Title

Life Cycle Cost Analysis Input Framework for Full Depth Recycling and Application on State Route 113 and State Route 84

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Publication Date

2023-04-01

DOI
10.7922/G2B856GT

April 2023
Technical Memorandum: UCPRC-TM-2022-01

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Partnered Pavement Research Center (PPRC) Project Number 2.05 (DRISI Task 3779):
eLCAP and RealCost Support

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation, and System Information
Office of Materials and Infrastructure

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NUMBER
UCPRC-TM-2022-01

2. GOVERNMENT ASSOCIATION NUMBER

3. RECIPIENT'S CATALOG NUMBER

4. TITLE AND SUBTITLE
Life Cycle Cost Analysis Input Framework for Full Depth Recycling and Application on State Route 113 and State Route 84

5. REPORT PUBLICATION DATE
April 2023

6. PERFORMING ORGANIZATION CODE

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8. PERFORMING ORGANIZATION REPORT NO.
UCPRC-TM-2022-01
UCD-ITS-RR-22-122

9. PERFORMING ORGANIZATION NAME AND ADDRESS
University of California Pavement Research Center
Department of Civil and Environmental Engineering, UC Davis
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Davis, CA 95616

10. WORK UNIT NUMBER

11. CONTRACT OR GRANT NUMBER

12. SPONSORING AGENCY AND ADDRESS
California Department of Transportation
Division of Research, Innovation, and System Information
P.O. Box 942873
Sacramento, CA 94273-0001

13. TYPE OF REPORT AND PERIOD COVERED
Technical Memorandum
December 2020 to July 2022

14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES
doi:10.7922/G2B856GT

16. ABSTRACT

Full depth recycling (FDR) has emerged as a feasible rehabilitation alternative in California. This study focuses on addressing the economic feasibility of example FDR structures using life cycle cost analysis (LCCA) that included probabilistic and deterministic life cycle agency costs and deterministic life cycle road user costs. Two LCCA case studies were performed to provide an initial understanding of the agency cost variation. Estimating roadway construction costs plays a key role in pavement LCCA and long-term planning. Materials costs per functional unit are the major input values affecting pavement cost and total construction cost, and they are dependent on project scale, market, region, risk, climate, and economic circumstances. Publicly available contract cost data from past roadway construction activities on the California state highway network were used in this study. Economies of scale suggest that high quantities of materials would have lower unit costs. Unsupervised machine learning techniques were employed to divide the available data into four volume categories (low, medium, high, very high) based on material quantities in a project to accomplish the probabilistic LCCA. Work zone delay road user costs were estimated in *RealCost-CA* and incorporated into the life cycle cost of each alternative. Case studies were conducted for rehabilitation of two California highways, State Route 113 (SOL 113) and State Route 84 (YOL 84), for a 60-year design life. Two different pavement rehabilitation alternatives were considered for the project, an FDR structure and a hot mix asphalt HMA reconstruction, along with their respective maintenance and rehabilitation sequences. Two different pavement structural design methods were also included in the study to enable comparison: R-value and CalME.

17. KEY WORDS
life cycle cost analysis (LCCA), machine learning, Monte Carlo simulations, probabilistic LCCA

18. DISTRIBUTION STATEMENT
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. SECURITY CLASSIFICATION (of this report)
Unclassified

20. NUMBER OF PAGES
78

21. PRICE
None

Reproduction of completed page authorized

UCPRC ADDITIONAL INFORMATION

1. DRAFT STAGE Final	2. VERSION NUMBER 1
3. PARTNERED PAVEMENT RESEARCH CENTER STRATEGIC PLAN ELEMENT NUMBER 2.05	4. DRISI TASK NUMBER 3779
5. CALTRANS TECHNICAL LEAD AND REVIEWER(S) Allen King	6. FHWA NUMBER CA233779A

7. PROPOSALS FOR IMPLEMENTATION
The approach used to develop input data for life cycle cost analysis presented in this technical memorandum can be implemented in LCCA processes.

8. RELATED DOCUMENTS
None

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

AASHTO ACCREDITED

10. SIGNATURES

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ACKNOWLEDGMENTS

The University of California Pavement Research Center acknowledges the following individuals and organizations who shared experiences and/or provided assistance, information, documentation, or materials:

- Allen King, Caltrans
- Christina Pang, Caltrans
- Deepak R Maskey, Caltrans
- Thomas Pyle, Caltrans
- Tyler Bodnar, California Nevada Cement Association
- Clay Slocum, California Nevada Cement Association
- Tom Tietz, California Nevada Cement Association

PROJECT OBJECTIVES

A case study was conducted for a life cycle cost analysis (LCCA) and life cycle assessment (LCA) of rehabilitation of two sections of pavement in Solano County on State Route 113 (SOL 113) and State Route 84 (YOL 84). Two alternatives were considered for each section: (1) full depth recycling using cement stabilization (FDR-C) and (2) hot mix asphalt (HMA) replacement. This technical memorandum summarizes the processes, the assumptions, and the results of the LCCA for both sections considering the agency cost and the road user cost. The LCA for the case studies is presented in a separate technical memorandum.

LIST OF ABBREVIATIONS

AADT	Annual average daily traffic
AB	Aggregate base
ARIMA	Autoregressive integrated moving average
CCD	Contract Cost Database
CWZD-RUC	Construction work zone delay road user cost
eLCAP	environmental Life Cycle Assessment for Pavements
EUAC	Equivalent uniform annual cost
FDR	Full depth recycling
FDR-C	Full depth recycling–cement stabilized
FDR-FA	Full depth recycling–foam asphalt stabilized
FHWA	Federal Highway Administration
HC	Hierarchical clustering
HMA	Hot mix asphalt
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
M&R	Maintenance and rehabilitation
NPC	Net present cost
RAP	Reclaimed asphalt pavement
RHMA	Rubberized hot mix asphalt
RUC	Road user cost
SG	Subgrade
SOL	Solano County
UCPRC	University of California Pavement Research Center
YOL	Yolo County

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
		MASS		
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
		AREA		
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C + 32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised April 2021)

1 INTRODUCTION

Pavement life cycle cost analysis (LCCA), an engineering analytical technique that uses economic principles to evaluate long-term alternative investment options, supports selection of a cost-effective pavement alternative by balancing initial construction costs and future maintenance and rehabilitation (M&R) costs of a new construction, reconstruction, or rehabilitation pavement project *(1)*.

LCCA accounts for costs relevant to the sponsoring agency, owner, facility operator, and road users that will accrue throughout the life of road infrastructure. Relevant costs include initial construction, future M&R, and road user costs *(2)*. Use of LCCA has been emphasized over the last two decades in place of the use of initial construction cost estimates in evaluating pavement design and construction alternatives for highway projects. The Federal Highway Administration (FHWA) published the *Life-Cycle Cost Analysis Primer* in 2002 *(2)* and distributed an LCCA tool, *RealCost*, to support the application of LCCA in the pavement project-level decision-making process in 2004 *(3)*. According to the California *Highway Design Manual* Topics 612 and 619, the State of California in 2007 started systematically implementing LCCA to evaluate the cost-effectiveness of alternative pavement designs for new highway construction and rehabilitation or reconstruction of existing highways *(4,5)*. The California Department of Transportation (Caltrans) published the *Life-Cycle Cost Analysis Procedures Manual (6)* and developed a customized version of FHWA's *RealCost*, *RealCost version 2.0CA* in 2008 and *version 2.5CA* in 2013 *(7,8,9)*. Additionally, an online training course was developed and is available on the Caltrans LCCA webpage *(8)*. Prior to 2007, Caltrans had a rudimentary LCCA summary sheet without detailed guidance on how to develop inputs that was seldom used in practice.

The cost calculation methods in *RealCost 2.5CA* require the unit costs and quantities for materials to determine the pavement costs of future M&R projects. The Caltrans *Life-Cycle Cost Analysis Procedures Manual* directs users to use the statewide uniform unit costs as the default. The analyst can find the project-specific unit costs in the Caltrans historical Contract Cost Database (CCD) *(10)* when the analyst considers the default unit costs to not fit the specific project in terms of quantities, climate regions, or material types. However, material unit costs vary by time, project size, geographic location, similarity to recent projects, and market and industrial factors, such as inflation, recent balance of demand and supply in materials, labor and equipment costs, regional availability of materials, transport distances, and environmental constraints *(11,12)*.

Several researchers have studied pavement cost estimate approaches and methodologies over the past two decades. Gransberg and Molenaar *(13)* analyzed existing design-build award methods to develop best-value award algorithms for applying awards based on the overall sustainability of highway pavement projects over their life cycle instead of conventional lowest-bid award methods. They found that the best-value award algorithm could be skewed by cost, time, and construction quality. Tighe presented guidelines for a probabilistic pavement LCCA procedure and followed principles similar to those developed by Gransberg and Molenaar and recommended using real interest rates over nominal interest rates so that interest rates “reflect the true value of money over time with no inflation premiums” *(14)*. For cost variation analysis, Tighe applied either a log-normal or a normal distribution to quantify the statistical distributions of materials depending on the data spread and used the goodness-of-fit test to examine the data distribution across material types and costs. The costs from bidders were compiled based on bidding prices and analyzed to observe the most common pricing for the unit costs of materials. Tighe’s guidelines used a Monte Carlo simulation to simulate the overall probability distribution for each material used. The guidelines suggested that a log-normal distribution be used for material costs and construction costs instead of a normal distribution as material and construction costs need to be greater than zero while maintaining the possibility of higher prices, though at a much-reduced frequency.

Swei et al. *(15)* estimated expected infrastructure construction and cost variation using a parametric approach. They used 15 pavement bid items across five states and investigated the bias and heteroscedasticity of the deterministic approach to calculating cost estimates. They found that current methods of LCCA result in biased low and heteroscedastic estimates, but applying principles of maximum likelihood can reduce the bias naturally present in material and construction costs.

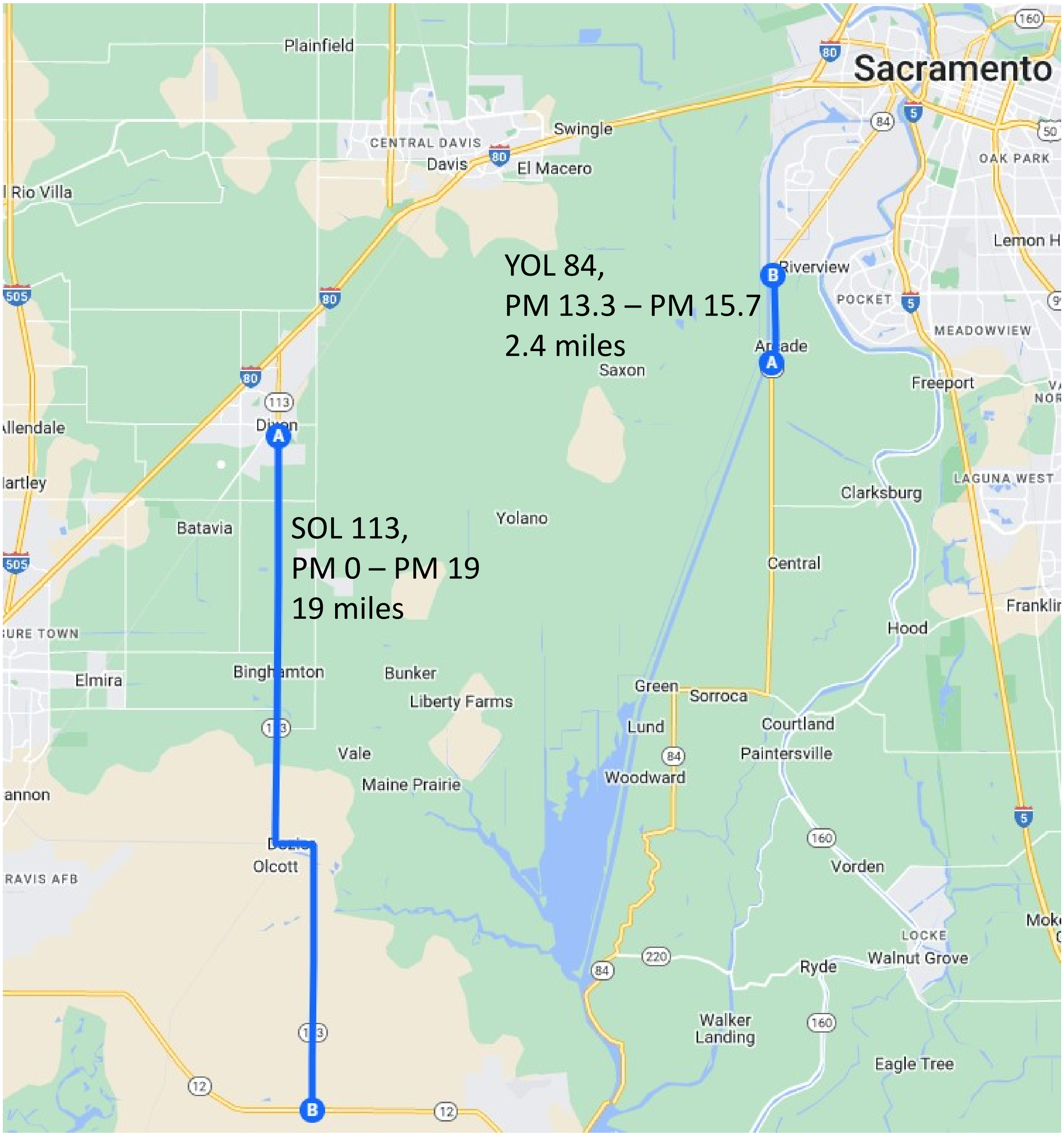
In 2020, Kim et al. *(11)* developed a statistical model to predict material unit prices for future M&R in highway LCCA in California. They investigated the trends in primary pavement material unit prices over time and developed statistical models and guidelines for using predicted unit prices of pavement materials instead of uniform unit prices for future M&R in LCCA. Their study categorized the unit costs of the popular pavement materials collected for the past 20 years in California by project size (small, medium, large, and extra-large) by considering material quantities. Small projects that require a low quantity of materials generally show higher unit costs than larger projects. These findings are expected because mobilization and other fixed costs are spread over a small quantity of material. They also found no statistically significant variation in the unit costs of both jointed plain concrete pavement and hot mix asphalt type-A by geographic location and climate region in California. They predicted the future values of four selected socioeconomic variables (crude oil price, population, number of vehicle registrations, and amount of transportation expenditure in the California budget [a measure of the availability or scarcity of work for contractors to bid on]) for the next 50 years of the LCCA period using a time series analysis (autoregressive integrated moving average, or ARIMA) modeling approach in the R programming language. They then developed multiple regression models to predict the unit costs of pavement materials for use in LCCA using the four socioeconomic variables as continuous independent variables and the project size as a discrete independent variable. The limitation of their study was that they categorized the projects by the sizes of each material with simple quartiles (25th, 50th, and 75th) of the quantities. As a result, the multiple regression models for some project categories did not fit well due to the lack of unit cost data for less widely used materials, such as hot mix asphalt open-graded.

Despite the fact that the FHWA has recommended use of probabilistic analysis since publication of the *Life-Cycle Cost Analysis Primer (2)* in 2002 and *RealCost (3)* in 2004 as the research previously described *(11,13,14,15)*, most LCCA performed in practice is deterministic. This deprives decision-makers of information regarding the uncertainty of future life cycle costs. This uncertainty is critical for assessing the robustness of rankings of alternatives (i.e., answering the question "how certain is it that the preferred alternative selected using deterministic analysis will remain the preferred alternative considering the uncertainty of the input values to the analysis?"). It is also well-known in construction statistical analysis that deterministic analysis using the most likely value selected from non-symmetric distributions—like the log-normal distributions inherent in construction costing and scheduling where there are built-in minimum practical cost and schedule values—results in estimates that are biased low, as demonstrated by Swei et al. *(15)*.

One of the likely reasons for the prevalent use of deterministic analyses is that they are much easier to conduct, especially when accessing large data sets of historical cost distributions and explanatory variables is difficult. Recent advances in the online availability of cost and explanatory variable data should facilitate use of these data, improvement of LCCA methods, and development of improved online tools to access those data and facilitate implementation of probabilistic LCCA within the time constraints of practical use. The purpose of this technical memorandum is to use recent updates in the online availability of Caltrans data and unsupervised machine learning techniques to improve probabilistic LCCA and use it to analyze the feasibility of using full depth recycling structures in two state routes. This work is part of a roadmap for development of an improved online LCCA tool, the Caltrans version of *RealCost*.

1.1 Project Description

LCCA case studies were completed for rehabilitation of two sections of pavement in Solano County in California on State Route 113 (SOL 113) and State Route 84 (YOL 84). Two alternatives were considered for each section: (1) full depth recycling using cement stabilization (FDR-C) and (2) hot mix asphalt (HMA) remove and replace (also referred to as HMA reconstruction). This technical memorandum summarizes the processes, the assumptions, and the results of the LCCA for both sections considering agency cost and road user cost (RUC). Figure 1.1. shows the sections considered in this technical memorandum. SOL 113 is a 19-mile section while YOL 84 is a 2.4-mile section, and both are two-lane roads.



YOL 84,
PM 13.3 – PM 15.7
2.4 miles

SOL 113,
PM 0 – PM 19
19 miles

Figure 1.1. Locations of the two sections, SOL 113 and YOL 84 (*16*).

1.2 Proposed Alternatives for Rehabilitation

HMA reconstruction (remove and replace) and FDR-C were the two alternatives shown by industry in a presentation provided to Caltrans and used in this study to compare LCCA for each pavement section *(17)*.

The two alternatives of HMA reconstruction and FDR-C were considered through multiple design methods:

- R-value design methodology using a 1.0 ft. FDR-C layer
- CalME design methodology using a 1.0 ft. FDR-C layer
- R-value design methodology using a 1.5 ft. FDR-C layer[1]

Table 1.1 and Table 1.2 show the structures resulting from the R-value and the CalME design methods for SOL 113 and YOL 84, respectively. Figure 1.2 to Figure 1.5 show the proposed alternatives in detail for SOL 113, and Figure 1.4 to Figure 1.7 show the proposed alternatives for YOL 84. The 1.5 ft. FDR-C structure from the R-value methodology and the corresponding results are presented in Appendix E for comparison purposes.

Table 1.1: Structure Designs for FDR-C and HMA Reconstruction Rehabilitation Alternatives for Different Design Methodologies for SOL 113

Design Method	FDR-C Rehabilitation Alternative Thickness (ft.)			HMA Reconstruction Rehabilitation Alternative Thickness (ft.)		
	RHMA	HMA	FDR-C	RHMA	HMA	AB
CalME	0.2	0.2	1.0	0.2	0.6	1.0
R-value	0.2	0.7	1.0	0.2	0.55	1.6

Table 1.2: Structure Designs for FDR-C and HMA Reconstruction Rehabilitation Alternatives for Different Design Methodologies for YOL 84

Design Method	FDR-C Rehabilitation Alternative Thickness (ft.)			HMA Reconstruction Rehabilitation Alternative Thickness (ft.)		
	RHMA	HMA	FDR-C	RHMA	HMA	AB
CalME	**0.2**	**0.2**	**1.0**	**0.2**	**0.6**	**1.0**
R-value	**0.2**	**0.5**	**1.0**	**0.2**	**1.05**	**—**

---

[1] Use of an FDR-C layer thicker than 1.0 ft. does not follow Caltrans practices. Thicker FDR-C layers such as this design have been used by local government, and the LCCA is included in Appendix E for reference.

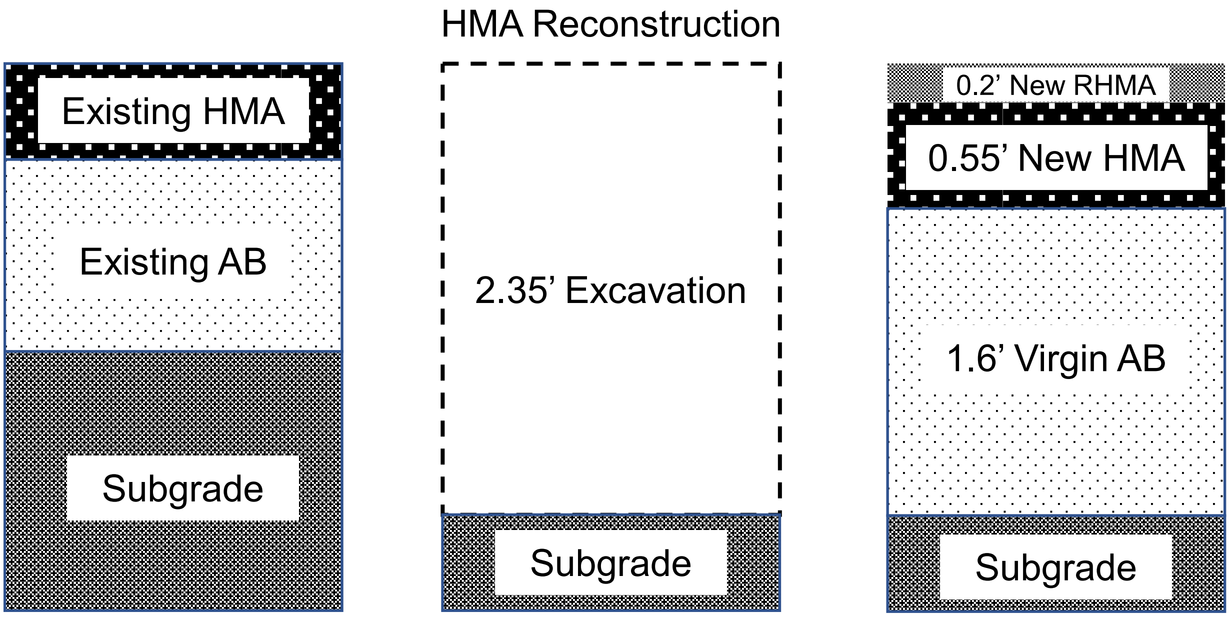


Figure 1.2. HMA reconstruction (remove and replace) alternative structure for SOL 113 using the R-value design methodology.

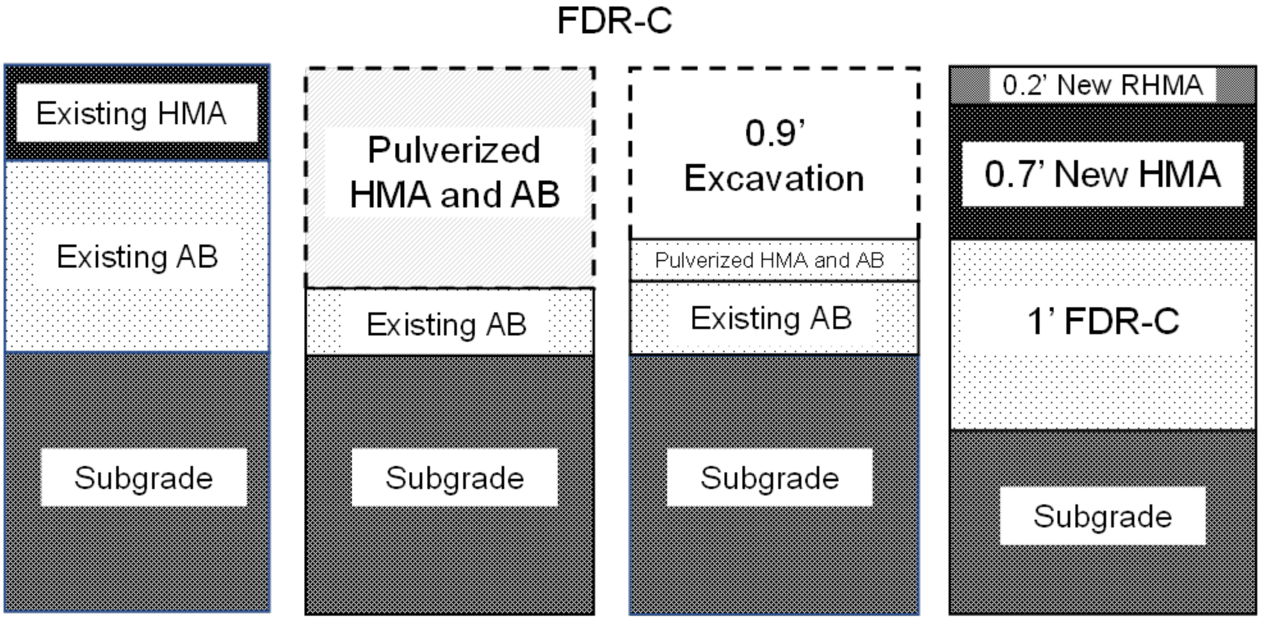


Figure 1.3: FDR-C rehabilitation alternative structure for SOL 113 using the R-value design methodology.

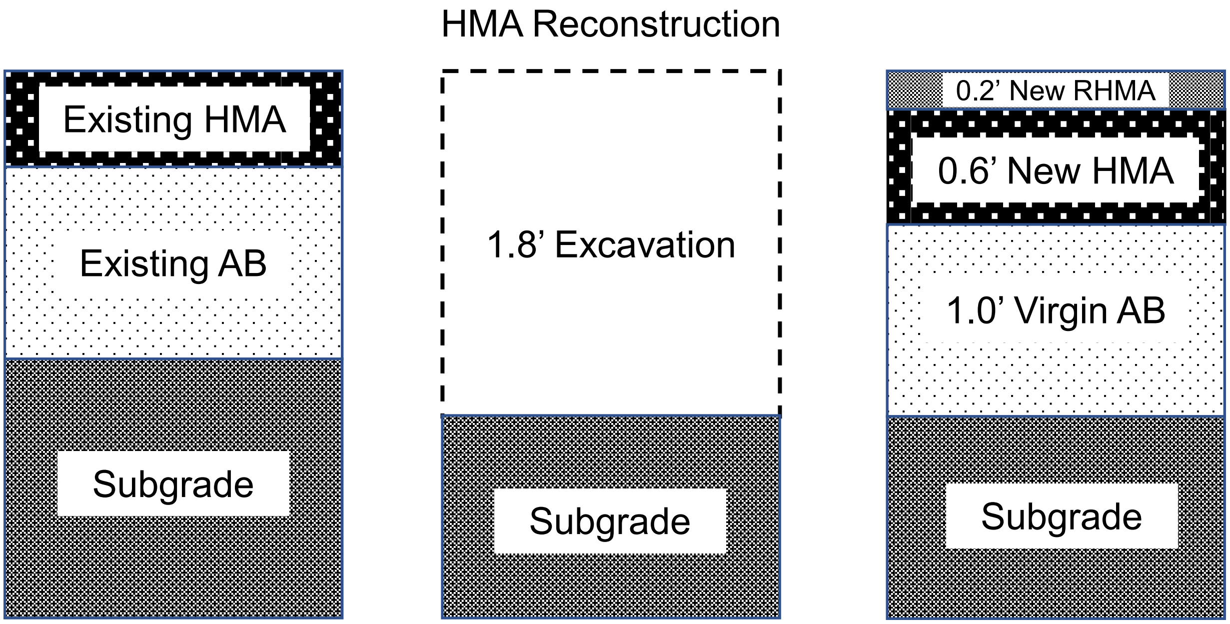


Figure 1.4: HMA reconstruction (remove and replace) rehabilitation alternative structure for SOL 113 and YOL 84 structure using the CalME design methodology.

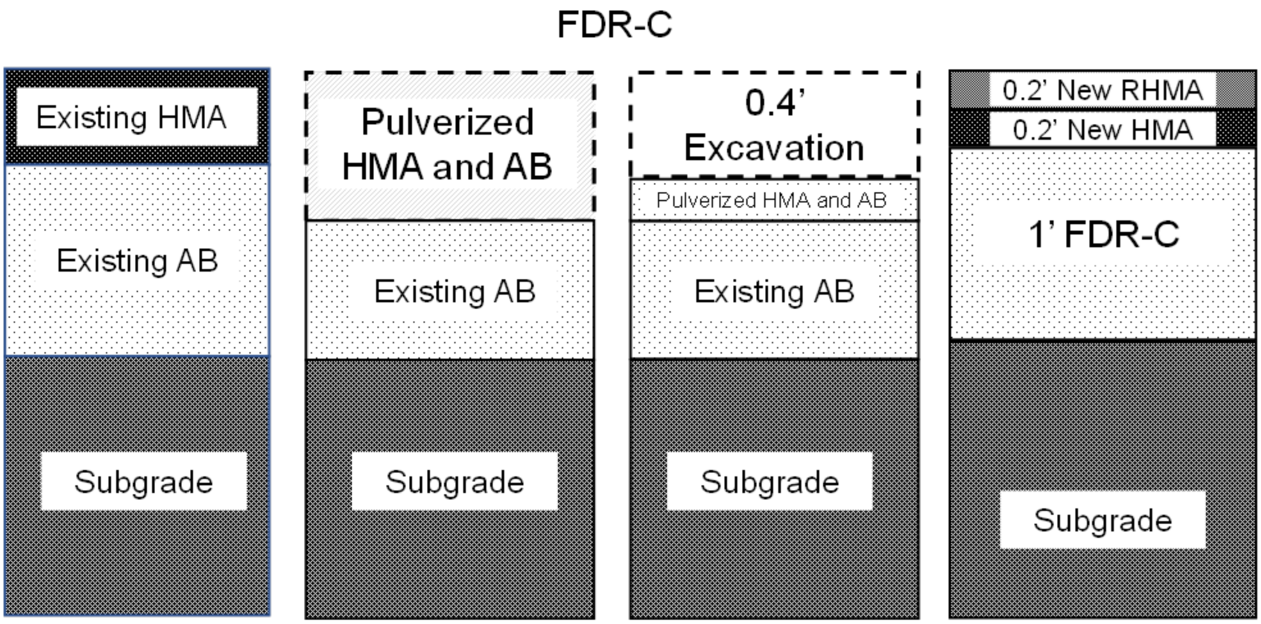


Figure 1.5: FDR-C rehabilitation alternative structure for SOL 113 and YOL 84 using the CalME design methodology.

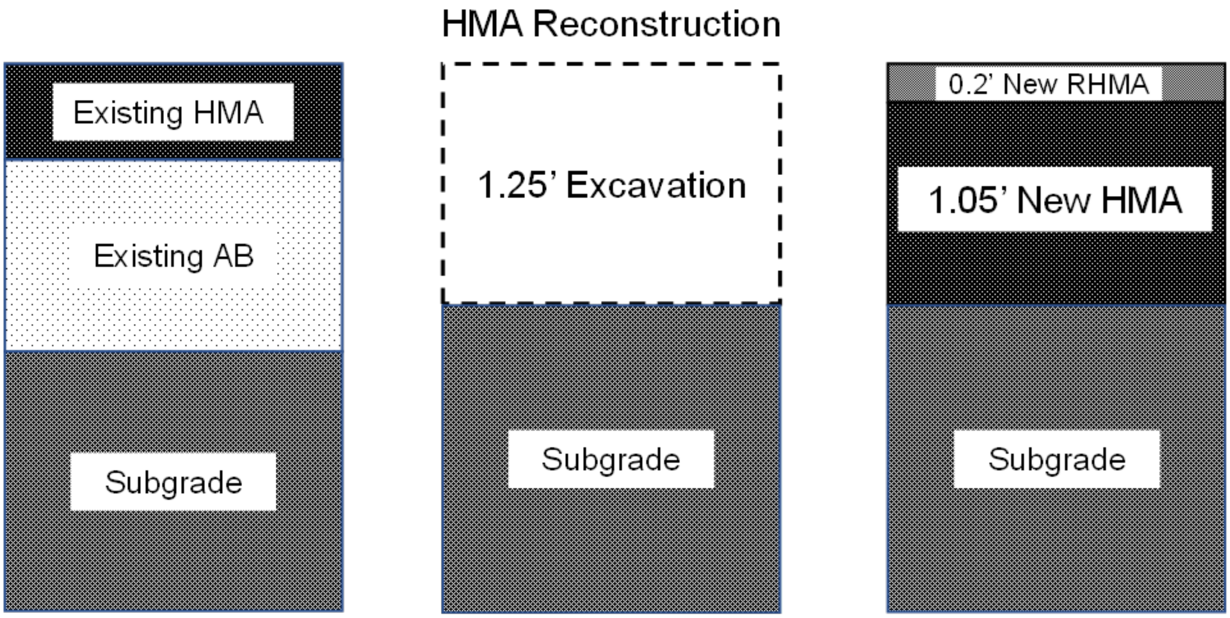


Figure 1.6: HMA reconstruction (remove and replace) rehabilitation alternative for YOL 84 structure using the R-value design methodology.

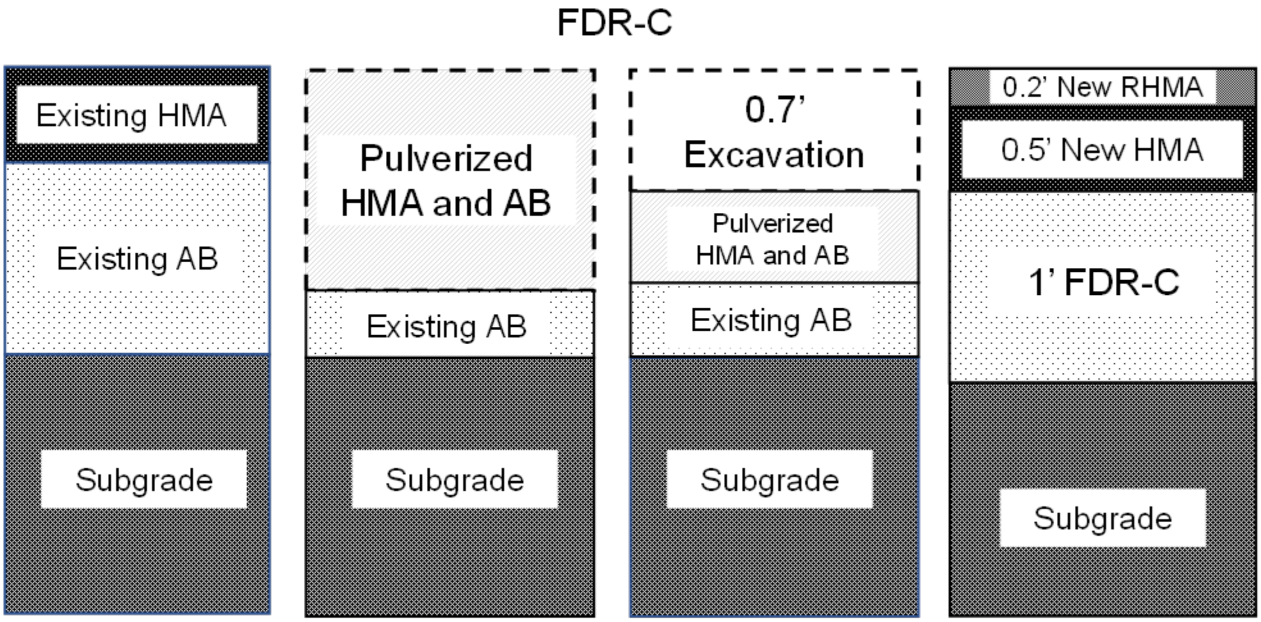


Figure 1.7: FDR-C rehabilitation alternative for YOL 84 structure using the R-value design methodology.

2 MAINTENANCE AND REHABILITATION SEQUENCES

A 60-year analysis period was selected based on the time for next rehabilitation of the longest-life alternatives in the sensitivity analysis included in this study. LCCA results for the two sections are dependent on the M&R sequences followed during their analysis periods and are shown in Table 2.1 to Table 2.8.

To provide sensitivity analysis, a best estimate of the M&R sequence (called "medium life") and shortest-likely life (called "short life") and longest-likely life (called "long life") sequences were considered. The medium-life alternative is the most likely and will be discussed in detail for all the three design methodologies. The M&R sequences for the short-life and long-life alternatives are included in Appendix F. Other variables considered in the sensitivity analysis are the following:

- Hauling distance: 20, 50, and 80 miles
- Construction speed: low, medium, and high

Other variables considered for study included the percentage of cement content in an FDR-C layer (2.5% and 5%) and the percentage of reclaimed asphalt pavement (RAP) in the HMA layers. These variables were found not to have an impact on the unit cost of the materials and are therefore not considered in this study. Salvage values were considered based on a linear depreciation of value over the life of the treatment.

Table 2.1 and Table 2.2 show the assumed M&R sequences for SOL 113 for FDR-C for the medium-life scenarios, and Table 2.3 and Table 2.4 show the M&R sequences for HMA reconstruction for the medium-life scenarios.

Table 2.1: FDR-C M&R Sequence for SOL 113 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	30
HMA	0.2	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Note: SOL 113, medium-life FDR-C (30-year life), 60-year analysis period.

Table 2.2: FDR-C M&R Sequence for SOL 113 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C (2.5% cement)	1.0	0	30
HMA	0.7	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Note: SOL 113, medium-life FDR-C (30-year life), 60-year analysis period.

Table 2.3: HMA Reconstruction M&R Sequence for SOL 113 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
AB and compact Subgrade	1.6	0	75
HMA	0.55	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Note: SOL 113, medium-life HMA reconstruction (22-year life), 60-year analysis period.

Table 2.4: HMA Reconstruction M&R Sequence for SOL 113 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
AB and compact Subgrade	1.0	0	75
HMA	0.6	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Note: SOL 113, medium-life HMA (22-year life), 60-year analysis period.

Similarly, Table 2.5 and Table 2.6 show the assumed M&R sequences for YOL 84 for FDR-C, and Table 2.7 and Table 2.8 show the M&R sequences for HMA reconstruction.

Table 2.5: FDR-C M&R Sequence for YOL 84 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	30
HMA	0.2	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Note: YOL 84, medium-life FDR-C (30 years), 60-year analysis period.

Table 2.6: FDR-C M&R Sequence for YOL 84 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	30
HMA	0.5	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Note: YOL 84, medium-life FDR-C (30-year life), 60-year analysis period.

Table 2.7: HMA Reconstruction M&R Sequence for YOL 84 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
HMA	1.05	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Note: YOL 84, short-life HMA reconstruction (22 years), 60-year analysis period.

Table 2.8: HMA Reconstruction M&R Sequence for YOL 84 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
AB and Compact Subgrade	1.0	0	75
HMA	0.6	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Note: YOL 84, medium-life HMA (22-year life), 60-year analysis period.

3 LIFE CYCLE COST ANALYSIS

3.1 Life Cycle Agency Cost

The first part of this chapter describes the cost data used in this study, which were obtained from the CCD maintained by Caltrans (*10*). The following sections focus on the use of unsupervised machine learning algorithms for clustering cost data to find appropriate costs for projects of different sizes and selection of an appropriate clustering methodology for the data. The chapter then presents the results of two different approaches for calculation of the life cycle agency cost: (1) deterministic and (2) probabilistic. The costs for the case study LCCA calculations presented in this chapter were selected from the cluster for the quantity of each material used in each case study. The deterministic approach calculates life cycle agency costs by choosing a single unit cost for construction of each of the pavement materials and multiplying the cost by the quantity of material in the project to determine the cost of the construction activity. For the probabilistic calculation of the life cycle agency costs, Monte Carlo simulations were performed by repeated random sampling from the statistical distribution of costs for the appropriate cluster for each material on each case study, calculation of the total cost from each set of random samples, and then calculation of the distribution of total costs from the repeated sets of samples.

3.1.1 Work Zone Assumptions

Assumptions were made regarding construction practices in the work zone. The assumption was made that an auxiliary lane would be built for the HMA reconstruction alternative for SOL 113 for the duration of the project to allow traffic flow because there is no existing shoulder capable of handling traffic. *CalME* simulations were used to design the auxiliary lane for a life of one year with 95% reliability. Table 3.1 shows the auxiliary lane specifications. It was also assumed the auxiliary lane would be left in place after construction as a pullout.

It was assumed that an auxiliary lane would not be needed for SOL 113 for the FDR alternative because it can be opened to traffic at the end of each day’s construction activities. There is no space on YOL 84 for an auxiliary lane, and it was assumed that the highway would be closed for the HMA reconstruction alternative. YOL 84 averages approximately 230 vehicles per day for both directions, while the average two-way traffic on SOL 113 is approximately 2,600 vehicles per day (from Caltrans traffic database accessed through the *eLCAP* [*environmental Life Cycle Assessment for Pavements*] software).

Table 3.1: Auxiliary Lane Specifications for SOL 113 HMA Reconstruction

Parameter	Value or Type
Lane width	12 ft.
Lane length	19 mi.
Subgrade type (assumed)	CH
Aggregate base (AB) type	Class 2
HMA type	PG 64
AB thickness	1 ft.
HMA thickness	2 in.

3.1.2 Unit Price Calculation for Construction Materials

This section describes the different processes and techniques used for arriving at unit costs for materials used in the construction of both alternatives (FDR-C and HMA reconstruction).

3.1.2.1 Construction Cost Data

Construction cost data are available from the online CCD. The CCD has unit cost, quantity, total cost, and year of work data for different construction activities for past Caltrans projects. The data can be filtered by Caltrans district, construction activity, year of construction, bid versus awarded contracts, and minimum and maximum quantities of the material used for the construction activity and unit costs *(10)*.

There are two different types of unit costs in the CCD: (1) unit costs and (2) adjusted unit costs. Adjusted unit cost is the cost of the activity adjusted for construction cost inflation between the time the project was advertised and the current year.

This study used the adjusted unit cost for 2022 for all calculations, which will be referred to as the "unit cost" elsewhere in this technical memorandum. Equation 3.1 shows the calculation used by Caltrans for calculating the adjusted unit cost.

$$P(e) = \frac{I(c)}{I(i)} * P(o) \tag{3.1}$$

Where: *P(e)* = adjusted unit cost

I(c) = current Caltrans Construction Cost Index for the last 12 months

I(i) = Caltrans Construction Cost Index for the quarter the project was advertised

P(o) = original unit cost

3.1.2.2 Clustering Construction Activity Quantities

Construction cost data usually follow an exponential decline in unit cost as quantity increases, shown in the example in Figure 3.1 for roadway excavation in three different districts. Economies of scale and spreading of mobilization, overhead, project management, and other fixed costs over a larger number of units are the reasons why the unit cost decreases as the quantity of material increases. Therefore, costs used in LCCA must be sensitive to the quantity of the construction activity. Based on engineering judgment and experience, the quantities of construction activities were clustered into four distinct volume levels: (1) low, (2) medium, (3) high, and (4) very high.

This study used unsupervised machine learning algorithms to cluster costs into those four categories. Gordon stated that unsupervised learning is "concerned with seeking valid summaries of data comprising classes of similar objects. An additional requirement for a partition is that the classes be well-separated, i.e., that objects be not only similar to other objects in the same class but also markedly different from objects in other classes" *(18)*. The term *unsupervised* refers to the fact that the data are untagged and the programming is not guided by any a priori idea of which data belong to certain clusters *(19,20)*. Two primary clustering methodologies were used for this analysis: (1) partitioning (k-means) and (2) hierarchical clustering (agglomerative).

Exploratory Data Analysis

Exploring the raw data is necessary for any dataset, and the data should be visualized and filtered so the analysis provides results that are meaningful and relevant. Typical steps for exploratory data analysis should include removing data that are not applicable as points of interest because of the very small quantities of construction materials. During this study, typical data cleaning included ensuring the same units of quantity across the historical cost data and filtering for construction activity volumes higher than a certain threshold so the results would not be skewed and would be appropriate for an analysis of roadway reconstruction (i.e., using data that represented activities with considerable quantities). The following discussion describes how this data cleaning was done for one of the construction activities of the case study.

Figure 3.1 shows cost data for roadway excavation extracted from the CCD. It shows the unit cost (adjusted to 2022) on awarded contracts for construction projects in Caltrans Districts 3, 4, and 10 from January 2016 to April 2021. The projects for this study were in District 4, but the other districts were included for comparison because of their geographical proximity to the District 4 project locations.

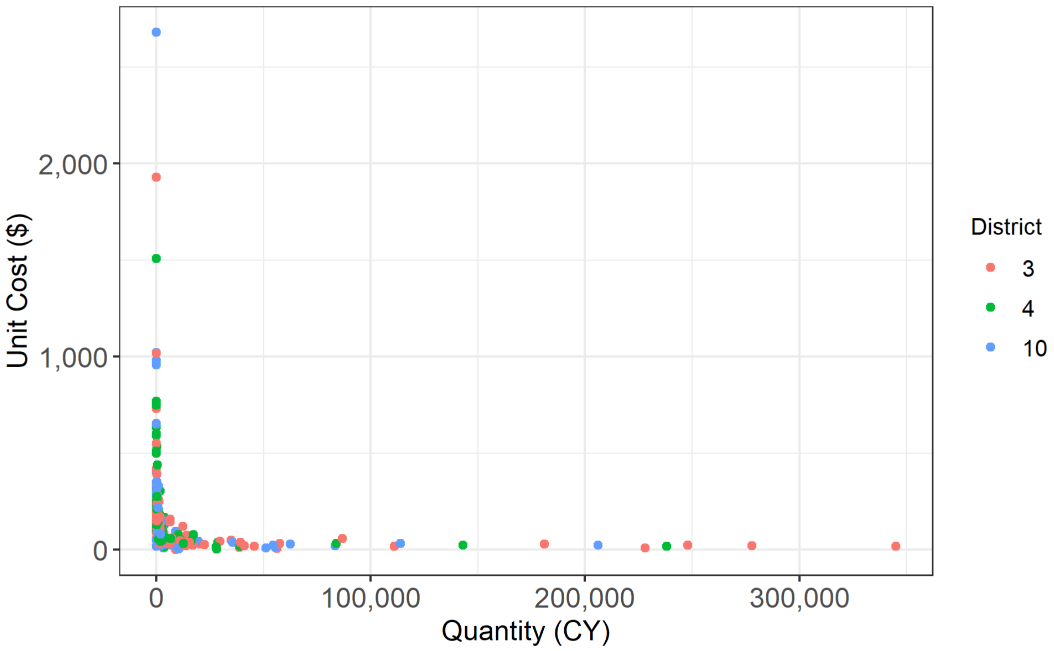


Figure 3.1: Raw data for roadway excavation costs in Caltrans Districts 3, 4, and 10 (January 2016 – April 2021).

Exploratory data analysis shows that 171 of the 320 projects (53.5%) had very low volumes (under 1,000 yd^2) and high unit costs (over \$350/yd^3). For example, the potential costs of a bridge renovation with a small amount of roadway excavation can be excluded compared to a project whose primary purpose is reconstruction or rehabilitation, such as a major rehabilitation of a long section of a highway. A simple calculation showed that one lane-mile of roadway with 0.5 ft. of excavation would result in an excavation volume of 1,173 yd^3 (1 mi. long [1,760 yd.] x 4 yd. wide x 0.5 ft. [0.17 yd.] deep). Based on this calculation, a minimum project size of 1,000 yd^3 was set, and projects with an excavation volume under 1,000 yd^3 were excluded from the cost data set to focus consideration on projects that are primarily rehabilitation and reconstruction projects. Setting a minimum project size of 1,000 yd^3 resulted in the unit cost-volume data shown in Figure 3.2, plotted on a log (base 10) scale to make the data easier to see and analyze.

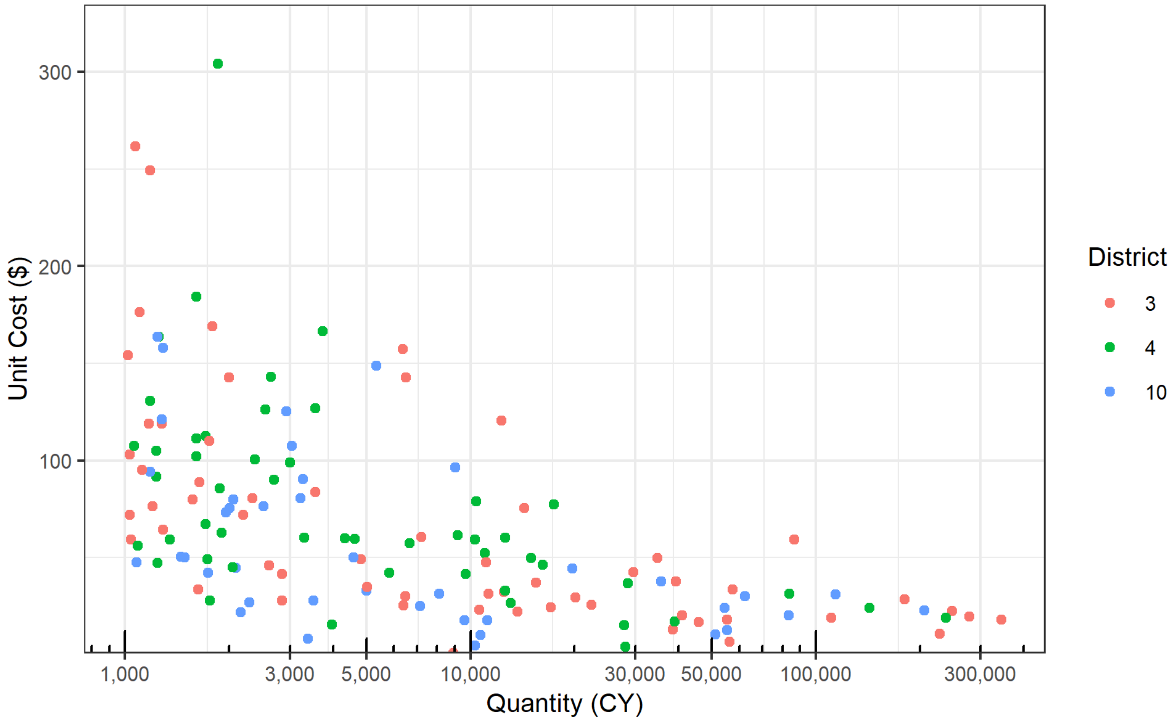


Figure 3.2: Roadway excavation costs in Caltrans Districts 3, 4, and 10 for projects larger than 1,000 yd^3 (January 2016 – April 2021).

K-Means Clustering

K-means clustering is a type of partition clustering that uses a stochastic and iterative approach to cluster available data into a predecided number of clusters. The "k" in the name alludes to "k" number of clusters provided by the user. K-means clustering follows the following steps to arrive at k clusters:

(1) k points are randomly chosen by the program within the range of the variables to be the centroids of the dataset. A centroid is a location representing the center of the cluster.

(2) Each data point is assigned to a cluster whose centroid is closest to the point.

(3) Based on the clustering achieved, the means of the points of each cluster are calculated and designated as the centroids for the next iteration.

(4) Every data point in the dataset is again assigned to a cluster whose centroid is closest to the data point.

(5) Steps 1 to 4 are iterated until the centroids are stabilized or, in the case of big datasets, until the defined number of iterations have been achieved.

The stochasticity is introduced in the form of the randomization of the locations of the initial k centroids. Depending on the locations, multiple runs of a k-means clustering can have slightly different results. Several programming languages provide the capability to run k-means clustering. The open-source statistical programming language R was used for this study.

Hierarchical Clustering

Hierarchical clustering (HC) is a method of cluster analysis that builds a hierarchy of clusters without the need for the user to select the number of clusters. It can be further divided into two types of clustering: (1) divisive and (2) agglomerative. Divisive clustering begins with all the data points in a single cluster and, at each step of the process, the most heterogeneous cluster is divided into two more clusters. This process is repeated until each data point is its own cluster. Agglomerative clustering, on the other hand, begins with each of the data points as its own cluster and, at each step of the process, the two "closest" clusters are combined to form one new, bigger cluster. The process is repeated until every point in the dataset is in a single cluster *(20)*. Agglomerative clustering was used in this study. The result of the process is a tree, which is plotted as a dendrogram (Figure 3.3). The tree is then "cut" at the desired number of "branches" or clusters to get the clustered data.

Different kinds of HC rely on the definition of the distances among clusters to combine and form the next cluster. Three such kinds of HC were analyzed as a part of this study:

1. Complete linkage: the distance between two clusters is based on the maximum distance between any two points in the two clusters.
2. Single linkage: the distance between two clusters is based on the minimum distance between any two points in the two clusters.
3. Average linkage: the distance between two clusters is based on the average distance between any two points in the two clusters.

Figure 3.3 highlights the differences in the clustering mechanisms, where each cost data point is its own cluster at the very bottom and hence is illegible. This dendrogram shows that at higher "branches," where the number of clusters is low, processes like single linkage produce highly skewed clusters where a few branches contain most of the data.

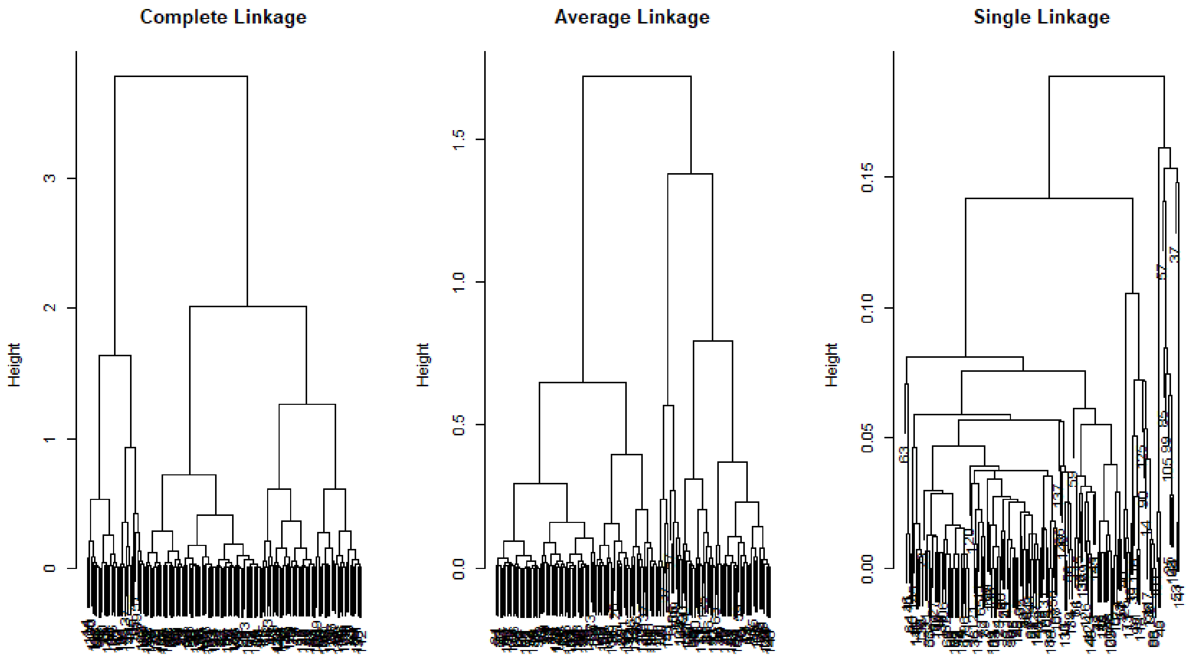
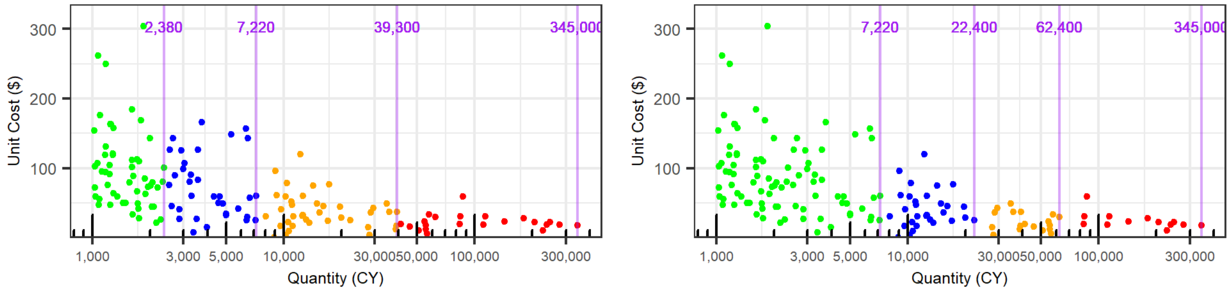


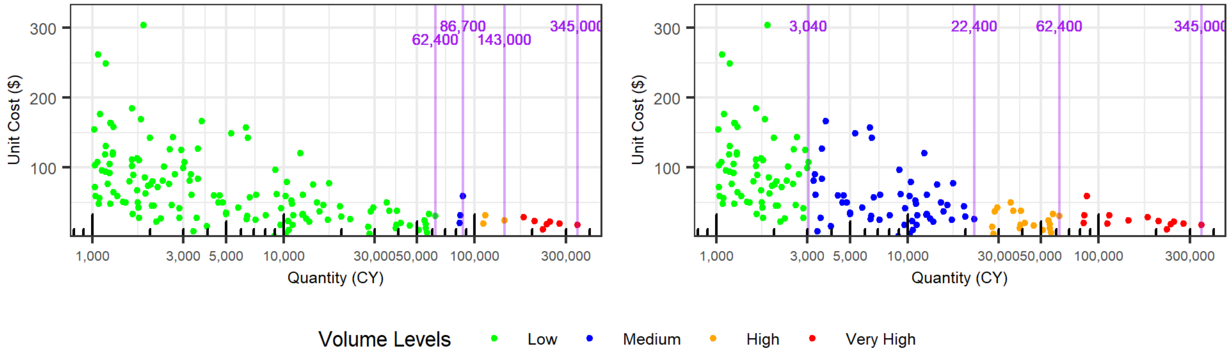
Figure 3.3: Dendrograms showing different linkage types in hierarchical clustering.

To demonstrate this process, the k-means clustering and the three types of HC were repeated for all the construction activities used in the life cycle of SOL 113 and YOL 84. Figure 3.4 illustrates the results of the different types of clustering for roadway excavation. Appendix A to Appendix D contain similar results for all the other construction activities. The purple lines and the numbers show the threshold for each volume (quantity) cluster.



(a) k-Means Clustering

(b) HC Average Linkage



(c) HC Single Linkage

(d) HC Complete Linkage

Figure 3.4: Results of cluster analysis on roadway excavation unit costs in Caltrans Districts 3, 4, and 10 (January 2016 – April 2021).

Clustering Results Discussion

The previous figures show that, depending on the methodology used, the threshold for the different volume clusters can vary widely. However, selecting a single clustering methodology is necessary to maintain uniformity across the analysis and to ease interpretation. Choosing the appropriate methodology depends on the type of data being analyzed and the use and application of the clustering. The unsupervised learning algorithms must be combined with a prior understanding of the data to get a complete picture. In this case, prior knowledge of the behavior of costs with respect to volume and their variation provides insight into the selection of the appropriate clustering methodology.

HC single linkage produced a very skewed dataset and ignores important variations in the clusters, and it was deemed unsuitable for clustering. K-means clustering provided well-distributed thresholds but failed to distinguish between the low- and medium-volume clusters with respect to the unit cost, which goes against the expected behavior of drastically lower unit costs at higher quantities. For the HC complete linkage and the HC average linkage, the thresholds are the same for high and very high volumes. However, HC average linkage captured more of the high prices associated with lower volumes and was therefore chosen for establishing volume thresholds for this study. Similar trends were observed across all the construction activities cost data. HC average linkage is also most appropriate for data that keep changing, such as cost data that are updated in the cost database as projects are finished. The intention is to use an approach that can be applied for routine periodic updating of information used in an online tool.

3.1.2.3 Probability Distributions of Unit Costs

In this study, log-normal distributions of unit costs were assumed. A log-normal distribution is different from a normal distribution in that the log-normal distribution is asymmetrical and creates a right-skewed curve. Log-normal distribution characterization of the unit costs is prudent as the right skew implies a reduced probability of high costs and an increased probability of low costs, which aligns with the understanding of cost behaviors. Unit cost data cannot follow a normal distribution because of the left-hand constraints placed on the data by the fact that costs must only be positive non-zero values while simultaneously also having a minimum cost of materials if they are not being produced at loss to the contractor. Figure 3.5 shows the probability distribution of roadway excavation for the very high volume cluster derived from an HC average linkage (Figure 3.4). Similar probability distributions were built for the different construction activities for all the four levels of volume clusters discussed previously.

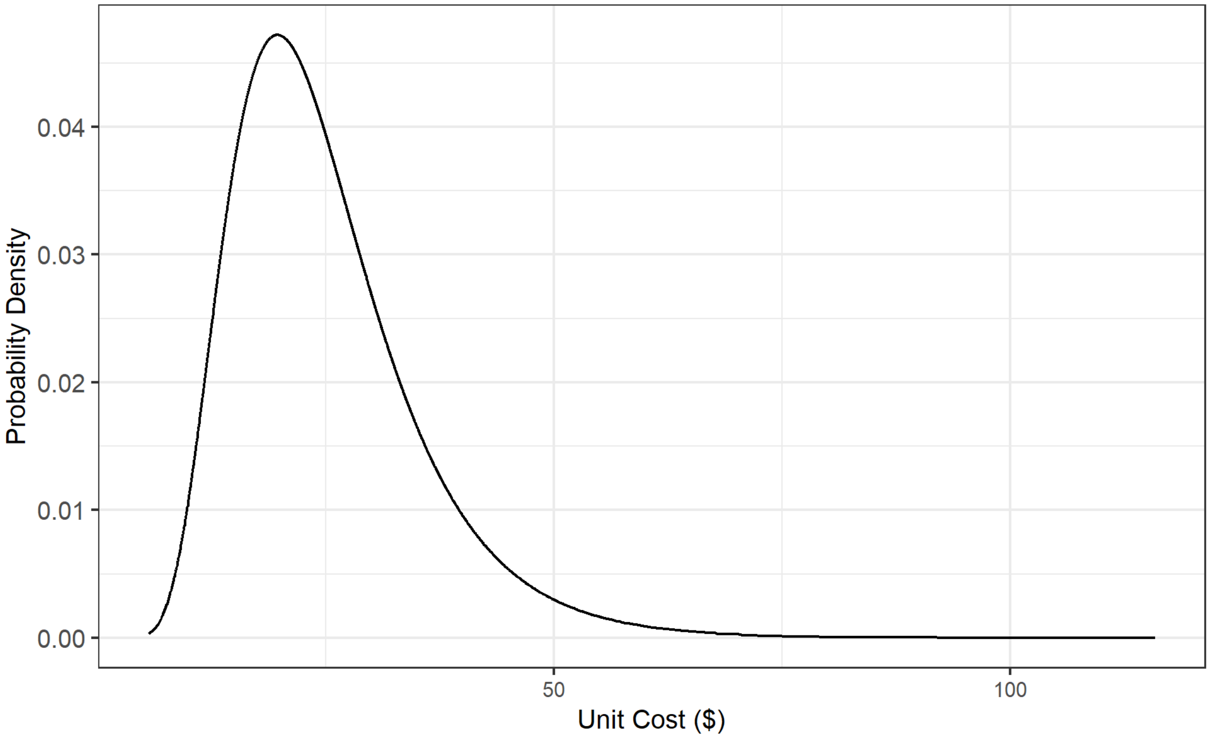


Figure 3.5: A log-normal probability distribution for the unit costs of a roadway excavation for a very high volume cluster.

3.1.3 Deterministic Calculation

Following the clustering and construction of probability distributions for each of the construction activities shown in the M&R sequences in Chapter 2, deterministic calculations were carried out for the life cycle agency cost for the different cases. The life cycle agency cost is represented as a sum of the net present costs of the individual construction activities in the life cycle of a pavement, shown in Equation 3.2.

$$NPC = \sum_{i=1}^{n} \frac{\left(Unit\,Cost_i * Quantity\,Used_i\right)}{\left(1+r\right)^t} \quad \text{.} \qquad \textbf{(3.2)}$$

Where: $Unit\ Cost_i$ = unit cost of construction activity i

$Quantity\ Used_i$ = quantity of the material used in construction activity i

r = discount rate (at 4%)

t = year of construction activity i

For this study, the unit cost of the construction activities was the median cost of the probability distributions (discussed in Section 3.1.2) for the corresponding quantity (low, medium, high, or very high) used for the project. The median costs for each of the construction activities in Chapter 2 are shown in Table 3.2 for SOL 113 and Table 3.3 for YOL 84.

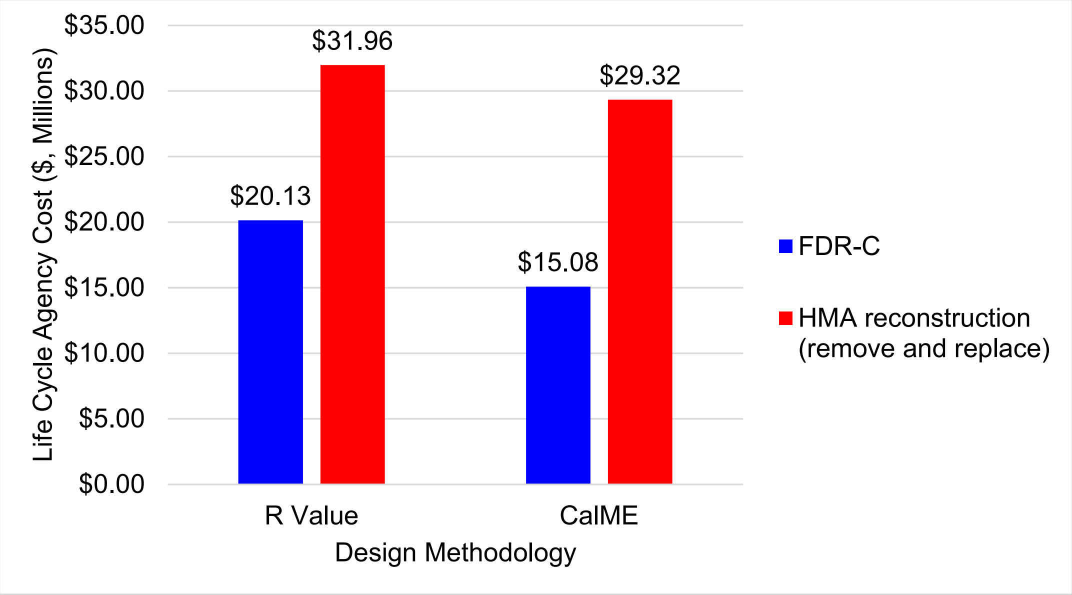
Table 3.2: Median Costs for Construction Activities for SOL 113

Construction Activity	Caltrans CCD Description (Item Code)	Median Cost ($/yd^2)
RHMA 0.2 ft.	Rubberized Hot Mix Asphalt (gap graded) (390137)	10.07
HMA 0.2 ft.	Hot Mix Asphalt (Type A) (390132)	11.04
HMA 0.55 ft.	Hot Mix Asphalt (Type A) (390132)	24.51
HMA 0.6 ft.	Hot Mix Asphalt (Type A) (390132)	26.74
HMA 0.7 ft.	Hot Mix Asphalt (Type A) (390132)	31.19
Mill and Thin Overlay (0.2 ft. RHMA)	Cold Plane Asphalt Concrete Pavement (153103), Rubberized Hot Mix Asphalt (gap graded) (390137)	11.82 (1.75 + 10.07)
Mill and Medium Overlay (0.2 ft. RHMA and 0.2 ft. HMA)	Cold Plane Asphalt Concrete Pavement (153103), Rubberized Hot Mix Asphalt (gap graded) (390137), Hot Mix Asphalt (Type A) (390132)	22.86 (1.75 + 10.07 + 11.04)
AB 1 ft. and Compact SG	Class 2 Aggregate Base (260203)	13.33
AB 1.6 ft. and Compact SG	Class 2 Aggregate Base (260203)	21.33
Aux Lane HMA 0.2 ft.	Hot Mix Asphalt (Type A) (390132)	11.04
Aux Lane AB 1 ft.	Class 2 Aggregate Base (260203)	13.33
Chip Seal	Not Applicable	3.75
Rodway Removal 0.4 ft.	Roadway Excavation (190101)	2.54
Roadway Removal 0.75 ft.	Roadway Excavation (190101)	5.60
Roadway Removal 0.8 ft.	Roadway Excavation (190101)	5.98
Roadway Removal 0.9 ft.	Roadway Excavation (190101)	5.72
Roadway Removal 1.8 ft.	Roadway Excavation (190101)	13.46
Roadway Removal 2.35 ft.	Roadway Excavation (190101)	17.57
FDR-C 1 ft. (5% cement)	Not Applicable	11.10
FDR-C 1.5 ft. (5% cement)	Not Applicable	13.30

Table 3.3: Median Costs for Construction Activities for YOL 84

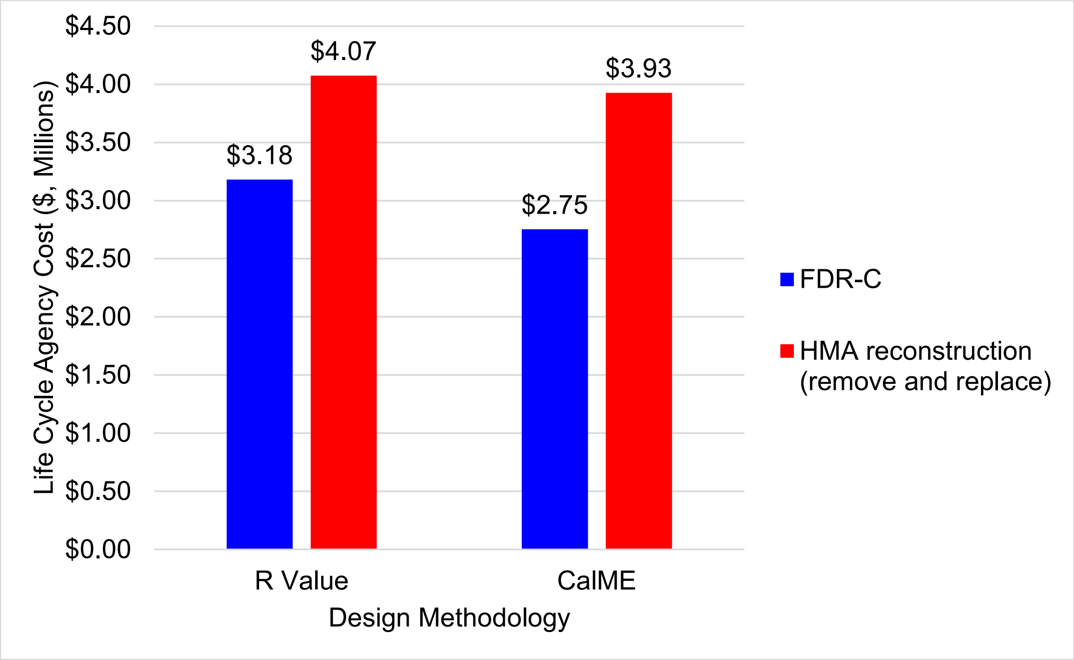
Construction Activity	Caltrans CCD Description (Item Code)	Median Cost ($/yd^2)
RHMA 0.2 ft.	Rubberized Hot Mix Asphalt (gap graded) (390137)	14.09
HMA 0.2 ft.	Hot Mix Asphalt (Type A) (390132)	16.83
HMA 0.3 ft.	Hot Mix Asphalt (Type A) (390132)	19.19
HMA 0.5 ft.	Hot Mix Asphalt (Type A) (390132)	31.98
HMA 0.6 ft.	Hot Mix Asphalt (Type A) (390132)	38.38
HMA 0.7 ft.	Hot Mix Asphalt (Type A) (390132)	44.77
Mill and Thin Overlay (0.2 ft. RHMA)	Cold Plane Asphalt Concrete Pavement (153103), Rubberized Hot Mix Asphalt (gap graded) (390137)	17.09 (3.00 + 14.09)
Mill and Medium Overlay (0.2 ft. RHMA, 0.2 ft. HMA)	Cold Plane Asphalt Concrete Pavement (153103), Rubberized Hot Mix Asphalt (gap graded) (390137), Hot Mix Asphalt (Type A) (390132)	33.92 (3.00 + 14.09 + 16.83)
AB 1 ft. and Compact SG	Class 2 Aggregate Base (260203)	18.00
Chip Seal	Not Applicable	3.75
Rodway Removal 0.4 ft.	Roadway Excavation (190101)	10.67
Roadway Removal 0.7 ft.	Roadway Excavation (190101)	8.17
Roadway Removal 0.8 ft.	Roadway Excavation (190101)	9.33
Roadway Removal 0.9 ft.	Roadway Excavation (190101)	10.50
Roadway Removal 1.25 ft.	Roadway Excavation (190101)	14.58
Roadway Removal 1.8 ft.	Roadway Excavation (190101)	11.46
FDR-C 1 ft. (5% cement)	Not Applicable	11.10
FDR-C 1.5 ft. (5% cement)	Not Applicable	13.30

Using the costs shown in Table 3.2 and Table 3.3, life cycle agency costs were calculated for both SOL 113 and YOL 84 for short-life, medium-life, and long-life structures. The medium-life costs are shown in Figure 3.6 and Figure 3.7. Calculations of the sensitivity to life among the different structure lives are included in Appendix F.



Note: Medium-life structures shown.

Figure 3.6: Deterministic life cycle agency costs for SOL 113 structures.



Note: Medium-life structures shown.

Figure 3.7: Deterministic life cycle agency costs for YOL 84 structures.

3.1.4 Probabilistic Calculation with Monte Carlo Simulations

The clustering of the cost data by volume only accounts partially for the variability of the unit costs. Figure 3.4 and Figure 3.5 show that there is considerable variation in the unit costs within each cluster, irrespective of the clustering methodology. This variation is clearly not explained by the explanatory variables available in the database, and it can have many underlying causes as costs change from project to project. Potential reasons for cost variation within a cluster include changes in trucking distances, terrain, traffic management, accessibility, and the type and length of projects. Given the unpredictable nature of future projects, a costing methodology should account for such cost changes. The probabilistic LCCA included in these case studies used Monte Carlo simulations of the total initial cost of the two alternative reconstruction options to arrive at probabilistic life cycle cost estimates. Variability in future M&R costs was not considered.

Monte Carlo simulations are a widely used tool to estimate the possible outcomes of a random event that has considerable unexplained uncertainty, like the unit costs of construction activities. Ulam and von Neumann (*21*) developed the modern version of these simulations during the Second World War. This methodology relies on running an experiment many times and drawing conclusions from the results about the possibilities of a certain event by sampling from a probability distribution such as a normal or a log-normal distribution. As discussed previously, this study used log-normal distributions.

Probability distributions were built for the different construction activities in Table 3.2 and Table 3.3 for all four levels of volume clusters discussed previously. Monte Carlo simulations were then run for the total cost of each reconstruction alternative using the following steps:

(1) The cluster analysis in Section 3.1.2 provides the limits for different quantity levels for all the construction activities. Using those limits, appropriate cluster levels were selected for each quantity and each project.

(2) Log-normal distributions were created for the selected clusters for every construction activity.

(3) The life cycle agency cost was then calculated, as shown in Equation 3.3, which is very similar to Equation 3.2. The only difference is that the unit cost of the construction activity is derived from randomly sampling the probability distribution of that construction activity from the appropriate cluster.

$$NPC = \sum_{i=1}^{n} \frac{\left(Unit\,Cost_i * Quantity\,Used_i\right)}{\left(1+r\right)^t} \tag{3.3}$$

Where: *Unit Cost*$_i$ = unit cost of construction activity *i* randomly picked from the probability distribution of the appropriate cluster

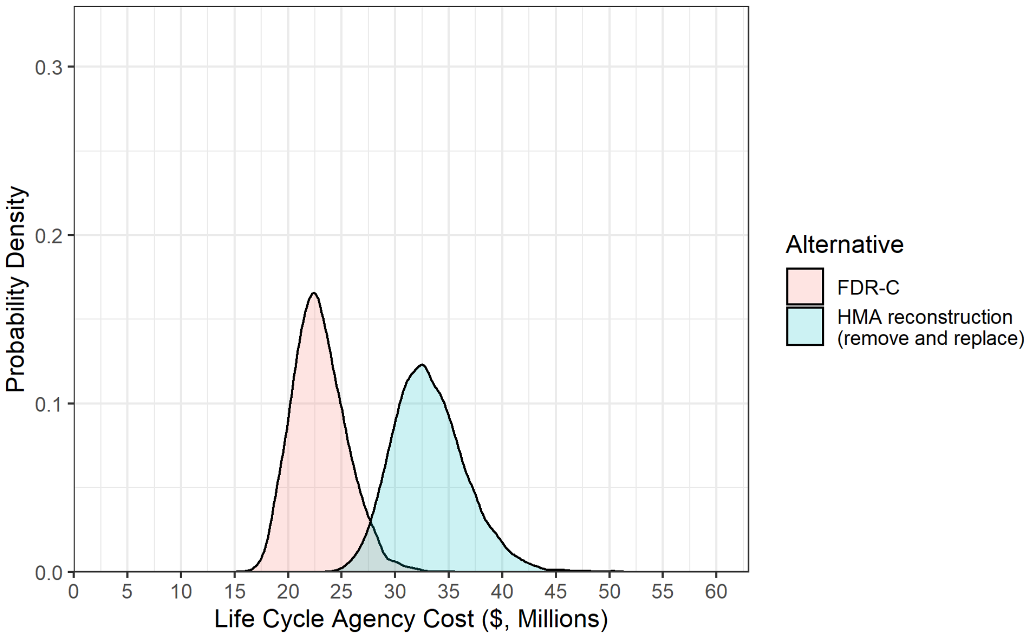
Quantity Used$_i$ = quantity of the material used in construction activity *i*

r = discount rate (at 4%)

t = year of construction activity *i*

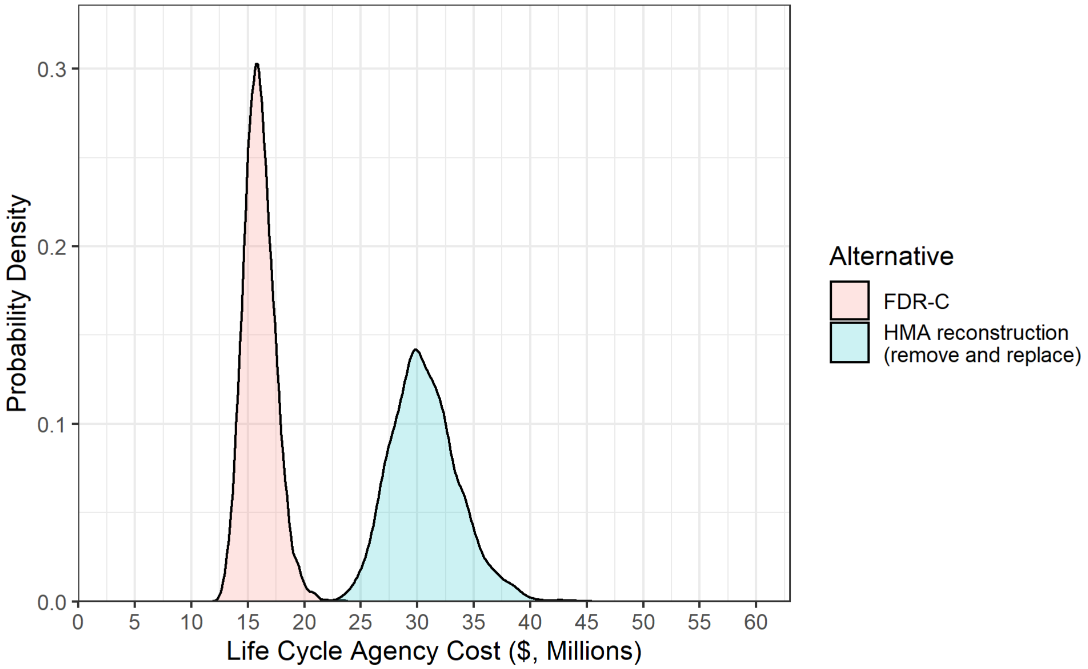
(4) The above calculations were performed repeatedly for 5,000 simulations to build the results of the Monte Carlo simulations.

The following figures show the results of the probabilistic estimation of life cycle agency costs. Figure 3.8 and Figure 3.9 show the results for SOL 113 while Figure 3.10 and Figure 3.11 show the results for YOL 84 for structures using the R-value and CalME design methodologies.



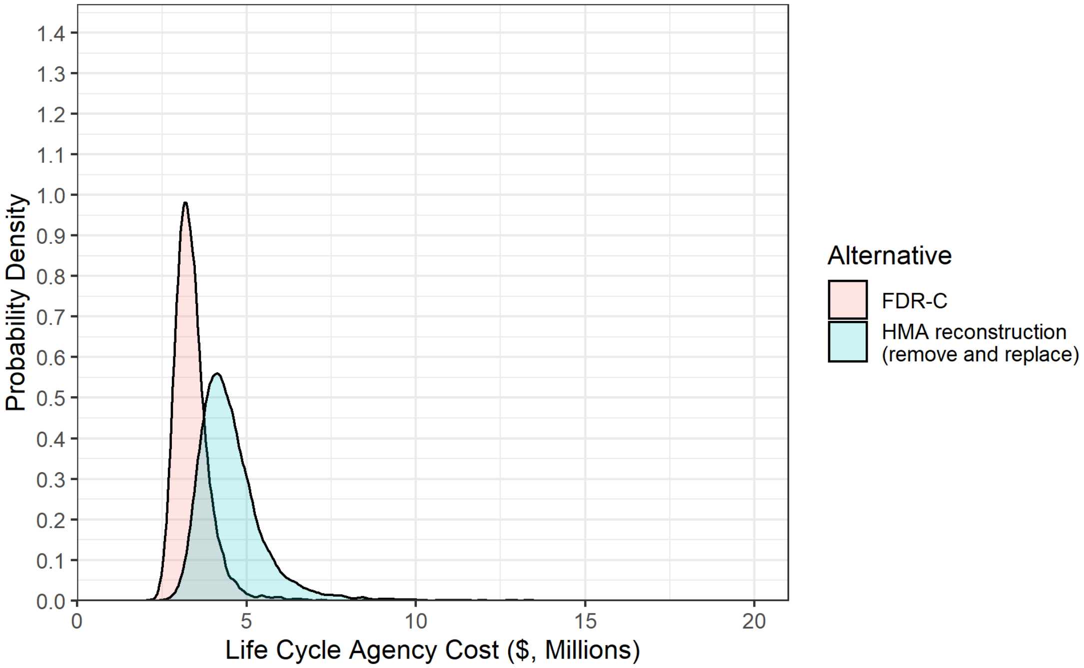
Note: Medium-life structures shown.

Figure 3.8: Probabilistic life cycle agency cost comparison for SOL 113 structures using the R-value design methodology.



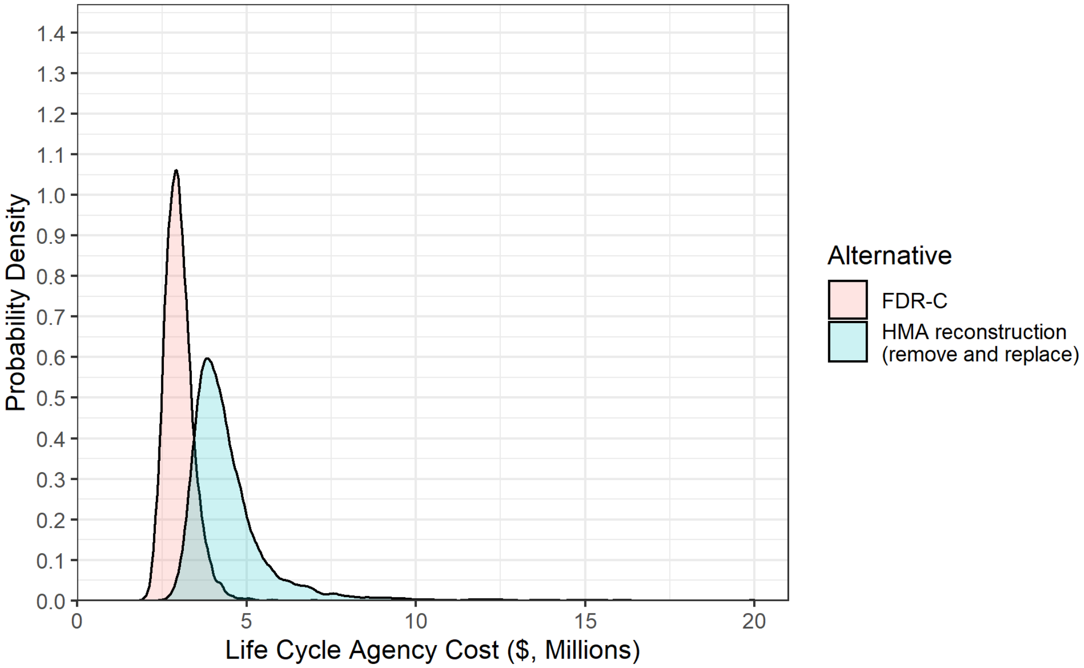
Note: Medium-life structures shown.

Figure 3.9: Probabilistic life cycle agency cost comparison for SOL 113 structures using the CalME design methodology.



Note: Medium-life structures shown.

Figure 3.10 Probabilistic life cycle agency cost comparison for YOL 84 structures using the R-value design methodology.



Note: Medium-life structures shown.

Figure 3.11 Probabilistic life cycle agency cost comparison for YOL 84 structures using the CalME design methodology.

Table 3.4 and Table 3.5 show the probabilistic calculations for SOL 113 and YOL 84, respectively, including the life cycle agency costs at the 10th, 25th, 50th, 75th, and 90th percentiles for comparison purposes.

Table 3.4: Life Cycle Agency Costs Summary for Probabilistic Calculations for SOL 113

Percentile	Life Cycle Agency Cost for Structures ($, Millions)			
	R-Value Design		CalME Design	
	Remove and Replace with AB	FDR-C	Remove and Replace with AB	FDR-C
10th	29.15	19.83	27.02	14.34
25th	30.82	21.16	28.58	15.07
50th	32.87	22.71	30.41	15.91
75th	35.27	24.50	32.47	16.86
90th	37.55	26.30	34.51	17.80

Table 3.5: Life Cycle Agency Costs Summary for Probabilistic Calculations for YOL 84

Percentile	Life Cycle Agency Cost for Structures ($, Millions)			
	R-Value Design		CalME Design	
	Remove and Replace with AB	FDR-C	Remove and Replace with AB	FDR-C
10th	3.57	2.84	3.43	2.53
25th	3.90	3.04	3.73	2.71
50th	4.34	3.3	4.15	2.953
75th	4.92	3.61	4.76	3.23
90th	5.64	3.99	5.64	3.54

3.2 Life Cycle Construction Work Zone Delay Road User Costs

3.2.1 Construction and Traffic Assumptions

To estimate the number of closures and to estimate additional traffic delay and the road user cost for each treatment, the following initial assumptions were used in the analysis:

- Traffic speed for no construction (no lane closure): 55 mph
- Traffic speed for construction (with lane closure): 45 mph
- Speed of FDR construction with 1.0 ft. depth: 1,800 ft./hour at low speed, 2,250 ft./hour at medium speed, and 2,700 ft./hour at high speed
- Mobilization for FDR: 1 hour
- Waiting time for FDR: 3 hours
- HMA or RHMA 0.2 ft.: 0.6 closure/mi.
- HMA 0.3-0.5 ft.: 0.72 closure/mi.
- HMA 0.7 ft.: 1.2 closure/mi.
- HMA mill and thin overlay: 0.85 closure/mi.
- HMA mill and medium overlay: 1.56 closure/mi.
- Chip seal: 1 closure/treatment
- Traffic capacity for no lane closure: 1,800 vehicle/hour/lane
- Traffic capacity of pilot car operation with lane closure: 250 vehicle/hour/lane
- Time value for passenger vehicles: $12/vehicle

- Time value for heavy vehicles: $28/vehicle
- Annual average traffic growth rate: 2%
- 38 lane-miles for SOL 113 and 4.8 lane-miles for YOL 84

3.2.2 Number of Closures for Pavement Construction Stages

Based on the current annual average daily traffic (AADT) volumes and hourly traffic distributions, the future AADT and hourly traffic distributions were predicted with the assumption of a 2% annual traffic growth rate for the future treatments for each project and the number of closures required to complete the project scope was calculated. Table 3.6 and Table 3.7 show the number of closures for the alternative FDR-C reconstruction (FDR-C, HMA and RHMA construction stages) by FDR construction speed and HMA thickness designed by the R-value and the CalME design methodologies for both SOL 113 and YOL 84.

In case of the R-value design methodology, the FDR-C reconstruction with low speed requires 28 closures for FDR-C 1.0 ft., 46 closures for HMA 0.7 ft., and 23 closures for RHMA 0.2 ft. (a total of 97 closures for the activity); the FDR-C reconstruction with medium speed requires 23 closures for FDR-C 1.0 ft., 46 closures for HMA 0.7 ft., and 23 closures for RHMA 0.2 ft. (a total of 92 closures for the activity); and the FDR-C reconstruction with high speed requires 19 closures for FDR-C 1.0 ft., 46 closures for HMA 0.7 ft., and 23 closures for RHMA 0.2 ft. (a total of 88 closures for the activity) for the 38 lane-miles of SOL 113. The FDR-C reconstruction with low speed requires 4 closures for FDR-C 1.0 ft., 4 closures for HMA 0.5 ft., and 3 closures for RHMA 0.2 ft. (a total of 11 closures for the activity), and the FDR-C reconstruction with high or medium speed requires 3 closures for FDR-C 1.0 ft., 4 closures for HMA 0.5 ft., and 3 closures for RHMA 0.2 ft. (a total of 10 closures for the activity) for the 4.8 lane-miles of YOL 84. Table 3.6 and Table 3.7 show the number of eight-hour closures for the alternative FDR-C 1.0 ft. on SOL 113 and YOL 84, respectively, with the pavement structure resulting from the R-value design methodology.

Table 3.6: Number of Eight-Hour Closures for the Alternative FDR-C on SOL 113 (R-Value Design Methodology, 38 lane-miles)

Activity Name	Construction Stages	Construction Productivity	Number of Closures per Treatment	Number of Closures for Activity
Low-Speed FDR-C Construction	RHMA 0.2 ft.	1.67 mi./closure	23	97
	HMA 0.7 ft.	0.83 mi./closure	46	
	FDR-C 1.0 ft.	1.36 mi./closure	28	
Medium-Speed FDR-C Construction	RHMA 0.2 ft.	1.67 mi./closure	23	92
	HMA 0.7 ft.	0.83 mi./closure	46	
	FDR-C 1.0 ft.	1.70 mi./closure	23	
High-Speed FDR-C Construction	RHMA 0.2 ft.	1.67 mi./closure	23	88
	HMA 0.7 ft.	0.83 mi./closure	46	
	FDR-C 1.0 ft.	2.05 mi./closure	19	

Table 3.7: Number of Eight-Hour Closures for the Alternative FDR-C on YOL 84 (R-Value Design Methodology, 4.8 lane-miles)

Activity Name	Construction Stages	Construction Productivity	Number of Closures per Treatment	Number of Closures for Activity
Low-Speed FDR-C Construction	RHMA 0.2 ft.	1.67 mi./closure	3	11
	HMA 0.5 ft.	1.38 mi./closure	4	
	FDR-C 1.0 ft.	1.36 mi./closure	4	
Medium-Speed FDR-C Construction	RHMA 0.2 ft.	1.67 mi./closure	3	10
	HMA 0.5 ft.	1.38 mi./closure	4	
	FDR-C 1.0 ft.	1.70 mi./closure	3	
High-Speed FDR-C Construction	RHMA 0.2 ft.	1.67 mi./closure	3	10
	HMA 0.5 ft.	1.38 mi./closure	4	
	FDR-C 1.0 ft.	2.05 mi./closure	3	

In case of the CalME design methodology, the FDR-C reconstruction with low speed requires 28 closures for FDR-C 1.0 ft., 23 closures for HMA 0.2 ft., and 23 closures for RHMA 0.2 ft. (a total of 74 closures for the activity); the FDR-C reconstruction with medium speed requires 23 closures for FDR-C 1.0 ft., 23 closures for HMA 0.2 ft., and 23 closures for RHMA 0.2 ft. (a total of 69 closures for the activity); and the FDR-C reconstruction with high speed requires 19 closures for FDR-C 1.0 ft., 23 closures for HMA 0.2 ft., and 23 closures for RHMA 0.2 ft. (a total of 65 closures for the activity) for the 38 lane-miles of SOL 113. The FDR-C reconstruction with low speed requires 4 closures for FDR-C 1.0 ft., 3 closures for HMA 0.2 ft., and 3 closures for RHMA 0.2 ft. (a total of 10 closures for the activity), and the FDR-C reconstruction with high or medium speed requires 3 closures for FDR-C 1.0 ft., 3 closures for HMA 0.2 ft., and 3 closures for RHMA 0.2 ft. (a total of nine closures for the activity) for the 4.8 lane-miles of YOL 84. Table 3.7 shows the number of eight-hour closures for the alternative FDR-C 1.0 ft. on SOL 113 and YOL 84 with the pavement structure resulting from the CalME design methodology.

The FDR-C 1.0 ft. structure by the CalME design methodology requires 23 fewer closures than the FDR-C 1.0 ft. structure by the R-value design methodology for the 38 lane-miles of SOL 113 regardless of the FDR-C construction speed because of the thinner HMA thickness. The FDR-C 1.0 ft. structure by the CalME design methodology requires one fewer closure than the FDR-C 1.0 ft. structure by the R-value design methodology for the 4.8 lane-miles of YOL 84 regardless of the FDR-C construction speed.

Table 3.8: Number of Eight-Hour Closures for the Alternative FDR-C on SOL 113 and YOL 84 (CalME Design Methodology)

Activity Name	Construction Stages	Construction Productivity	SOL 113 (38 lane-miles)		YOL 84 (4.8 lane-miles)	
			Number of Closures per Treatment	Number of Closures for Activity	Number of Closures per Treatment	Number of Closures for Activity
Low-Speed FDR-C Construction	RHMA 0.2 ft.	1.67 mi./closure	23	74	3	10
	HMA 0.2 ft.	1.67 mi./closure	23		3	
	FDR-C 1.0 ft.	1.36 mi./closure	28		4	
Medium-Speed FDR-C Construction	RHMA 0.2 ft.	1.67 mi./closure	23	69	3	9
	HMA 0.2 ft.	1.67 mi./closure	23		3	
	FDR-C 1.0 ft.	1.70 mi./closure	23		3	
High-Speed FDR-C Construction	RHMA 0.2 ft.	1.67 mi./closure	23	65	3	9
	HMA 0.2 ft.	1.67 mi./closure	23		3	
	FDR-C 1.0 ft.	2.05 mi./closure	19		3	

Table 3.9 and Table 3.10 show the numbers of closures for the alternative HMA rehabilitation (HMA and compact SG or AB and compact SG) by HMA thickness designed by the R-value and the CalME design methodolgies for both SOL 113 and YOL 84.

For the HMA rehabilitation alternative on SOL 113, the HMA structure designed by the R-value methodology requires 23 closures for RHMA 0.2 ft. and 224 closures for HMA 0.55 ft. with AB 1.6 ft. with low speed, a total of 247 closures for the 38 lane-miles. HMA 0.55 ft. with AB 1.6 ft. with high speed requires 33 fewer closures than with medium speed and 105 fewer closures less than with low speed. For the HMA rehabilitation on YOL 84, the HMA structure designed by the R-value methodology requires 3 closures for RHMA 0.2 ft. and 20 closures for HMA 1.05 ft. with low speed. HMA 1.05 ft. with high speed requires 3 fewer closures than with medium speed and 9 fewer closures than with low speed.

Table 3.9: Number of Eight-Hour Closures for the HMA Rehabilitation on SOL 113 and YOL 84 (R-Value Design Methodology)

Activity Name	Construction Stages	Construction Productivity	SOL 113 (38 lane-miles)		YOL 84 (4.8 lane-miles)	
			No. of Closures per Treatment	No. of Closures for Activity	No. of Closures per Treatment	No. of Closures for Activity
Low-Speed HMA Rehabilitation	RHMA 0.2 ft.	1.67 mi./closure	23	247	—	—
	HMA 0.55 ft. with AB 1.6 ft.	0.17 mi./closure	224			
Medium-Speed HMA Rehabilitation	RHMA 0.2 ft.	1.67 mi./closure	23	175	—	—
	HMA 0.55 ft. with AB 1.6 ft.	0.25 mi./closure	152			
High-Speed HMA Rehabilitation	RHMA 0.2 ft.	1.67 mi./closure	23	142	—	—
	HMA 0.55 ft. with AB 1.6 ft.	0.32 mi./closure	119			
Low-Speed HMA Rehabilitation	RHMA 0.2 ft.	1.67 mi./closure	—	—	3	23
	HMA 1.05 ft.	0.25 mi./closure			20	
Medium-Speed HMA Rehabilitation	RHMA 0.2 ft.	1.67 mi./closure	—	—	3	17
	HMA 1.05 ft.	0.35 mi./closure			14	
High-Speed HMA Rehabilitation	RHMA 0.2 ft.	1.67 mi./closure	—	—	3	14
	HMA 1.05 ft.	0.46 mi./closure			11	

For the HMA rehabilitation alternative on SOL 113, the HMA structure designed by the CalME methodology requires 23 closures for RHMA 0.2 ft. and 190 closures for HMA 0.6 ft. with AB 1.0 ft. with low speed, a total of 213 closures for 38 lane-miles. HMA 0.6 ft. with AB 1.0 ft. with high speed requires 33 fewer closures than with medium speed and 87 fewer closures less than with low speed. For the HMA rehabilitation on YOL 84, the HMA structure designed by the CalME methodology requires 3 closures for RHMA 0.2 ft. and 24 closures for HMA 0.6 ft. with AB 1.0 ft. with low speed. HMA 0.6 ft. with AB 1.0 ft. with high speed requires 5 fewer closures than with medium speed and 14 fewer closures than with low speed.

The HMA rehabilitation alternatives with the CalME design methodology require 16 to 34 fewer closures than the R-value design methodology for SOL 113 and 2 to 4 fewer closures than the R-value design methodology for YOL 84, depending on construction speed.

Table 3.10: Number of Eight-Hour Closures for the HMA Rehabilitation on SOL 113 and YOL 84 (CalME Design Method)

Activity Name	Construction Stages	Construction Productivity	SOL 113 (38 lane-miles)		YOL 84 (4.8 lane-miles)	
			Number of Closures per Treatment	Number of Closures for Activity	Number of Closures per Treatment	Number of Closures for Activity
Low-Speed HMA Rehabilitation	RHMA 0.2 ft.	1.67 mi./closure	23	213	3	27
	HMA 0.6 ft. with AB 1.0 ft.	0.20 mi./closure	190		24	
Medium-Speed HMA Rehabilitation	RHMA 0.2 ft.	1.67 mi./closure	23	159	3	21
	HMA 0.6 ft. with AB 1.0 ft.	0.28 mi./closure	136		18	
High-Speed HMA Rehabilitation	RHMA 0.2 ft.	1.67 mi./closure	23	126	3	16
	HMA 0.6 ft. with AB 1.0 ft.	0.37 mi./closure	103		13	

3.2.3 Construction Work Zone Delay Road User Cost Calculation

Based on the number of closures of each treatment, the construction work zone delay road user cost (CWZD-RUC) for initial construction and future M&R activities discussed in Chapter 2 were calculated for each reconstruction alternative. The CWZD-RUCs were converted to the net present cost (NPC) with a 4% discount rate and the equivalent uniform annual cost (EUAC). The additional travel times (delay) caused by traffic capacity reduction due to lane closure were converted to road user costs. Life cycle CWZD-RUCs were then combined with life cycle agency costs to determine the life cycle cost for each alternative material.

For the R-value design methodology, the CWZD-RUCs of the FDR-C reconstruction were $3.86 million, $3.68 million, and $3.52 million for the low, medium, and high construction speeds, respectively, and the CWZD-RUCs of the HMA rehabilitation were $9.55 million, $6.91 million, and $5.52 million for the low, medium, and high construction speeds, respectively, on SOL 113. The CWZD-RUCs of the FDR-C reconstruction were 41% to 64% of the CWZD-RUCs of the HMA rehabilitation on SOL 113 for the R-value design methodology.

For the CalME design methodology, the CWZD-RUCs of the FDR-C reconstruction were $2.96 million, $2.76 million, and $2.60 million for the low, medium, and high construction speeds, respectively, and the CWZD-RUCs of the HMA rehabilitation were $8.67 million, $6.35 million, and $5.03 million for the low, medium, and high construction speeds, respectively, on SOL 113. The CWZD-RUCs of the FDR-C reconstruction were 34% to 52% of the CWZD-RUCs of the HMA rehabilitation on SOL 113 for the CalME design methodology.

Comparing the CWZD-RUCs shows that the CalME design methodology has 24% to 26% less CWZD-RUCs than the R-value design methodology for the FDR-C reconstruction, and the CalME design methodology has 8% to 9% less CWZD-RUCs than the R-value design methodology for the HMA rehabilitation on SOL 113.

For both the R-value design methodology and the CalME design methodology on YOL 84, the CWZD-RUCs were less than $20,000 and were insignificant when the CWZD-RUCs were compared to the agency construction costs discussed in Section 3.1.

Table 3.9 shows the number of total closures for the activities and the CWZD-RUCs for the FDR-C reconstruction and the HMA rehabilitation on SOL 113 and YOL 84 for both the CalME and R-value design methodologies with low, medium, and high construction speeds.

Table 3.11: CWZD-RUCs for the FDR-C Reconstruction and the HMA Rehabilitation on SOL 113 and YOL 84

Design Methodology	Construction Speed	Activity Name	SOL 113 (19 lane-miles)		YOL 84 (3 lane-miles)	
			Number of Closures	CWZD-RUC ($)	Number of Closures	CWZD-RUC ($)
R-value	Low Speed	FDR-C Reconstruction	97	3,875,800	11	4,800
		HMA Rehabilitation	247	9,550,500	23	15,100
	Medium Speed	FDR-C Reconstruction	92	3,676,100	10	4,300
		HMA Rehabilitation	175	6,912,700	17	10,500
	High Speed	FDR-C Reconstruction	88	3,516,100	10	4,300
		HMA Rehabilitation	142	5,516,100	14	8,200
CalME	Low Speed	FDR-C Reconstruction	74	2,956,900	10	4,900
		HMA Rehabilitation	213	8,669,500	27	14,600
	Medium Speed	FDR-C Reconstruction	69	2,757,100	9	4,500
		HMA Rehabilitation	159	6,352,800	21	11,000
	High Speed	FDR-C Reconstruction	65	2,597,100	9	4,500
		HMA Rehabilitation	126	5,034,300	16	7,700

3.3 Life Cycle Costs

Life cycle costs were calculated by adding total agency costs and road user costs for each material over the 60-year analysis period. The life cycle cost for the FDR-C rehabilitation was compared with the life cycle cost of the HMA reconstruction with the CalME design methodology and the R-value design methodology. For the FDR-C alternatives, 2.5% and 5.0% cement contents with 15-year, 30-year, and 45-year design lives were included. For the HMA reconstruction alternatives, 15% and 25% RAP contents with low, medium, and high (12, 15, and 30 years, respectively) design lives were included. In addition to cement contents for the FDR and RAP contents for HMA, hauling distances and construction speed (slow, medium, and high) were included in the analysis to compare life cycle costs by hauling distance and construction speed. (Note that the agency costs for 15% and 25% RAP alternatives stay the same because the same costs were assumed for both types of HMA mixtures.)

The results of the life cycle costs are shown in Table 3.11 for SOL 113 and Table 3.12 for YOL 84. For SOL 113, the FDR-C alternatives are less expensive than the HMA reconstruction alternatives for both the CalME and R-value design methodologies. The same is true for YOL 84; for the same set of construction conditions, FDR-C alternatives were all cheaper than HMA reconstruction. The life of the initial construction is the most important variable within each alternative type showing the value of better-quality construction and materials.

Table 3.12: Deterministic Life Cycle Agency Costs and Road User Costs as NPC and EUAC for SOL 113

Design Methodology	Construction Speed	Structure Type	Life Cycle Agency Cost (NPC) ($, Millions)	Life Cycle CWZD-RUC (NPC) ($, Millions)	Life Cycle Cost (NPC) ($, Millions)	Life Cycle Cost (EUAC) ($, Millions)
R-value	Low	FDR-C	20.13	40.56	40.41	2.68
		HMA	31.96	46.26	55.09	3.46
	Medium	FDR-C	20.13	40.42	40.34	2.68
		HMA	31.96	43.62	53.77	3.34
	High	FDR-C	20.13	40.26	40.26	2.67
		HMA	31.96	42.26	53.09	3.28
CalME	Low	FDR-C	15.08	39.70	34.93	2.42
		HMA	29.32	45.38	52.01	3.30
	Medium	FDR-C	15.08	39.54	34.85	2.41
		HMA	29.32	43.06	50.85	3.20
	High	FDR-C	15.08	39.38	34.77	2.41
		HMA	29.32	41.78	50.21	3.14

Table 3.13: Life Cycle Agency Costs and Road User Costs as NPC and EUAC for YOL 84

Design Method	Construction Speed	Structure Type	Life Cycle Agency Cost (NPC) ($, Millions)	Life Cycle CWZD-RUC (NPC) ($, Millions)	Life Cycle Cost (NPC) ($, Millions)	Life Cycle Cost (EUAC) ($, Millions)
R-value	Low	FDR-C	3.18	0.03	3.75	0.14
		HMA	4.07	0.05	4.59	0.18
	Medium	FDR-C	3.18	0.03	3.75	0.14
		HMA	4.07	0.05	4.59	0.18
	High	FDR-C	3.18	0.03	3.75	0.14
		HMA	4.07	0.03	4.58	0.18
CalME	Low	FDR-C	2.75	0.03	3.47	0.12
		HMA	3.92	0.05	4.39	0.18
	Medium	FDR-C	2.75	0.03	3.47	0.12
		HMA	3.92	0.05	4.39	0.18
	High	FDR-C	2.75	0.03	3.47	0.13
		HMA	3.92	0.03	4.38	0.17

4 SUMMARY

Pavement LCCA, an engineering analytical technique that uses economic principles to evaluate long-term alternative investment options, supports selection of a cost-effective pavement alternative by balancing initial construction costs and future M&R costs of a new construction, reconstruction, or rehabilitation pavement project. LCCA case studies were completed for rehabilitation of two sections of pavement in Solano County in California on State Route 113 (SOL 113) and State Route 84 (YOL 84). Two alternatives were considered for each section: (1) full depth recycling using cement stabilization (FDR-C) and (2) hot mix asphalt (HMA) remove and replace (also referred to as HMA reconstruction). Costs considered were initial construction, future M&R, and road user construction work zone delay costs. LCCA calculations were completed using a deterministic cost approach and a probabilistic cost approach. In this study a methodology was selected to cluster historical cost data to support both the deterministic and probabilistic approaches and to use that cluster information to build probabilistic estimates of the total costs of a reconstruction alternative using Monte Carlo simulations.

This study looked at specific design cross sections and assumed M&R schedules, unit costs, materials designs, haul distances, and construction times. Two design methodologies were used to determine design cross sections for both the FDR-C and HMA reconstruction alternatives: (1) the empirical R-value method and (2) the mechanistic-empirical CalME method. For the deterministic analysis for the SOL 113 project, with the R-value design methodology and the same design life, haul distance, and construction speed sensitivity variables, the FDR-C agency life cycle costs were approximately 35% less than those of the HMA reconstruction alternatives, the road user delay costs were similar, and the total life cycle costs (agency cost plus road user delay cost) of the FDR-C were approximately 22.5% less than those of the HMA reconstruction. The CalME design methodology for SOL 113 called for less HMA thickness on both alternatives than the R-value designs, particularly for the FDR-C alternative. The CalME design methodology for FDR-C life cycle agency costs were approximately 50% less than those of the HMA reconstruction alternatives, the road user delay costs were approximately 10% less for the FDR-C alternatives, and the total life cycle costs of the FDR-C were approximately 22.5% less than those of the HMA reconstruction.

Road user construction work zone delay costs were of similar scale to agency costs for SOL 113, which has an AADT of approximately 2,600 vehicles per day. The HMA reconstruction alternative included construction of an auxiliary lane to handle traffic during construction, which increased its agency costs. The effects of the life of treatments were important for life cycle cost considerations due to more frequent maintenance interventions in lower-life structures, followed by construction speed related to road user cost.

For YOL 84, for the R-value design methodology and the same design life, haul distance, and construction speed sensitivity variables, the FDR-C agency life cycle costs were approximately 22% less than those of the HMA reconstruction alternatives, the road user delay costs were approximately one-third less, and the total life cycle costs (agency cost plus road user delay cost) of the FDR-C were approximately 18% less than those of the HMA reconstruciton. The CalME design methodology for YOL 84 called for less HMA thickness than the R-value design methodology. The CalME design methodology FDR-C agency life cycle costs were approximately 30% less than those of the HMA reconstruction alternatives, the road user construction work zone delay costs were approximately one-third less, and the total life cycle costs (agency cost plus road user delay cost) of the FDR-C were approximately 25% of those of the HMA reconstruction. Road user construction work zone delay costs were less than 1% of agency costs for YOL 84 because of the very low AADT of approximately 230 vehicles per day.

The results presented for these two case studies provide an early indication of the ranges of differences in life cycle costs, both for the agency and for the road user traveling through the construction work zone. However, as shown by variability of the differences in cost between just these two projects, the full range of cost differences will need to be determined by completing more life cycle cost studies of this type over the full range of contextual variables for projects where FDR-C and HMA reconstruction will be both be considered.

The probabilistic analyses showed the distributions of life cycle costs between the two treatment alternatives for each case study and the amount of overlap of those costs. The probabilistic analyses, supported by the innovative use of machine learning to create agency cost clusters, provide better decision support information regarding the likelihood that one alternative will cost less than the other.

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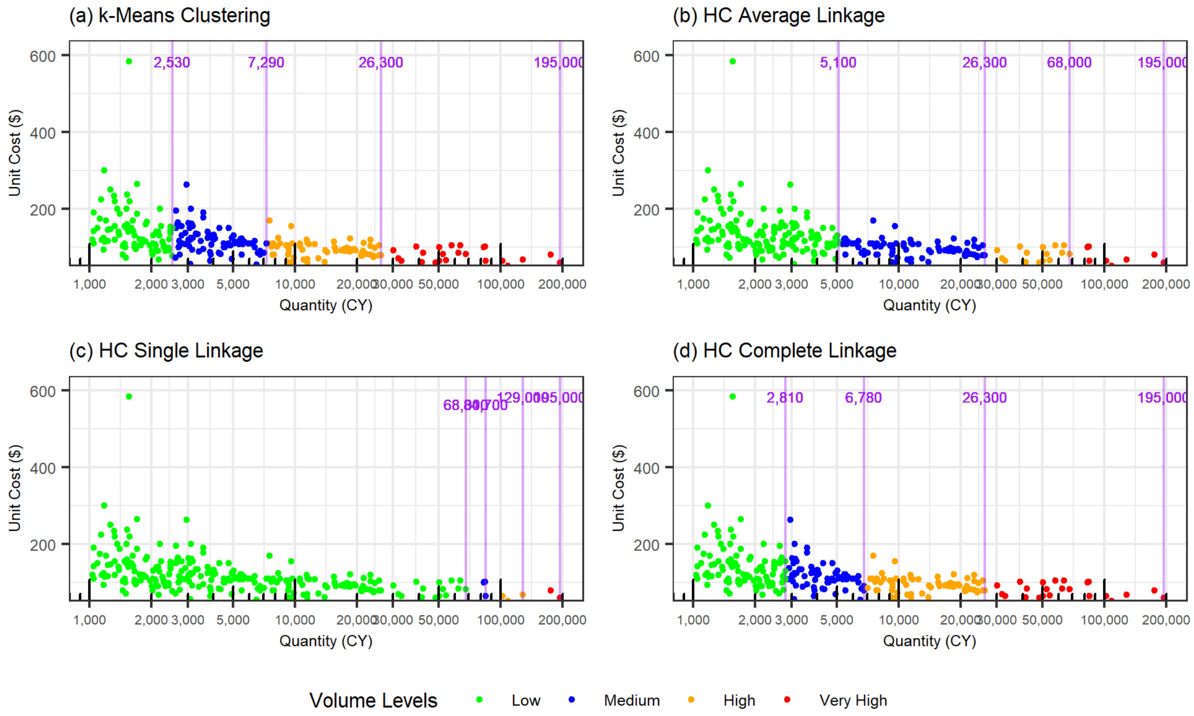
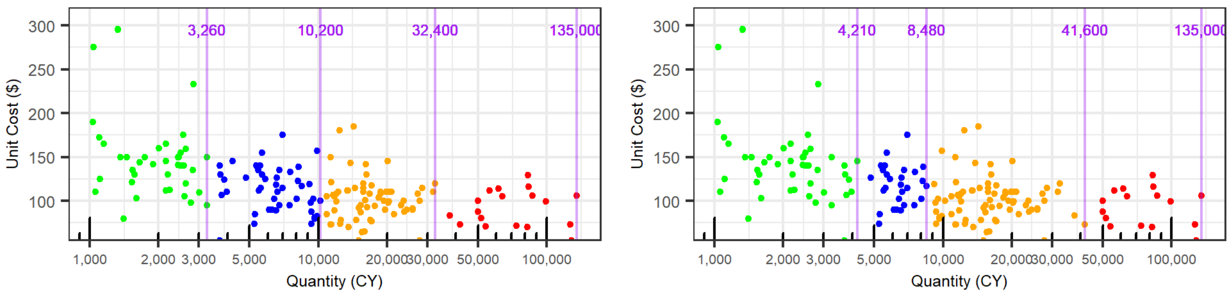
APPENDIX A CLUSTERING RESULTS OF HOT MIX ASPHALT



APPENDIX B CLUSTERING RESULTS OF RUBBERIZED HOT MIX ASPHALT

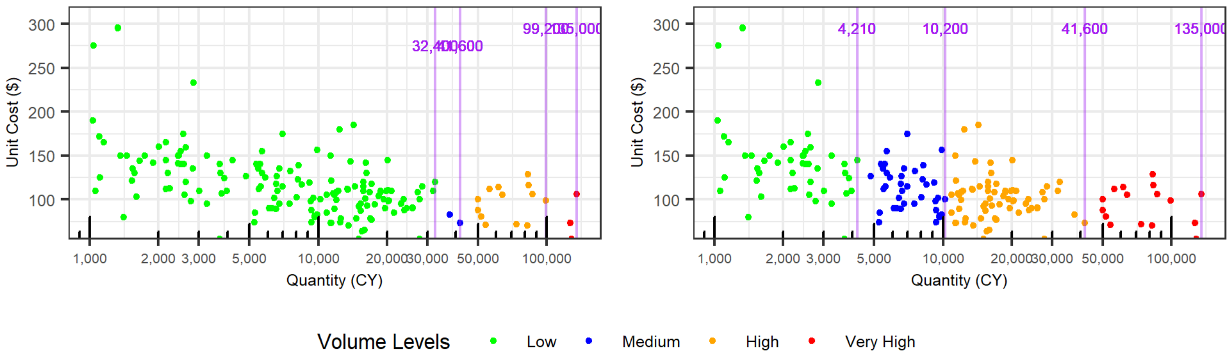
(a) k-Means Clustering

(b) HC Average Linkage

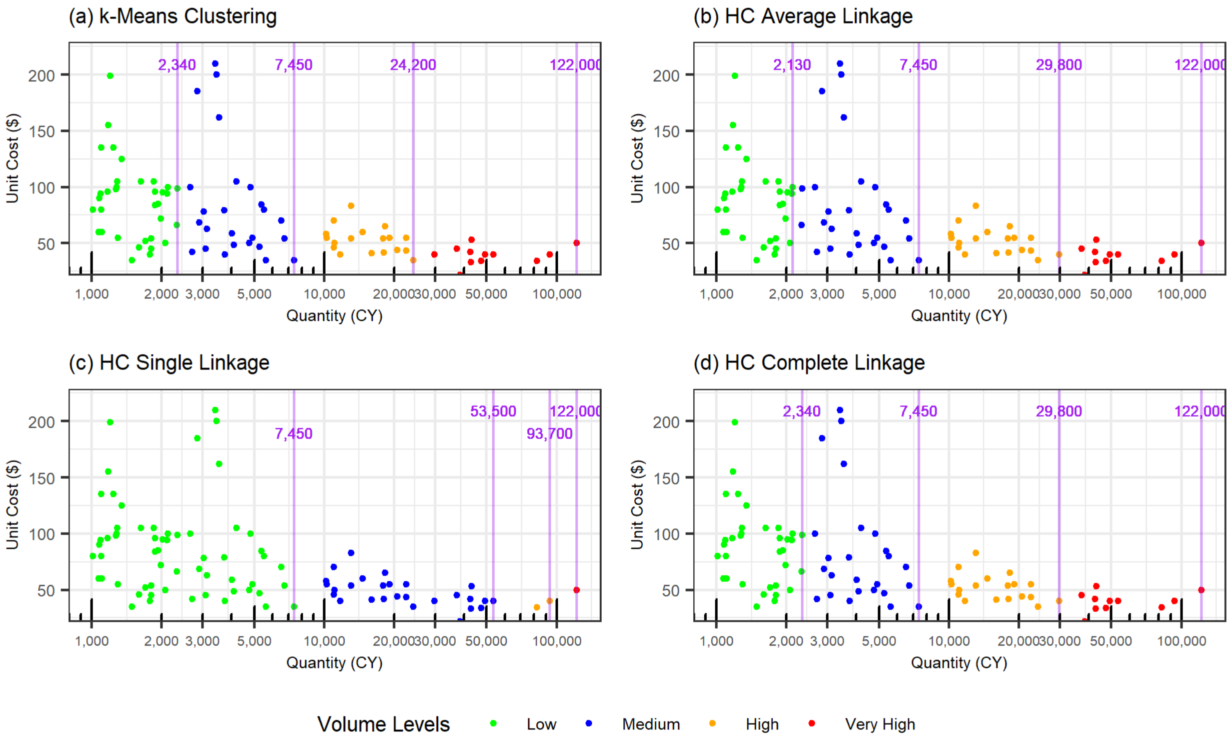


(c) HC Single Linkage

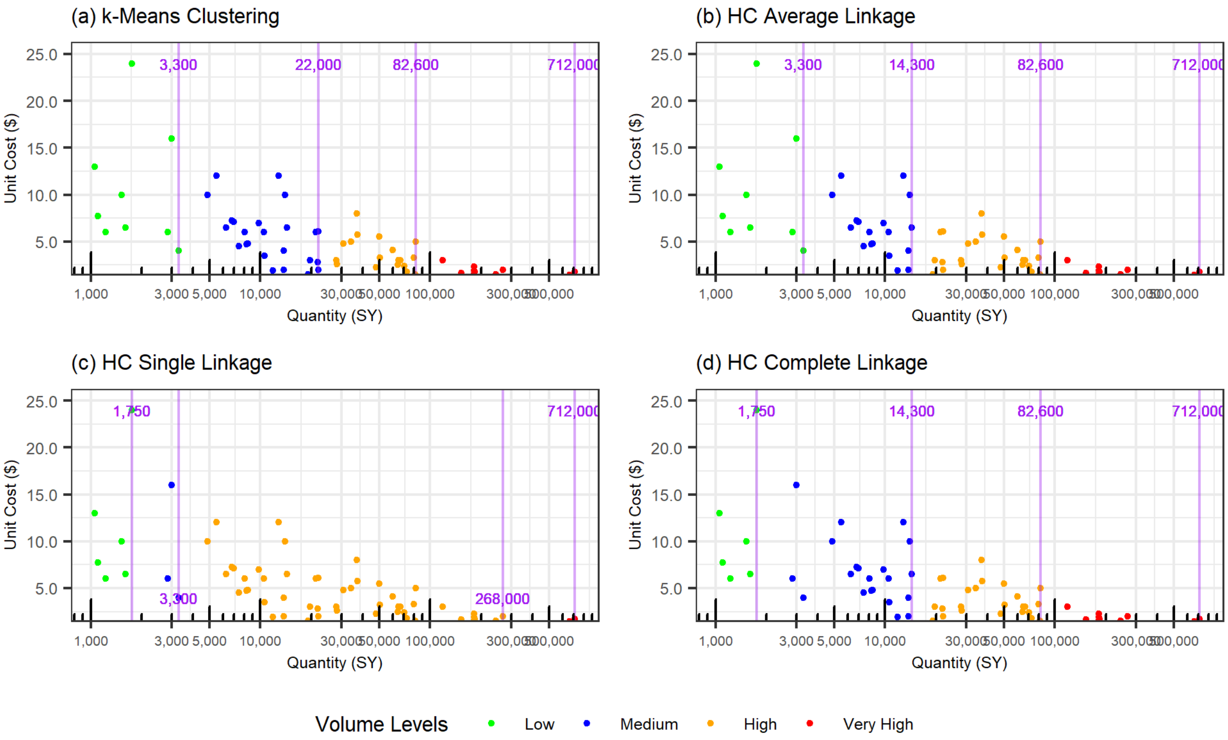
(d) HC Complete Linkage



APPENDIX C CLUSTERING RESULTS OF AGGREGATE BASE



APPENDIX D CLUSTERING RESULTS OF COLD PLANE



APPENDIX E R-VALUE DESIGN ALTERNATIVE USING 1.5 FT. FDR-C AND LIFE CYCLE COST RESULTS

This section describes a third design methodology, in addition to the R-value and CalME methodologies discussed in this report. Another structural alternative was considered with a 1.5 ft. FDR-C layer instead of the 1 ft. FDR-C layer using the R-value methodology. This section includes the design description, M&R sequences, and life cycle cost results for that structure. Figure E.1 and Figure E.2 show the structures for SOL 113 and YOL 84, respectively.

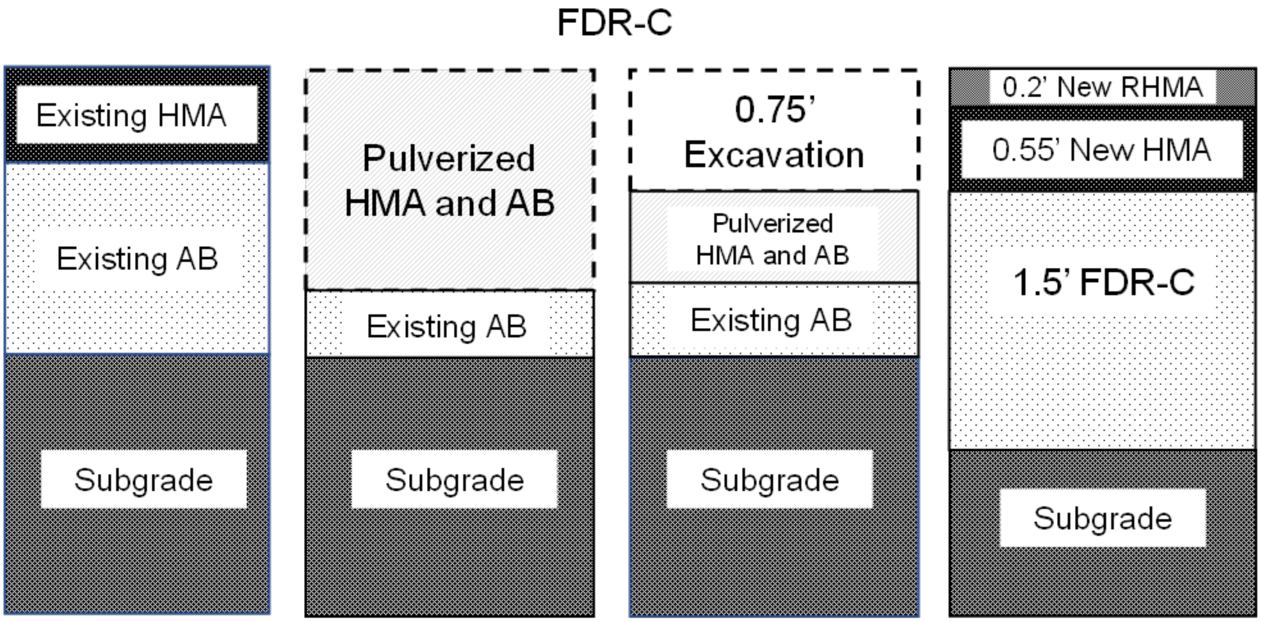


Figure E.1: FDR-C structure for SOL 113 using a 1.5 ft. FDR-C layer designed with the R-value method.

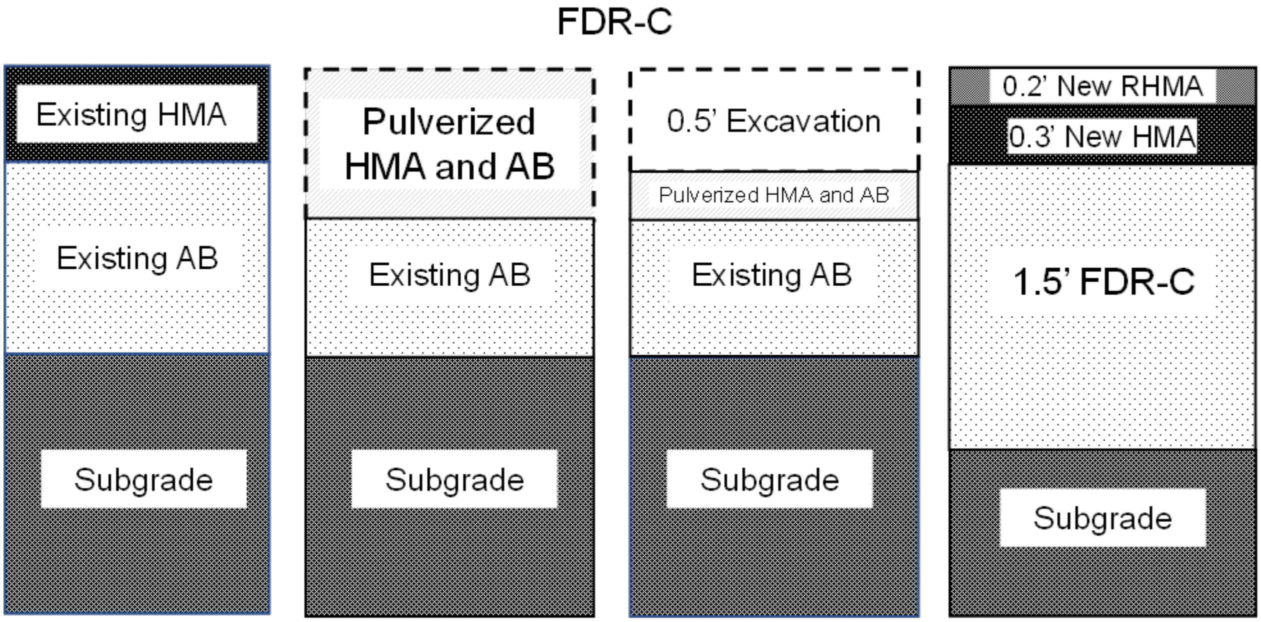


Figure E.2: FDR-C structure for YOL 84 using a 1.5 ft. FDR-C layer designed with the R-value method.

Table E.1 and Table E.2 show the assumed M&R sequences for the SOL 113 and YOL 84 structures.

Table E.1: FDR-C M&R Sequence for SOL 113 using the R-Value Design Methodology with a 1.5 ft. FDR-C Layer

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C (2.5% cement)	1.5	0	30
HMA	0.55	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Table E.2: FDR-C M&R Sequence for YOL 84 using the R-Value Design Methodology with a 1.5 ft. FDR-C Layer

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C (2.5% cement)	1.5	0	30
HMA	0.3	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Mill and Medium Overlay	0.4	30	15
Chip Seal	n/a	38	7
Mill and Thin Overlay	0.2	45	10
Chip Seal	n/a	50	5
Mill and Thin Overlay	0.2	55	5

Using the methodologies described in Section 3.1.3 and Section 3.1.4, the life cycle agency cost was determined for the structures shown in Figure E.1 and Figure E.2. Figure E.3 and Figure E.4 show the probabilistic cost comparison of the life cycle agency costs of the 1.5 ft. FDR-C structure and the HMA reconstruction alternative (described in Section 1.2). Figure E.5 and Figure E.6 show the deterministic cost comparisons for the same conditions.

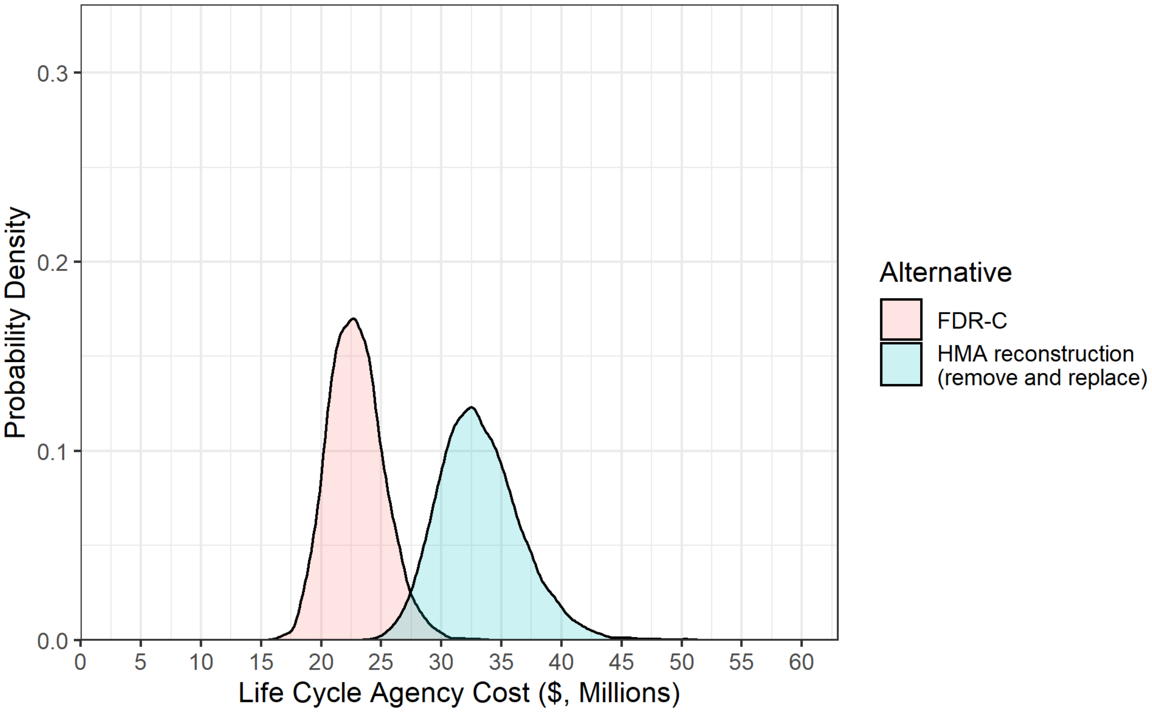


Figure E.3: Probabilistic cost comparison for SOL 113 structures using R-value design methodology with a 1.5 ft. FDR-C layer.

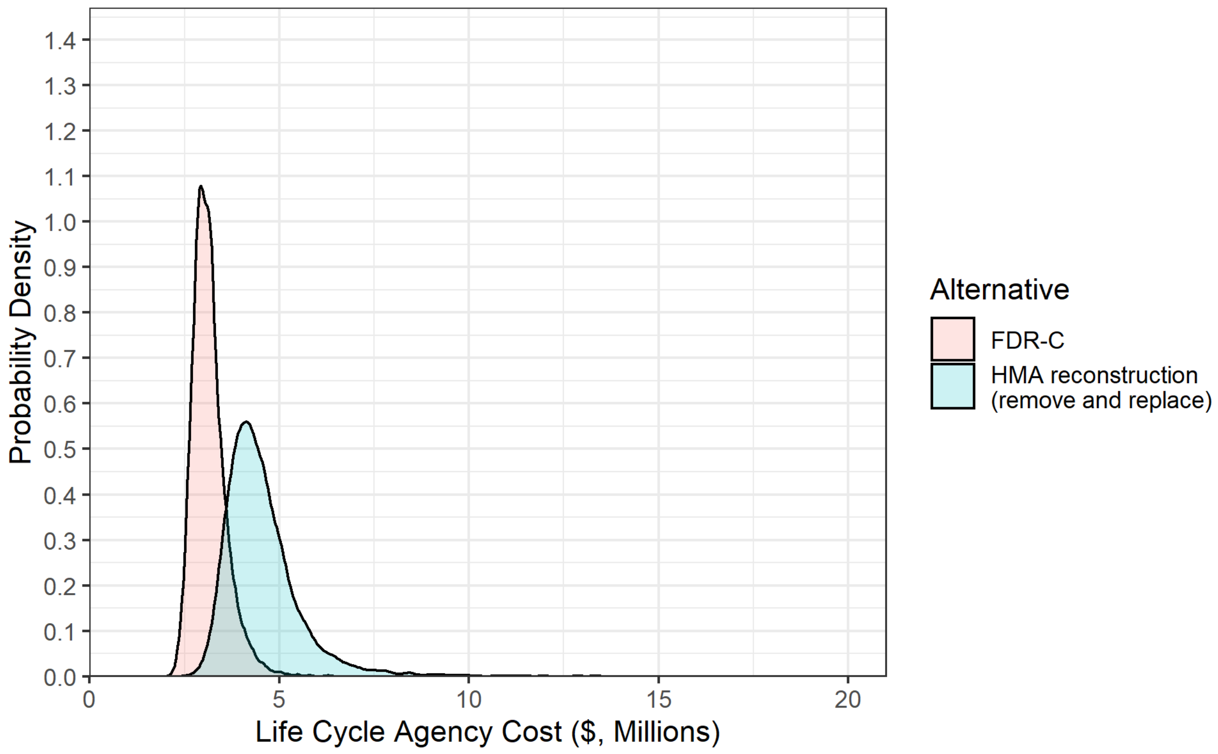


Figure E.4: Probabilistic cost comparison for YOL 84 structures using R-value design methodology with a 1.5 ft. FDR-C layer.

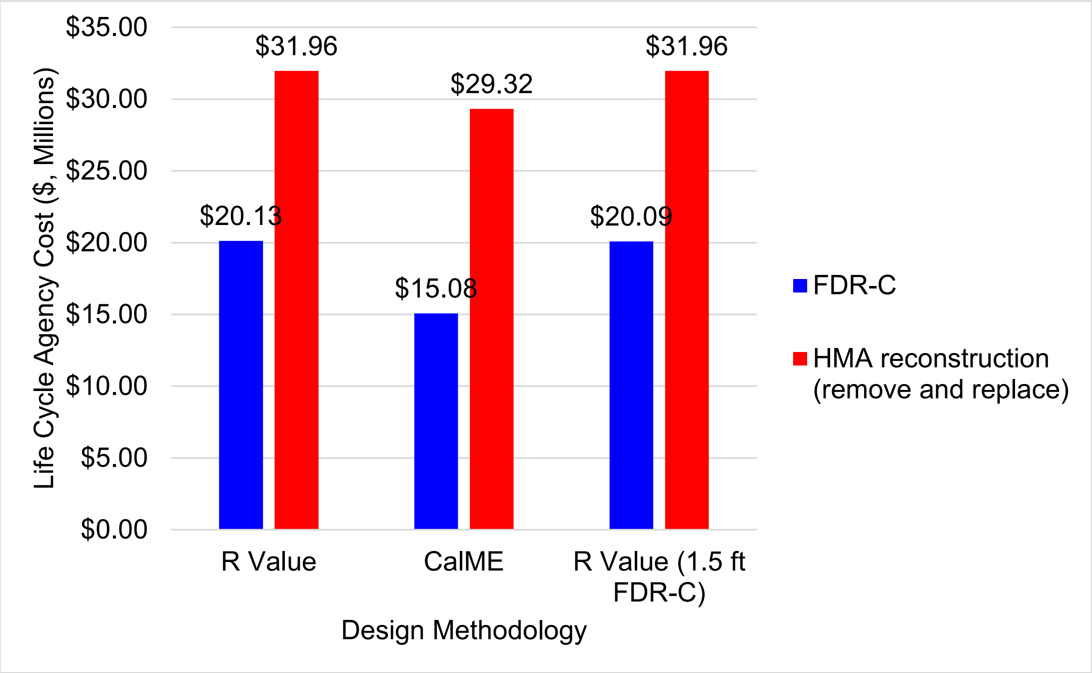


Figure E.5: Deterministic life cycle agency costs for SOL 113 structures including the 1.5 ft. FDR-C structure.

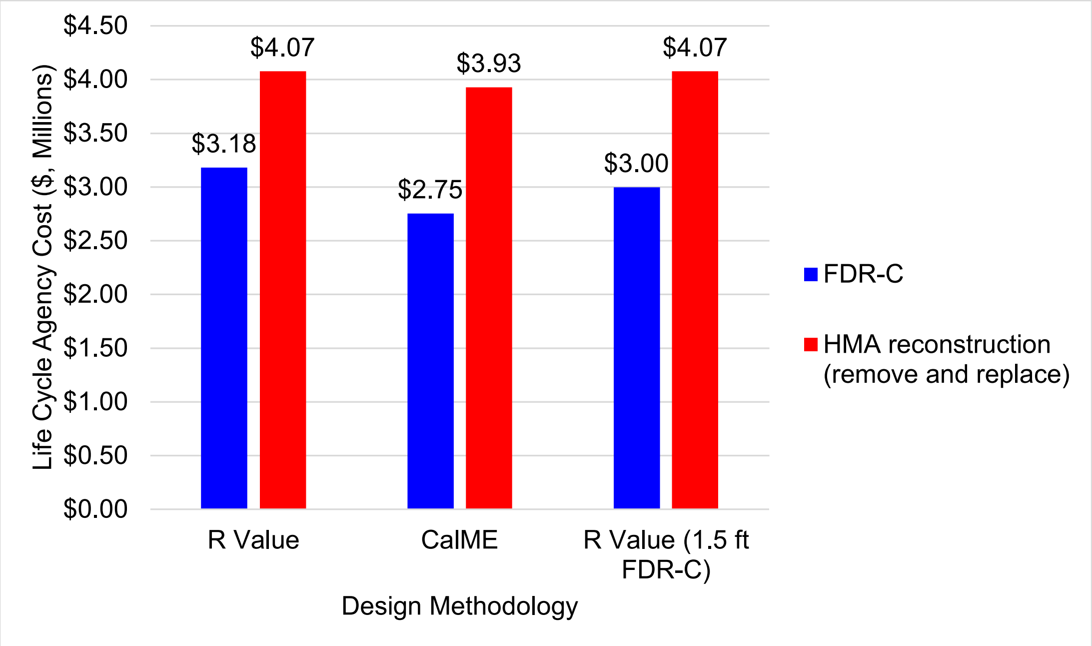


Figure E.6: Deterministic life cycle agency costs for YOL 84 structures including the 1.5 ft. FDR-C structure.

APPENDIX F SENSITIVITY ANALYSIS FOR STRUCTURE LIFE

This section describes the life cycle costing for short-term and long-life structures. Chapter 3 reviewed the results for the medium-life structures. This section contains the M&R schedules and the probabilistic and deterministic life cycle agency costs for the short-term and long-life structures for SOL 113 and YOL 84 to address the sensitivity of the life cycle costing process to varying structure life. The variation in structure life can be caused by material quality and construction procedures followed. Table F.1 to Table F.10 show the M&R structures for the short-life and long-life structures for SOL 113 using the R-value and CalME design methodologies.

Table F.1: Short-Life FDR-C M&R Sequence for SOL 113 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	15
HMA	0.7	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	15
Chip Seal	n/a	30	7
FDR-C	1.0	37	15
HMA	0.7	37	22
RHMA	0.2	37	22
Chip Seal	n/a	45	7
Chip Seal	0.2	52	7
Mill and Medium Overlay	0.4	59	15

Note: SOL 113, short-life FDR-C (15-year life), 60-year analysis period.

Table F.2: Short-Life FDR-C M&R Sequence for SOL 113 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	15
HMA	0.2	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	15
Chip Seal	n/a	30	7
FDR-C	1.0	37	15
HMA	0.2	37	22
RHMA	0.2	37	22
Chip Seal	n/a	45	7
Chip Seal	0.2	52	7
Mill and Medium Overlay	0.4	59	15

Note: SOL 113, short-life FDR-C (15-year life), 60-year analysis period.

Table F.3: Short-Life FDR-C M&R Sequence for SOL 113 Using the R-Value Design Methodology with a 1.5 ft. FDR-C Layer

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.5	0	15
HMA	0.55	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	15
Chip Seal	n/a	30	7
FDR-C	1.0	37	15
HMA	0.55	37	22
RHMA	0.2	37	22
Chip Seal	n/a	45	7
Chip Seal	0.2	52	7
Mill and Medium Overlay	0.4	59	15

Note: SOL 113, short-life FDR-C (15-year life), 60-year analysis period.

Table F.4: Short-Life HMA Reconstruction M&R Sequence for SOL 113 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
Aux Lane HMA	0.2	0	1
Aux Lane AB	1	0	1
AB and compact Subgrade	1.6	0	60
HMA	0.55	0	12
RHMA	0.2	0	12
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	10
Chip Seal	n/a	27	5
HMA	0.55	32	12
RHMA	0.2	32	12
Chip Seal	n/a	40	7
Chip Seal	n/a	47	7
Mill and Medium Overlay	0.4	54	10

Note: SOL 113, short-life HMA (12-year life), 60-year analysis period.

Table F.5: Short-Life HMA Reconstruction M&R Sequence for SOL 113 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
Aux Lane HMA	0.2	0	1
Aux Lane AB	1	0	1
AB and compact Subgrade	1	0	60
HMA	0.6	0	12
RHMA	0.2	0	12
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	10
Chip Seal	n/a	27	5
HMA	0.6	32	12
RHMA	0.2	32	12
Chip Seal	n/a	40	7
Chip Seal	n/a	47	7
Mill and Medium Overlay	0.4	54	10

Note: SOL 113, short-life HMA (12-year life), 60-year analysis period.

Table F.6: Long-Life FDR-C M&R Sequence for SOL 113 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	45
HMA	0.7	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	5
Mill and Thin Overlay	0.2	52	15

Note: SOL 113, long-life FDR (45-year life), 60-year analysis period.

Table F.7: Long-Life FDR-C M&R Sequence for SOL 113 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	45
HMA	0.2	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	5
Mill and Thin Overlay	0.2	52	15

Note: SOL 113, long-life FDR (45-year life), 60-year analysis period.

Table F.8: Long-Life FDR-C M&R Sequence for SOL 113 Using the R-Value Design Methodology with a 1.5 ft. FDR-C Layer

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.5	0	45
HMA	0.55	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	5
Mill and Thin Overlay	0.2	52	15

Note: SOL 113, long-life FDR (45-year life), 60-year analysis period.

Table F.9: Long-Life HMA Reconstruction M&R Sequence for SOL 113 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
Aux Lane HMA	0.2	0	1
Aux Lane AB	1	0	1
AB and Compact SG	1.6	0	60
HMA	0.55	0	30
RHMA	0.2	0	30
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	7
Mill and Thin Overlay	0.2	52	15

Note: SOL 113, long-life HMA (30-year life), 60-year analysis period.

Table F.10: Long-Life HMA Reconstruction M&R Sequence for SOL 113 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
Aux Lane HMA	0.2	0	1
Aux Lane AB	1	0	1
AB and Compact SG	1	0	60
HMA	0.6	0	30
RHMA	0.2	0	30
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	7
Mill and Thin Overlay	0.2	52	15

Note: SOL 113, long-life HMA (30-year life), 60-year analysis period.

Table F.11 to Table F.20 show the M&R structures for the short-term and long-life structures for YOL 84 using the R-value and CalME design methodologies.

Table F.11: Short-Life FDR-C M&R Sequence for YOL 84 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	15
HMA	0.5	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	15
Chip Seal	n/a	30	7
FDR-C	1.0	37	15
HMA	0.7	37	22
RHMA	0.2	37	22
Chip Seal	n/a	45	7
Chip Seal	0.2	52	7
Mill and Medium Overlay	0.4	59	15

Note: YOL 84, short-life FDR-C (15-year life), 60-year analysis period.

Table F.12: Short-Life FDR-C M&R Sequence for YOL 84 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	15
HMA	0.2	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	15
Chip Seal	n/a	30	7
FDR-C	1.0	37	15
HMA	0.2	37	22
RHMA	0.2	37	22
Chip Seal	n/a	45	7
Chip Seal	0.2	52	7
Mill and Medium Overlay	0.4	59	15

Note: YOL 84, short-life FDR-C (15-year life), 60-year analysis period.

Table F.13: Short-Life FDR-C M&R Sequence for YOL 84 Using the R-Value Design Methodology with a 1.5 ft. FDR-C Layer

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.5	0	15
HMA	0.3	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	15
Chip Seal	n/a	30	7
FDR-C	1.0	37	15
HMA	0.3	37	12
RHMA	0.2	37	12
Chip Seal	n/a	45	7
Chip Seal	0.2	52	7
Mill and Medium Overlay	0.4	59	15

Note: YOL 84, short-life FDR-C (15-year life), 60-year analysis period.

Table F.14:. Short-Life HMA Reconstruction M&R Sequence for YOL 84 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
HMA	1.05	0	12
RHMA	0.2	0	12
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	10
Chip Seal	n/a	27	5
HMA	1.05	32	12
RHMA	0.2	32	12
Chip Seal	n/a	40	7
Chip Seal	n/a	47	7
Mill and Medium Overlay	0.4	54	10

Note: YOL 84, short-life HMA (12-year life), 60-year analysis period.

Table F.15: Short-Life HMA Reconstruction M&R Sequence for YOL 84 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
AB and compact Subgrade	1	0	60
HMA	0.6	0	12
RHMA	0.2	0	12
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Medium Overlay	0.4	22	10
Chip Seal	n/a	27	5
HMA	0.6	32	12
RHMA	0.2	32	12
Chip Seal	n/a	40	7
Chip Seal	n/a	47	7
Mill and Medium Overlay	0.4	54	10

Note: YOL 84, short-life HMA (12-year life), 60-year analysis period.

Table F.16: Long-Life FDR-C M&R Sequence for YOL 84 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	45
HMA	0.5	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	5
Mill and Thin Overlay	0.2	52	15

Note: YOL 84, long-life FDR (45-year life), 60-year analysis period.

Table F.17: Long-Life FDR-C M&R Sequence for YOL 84 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.0	0	45
HMA	0.2	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	5
Mill and Thin Overlay	0.2	52	15

Note: YOL 84, long-life FDR (45-year life), 60-year analysis period.

Table F.18: Long-Life FDR-C M&R Sequence for YOL 84 Using the R-Value Design Methodology with a 1.5 ft. FDR-C layer

Activity Name	Thickness (ft.)	Year of Work	Life (years)
FDR-C	1.5	0	45
HMA	0.3	0	22
RHMA	0.2	0	22
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	5
Mill and Thin Overlay	0.2	52	15

Note: YOL 84, long-life FDR (45-year life), 60-year analysis period.

Table F.19: Long-Life HMA Reconstruction M&R Sequence for YOL 84 Using the R-Value Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
HMA	1.05	0	30
RHMA	0.2	0	30
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	7
Mill and Thin Overlay	0.2	52	15

Note: YOL 84, long-life HMA (30-year life), 60-year analysis period.

Table F.20: Long-Life HMA Reconstruction M&R Sequence for YOL 84 Using the CalME Design Methodology

Activity Name	Thickness (ft.)	Year of Work	Life (years)
AB and Compact SG	1	0	60
HMA	0.6	0	30
RHMA	0.2	0	30
Chip Seal	n/a	8	7
Chip Seal	n/a	15	7
Mill and Thin Overlay	0.2	22	15
Chip Seal	n/a	30	7
Mill and Medium Overlay	0.4	37	15
Chip Seal	n/a	45	7
Mill and Thin Overlay	0.2	52	15

Note: YOL 84, long-life HMA (30-year life), 60-year analysis period.

Figure F.1 to Figure F.6 show the probabilistic costs for SOL 113 for short-life and long-life structures.

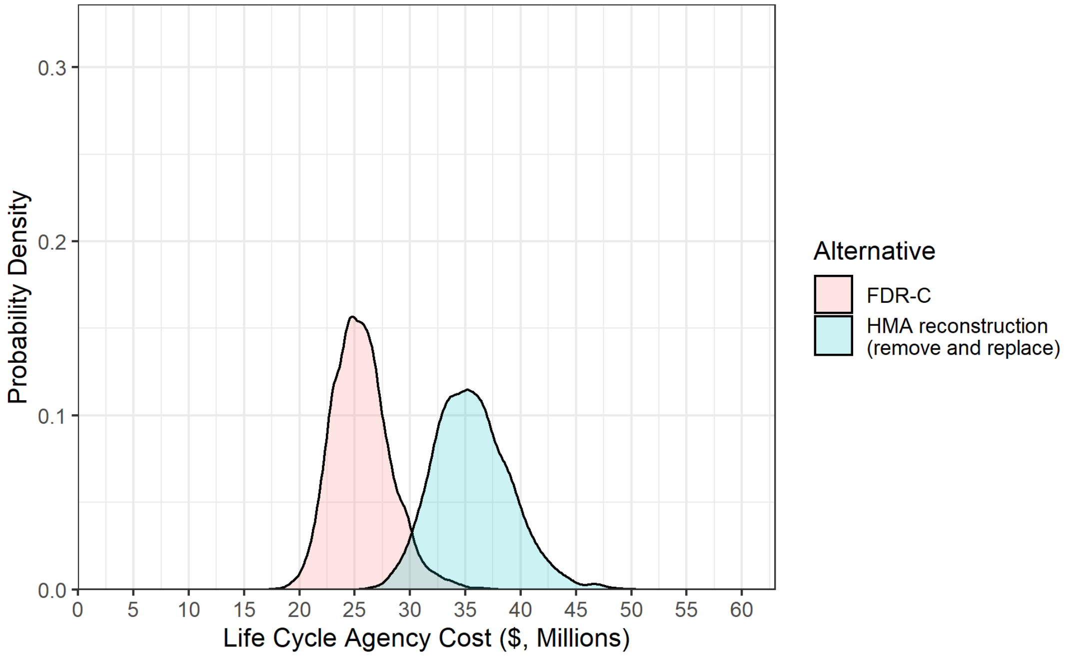


Figure F.1: Probabilistic cost comparison for SOL 113 structures using the R-value design methodology for short-life structures.

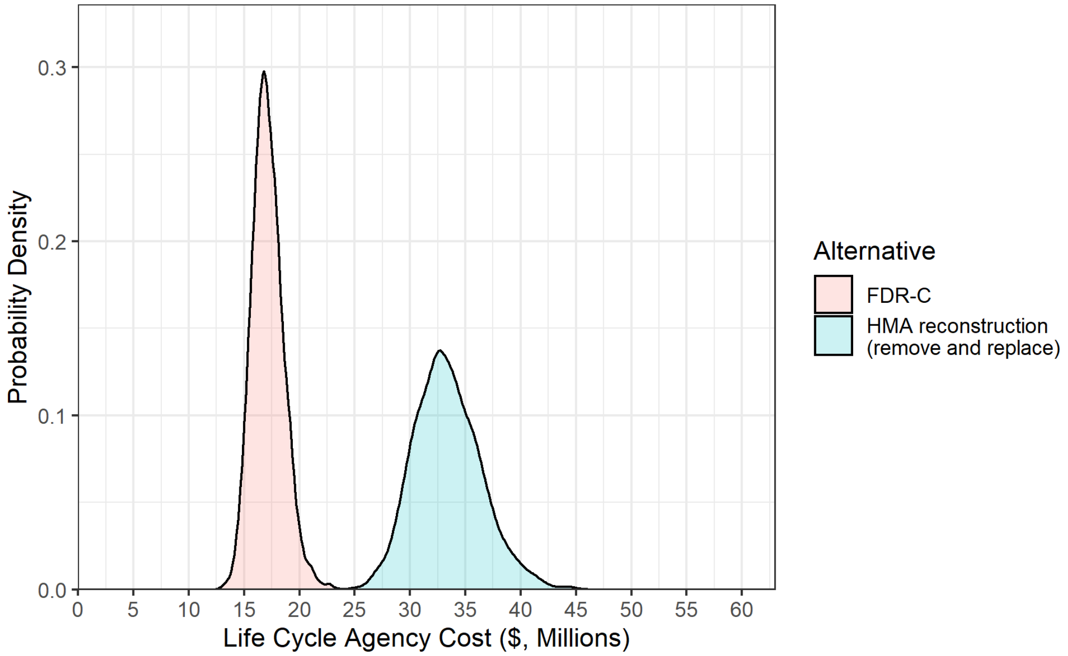


Figure F.2: Probabilistic cost comparison for SOL 113 structures using the CalME design methodology for short-life structures.

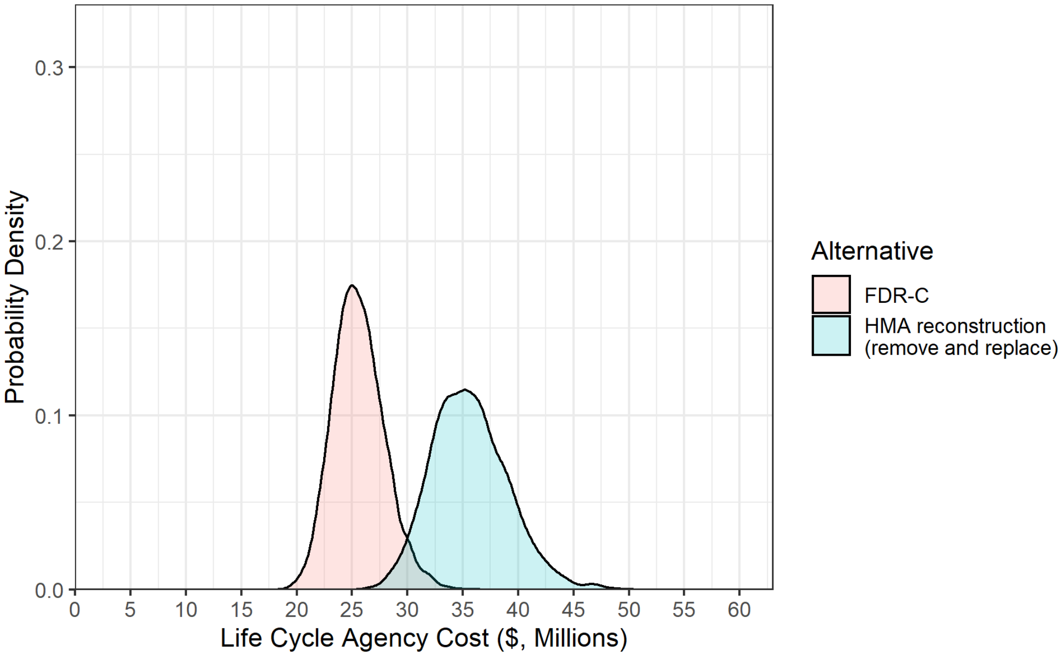


Figure F.3: Probabilistic cost comparison for SOL 113 structures using the R-value design methodology with a 1.5 ft. FDR-C layer for short-life structures.

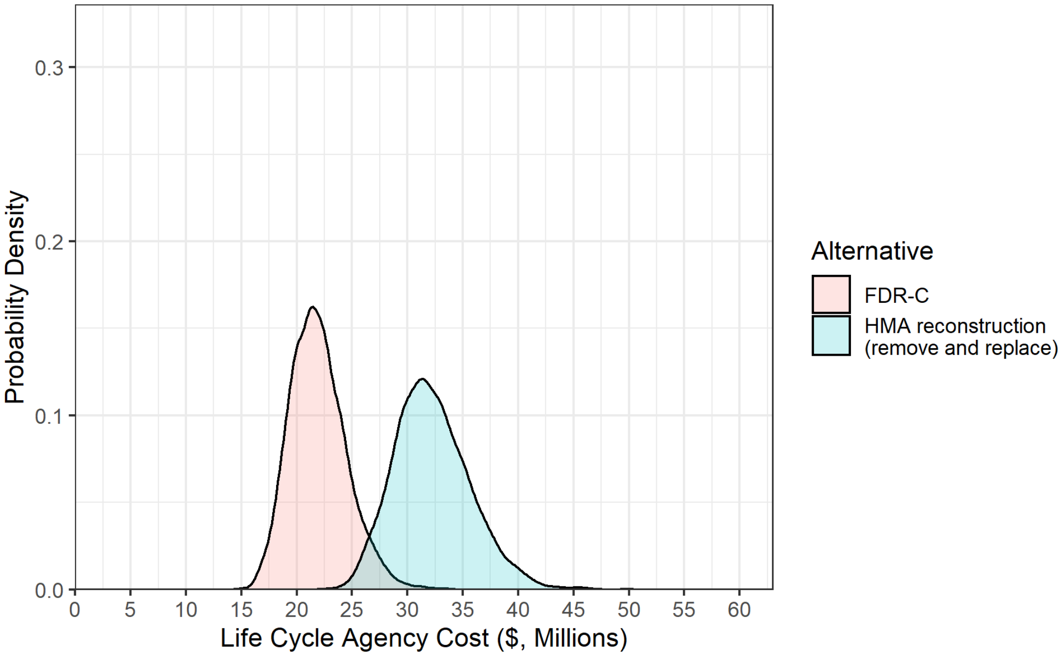


Figure F.4: Probabilistic cost comparison for SOL 113 structures using R-value design methodology for long-life structures.

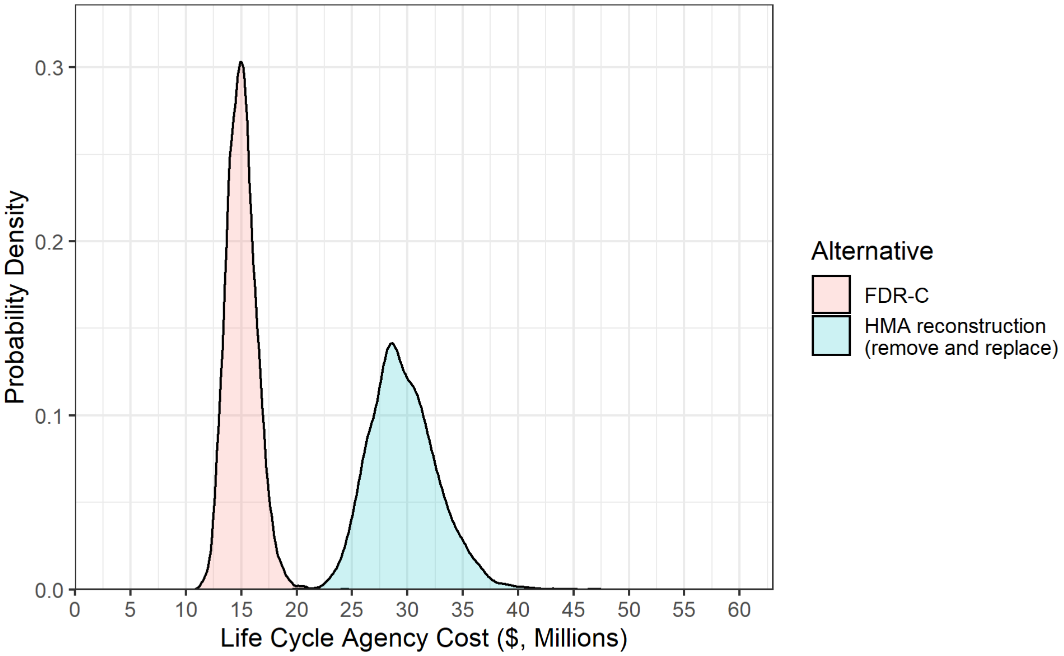


Figure F.5: Probabilistic cost comparison for SOL 113 structures using the CalME design methodology for long-life structures.

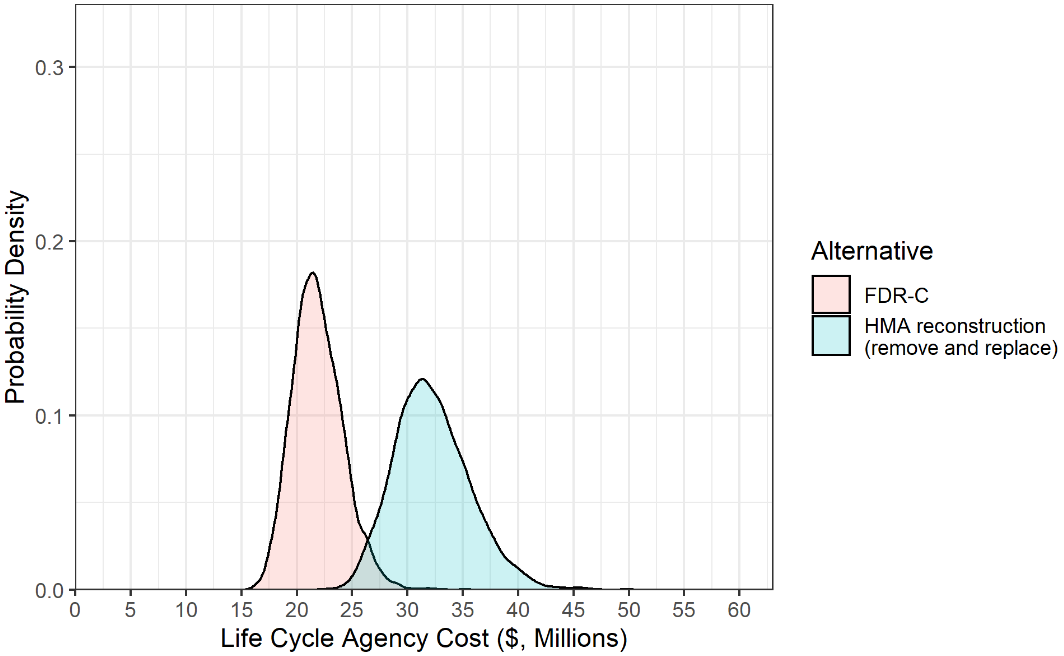


Figure F.6: Probabilistic cost comparison for SOL 113 structures using the R-value design methodology with a 1.5 ft. FDR-C layer for long-life structures.

Figure F.7 to Figure F.12 show the probabilistic costs for YOL 84 for short-life and long-life structures.

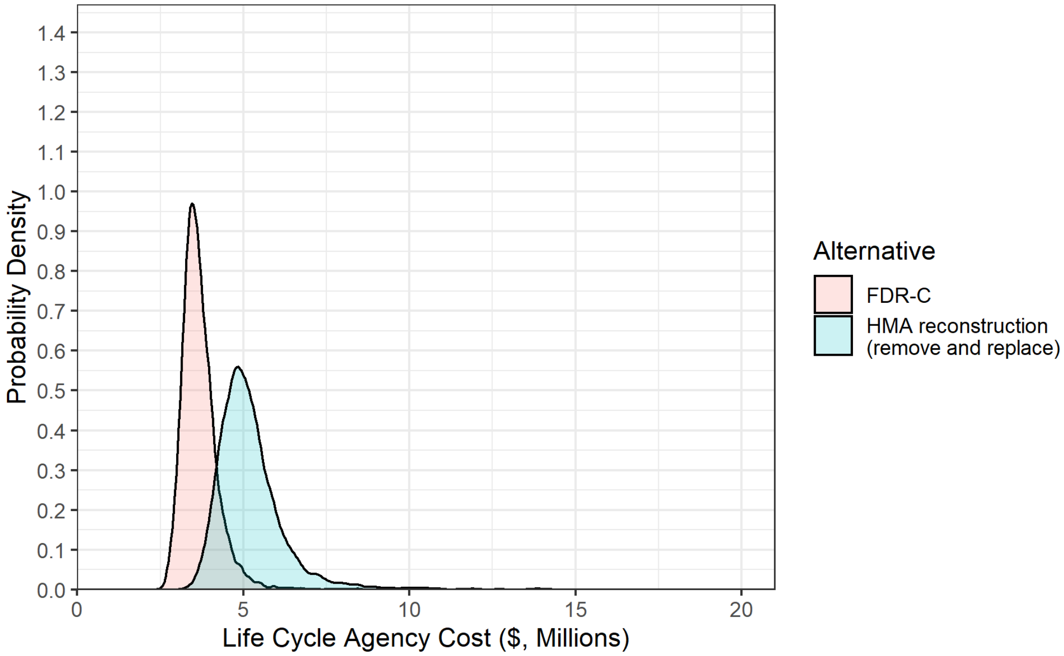


Figure F.7: Probabilistic cost comparison for YOL 84 structures using R-value design methodology for short-life structures.

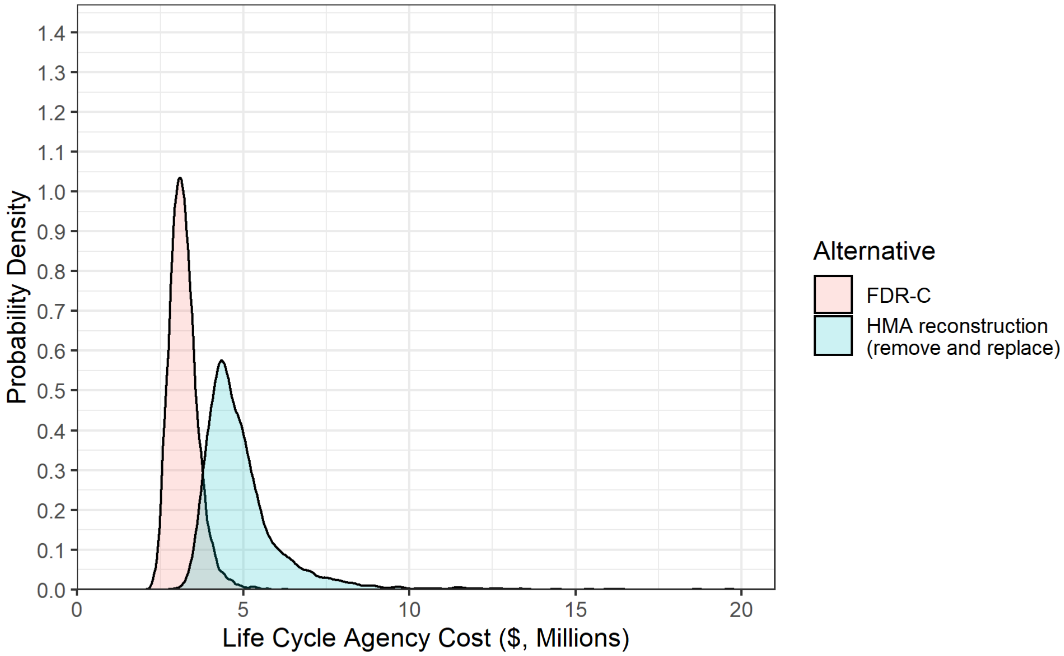
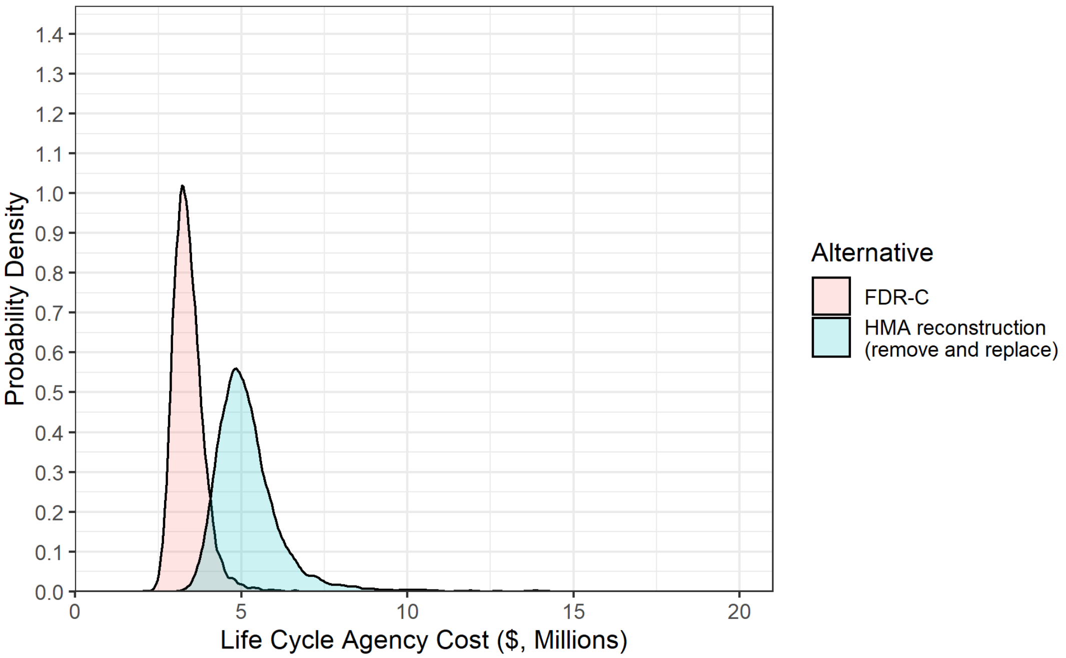


Figure F.8: Probabilistic cost comparison for YOL 84 structures using the CalME design methodology for short-life structures.



FigureF.9: Probabilistic cost comparison for YOL 84 structures using the R-value design methodology with a 1.5 ft. FDR-C layer for short-life structures.

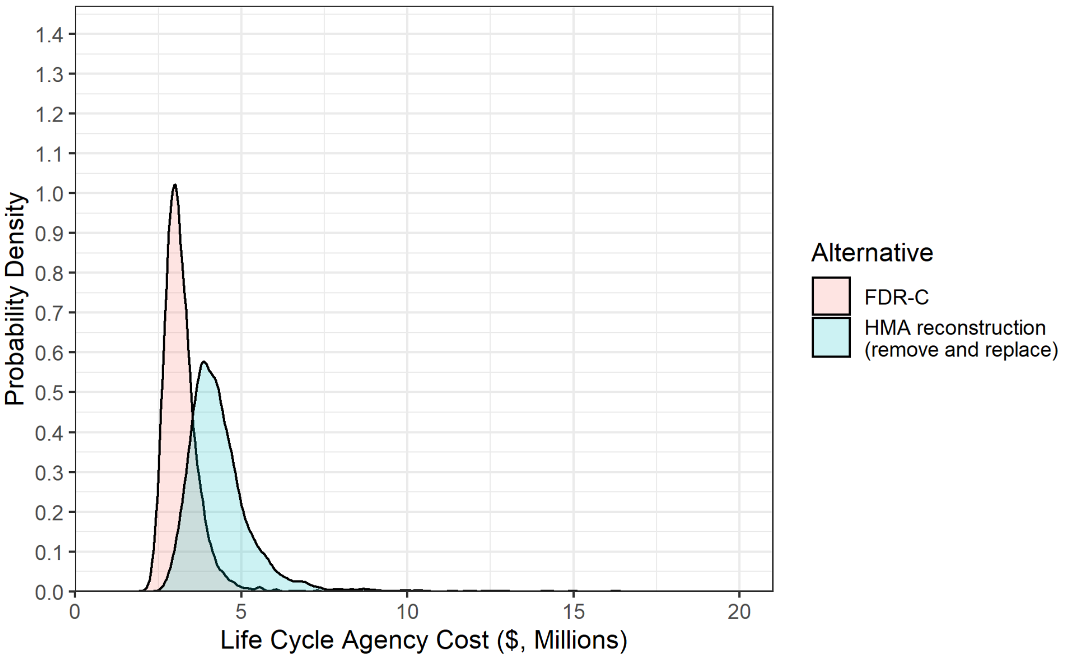


Figure F.10: Probabilistic cost comparison for YOL 84 structures using R-value design methodology for long-life structures.

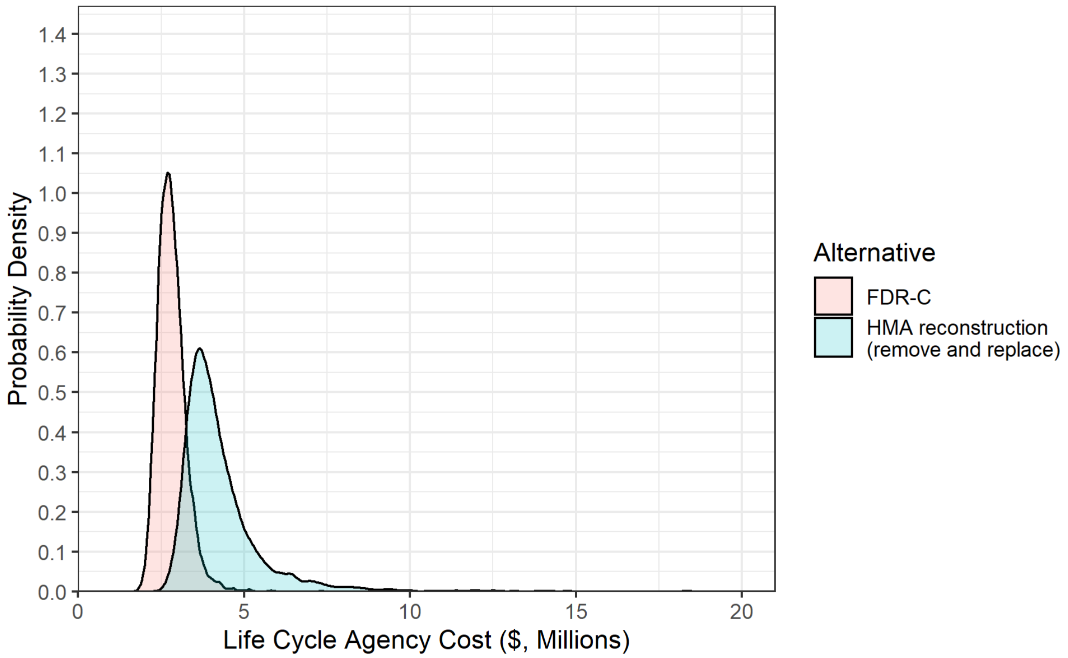


Figure F.11: Probabilistic cost comparison for YOL 84 structures using the CalME design methodology for long-life structures.

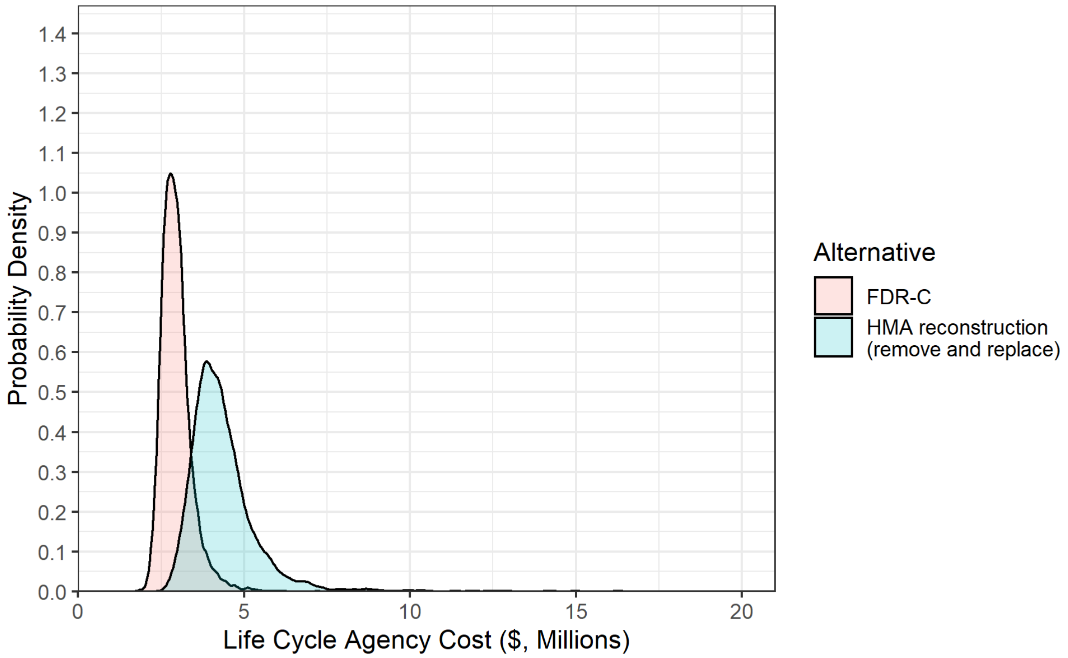


Figure F.12: Probabilistic cost comparison for YOL 84 structures using the R-value design methodology with a 1.5 ft. FDR-C layer for long-life structures.

Figure F.13 and Figure F.14 show the deterministic life cycle agency cost for SOL 113 structures for short-life and long-life structures, respectively.

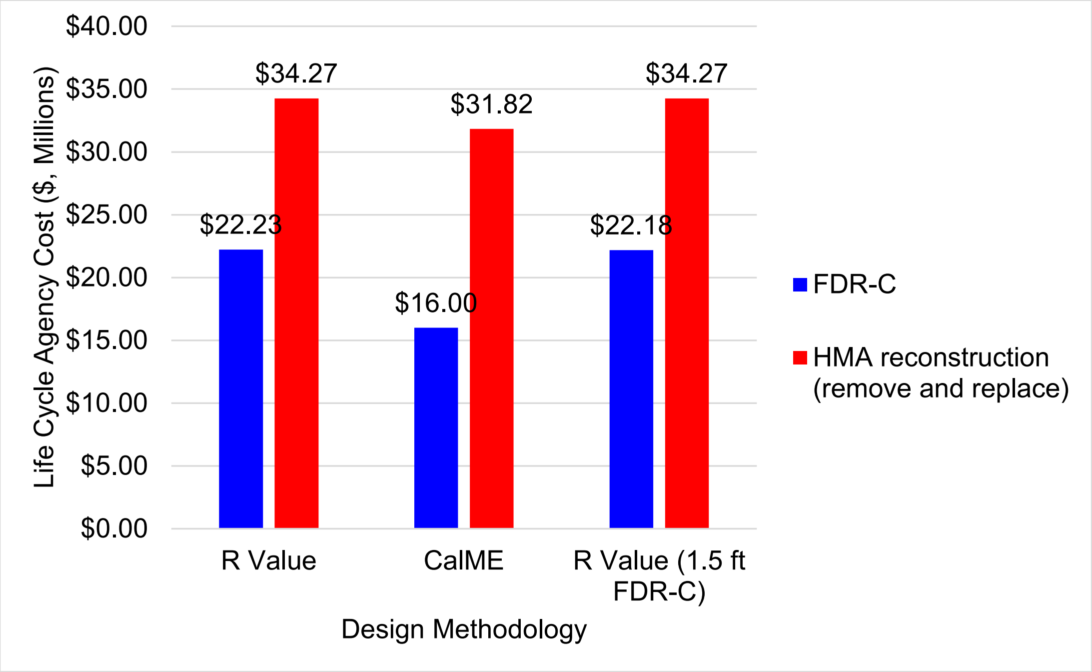


Figure F.13: Life cycle agency cost for SOL 113 for short-life structures.

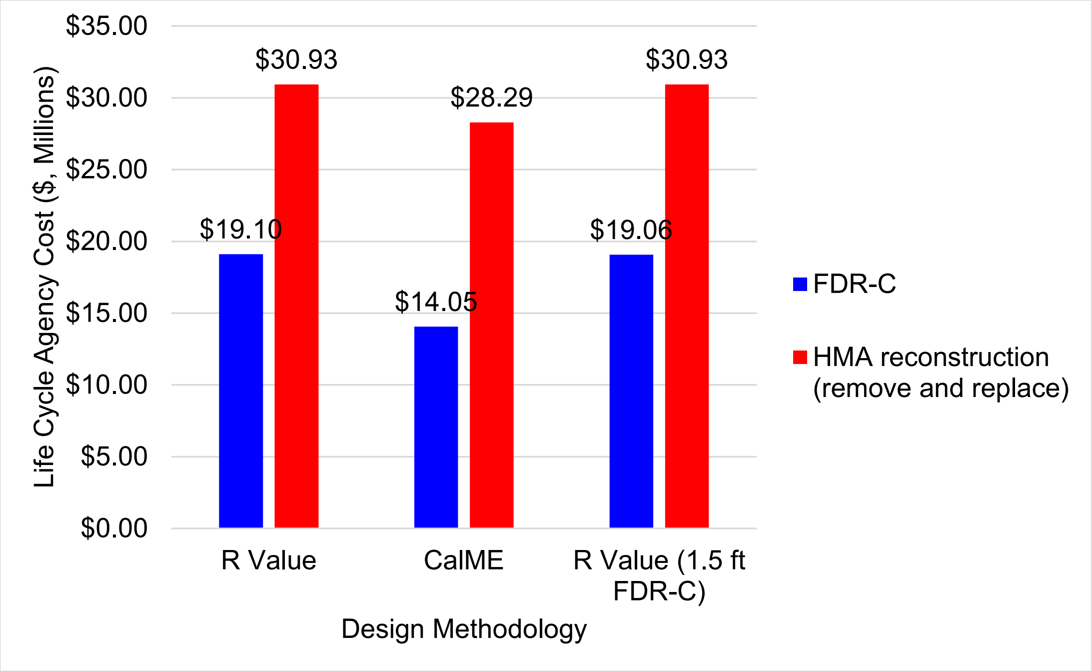


Figure F.14: Life cycle agency cost for SOL 113 for long-life structures.

Figure F.15 and Figure F.16 show the deterministic life cycle agency cost for YOL 84 structures for short-life and long-life structures, respectively.

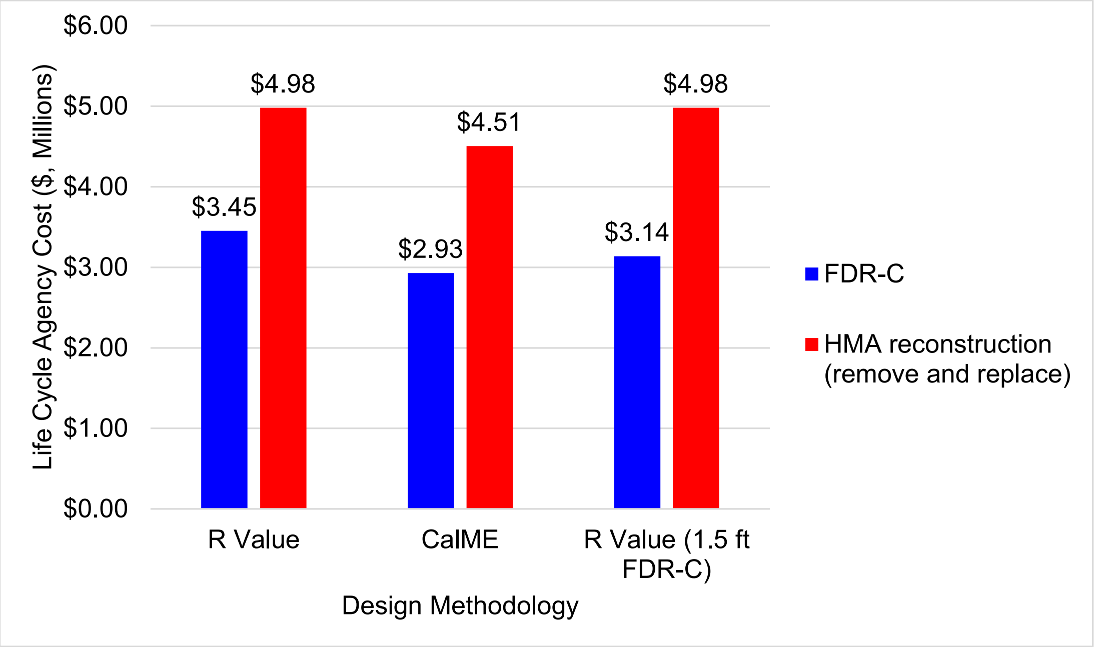


Figure F.15: Life cycle agency cost for YOL 84 for short-life structures.

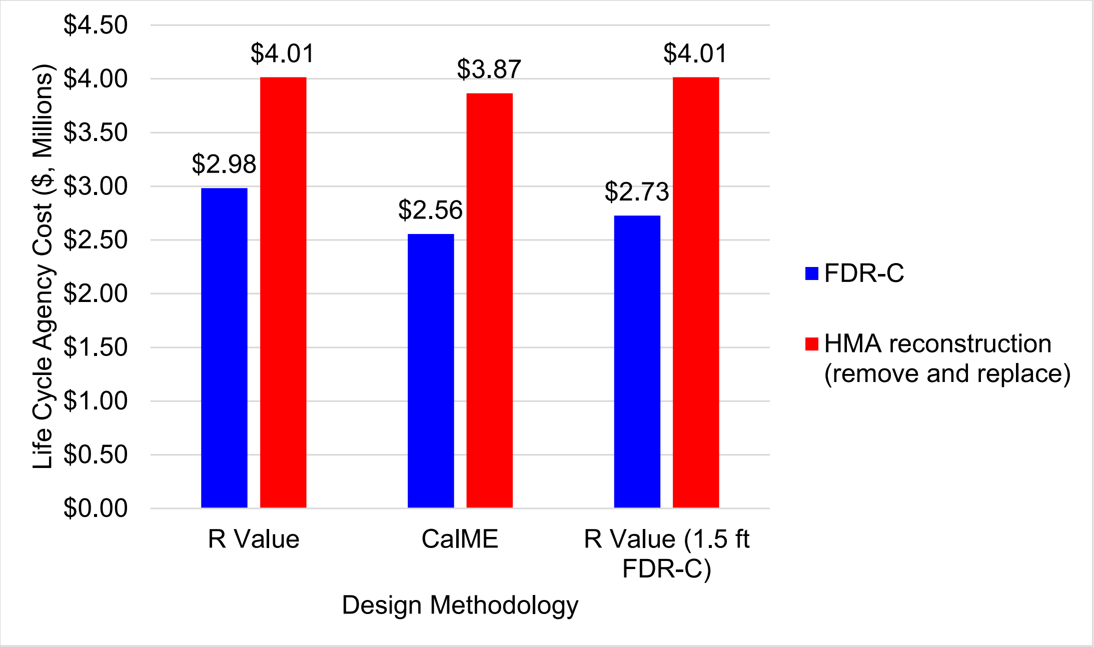


Figure F.16: Life cycle agency cost for YOL 84 for long-life structures.