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# LIFE-CYCLE STRATEGY ANALYSIS FOR CONCRETE BRIDGE DECKS IN PENNSYLVANIA

Shervin Jahangirnejad, Ph.D., P.E.

Dennis Morian, M.S., P.E.

# Acknowledgements

- Quality Engineering Solutions (QES)
  - Dennis Morian
  
- Pennsylvania State University (Penn State)
  - Aleksandra Radlińska
  - Farshad Rajabipour
  - Gordon Warn
  - Travis Hopper
  - Amir Manafpour
  
- Pennsylvania Department of Transportation (PennDOT)
  - Robert Watral
  - Marcy Lucas
  - Teresa Thompson

# Background

- Project Title
  - Bridge Deck Cracking: Effects on In-Service Performance, Prevention, and Remediation
- Main Objectives:
  - To identify the causes of early-age cracking in concrete bridge decks
  - To provide recommendations for effective mitigation of early-age cracking
  - To assess the effect of cracks on the long-term durability and performance of concrete bridge decks
  - To identify the best and most cost-effective (on a life-cycle cost basis) remediation practices and optimum time to remediate to extend the life of bridge decks

# Bridge Deck Remediation Methods

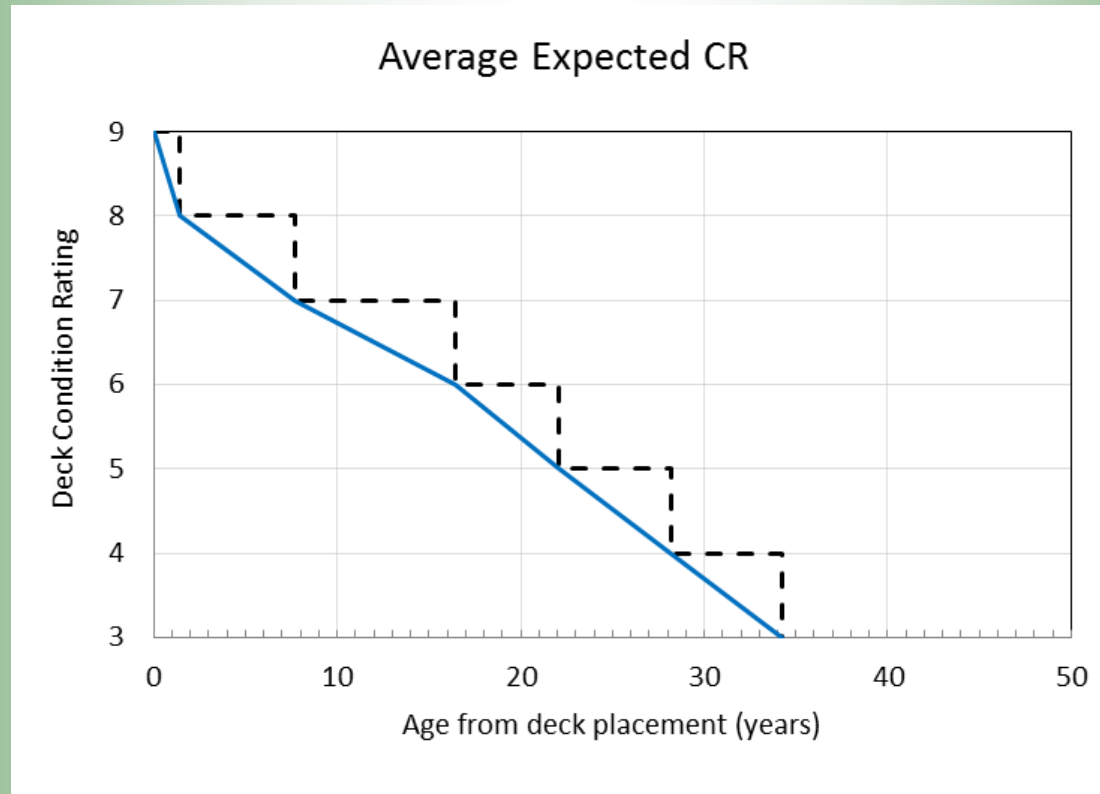
- Epoxy Based Surface Treatment
- Latex Modified Concrete (LMC) Overlay
- Waterproofing Membrane & Bituminous Overlay
- Other methods such as methyl methacrylate (MMA) sealers, etc.
- Reconstruction



# Remediation Matrix

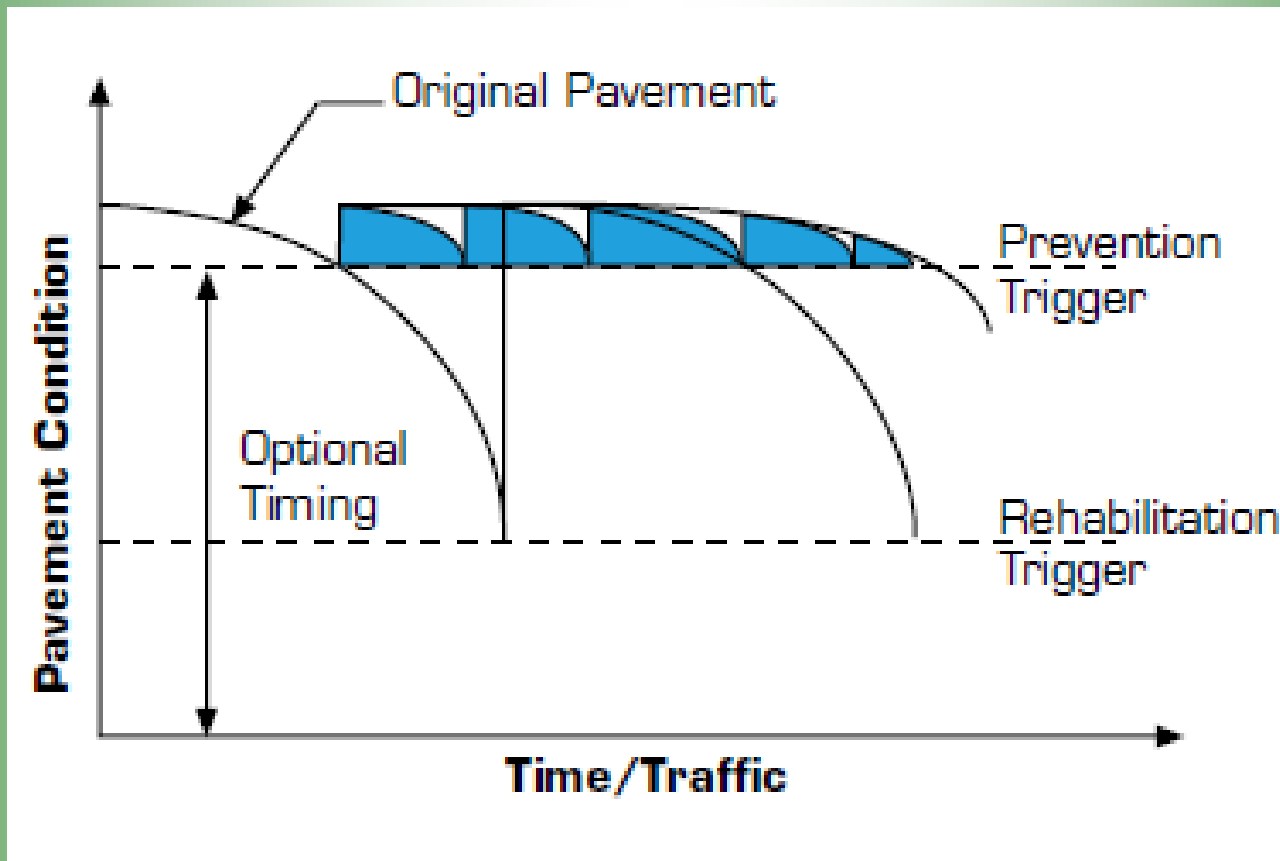
BPN 1&2														
Deck Age -->			< 15 Years				15 - 30 Years				> 30-Years			
Current Deck Rating -->			7	6	5	4	7	6	5	4	7	6	5	4
Remediation Category	Base cost/SY (2012 dollars)	Remediation Service Life Metric	Yellow highlighted options are recommended				Yellow highlighted options are recommended				Yellow highlighted options are recommended			
Epoxy Based Surface Treatment	\$60	Service Life, Yrs.	10	8			10	8		Note-4	10	8		Note-4
		\$/SY/YR	\$6.00	\$7.50			\$6.00	\$7.50			\$6.00	\$7.50		
Waterproofing Membrane & Bituminous Overlay	\$50	Service Life, Yrs.		15	15			15	15	Note-4		15	15	Note-4
		\$/SY/YR		\$3.33	\$3.33			\$3.33	\$3.33			\$3.33	\$3.33	
Latex Modified Concrete	\$80	Service Life, Yrs.	25	20	15	10	25	20	15	Note-4	25	20	15	Note-4
		\$/SY/YR	\$3.20	\$4.00	\$5.33	\$8.00	\$3.20	\$4.00	\$5.33		\$3.20	\$4.00	\$5.33	
Type II Patching			X	X	X	X	X	X	X	X	X	X	X	X
Type III Patching					X	X			X	X			X	X

# Deterioration Model



Deterioration model based on 22,000 bridge deck condition data over 30 years

# Extending the Useful Life of Pavement



Source: Optimizing Highway Performance: Pavement Preservation, Federal Highway Administration, <http://www.fhwa.dot.gov/construction/fs00013.pdf>

# Deterioration Model

BPN1&2			
Rating before remediation	Treatment (approximate service life in years)	Rating immediately after treatment	Expected rating at end of service life (rounded to nearest rating)
7	Epoxy (10)	8	6
	LMC (25)	8	4
6	Epoxy (8)	7	6
	LMC (20)	8	5
	Bituminous (15)*	8	5
5	LMC (15)	7	5
	Bituminous (15)*	7	5
4	LMC (10)	6	4

\* Applied when the deck age is 30 years or higher and the deck rating is 6 or 5.



# Life-Cycle Cost Analysis (LCCA)

LCCA can be effective in evaluating bridge deck performance:

- Useful for comparing alternative remediation strategies
- Comparison of remediation sequences
- Process is flexible, can vary analysis period, adjust to changing economics, etc.
- Can consider user cost impacts
- RealCost software can provide deterministic or probabilistic analysis results

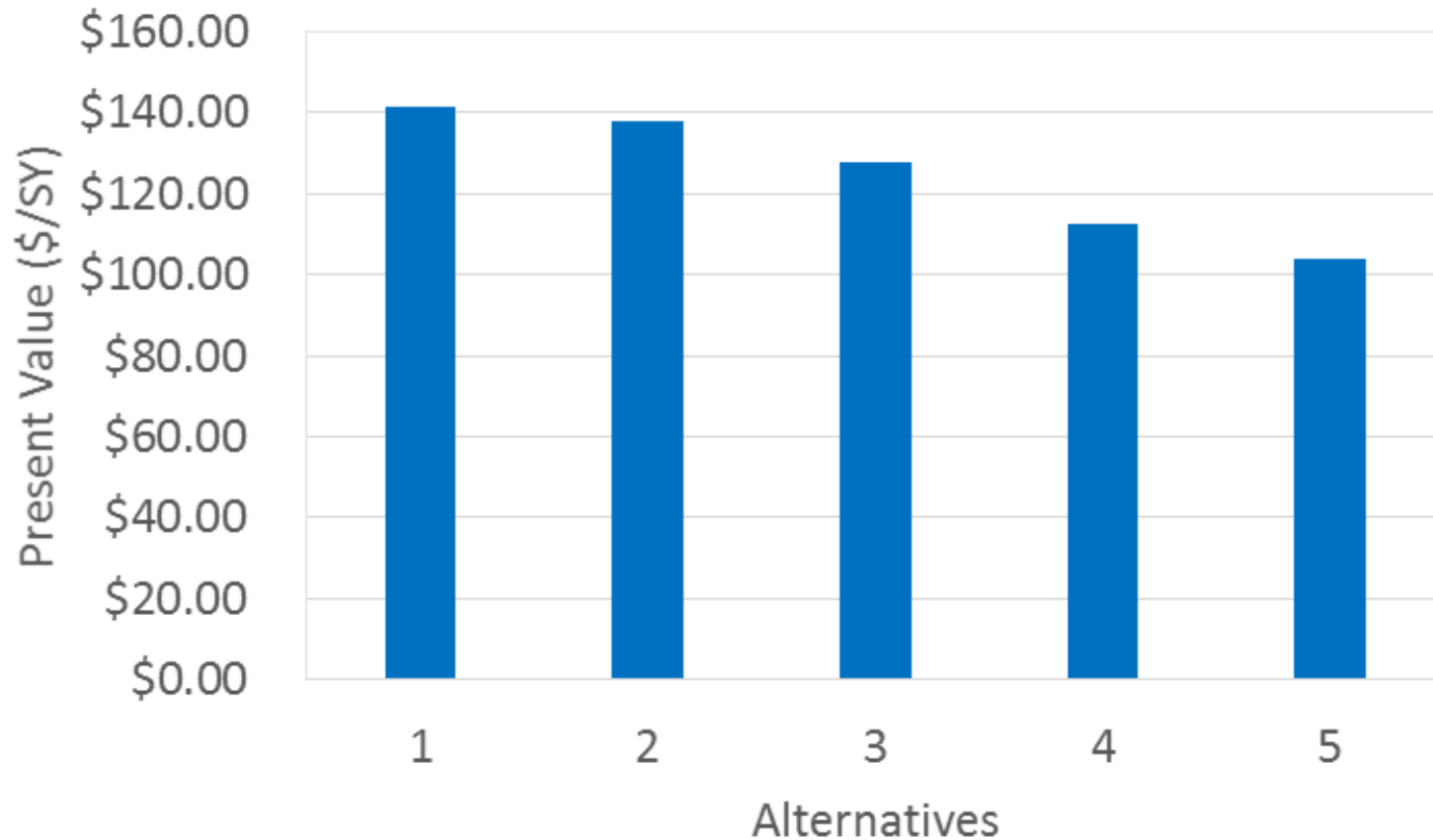


# Remediation Sequences for Deck Age = 5 and Deck Rating = 6

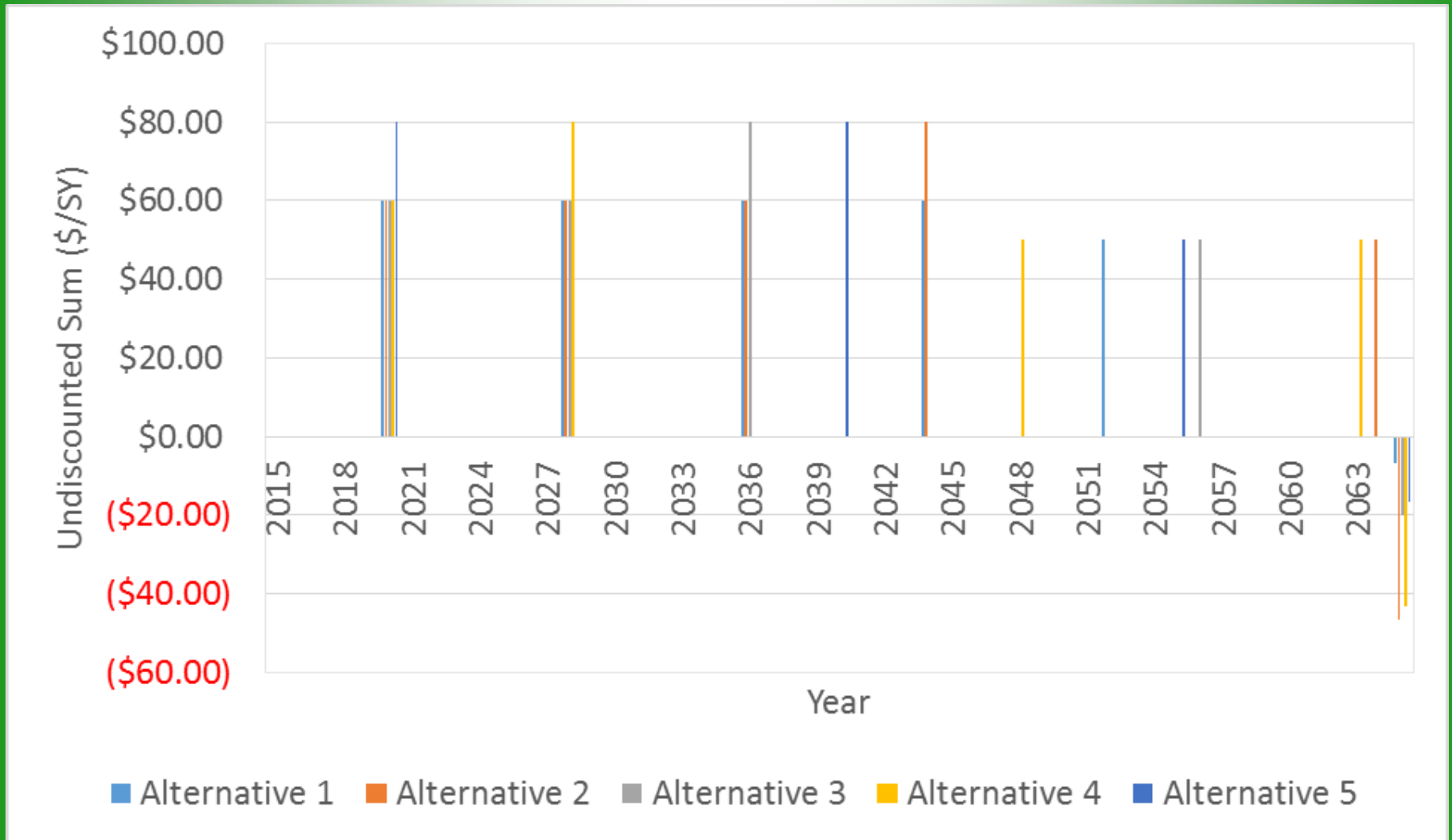
Deck Age (Yrs)	Deck Rating Before Treatment	1st Treatment			Deck Rating Before Treatment	2nd Treatment			Deck Rating Before Treatment	3rd Treatment			Deck Rating Before Treatment	4th Treatment			Deck Rating Before Treatment	5th Treatment			Cost Present Value (\$/SY)
		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)	
5	6	EP (8)	7	13	6	EP (8)	7	21	6	EP (8)	7	29	6	EP (8)	7	37	6	WB (15)	8	52	\$141.70
5	6	EP (8)	7	13	6	EP (8)	7	21	6	EP (8)	7	29	6	LMC (20)	8	49	5	WB (15)	7	64	\$138.08
5	6	EP (8)	7	13	6	EP (8)	7	21	6	LMC (20)	8	41	5	WB (15)	7	56					\$127.66
5	6	EP (8)	7	13	6	LMC (20)	8	33	5	WB (15)	7	48	5	WB (15)	7	63					\$112.58
5	6	LMC (20)	8	25	5	LMC (15)	7	40	5	WB (15)	7	55									\$103.83

Deck Age (Yrs)	Deck Rating	Alternatives	Treatment Sequence	Present Value (\$/SY)
5	6	1	EEEEB	\$141.70
		2	EEELB	\$138.08
		3	EELB	\$127.66
		4	ELBB	\$112.58
		5	LLB	\$103.83

# Present Value: Agency Cost



# Expenditure Stream: Agency Cost



# General Observations

- In general, fewer remediation treatments applied during the performance period results in lower LCC. This can be achieved by:
  - Extending the time before remediation is needed
  - Use of longer performing remediation treatments
- Latex-modified overlay and combination of Latex and Bit. w/waterproof membrane appear most cost effective for most circumstances

# Using LCCA for Construction and Design Considerations

- Construction and design considerations to reduce the number of deck remediation treatments (through increasing the time before the application of the first remediation treatment):
  - Sealing the cracks
  - Using pozzolanic or other SCMs
  - Increasing the concrete cover

# Concluding Remarks

- LCCA can be used to compare the effect of applying different treatments at different times on LCC.
- LCCA is a dynamic tool which can be used on a case-by-case basis for individual projects in order to assist decision makers in developing their remediation and construction/design plan.

# Thank You!



# Full Version



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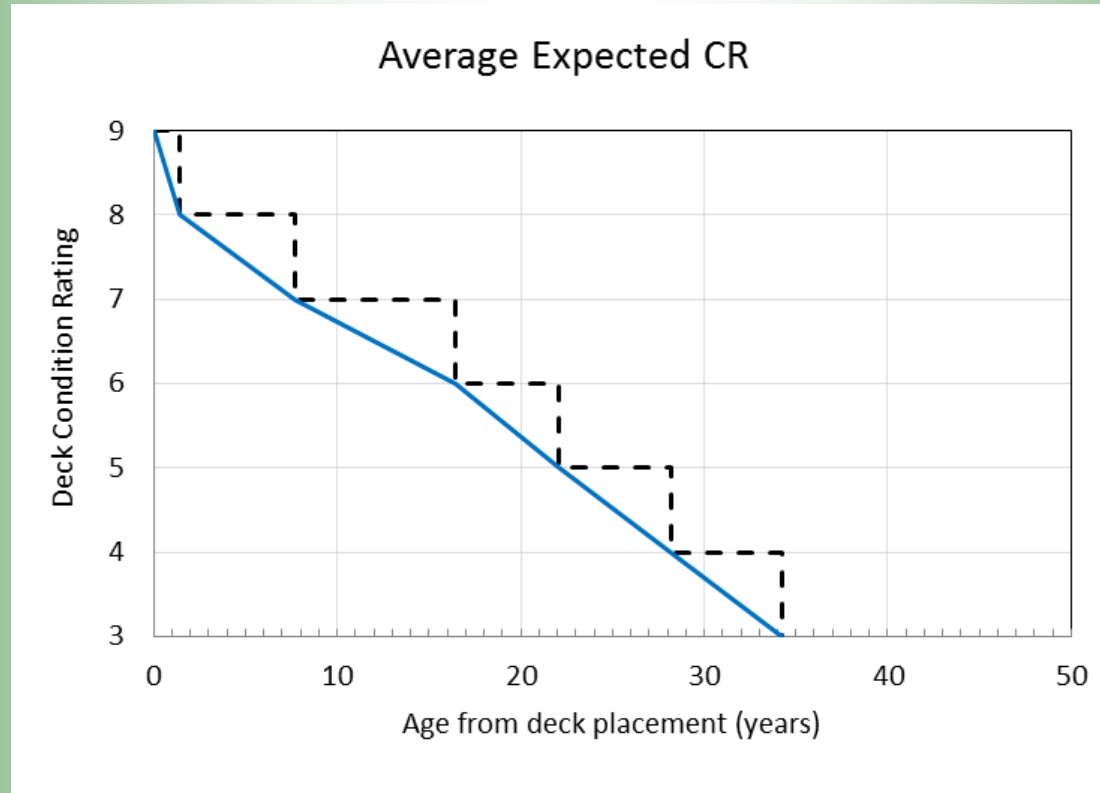


# Remediation Matrix

BPN 1&2

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Type II Patching			X	X	X	X	X	X	X	X	X	X	X	X
Type III Patching					X	X			X	X			X	X

# Deterioration Model



Deterioration model based on 22,000 bridge deck condition data over 30 years

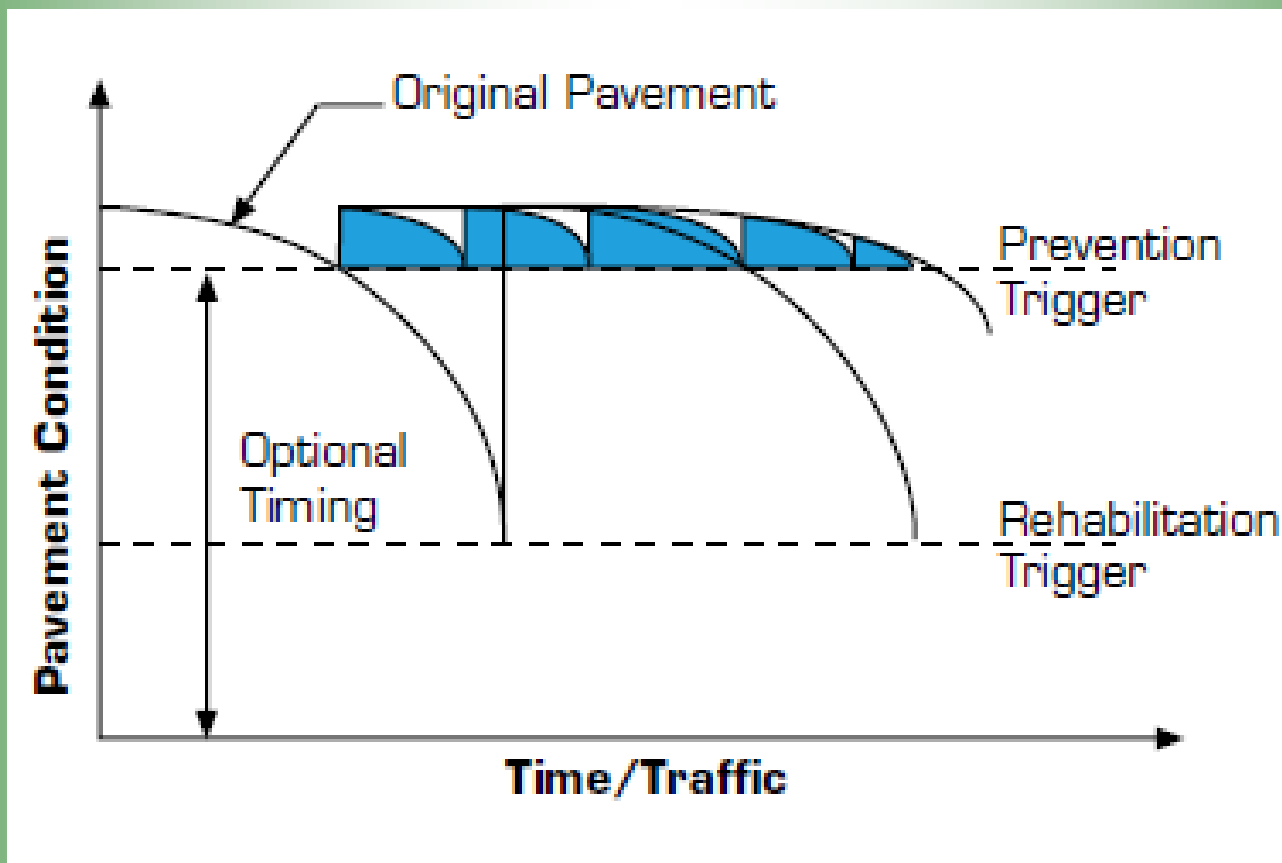
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\* Applied when the deck age is 30 years or higher and the deck rating is 6 or 5.



# Extending the Useful Life of Pavement



Source: Optimizing Highway Performance: Pavement Preservation, Federal Highway Administration, <http://www.fhwa.dot.gov/construction/fs00013.pdf>

# Life-Cycle Cost Analysis (LCCA)

LCCA can be effective in evaluating bridge deck performance:

- Useful for comparing alternative remediation strategies
- Comparison of remediation sequences
- Process is flexible, can vary analysis period, adjust to changing economics, etc.
- Can consider user cost impacts
- RealCost software can provide deterministic or probabilistic analysis results

# What is LCCA & How Can it Be Used?

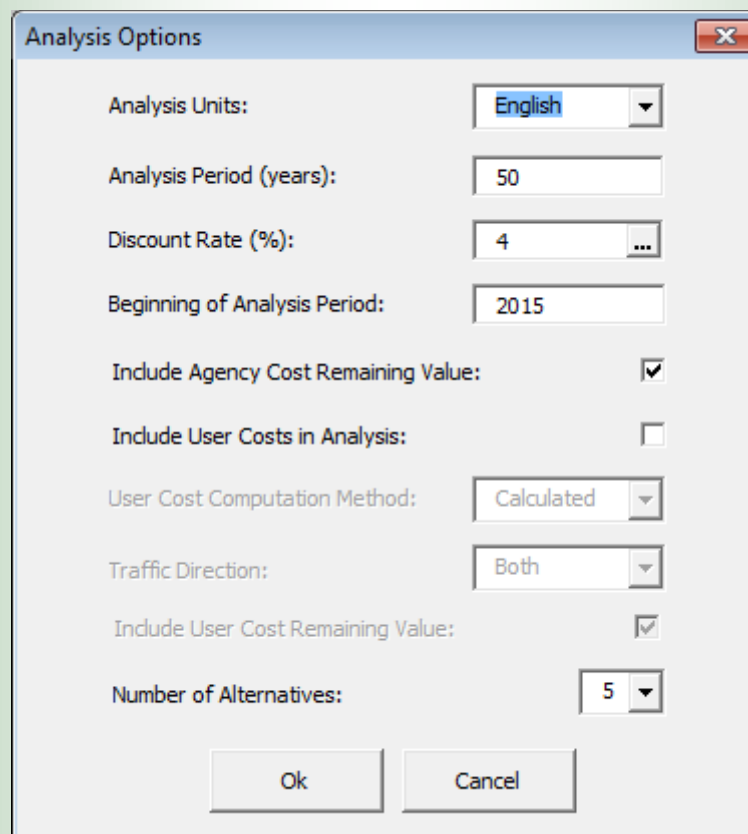
LCCA is an engineering economic analysis tool useful in comparing the relative economic merits of competing construction or rehabilitation design alternatives for a single project.

- Assessment of all cost considered during a defined analysis period
- Useful for comparing costs of alternatives over the life of an asset
- Can also be used to assess the optimization of costs during the asset life
- Useful forms for transportation assets PV, EUAC

# LCCA Inputs

- Define analysis period
- Discount Rate (interest-inflation)
- Treatment strategy cycle throughout the analysis period
- Performance for individual treatments
- Costs of treatments (and user costs if applicable)

# RealCost Analysis Options



The image shows a software dialog box titled "Analysis Options" with a close button (X) in the top right corner. The dialog contains the following settings:

- Analysis Units: English (dropdown menu)
- Analysis Period (years): 50 (text input)
- Discount Rate (%): 4 (text input with a browse button "...")
- Beginning of Analysis Period: 2015 (text input)
- Include Agency Cost Remaining Value:
- Include User Costs in Analysis:
- User Cost Computation Method: Calculated (dropdown menu)
- Traffic Direction: Both (dropdown menu)
- Include User Cost Remaining Value:
- Number of Alternatives: 5 (dropdown menu)

At the bottom of the dialog are two buttons: "Ok" and "Cancel".

# RealCost Alternatives and Activities

Alternative 1 ✕

Alternative: 1

Alternative Description:  Number of Activities: 6

Activity 1 | Activity 2 | Activity 3 | Activity 4 | Activity 5 | Activity 6

Activity Description:

**Activity Cost and Service Life Inputs**

Agency Construction Cost (\$1000): <input style="width: 60px;" type="text" value="0.06"/>	Activity Service Life (years): <input style="width: 60px;" type="text" value="8"/>
User Work Zone Costs (\$1000): <input style="width: 60px;" type="text"/>	Activity Structural Life (years): <input style="width: 60px;" type="text"/>
Maintenance Frequency (years): <input style="width: 60px;" type="text"/>	Agency Maintenance Cost (\$1000): <input style="width: 60px;" type="text"/>

**Activity Work Zone Inputs**

Work Zone Length (miles): <input style="width: 60px;" type="text"/>	Work Zone Duration (days): <input style="width: 60px;" type="text"/>
Work Zone Capacity (vphpl): <input style="width: 60px;" type="text"/>	Work Zone Speed Limit (mph): <input style="width: 60px;" type="text"/>
No of Lanes Open in Each Direction During Work Zone: <input style="width: 60px;" type="text"/>	Traffic Hourly Distribution: <span style="border: 1px solid gray; padding: 2px;">Week Day 1</span>

Work Zone Hours

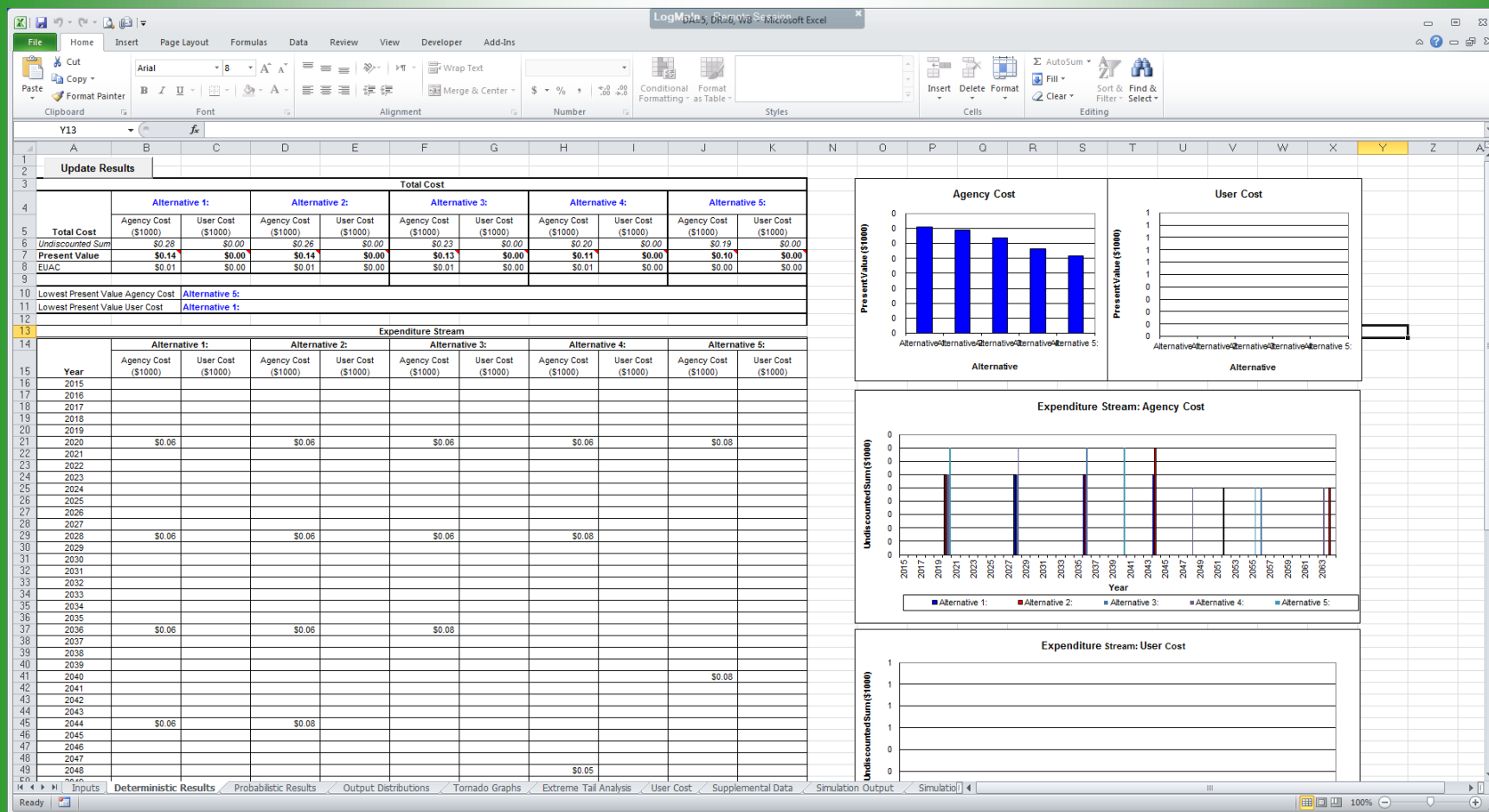
		Inbound		Outbound	
		Start	End	Start	End
First Period of Lane Closure:		<input style="width: 40px;" type="text"/>	<input style="width: 40px;" type="text"/>	<input style="width: 40px;" type="text"/>	<input style="width: 40px;" type="text"/>
Second Period of Lane Closure:		<input style="width: 40px;" type="text"/>	<input style="width: 40px;" type="text"/>	<input style="width: 40px;" type="text"/>	<input style="width: 40px;" type="text"/>
Third Period of Lane Closure:		<input style="width: 40px;" type="text"/>	<input style="width: 40px;" type="text"/>	<input style="width: 40px;" type="text"/>	<input style="width: 40px;" type="text"/>

Copy Activity  
Paste Activity

Open...
Save...
Ok
Cancel



# RealCost Output Deterministic Results





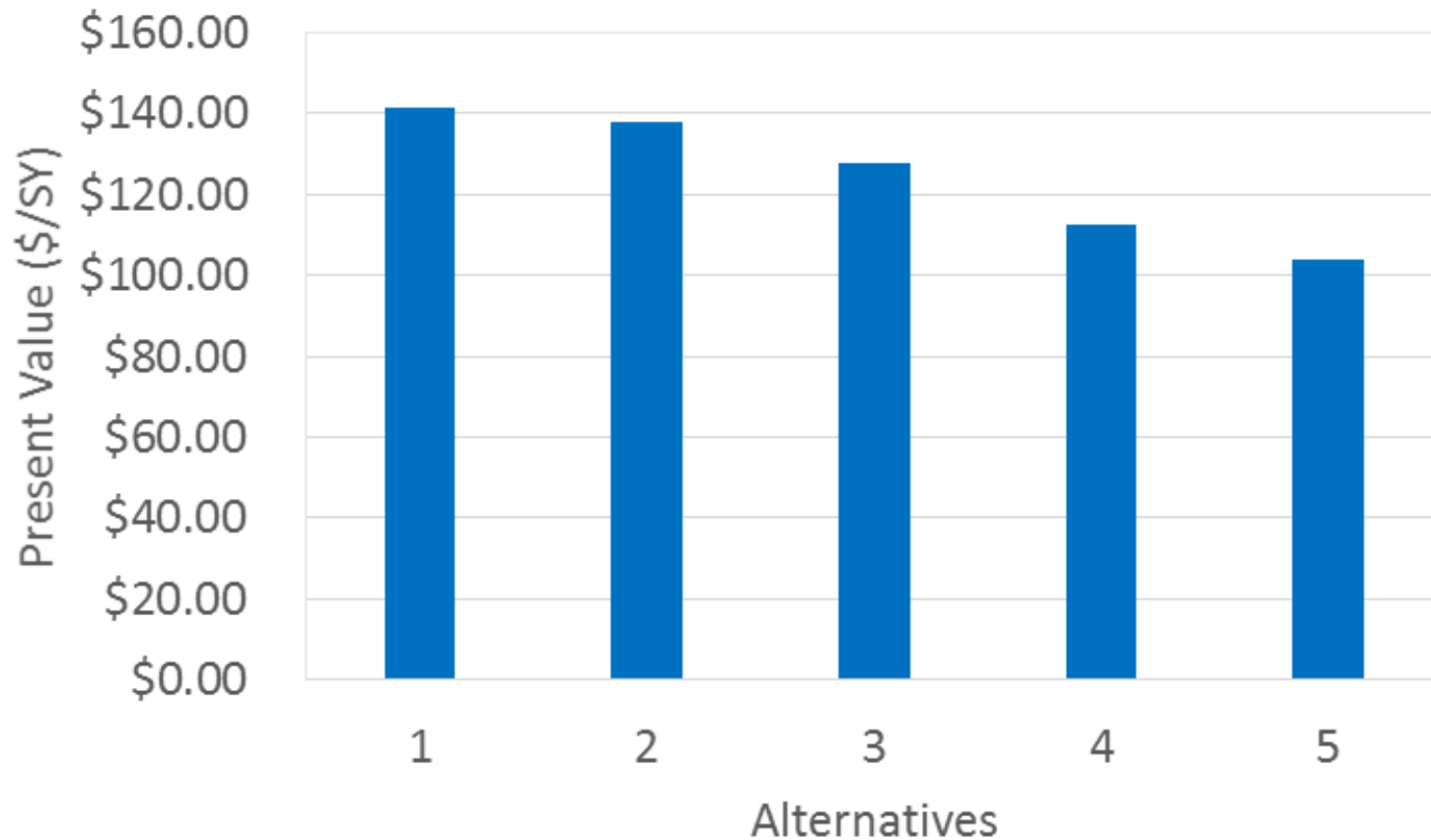
# Remediation Sequences for Deck Age = 5 and Deck Rating = 6

Deck Age (Yrs)	Deck Rating Before Treatment	1st Treatment			Deck Rating Before Treatment	2nd Treatment			Deck Rating Before Treatment	3rd Treatment			Deck Rating Before Treatment	4th Treatment			Deck Rating Before Treatment	5th Treatment			Cost Present Value (\$/SY)
		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life, Yrs)	Deck Rating After Treatment	Deck Age (Yrs)	
5	6	EP (8)	7	13	6	EP (8)	7	21	6	EP (8)	7	29	6	EP (8)	7	37	6	WB (15)	8	52	\$141.70
5	6	EP (8)	7	13	6	EP (8)	7	21	6	EP (8)	7	29	6	LMC (20)	8	49	5	WB (15)	7	64	\$138.08
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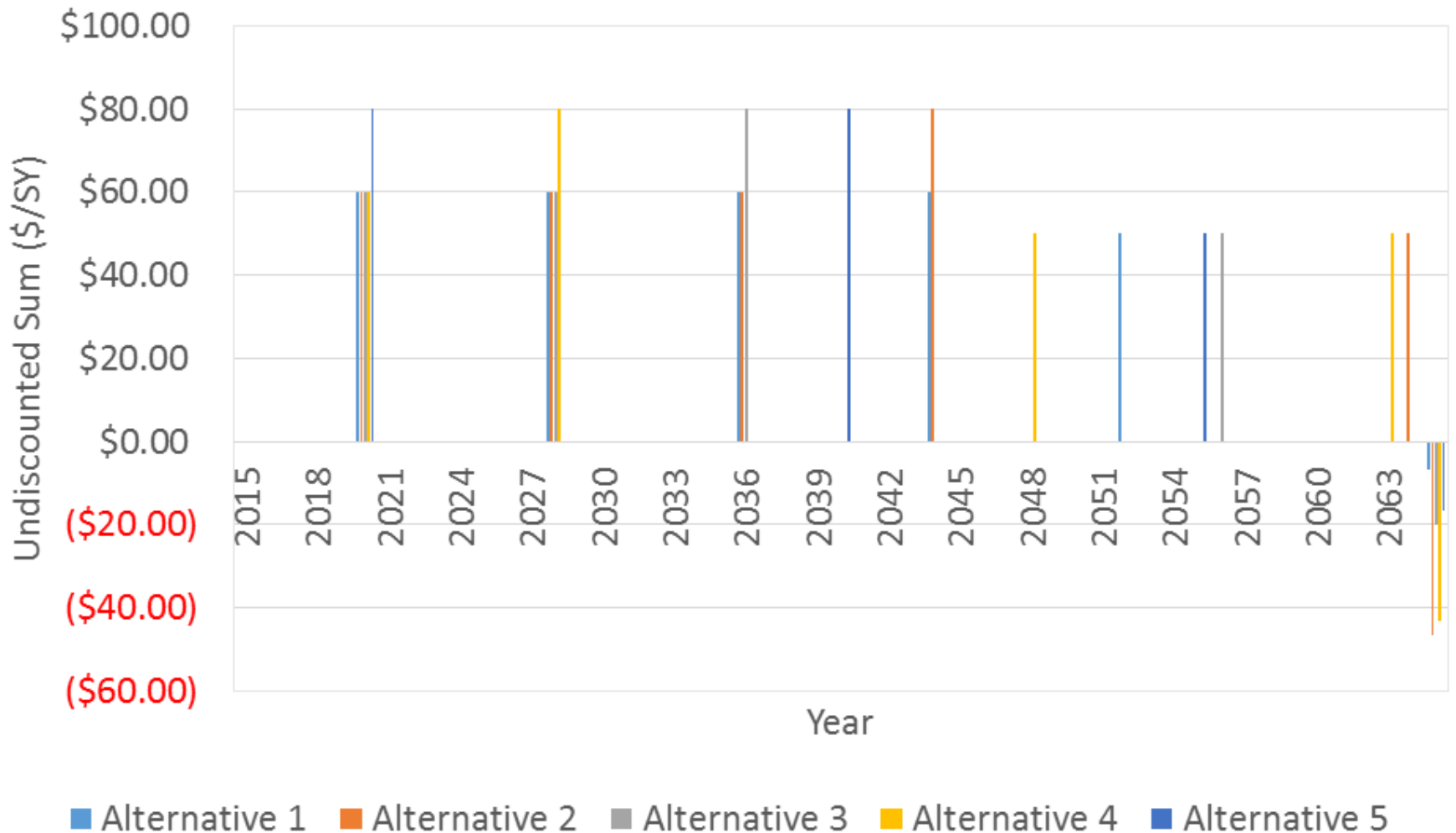
Deck Age (Yrs)	Deck Rating	Alternatives	Treatment Sequence	Present Value (\$/SY)
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# Present Value: Agency Cost



# Expenditure Stream: Agency Cost



# General Observations

- In general, fewer remediation treatments applied during the performance period results in lower LCC. This can be achieved by:
  - Extending the time before remediation is needed
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- Latex-modified overlay and combination of Latex and Bit. w/waterproof membrane appear most cost effective for most circumstances

# Using LCCA for Construction and Design Considerations

- Construction and design considerations to reduce the number of deck remediation treatments (through increasing the time before the application of the first remediation treatment):
  - Sealing the cracks
  - Using pozzolanic or other SCMs
  - Increasing the concrete cover

# Using LCCA for Construction and Design Considerations

- Key value to provide the basis for the analysis:
  - Time to beginning of serious corrosion damage
- It was predicted for several cases using the LIFE-365 prediction model

Concrete	Rebar	Cracked?	Concrete Cover (in)	Corrosion Initiation (yrs)
AAA	epoxy	N	2	20.8
AAA	epoxy	Y	2	13.5
AAA	epoxy	Y	3	22.2
AAAP	epoxy	Y	2	19.1

# Using LCCA for Construction and Design Considerations

## ➤ Base Scenario

Deck Age (Yrs)	Deck Rating Before Treatment	1st Treatment			Deck Rating Before Treatment	2nd Treatment			Deck Rating Before Treatment	3rd Treatment		
		Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)
5	7	Epoxy (10 Yrs)	8	15	6	LMC (20 Yrs)	8	35	5	WM&B (15 Yrs)	7	50

## ➤ Sealed vs. Unsealed Cracks

Practice	Deck Age (Yrs)	Deck Rating Before Treatment	1st Treatment			Deck Rating Before Treatment	2nd Treatment			Deck Rating Before Treatment	3rd Treatment		
			Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)
Unsealed	11	6	LMC (20 Yrs)	8	31	5	WM&B (15 Yrs)	7	46	5	WM&B (15 Yrs)	7	61
Sealed	18	5	LMC (15 Yrs)	7	33	5	WM&B (15 Yrs)	7	48	5	WM&B (15 Yrs)	7	63

# Using LCCA for Construction and Design Considerations

## ➤ AAA vs. AAAP Mixture Design

Practice	Deck Age (Yrs)	Deck Rating Before Treatment	1st Treatment			Deck Rating Before Treatment	2nd Treatment			Deck Rating Before Treatment	3rd Treatment		
			Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)
AAA	11	6	LMC (20 Yrs)	8	31	5	WM&B (15 Yrs)	7	46	5	WM&B (15 Yrs)	7	61
AAAP	17	6	LMC (20 Yrs)	8	37	5	WM&B (15 Yrs)	7	52				

## ➤ 2" vs. 3" Concrete Cover

Practice	Deck Age (Yrs)	Deck Rating Before Treatment	1st Treatment			Deck Rating Before Treatment	2nd Treatment			Deck Rating Before Treatment	3rd Treatment		
			Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)		Treatment (Service Life)	Deck Rating After Treatment	Deck Age (Yrs)
2" cover	11	6	LMC (20 Yrs)	8	31	5	WM&B (15 Yrs)	7	46	5	WM&B (15 Yrs)	7	61
3" cover	20	5	LMC (15 Yrs)	7	35	5	WM&B (15 Yrs)	7	50				



# Using LCCA for Construction and Design Considerations

## LCCA Results:

Practice	Present Value	Undiscounted Sum	EUAC
Base Scenario	\$691,737	\$728,889	\$32,200
Unsealed	\$675,493	\$708,148	\$31,444
Sealed	\$669,078	\$705,505	\$31,146
AAA	\$675,493	\$708,148	\$31,444
AAAP	\$667,487	\$699,259	\$31,072
2" Cover	\$675,493	\$708,148	\$31,444
3" Cover	\$671,192	\$707,111	\$31,244



# Concluding Remarks

- The LCCA can be used to compare the effect on LCC of applying treatments at different times throughout the analysis period, or of different treatments.
- LCCA is a dynamic tool which can be used on a case-by-case basis for individual projects in order to assist decision makers in developing their remediation and construction/design plan.

# Thank You!