \sigma)$$

Where $IRI_{i,t}$ is the pavement condition at age t in segment i. The model parameters are given weakly informative prior distributions shown below. Here, the exponential distribution is parametrized by its rate parameter so 0.1 gives a prior mean of 10.

$$\alpha \sim \text{Normal}\ (0\ , 5)$$

$$\sigma \sim \text{Exponential}(0.1)$$

3 Results

3.1 Exploratory Analyses

Figure 6 shows the overall distribution in year-to-year changes in the segments considered and Figure 7 shows the pavement condition trends for 12 randomly sampled segments.

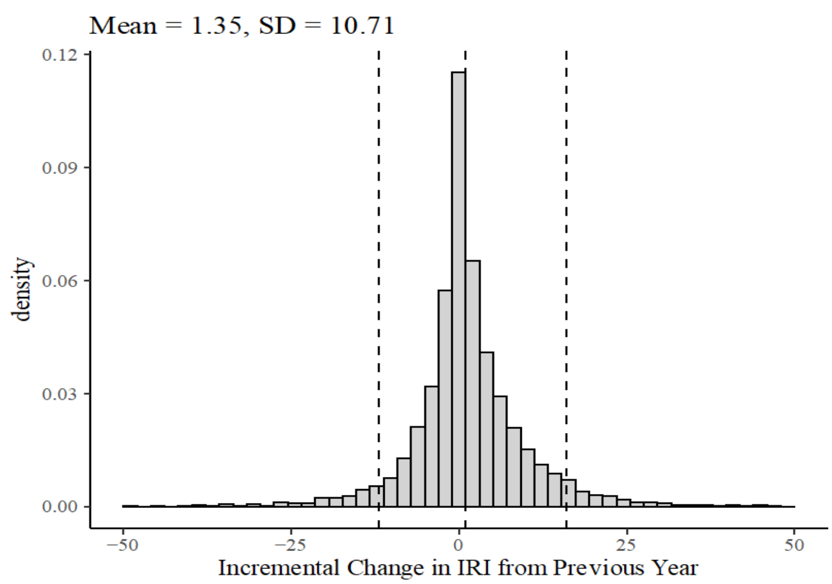


Figure 6. The overall distribution of year-to-year change in IRI. The dashed lines are 5%, 50% (median), and 95% quantiles of the data.

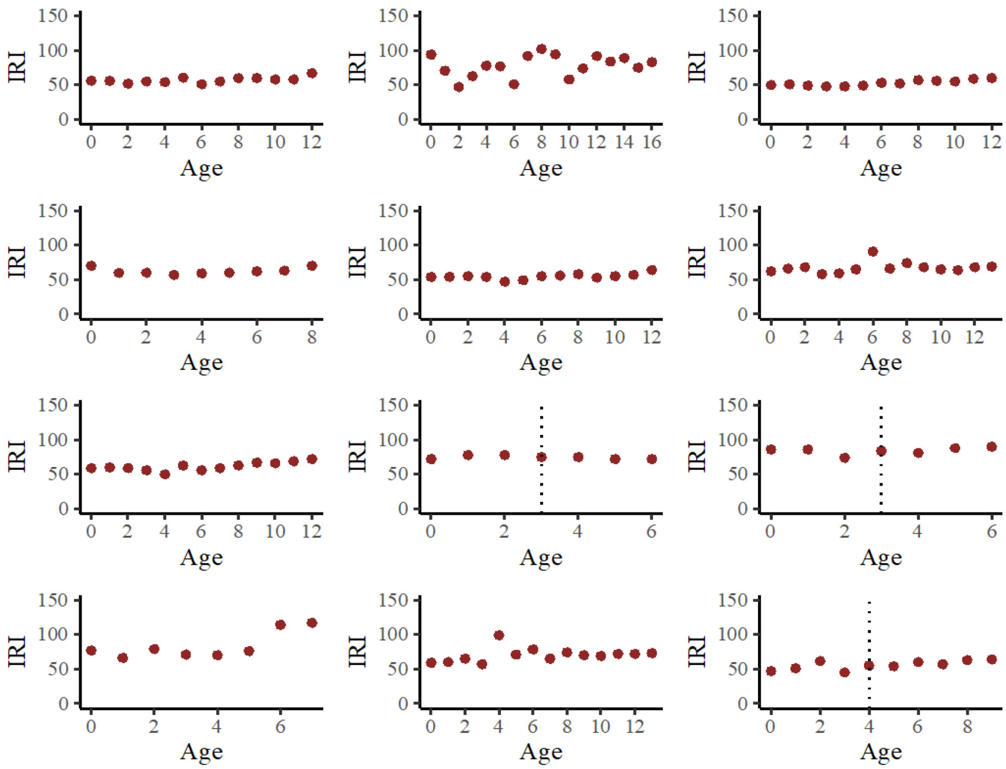


Figure 7. A qualitative summary of IRI deterioration trends for 12 randomly sampled segments. The dotted lines indicate years that maintenance was recorded

These examples illustrate several important qualitative trends present in the data, namely:

- A clear deterioration trend is often not present. For some segments, particularly those with less data, the condition is relatively uniform from year to year.
- The data can be very noisy, sometimes showing apparent decreases in IRI year-to-year
- Maintenance does not consistently appear to improve pavement condition.

We now discuss these three trends and hypothesize why they could be occurring.

First, the measurement of IRI could be biased high or low by temporary environmental conditions like temperature even if the IRI measurements are made without error. Because it is difficult (or impossible) to control the environment when taking the measurements, this could manifest as temporary year-over-year improvements. To illustrate, a concrete pavement may be subject to thermal expansion on a hot day, potentially leading to deformation and heaving and a temporary reduction in ride quality. If the IRI was measured on a hot day one year and a colder day the next an apparent improvement would be present in the raw data even if the true condition did not change substantially.

Secondly, sources of measurement error or "noise" in the IRI measurements may be obscuring a clear deterioration trend, as simulated in Figure 8. This can also be exacerbated if, like in the simulated example, the rate of deterioration starts small and increases over time but we only have data for limited age range.

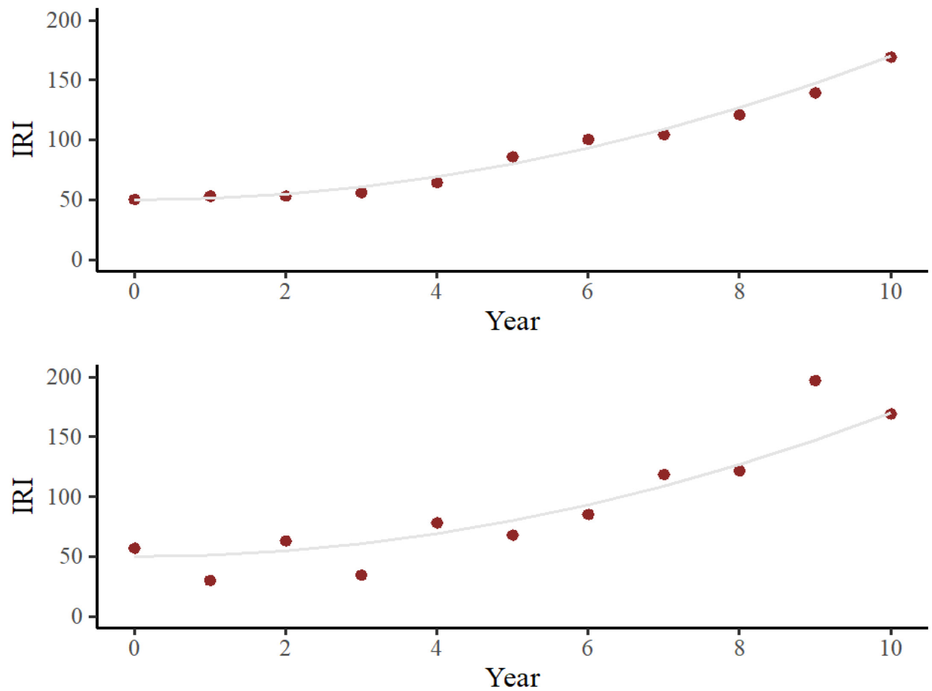


Figure 8. Simulated IRI data for a low (above) and high (below) measurement variability. In this conceptual example, the true trend (shown in light gray) is given by $IRI = 0.5 * t^2 + 50$. The trend is much more reliably identified in the low measurement variability case, as would be expected

The potential measurement variability will be bounded below by the precision of the profiling device and data acquisition system. However, it will also be influenced (possibly quite substantially) by the speed of the measurement vehicle, the path driven by the measurement vehicle, and the processing steps used to geospatially locate the measurements and join them with the dataset. In essence, these factors relate to how confident we can be that the exact same longitudinal profile is being measured each year with the same procedure. These will depend on the how strict test procedures required by the agency are and the quality assurance program used to ensure consultants are meeting the requirements. Any year-to-year changes to the actual test procedures performed because of uncontrollable environmental factors like weather traffic, operator errors, or simply changing the consultant/equipment used to run the test will also result in increased measurement variability.

Thirdly, maintenance activities should theoretically account for the unrealistic improvements in pavement condition. However, observing this effect is limited by how reliably maintenance is recorded. To illustrate, across the all the sites included in the model development only 206 maintenance activities are recorded over a 16 year period. This suggests that there may be maintenance activities that are performed but not recorded. Additionally, if we look at the incremental change observed in years where maintenance is recorded a clear improvement from the previous year is not reliably identified.

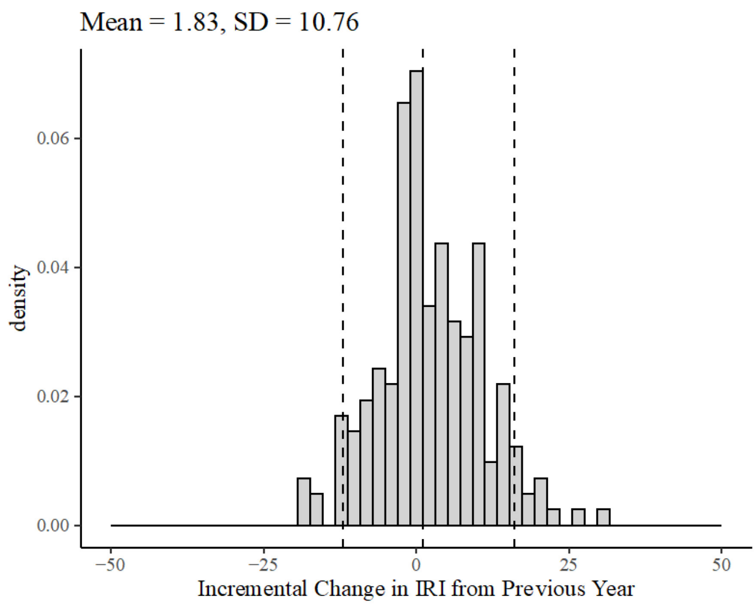


Figure 9. The distribution of year-to-year change in IRI in years with recorded maintenance. The dashed lines are 5%, 50% (median), and 95% quantiles of the data.

This suggests several possible explanations. First, the maintenance performed may not actually impact the IRI measurements. For example, if pothole patching or crack sealing is recorded but the treated regions do not lie within the path of the longitudinal profile measurements, the measured IRI will not be affected. Second, the IRI measurements may not be consistently taken after the maintenance is performed. This would result in the improvement actually showing up in the *next* years measurements. Finally, the maintenance activities may be inaccurately located. For example, maintenance may be recorded between a beginning and end mile posts, but the actual portion of roadway treated may be a smaller subset of that range.

Finally, factors such as soil/pavement material properties, weather, and traffic will affect the acceleration or de-acceleration of deterioration curves but in theory should not prevent identification of overall trends as long as IRI can be measured precisely. However, if pavement condition is only measured over a relatively small-time interval, a changing deterioration rate may be difficult to distinguish from noise.

Ultimately, these are merely plausible post-hoc explanations and further research is required to quantify if they truly are the cause of observed trends in the data and if so, how much of an impact they actually have.

3.2 Comparison of Different Pavement Distress Metrics

The figures below show the pavement condition trajectories for the same 12 randomly sampled segments summarized in Figure 4 but considering now different distress metrics different than IRI, in particular, fatigue cracking (Figure 10), transversal cracking (Figure 11), and rutting depth (Figure 12).

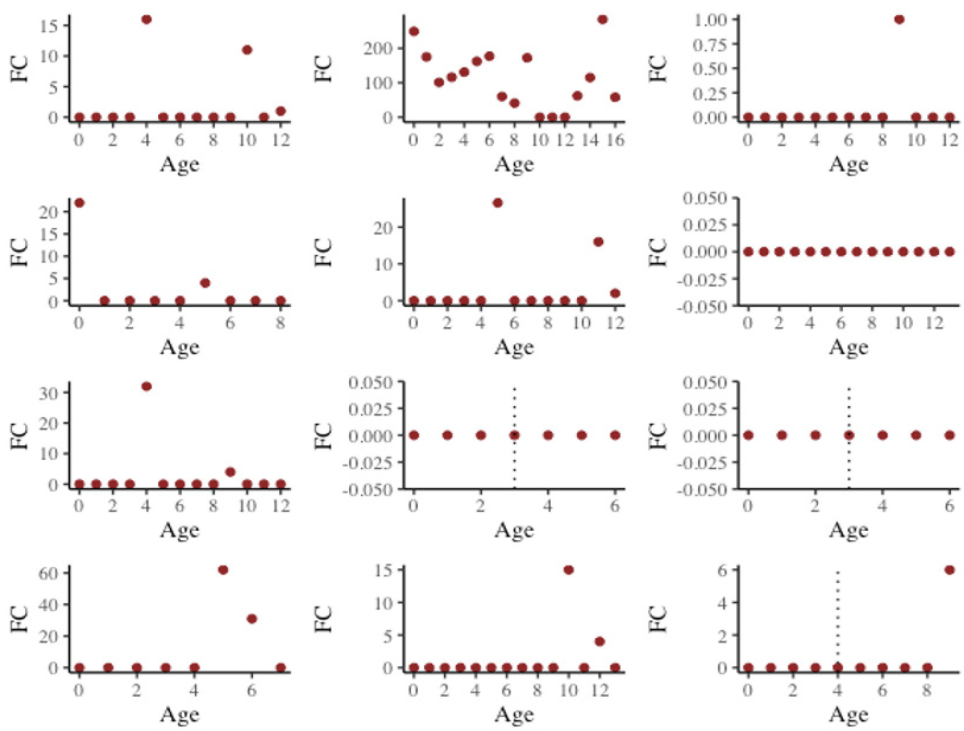


Figure 10. A qualitative summary of fatigue cracking (FC) deterioration trends for 12 randomly sampled segments. The dotted lines indicate years that maintenance was recorded

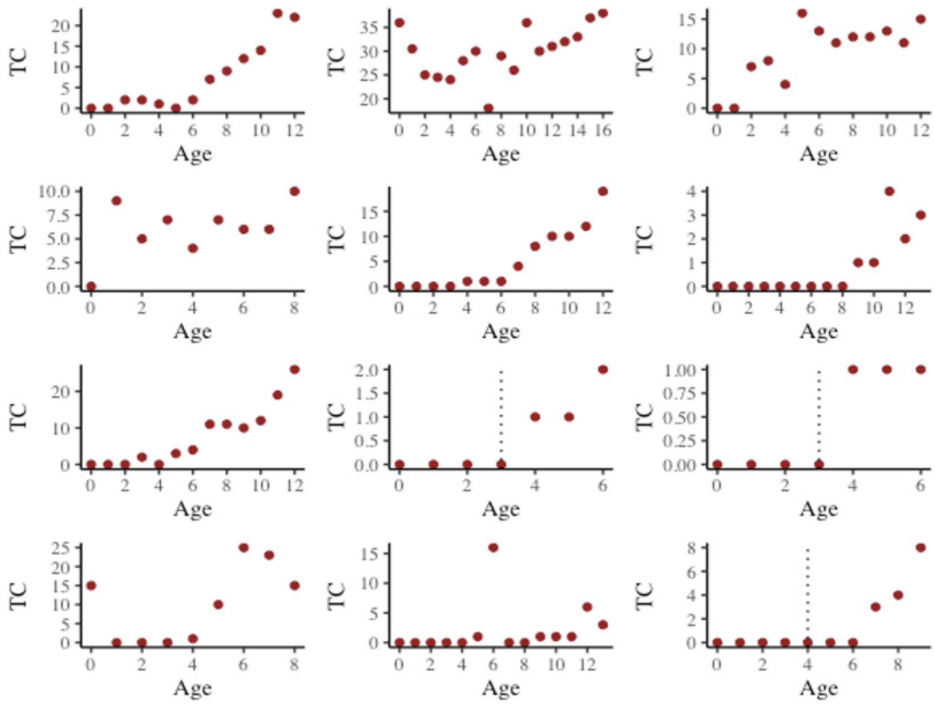


Figure 11. A qualitative summary of transversal cracking (TC) deterioration trends for 12 randomly sampled segments. The dotted lines indicate years that maintenance was recorded

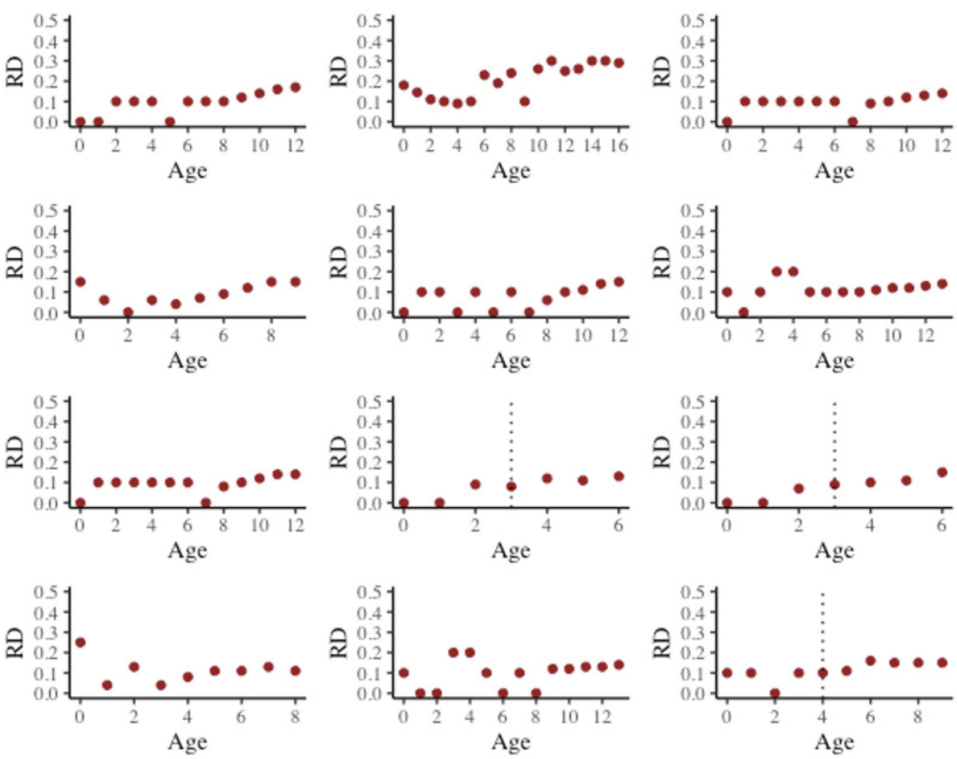


Figure 12. A qualitative summary of rutting depth (RD) deterioration trends for 12 randomly sampled segments. The dotted lines indicate years that maintenance was recorded

In general, IRI appears to be the most reliable metric followed by RD then FC or TC, with the final two being of similar quality. FC and TC have many years with an implausible 0 value. The years that do have recorded data show vary little change in condition and a clear deterioration trend is not generally observed compared to the other metrics. RD does show somewhat of a deterioration trend but is generally limited by the small range of the observed values. The RD observations also appear to show a change in measurement resolution, with earlier ages only observed in increments of 0.1 inch and later ages observed in a more continuous fashion.

These qualitative comparisons of the reliability of different pavement distress metrics are further supported by analyzing the aggregated year-over-year changes for each, shown in Figure 13, Figure 14, and Figure 15 for fatigue cracking, transversal cracking, and rutting depth, respectively. When comparing these figures with the year-to-year change observed in IRI (Figure 6), these results suggest that IRI shows a more reasonable distribution characterizing deterioration than other metrics. It is important to note that rutting depth showed a reasonable deterioration trend in the qualitative summary (Figure 12) but the distribution of year-to-year change (Figure 15) shows unreasonable improvements that are also influenced by the limited sensitivity of rutting measurements (i.e., in 0.1 in increments).

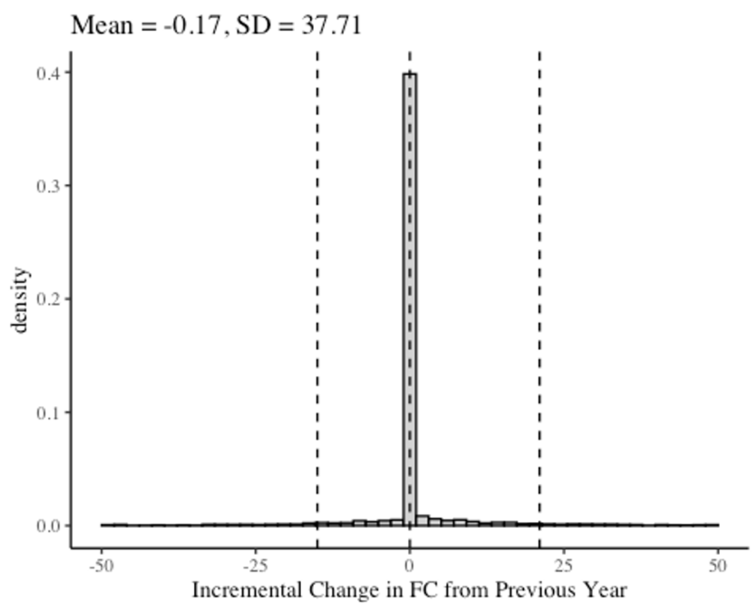


Figure 13. The overall distribution of year-to-year change in fatigue cracking (FC). The dashed lines are 5%, 50% (median), and 95% quantiles of the data.

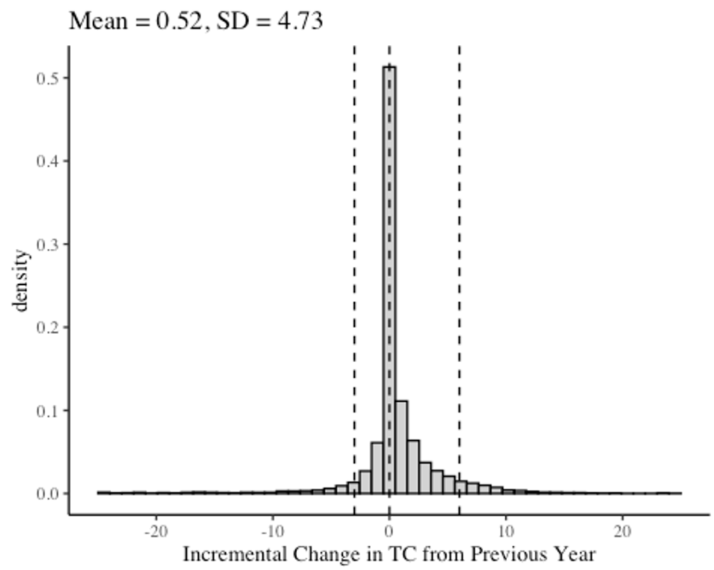


Figure 14. The overall distribution of year-to-year change in transversal cracking (TC). The dashed lines are 5%, 50% (median), and 95% quantiles of the data.

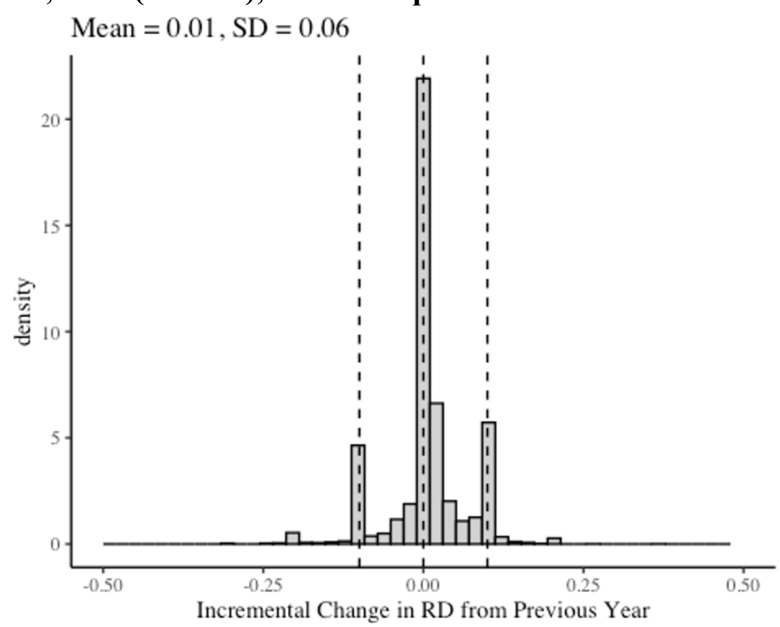
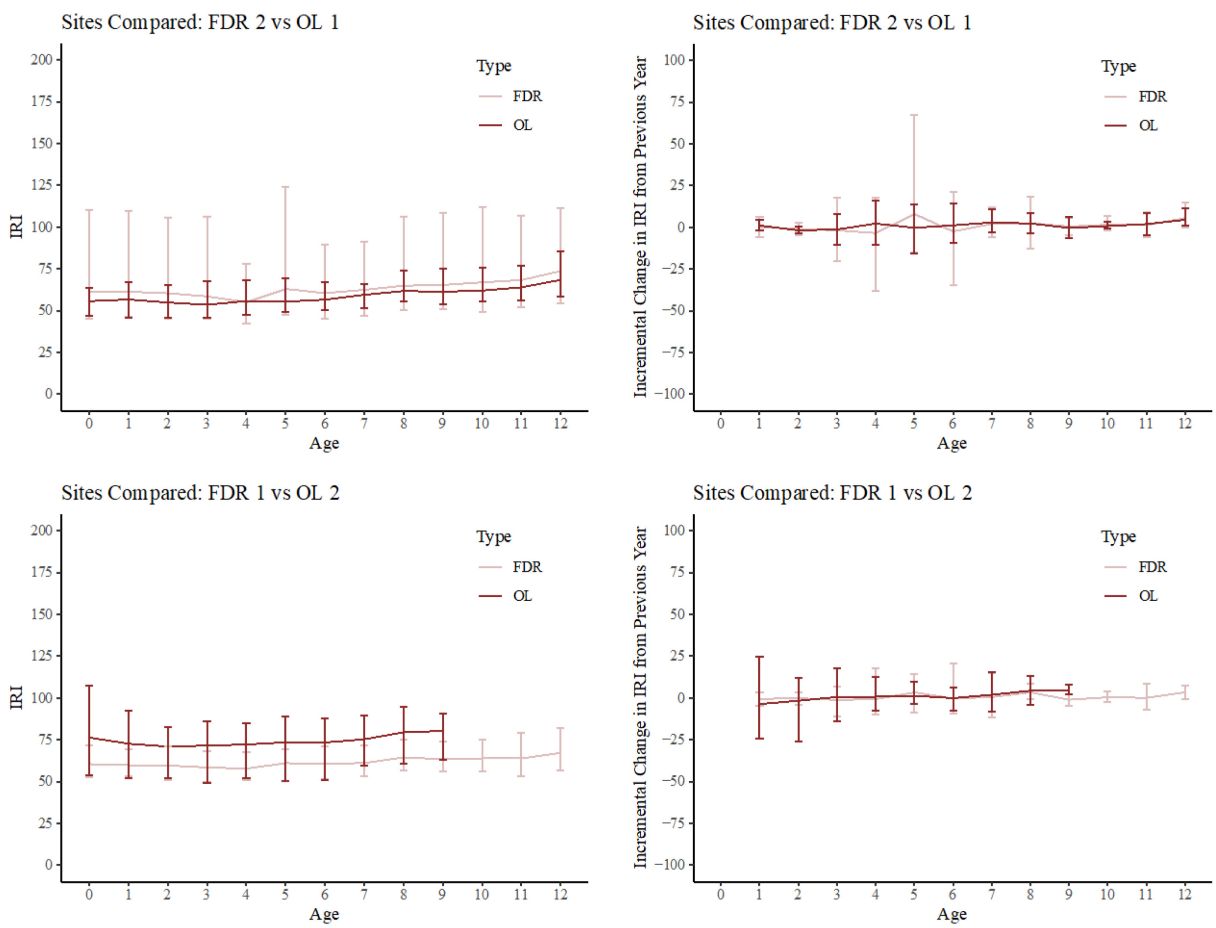


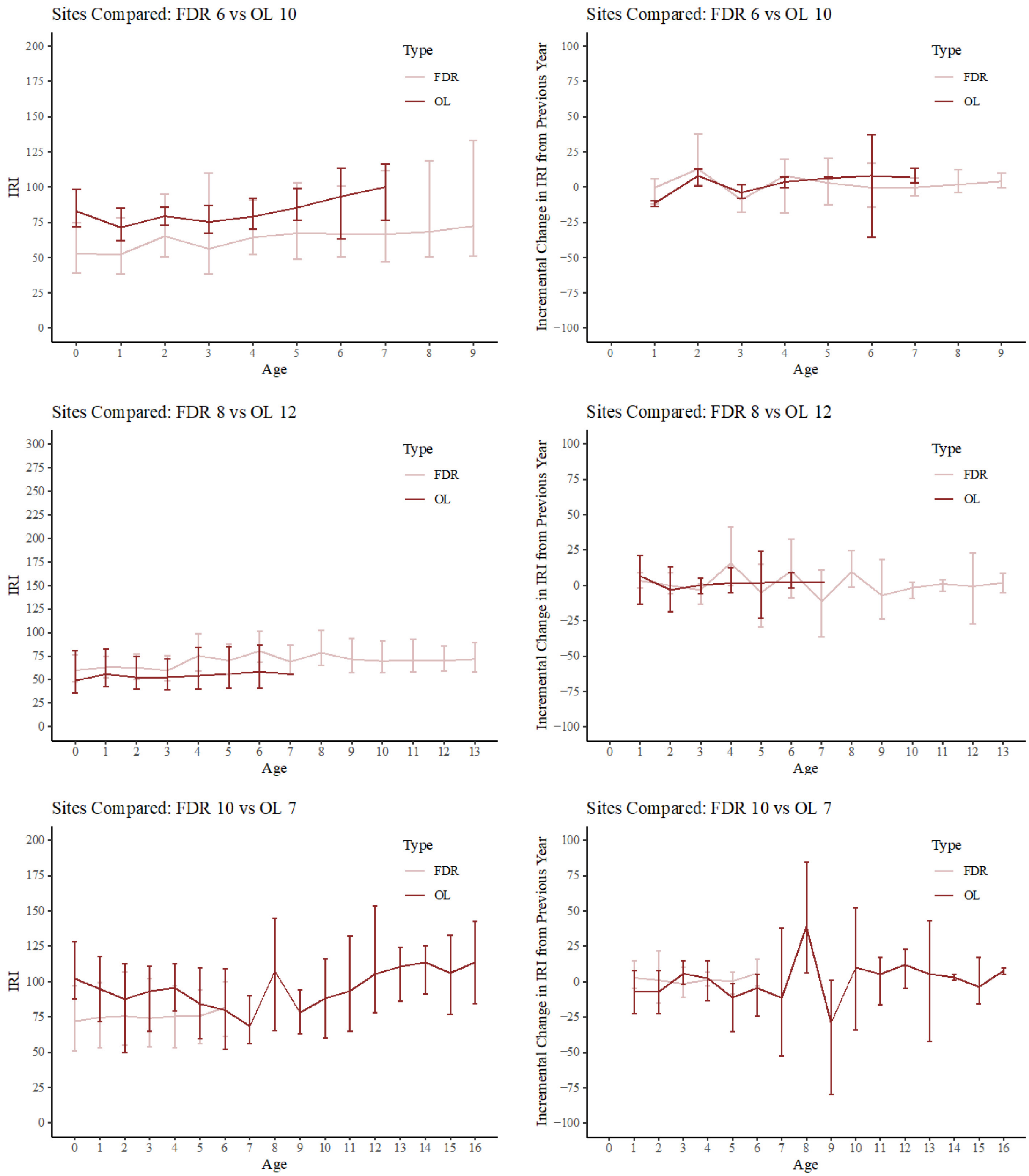
Figure 15. The overall distribution of year-to-year change in rutting depth (RD). The dashed lines are 5%, 50% (median), and 95% quantiles of the data.

These results, together with the trends presented above, suggest that in this dataset, IRI is a more reliable measurement of pavement condition than the other pavement distress metrics (FC, TC, and RD). Based on these results, the analysis of long-term deterioration will be based on IRI.

3.3 *Comparison of FDR and Overlay Sites*

The figures below compare the performance of FDR and OL sites within the 5 comparative cases summarized in Table 13. Each of these pairwise comparisons analyze IRI values over time (figures in the left) as well as incremental changes in IRI from previous year (figures in the left). For each case, the pavement condition is aggregated across the site to identify mean trends and variability in both yearly condition and year-to-year incremental deterioration. However, it should be noted that the calculated variability will be influenced by the size of the project site. Sites that are longer and span a wider range of weather, traffic, and subgrade conditions will naturally have higher variability within each year. In these figures, variability is depicted by the error bars, which indicate 2.5th and 97.5th quantiles (capturing thus 99% of the data).





In general, three prominent trends are present in the pairwise aggregated comparisons. First, the spread of pavement condition values within a site for a given year can be quite large. The incremental change from the previous year shows a similar level of variability. As mentioned previously, some of this variability is potentially because of changing traffic, weather, subgrade conditions, or maintenance history within the site (for longer sites). Second, the FDR and overlay sites generally show similar deterioration trends. The primary difference between the curves is their initial value, not in their deterioration rates. Finally, there does not appear to be a noticeable increase or decrease in deterioration over time.

Overall, these results indicate that the performance of FDR and overlay sites are similar enough to be handled by the same deterioration model given the limitations of the current dataset.

3.4 Deterioration Model

The parameters of the proposed deterioration model (α and σ) considered in the proposed deterioration model (below) are summarized in Table 14.

$$IRI_{i,t+1}|IRI_{i,t} \sim \text{Normal}\ (\alpha + IRI_{i,t}, \sigma)$$

Table 14: Calibrated parameters of proposed deterioration model

Variable	Mean	Standard Deviation	q5	q95
Alpha (α)	1.35	0.12	1.15	1.56
Sigma (σ)	10.72	0.09	10.58	10.86

Notably, the estimated incremental deterioration is relatively small (about 1-2 IRI points per year – value given by the average α) and the variability in incremental is relatively large (+/- about 20 IRI points on average – value given by adding and subtracting σ from the average deterioration rate). However, a large portion of this year-to-year variability is expected to be the result of changing weather, traffic, and maintenance activities. Models that explicitly incorporate these covariates should see a decreased σ and a model that properly accounts for all the factors that affect pavement deterioration should see a σ consistent with only the measurement variability of IRI itself. We explored more complex models accounting for these factors, but the prediction accuracy of the model was not significantly larger – probably due to the limited number of sites under analysis and the high variability in condition measurements.

Next, we look at how well the model fits the observed data (Figure 16). In general, the model fits the data reasonably well – the observed data points fall within the estimated uncertainty ranges. Because only a single α is estimated, all the segments have the same slope of the mean trend and we can see some evidence of suppressing segment-to-segment variability.

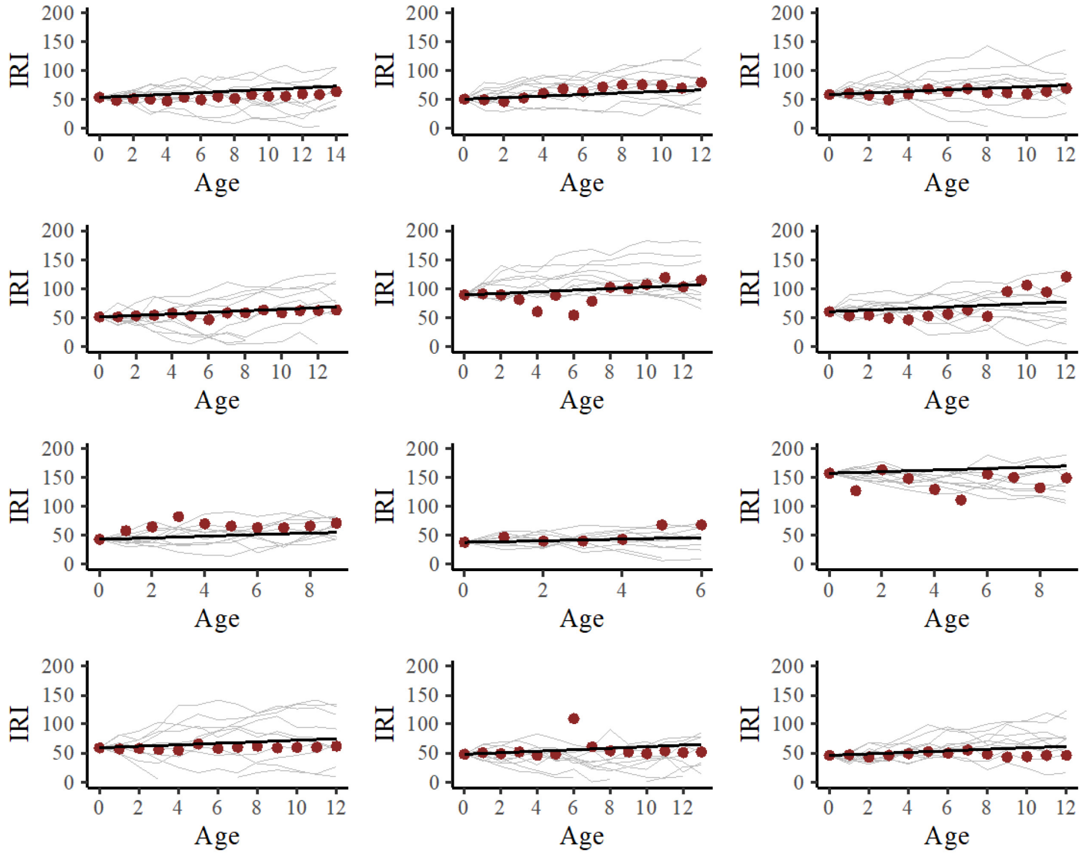


Figure 16. Fit of the deterioration model to the data. The dark red points are measured IRI values, the gray lines are sampled trajectories within 95% uncertainty intervals and the solid black line is the mean trend.

4 Conclusions

Our exploratory analysis of long-term performance of FDR and overlay pavements found several important qualitative trends in the data: (1) a clear deterioration trend is often not present – for some segments, particularly those with less data, the condition is relatively uniform from year to year; (2) condition data can be very noisy, sometimes showing apparent decreases in IRI year-to-year; and (3) maintenance does not consistently appear to improve pavement condition. Additionally, we found that IRI was a more reliable measurement of pavement condition than the other pavement distress metrics (FC, TC, and RD) in the dataset.

The pairwise comparison of FDR and overlay pavements with similar characteristics found three prominent trends. First, the spread of pavement condition values within a site for a given year can be quite large. The incremental change from the previous year shows a similar level of variability. Second, the FDR and overlay sites generally show similar deterioration trends. The primary difference between the curves is their initial value, not in their deterioration rates. Finally, there does not appear to be a noticeable increase or decrease in deterioration over time.

Overall, these results indicate that the performance of FDR and overlay sites are similar enough to be handled by the same deterioration model given the limitations of the current dataset. An incremental deterioration model based on Markov and a Bayesian inference of parameters was developed. The model fits the data reasonably well – the observed data points fall within the estimated uncertainty ranges. This model is recommended for the time being with the caveat that it will understate segment-to-segment variability in deterioration rates.

Chapter 4. Life-Cycle Cost Analysis

1 Introduction

The goal of this chapter is to compare the life-cycle costs of two rehabilitation strategies: Full-Depth Reclamation (FDR) and traditional overlays (OL). Life-Cycle cost analysis (LCCA) is an evaluation technique that enables comparing the total cost of competing design (or rehabilitation and preservation) alternatives, each of which is appropriate for implementation of a transportation project (FHWA 2002). LCCA is applied when an agency must undertake a project and is seeking to determine the lowest life-cycle-cost (i.e., most cost-effective) means to accomplish the project's objectives (FHWA 2003). In LCCA, all of the relevant costs that occur throughout the life of an alternative, not simply the original expenditures, are included. To account for the impact of time on the value of a dollar, an economic analysis technique known as "discounting" is used to all projected costs to convert them into present dollars and summed to produce a net present value (NPV) (FHWA 2023).

To account for the uncertainties associated with the evaluation, the analysis considers a probabilistic approach. A probabilistic LCCA includes a mean, variance, and probability distribution to characterize the variables influencing the evaluation, in contrast to a more simplistic deterministic approach that incorporates a single point value (Tighe 2001). The probabilistic approach is better suited to accounting for uncertainties such as the impact of maintenance activities in pavement performance, the cost of maintenance alternatives, etc. This probabilistic perspective is strongly recommended by the Federal Highway Administration (FHWA) (Walls and Smith 1998) and implemented in the FHWA RealCost software, currently recommended in CDOT pavement design manual to conduct probabilistic LCCA (CDOT 2024). Given the high variabilities found in the analysis of costs and maintenance needs of FDR and overlay pavements (Chapter 2), as well as their long-term performance (Chapter 3), a probabilistic approach seems particularly suitable in this project.

LCCA is appropriately applied only to compare alternatives that would yield the same level of service and benefits to the project user (FHWA 2002). If the benefits vary among the candidate alternatives (e.g., if they provide different levels of service), then the alternatives cannot be compared solely on the basis of cost and a comparison of benefits should also be included in the analysis. Ideally, benefits should be quantified in monetary terms, so that they can be compared to costs by using ratios such as benefit-cost. A monetary quantification of benefits, however, is not always possible because the effectiveness of alternatives may involve nonmonetary benefits (Khurshid et al. 2009). To overcome this situation, other metrics of benefits such as the area bounded by the performance curve (i.e., AOC) can be used as a proxy for measuring benefits.

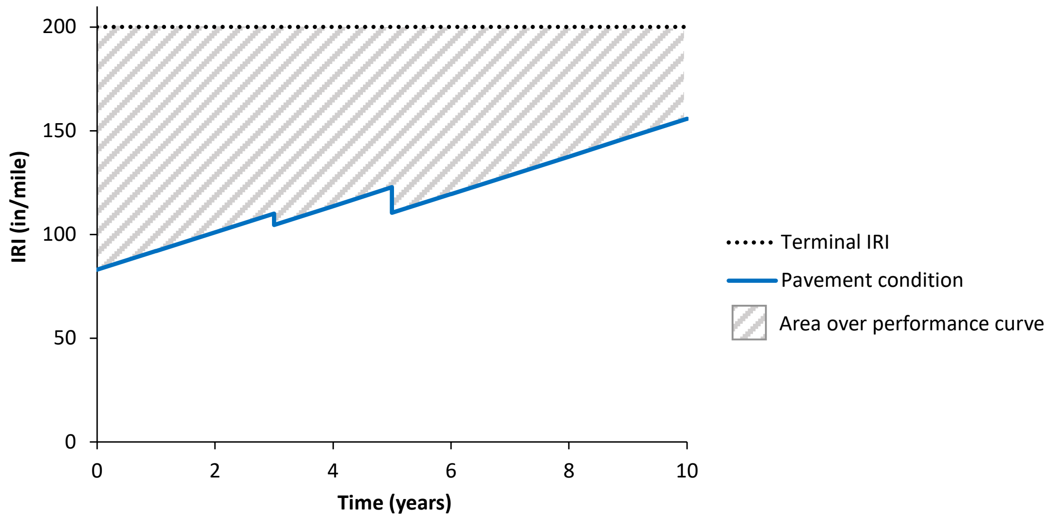


Figure 17: The area over the pavement performance curve can be used as a measure of long-term effectiveness and overall benefits

The area bounded by the performance curve and a threshold value of condition (e.g., maximum IRI) measures the long-term effectiveness of treatment alternatives (Figure 17), thus embodying both concepts of average pavement condition and service life (Khurshid et al. 2009). The reasoning behind this approach is twofold. Firstly, a well-maintained pavement will have a smooth deterioration that will result in a larger area over the curve when compared to a poorly maintained pavement. Secondly, since the benefits of a well-maintained pavement are extensive and not easily quantifiable in monetary terms, the area over the curve can serve as a proxy for overall benefits, encompassing reduced accidents, travel time, vehicle operating and maintenance expenses, among other factors. Importantly, this concept of AOC has been widely applied to quantify the long-term performance of maintenance alternatives in pavement management applications (Geoffroy 1996; Khurshid et al. 2009; Torres-Machi et al. 2015, 2017; Yepes et al. 2016).

To compare the differences in the long-term performance of FDR and overlay pavements, we will compute the area over the curve of both maintenance alternatives. When using this metric as a proxy for overall benefits, a ratio of Cost-Effectiveness (i.e., CE) can also be estimated to include differences in costs. As described in the equation below, calculating CE requires calculated values for the area over the curve (AOC) and the pavement's life-cycle costs (Torres-Machi et al. 2015).

$$CE = \frac{AOC}{LCC}$$

In the following sections, we summarized the methods used to perform LCCA, the results obtained in this analysis, and we derive conclusions and future recommendations.

2 Methods

To calculate the life-cycle costs, long-term performance, and cost-effectiveness of maintenance alternatives, the study followed a three-steps approach. First, we defined input parameters for LCCA related to the length of the analysis period, the criteria used to measure the value of pavements at the end of the analysis period, and the discount rate considered to account for the impact of time on the value of economic resources. Then, we explored different tools available to perform a probabilistic life-cycle analysis. Finally, we computed life-cycle costs and perform a sensitivity analysis.

2.1 Input Parameters for Life-Cycle Cost Analysis

Analysis Period

The analysis period denotes the duration during which the pavement is subject to study. Testing multiple different analysis periods is advantageous to observe the depreciation of a pavement's value over several time periods. The most common analysis periods used to evaluate pavement design alternatives range between 25 to 40 years (Babashamsi et al. 2016; Demos 2006; Hallin et al. 2011; Shi et al. 2019). CDOT's default value to use in M-E pavement design is 40 years (CDOT 2024). For rehabilitation strategies, however, the analysis periods are usually considerably shorter than these. For example, CDOT pavement design manual recommends a design period of 10 years for rehabilitation strategies.

Based on this, we propose performing LCCA with analysis periods established at 10 and 20 years. These periods align with CDOT'S recommendations for rehabilitation strategies (i.e., 10 years) while, at the same time, allows to explore longer periods of performance (i.e., 20 years).

Discount Rate

Discount rate is used to account for the time value of resources. This concept differs from inflation (which most people are familiar with) and accounts for the opportunity costs of resources. The FHWA clarifies the differences between these terms in the "Life-Cycle Cost Analysis Primer" (FHWA 2002): "*Analytically, adjusting for inflation and discounting are entirely separate concerns, and they should not be confused by attempting to calculate both at once. Instead, future* *costs and benefits of a project should be expressed in constant dollars and then discounted to the present at a discount rate that reflects only the opportunity value of time (known as a real discount rate). This is because public sector project benefits should be dependent only upon real gains (cost savings or expanded output), rather than purely price effects.*" In this study, we followed the recommendations from the FHWA and accounted for inflation to translate historic costs into values in the base year (i.e., 2021), and then used discount rate to translate future values into present costs in the life-cycle cost analysis.

Common ranges of discount rates vary from 3 to 5% (Demos 2006; Hallin et al. 2011). Some studies have used 2-4% (Babashamsi et al. 2016) and 1.5% (Shi et al. 2019). In the most recent pavement design guide, CDOT recommends a value of 1.06 ± 0.562 % (CDOT 2024) and this is the range considered in this study.

Given that the value of discount rate recommended in CDOT's pavement design guide is lower than the values considered by other agencies, a sensitivity analysis on the impact of this parameter on life-cycle cost was performed. In this sensitivity analysis, two additional scenarios considering average discount rates of 2% and 5% are run. The results of these scenarios are compared with the ones obtained with CDOT's recommended value (i.e., 1.06%). In these scenarios, all the other input parameters of the analysis remained unchanged (including the standard deviation of the discount rate).

Salvage Value

Salvage value refers to the estimated residual worth of a pavement at the end of its service life, estimating the potential value that the pavement may provide through recycling or rehabilitation. Since different maintenance alternatives may result in different pavement conditions at the end of the analysis period, estimating Salvage Value is an important factor in the LCCA calculation.

The most common approach to estimate Salvage Value is by calculating the relative value of the remaining serviceability with respect to the cost of rehabilitation. In the LCCA, salvage value is computed as a negative cost (i.e., benefit) to account for the fact that a pavement in better condition at the end of the design period will be preferred:

$$SV = Cost_{Rehab} \cdot \frac{1}{(1+i)^T} \cdot \frac{IRI_{Terminal} - IRI_T}{IRI_{Terminal} - IRI_0}$$

Where SV is the salvage value, $Cost_{Rehab}$ is the initial cost of rehabilitation, *i* is the discount rate, *T* is the analysis period, $IRI_{Terminal}$ is the threshold value of IRI (in this project, 200 in/mile),

IRI_T is the condition at the end of the analysis period (T), and IRI_0 is the condition at the beginning of the analysis period (i.e., after FDR or overlay rehabilitation).

2.2 Exploration of Tools for Probabilistic LCCA

In this project, we considered two software packages to perform probabilistic life-cycle costs analyses: RealCost and a probabilistic analysis coded on Matlab. RealCost software, developed by the Federal Highway Administration, supports the comparison of pavement alternatives in LCCA values (FHWA 2004) and is the recommended software to use by CDOT in the design of new pavements (CDOT 2021, 2024). Coding a probabilistic analysis, in turn, provides more flexibility in the variables considered in the analysis. After an exploration of both alternatives, coding a probabilistic analysis using Monte Carlo simulation was found to be better suited for this analysis because RealCost does not allow to incorporate deterioration modeling in the analysis, limiting thus the comparison of alternatives to a monetary quantification. The alternative used in the study, which considered Monte Carlo simulations to estimate the life-cycle cost analysis, allowed to also quantify the differences in long-term performance of FDR and overlay sites.

2.3 Estimation of Probabilistic Life-Cycle Costs and Long-Term Performance

Probabilistic and deterministic inputs were considered in the life-cycle costs analysis and the deterioration modeling for both FDR and overlay solutions (Figure 18). For both rehabilitation alternatives, a reference pavement section of 1 lane/mile was analyzed.

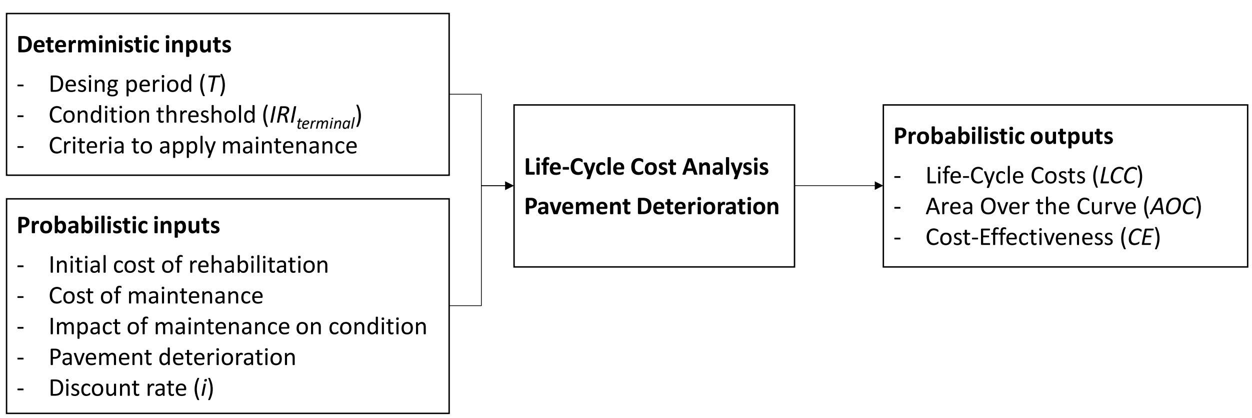


Figure 18: Approach to calculate life-cycle costs and long-term performance

To account for the uncertainty in probabilistic inputs of the model, we considered Monte Carlo simulations. In Monte Carlo simulation, a random sampling is used to formulate a probability distribution of outcomes that accounts for correlation and dependencies. This approach has been widely used in probabilistic LCCA applied to pavements, such as (Swei et al. 2013, 2015). Details on the specific distributions and parameters considered in the probabilistic inputs of the model are summarized in Table 15. Normal distributions truncated to positive values were considered to characterize the probabilistic input variables. This approach restricts the Monte Carlo simulation outcomes to be positive. This approach eliminates instances of negative outcomes in the Monte Carlo sampling, an important consideration given the nature of the variables considered in our analysis (e.g., it will not be reasonable to have negative values for initial construction costs).

Table 15: Characterization of probabilistic inputs

Probabilistic input	Average	Standard Deviation	Justification and comments
FDR initial cost ($/ln-mile)	617,161	497,213	Chapter 2
OL initial cost ($/ln-mile)	337,778	206,182	Chapter 2
FDR cost of pothole patching ($/ln-mile)	17	25	Chapter 2 – Applied annually
FDR cost of crack sealing ($/ln-mile)	2,000	3,300	Chapter 2 – Applied year 5
FDR cost of seal coat ($/ln-mile)	85,254	60,362	Chapter 2 – Applied year 8
OL cost of pothole patching ($/ln-mile)	115	208	Chapter 2 – Applied annually
OL cost of crack sealing ($/ln-mile)	3,100	1,900	Chapter 2 – Applied year 3
OL cost of functional overlay ($/ln-mile)	256,256	181,436	Chapter 2 – Applied year 5 & 10
FDR and OL deterioration (IRI_{t+1})	1.35 + IRI_t	10.7	Chapter 3
FDR impact crack sealing (%IRI)	-0.03	0.05	Chapter 2
FDR impact seal coat (%IRI)	0.14	0.08	Chapter 2
OL impact crack sealing (%IRI)	-0.03	0.05	Chapter 2
OL impact functional overlay (%IRI)	-0.15	0.05	Chapter 2
Discount rate (%)	1.06	0.562	(CDOT 2024)

For each rehabilitation alternative, 10,000 iterations were performed to derive probability distributions of life-cycle analysis outputs: life-cycle costs, long-term performance evaluated as the area over the performance curve, and cost-effectiveness. Finally, a sensitivity analysis was run to estimate the impacts of input parameters on the outputs of the life-cycle analysis.

3 Results of Life-Cycle and Sensitivity Analysis

Our analysis considered an analysis period of 10 years. Considering longer analysis periods resulted in pavement failures. When considering 20 years of analysis, both FDR and overlay pavements failed (i.e., reached an IRI larger than 200 in/mile) before the end of the design period in more than 93% of the iterations. Based on these results, we adjusted the design period to 10 years. This assumption seems reasonable because it is aligned with CDOT design criteria for rehabilitation projects (CDOT 2021).

Results of life-cycle costs for FDR and overlay pavements allows us to conclude that FDR pavements have, on average, lower life-cycle costs than overlay pavements (Table 16). On average, the life-cycle cost of FDR pavements is $178,243/ln-mi less expensive than overlay pavements (i.e., the average life-cycle costs of FDR pavements is $576,312, compared to $754,555 for overlays). That is, FDR solutions result in 30% cost savings over the pavement life-cycle, when compared to overlays.

Table 16: Summary statistics of life-cycle cost

Pavement type	Average (2021 US $/ln-mile)	Standard Deviation (2021 US $/ln-mile)	95% confidence interval (2021 US $/ln-mile)
FDR	576,312	303,162	(570,369 ; 582,255)
Overlay	754,555	247,391	(749,706 ; 759,405)

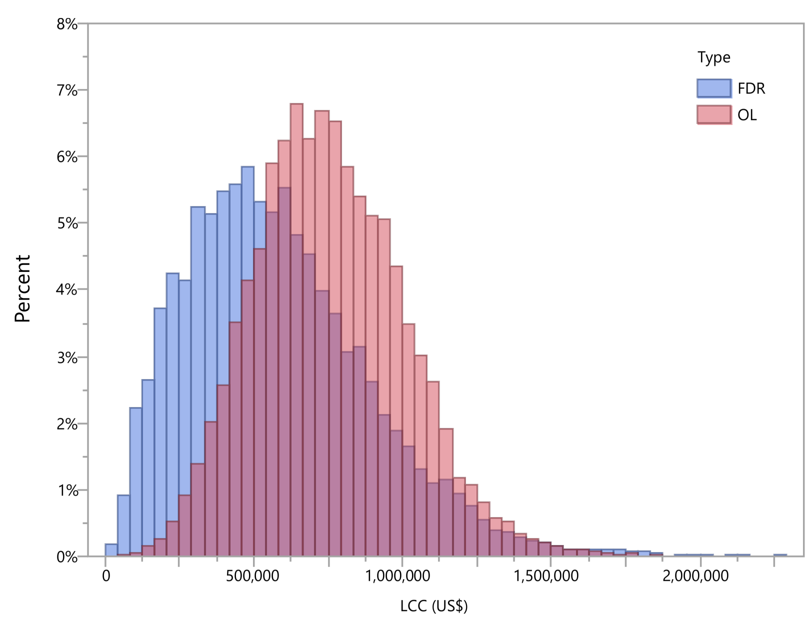


Figure 19. Life-cycle costs of FDR and OL pavements over an analysis period of 10 years

The distribution of these costs (Figure 19) shows that the life-cycle cost of both rehabilitation solutions have similar variability (i.e., the standard deviation of overlay life-cycle costs is $247,391, which is similar than the one of FDR, $303,164). A non-parametric Wilcoxon-Mann-Whitney test (Wilcoxon 1945) was performed to assess whether the differences in life-cycle cost for these rehabilitation strategies is statistically significant. This test found, with a 0.05 significance, that the life-cycle cost of FDR pavements is statistically significant less than the life-cycle cost of overlays (p-value < 0.0001). This conclusion can also be derived from the fact that the 95% confidence intervals of life-cycle costs for overlay and FDR pavements do not overlap (Table 16). This allows us to conclude that pavement rehabilitated with FDR have lower life-cycle costs than overlays and this difference is statistically significant with a significance level of 5%.

The analysis of long-term effectiveness of FDR and overlay showed that, in general, FDR pavements have a better performance than overlays (Table 17 and Figure 20). This difference was found to be statistically significant with a significance level of 0.05 (p-value of non-parametric Wilcoxon-Mann-Whitney test is < 0.0001). On average, the long-term effectiveness of FDR pavements is 32.2% larger than that of overlay pavements (i.e., 961.6 IRI*years for FDR, compared to 726.9 IRI*years for overlays). FDR pavements have a better performance (i.e., lower IRI) over the analysis period, when compared to overlay pavements. On average, FDR pavements have an IRI over the 10 years analysis period of 104 in/mi, compared to 124 in/mi for overlays.

Table 17: Summary statistics of long-term performance measured in terms of the area over the performance curve (AOC)

Pavement type	Average (IRI*years)	Standard Deviation (IRI*years)	95% confidence interval (IRI*years)
FDR	961.6	159.1	(958.5 ; 964.7)
Overlay	726.9	230.4	(722.3 ; 731.4)

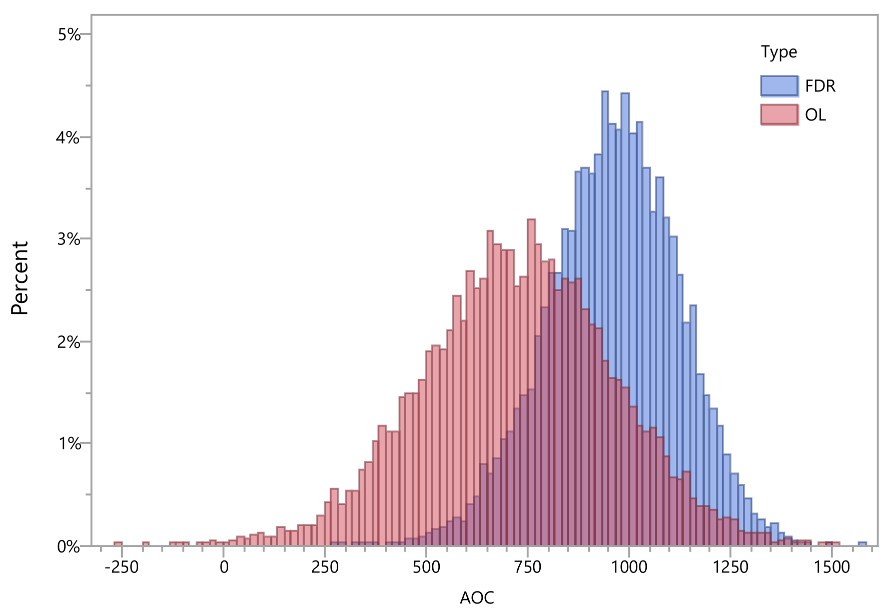


Figure 20. Long-term performance of FDR and OL pavements over a 10 years period

To account for both the costs and the long-term performance of these rehabilitation strategies, we computed the cost-effectiveness (CE) of each of these alternatives (Table 18). These results show that, on average, the cost-effectiveness of FDR is 1.26 times larger than the one of overlays (i.e., $2.51 \cdot 10^{-3}$ for FDR compared to $1.11 \cdot 10^{-3}$ for overlays). These results suggest that, FDR is a more cost effective rehabilitation alternative than overlay. This difference was found to be statistically significant (p-value of non-parametric Wilcoxon-Mann-Whitney test is < 0.0001).

Table 18: Summary statistics of cost-effectiveness

Pavement type	**Average (IRI*years/2021 $)**	**Standard Deviation (IRI*years/2021 $)**	**95% confidence interval (IRI*years/2021 $)**
FDR	$2.51 \cdot 10^{-3}$	$2.54 \cdot 10^{-3}$	$(2.46 \cdot 10^{-3} ; 2.56 \cdot 10^{-3})$
Overlay	$1.11 \cdot 10^{-3}$	$0.64 \cdot 10^{-3}$	$(1.10 \cdot 10^{-3} ; 1.12 \cdot 10^{-3})$

3.1 Sensitivity Analysis

A sensitivity analysis of the input variables and their impact on life-cycle costs found that one of the main drivers of the significant difference in life-cycle costs between FDR and overlay solutions is a result of the high maintenance costs of overlays. Despite FDR pavements have higher costs for initial construction (i.e., FDR construction is 82% more expensive than overlays, with an average construction cost of $617,161/ln-mi, compared to $337,778 ln-mi), the costs of maintenance of FDR pavements are significantly lower than those of overlay pavements.

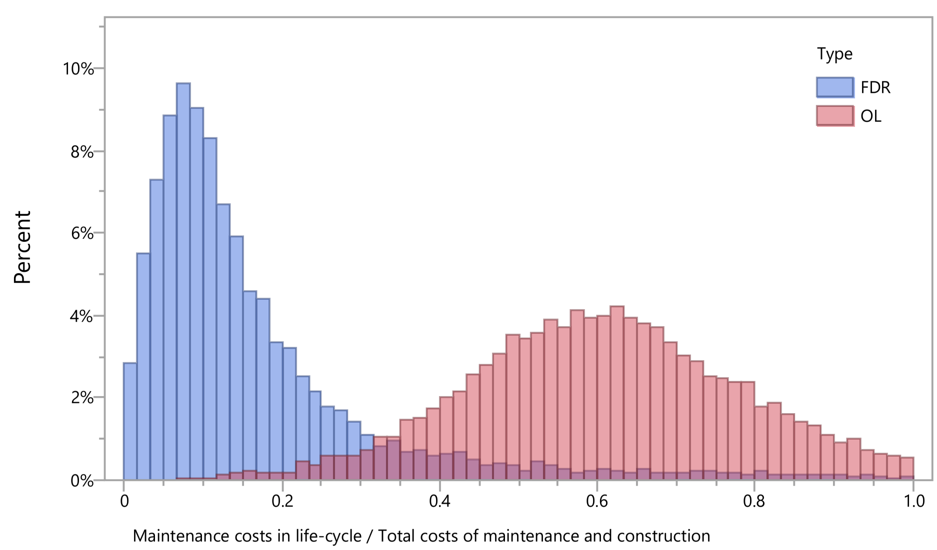


Figure 21: Relative importance of maintenance costs in the pavement life-cycle, expressed as a percentage of the total costs of construction and maintenance

Figure 21 shows that, on average, the maintenance costs of FDR pavements represent 16.0% of the total costs the agency needs to spend in building and maintaining these pavements over a 10 year period. Overlay pavement, despite having lower cost for construction, need significantly higher levels of maintenance over their life-cycle. In this study, the maintenance costs of overlay pavements represented, on average, 60.6% of the total costs of construction and maintenance needed over the analysis period. These results are reasonable because an overlay treatment is not significantly improving the structural capacity of the pavement, as FDR is. As a result of this, pavements rehabilitated with an overlay will require more frequent maintenance that pavements rehabilitated with FDR.

Two additional scenarios were also analyzed to quantify the effect of the discount rate on the results. These scenarios considered discount rates of 2.0% and 5.0%, with the remaining input parameters unchanged. Table 19 and Figure 22 summarize the results obtained in these scenarios, in comparison with the baseline using CDOT recommended value of 1.06%. Although these scenarios result in different values of the life-cycle cost, the conclusions derived from the comparison between FDR and overlay remain unchanged: In all the scenarios, FDR results in lower life-cycle costs over the analysis period. Since the goal of this analysis is to compare both alternatives, we can conclude that, in the ranges explored (between 1.06% and 5%) the discount rate does not have a significant impact on the conclusions derived from this study.

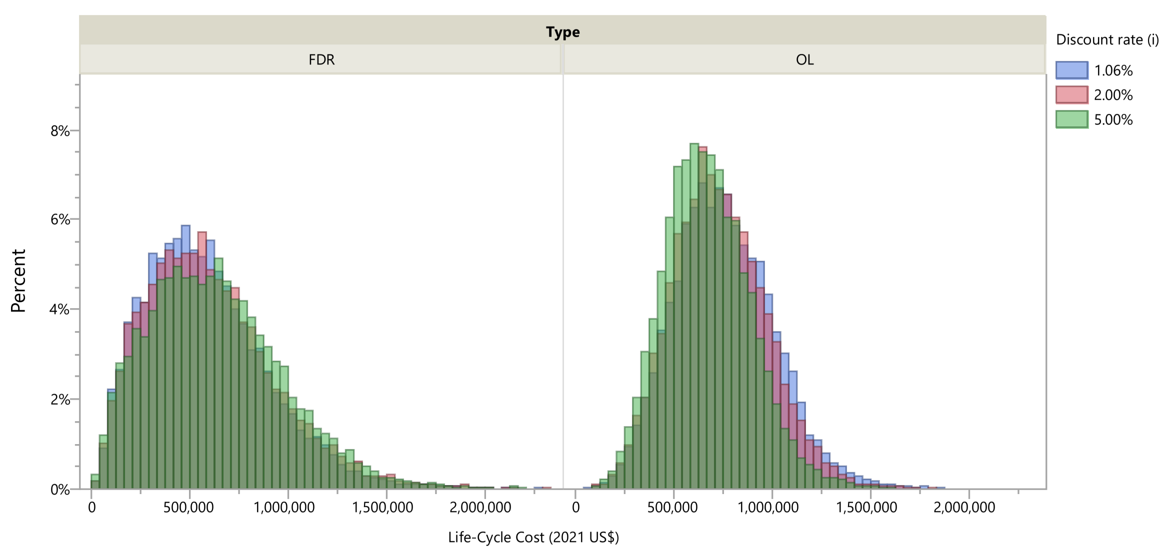


Figure 22: Impact of discount rate on life-cycle cost for FDR and overlay pavements

Table 19: Average life-cycle costs (2021 US$/ln-mile) for different scenarios of discount rate

Pavement type	i = 1.06% (baseline)	i = 2.00%	i = 5.00%
FDR	576,312	597,440	627,817
Overlay	754,555	729,158	668,608

4 Conclusions

This analysis allows us to derive the following conclusions:

FDR pavements have significantly lower life-cycle costs than overlay pavements. FDR solutions result in 30% cost savings over the pavement life-cycle, when compared to overlays. The life-cycle costs of FDR pavements is, on average, $178,243/ln-mi less expensive than overlay pavements (i.e., the average life-cycle costs of FDR pavements is $576,312, compared to $754,555 for overlays).

FDR pavements have a better long-term performance than overlays. On average, the long-term effectiveness of FDR pavements is 32.2% larger than that of overlay pavements. FDR pavements have an average IRI over the 10 years analysis of 104 in/mi, compared to 124 in/mi for overlays.

On average, the cost-effectiveness of FDR is 1.26 times larger than the one of overlays (i.e., $2.51 \cdot 10^{-3}$ for FDR compared to $1.11 \cdot 10^{-3}$ for overlays). These results suggest that, FDR is a more cost effective rehabilitation alternative than overlay. This difference was found to be statistically significant (p-value of non-parametric Wilcoxon-Mann-Whitney test is < 0.0001).

A sensitivity analysis of the input variables and their impact on life-cycle costs found that one of the main drivers of the significant difference in life-cycle costs between FDR and overlay solutions is a result of the high maintenance costs of overlays. On average, the maintenance costs of FDR pavements represent 16.0% of the total costs the agency needs to spend in building and maintaining these pavements over a 10 year period. The contribution of maintenance to total cost in overlay pavements is significantly larger (i.e., 60.6%). These results are reasonable because an overlay treatment is not significantly improving the structural capacity of the pavement, as FDR is. As a result of this, pavements rehabilitated with an overlay will require more frequent maintenance that pavements rehabilitated with FDR.

Overall, this study found that FDR is an effective alternative for pavement rehabilitation. It results in lower life-cycle costs than alternative overlays, have higher long-term performance, and this results in FDR being a more cost-effective solution. Despite FDR is a more costly solution in terms of initial treatment costs, its superior performance and lower maintenance costs result in lower life-cycle costs than overlay alternatives.

Chapter 5. Conclusions and Recommendations

This project analyzed the long-term performance and life-cycle costs of FDR pavements and compared this rehabilitation solution with traditional overlay methods used by CDOT. For each of these alternatives, a set of reference sections (i.e., 10 FDR and 12 overlay sections) were analyzed. Historical information of costs, maintenance history and pavement conditions were characterized using statistical analyses. Pavement condition records were further analyzed to compare the long-term performance of FDR and overlay pavements and to characterize the long-term performance of these rehabilitation solutions. This information was then incorporated into a probabilistic life-cycle analysis using Monte Carlo simulations to account for the uncertainty in the model inputs. Outputs related to life-cycle costs, long-term condition, and cost-effectiveness were estimated for both FDR and overlay pavements.

1 Conclusions and Recommendations

The analysis of historical data related to initial costs of rehabilitation, maintenance costs, and impact of maintenance on condition (Chapter 2) found high variability in these variables. To account for this variability, the research team performed a probabilistic approach in the life-cycle cost analysis.

Our analysis of long-term performance of FDR and overlay pavements (Chapter 3) found several important qualitative trends in the data such as a lack of clear deterioration trends, noisy condition data, and no clear improvements in condition derived from maintenance activities. The pairwise comparison of FDR and overlay pavements with similar characteristics found three prominent trends. First, the spread of pavement condition values within a site for a given year can be quite large. Second, the FDR and overlay sites generally show similar deterioration trends. The primary difference between the curves is their initial value, not in their deterioration rates. Finally, there does not appear to be a noticeable increase or decrease in deterioration over time.

Overall, our analysis of the long-term performance of FDR and overlays (Chapter 3) indicate that the performance of FDR and overlay sites are similar enough to be handled by the same deterioration model given the limitations of the current dataset. An incremental deterioration model based on Markov and a Bayesian inference of parameters was developed. The model fits the data reasonably well – the observed data points fall within the estimated uncertainty ranges. This model is recommended for the time being with the caveat that it will understate segment-to-segment variability in deterioration rates. More advanced models of deterioration are recommended for exploration in future research.

The probabilistic life-cycle and long-term performance analysis (Chapter 4) allows us to conclude that FDR pavements have significantly lower life-cycle costs than overlay pavements. On average, the life-cycle cost of FDR pavements is $178,243/ln-mi less expensive than overlay pavements, resulting in a potential cost saving of 30%. FDR pavements also have a better long-term performance than overlays. FDR pavements have an average IRI over the 10 years analysis of 104 in/mi, compared to 124 in/mi for overlays. When both life-cycle costs and long-term performance are combined in a cost-effectiveness ratio, our analysis found that FDR are more cost-effective than overlay pavements.

These results suggest that, although FDR have higher initial costs of construction, it is a more cost effective solution than overlays that result in lower life-cycle costs and higher long-term performance than overlays.

2 Future Research

The analysis conducted in this research is limiting the characterization of these alternatives to direct costs and long-term condition terms. This approach neglects the environmental benefits derived from recycling existing pavements – one of the important advantages of FDR, when compared to traditional overlays. Future research analyzing the environmental impacts of these alternatives is recommended to fully capture the differences between FDR and traditional overlays.

Our analysis found some unexpected trends and inconsistencies in the historical pavement condition data that would be worth exploring further. In our study, we hypothesize some potential causes for these discrepancies (e.g., inconsistent maintenance records, high variability in measurements) but further investigation is needed to better understand the deterioration process of pavements and propose a more accurate process to measure and characterize pavement deterioration. Given that the process to evaluate pavement condition requires a substantial investment from CDOT on an annual basis, we believe a detailed analysis of the quality of this performance data will benefit CDOT condition reporting and overall pavement management.

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Appendix

Table A.1: FDR Pavement characteristics from as-builts

ID	HMA top layer depth [in]	HMA top layer Type	HMA bottom layer depth [in]	HMA bottom layer Type	FDR depth [in]
FDR 1	2	GR SX (75) (PG 64-28)	2	(GR SX) (75) (PG 64-22)	8
FDR 2	2	GR SX (75) (PG 64-28)	2	(GR SX) (75) (PG 64-22)	8
FDR 3	2	S 75 PG 58-34	2	S 75 PG 58-34	8
FDR 4	2	S75 (PG 64-28)	2	S75 (PG 64-22)	8
FDR 5	2	S75 (PG 64-28)	2	S75 (PG 64-22)	8
FDR 6	2	GR SX (75) (PG 64-22)	2	(GR SX) (75) (PG 64-22)	10
FDR 7	2	SX75 (PG 64-28)	2	SX75 (PG 64-22)	12
FDR 8	2	SX 75 PG 58-28	3	SX 75 PG 58-28	10
FDR 9	2	SX 75 PG 58-34	3	SX 75 PG 58-28	8
FDR 10	2	SX75 (PG 64-28)	3	SX 75 PG 58-28	8

Table A.2: Overlay pavement characteristics from as-builts

ID	HMA top layer depth [in]	HMA top layer Type	HMA bottom layer depth [in]	HMA bottom layer Type	Milling depth [in]
OL1	2.0	GR SX (75) (PG 64-28)	2.0	GR SX (75) (PG 64-22)	2.0
OL2	1.5	GR SX (75) (PG 64-22)	1.5	GR SX (75) (PG 64-28)	0.0
OL3	2.0	SMA 1/2 nom. max size	2.0	GR SX (75) (PG 64-22)	4.0
OL4	2.8	SX(100)(PG 76-28)			2.25
OL5	2.5	SX(100)(PG 76-28)			2.0
OL6	2.0	SMA Fiber Asphalt			2.0
OL7	2.0	HBP Gr. SX (75)			2.0
OL8	2.0	GR SX (75) (PG 64-28)	1.0	GR SX (75) (PG 64-22)	3.0
OL9	2.0	GR SX (75) (PG 64-28)	1.0	GR SX (75) (PG 64-22)	2.0
OL10	2.0	GR SX (100) (PG 64-22)			0.0
OL11	2.0	SX (75) (PG 58-28)			2.0
OL12	2.0	SX (75) (PG 58-28)			0.0

Table A.3: Unit construction costs estimates for FDR pavements

ID	Quantity [sqyd]	Quantity [ln-mi]	Project budget [$]	Adjusted project budget to FDR length [$]	Project budget [2021 $]	2021 $ / sqy	2021 $ / lane-mile
FDR 1	41,106	5.84	3,601,378	3,156,763	4,391,721	38.2	269,135*
FDR 2	73,772	10.48	-	-	-	-	-
FDR 3	93,402	13.27	3,095,182	3,095,182	4,478,582	47.9	337,565
FDR 4	247,590	35.17	7,140,221	5,871,204	8,312,405	33.6	236,356
FDR 5	25,813	3.67	7,140,221	1,269,017	1,796,665	69.6	490,006
FDR 6	311,148	44.20	12,599,658	12,599,658	16,490,823	53.0	373,120
FDR 7	111,546	15.84	3,232,110	3,232,110	4,064,311	36.4	256,511
FDR 8	56,683	8.05	3,819,746	3,819,746	5,407,967	95.4	671,667
FDR 9	56,853	8.08	8,222,886	8,222,886	11,439,761	201.2	1,416,564
FDR 10	75,219	10.68	13,263,858	13,263,858	16,064,493	213.6	1,503,530

* FDR1 and FDR2 are part of the same project. Their quantities are combined to calculate unit cost.

Table A.4: Unit construction costs estimates for FDR pavements

ID	Quantity [sqyd]	Quantity [ln-mi]	Project budget [$]	Adjusted project budget to OL length [$]	Project budget [2021 $]	2021 $ / sqy	2021 $ / lane-mile
OL1	16,792	2.39	3,601,378	444,615	618,552	36.8	259,326
OL2	42,709	6.07	1,833,130	1,833,130	2,305,123	54.0	379,965
OL3	104,474	14.84	3,320,200	3,320,200	4,175,082	40.0	281,339
OL4	92,568	13.15	1,267,374	1,267,374	1,925,087	20.8	146,407
OL5	63,182	8.97	3,997,120	1,608,037	1,978,410	31.3	220,443
OL6	93,833	13.33	4,264,378	4,264,378	4,684,604	49.9	351,471
OL7	39,220	5.57	4,247,642	1,401,698	2,129,120	54.3	382,178
OL8	14,706	2.09	4,111,984	1,274,321	1,804,174	122.7	863,676
OL9	64,371	9.14	3,703,715	3,703,715	5,243,691	81.5	573,482
OL10	49,984	7.10	7,339,995	1,657,920	2,039,783	40.8	287,293
OL11	69,411	9.86	6,700,388	1,019,624	1,234,916	17.8	125,251
OL12	265,408	37.70	13,263,858	5,680,764	6,880,245	25.9	182,500