Illinois Center for Transportation
University of Illinois at Urbana Champaign

Functional Unit Choice for Comparative Pavement LCA Involving Use-Stage with Pavement Roughness Uncertainty Quantification (UQ)

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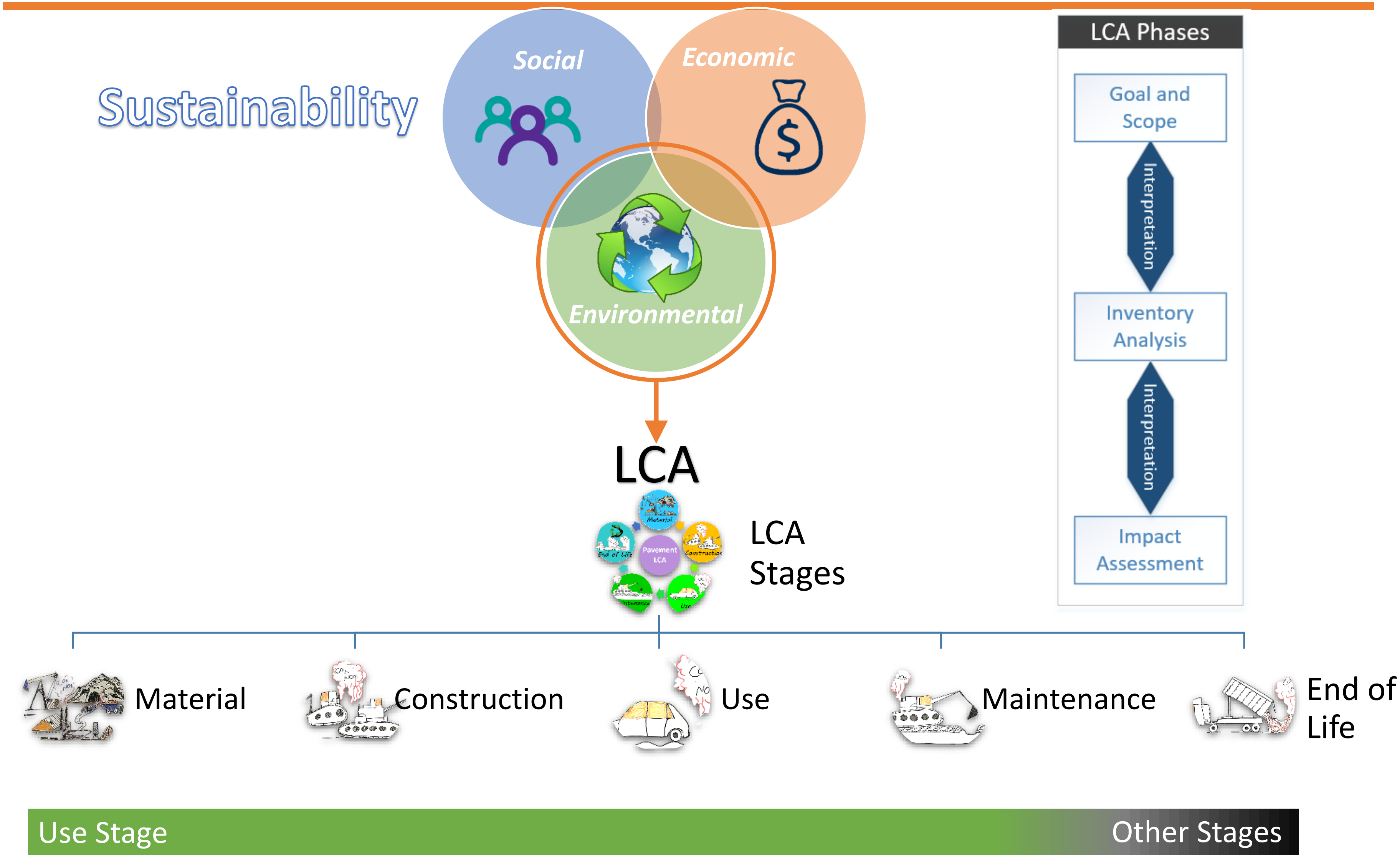
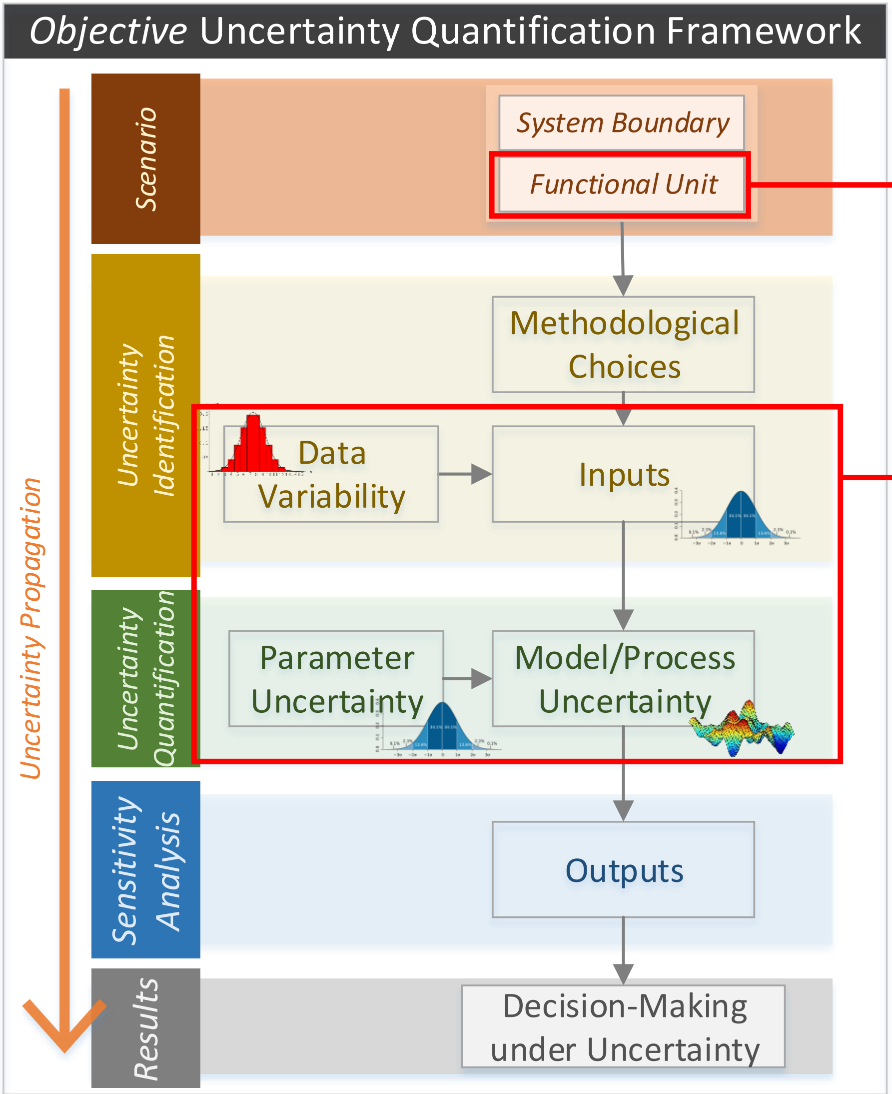
Sustainability & LCA



Outline



Pavement Use Stage

- **Functional unit choice**
- ***Objective* Uncertainty analysis**

Uncertainty Sources:

- Systematic errors
- Random errors
- Data uncertainty
- Model uncertainty
- Completeness uncertainty
- Scenario uncertainty

Functional Unit (FU) Choice

- A unit of measurement of system components to which inputs and outputs of LCA are normalized
- FHWA reference doc: “particular length of pavement with a specified geometry that meets the acceptance criteria over a specified length of time.”
- Common FUs used in the literature:
  - **Physical**
    - Lane-mile (LM)
  - **Annualized**
    - Lane-mile year (LMY)
  - **Structural or performance-based**
    - Performance-lane-length (PCR-lane-mile)

FU Choice in Comparative LCA

- FU for different design alternatives for a specific project/corridor/location.

Example FU:

- ***20 lane-mile of pavement section serving 40,000 traffic for 50 years.***

FU Choice in Comparative LCA

- What to do for comparative LCA of different projects?

  it is not straightforward for projects with different characteristic or design inputs.

  - This is the case of benchmarking studies where projects from past, for example, are compared to current designs
  - *Example of Illinois Tollway pavement sustainability projects: Current projects to be evaluated against baseline projects from 1990s.*
    - *Not similar designs!*

FU Choice in Comparative LCA

- Take previous FU as example:
  - ***20 lane-mile of pavement section serving 40,000 traffic over 50 years.***
  - This fails to describe differences among projects.

- Therefore, a new FU in terms of Vehicle-length-traveled was defined e.g. vehicle-miles-traveled

- If the use stage accounts for the performance, then no need to include it directly in the FU.
  - Assuming poor performing pavement will result in higher impacts

Example Application – widening projects

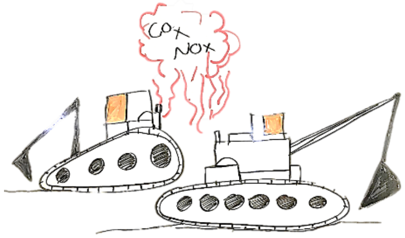
Toll Road	Year	Project Code	MP	Length (mi)	Analysis Period (yr)	AADT; % Truck	Description
Jane Addams Memorial I-90/I-39/ US 51	2012-2013	4077 A	49.7 to 53.6	3.9	62 yrs; 3 overlays	28,460 EB; 13.3%	Roadway widening (3 lanes 12-inch JPCP) and reconstruction
	2014	4133 B	24.9 to 33.5	8.6	62 yrs; 3 overlays	19,240 WB; 20.3%	Roadway widening (3 lanes 11.25-inch JPCP) and reconstruction
Tri-State I-94/I-294/ I-80	2007-2008	5228 C	15.84 to 13.24	2.6	62 yrs; 3 overlays	148,200 14.6%	Roadway widening and reconstruction (with 12-inch JPCP) from 3 to 4 lanes
Ronald Reagan Memorial I-88	1999	723 D	133.7 to 138.8	5.1	44 yrs; 2 overlays	76,680 EB; 80,670 WB; 9.8%	Roadway widening and reconstruction to 3 (12-inch JPCP) lanes

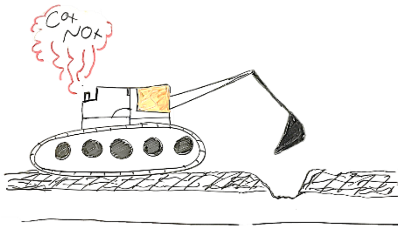
Methodology

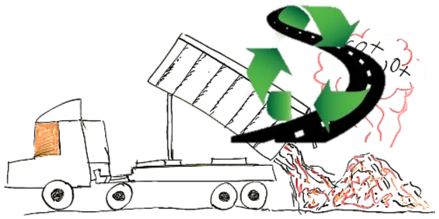
- ***Material, Construction, Maintenance, and End-of-Life Stages***

  A life-cycle inventory database was developed combining operational or process activity data collected with processes available in commercial software and databases such as SimaPro and US-Ecoinvent.

  (Yang et al., 2016; Kang et al., 2014)



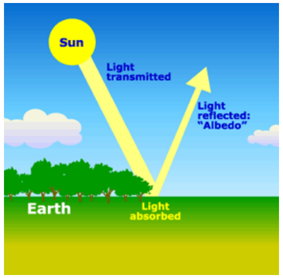




Methodology

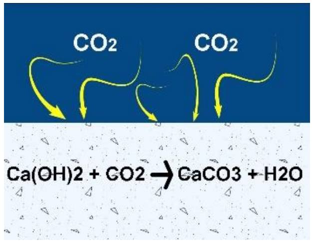
- ***Use Stage***

1. Albedo (Harvey, et al., 2016)



$$m_{CO2} = \sum_{n=1}^{N} 100 * \left(\alpha_{new}^{n} - \alpha_{ref}\right) * \left(f_{RF}\right) * A$$

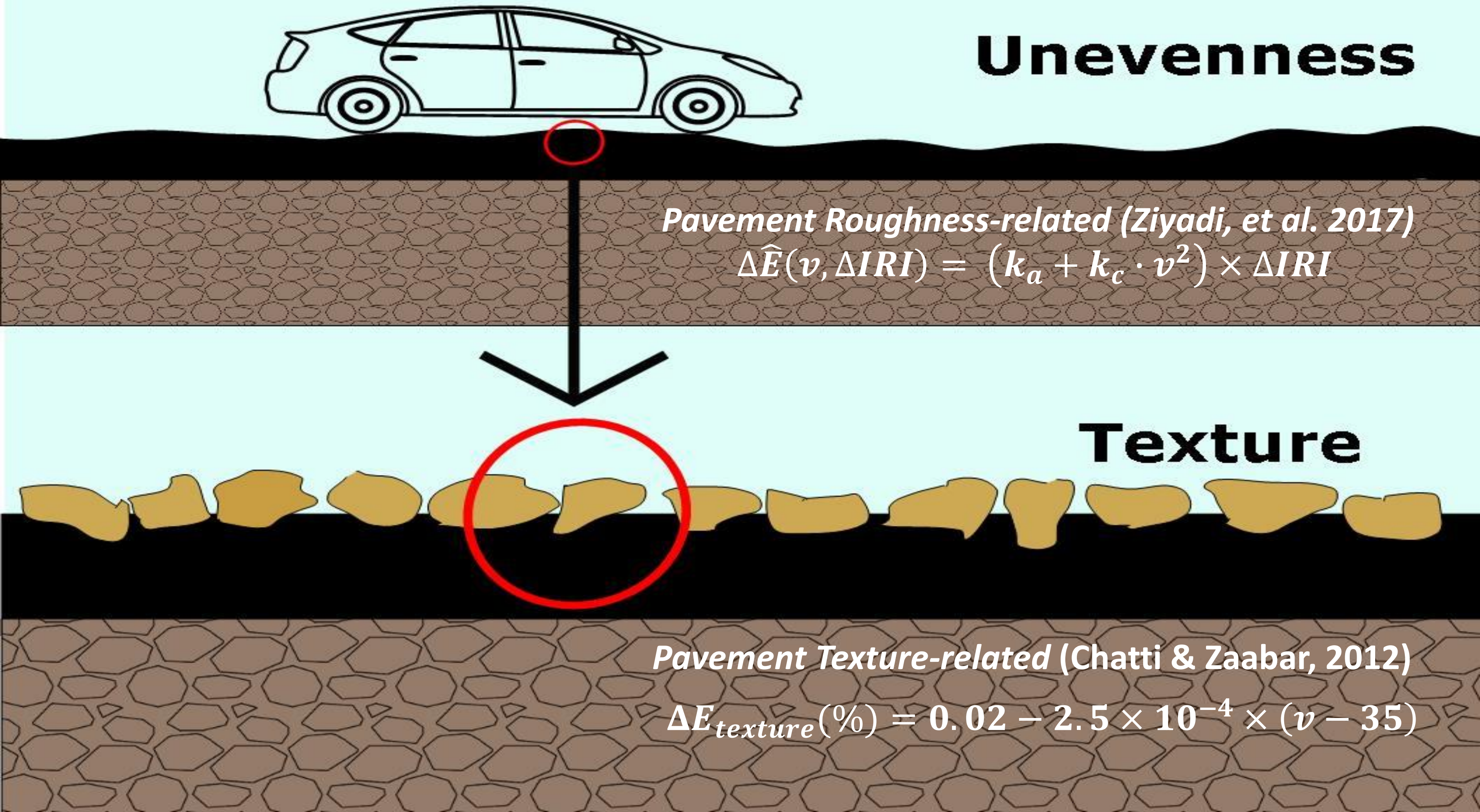
2. Carbonation (Lagerblad, 2005)



$$CO_2(kg) = k \times t^{0.5} \times c \times CaO \times r \times A \times M$$

Methodology

3. Rolling Resistance (RR)

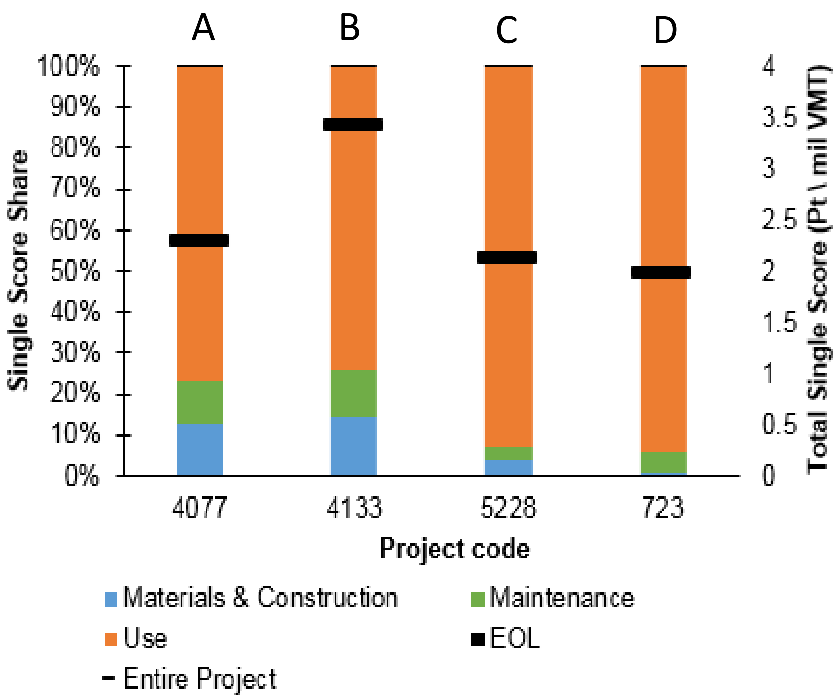


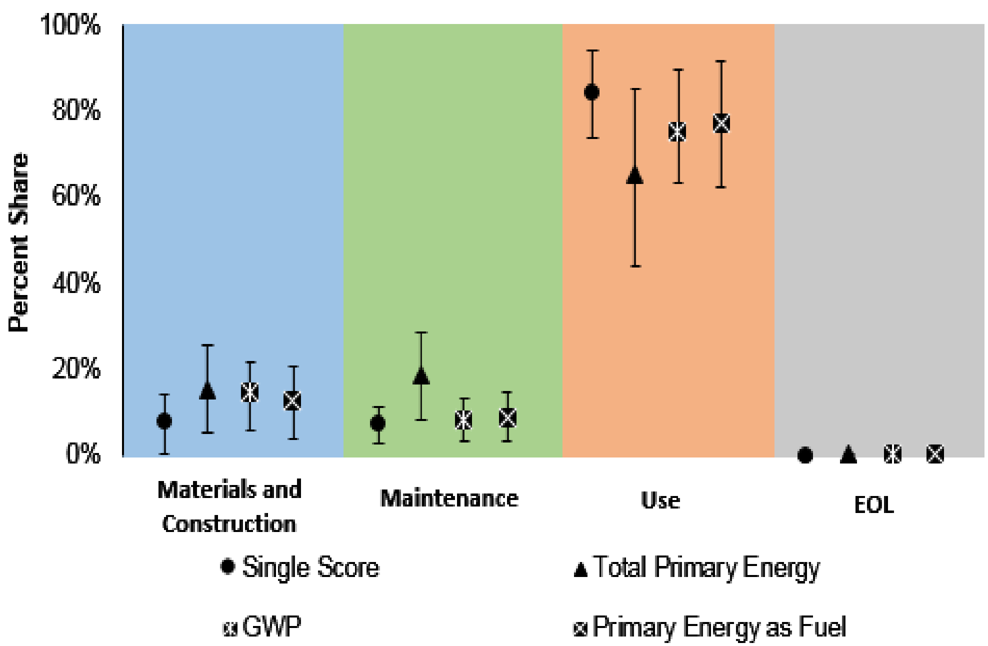
Comparison of Use Stage for Different FU

Output	GWP (tonne-CO_2-eq)			
	Project Code			
	4077 A	4133 B	5228 C	723 D
Total (tonne-CO_2-eq.)	38,915	70,331	129,939	132,931
Total VMT (millions)	4,199	6,354	12,451	20,921
Lane-Mile (LM) (tonne-CO_2-eq. / lane-mile)	3,326	2,726	12,494	8,688
Lane-Mile Year (LMY) (tonne-CO_2-eq. / lane-mile-yr)	54	44	202	197
VMT (tonne-CO_2-eq. / million VMT)	9.3	11.1	10.4	6.4

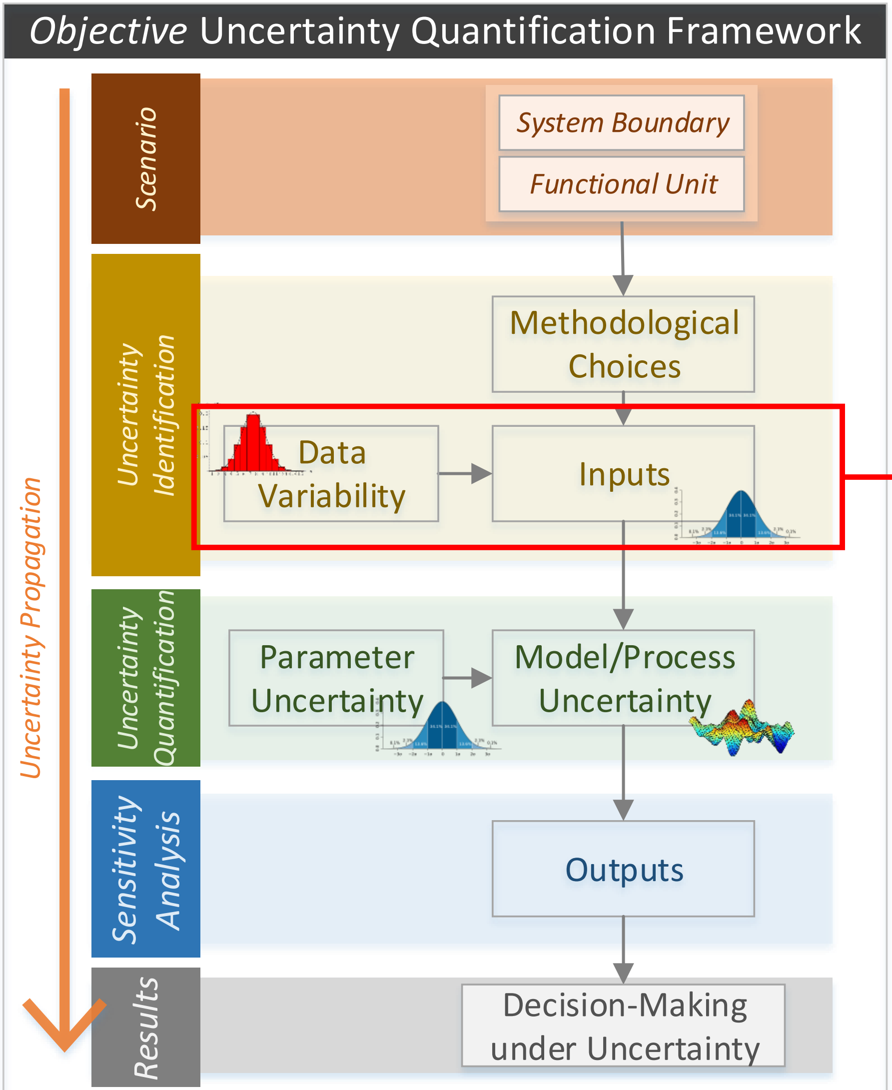
Range of Outputs

- For VMT as FU the following range of results were obtained





Uncertainty of Pavement Roughness



Pavement Use Stage

- Uncertainty analysis of pavement roughness

Uncertainty of Pavement Roughness

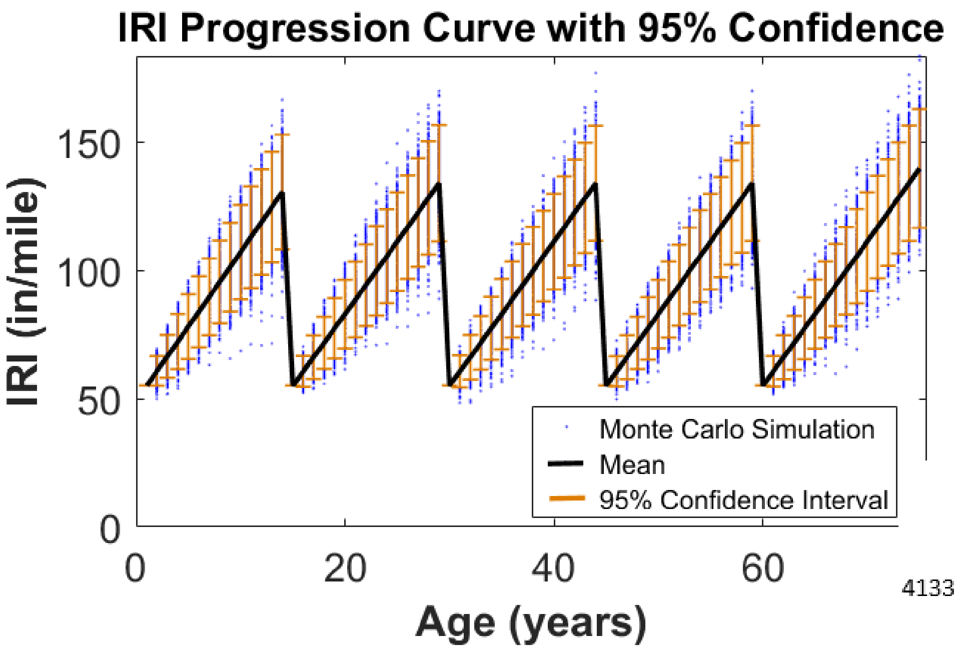
- IRI Progression and drop model developed
- Stochastic approach for IRI uncertainty by adding random noise

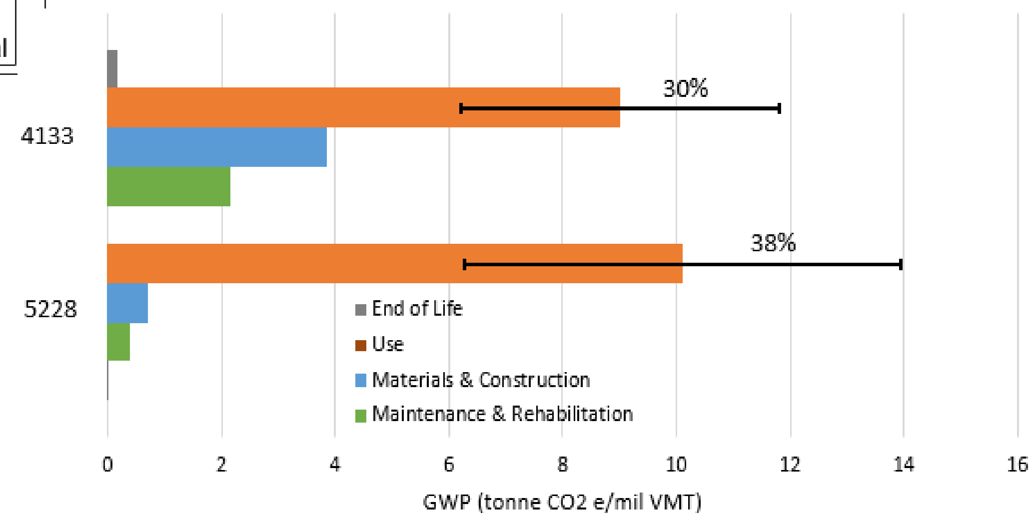
IRI progression model:

$$IRI_t = IRI_{t-1} + a * Thickness^b * ESALs^c + \varepsilon \sim N(0, \sigma^2)$$

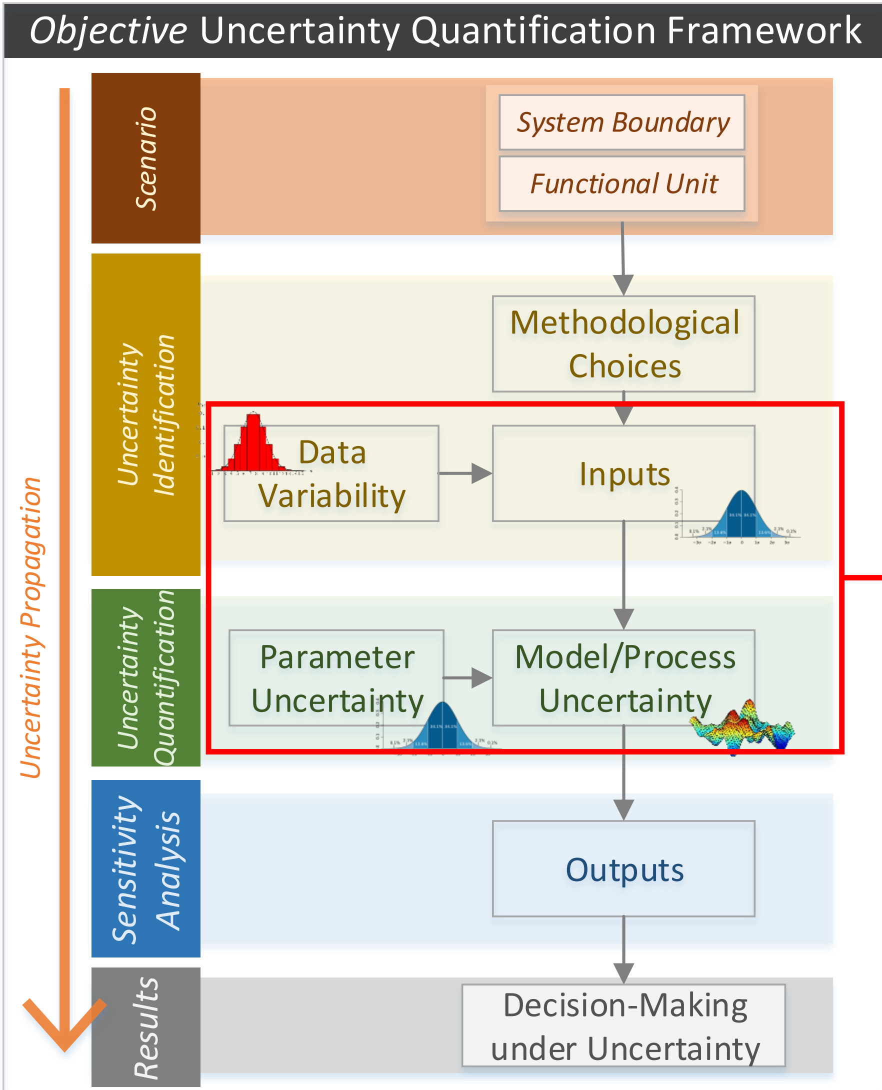
Uncertainty of Pavement Roughness

- IRI Progression with 95% confidence interval





Uncertainty of Pavement Roughness



Pavement Use Stage

Input/Parameter and Model Uncertainty

- **Input** uncertainty: **AADT**, **Truck%** and **V**
  - Probability distributions
- **Model** uncertainty: **parameters**
  - Bayesian inference

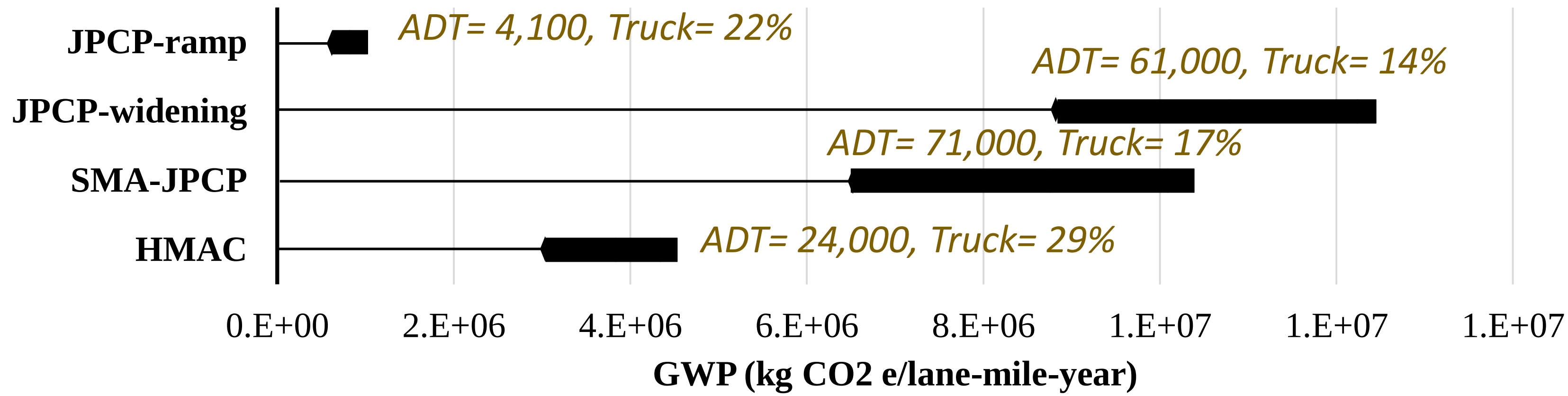
$$\Delta\hat{E}(v, \Delta IRI) = \sum_{ADT} (k_a + k_c \cdot v^2) \times \Delta IRI$$

Projects

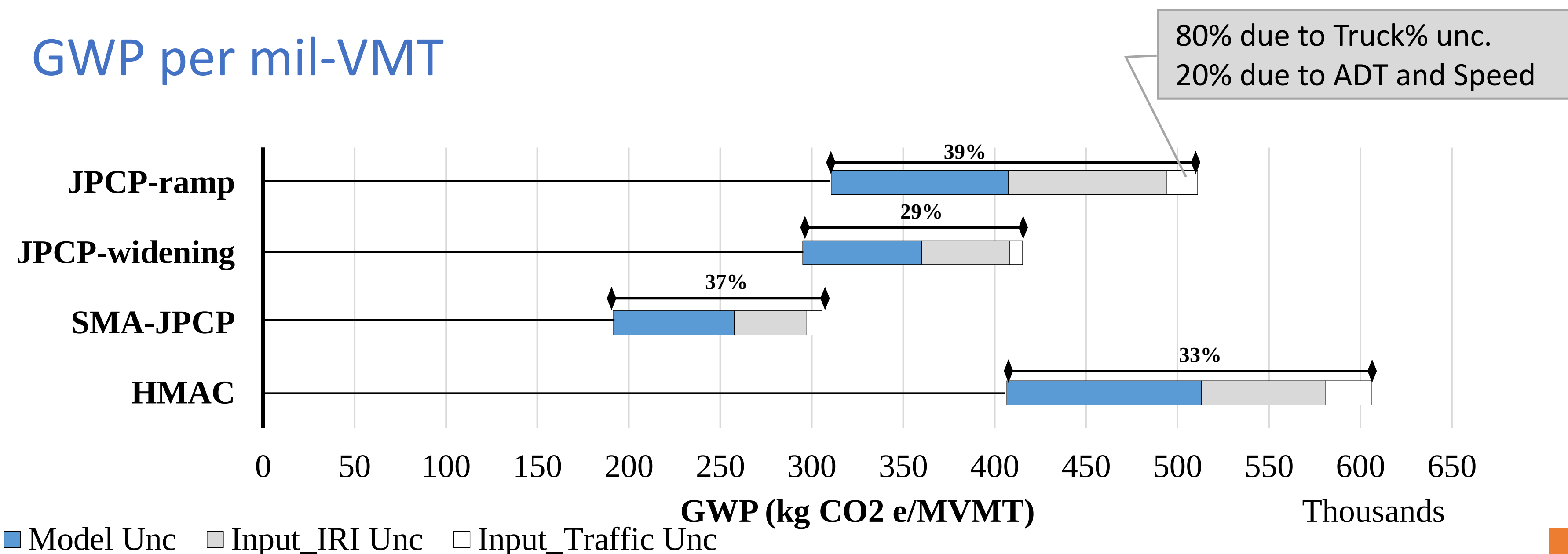
Toll Road	Milepost	Year	Code	Length (mi)	Analysis Period (yr)	AADT; % Truck	Description
Jane Addams Memorial I-90/I-39/ US 51	8.9 to 3.9	2008	I-08-5542 HMAC	5	75 yrs; 4 overlays	24,120 EB; 29.4% 1.47% Growth	Roadway (with 12 and 15-inch HMAC) of 3 lanes and bridge reconstruction. from Plaza 1 (SO Beloit) to IL RT 173 EB.
Tri-State I-94/I-294/ I-80	17.3 to 30.1	2001 - 2002	RR-99-8101 SMA-JPCP	12.8	58 yrs; 4 overlays	70,864 NB, 17.1%, 0.92% G	Roadway partial resurfacing and rehabilitation (3-inch SMA overlay over 4 lanes JPCP)
Tri-State I-94/I-294/ I-80	15.84 to 13.24	2007 - 2008	I-07-5228 JPCP-widening	2.6	62 yrs; 3 overlays	61,270 SB 13.8% 0.92% G	Roadway widening and reconstruction (with 12-inch JPCP) from 3 to 4 lanes
Tri-State I-94/I-294/ I-84	7.5 to 7.8	2013 - 2014	I-12-4066 JPCP-ramp	1.2	62 yrs; 3 overlays	4,100 NB; 22.1% 0.92% G	A new highway interchange ramp (2 lanes 12-inch JPCP) construction at the junction of I-57 and I-294.

Use Stage - Roughness Uncertainty

- GWP per lane-mile year



- GWP per mil-VMT



Summary

- Functional unit choice as an important methodological choice
- Introduced Vehicle-length-traveled (e.g. VMT) as a feasible FU for benchmarking projects
- Importance of uncertainty quantification in LCA
- 30-40% variance in use stage results due to input/model uncertainties
- Expand the uncertainty analysis to other stages

Thank You!

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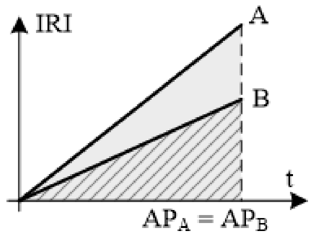
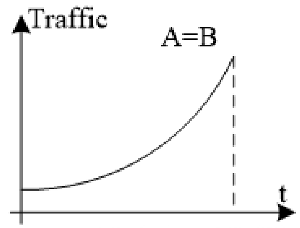
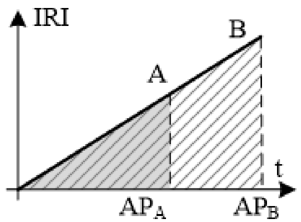
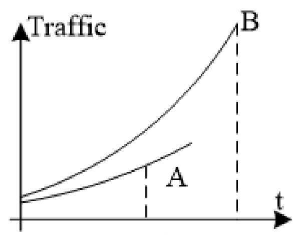
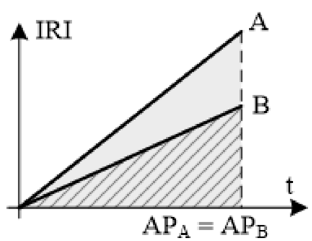
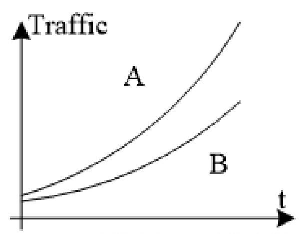
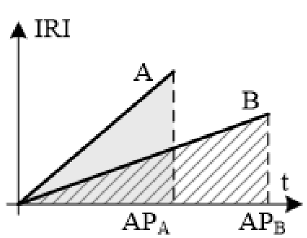
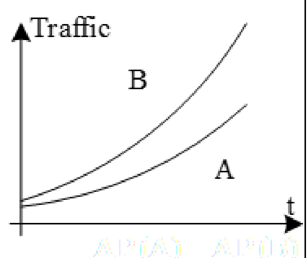
Study Assumptions

Parameter	Uncertain Quantity and Assumptions
Speed	- Speed distributions obtained from 2015 Traffic data report (CDM SMITH, 2015). - Ramp section speed was assumed posted speed of 35 mph. - Yearly average speed variation was not considered
Traffic Data	- Average daily traffic (ADT), and percent truck traffic collected from 2015 Traffic data report (CDM SMITH, 2015) for each section. % measured error in ADT reported as (ADT ~ N(μ,0.1μ/2)). - 10% error in truck percentage. Truck composition according to WIM data from I-294 and I-94 sections (Years 2012 and 2014, Jan, Feb and Apr months): 90% large, 9% medium and 1% small truck. - Truck classification and conversion between different systems can be found elsewhere (TRB, 2016?)
Truck Loading	- Sample WIM data from I-294 and I-94 sections. - Years 2012 and 2014 - Gaussian mixture model was generated from real WIM data for simulation.
Temperature	- 2010 Average monthly temperature data from Chicago O'hare weather station (https://www.ncdc.noaa.gov, accessed 2/2017)
IRI	- Initial IRI values of 55 in/mile for asphalt and 60 in/mile for concrete sections. Averaged from historic Tollway data. - Section specific IRI progression curves adopted from literature (TRB, 2016) - Data variances were calculated from sections with similar pavement surface type throughout the network.
Material	- 10% error in section surface area (Area ~ N(μ,0.1μ/2)) - Albedo of AC: [0.15 – 0.05], PCC = [0.4 – 0.2] (Yu et al., 2013, Kaloush et al., 2008) - RF = [-2.9 to -1.3] (Xu, et al., 2016)

Scenario Description for Comparison	**Performance (in terms of IRI)**	**Traffic**	**Functional Unit Choice and Consequences on Use-stage Impact**
Alternative pavement trials for the same traffic with same design lives. Different expected performance (poor performance for A) with same analysis period.			LM: A > B LMY: A > B VMT: A > B *Consistent results when analysis period is the same.*
Different designs with different design lives accounting for traffic volume differences. Similar expected performance within the analysis period (shorter life for pavement A).			LM: B > A LMY: most likely B > A VMT: most likely A = B *LM and LMY will penalize longer living pavement. Results depend on change in AP and differences in performance and traffic.*
Arbitrary selection from network with different performance and traffic. Same or different design lives. Assume A is the poor performing with higher traffic and same analysis period.			LM: A > B LMY: A > B VMT: most likely A > B *- VMT will favor better performing pavement B if traffic volume is not too low. - If traffic volume is too low, indication of overdesign.*
Arbitrary selection from network with different performance and traffic. Same or different design lives. Assume A is the poor performing with different traffic.			Total: can vary. LM: can vary. LMY: can vary. VMT: most likely A > B *- VMT will favor better performing pavement B.* *- Under higher traffic conditions LM and LMY may penalize pavement B.*

AP = analysis period

LCA Stage	Component	GWP (tonne-CO_2-eq)			
		Project Code			
		4077	4133	5228	723
Use-stage	Roughness-Related Passenger Vehicle	25,144	35,950	93,047	114,648
	Roughness-Related Small Truck	624	1,483	2,577	2,018
	Roughness-Related Medium Truck	824	1,957	3,400	2,662
	Roughness-Related Large Truck	2,988	7,095	12,325	9,651
	Texture-Related Medium Truck	1,413	3,263	5,604	5,457
	Texture-Related Large Truck	2,738	6,324	10,860	10,576
	Albedo Mainline	3,148	6,943	1,111	-8,321
	Albedo Shoulders	2,087	7,423	1,056	-3,645
	Carbonation Mainline	-55	-111	-46	-116
	Carbonation Shoulders	0	0	0	0
Total (tonne-CO_2-eq.)		*38,915*	*70,331*	*129,939*	*132,931*
Total VMT (millions)		*4,199*	*6,354*	*12,451*	*20,921*
Per Functional Unit of Lane-Mile (LM) *tonne-CO_2-eq. / lane-mile*		**3,326**	**2,726**	**12,494**	**8,688**
Per Functional Unit of Annualized Lane-Mile (LMY) *tonne-CO_2-eq. / lane-mile-year*		**54**	**44**	**202**	**197**
Per Functional Unit of Vehicles Mile Travelled (VMT) *tonne-CO_2-eq. / million VMT*		**9.3**	**11.1**	**10.4**	**6.4**