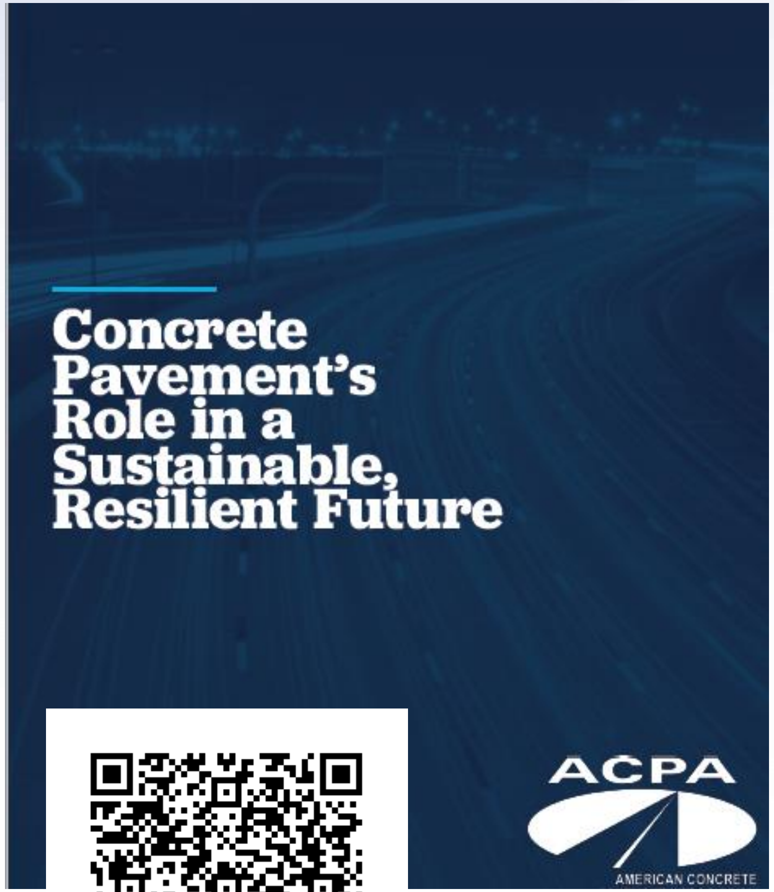
Designing More Sustainable Pavements



North Carolina Fall Concrete Pavement Conference

November 28, 2023

Eric Ferrebee, P.E.

Senior Director of Technical Services

AMERICAN CONCRETE PAVEMENT ASSOCIATION

Sustainability is a Major Focus

- Meeting the needs of today without compromising future generations' ability to meet their own

Sustainable practices are simply good engineering

Concrete Pavement Sustainability – Environmental Impacts

- We start to quantify!

ENVIRONMENTAL IMPACTS

Declared Product:
Mix 1618915 • Santa Clara Plant
A4GRC 658 C+S 30% BL AIR WR
Compressive strength: 5000 PSI at 28 days

Declared Unit: 1 m^3 of concrete

Global Warming Potential (kg CO_2-eq)	392
Ozone Depletion Potential (kg CFC-11-eq)	1.1E-5
Acidification Potential (kg SO_2-eq)	2.06
Eutrophication Potential (kg N-eq)	0.46
Photochemical Ozone Creation Potential (kg O_3-eq)	45.5
Abiotic Depletion, non-fossil (kg Sb-eq)	1.4E-6
Abiotic Depletion, fossil (MJ)	695
Total Waste Disposed (kg)	2.71
Consumption of Freshwater (m^3)	1.01

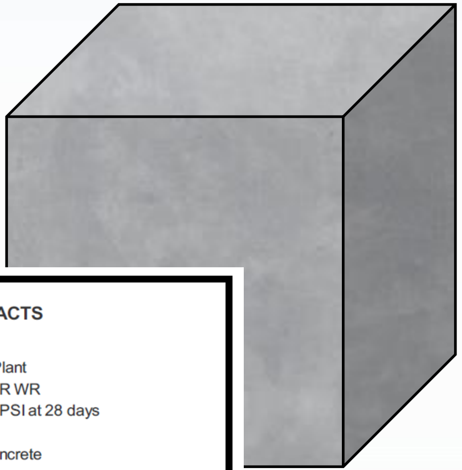
Product Components: crushed aggregate (ASTM C33), natural aggregate (ASTM C33), Portland cement (ASTM C150), slag cement (ASTM C989), batch water (ASTM C1602), admixture (ASTM C494), admixture (ASTM C260)

- Environmental Product Declarations are a good starting point.

Table 8a. Summary Results (A1-A3): 3001-4000 psi (20.7-27.6 MPa) RMC produc

		Minimum	Maximum	3001-4000-00-FA/SL	3001-4000-20-FA	3001-4000-30-FA	3001-4000-40-FA	3001-4000-SL
Core Mandatory Impact Indicators								
GWP	kg CO_2e	261.19	426.75	426.75	365.48	332.37	297.41	32
ODP	kg CFC11e	7.84E-06	1.11E-05	1.11E-05	9.56E-06	8.73E-06	7.84E-06	1.01
AP	kg SO_2e	0.99	1.33	1.33	1.17	1.08	0.99	
EP	kg Ne	0.37	0.55	0.55	0.48	0.44	0.40	
POCP	kg O_3e	21.38	28.22	28.22	24.98	23.23	21.38	2
ADPf	MJ, NCV	1,522.19	2,229.70	2,229.70	1,921.20	1,754.51	1,578.49	1,85
ADPe	kg Sbe	2.44E-04	3.69E-04	3.69E-04	3.25E-04	3.02E-04	2.77E-04	2.94
FFD	MJ Surplus	143.16	180.58	180.58	162.85	153.28	143.16	17

Focusing solely on EPDs loses context



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Additional detail and impacts are reported on page three of this EPD

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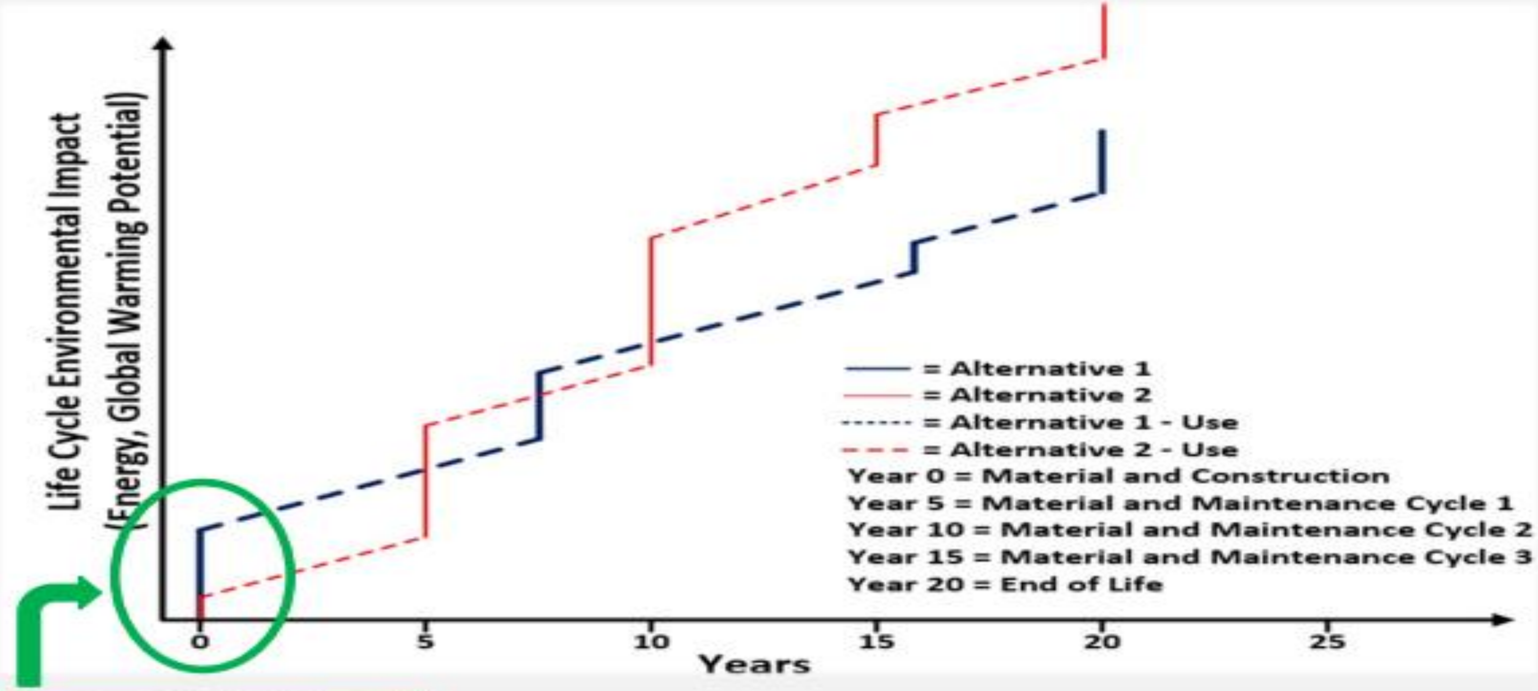
WHERE DO EPDS FIT IN?

ABC Ready-Mix Environmental Impacts	
Serving Size: 1 cubic yard of concrete mix no. 123	
Global Warming Potential [kg CO_2 eq]	3.06×10^3
Ozone Depletion Potential [CFC-11 eq]	4.24×10^{-6}
Acidification Potential [kg SO_2 eq]	21.7
Eutrophication Potential [kg N eq]	9.25×10^{-2}
Photochemical Oxidant Creation Potential [kg O_3 eq]	30.7
TOTAL ENERGY DEMAND [MJ]:	1166
Non-renewable [MJ]	586
Renewable [MJ]	580



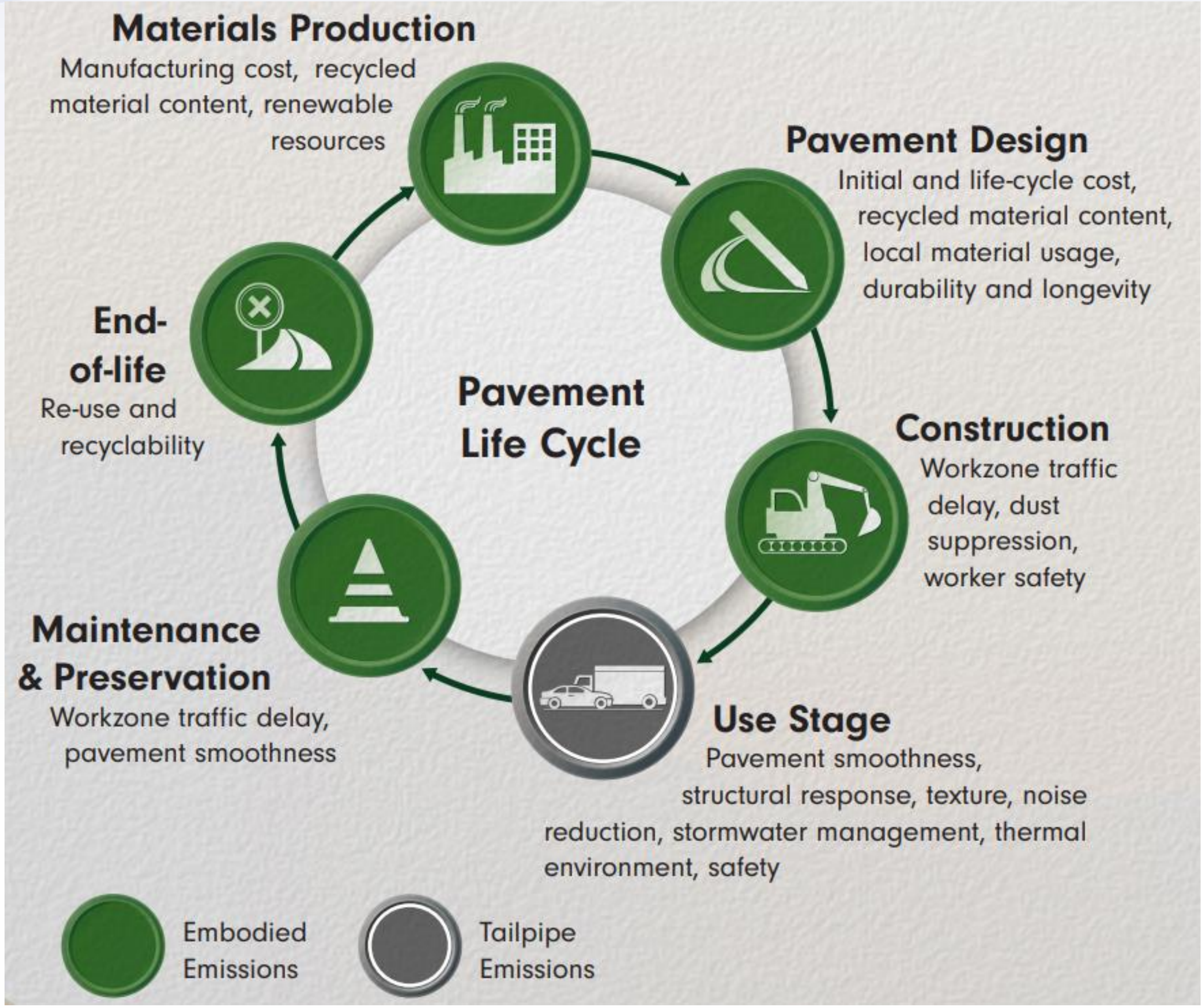
Supplier EPDs for materials

Product Stage			Construction Stage		Use Stage					End-of-Life Stage				Benefits & Loads
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw materials supply	Transport	Manufacturing	Transport	Installation	Use Stage	Maintenance	Repair	Replacement	Refurbishment	De-construction	Transport	Waste Processing	Disposal	Reuse, recovery, recycling potential

Projects

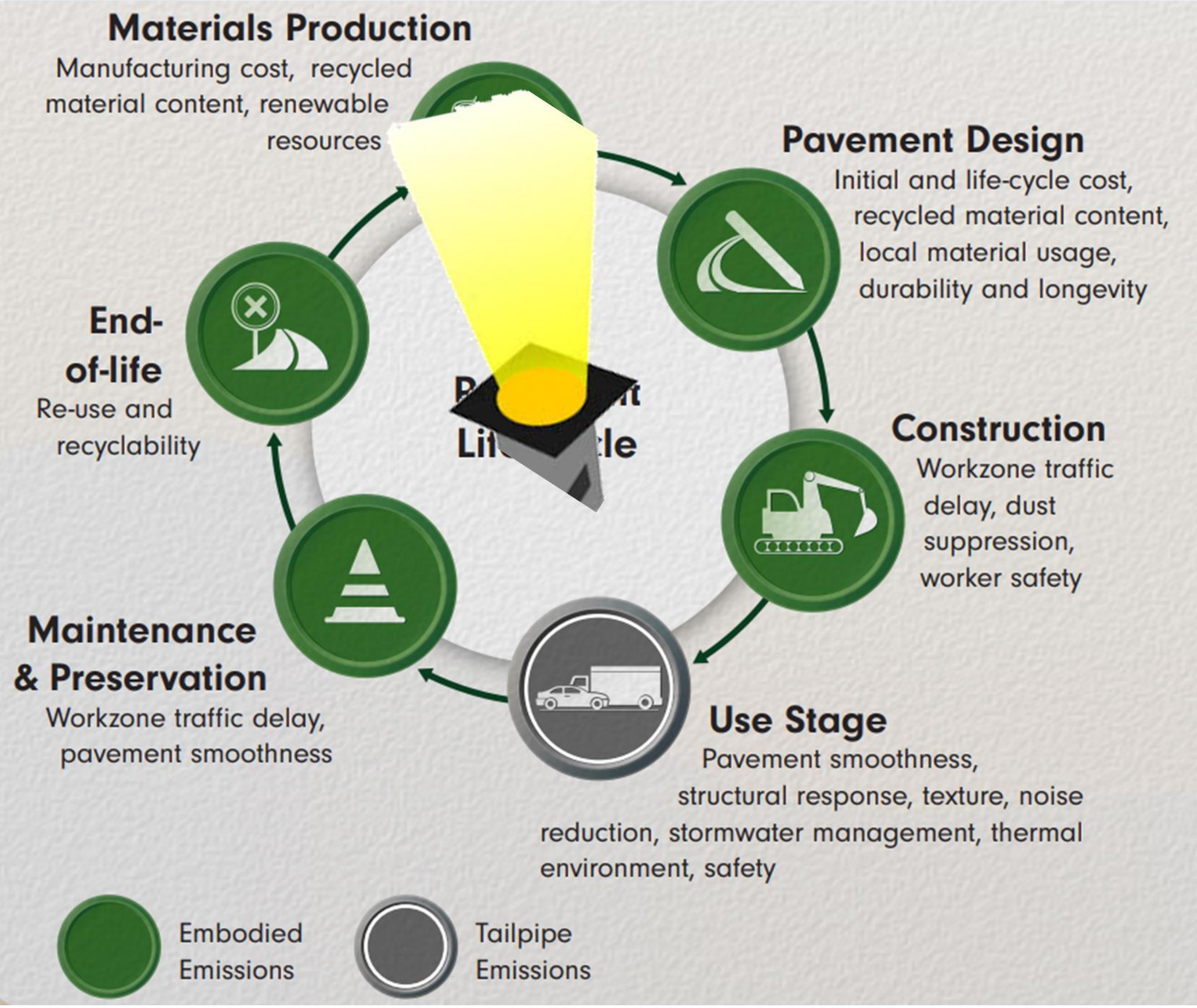
[Source: Jacquelyn Wong (CalTrans)]

Concrete Pavement Life Cycle



Source: FHWA - https://www.fhwa.dot.gov/infrastructure/climatechallenge/images/20211103_Emissions%20Infographic_508compl_toHPA.pdf

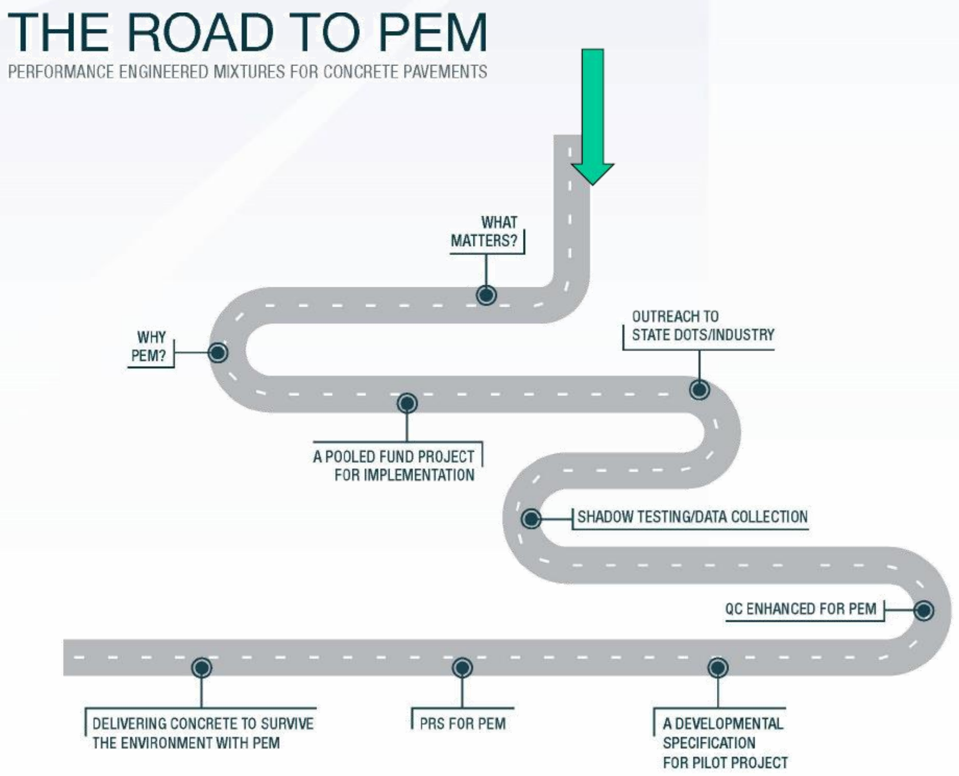
Concrete Pavement Life Cycle



- Materials Phase
  - EPDs live here!
  - PCA's Road Map
  - PLC
  - Performance Engineered Mixtures (PEM)
  - Recycling
  - New technologies and materials!

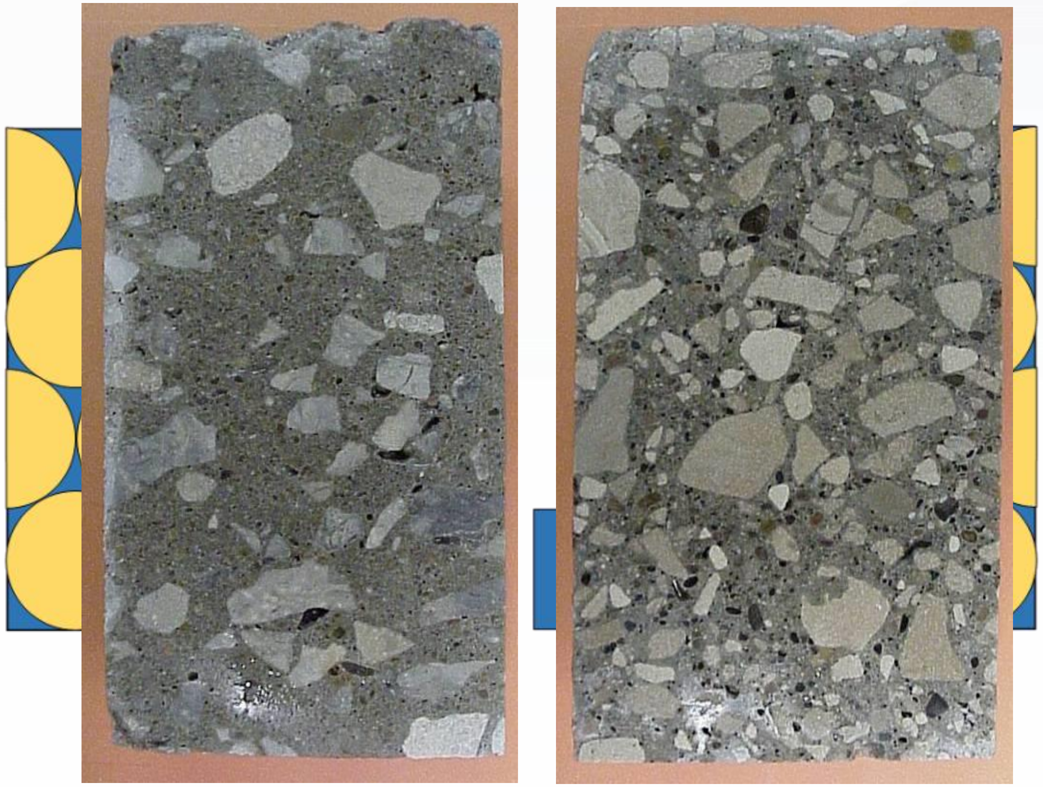
Optimizing Mix Designs

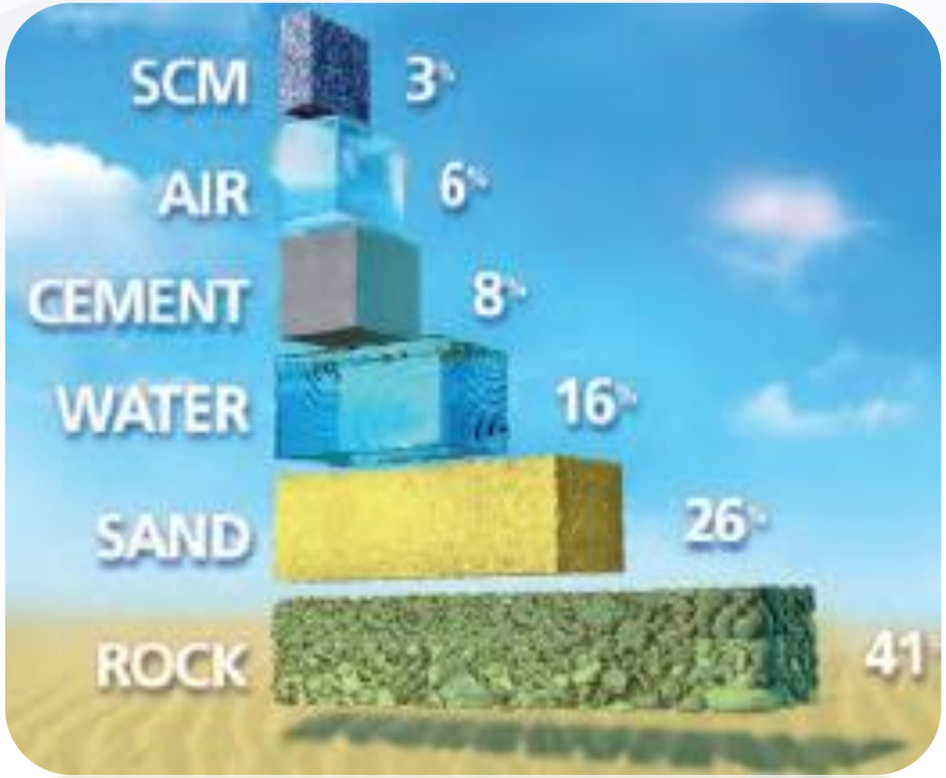
- Performance Engineered Mixtures (PEM)



Optimizing Mix Designs

- Performance Engineered Mixtures (PEM)
  - Optimized cement gradations lead to optimized cementitious contents

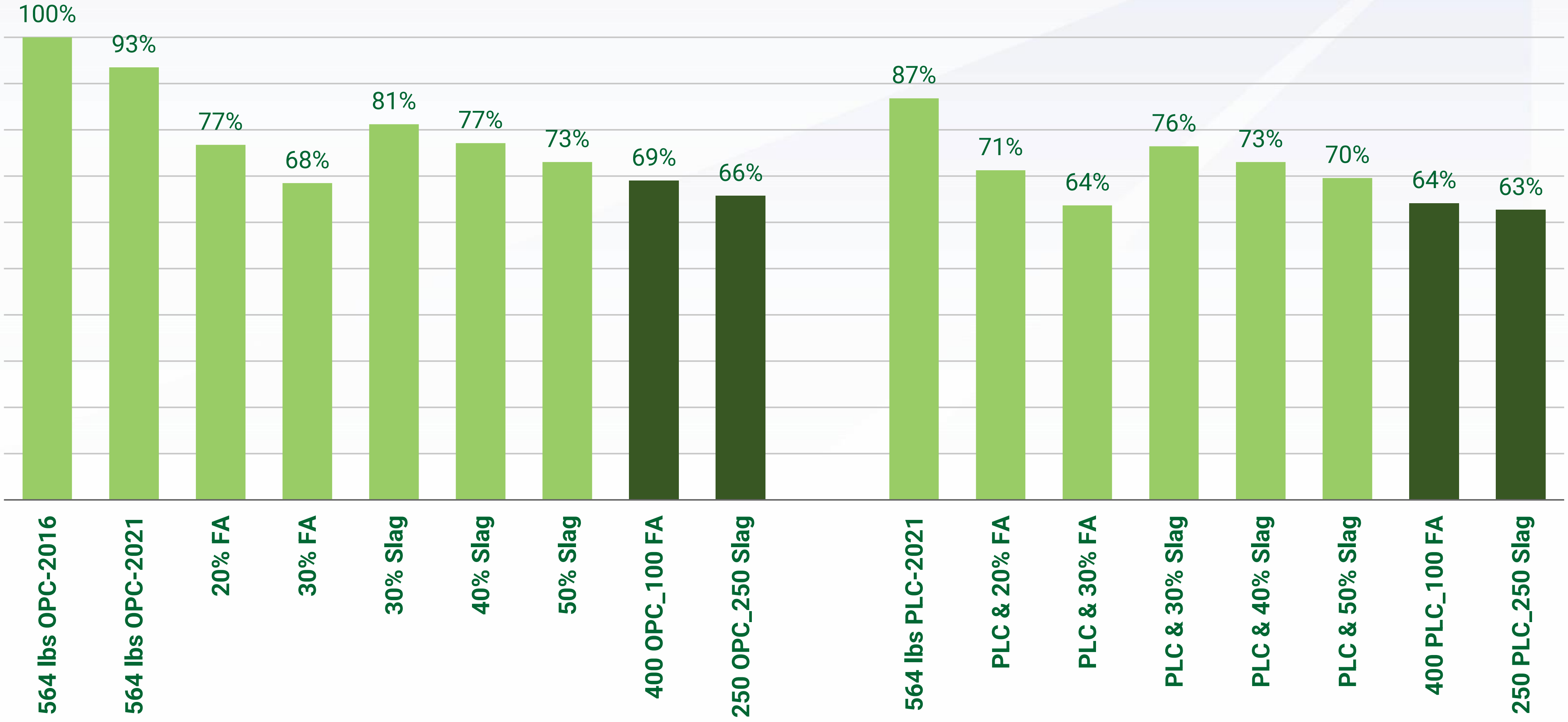




Optimizing Mix Designs

Using SCMs and optimizing concrete mix designs lowers CO_2 of the mix

Using Portland Limestone Cements lowers the CO_2 impacts some more



GWP - global warming potential
For standard six sack (564lb/cy) Mix; Assumed Slag shipping Distance = 10,500 miles (*Rizhao to FL)*

Use Innovative Low-Carbon Cementitious Materials

- Test sections recently constructed at MNRoad
  - Assess CO_2 savings
  - Measure performance under traffic
  - 16 sections
    - Control and optimized mixtures
    - Reclaimed fly ashes
    - Geopolymers
    - Carbon injection
    - Innovative SCMs

Concrete Pavement Life Cycle – Materials Phase

- Recycling
  - Reduced virgin material
  - Eliminates disposal
  - 140 M Tons Annually

Top 10 Recycled

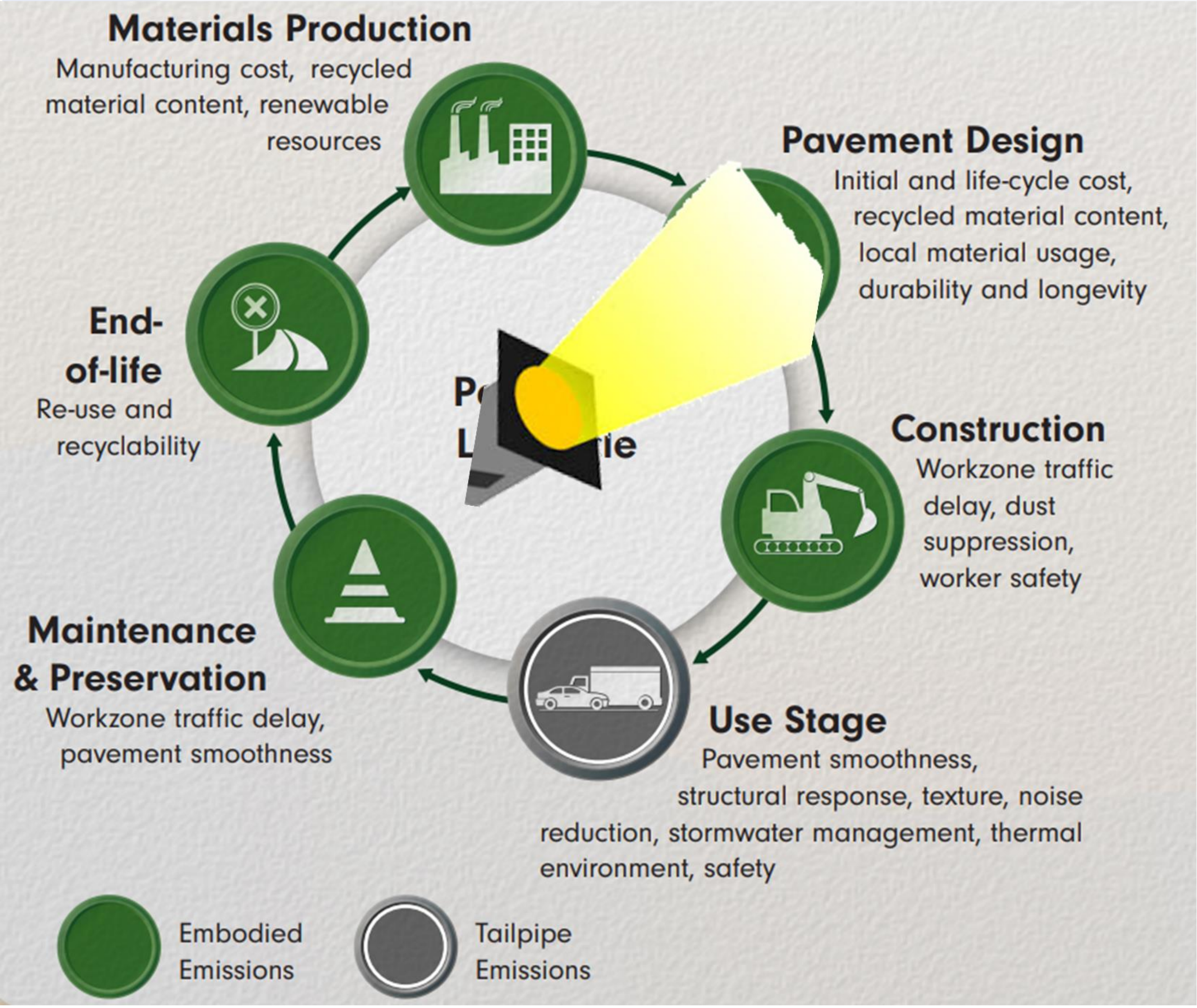
1. Concrete
2. Steel
3. Aluminum
4. Plastic (PET)
5. Newspapers
6. Corrugated Cardboard
7. Plastics (HDPE)
8. Glass
9. Mixed Papers
10. Used Motor Oil

National Concrete Pavement Technology Center

Iowa State University
Institute for Transportation

Cavalline

Concrete Pavement Life Cycle



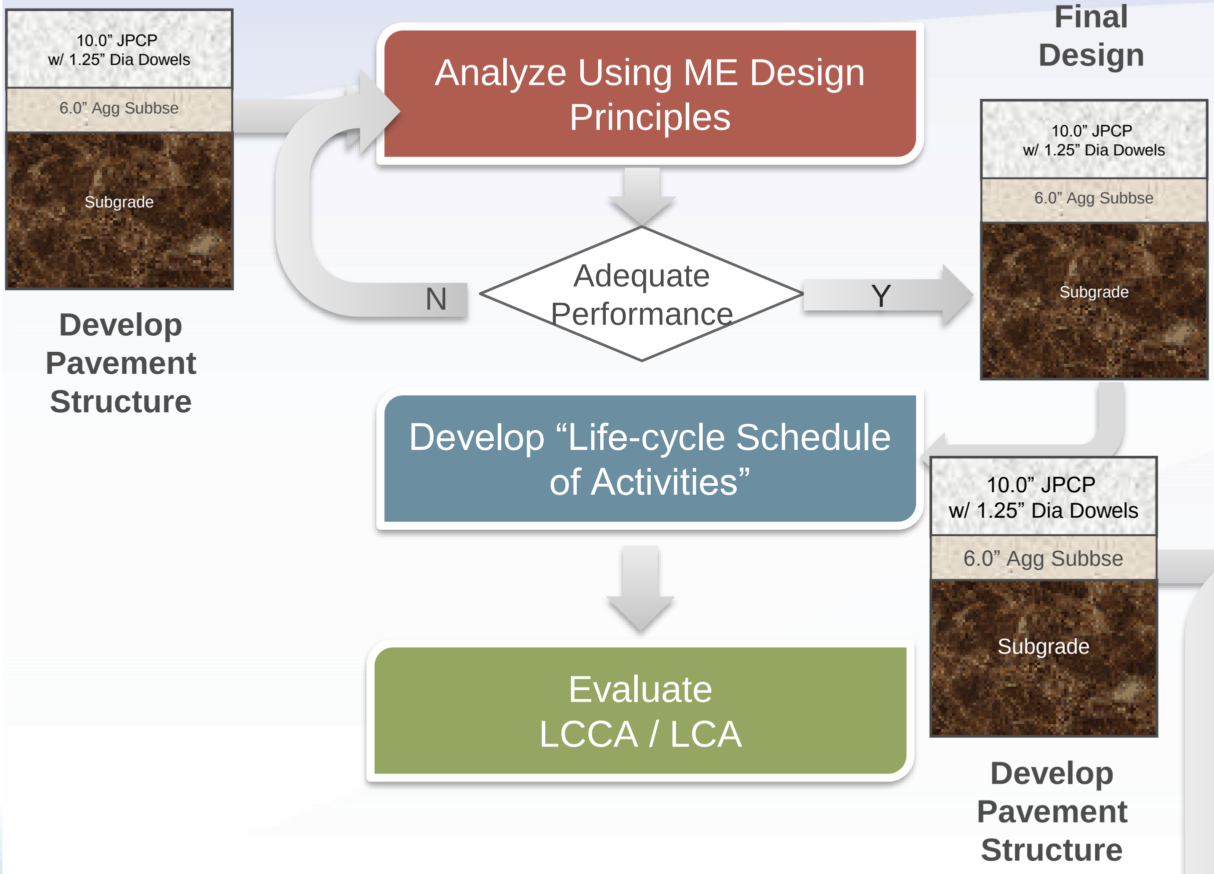
- Design Phase
  - Most flexibility
  - Evaluate options
  - “Optimized” designs

Concrete Pavement Life Cycle – Design Phase

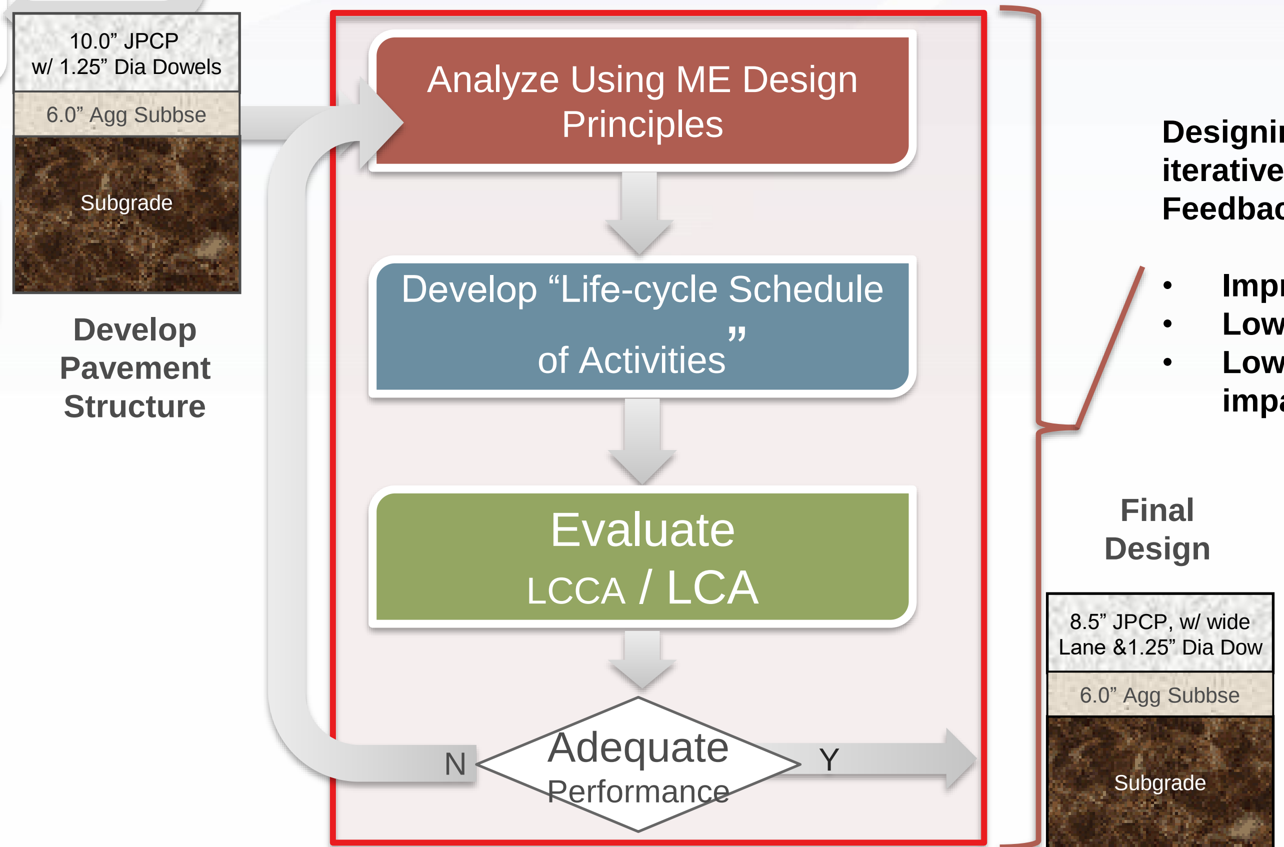
- Use the best available design tools
  - Pavement ME Design
  - *PavementDesigner.org*
- Long-life Pavements
  - Low hanging fruit (double life = ½ CO_2)
- Concrete overlays
  - Capitalize on equity already in pavement
  - Long-life and low-carbon design solution
- OPTIMIZE!!!

Optimize Pavement Designs

Traditional Design Process



Optimized Design Based on Life Cycle Thinking

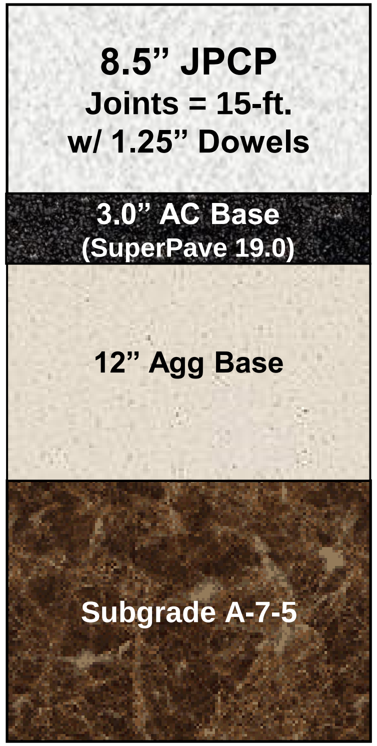


Designing pavements in an iterative procedure provides a Feedback Loop

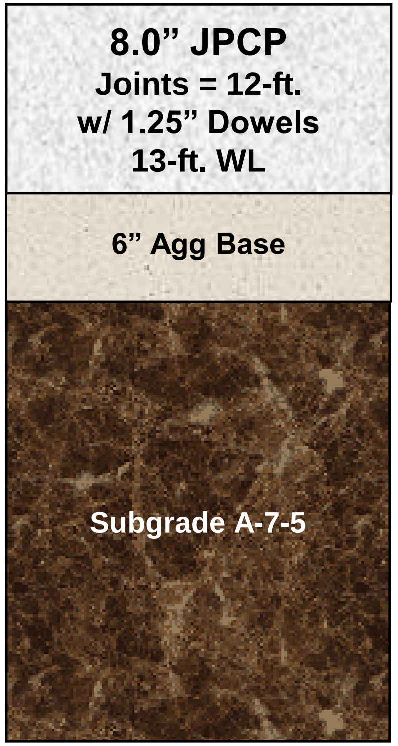
- **Improves performance**
- **Lowers cost**
- **Lowers environmental impacts**

PAVEMENT ME PROVIDES A PROCESS TO COMPARE DIFFERENT DESIGNS / DIFFERENT FEATURES

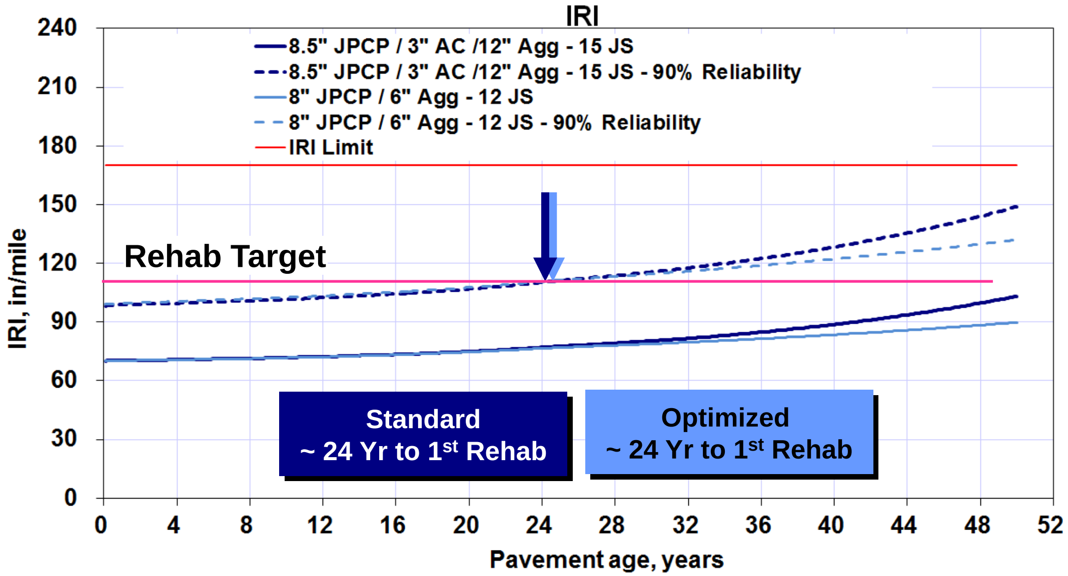
Original Concrete Design

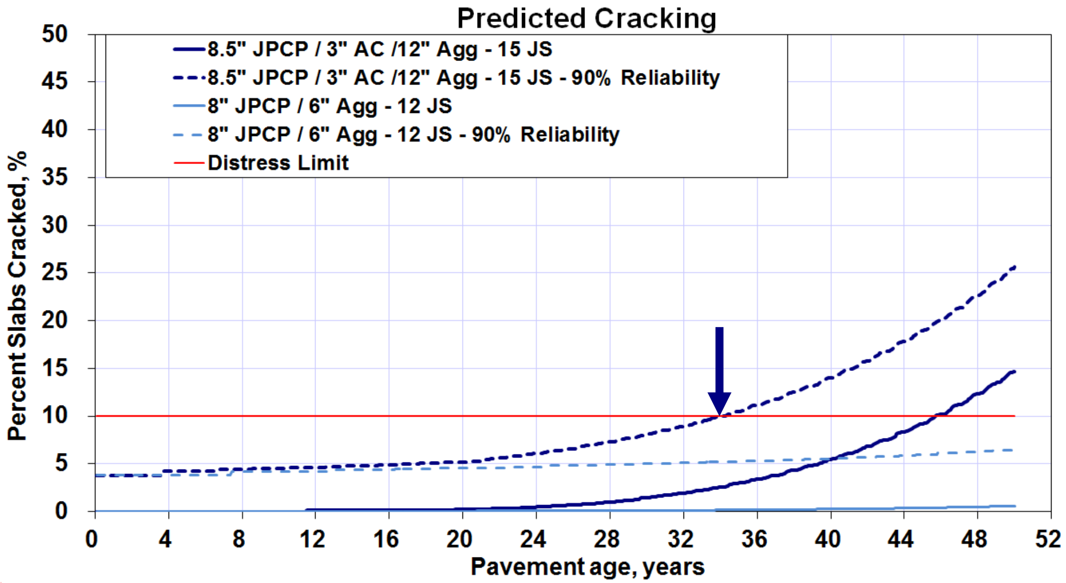


Optimized Concrete Design



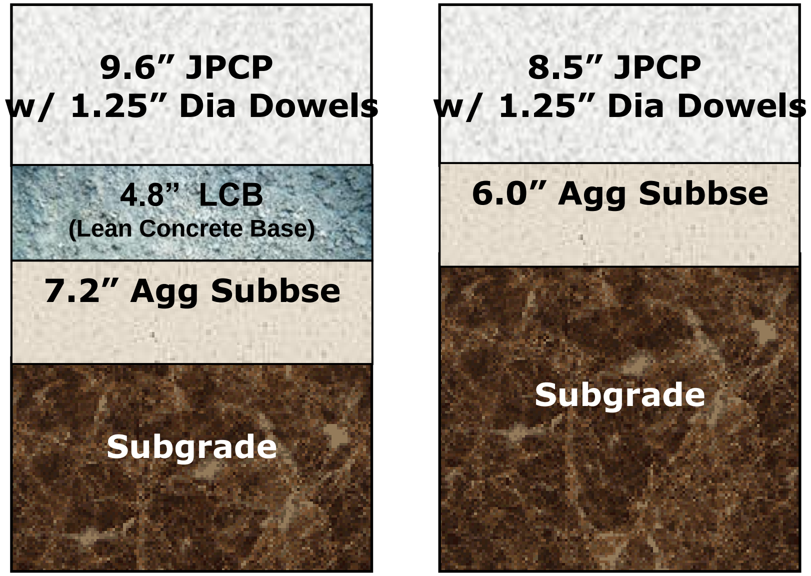
Pavement ME gives a repeatable, non-biased, scientific process to determine how a specific pavement design will perform





PROJECT SPECIFIC PAVEMENT DESIGN LOWERS COST AND ENVIRONMENTAL IMPACT

CALTRANS Concrete Design | **Optimized Concrete Design**



	Original CALTRANS Schedule		Optimized Pavement-ME Design	
	LCA (tons CO2e)	LCCA (NPV $)	LCA (tons CO2e)	LCCA (NPV $)
Initial Const.	**3,954**	**$3,147,585**	**3,063**	**$2,256,638**
Pavement	*2,860*	*$2,229,803*	*2,803*	*$2,021,307*
LCB	*781*	*$644,902*	*--*	*--*
Agg Subbase	*313*	*$272,880*	*260*	*$235,331*
Rehabilitation	**479**	**$911,663**	**54**	**$315,798**
Carbonation	**(123)**		**(87)**	
PVI-Deflection	**604**		**704**	
PVI-Roughness	**1,912**		**2,110**	
Total	**6,826**	**$4,059,248**	**5,844**	**$2,572,437**

Optimization reduced the initial construction GWP by 890 tons (22.5%) and the life cycle GWP by 980 tons (14.3%)

Optimization reduced the initial construction costs by $890k (28.3%) and the life cycle cost $1.48M (36.6%)

Caltrans Concrete Design: From Table 623.1E (South Coast/Central Coast, Type II SG
Initial AADTT = 1,357 / day, 4% Compound Growth (Initial ESAL = 335,000 / yr)
20 Yr ESALs = 10,650,000; 50 Yr ESALS = 51,151,000

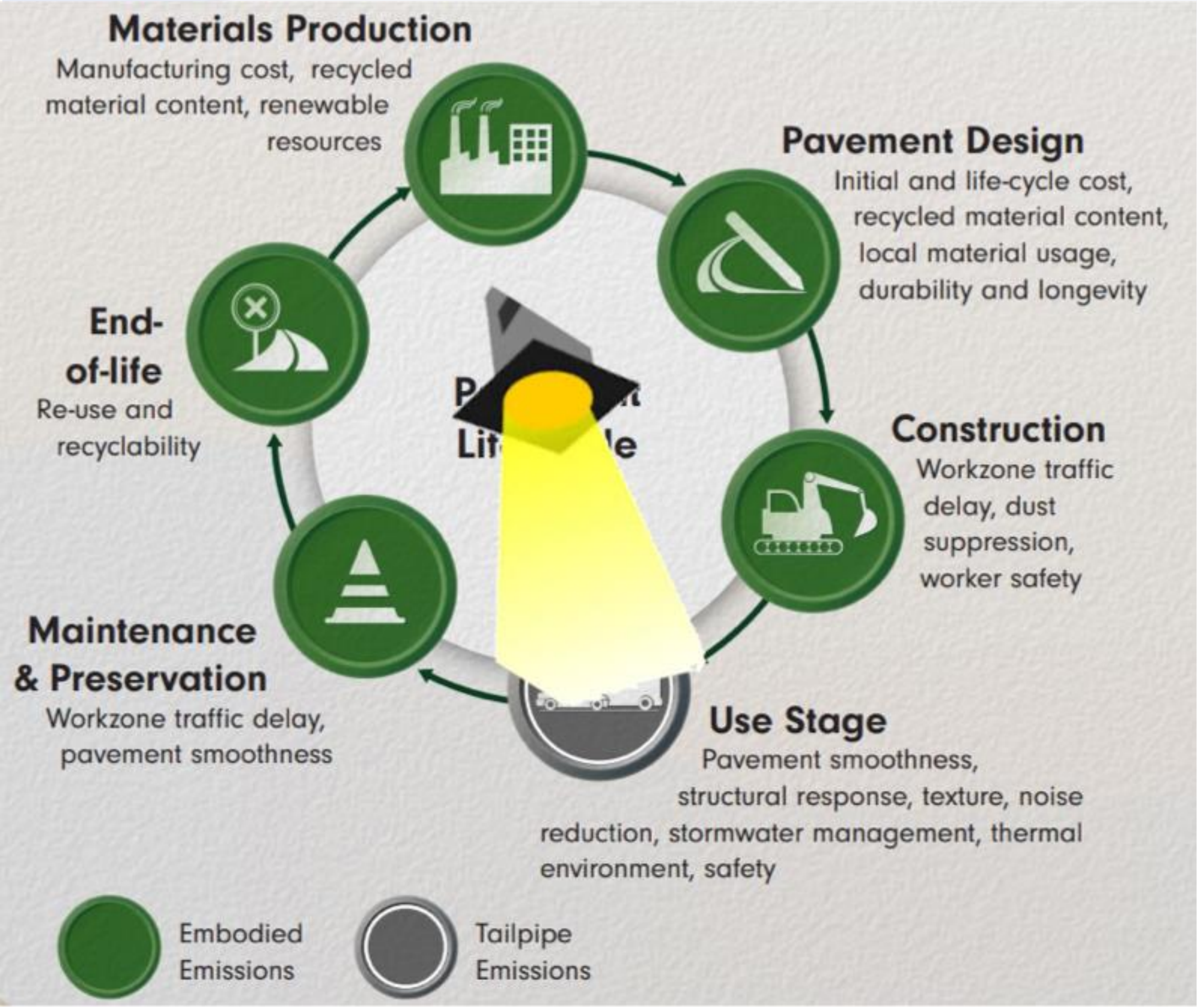
DESIGN IMPROVEMENTS FOR CONCRETE PAVEMENTS

Each Design Feature Needs to Balance Performance and Cost

Feature	Options or Benefits
Shorten Joint Spacing	Use 12-ft to reduce curling & warping stresses (reduces thickness but does increase joint sawing and dowel costs)
Change Shoulder Design	Use Tied Shoulders - Concrete vs AC vs RCC ; increases load transfer to shoulder (reduces thickness)
Apply Dowels	Use Dowel Bars – always Dowel ; Dowel Size ; increases load transfer and reduces faulting (reduces thickness)
Use Widened Lanes	Use 13-ft Widened Outside Lanes - Shifts loading to “interior loading” condition (reduces thickness)
Change Base Type	Granular vs asphalt treated vs cement treated ; subgrade / chemical stabilization ; reduce base thickness ; Speed of construction
Higher PCC Strength	Increased Concrete Strength - higher concrete strength reduces deflection (reduces thickness)
Optimized Mix Design	Optimized Gradation - Reduces cement content and creates denser mix ; models specific aggregate properties

“Features” have a significant impact on performance & cost

Concrete Pavement Life Cycle – Use Phase



- Use Phase
  - Pavement Vehicle Interactions (PVI)
  - Albedo
  - Urban heat island
  - Lighting
  - Carbonation / Sequestration

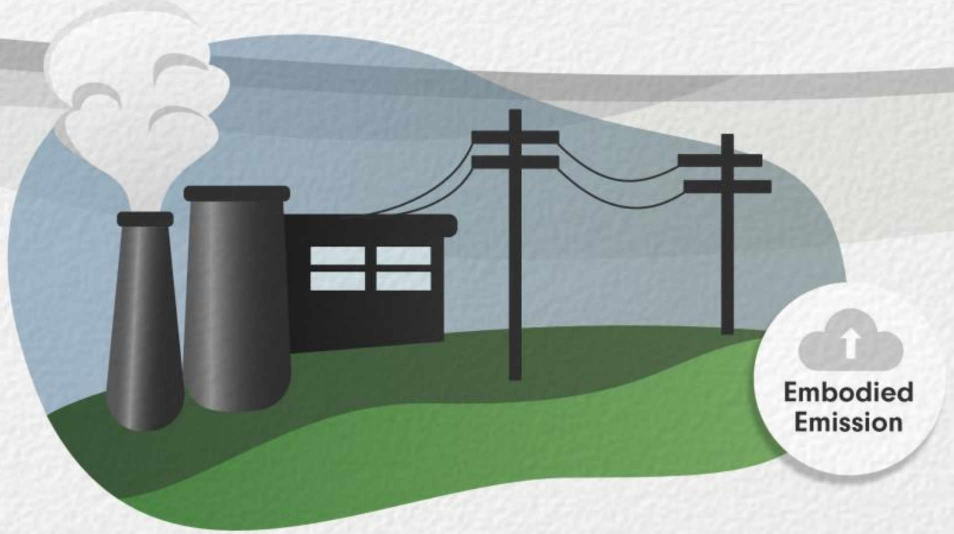
Concrete Pavement Life Cycle – Use Phase

EMISSIONS FROM HIGHWAY TRANSPORTATION SYSTEMS

A Look Beyond the Tailpipe

What are tailpipe emissions?

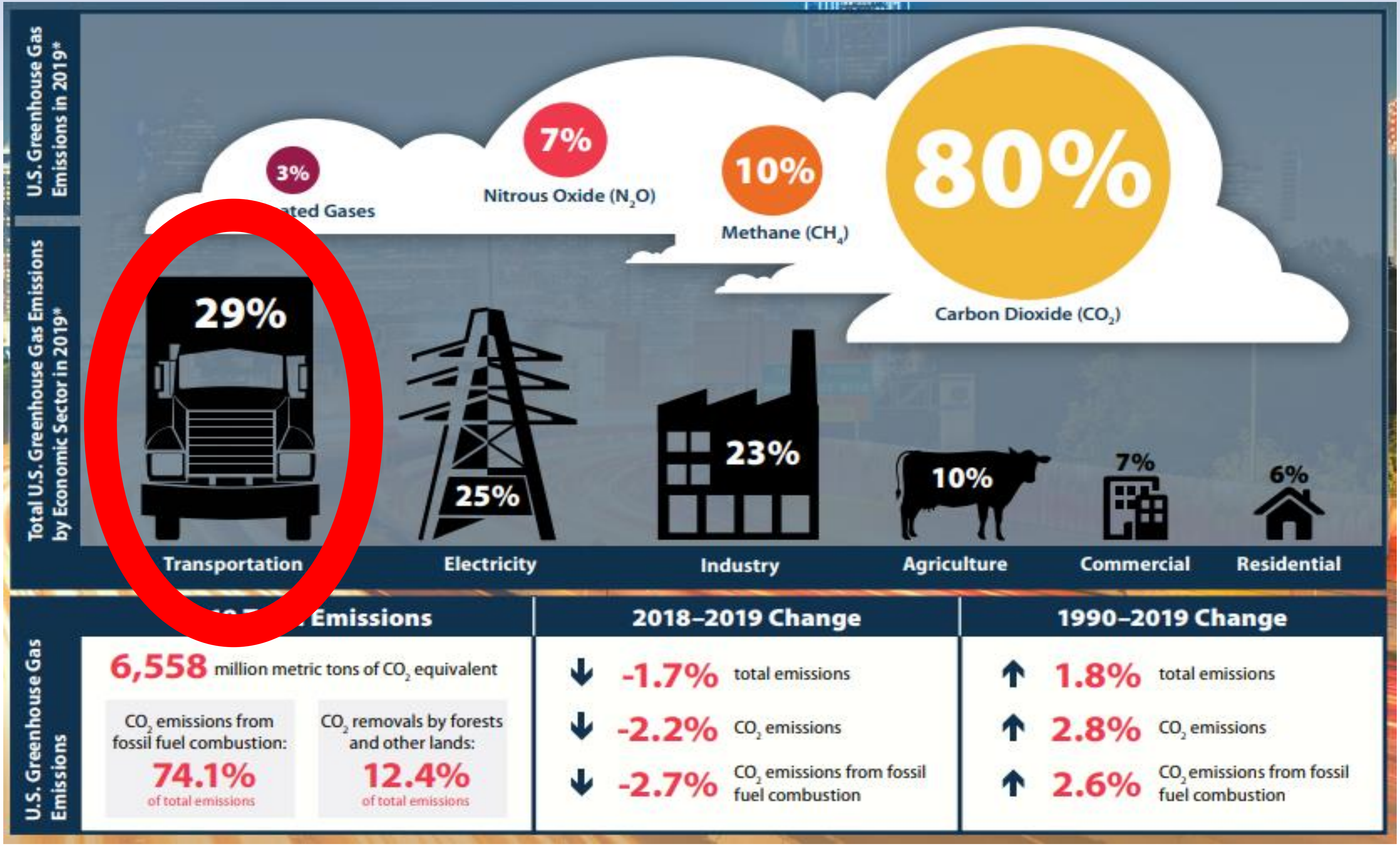
Tailpipe emissions are pollutants from exhaust gases discharged from vehicles equipped with an internal combustion engine. Tailpipe emissions incurred during the use stage of the pavement life cycle are considered operational emissions.



What are embodied emissions?

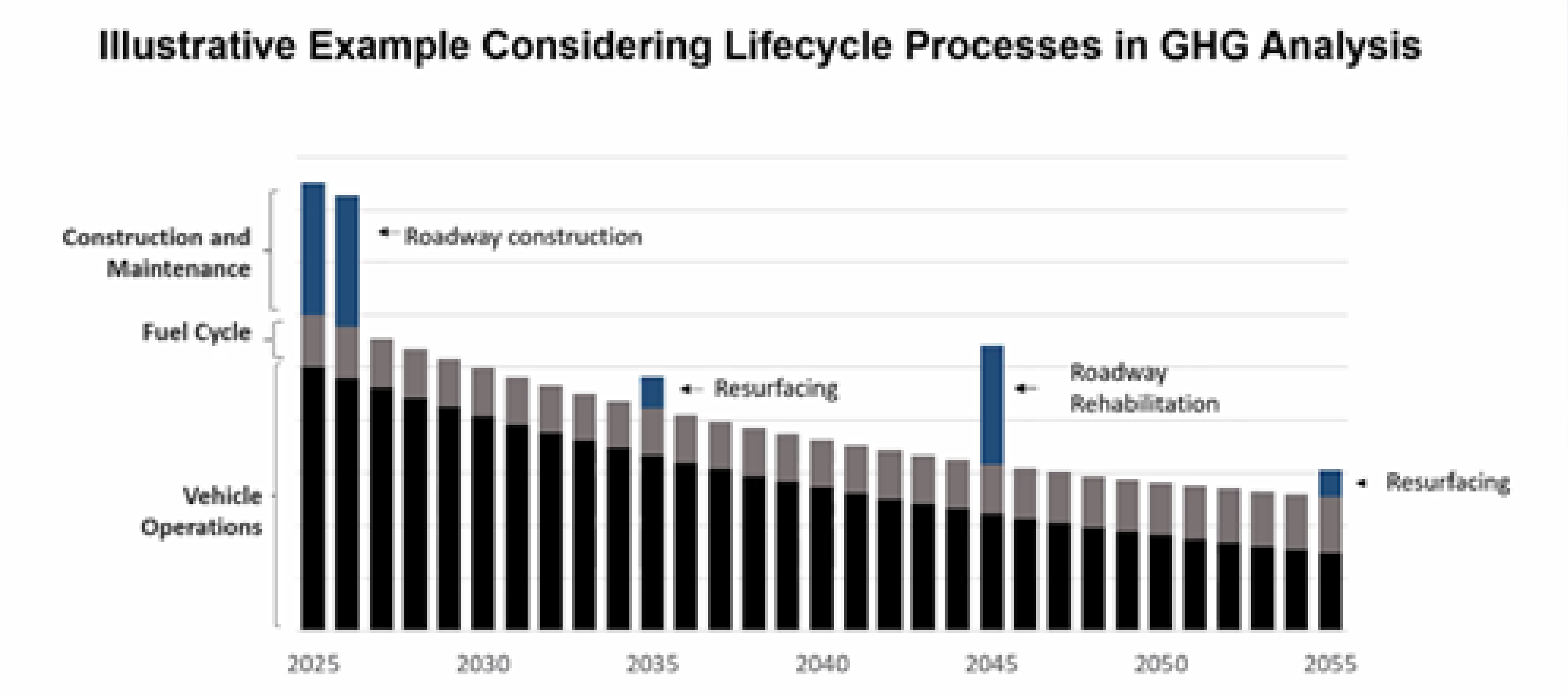
Embodied emissions include emissions from manufacturing, material transport, construction, maintenance, and disposal of transportation infrastructure building materials. Embodied emissions of greenhouse gases (GHG) are also known as embodied carbon.

CONTEXT



Source: EPA 430-F-21-011

The Impact of Vehicle Operations



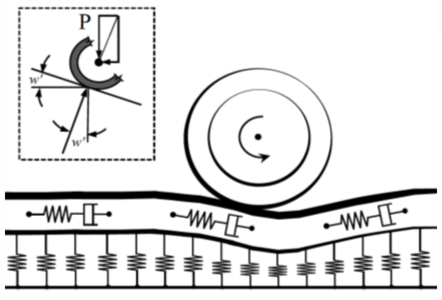
Source: Data is from FHWA based on illustrative example

Reducing Use Phase Impacts – PVI

Pavement Vehicle Interaction (PVI) Impacts the Excess Fuel Usage (EFC)

- Pavement texture:
  - The micro-surface of the pavement "grabs" the tire, which increases friction and lowers fuel efficiency.
  - Tire industry. Critical for safety. Tire-pavement contact area

- Roughness/smoothness*:
  - Higher roughness "bounces" the cars and increases fuel usage
  - Absolute value = vehicle dependent.
  - Changes / evolves over time: material specific

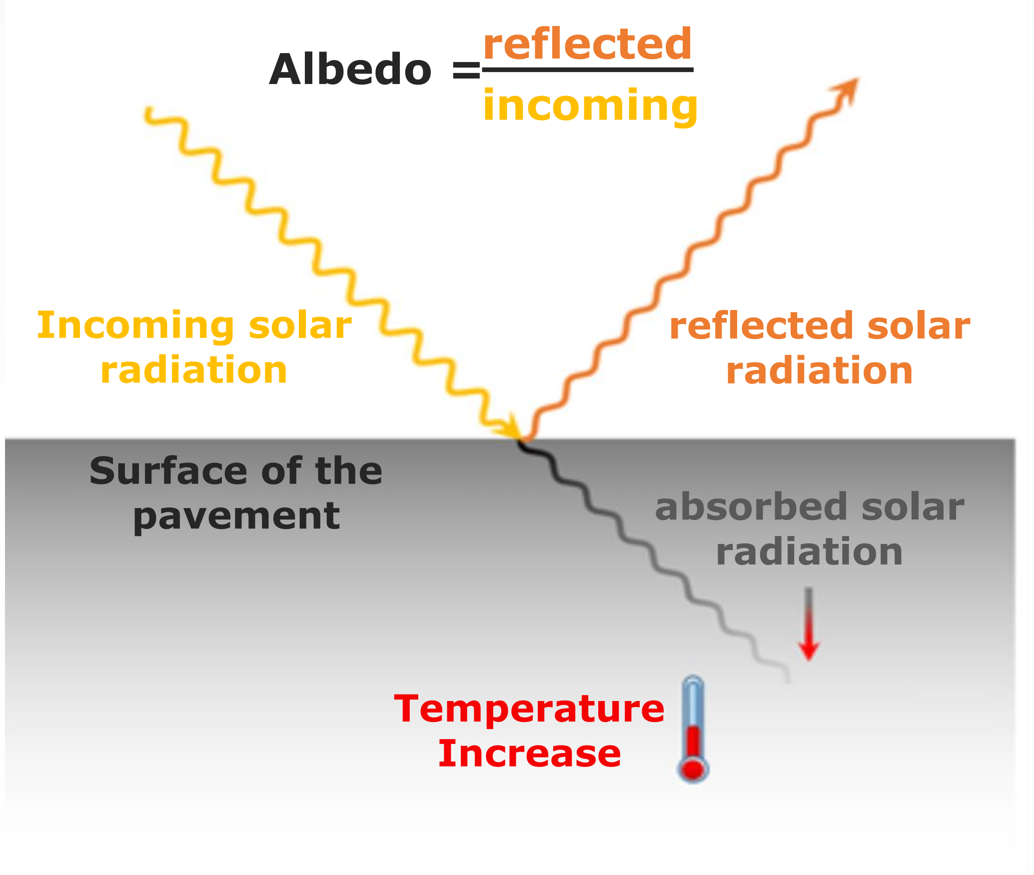


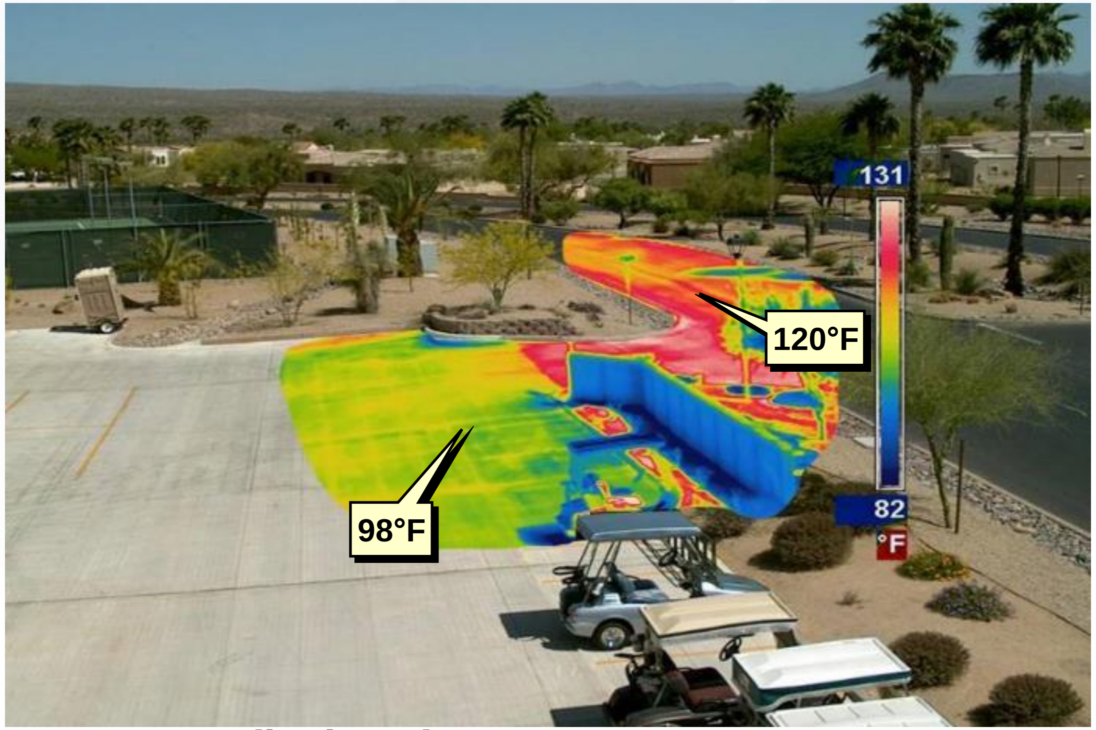
- Deflection/dissipation induced PVI**:
  - Vehicle deflects the pavement and vehicle drives up a hill
  - Pavement Design Parameters (materials, stiffness & thickness) matter
  - Speed and temperature dependent, especially for inter-city pavement systems

*Zaabar, I., Chatti, K. 2010. Calibration of HDM-4 Models for Estimating the Effect of Pavement Roughness on Fuel Consumption for U.S. Conditions. Transportation Research Record: **Journal of the Transportation Research Board**, No. 2155. Pages 105-116.
** Akbarian M., Moeini S.S., Ulm F-J, Nazzal M. 2012. Mechanistic Approach to Pavement-Vehicle Interaction and Its Impact on Life-Cycle Assessment. Transportation Research Record: **Journal of the Transportation Research Board**, No. 2306. Pages 171-179.

Reducing Use Phase Impacts – Albedo

- Albedo – The measure of solar energy reflected by surface





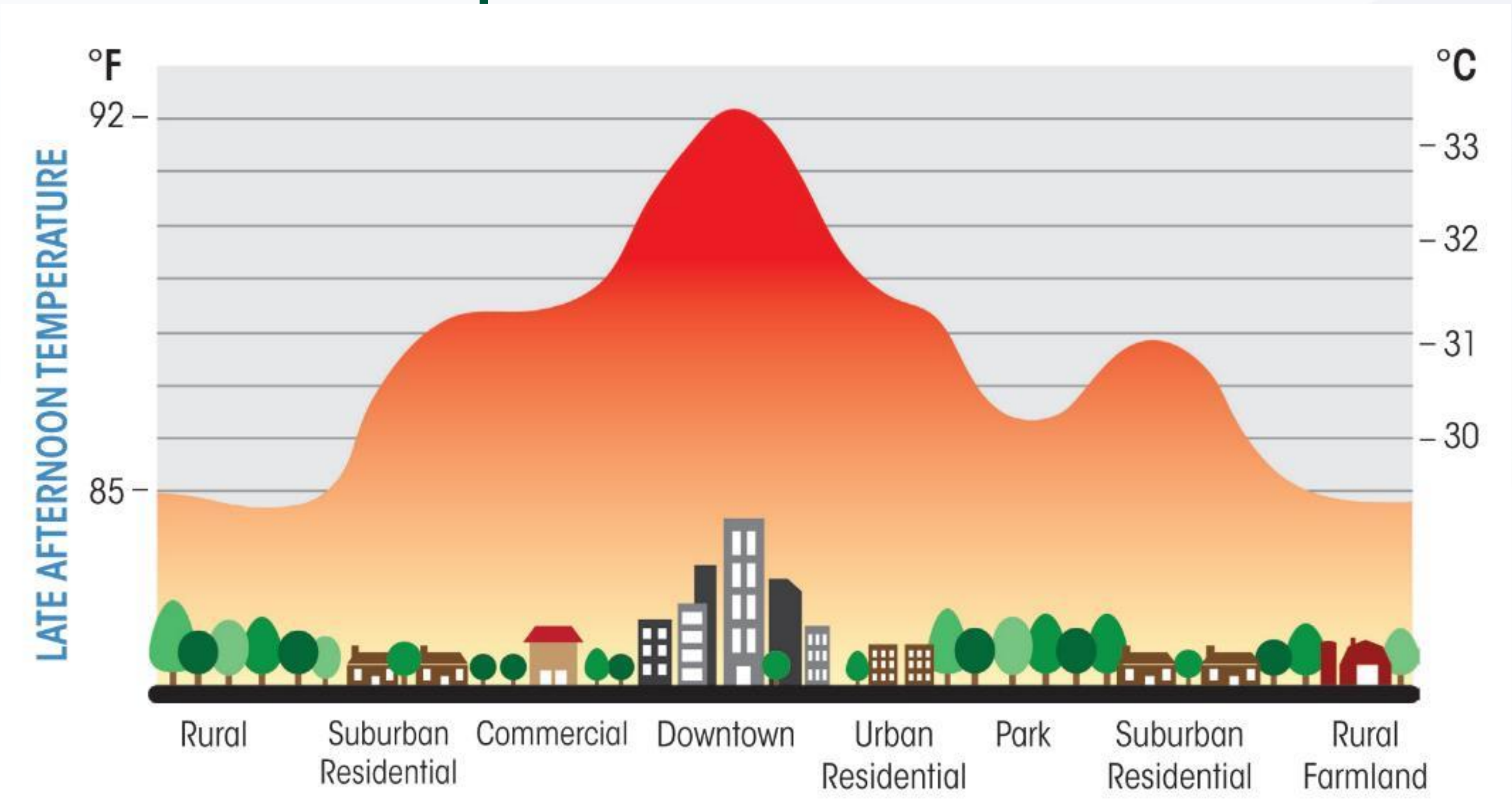
Albedo Values

- Concrete ≈ 0.40 (new) to 0.2 (old)
  Concrete with PLC &/or Slag ≈ 0.45 to 0.55
- Asphalt ≈ 0.05 (new) to 0.15 (old)
- Earth Avg ≈ 0.3 to 0.35

Reducing Use Phase Impacts – Urban Heat Island

- Concrete's high albedo reduces Urban Heat Island impact

Example of Heat Island effect



Increasing pavement albedo by 0.20 (asphalt to concrete) can reduce city temperatures by :

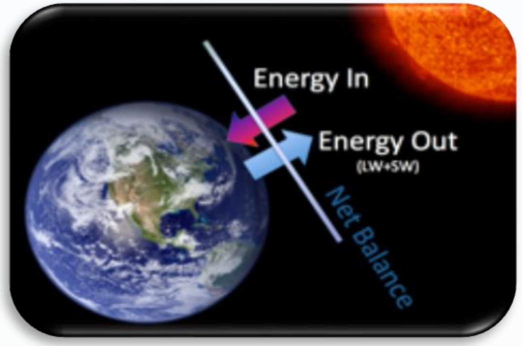
- **0.3° C (Boston)**
- **2.1° C (Phx)**

Sources:
http://www.cleanairpartnership.org/files/urbanheatisland.jpg
http://cshub.mit.edu/pavements/albedo

Concrete Pavement Life Cycle – Use Phase

Increasing pavement albedo is meaningful and low-cost and low risk endeavor to address climate change

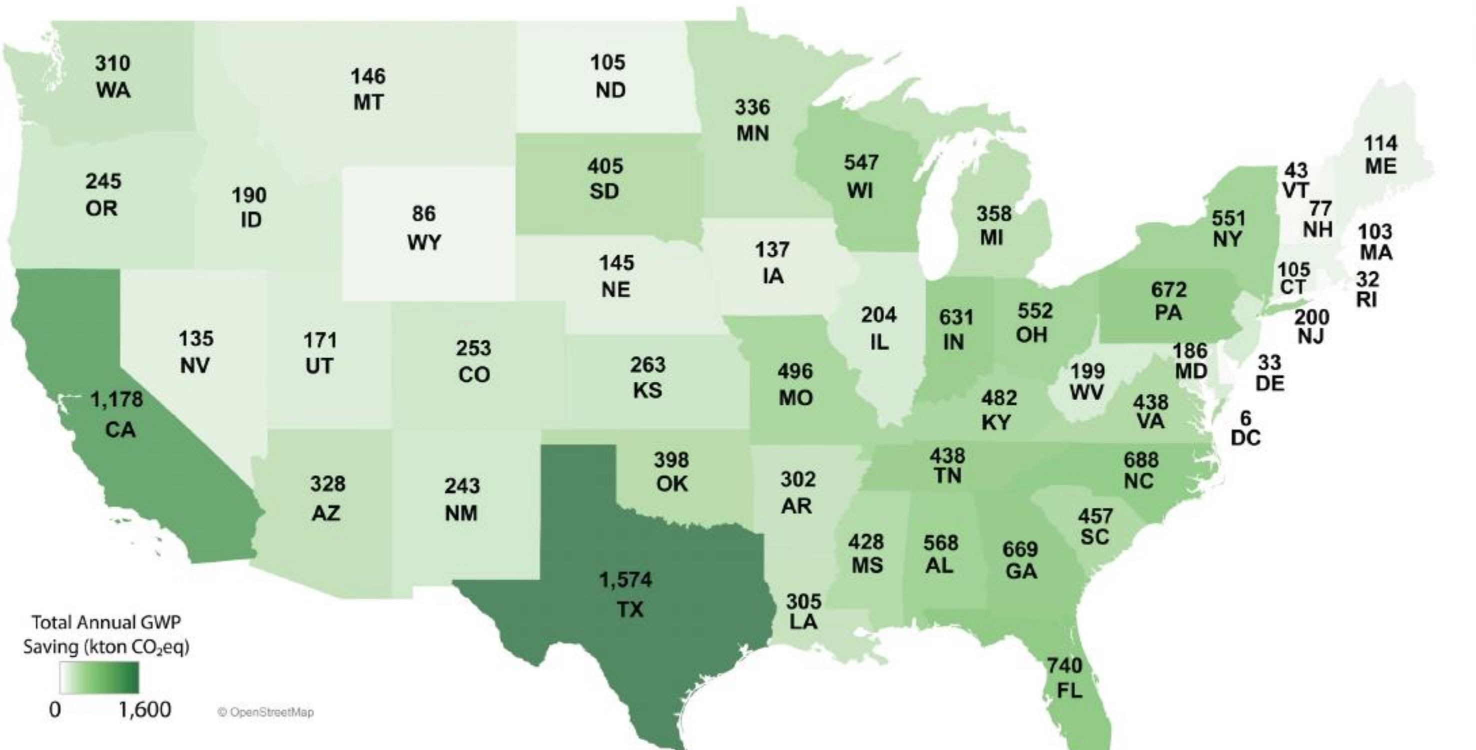
Earth's Energy Balance



Radiative forcing

Albedo improves the Earth's Energy Balance to create **Cooling Benefits**

Annual GWP savings due to increasing the surface reflectivity of all pavements across the continental U.S. (kton CO_{2eq})

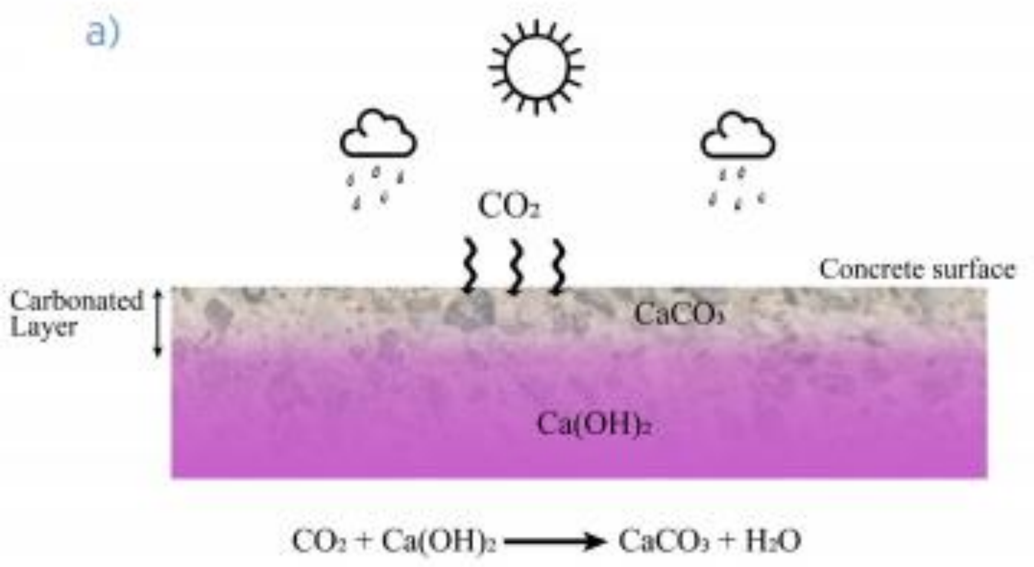


Sources:
http://www.cleanairpartnership.org/files/urbanheatisland.jpg
http://cshub.mit.edu/pavements/albedo

An increase in pavement albedo on all U.S. roads would reduce CO2-eq by 17.45 Mton per year due to radiative forcing—equivalent to ~ 4 million cars

Reducing Use Phase Impacts – Carbonation

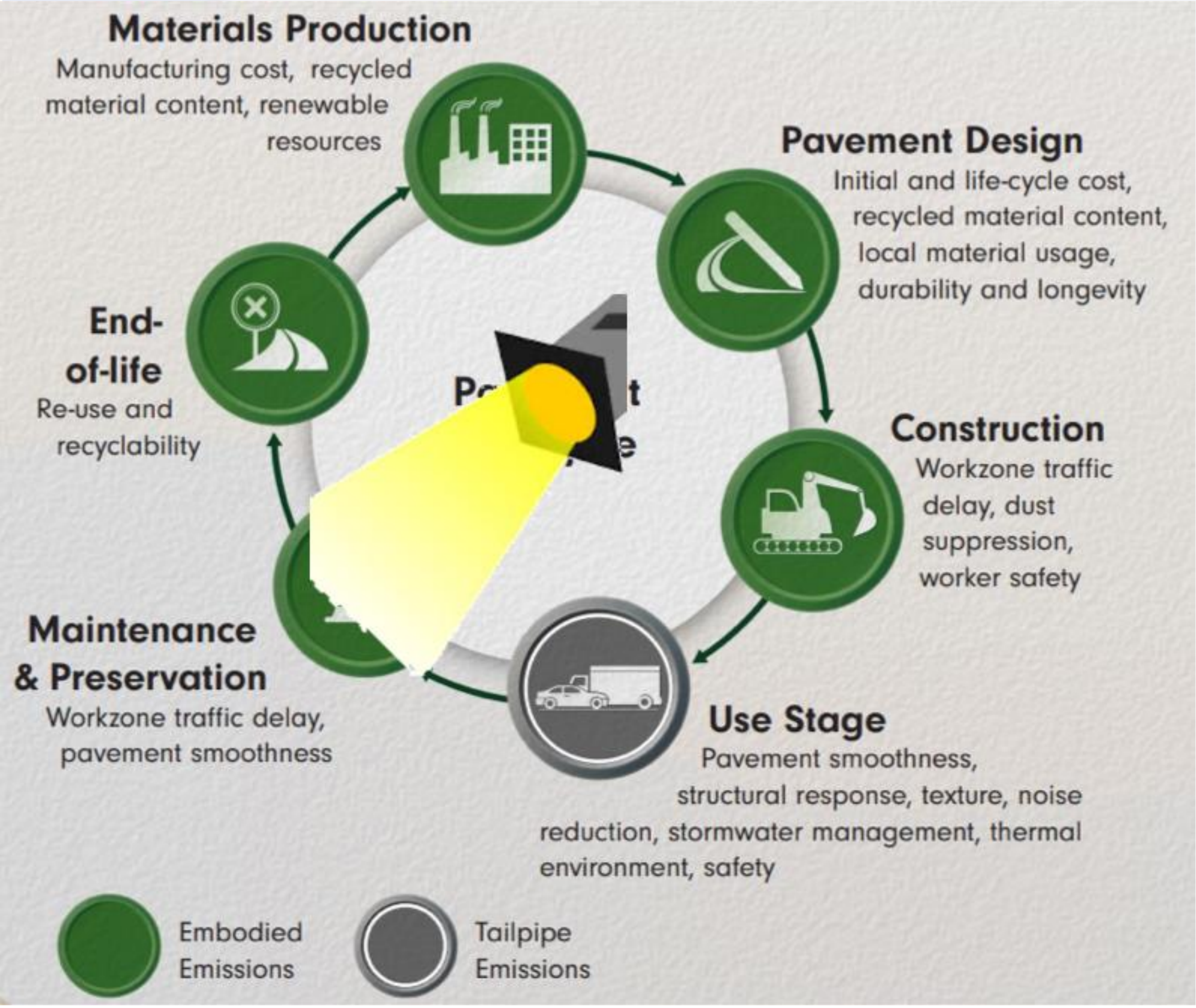
- Concrete – CO_2 Absorption
- Carbonation CO_2 reacts with calcium carbonate in concrete
- In US, concrete pavements could absorb about 2.8 million tons of CO2 30 years use
  - More in states w/ concrete pavements



https://news.mit.edu/2021/unravelling-carbon-uptake-concrete-pavements-0126

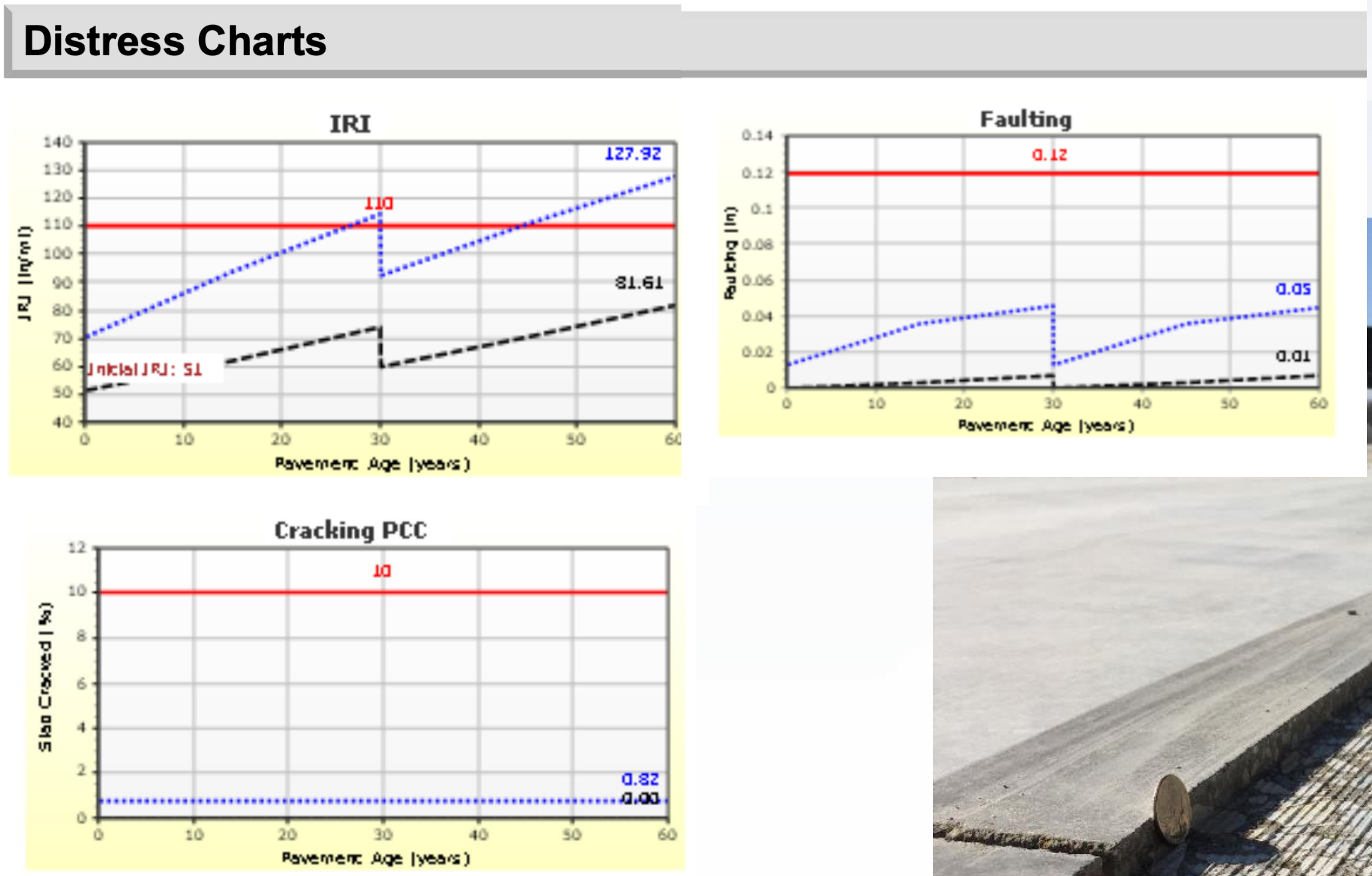
https://cshub.mit.edu/sites/default/files/images/0120%20Carbon%20Uptake%20Bri

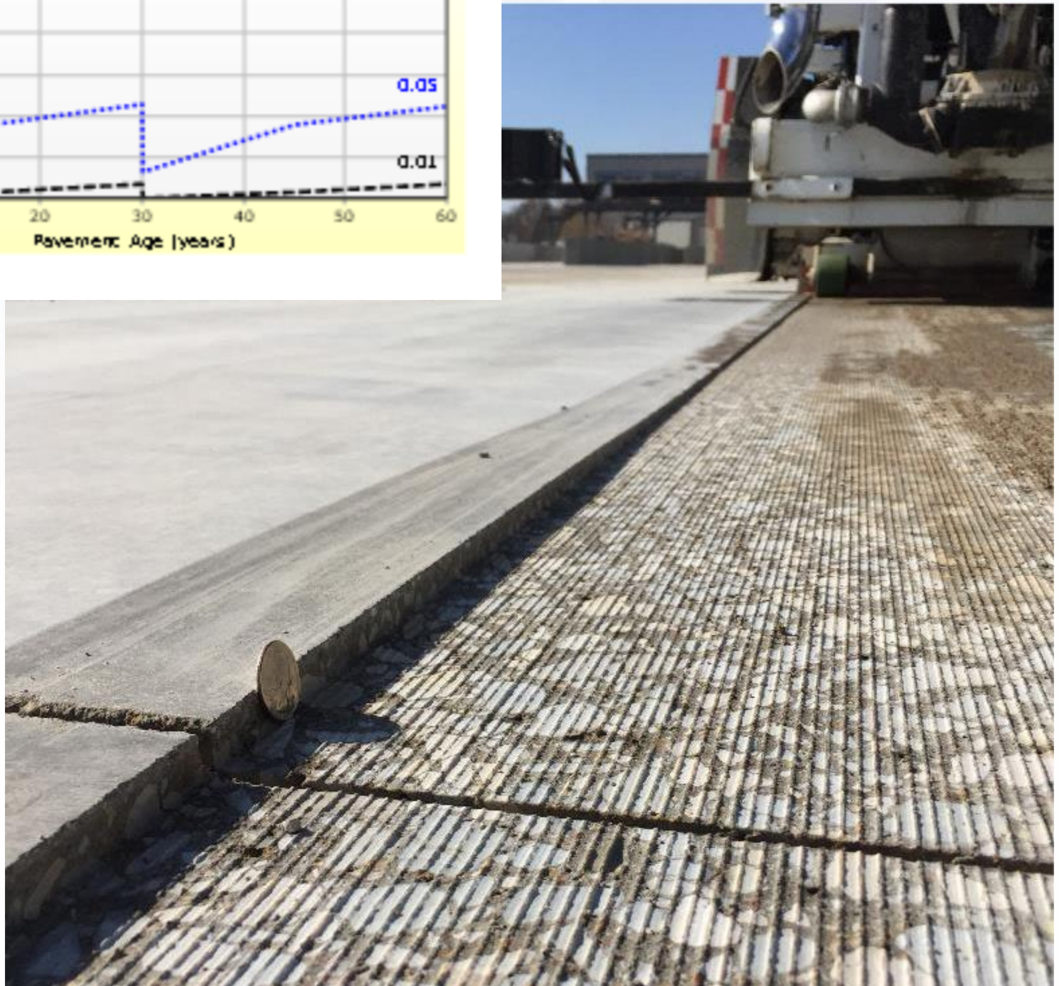
Concrete Pavement Life Cycle – M&R Phase



- Maintenance, Preservation, & Rehabilitation
  - Diamond grinding
  - Patching
  - Sealing
  - Overlays

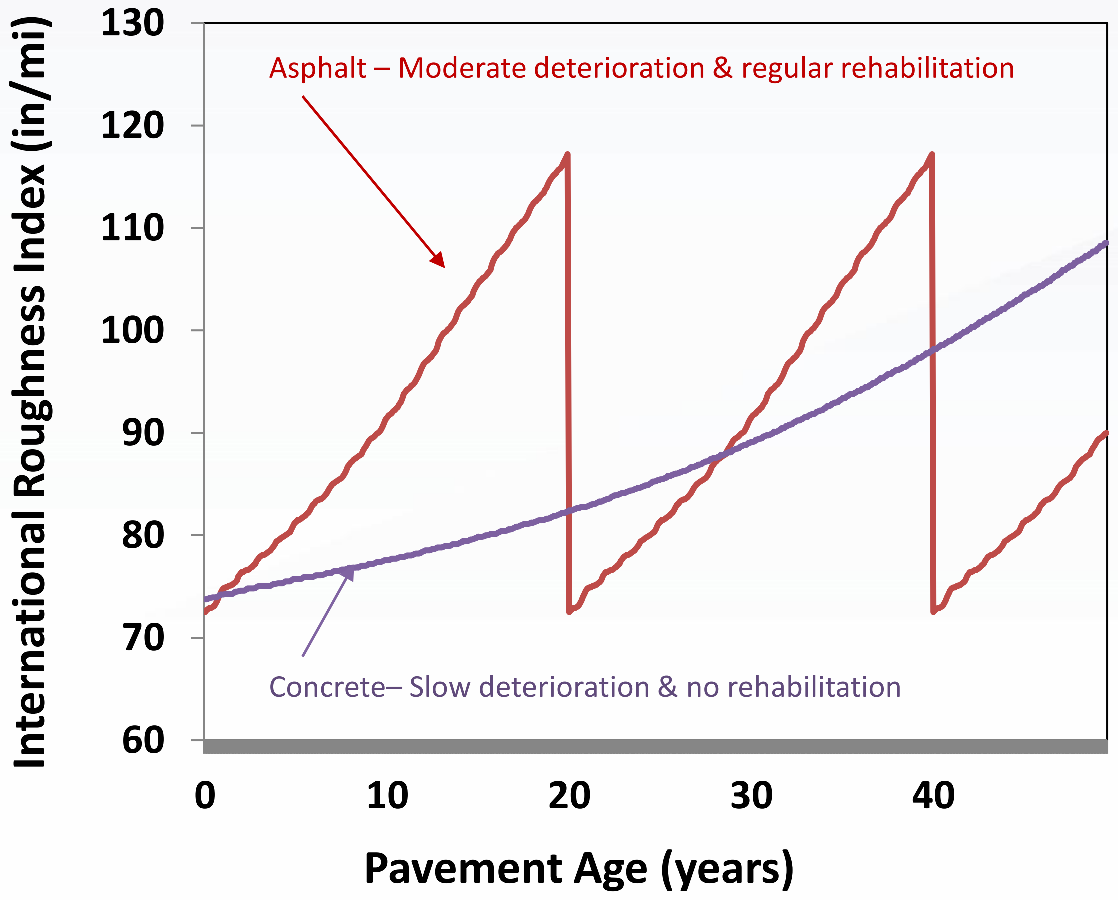
Concrete Pavement Life Cycle – M&R Phase

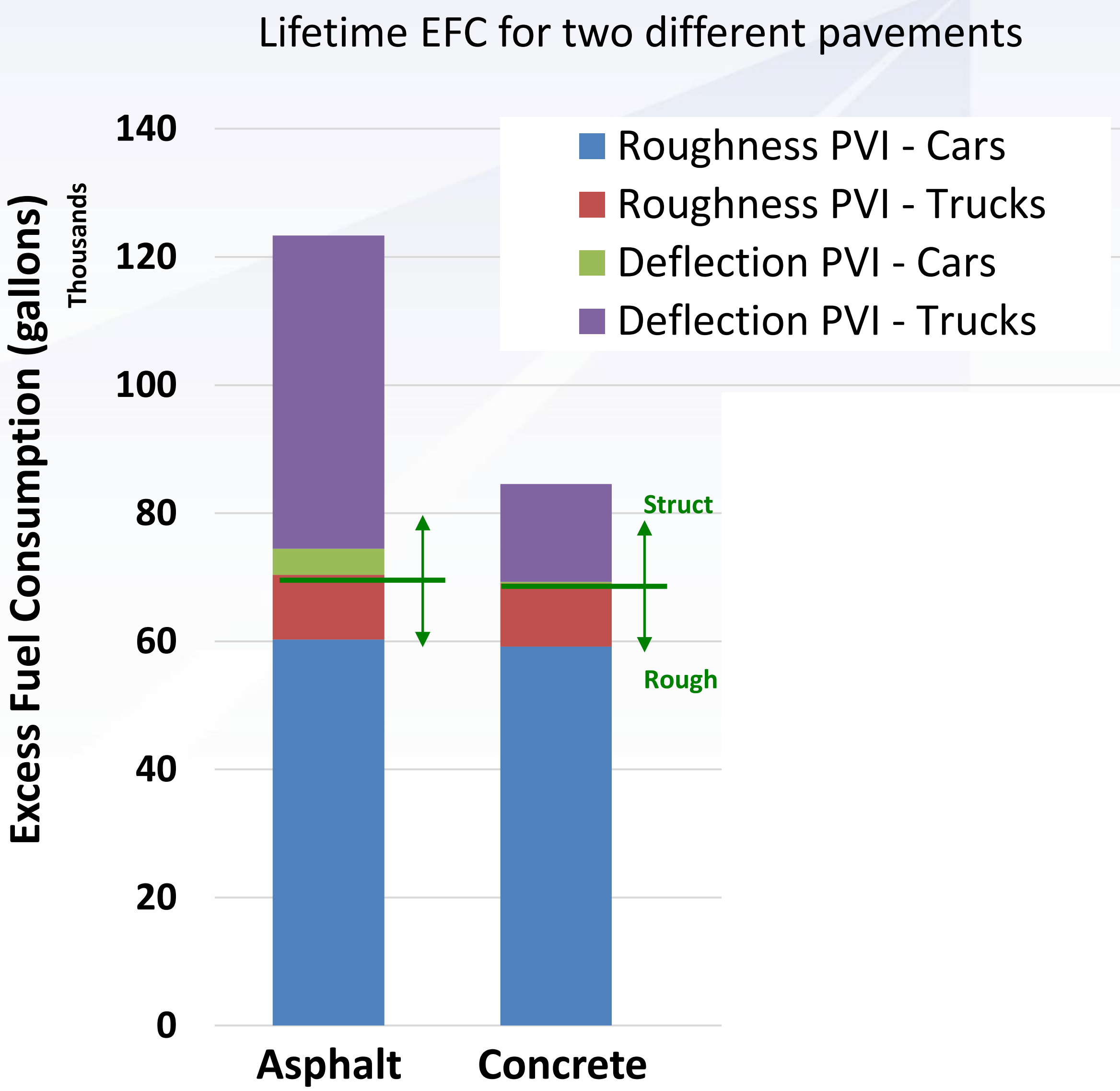




Excess Fuel Consumption Based on 2 Primary Strategies

Local highway in MO. Equivalent AC and PCC

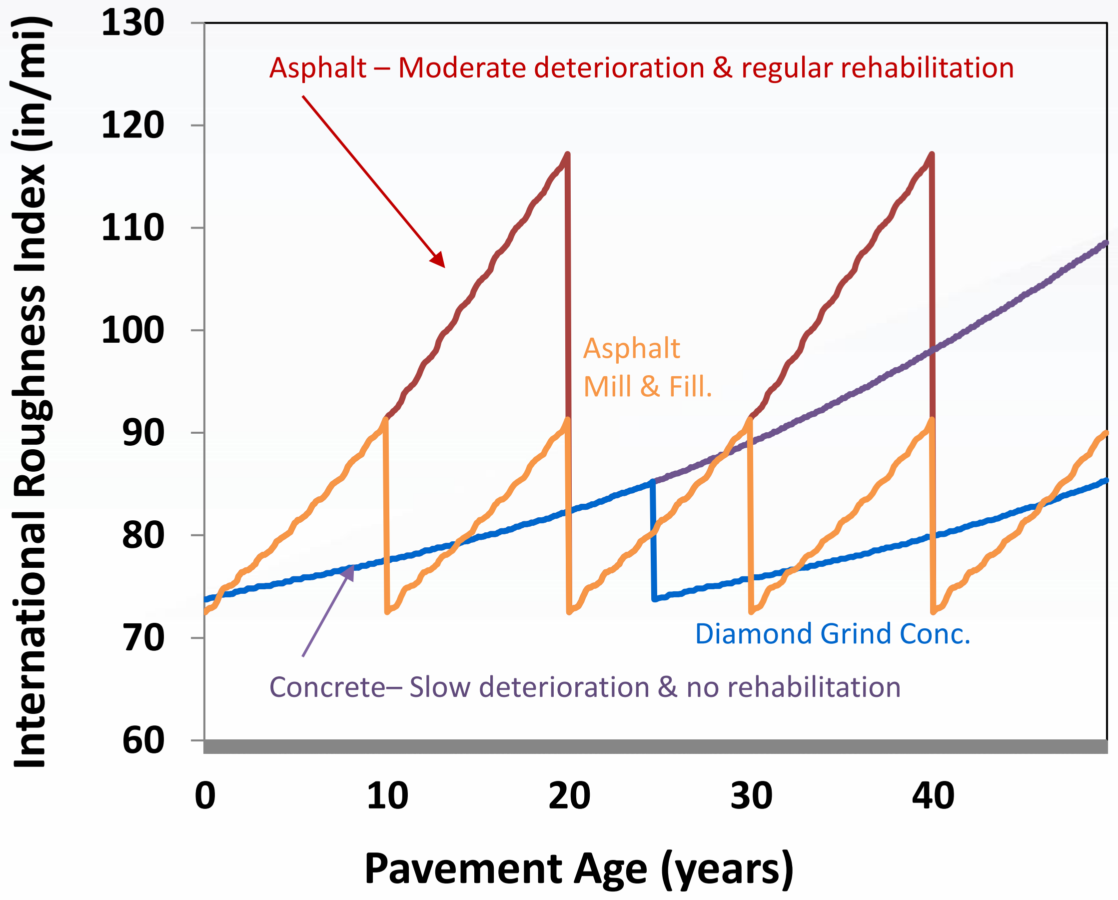


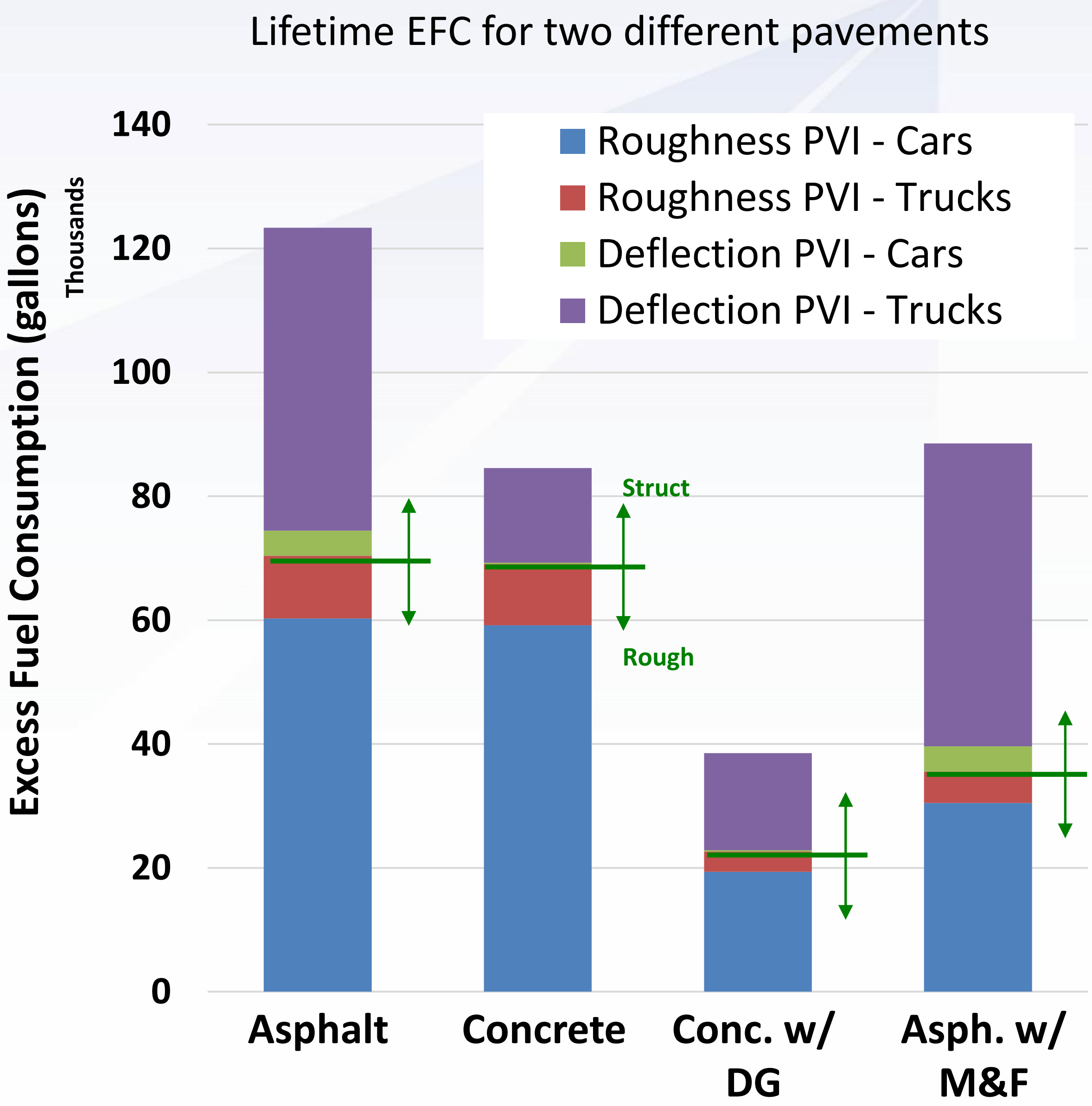


Pavement design developed by Applied Research Associates (ARA), Inc,:
Local Highway - AADTT 300/day; 2 lanes; Wet-freeze-MO;

EFC Based on 2 Primary Strategies w/ Preservation

Local highway in MO. Equivalent AC and PCC

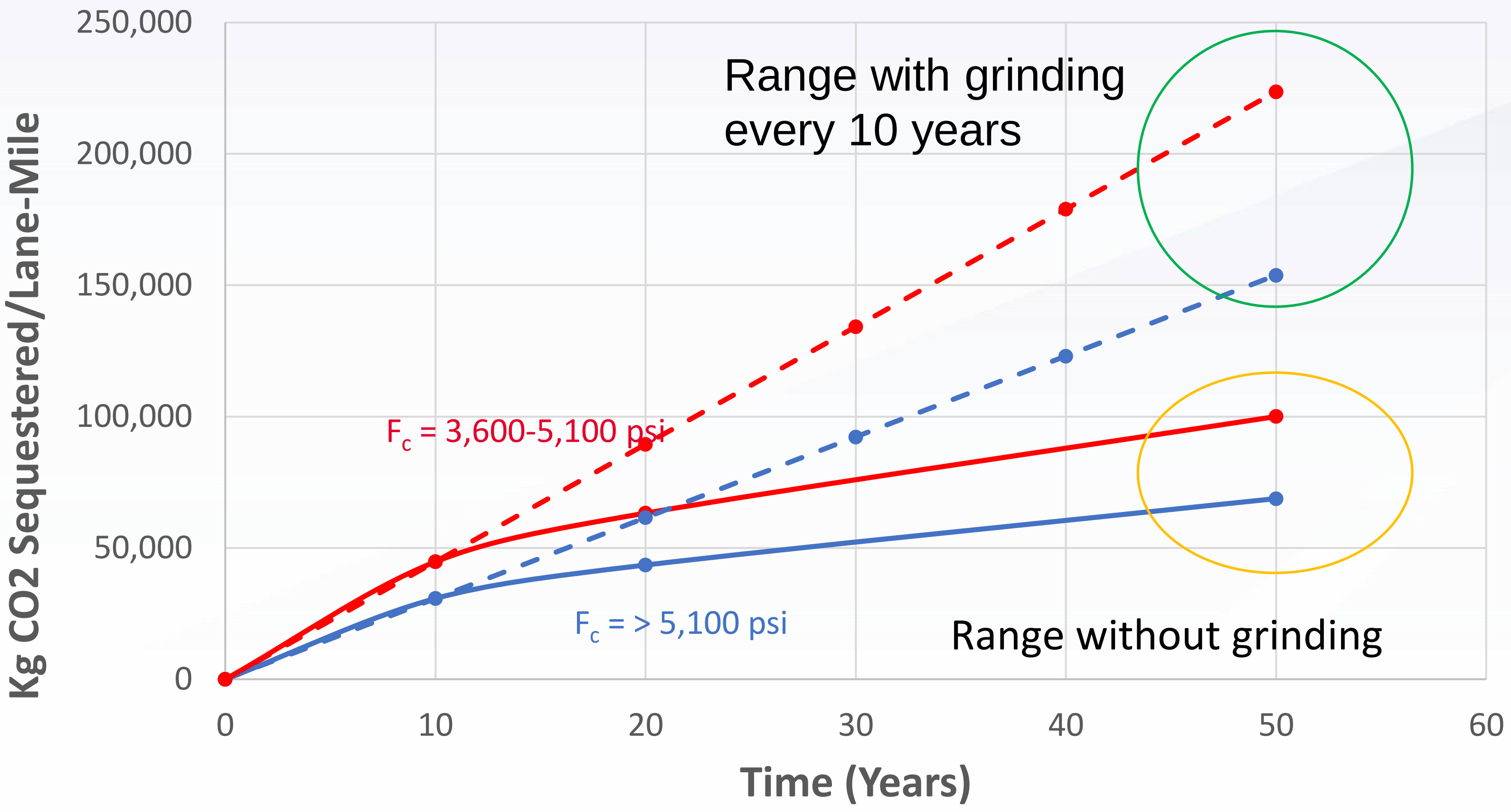




Pavement design developed by Applied Research Associates (ARA), Inc,:
Local Highway - AADTT 300/day; 2 lanes; Wet-freeze-MO;

Reducing Use Phase Impacts – With Preservation

CO_2 Sequestered Over Time per Lane-Mile with Diamond Grinding



Additional Diamond Grinding also improves vehicle fuel efficiency due to improved smoothness and increases Albedo resulting in even greater GHG reductions

Source: Information courtesy of Tom Van Dam, NCE

MIT Fuel/Carbon Savings Calculator

This app was developed using the concepts and models discussed in Journal of Cleaner Production in 2016. The Fuel/Carbon Saving App looks at an instantaneous improvement in IRI for a set amount of traffic on a daily basis. This daily savings can then be used to estimate annual savings for a set period of time. Estimating actual IRI for future years was considered but not used due to the fact that the estimates could never be confirmed. Allowing the user to extrapolate the findings on a daily level to an annual level was seen as the best estimate. Users should understand these are only estimates based on current traffic and smoothness calculations.

IGGA International Grooving & Grinding Association
Your Pavement Preservation Resource® since 1972

MIT Concrete Sustainability Hub

Estimated IRI Pre-Grind: 112 in/mi
Estimated IRI Post-Grind: 75 in/mi
Traffic Speed: 60 mph
Average Daily Traffic: 30000
Traffic Growth Rate: 1.28 %
Heavy Commercial: 10 %
Gasoline Cost (Per Gallon): $ 3.5 USD
Diesel Cost (Per Gallon): $ 5 USD
Length Of Road: 1 miles
Lane Width (Cost Estimate): 12 feet
Diamond Grinding Cost (Per Yard): $ 7 USD

☐ Is this a concrete pavement?

Calculations

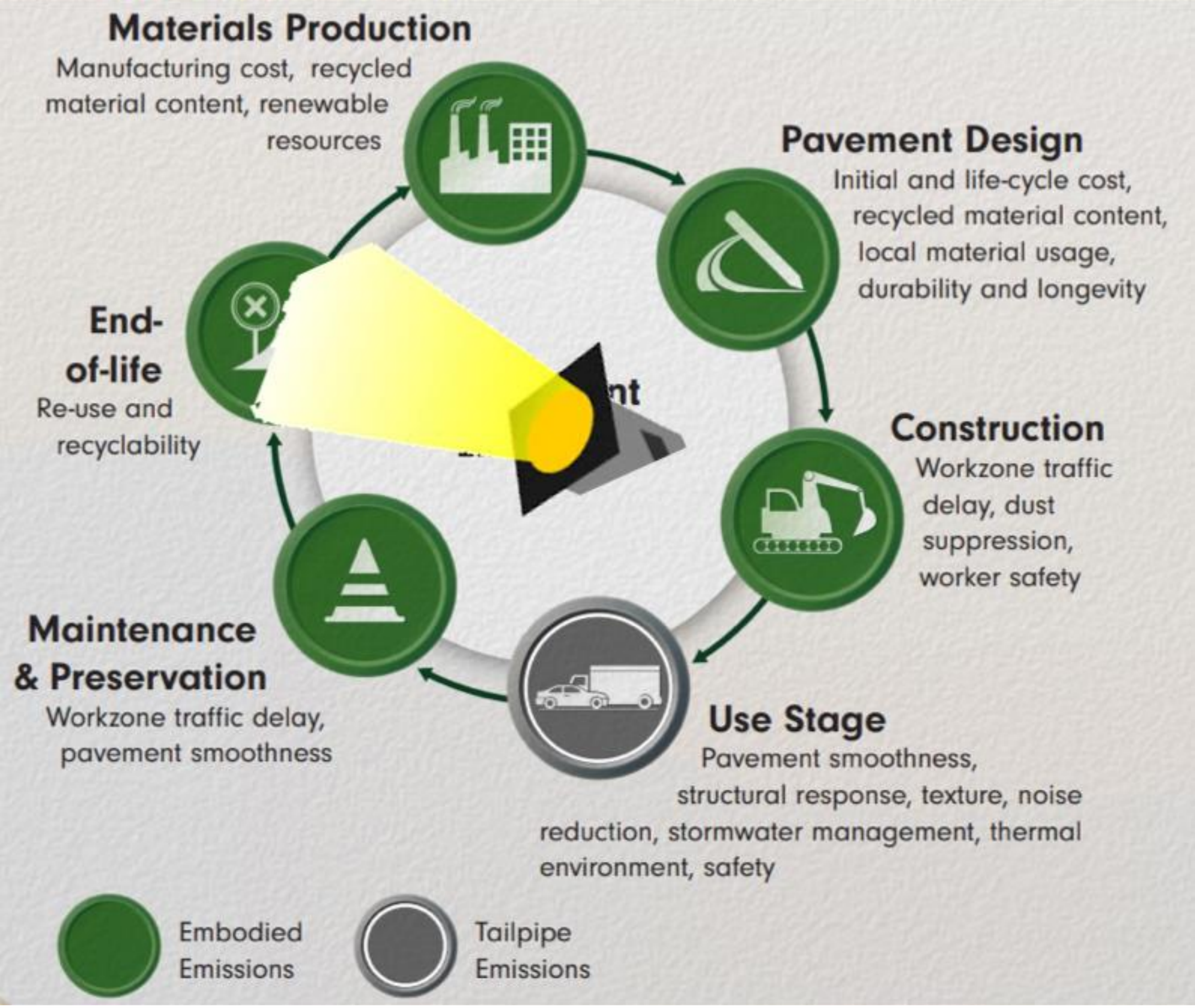
Cars Per Day	27,000
Trucks Per Day	3,000
Daily Fuel Savings Per Mile	$74.08
Annual Fuel Savings Per Mile	$27,040.13
Ten Year Fuel Savings Per Mile	$270,401.33
Cars - Carbon Savings Daily (kg/km)	77.78
Trucks - Carbon Savings Daily (kg/km)	31.83
Carbon Savings Annual (metric tons/mile)	32.21
Carbon Associated With Fuel Consumed During Diamond Grinding (lbs)	19,008
Diamond Grind Cost	$49,280.00

Cost Carbon Benefit Table

Print

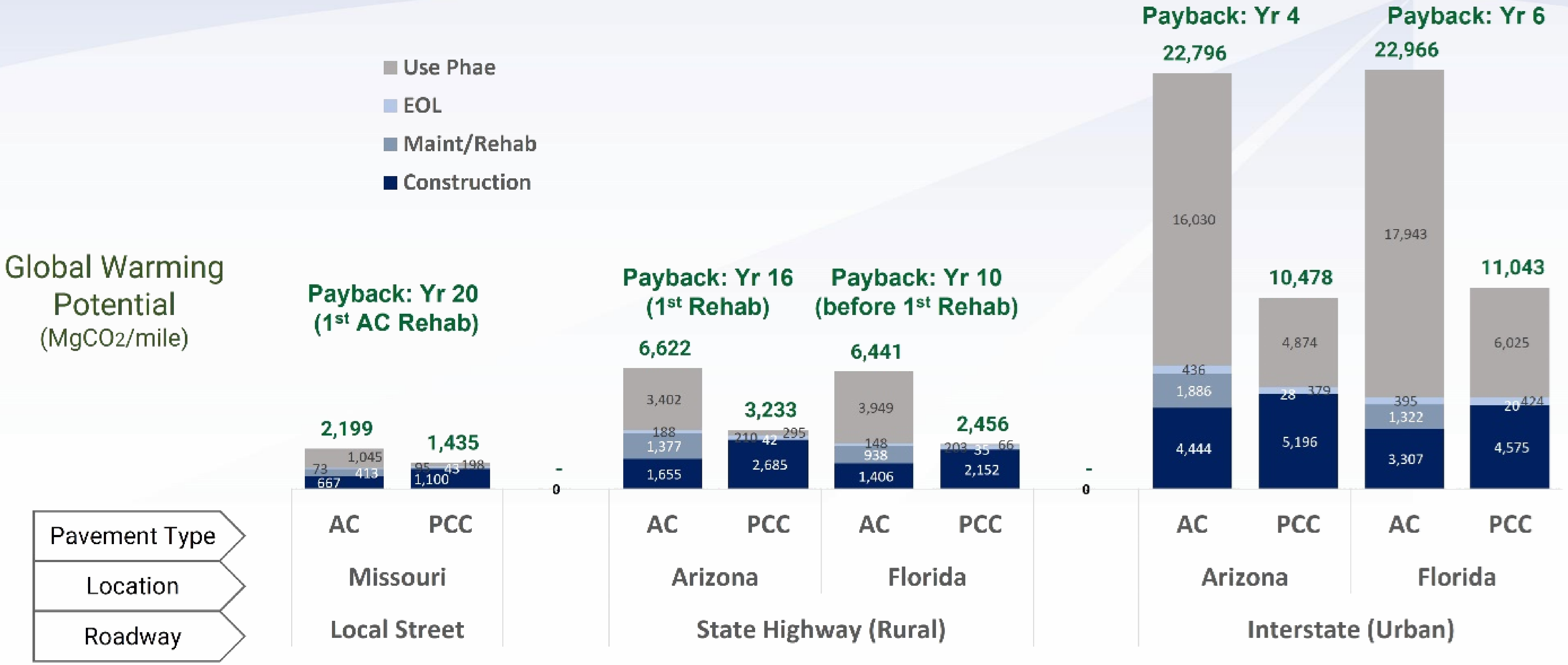
Category	10 Year Benefit		20 Year Benefit	
	Cost ($)	Carbon (Metric Tons)	Cost ($)	Carbon (Metric Tons)
Savings for IRI	$270,401.33	322.06	$540,802.66	644.12
Cost of Grinding	$49,280.00	9.50	$49,280.00	9.50
Total (savings)	$221,121.33	312.55	$392,962.66	634.61

Concrete Pavement Life Cycle – EOL Phase

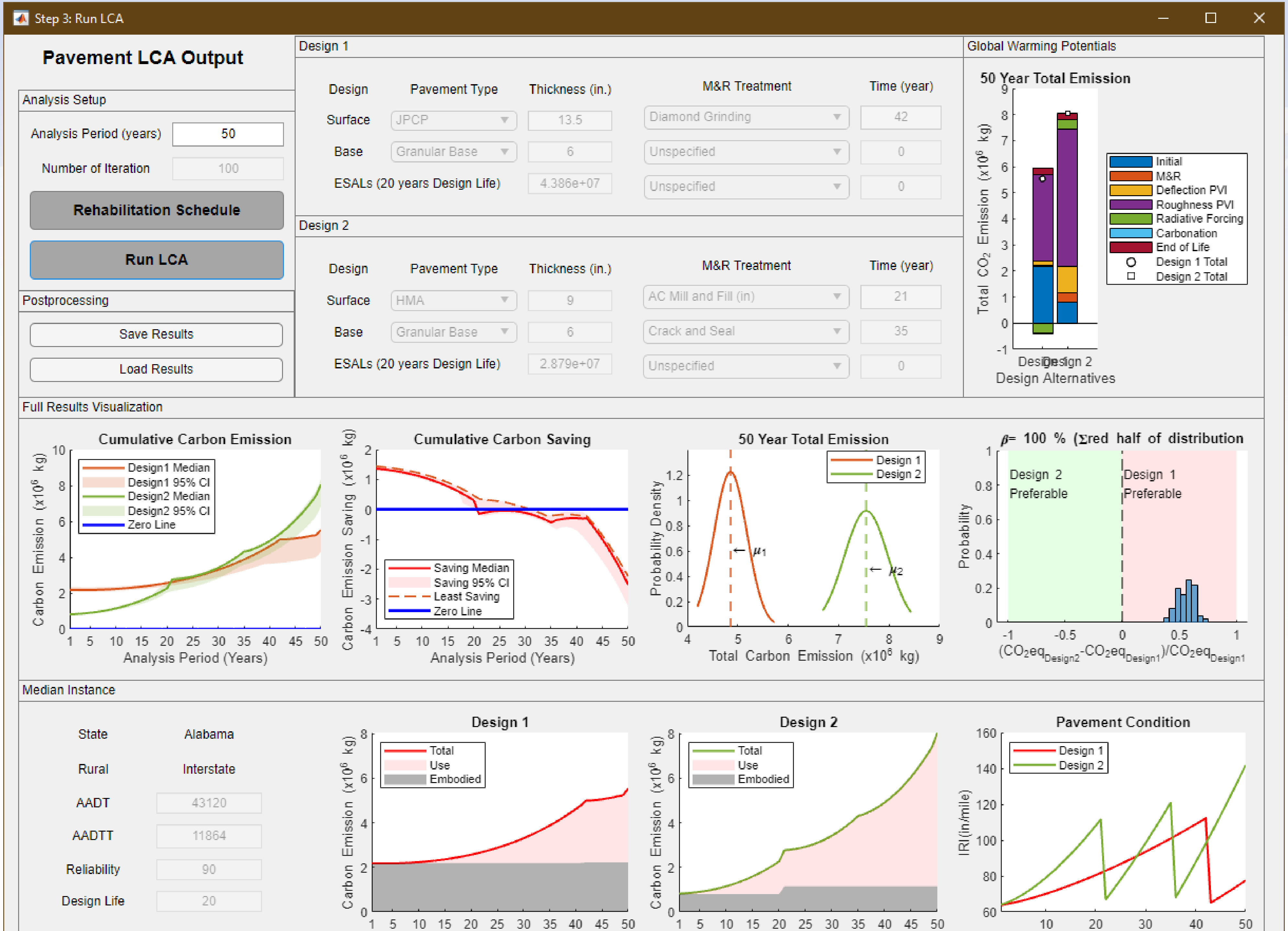


- End of Life Phase
  - Overlay
  - Re-Use
  - Recycle
  - Start over
  - Begin with the end in mind
  - Permanent pavement structures

Getting the Full Picture



- Sources: MIT Concrete Sustainability Hub. *Scenario Analysis of Comparative Pavement Life Cycle Assessment Using a Probabilistic Approach* and *Supplementary Information for Comparative Pavement Life Cycle Assessment and Life Cycle Cost Analysis*
- Total GWP by phases for 1 mile of pavement with Design life = 30 years and analysis period = 50 years. Use phase includes Pavement Vehicle interaction (Fuel efficiency) and Albedo


Step 3: Run LCA
Pavement LCA Output
Analysis Setup
Analysis Period (years)
50
Number of Iteration
100
Rehabilitation Schedule
Run LCA
Postprocessing
Save Results
Load Results
Design 1
Design
Pavement Type
Thickness (in.)
M&R Treatment
Time (year)
Surface
JPCP
13.5
Diamond Grinding
42
Base
Granular Base
6
Unspecified
0
ESALs (20 years Design Life)
4.386e+07
Unspecified
0
Design 2
Design
Pavement Type
Thickness (in.)
M&R Treatment
Time (year)
Surface
HMA
9
AC Mill and Fill (in)
21
Base
Granular Base
6
Crack and Seal
35
ESALs (20 years Design Life)
2.879e+07
Unspecified
0
Global Warming Potentials
50 Year Total Emission
Total CO_2 Emission ($x10^6$ kg)
Initial
M&R
Deflection PVI
Roughness PVI
Radiative Forcing
Carbonation
End of Life
Design 1 Total
Design 2 Total
Design 1
Design 2
Design Alternatives
Full Results Visualization
Cumulative Carbon Emission
Carbon Emission ($x10^6$ kg)
Design1 Median
Design1 95% CI
Design2 Median
Design2 95% CI
Zero Line
Analysis Period (Years)
Cumulative Carbon Saving
Carbon Emission Saving ($x10^6$ kg)
Saving Median
Saving 95% CI
Least Saving
Zero Line
Analysis Period (Years)
50 Year Total Emission
Probability Density
Design 1
Design 2
μ_1
μ_2
Total Carbon Emission ($x10^6$ kg)
β= 100 % (Σred half of distribution
Probability
Design 2 Preferable
Design 1 Preferable
$(CO_2eq_{Design2}-CO_2eq_{Design1})/CO_2eq_{Design1}$
Median Instance
State
Alabama
Rural
Interstate
AADT
43120
AADTT
11864
Reliability
90
Design Life
20
Design 1
Carbon Emission ($x10^6$ kg)
Total
Use
Embodied
Design 2
Carbon Emission ($x10^6$ kg)
Total
Use
Embodied
Pavement Condition
IRI(in/mile)
Design 1
Design 2

Focus on where we can make the greatest impacts

- Design and Materials Phase
  - Most flexibility
  - Optimizing pavement designs
  - Reducing cement's carbon footprint
  - Optimizing mix designs
  - Improving resilience and durability
  - Quantifying

theta
by WAP Sustainability

- Use Phase
  - Typically largest impacts
  - Improving fuel efficiency
  - Increased pavement albedo
  - Take advantage of carbonation
  - Optimize with proper preservation

Re-Focusing Sustainability

- Meeting the needs of today without compromising future generations' ability to meet their own

Sustainable practices are simply good engineering

Acknowledgements

- Jim Mack – Cemex
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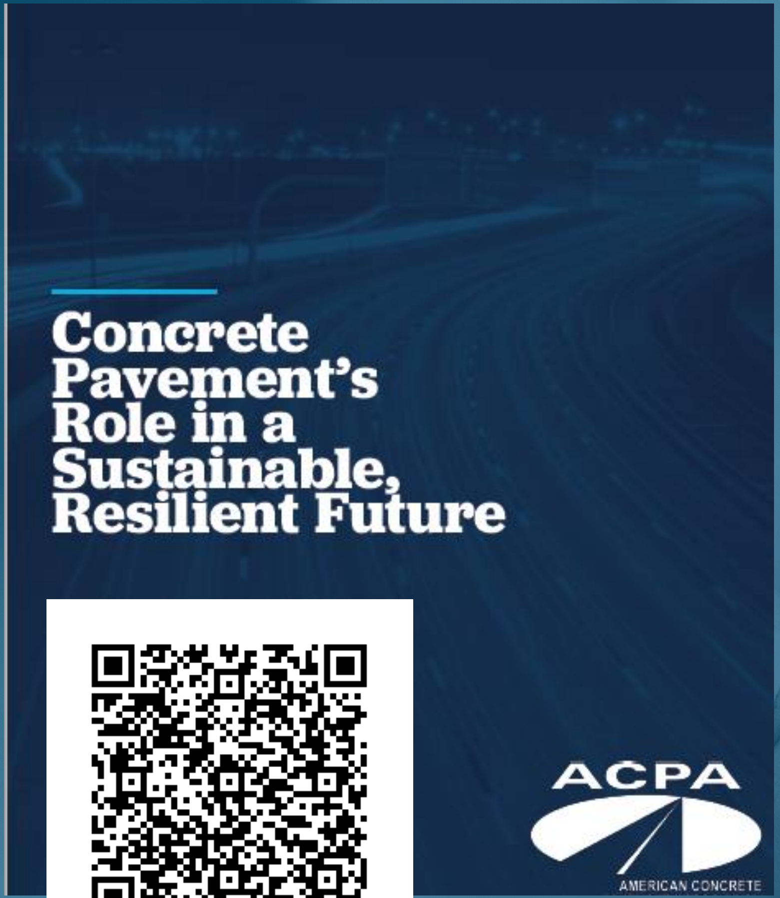
- PCA
- NRMCA
- MIT's CSHub



Thank you!

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American Concrete Pavement Association

ACPA