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Advances in Sustainability and Competitiveness of Concrete Pavements

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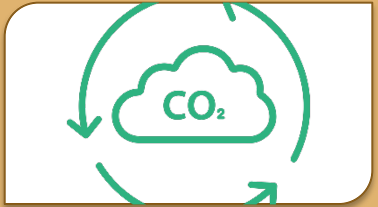
14vo Congreso Iberoamericano de Pavimentos de Concreto
2do Congreso Iberoamericano de Pisos Industriales de Concreto

July 2025

The CSHub is reshaping the way that stakeholders understand concrete as a solution within three contexts



Carbon - Neutral Industry

Sustainable Infrastructure

Resilient Cities

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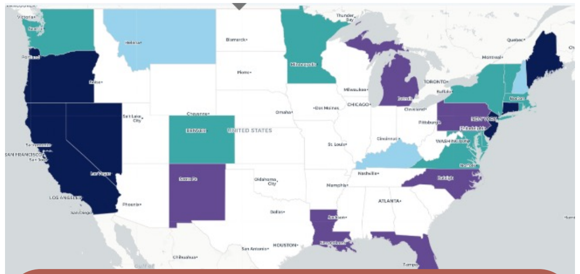
CSHub Research Positions Cement & Concrete as Solution to Two Core Sustainability Challenges: Climate & Resilience

Climate Pressure

SCIENCE BASED TARGETS

>6,000 Organizations have made climate commitments

C2ES
CENTER FOR CLIMATE AND ENERGY SOLUTIONS



States & municipalities are enacting climate policies

Cement & concrete are key to solving these problems

CSHub research shows that connection

Resilience

npr

CLIMATE

Why hurricanes feel like they're getting more frequent

February 27, 2023 · 1:47 PM ET

Rebecca Hersher

THE CONVERSATION

Academic rigor, journalistic flair

Extreme heat waves don't just break records – they shatter them

Published: July 23, 2021 8.14am EDT

Pavement Life Cycle Assessment (LCA) is the key to reducing pavements' total carbon footprint

WIRED BACKCHANNEL BUSINESS CULTURE GEAR IDEAS SCIENCE SECURITY MERCH PRIME DAY

The Beguiling Science of Making Planet-Saving Pavement

Turns out it's not so easy to improve the way we produce the stuff beneath our feet.

Past efforts to combat the carbon footprint of pavement have shown an annoying tendency to backfire. Now, researchers are considering the full lifecycle of the stuff beneath our feet. PATRICK T. FALLON/BLOOMBERG/GETTY IMAGES

"A pavement composed of all-recycled materials sounds great,

until you consider that it requires more truck-driving construction workers to maintain it, and might need to be replaced in a couple of years instead of a handful…"

Source: https://www.wired.com/story/pavement-environment-science/

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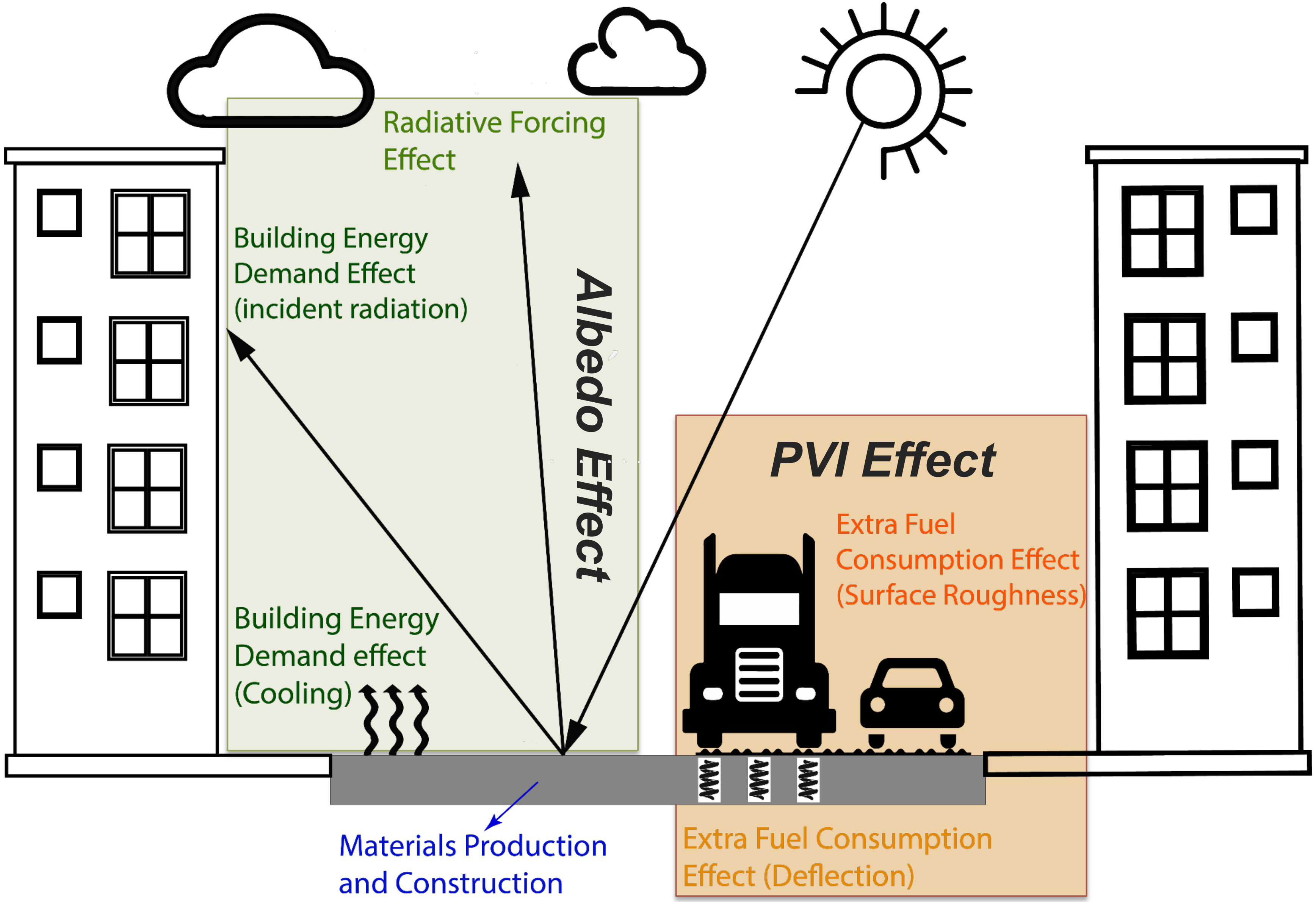
Pavement design and materials impact carbon emissions of vehicles and buildings



https://cshub.mit.edu/wp-content/uploads/2023/01/TopicSummary_ContextDependantLCA.pdf

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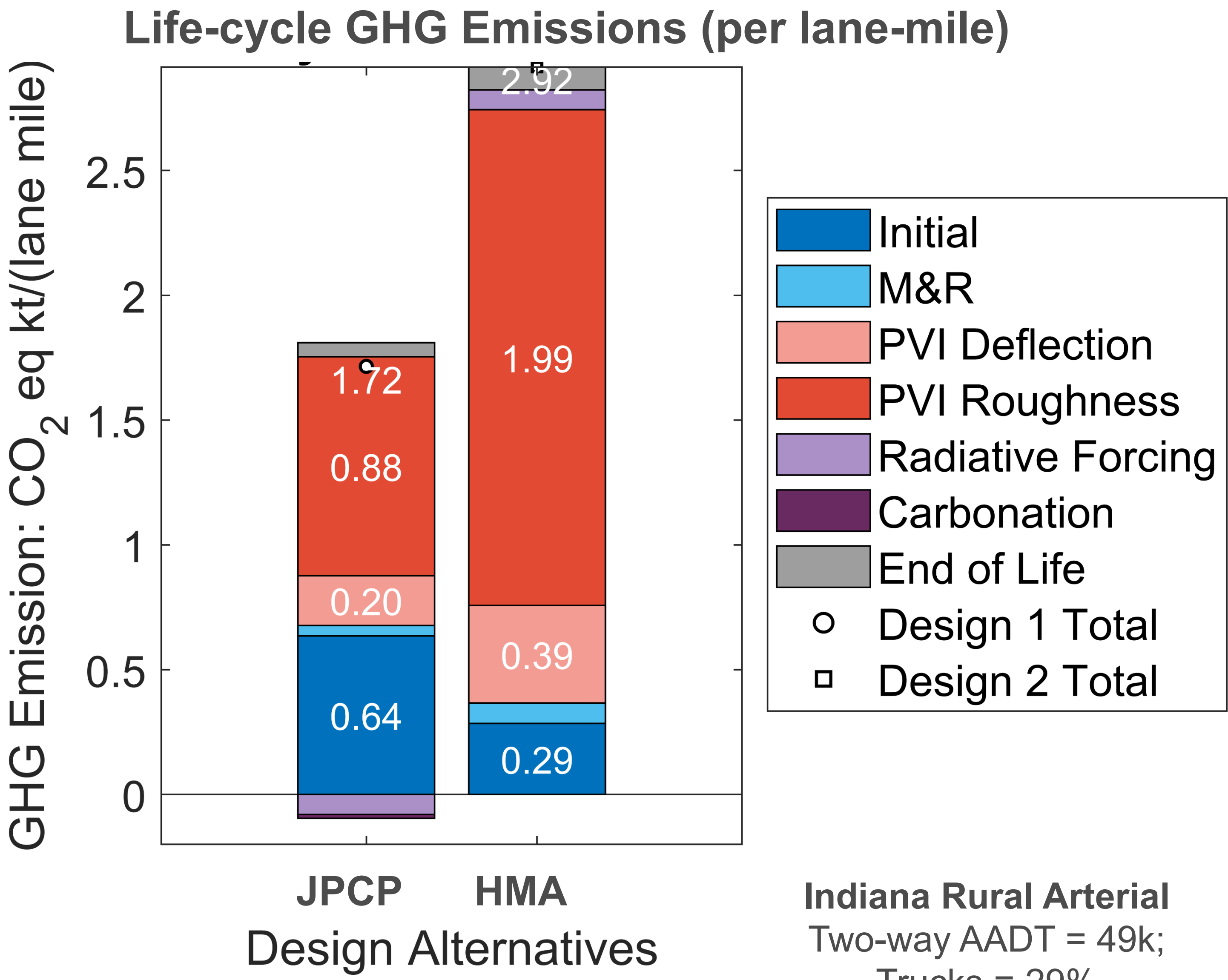
Life cycle perspective matters:
Use phase impacts can be the majority of total emissions

- Initial
  - Materials & construction
- M&R
  - Maintenance & repair
- Pavement vehicle interaction (PVI)
  - Emissions from excess vehicle fuel use from Deflection and Roughness
- Radiative forcing
  - Additional Reflection or absorption of solar energy
- Carbonation
  - Direct absorption of CO_2

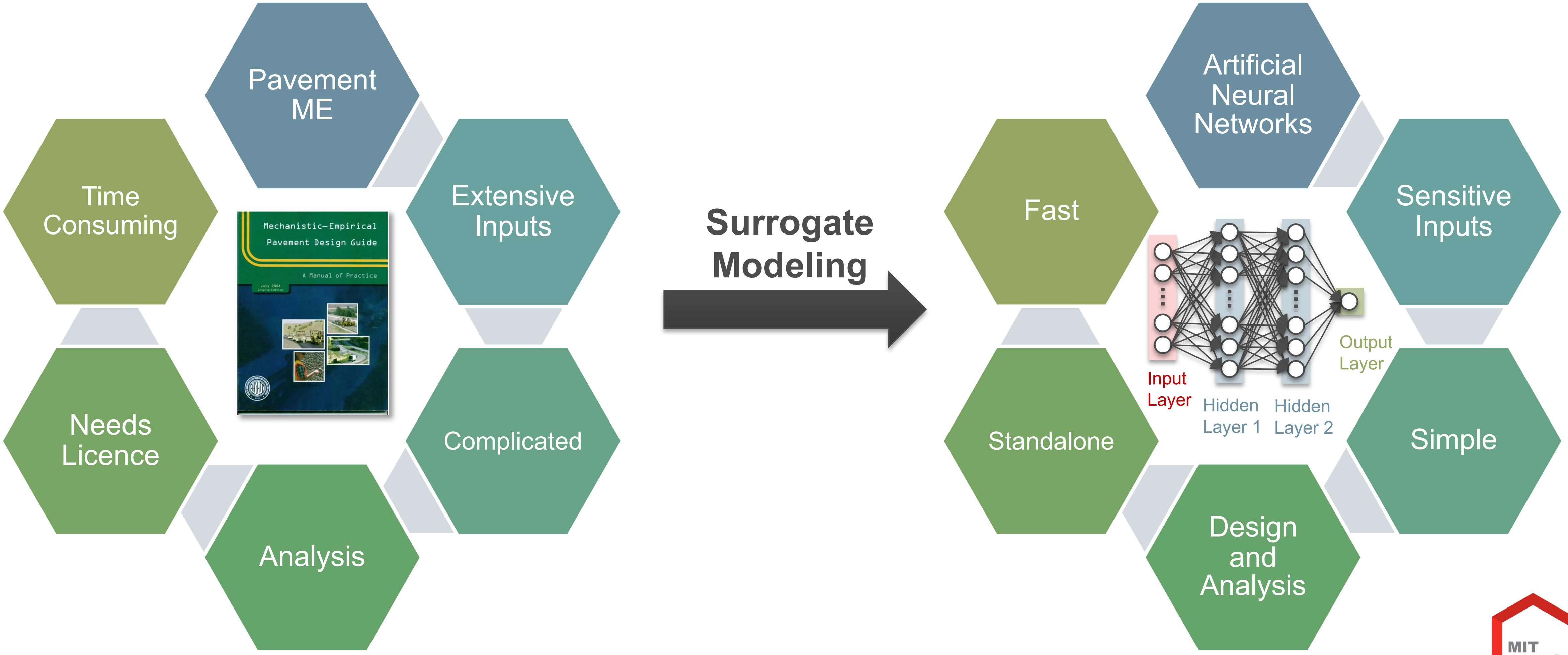


Indiana Rural Arterial
Two-way AADT = 49k;
Trucks = 29%

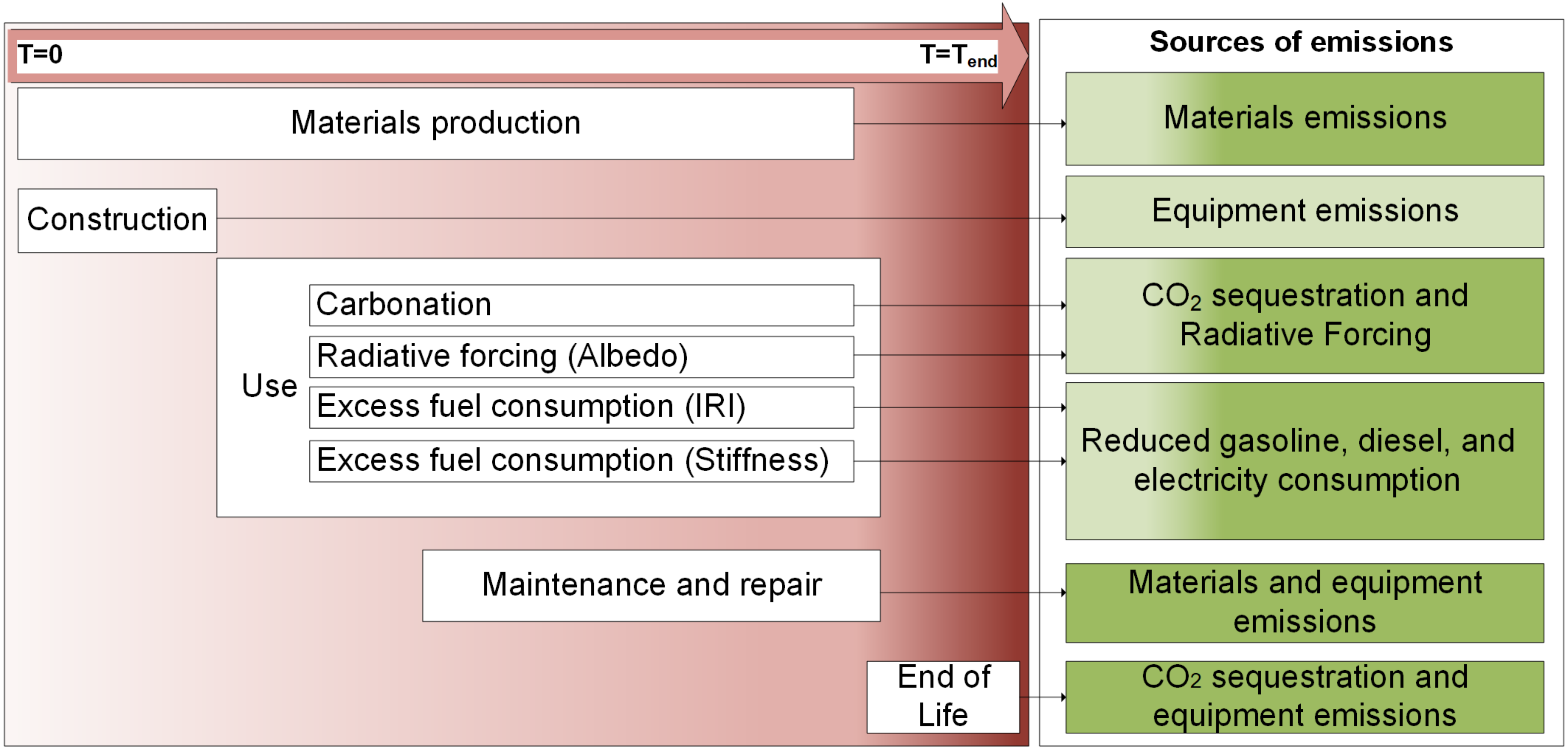
Pavement LCA tool needs to be 1) easy to use (limited new data demands), 2) comprehensive, and 3) defensible

Gaps		Proposed solutions
Conducting pavement LCA is costly and labor intensive	→	Develop a **streamlined** pavement LCA framework
Pavement LCA requires extensive data	→	Leverage **publicly-available data**
The uncertainty associated with pavement LCA creates challenges in the decision-making process	→	Employ **probabilistic comparative analysis**

Surrogate modeling offers an efficient method for implementing AASHTO MEPDG pavement design in LCA



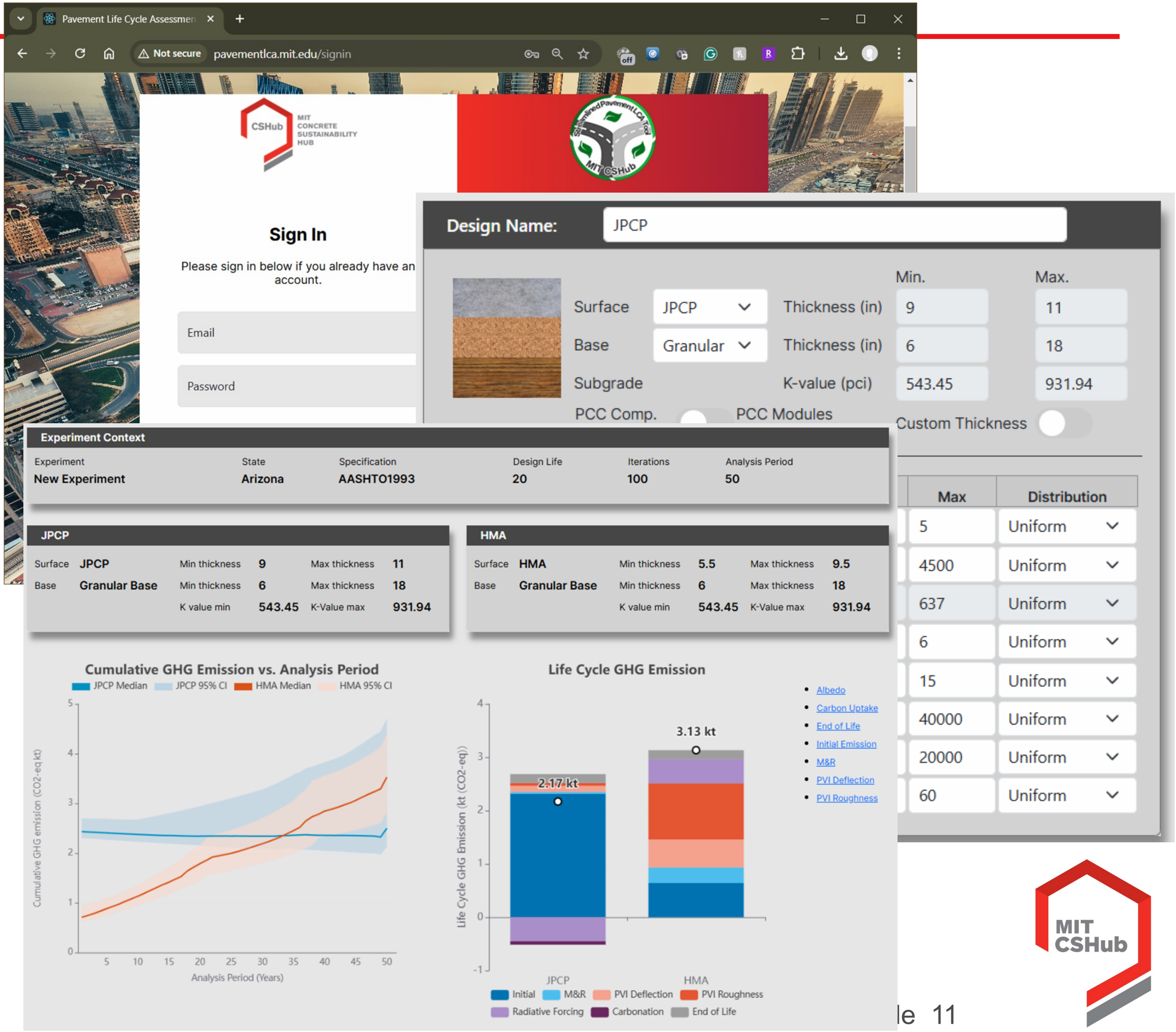
CSHub streamlined pavement LCA framework incorporates and tracks the life cycle emissions of pavements capturing different GHG sources



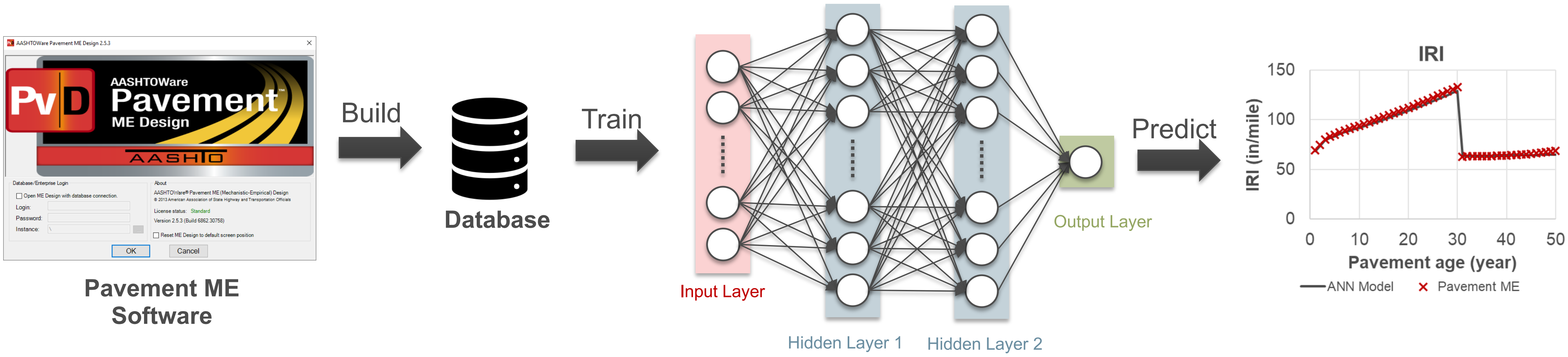
New Tools Will Make Engaging with Stakeholders Easier

CSHub Lifecycle Tool is NOW Live and Ready for Testing

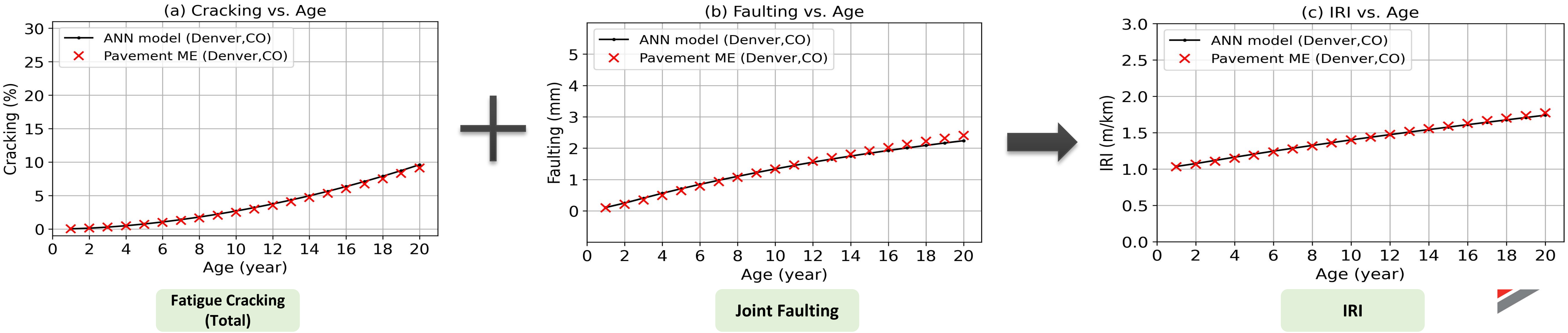
- http://pavementlca.mit.edu/
  - Use your laptop. The site is not yet optimized for phones.
- You can run an analysis with as little information as
  - State
  - Road class (Functional system such as interstate, collector, …)
  - Traffic level (High, medium, low)



Rapid Pavement Performance Simulator Offers an Efficient Method for AASHTO MEPDG-based Pavement Design in LCA/LCCA



Model Fidelity is High



Step One: Define Context (Where is this road? & What does it do?)

Input Data

Pavement Contexts

- **Geographical Location**
- **Climatic Conditions**
- **Traffic**

Climate

State	California
Annual Precipitation Days	40
Precipitation Threshold (in./hr)	0.1
Solar Radiation	221.52

Function and Reliability

Urban-Rural Class	Urban
Functional System	Interstate
Reliability	Medium

Traffic Content

Traffic Volume	High
Truck Percentage	High
Traffic Direction	Two-way
Traffic Speed	Medium
Traffic Growth	Medium
Number of Lanes	4
Pavement Length (mile)	1
Lane Width (ft)	12
Shoulder Type	Tied PCC
Shoulder Width (ft)	10

Detailed Traffic Data

Save and Next

Data sources: FHWA and NASA

Traffic parameters can be refined further if available

Context Parameters

Parameters	Min.	Mean	Max.	Distribution
AADT per Lane	15900	18700	21500	Uniform
AADT All Lanes	63500	74800	86000	Uniform
Truck Percentage (%)	9	11	12	Uniform
AADTT per Lane	1430	2000	2580	Uniform
AADTT All Lanes	5722.2	8026	10329.12	Uniform
Traffic Growth (%)	1	1.5	2	Uniform
Traffic Speed (mph)	55	60	65	Uniform
Reliability (%)	90	92.5	95	Uniform

Data source: FHWA

Step Two: Define materials (including mix design, if desired)

What is this road made of?

State: California | PCC Compressive Strength (psi)

Materials (A1)

Portland Cement	294.8204	kg/ m^3
Fly Ash	43.3036	kg/ m^3
Slag Cement	0	kg/ m^3
Mixing Water	194.5696	kg/ m^3
Crushed Coarse Aggregate	444.9	kg/ m^3
Natural Coarse Aggregate	422.9516	kg/ m^3
Crushed Fine Aggregate	105.5896	kg/ m^3
Natural Fine Aggregate	751.58	kg/ m^3
Air	6	%
Air Entraining Mixture	0	kg/ m^3
Water Reducer	0	kg/ m^3
High Range Water Reducer	0	kg/ m^3
Accelerator	0	kg/ m^3

Transportation (A2)

Transportation Emission	14.522	kg CO_2 eq / m^3

Energy (A3)

Purchased Electricity		
Natural Gas		
Secondary Fuels - Liquid		
Secondary Fuels - Solid		
Fuel Oil (other than diesel)		
Diesel		
Gasoline	0	lit
LPG	0	lit

Total Emission (A1+A2+A3)

	Material (A1)	Transportation (A2)	Energy (A3)
	271.586	14.522	7.167
Total Emissions		293.276	kg CO_2eq / m^3

State: California

Materials (A1)

Bitumen content	0.04	
Bitumen impact	637.	$kgCO_2/t_{asphalt}$
Gravel impact	3.81	$kgCO_2/m^3_{asphalt}$
Sand impact	3.81	$kgCO_2/m^3_{asphalt}$
RAP and WAP Modification		
RAP Content	0.16	
WAP Content	0.24	

Transportation (A2)

Transportation GHG	14.4	$kgCO_2/m^3_{asphalt}$

Energy (A3)

Asphalt heating impact	48.4	$kgCO_2/m^3_{asphalt}$

Total Emissions (A1+A2+A3)

	Material (A1)	Transportation (A2)	Energy (A3)
	69.72	14.43	48.48
Total Emissions		132.63	kg CO_2eq / m^3

Data sources: NRMCA and NAPA

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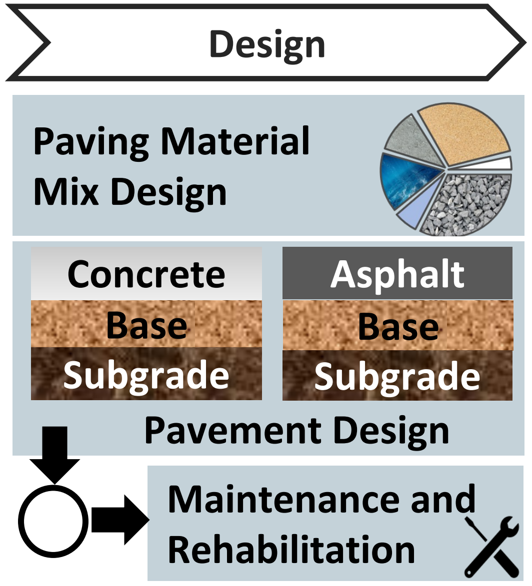
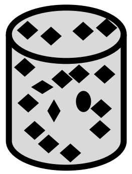
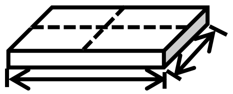
Step Three: Define the pavement design and Specify maintenance and repair treatment actions



Material Properties



Pavement Geometry



Maintenance and Rehabilitation (M&R) Schedule

Timing (years)			Material	
Min	Max	Treatment Type	Removal	Addition
33	38	100% Diamond Grinding w/ Full Depth Re	3	3
0	0	Unspecified	0	0
0	0	Unspecified	0	0
0	0	Unspecified	0	0
0	0	Unspecified	0	0
0	0	Unspecified	0	0

Design Name: JPCP

			Min.	Max.
Surface	JPCP	Thickness (in)	11.5	13.5
Base	Granular	Thickness (in)	6	21
Dowel Bar		Dowel diameter (in)	1.5	1.5
Subgrade		K-value (pci)	212.49	1089.49
PCC Comp. Strength (psi)		PCC Modules of Rupture (psi): MR	Custom Design	

Parameters	Min	Mean	Max	Distribution
PCC Elastic Modulus (10^6 psi)	3	4	5	Uniform
PCC Comp. Strength (psi)	3500	4000	4500	Uniform
PCC Modules of Rupture (psi)	562	600	637	Uniform
Coefficient of Thermal Expansion (10^-6 in/in/F)	4	5	6	Uniform
Joint Spacing (ft)	15	15	15	Uniform
Base Resilient Modulus (ESB): psi	20000	30000	40000	Uniform
Subgrade Resilient Modulus (MR): psi	8000	14000	20000	Uniform
Depth to Rigid Foundation (ft)	6	8	10	Uniform

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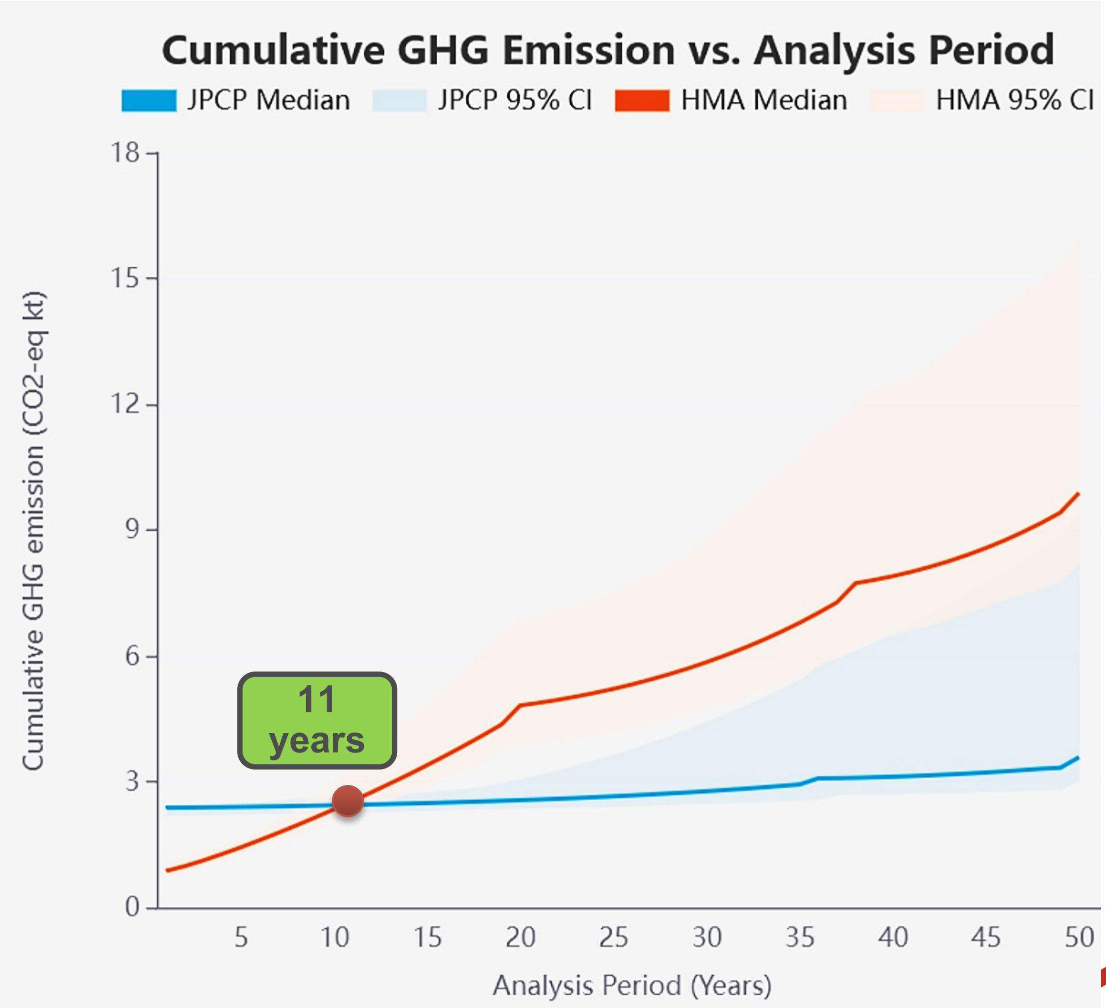
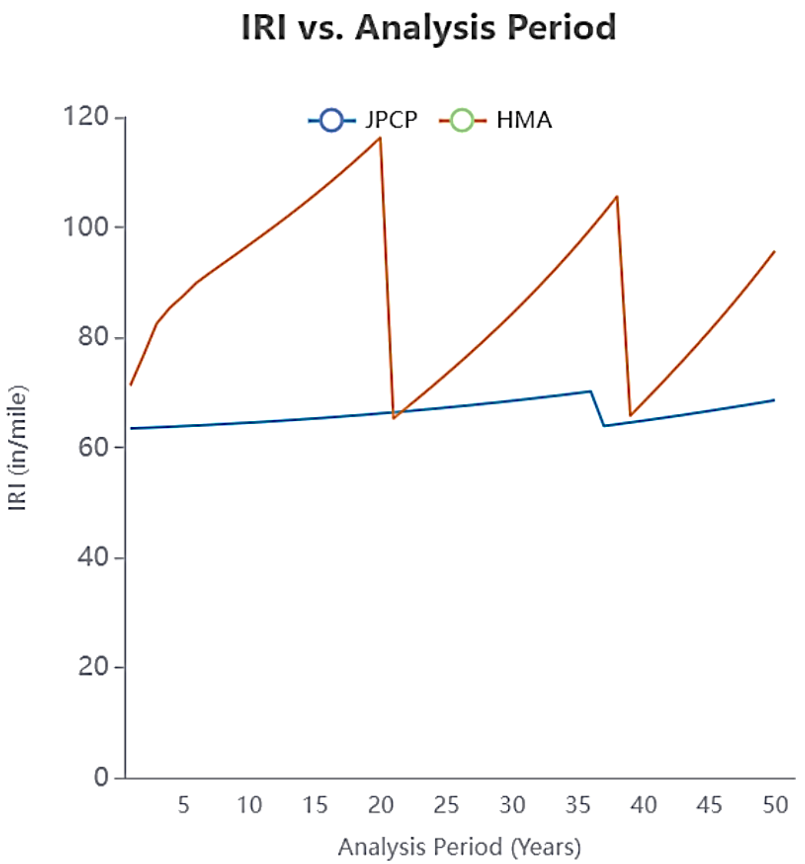
Case study of a California interstate highway:
Time-dependent GHG emission profile

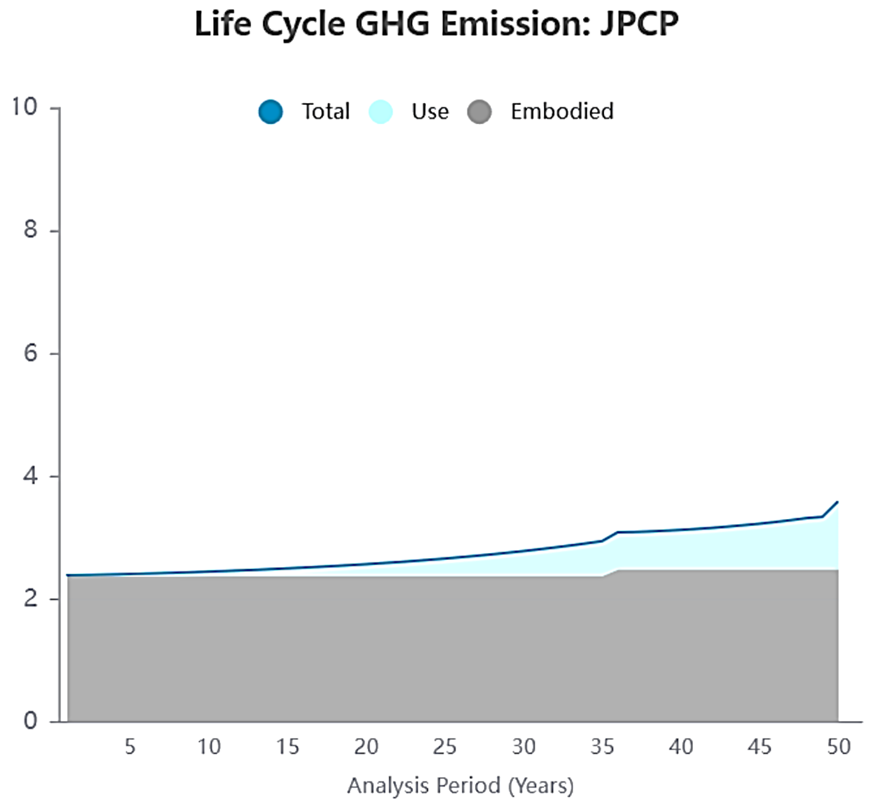
Parameters	Value
State	California
Traffic System	Urban-Interstate
AADT (two-way)	74,800
Truck Percentage	11%
Segment Length	1 mile

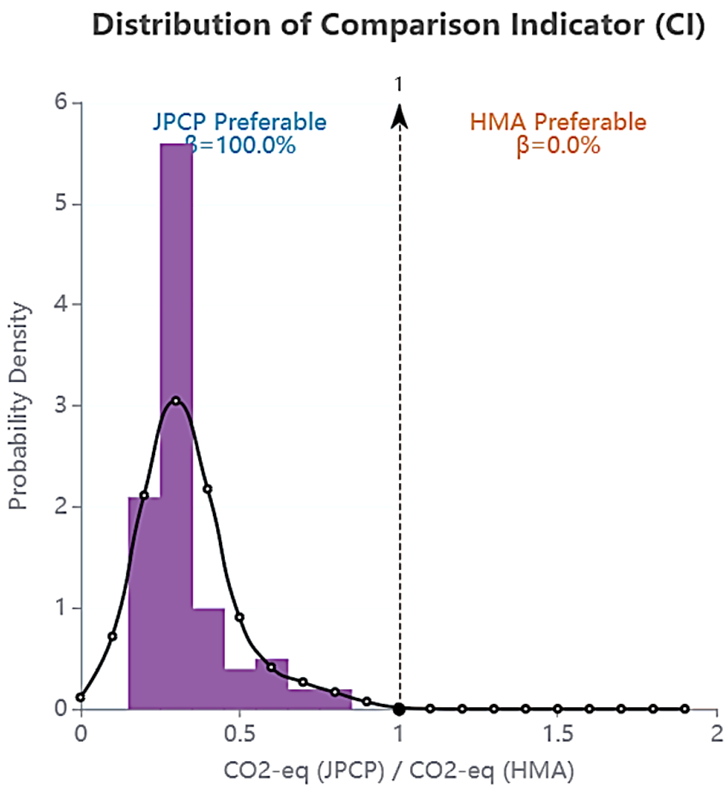
Pavement Design	
Design 1: JPCP • 12.5-in PCC • 1.5-in dowel bar • 13-in aggregate base • 12-ft slab width	**Design 2: HMA** • 9-in HMA • 13-in aggregate base • 12-ft slab width



Additional Results Detail the Pavement Performance Prediction and Provide Statistical Details on the Comparison





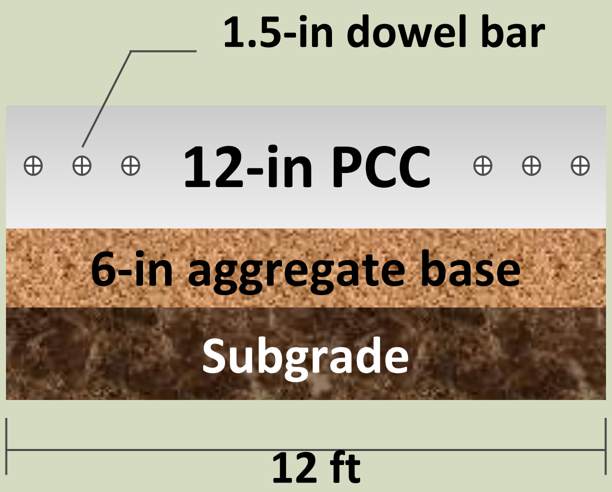


Case Study 1: Compare Two Design Alternatives for California Rural Interstate Road Pavement

A California Rural Interstate Pavement

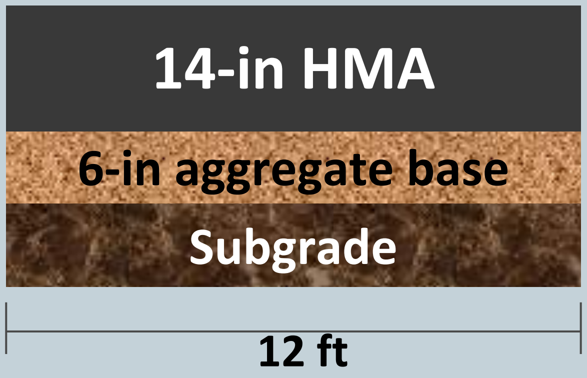
Considering the context[1], what is the impact of material choice?

Concrete Pave



VS

t Pavement



Context means the climate, traffic, local materials, construction and M&R practices

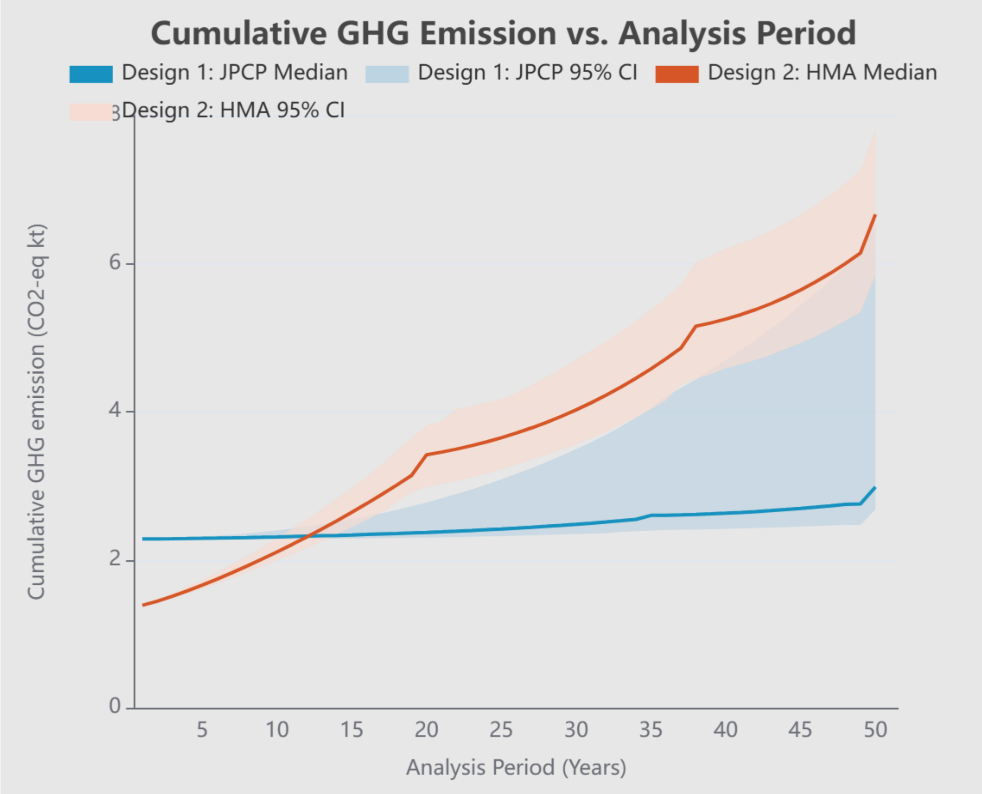
Lesson Learnt 1: While uncertainty exists, robust decision can be still made by using the probabilistic and comparative LCA

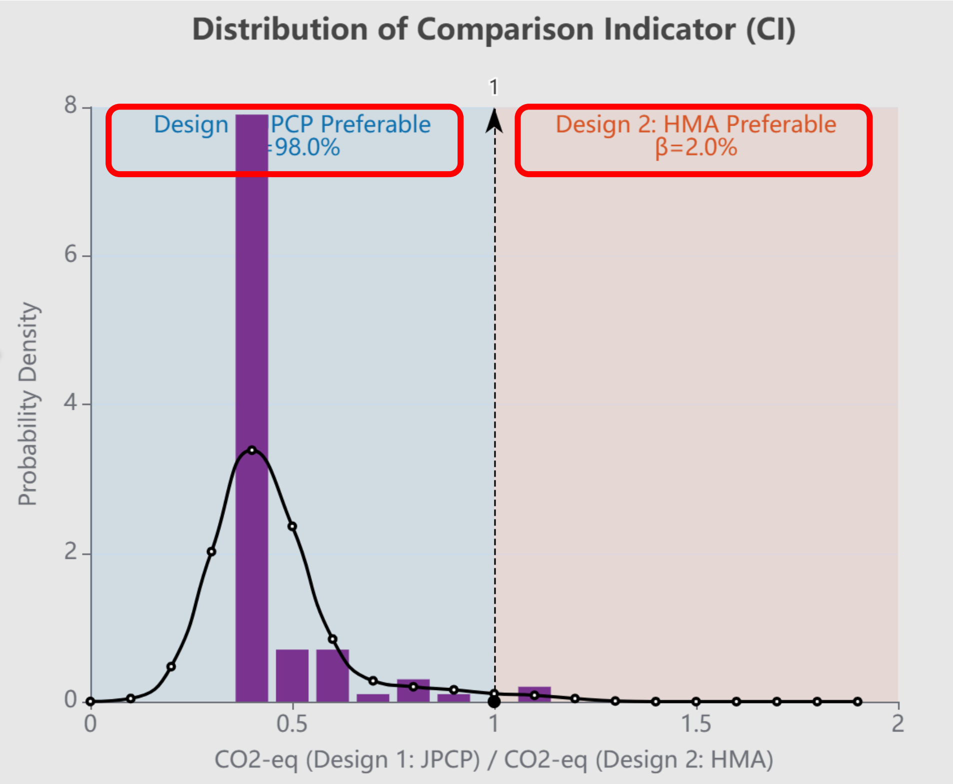
Design 1: JPCP

Surface	JPCP	Min thickness	12	Max thickness	12
Base	Granular Base	Min thickness	6	Max thickness	6
		K value min	200.00	K-Value max	200.00

Design 2: HMA

Surface	HMA	Min thickness	14	Max thickness	14
Base	Granular Base	Min thickness	6	Max thickness	6
		K value min	200.00	K-Value max	200.00





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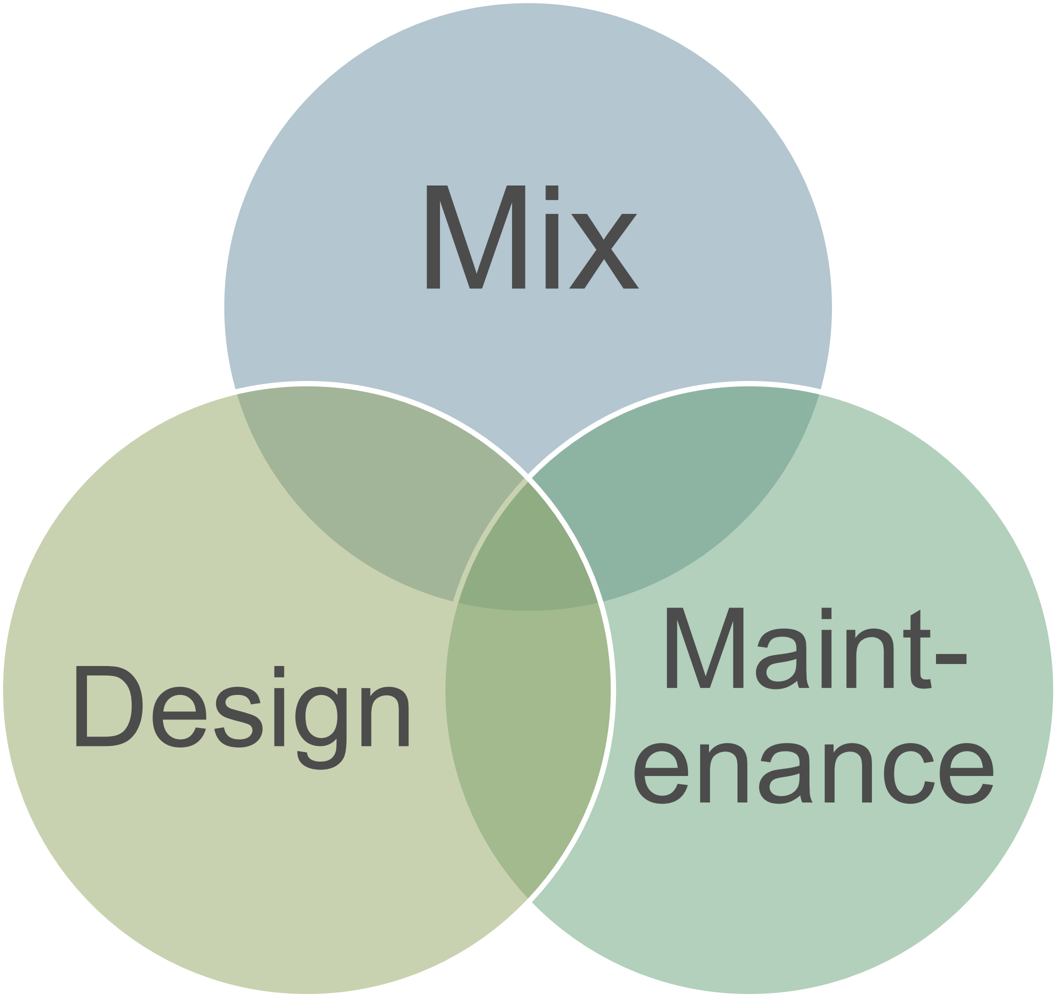
Significant Opportunities Still Exist to Improve Pavement Design and Maintenance

Current low-carbon policies target ONLY upfront emissions, missing opportunities to reduce impacts throughout lifecycle

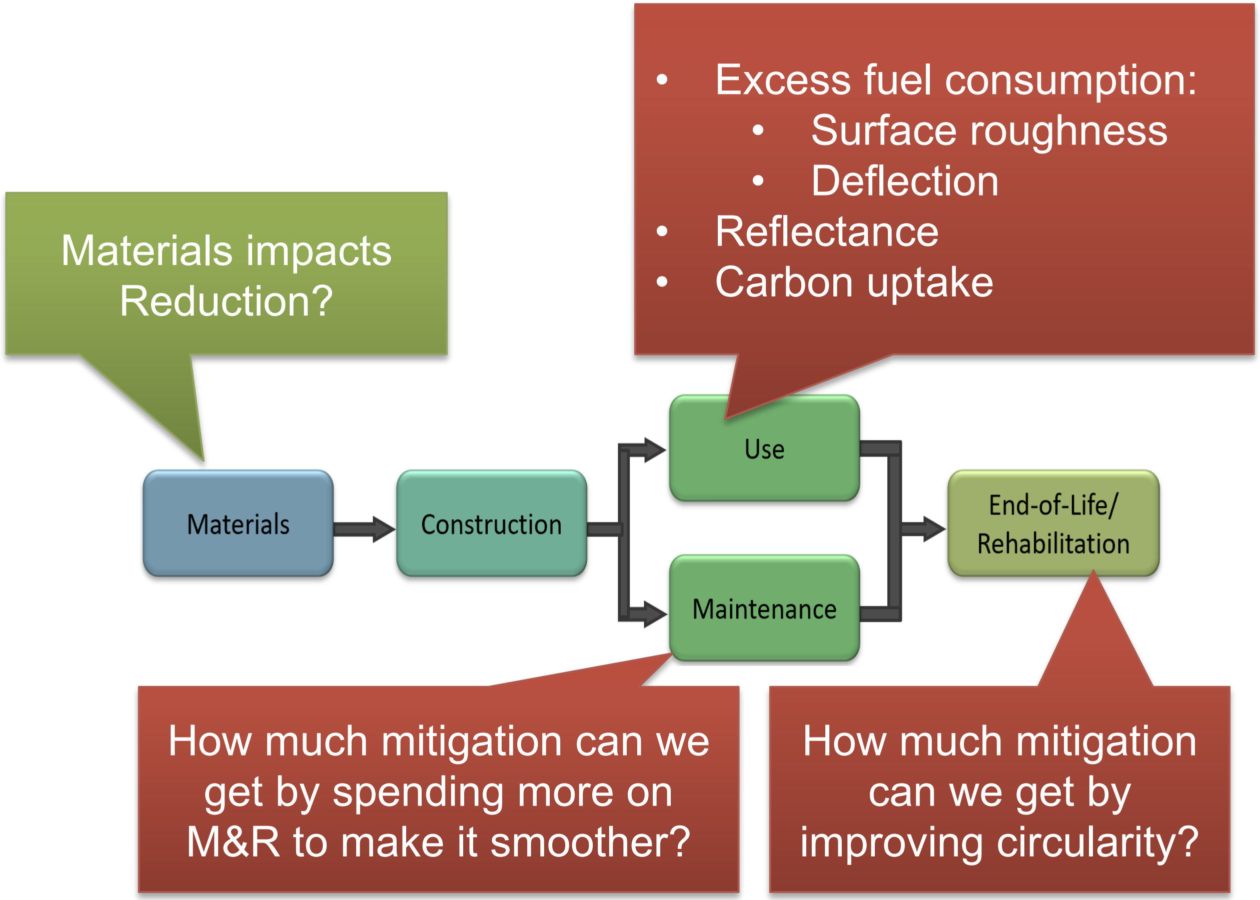
Impacts can be Reduced Throughout the Lifecycle



Regulations around low-carbon concrete pavements address the upfront emissions, but the potential is extremely larger

Potential parts of the low-carbon policies:

1) Impact of Materials choice on the rest of the life cycle
2) Solutions for achieving low use and end-of-life emissions



Lifecycle Perspective Reveals Important Opportunities to Manage Emissions Through Design and Maintenance

- Case Study:
  - Roller Compacted Concrete
  - State Highway
  - Around Miami, FL

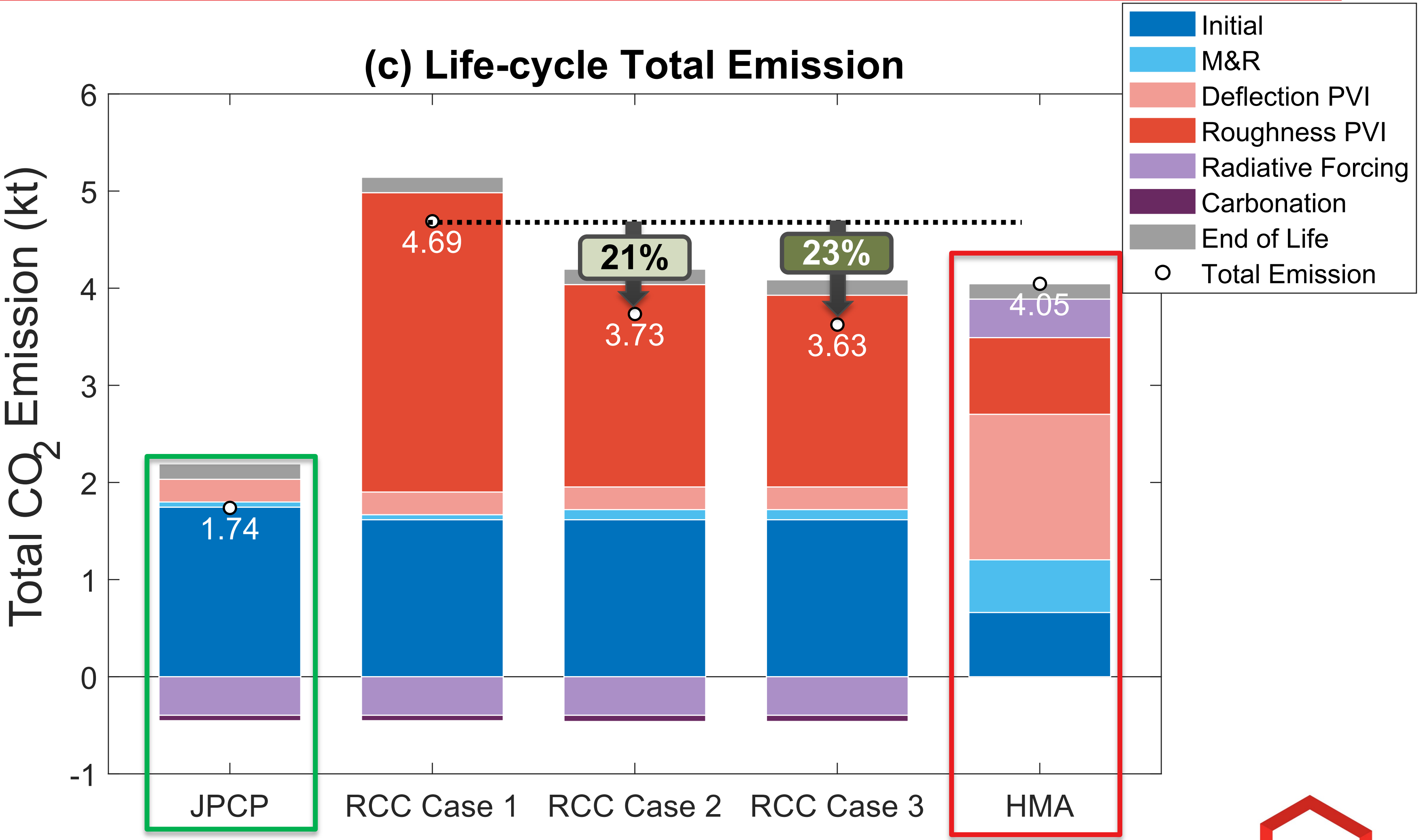
[Semix | What is Roller Compacted Concrete (RCC) ?]

- Traffic - State Highway (Rural)
  - Two-way Annual Average Daily Traffic (AADT) = 17,000
  - Truck percent (%): 5.88
  - Traffic Speed: 35-45 mph

- Designs
  - JPCP
    - DG @ year 30
  - RCC
    - 1 – DG @ years 0 & 30
    - 2 – DG @ years 0, 15, & 30
    - 3 – DG @ years 0, 20, & 40

Scenario 1: Implementing Well-timed Diamond Grindings can Reduce Life-cycle GHG Emissions by up to 23%

M&R	Activities
RCC Case 1	DG and 5% FDR @ 30 year
RCC Case 2	DG and 5% FDR @ 15 and 30 years
RCC Case 3	DG and 5% FDR @ 20 and 40 years



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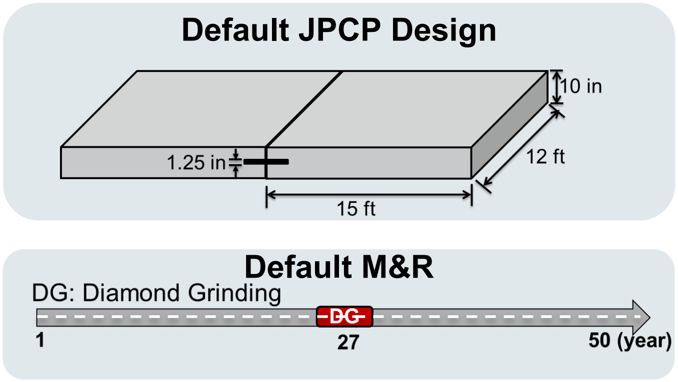
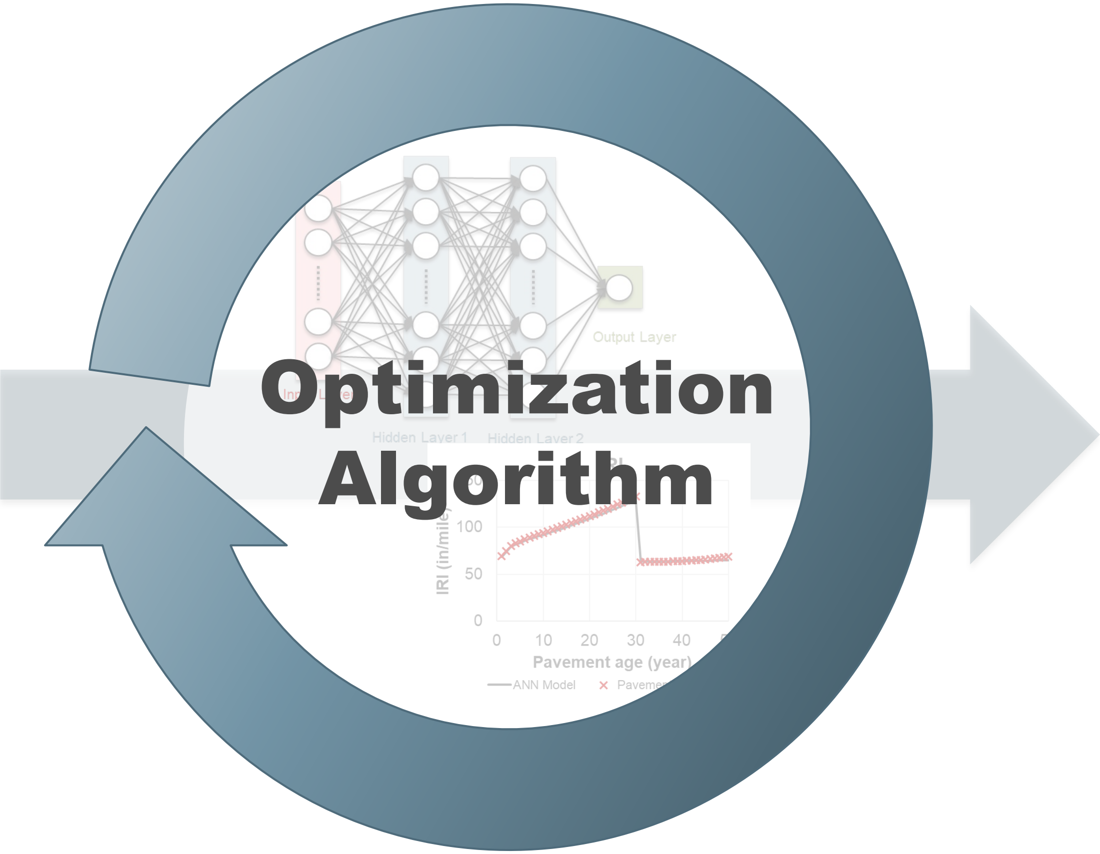
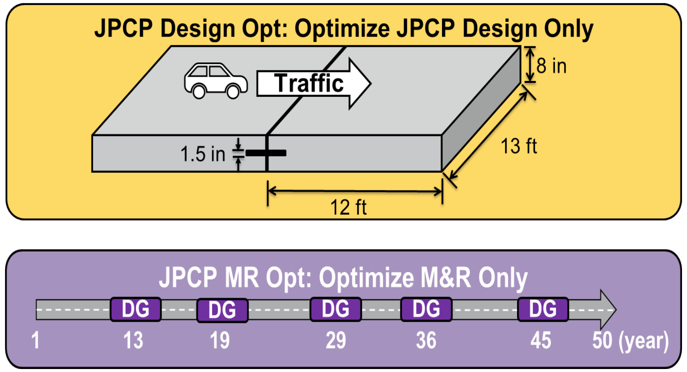
Using the MIT CSHub Rapid Performance Simulator, we can Converge on High-Performance Designs & Maintenance Plans

Initial Design & Maintenance





High Performance Design & Maintenance



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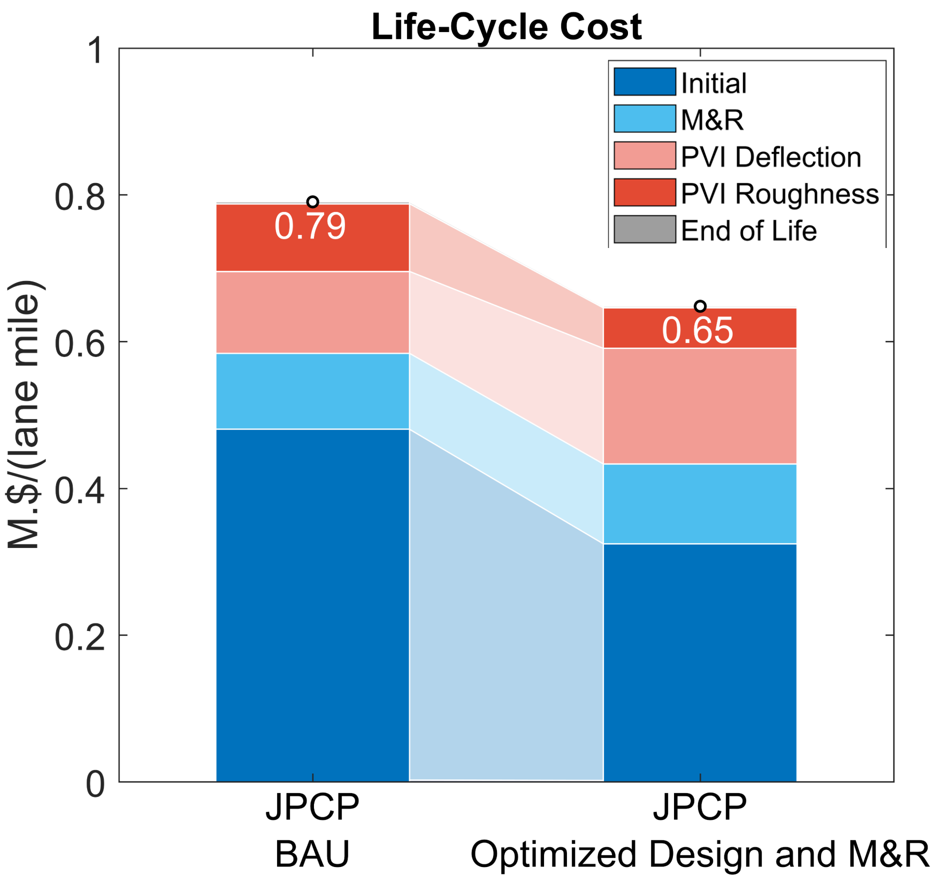
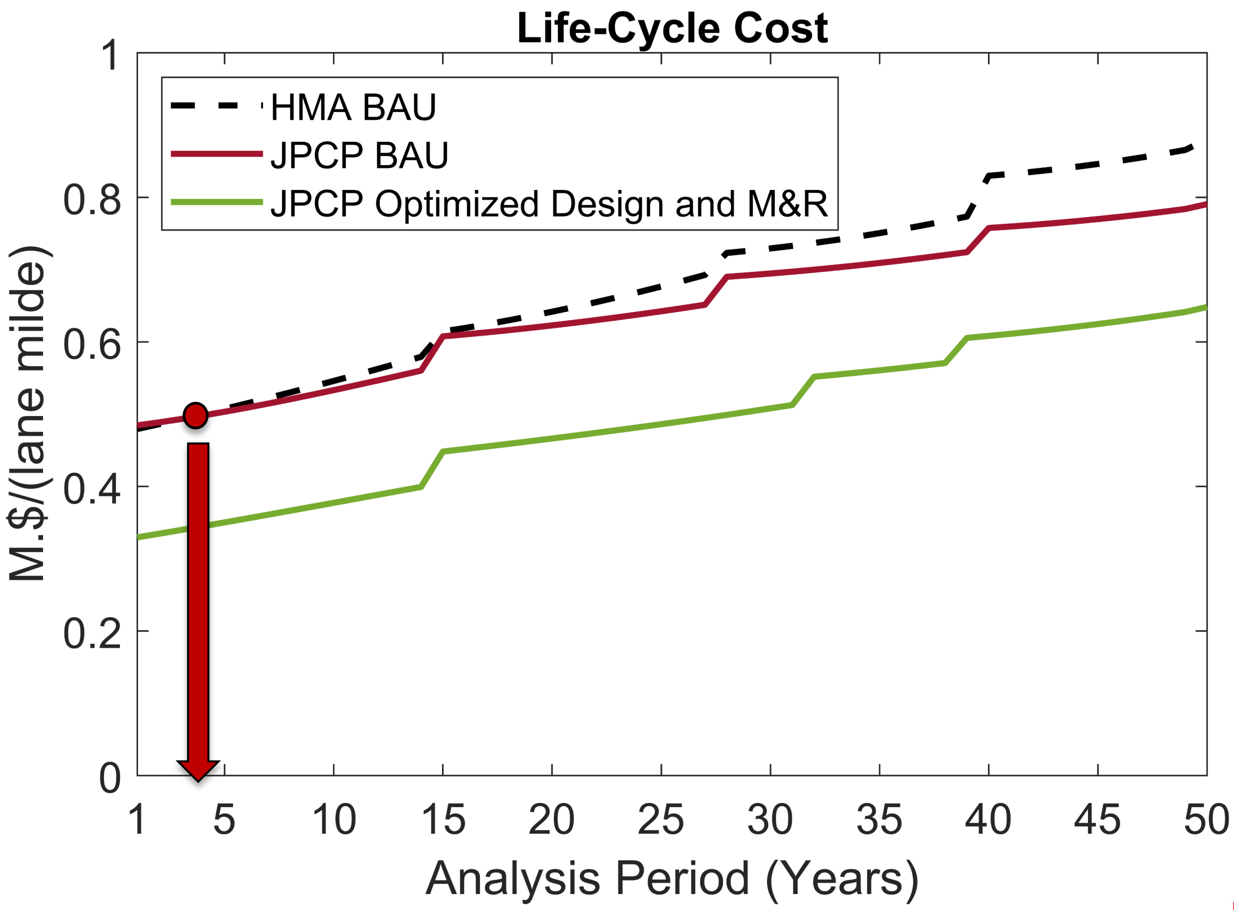
Opportunity to Reduce Pennsylvania JPCP Life-cycle GHG Emissions and Life-cycle Cost

Parameters	JPCP BAU	JPCP Optimized Design and M&R
PCC thickness (in)	12	9
Base type	4-in cement treated base with 6-in subbase	6-in aggregate base
Joint spacing (ft)	15	13
Slab width (ft)	12	13 (widened lane)
Shoulder type	Tied PCC	Tied PCC
Dowel bar diameter (in)	1.5	1.5
M&R schedule	• 100%DG and FDR @ 15 years • 100%DG and FDR @ 28 years • 100%DG and FDR @ 40 years	• 100%DG and FDR @ 15 years • 100%DG and FDR @ 32 years • 100%DG and FDR @ 39 years

Optimization of Design and Maintenance Reduces Lifecycle Costs of Concrete the Solution by ~20%

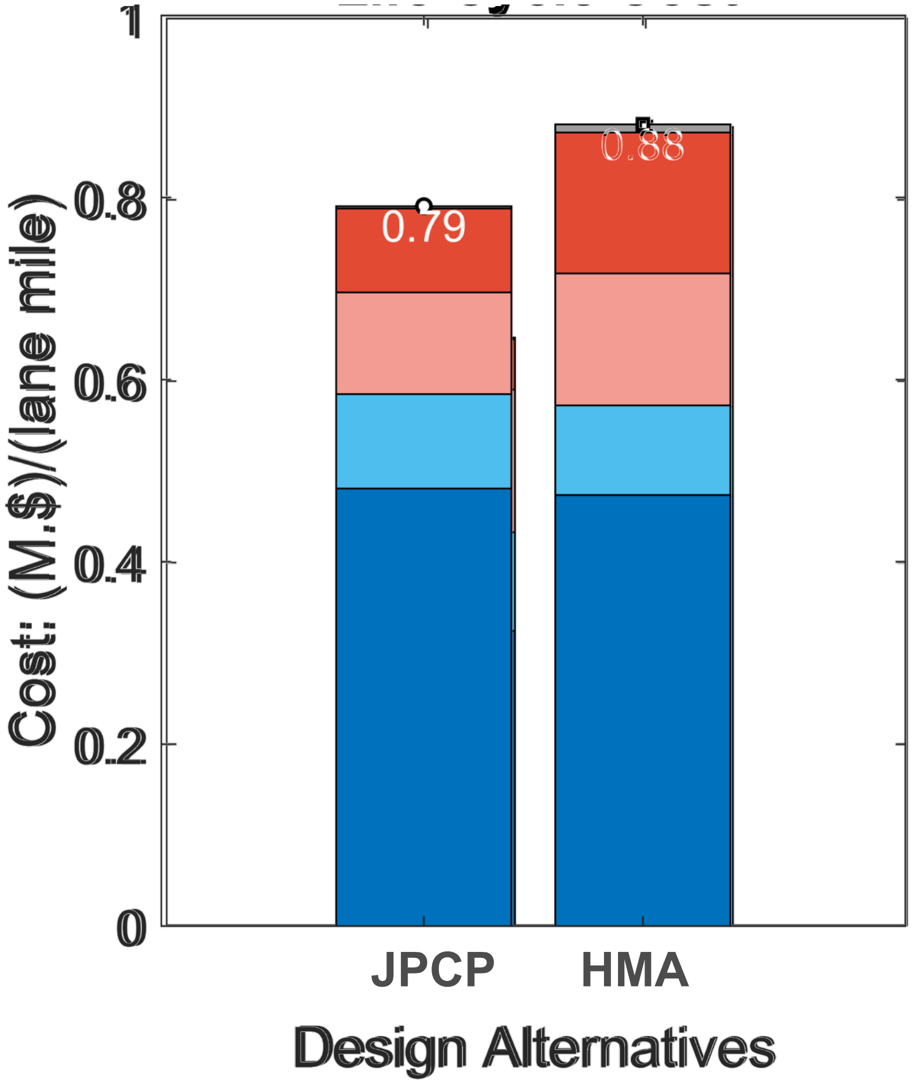




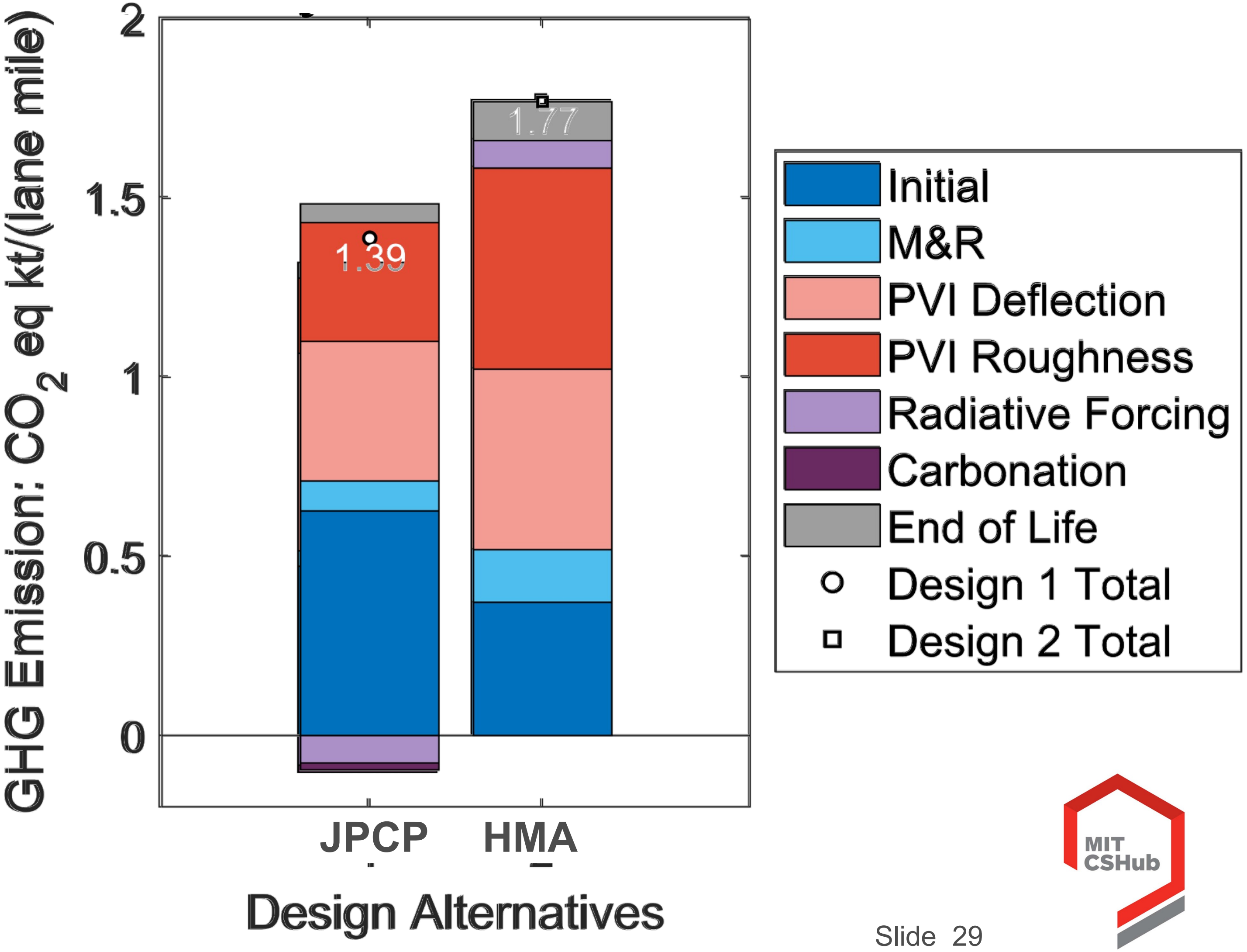
Optimization of Design and Maintenance Makes Concrete Solutions Even More Attractive

PA Rural Interstate
Two-way AADT = 37k;
Trucks = 29%

Life-cycle COST (M$/ lane-mile)



Life-cycle GHG Emissions (CO_2/ lane-mile)



To Reduce Maximize the Value of Concrete Pavements, Consider Materials, Design, & Maintenance

Remove prescriptive specifications

- Encourage innovation in mix design
- Select low-carbon concrete mixes

Optimize Pavement Design

- Right-size pavement thickness & dowel size
- Where possible, opt for…
  - Wider lanes
  - Shorter joint spacing
  - Tied shoulders

Optimize Pavement Maintenance & Rehabilitation

Implement flexible asset management

It is Critical to Continue to Educate Stakeholders on the Benefits of Concrete Pavements

- Concrete pavements can be the economical and sustainable solution
  - We must continue to educate on the benefits of concrete pavements
- Significant opportunities exist to improve current design and maintenance
  - Design and maintenance decisions strongly affect life-cycle cost
- New tools are available to make engaging with stakeholders easier

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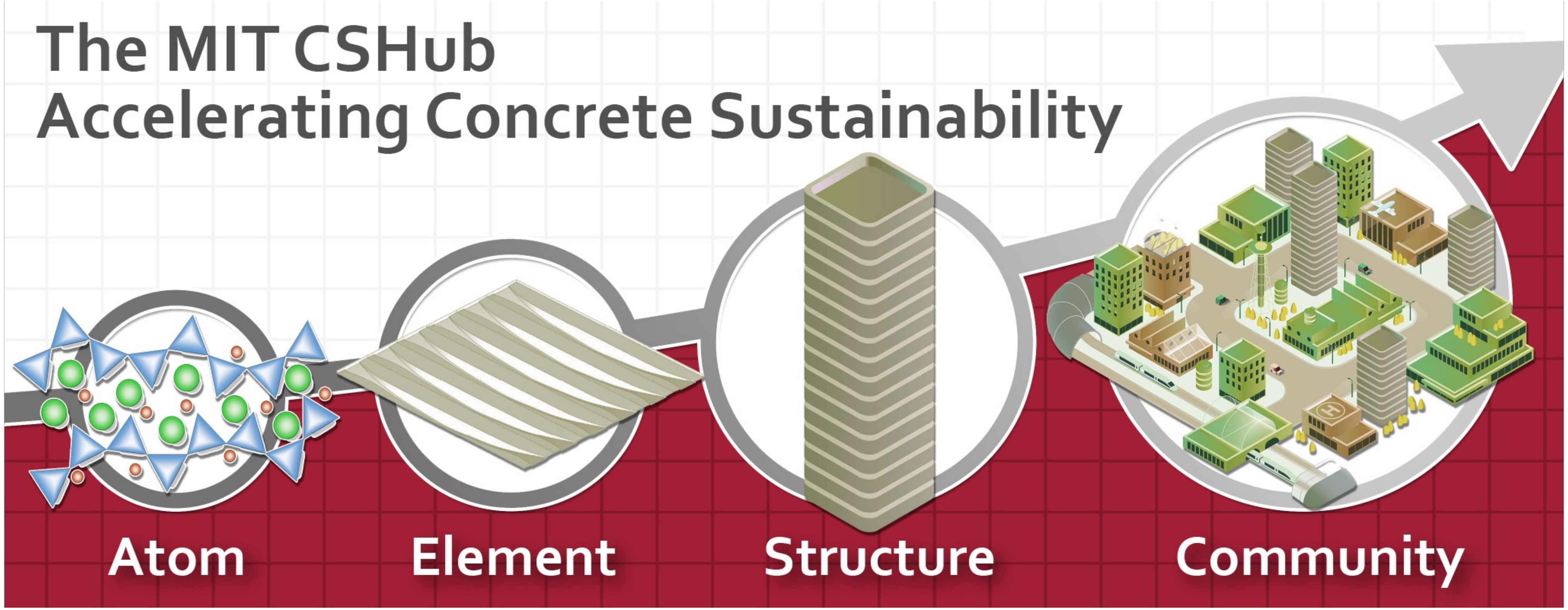
Thank you



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Questions?

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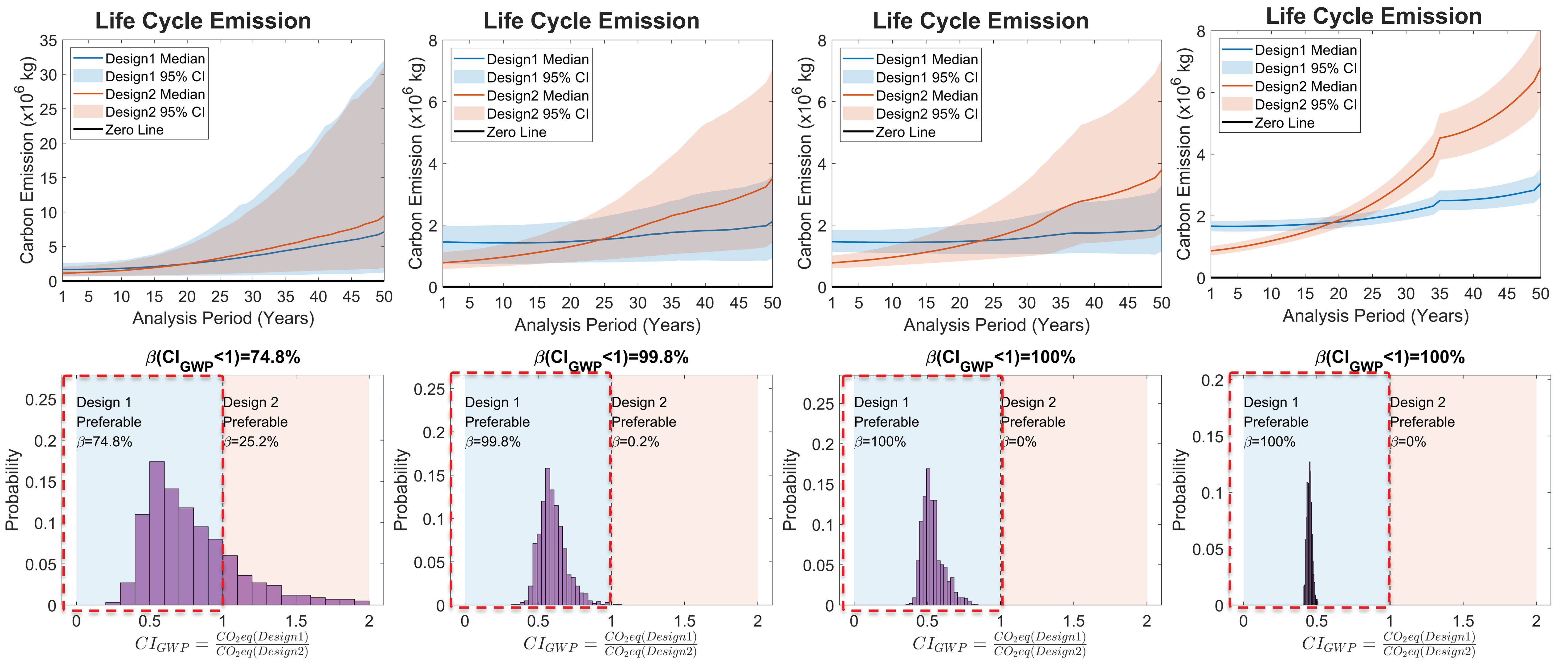
The structured data specifications streamline the LCA, enabling it to accommodate data inputs at any level

Pavement Features		Underspecification Level: M1 (+)	M2 (++)	M3 (+++)	M4 (++++)
Traffic System		Arizona	Arizona: Urban	Arizona: Urban-Minor Arterial	Arizona: Urban-Minor Arterial with medium truck volume
Pavement Structures and Material Properties	Design 1	PCC / Base / Subgrade	Standard Grade Concrete / Granular Base / Granular Material	M25 Concrete / AASHTO Standard Soil / Silt-Sand Subgrade	fc' = 3,800 psi / A-1-b: MR=38,000 psi / A-2-6: MR=26,000 psi
	Design 2	Asphalt / Base / Subgrade	HMA / Granular Base / Granular Material	High stiffness HMA / AASHTO Standard Soil / Silt-Sand Subgrade	E=350,000 psi / A-1-b: MR=38,000 psi / A-2-6: MR=26,000 psi
M&R	M&R				
	Design 1	$M\&R \times 1$	Minor Repair; 28-40 year	DG and FDR; 32-38 year	100%DG and 5% FDR; 35
	Design 2	$M\&R \times 1$	Minor Repair; 28-40 year	AC Mill and Fill; 32-38 year	3-in AC Mill and Fill; 35

Least Specific Data → **Most Specific Data**

Level M2 data specification is sufficient for making statistically defensible decision for urban roads in Arizona

Underspecification Level			
M1 (+)	M2 (++)	M3 (+++)	M4 (++++)

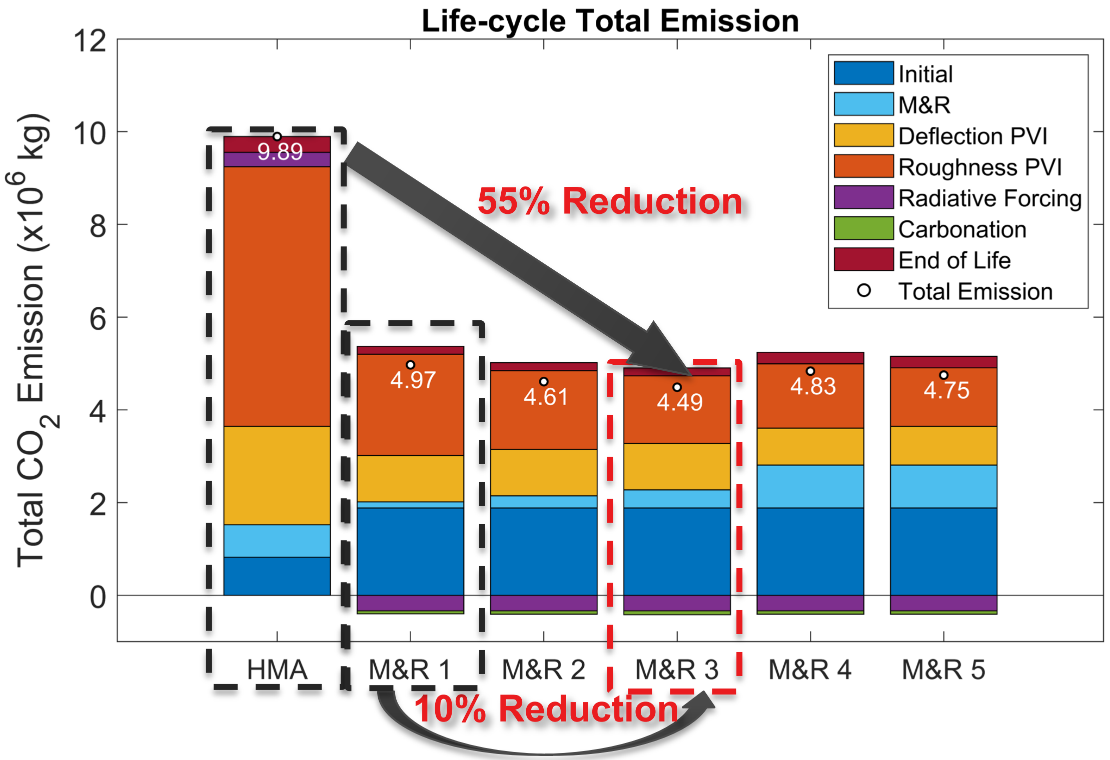


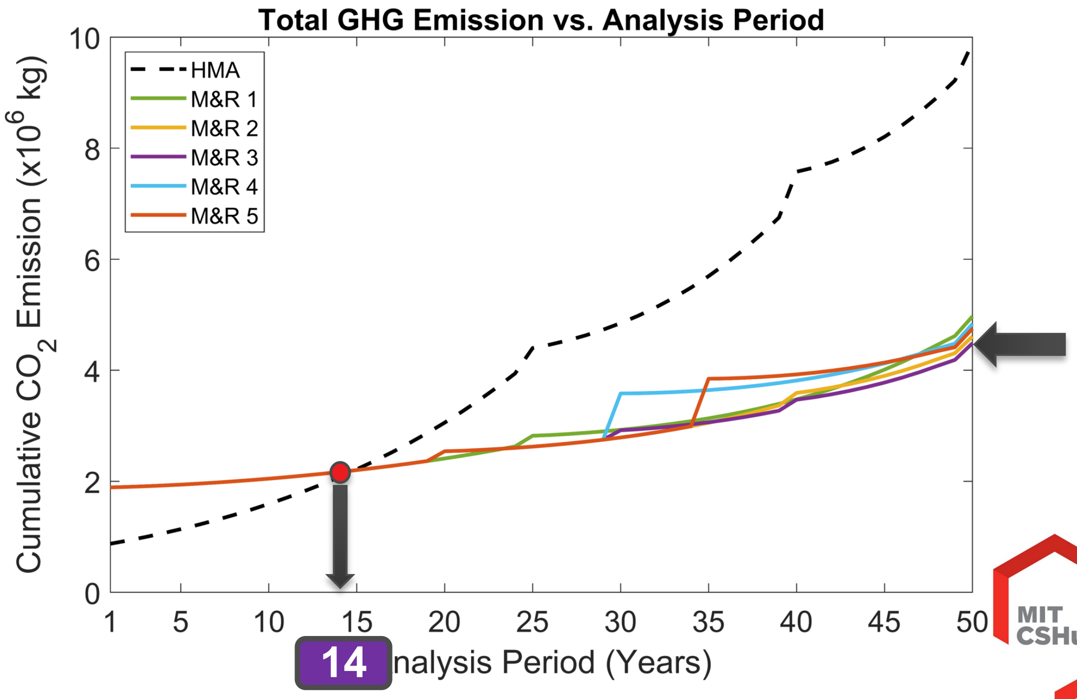
Conclusions

- For a urban road in Arizona, an M2 level (++) data specification is sufficient for approaching statistically defensible results
- **The improved JPCP M&R schedule can:**
    - Reduce life-cycle GHG emissions by up to **22%** compared to the original M&R schedule, and by up to **40%** compared to the hot mix asphalt (HMA) design alternative
    - Shorten the payback period of JPCP from **22** to **18** years.
- **The improved JPCP design can:**
    - Lead to a reduction of up to **35%** in life-cycle GHG emissions compared to the original JPCP design, and up to **50%** reduction when compared to the HMA design alternative
    - Shorten the payback period of JPCP from **22** to **14** years.

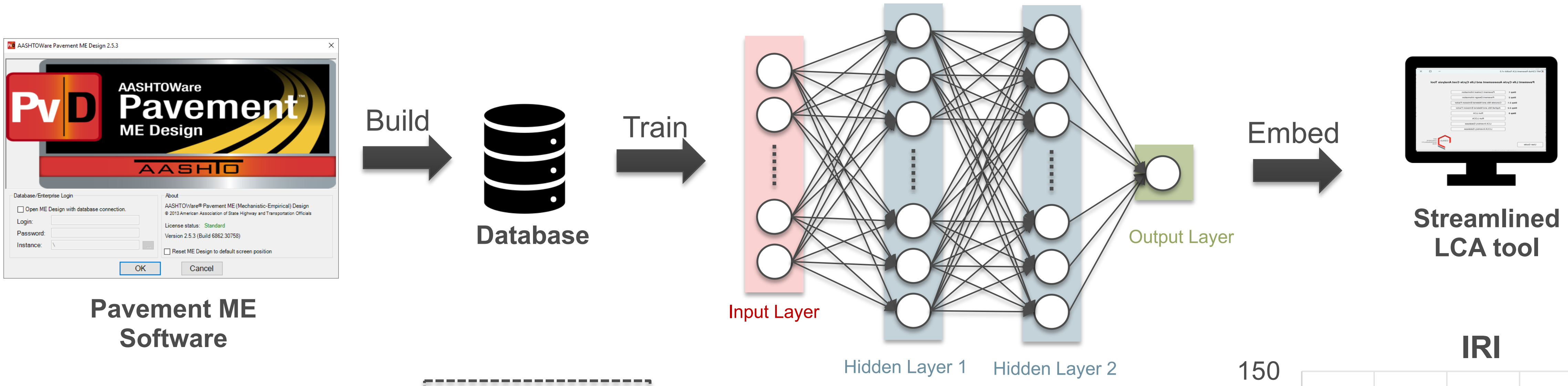
Combined JPCP Design and M&R Optimization can reduce 55% life cycle GHG emission compared to HMA alternative

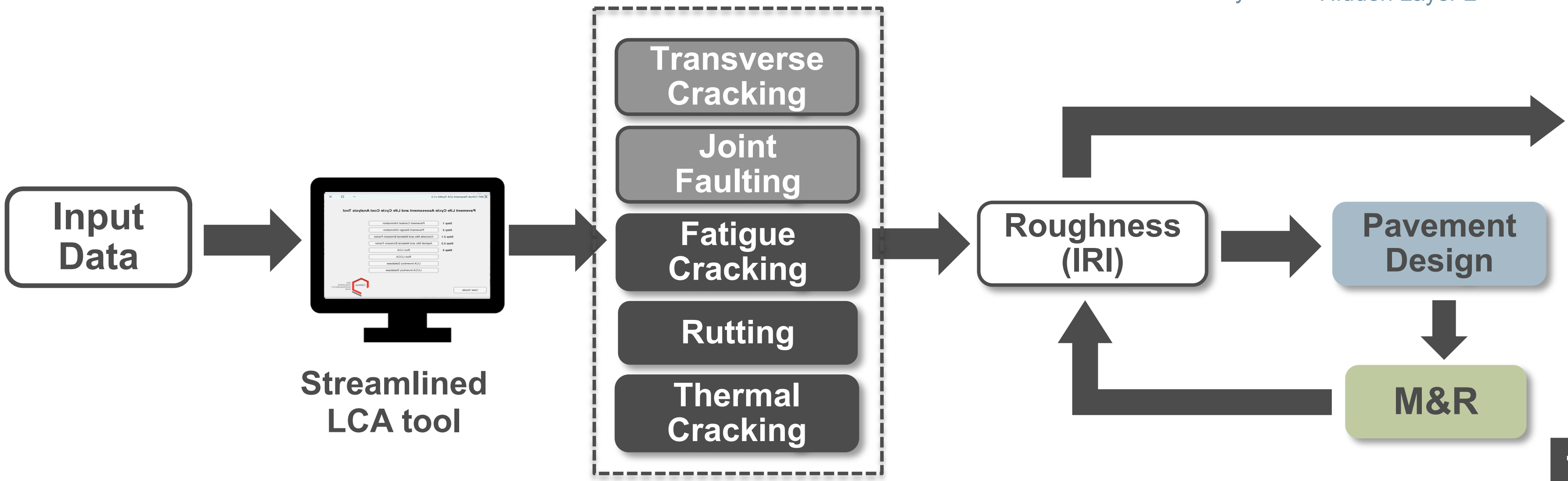
JPCP M&R Optimization	Activities
M&R Schedule 1 (original)	100% Diamond Grind (DG) with 5% Full Depth Replacement (FDR) @ **25** year
M&R Schedule 2	100% DG with 5% DG @ **20** and **40** year
M&R Schedule 3	100% DG with 5% DG @ **20**, **30**, and **40** year
M&R Schedule 4	100% DG with 5% DG @ **20** and **Bonded 4-in PCC Overlay** @ **30** year
M&R Schedule 5	100% DG with 5% DG @ 20 and **Bonded 4-in PCC Overlay** @ **35** year

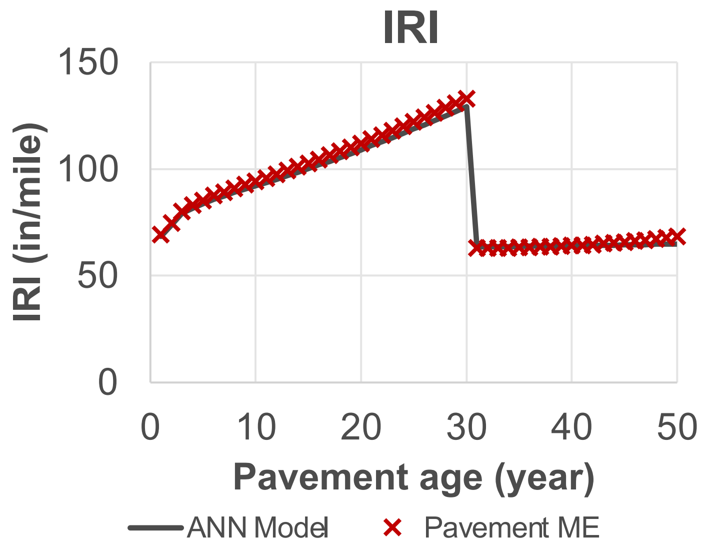




Surrogate models of Pavement ME reduce computational time without loss of accuracy

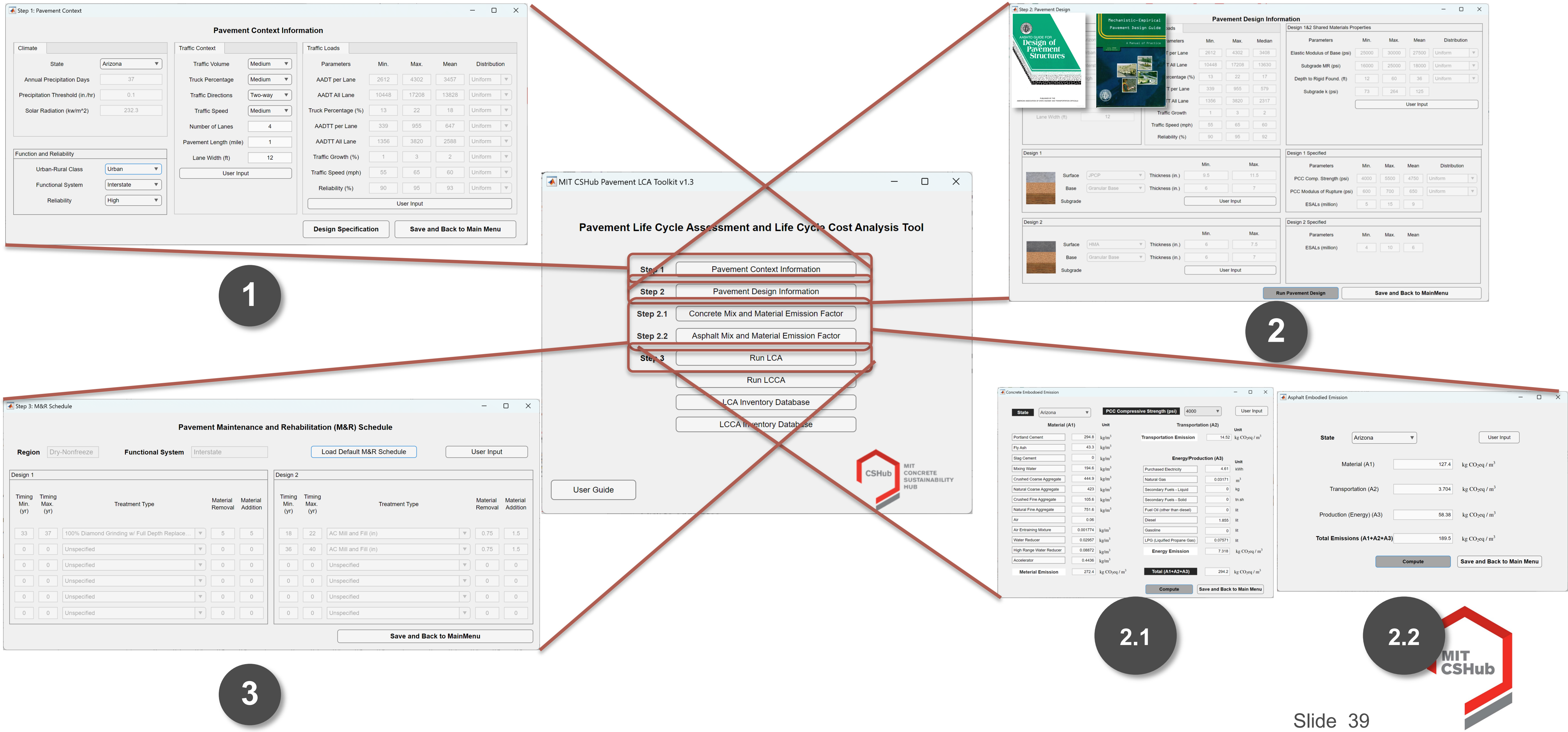




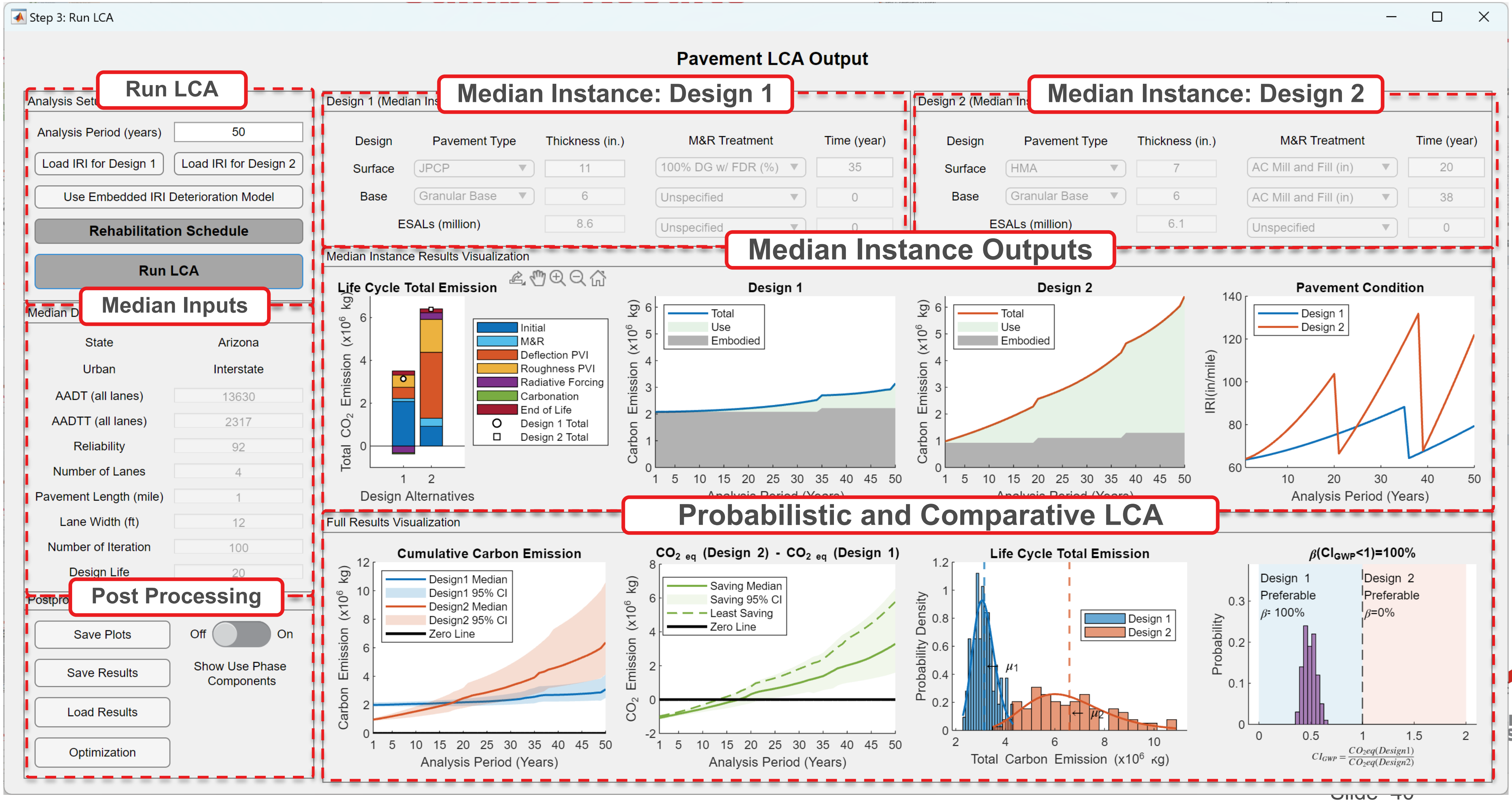


Tool	ANN Model	Pavement ME
Time	0.02 sec	10 mins

The Streamlined Pavement LCA Tool (version 1.3)



Sample Outputs of the Streamlined Pavement LCA Tool



Structured data specification can accommodate any data level

Underspecification Level			
M1 (+)	M2 (++)	M3 (+++)	M4 (++++)

General details with broad variation → Specified details with limited variation of options