6º CONGRESO IBEROAMERICANO de Pavimentos de Hormigón

Puerto Iguazú, Argentina

23 y 24 de abril de 2015

Organizan:

Federación Iberoamericana del Hormigón Premezclado

ASOCIACION ARGENTINA del HORMIGON ELABORADO

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CSHub

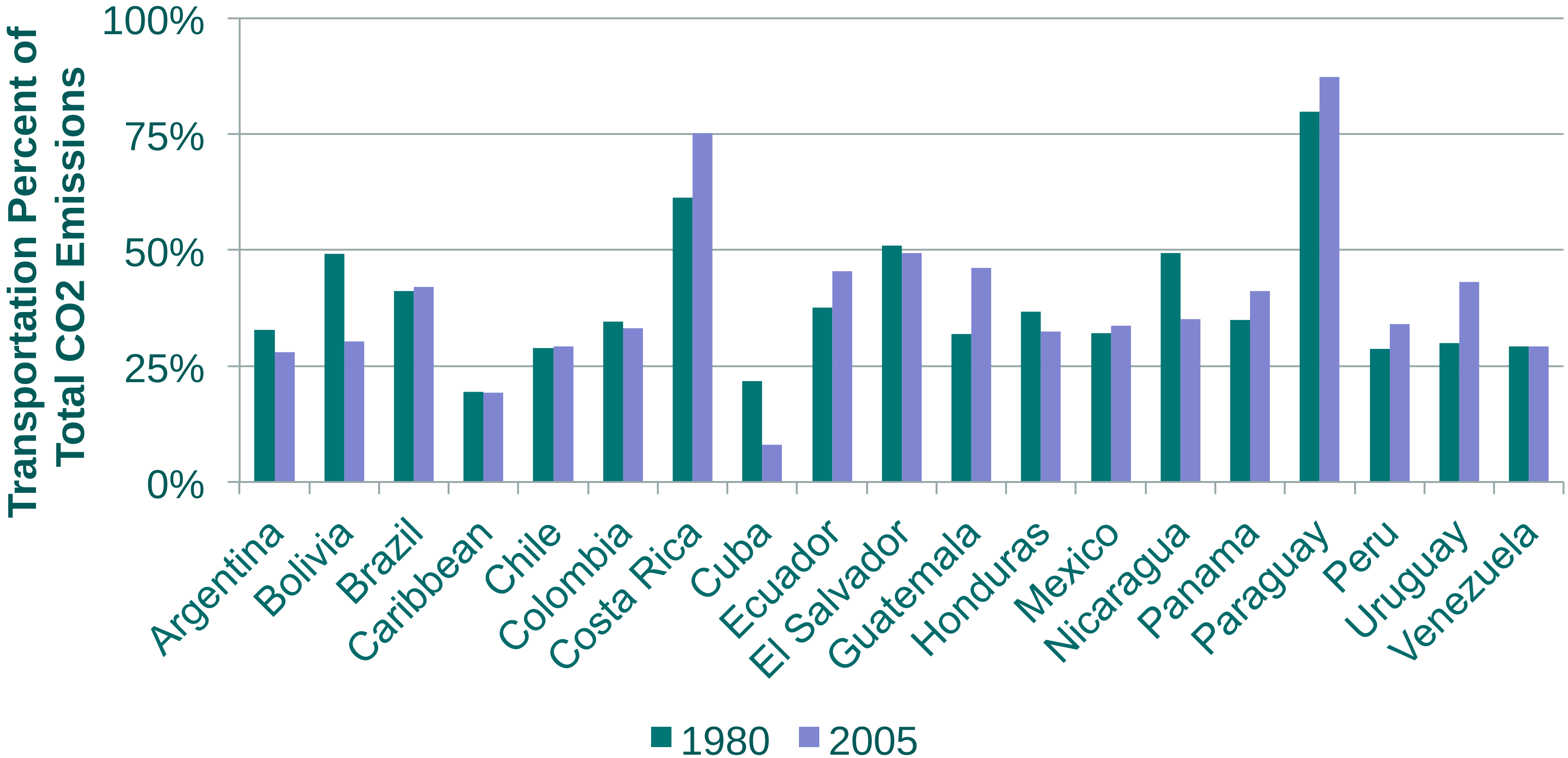
CONCRETE SUSTAINABILITY HUB

New Developments in the Debate on Pavement-Vehicle Interaction: The Impact of Pavement Design on Fuel Consumption

Reed Miller, Mehdi Akbarian, Arghavan Louhghalam, Franz-Josef Ulm. Jeremy Gregory,

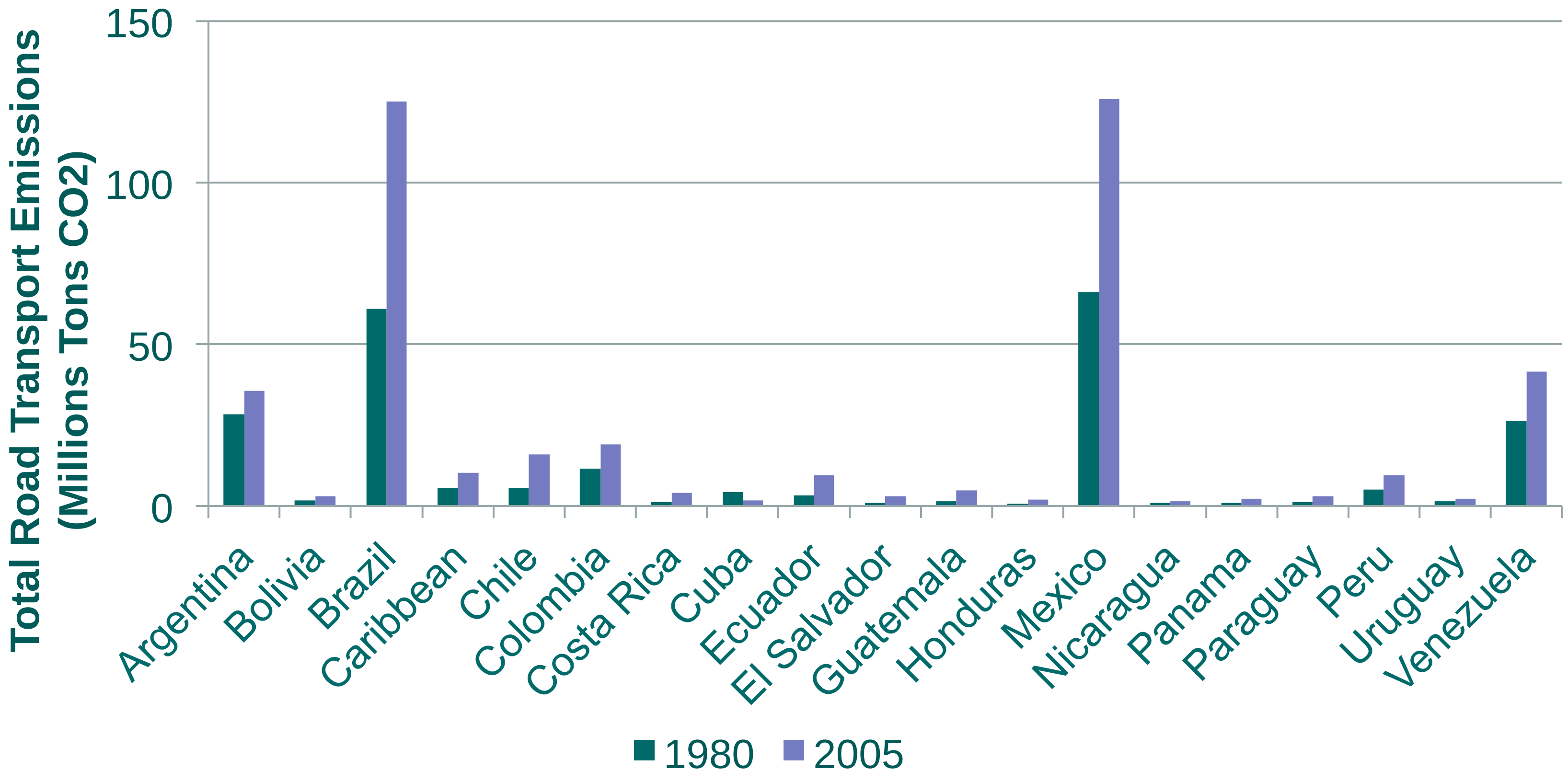
April 24, 2014

Latin American transportation emissions account for considerable portion of impact



World Bank 2008

Latin American road transportation emissions are large and growing

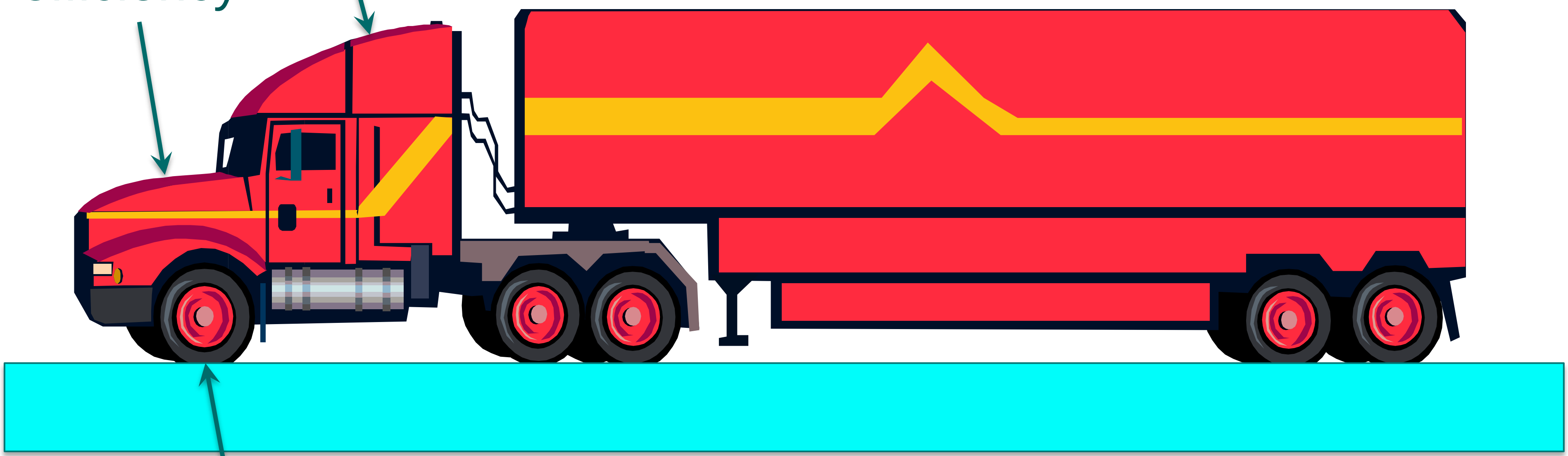


World Bank 2008

Engineering strategies for transportation carbon management

Improve energy efficiency

Improve aerodynamics



Reduce rolling resistance,
including pavement-vehicle interaction

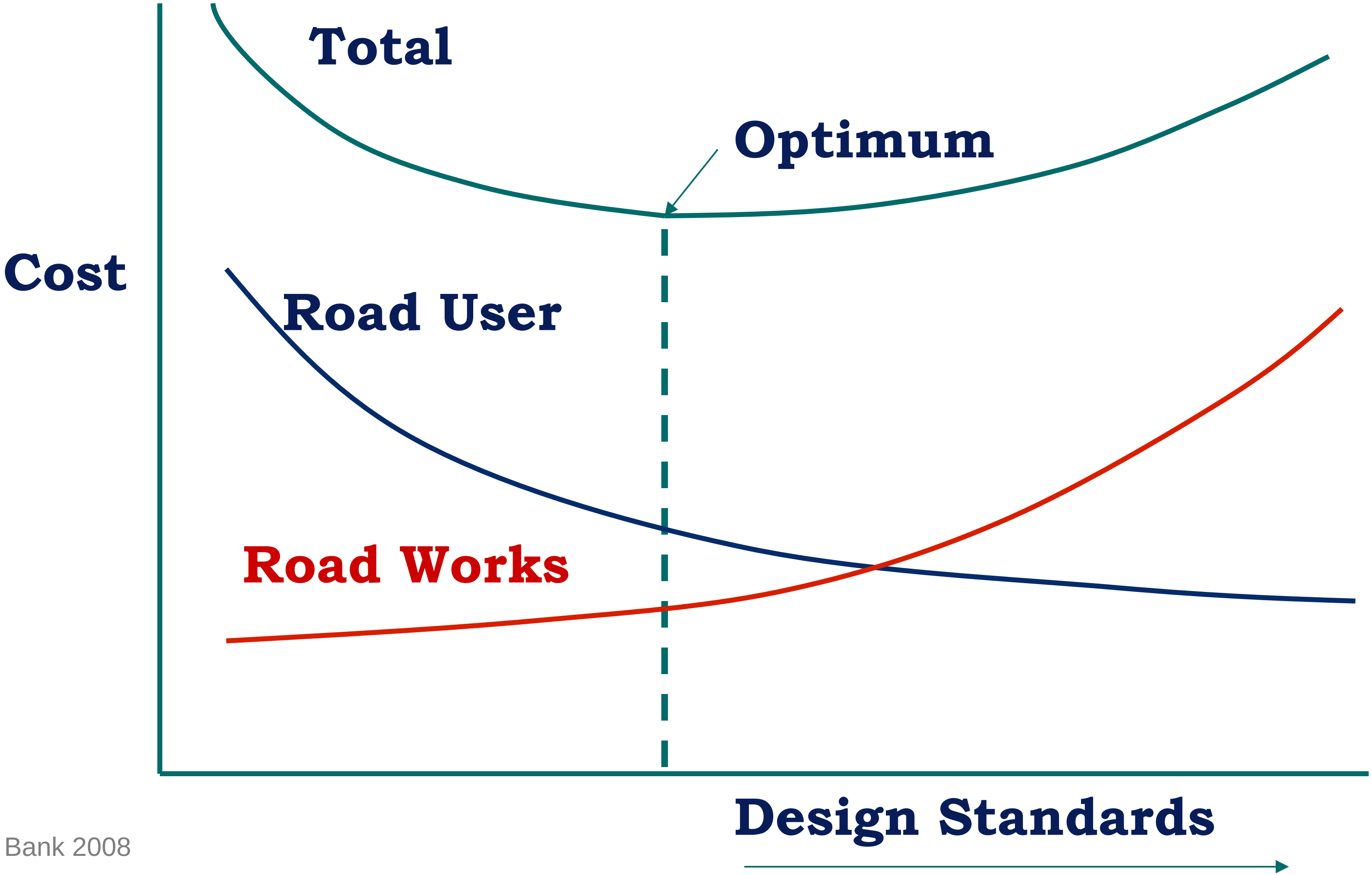
Policy strategies for transportation carbon management

Many countries have vehicle exhaust emissions standards:

Argentina, Brazil, Chile, Colombia, Ecuador, El Salvador, Mexico…

What about fuel efficiency standards for ***pavements***?

Minimizing Total Society Costs

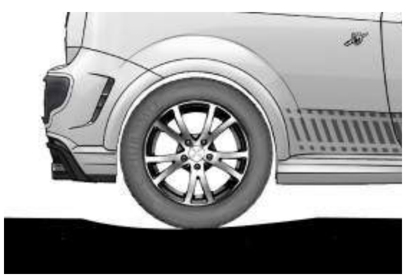


World Bank 2008

Key drivers of rolling resistance & PVI

- **Pavement Texture**:
  - Relevant to vehicle control and safety
  - Tire-pavement contact area is important

- **Roughness**:
  - Related to pavement maintenance and location
  - Evolves over time



- **Deflection**:
  - Related to pavement design: stiffness, thickness matter
  - Speed and temperature dependent

PVI relationship to fuel consumption

Quantify pavement and vehicle properties → Calculate excess fuel consumption → Estimate excess cost and environmental impact

Accomplished for roughness and deflection using:

- Experimental results
- Empirical models
- Mechanistic models

MIT approach: model-based assessment of PVI

Roughness

- ***Vehicle*-specific**
- **HDM4**
- Model Inputs:
  - Pavement roughness
  - Vehicle energy dissipation data

Deflection

- ***Pavement*-specific**
- **MIT Mechanistic Model**
- Model Inputs:
  - Pavement structural and material properties
  - Vehicle weight

Key drivers of rolling resistance & PVI

- **Pavement Texture**:
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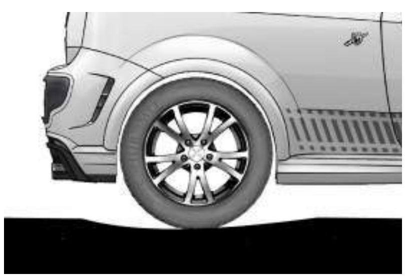

- **Deflection:**
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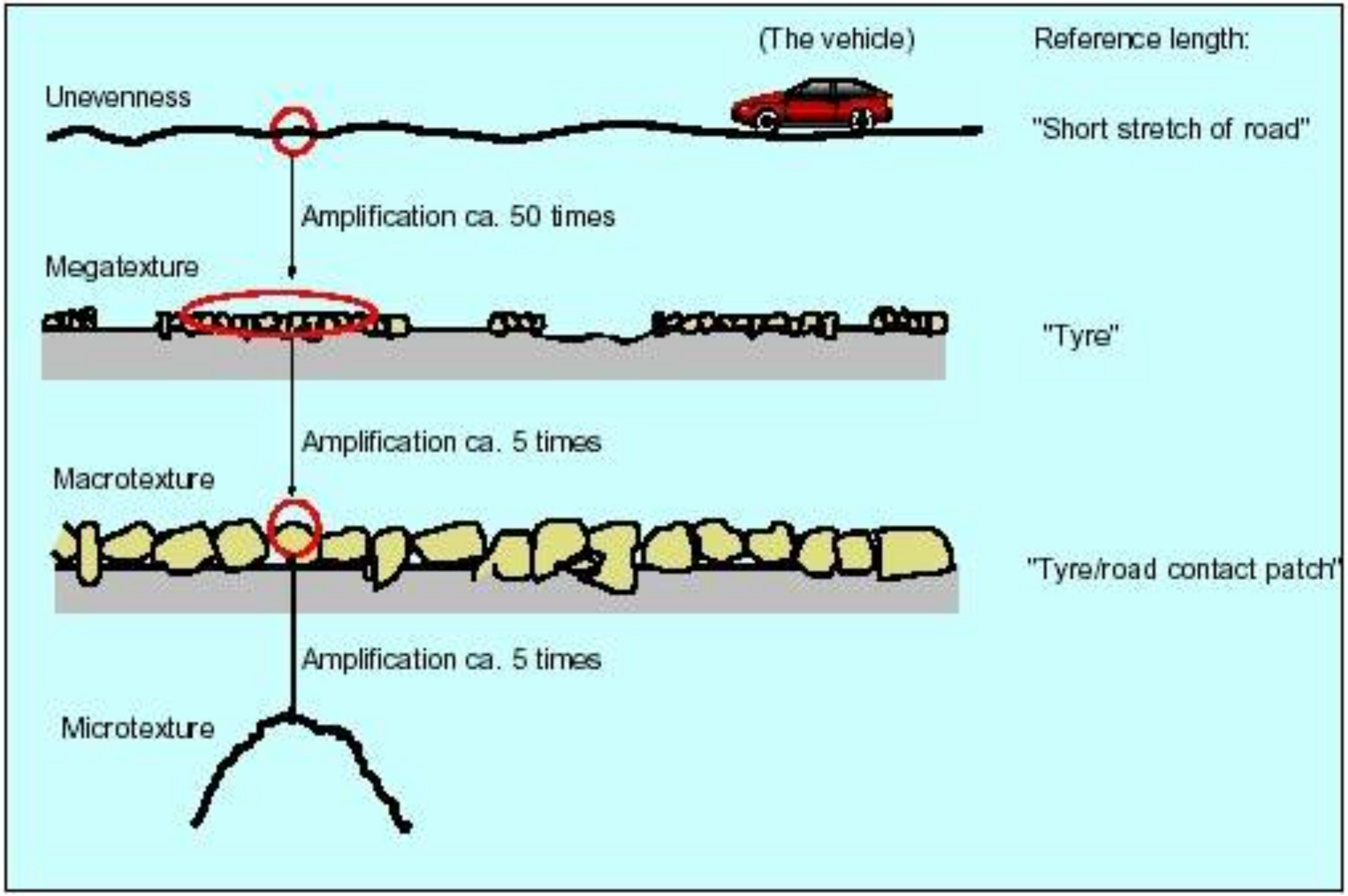
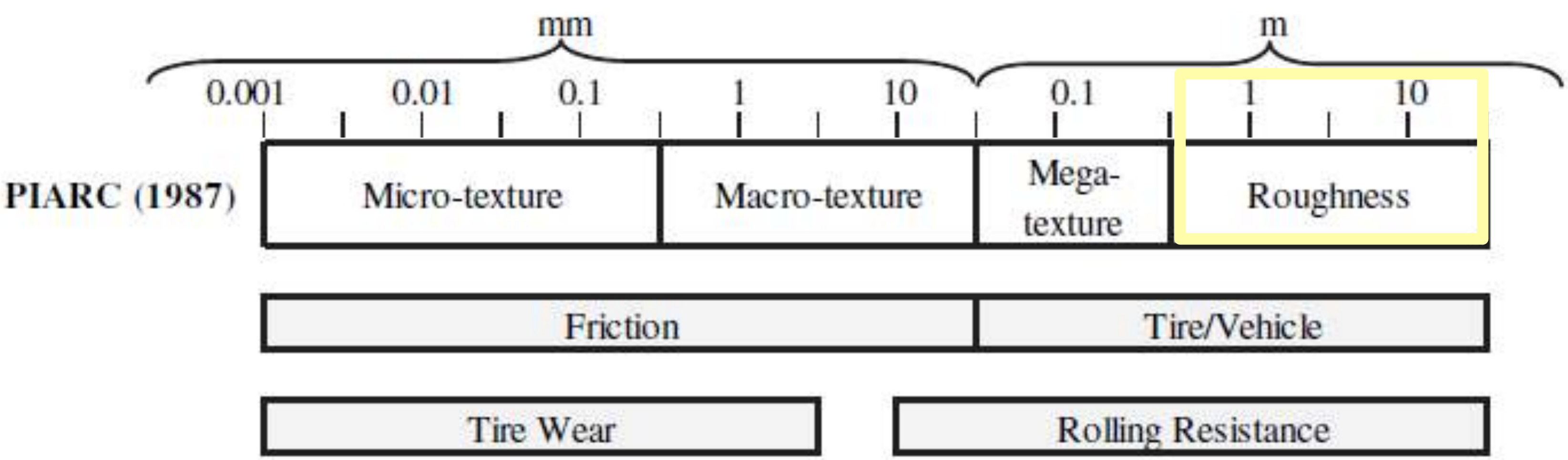
Roughness versus Texture Wavelength



Ulf Sandberg VTI

Roughness versus Texture Wavelength



1 mm = 0.04 in, 1 m = 3.3 ft.

PIARC: Permanent International Association of Road Congresses

Source: adapted from Henry (2000) and Sandberg and Ejsmont (2002)

NCHRP 2012

Roughness: vehicle-specific energy dissipation and excess fuel consumption

Uneven road surface

↓

Energy dissipated in suspension

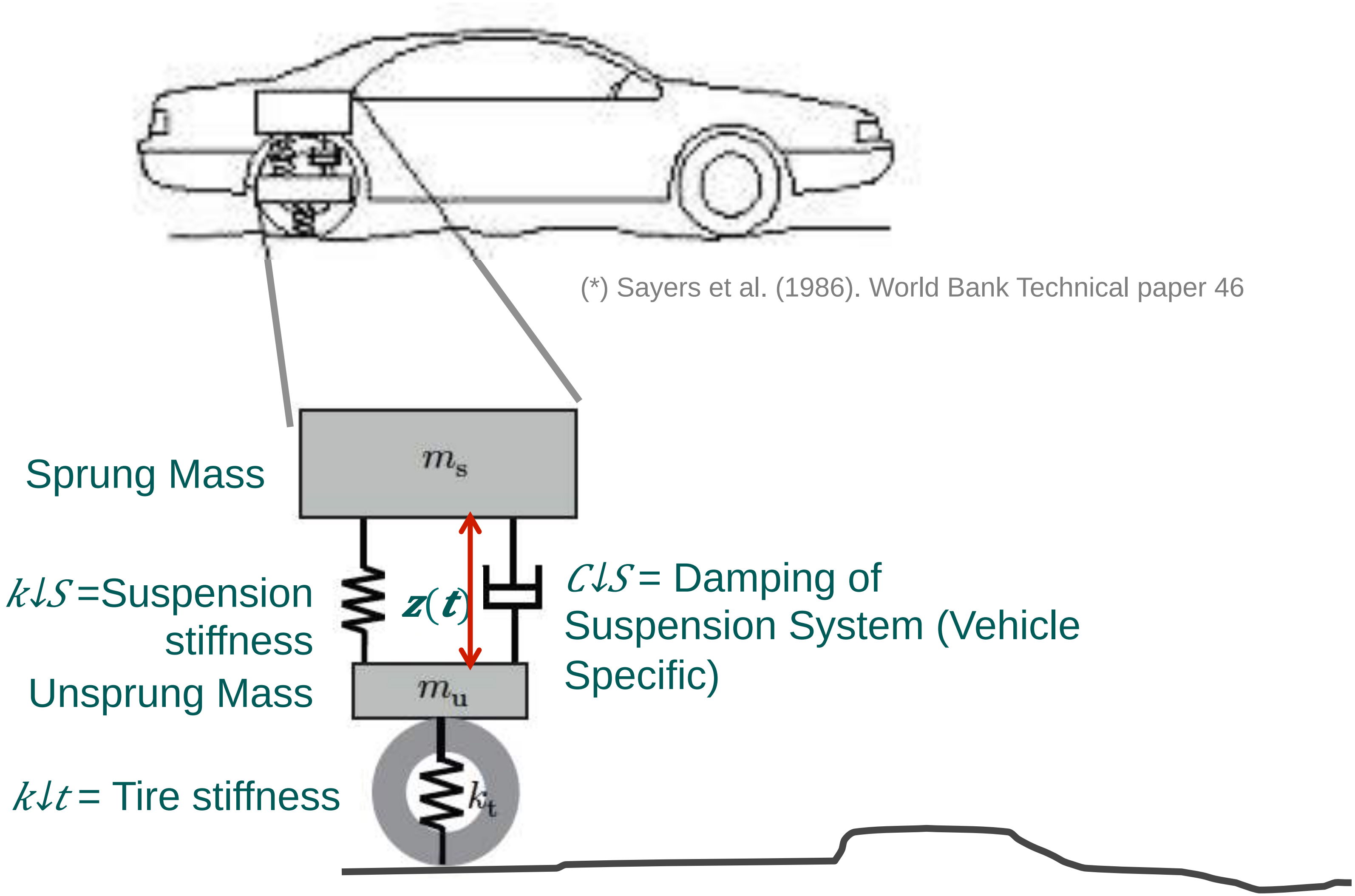
↓

Engine compensates with more power

↓

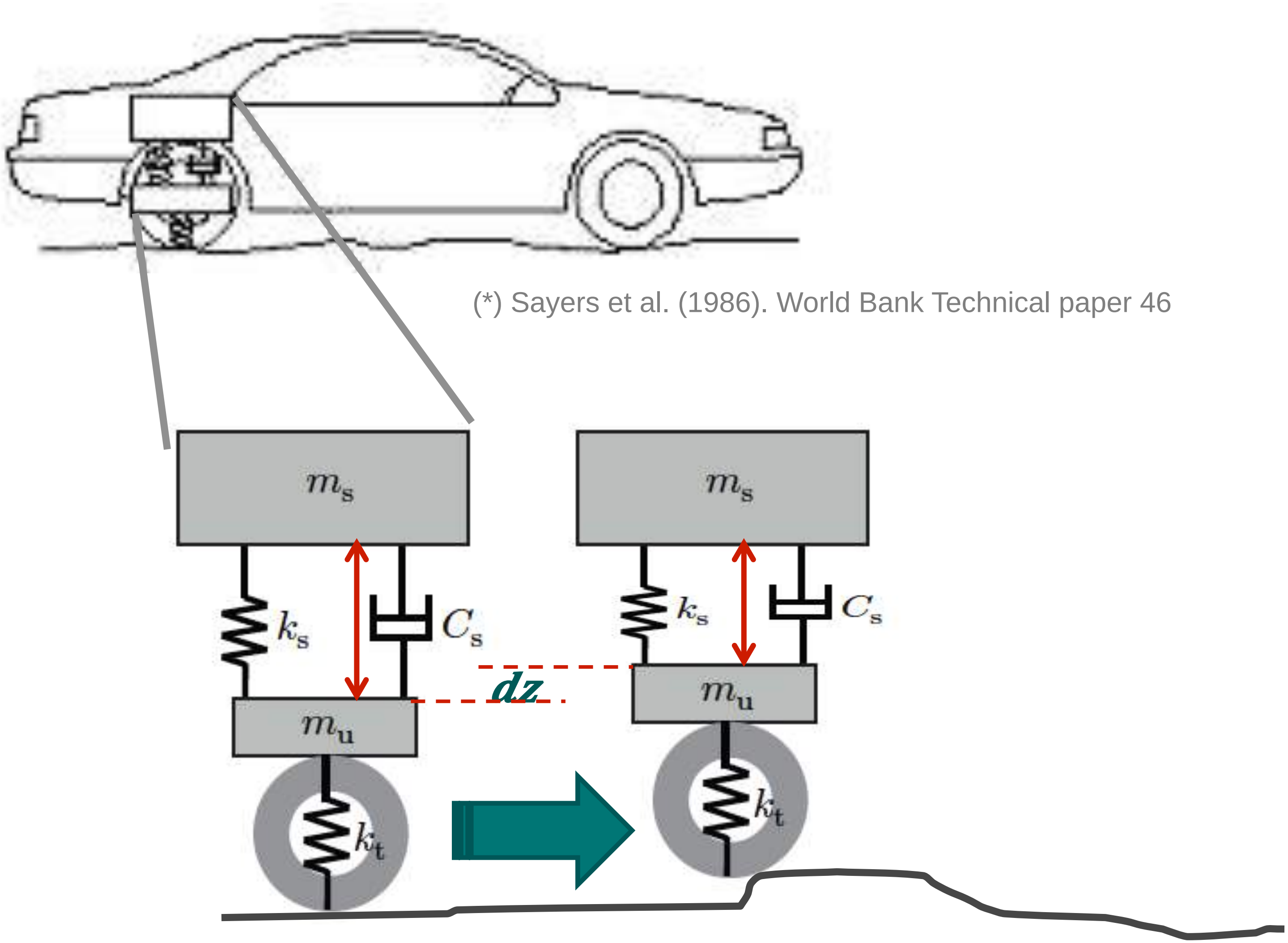
Excess fuel consumption

Roughness impact: Quarter-Car Model



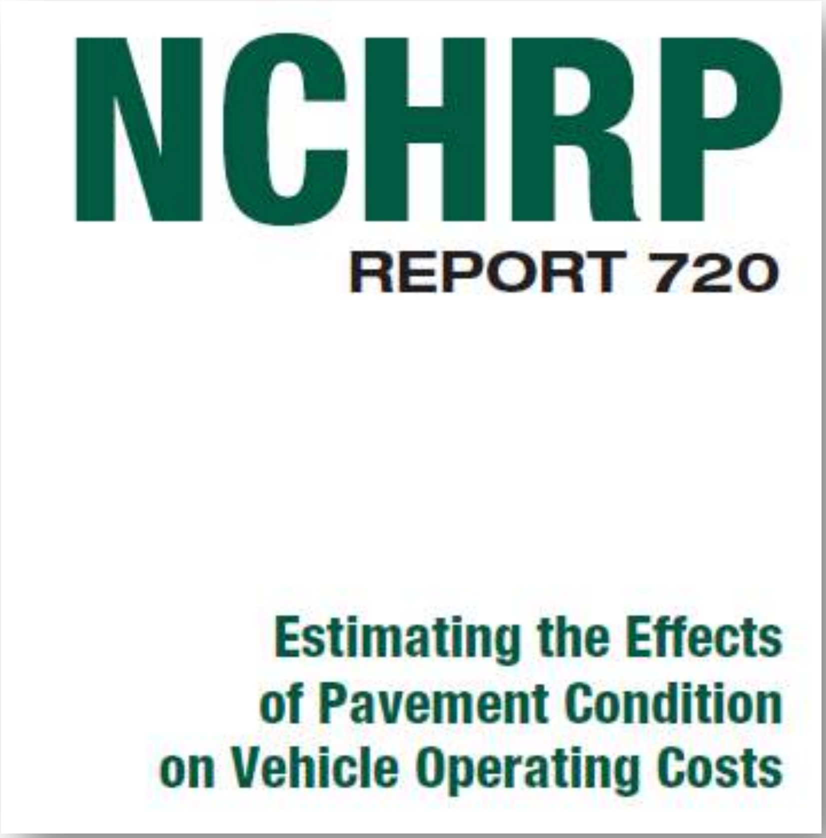
(*) Sayers et al. (1986). World Bank Technical paper 46

Roughness impact: Quarter-Car Model



(*) Sayers et al. (1986). World Bank Technical paper 46

Roughness: Models to estimate excess fuel

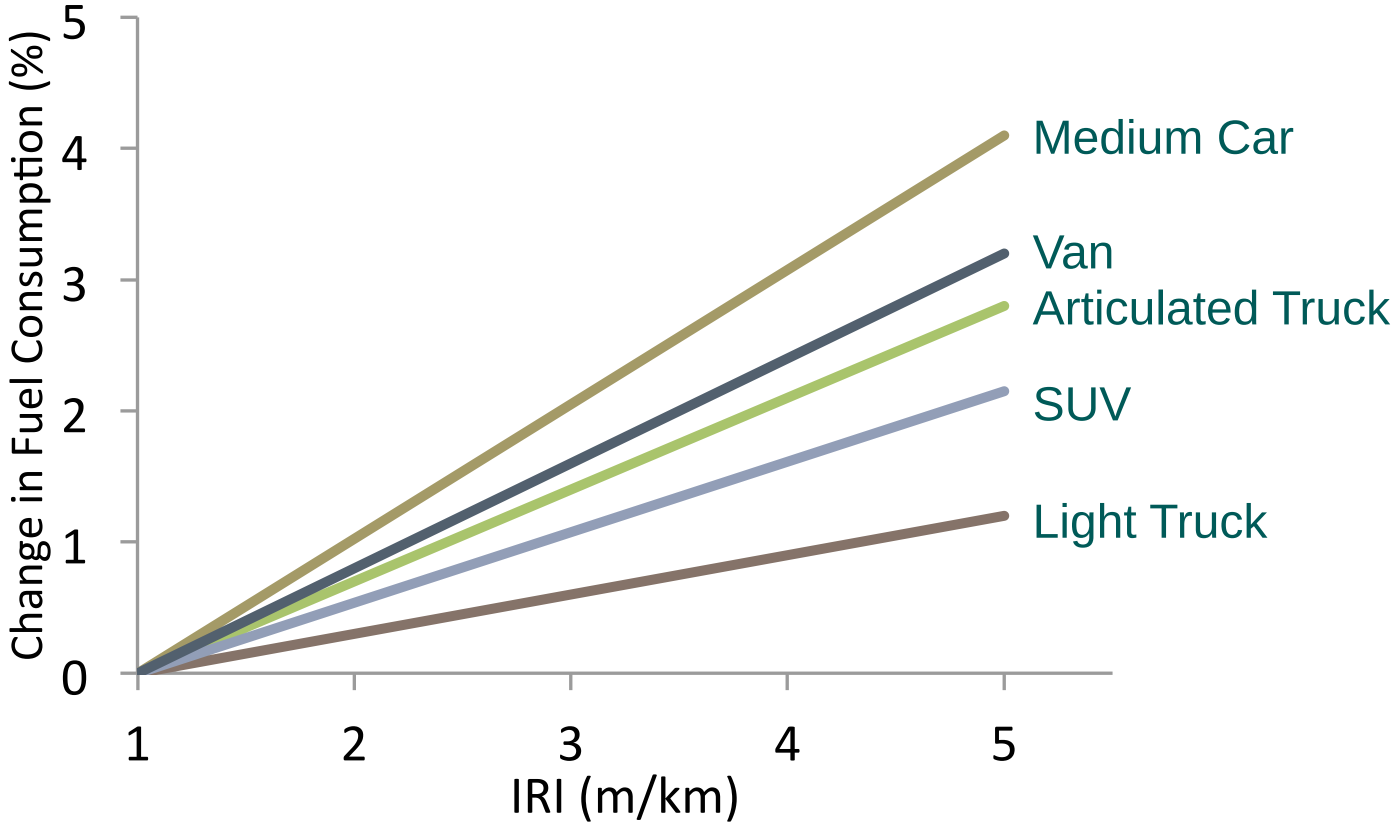

NCHRP
REPORT 720
Estimating the Effects of Pavement Condition on Vehicle Operating Costs

- Reviews of existing models, including:

HDMGLOBAL
HDM-4 Version 2

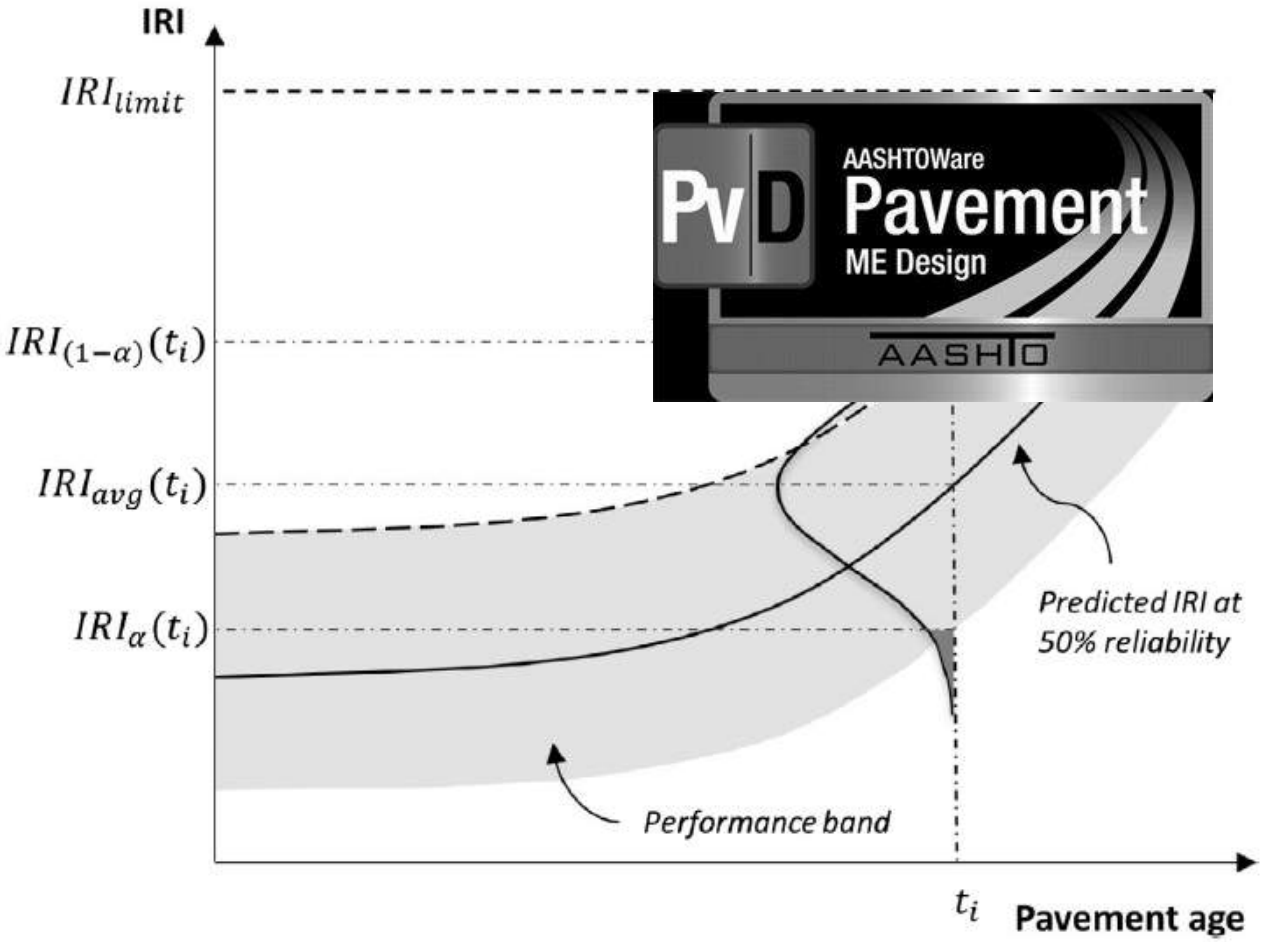
- Calculation details for roughness induced:
  - Fuel consumption
  - Tire wear
  - Vehicle maintenance

Roughness: vehicle-specific energy dissipation and excess fuel consumption



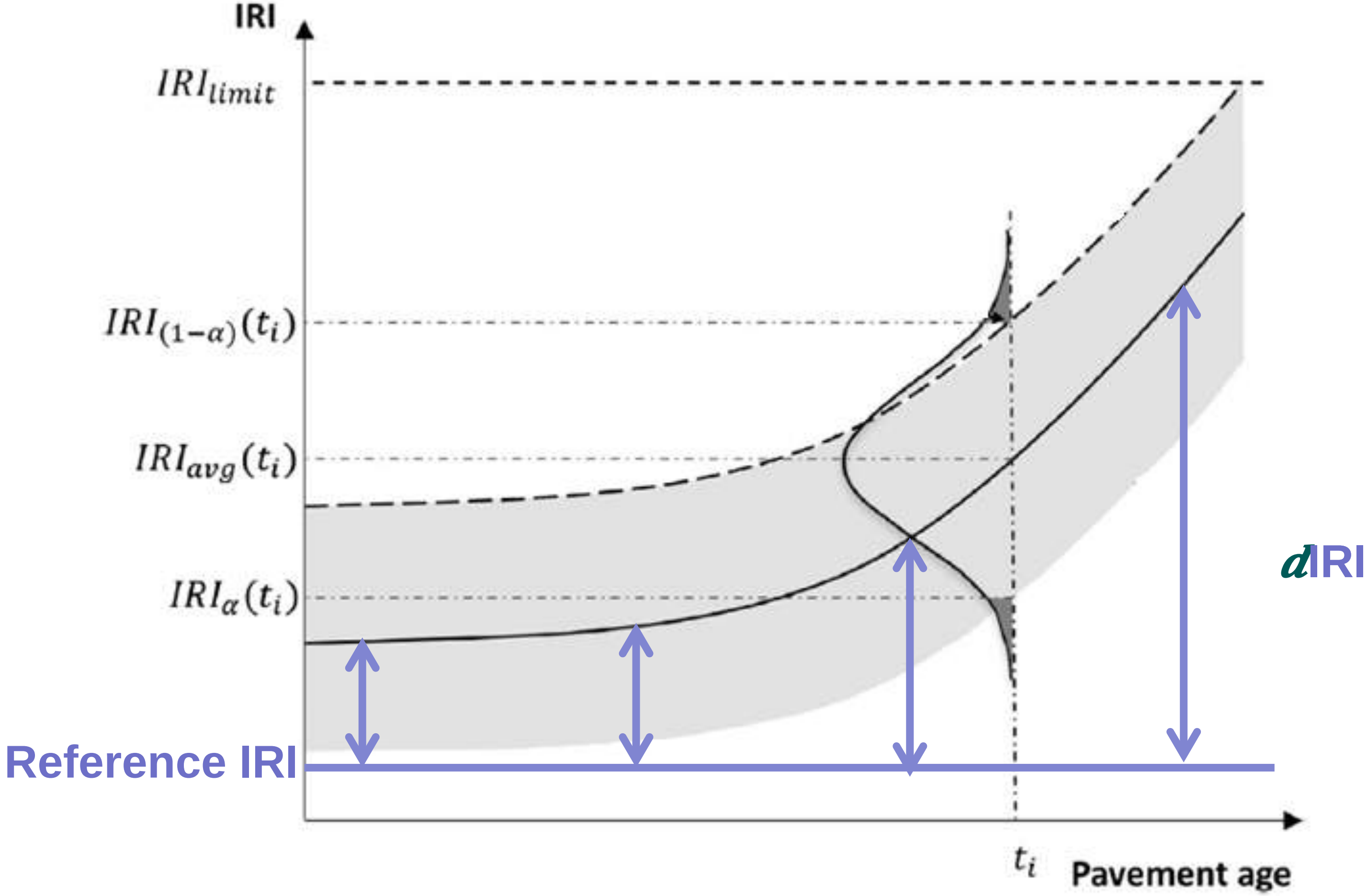
(**) Zaabar I., Chatti K. (2010) TRB, No. 2155, 105-116.

Roughness model: IRI over time



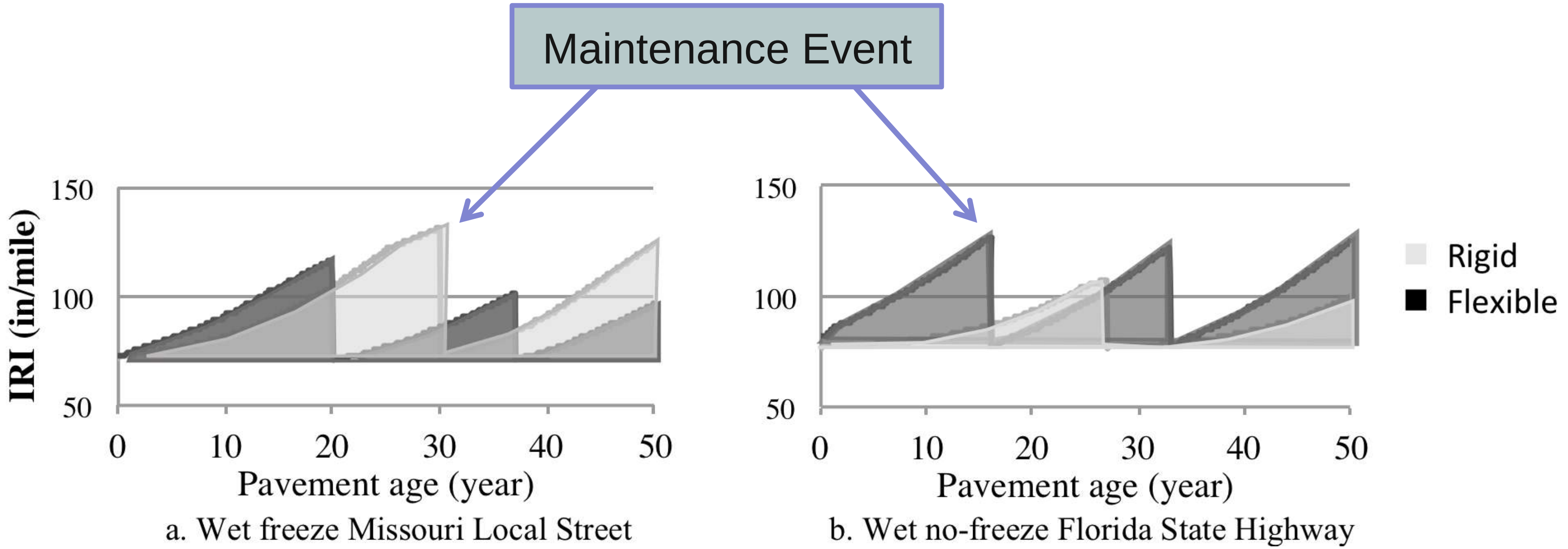
Source: American Association of State Highway and Transportation Officials (2008).

Roughness model: *d*IRI over time



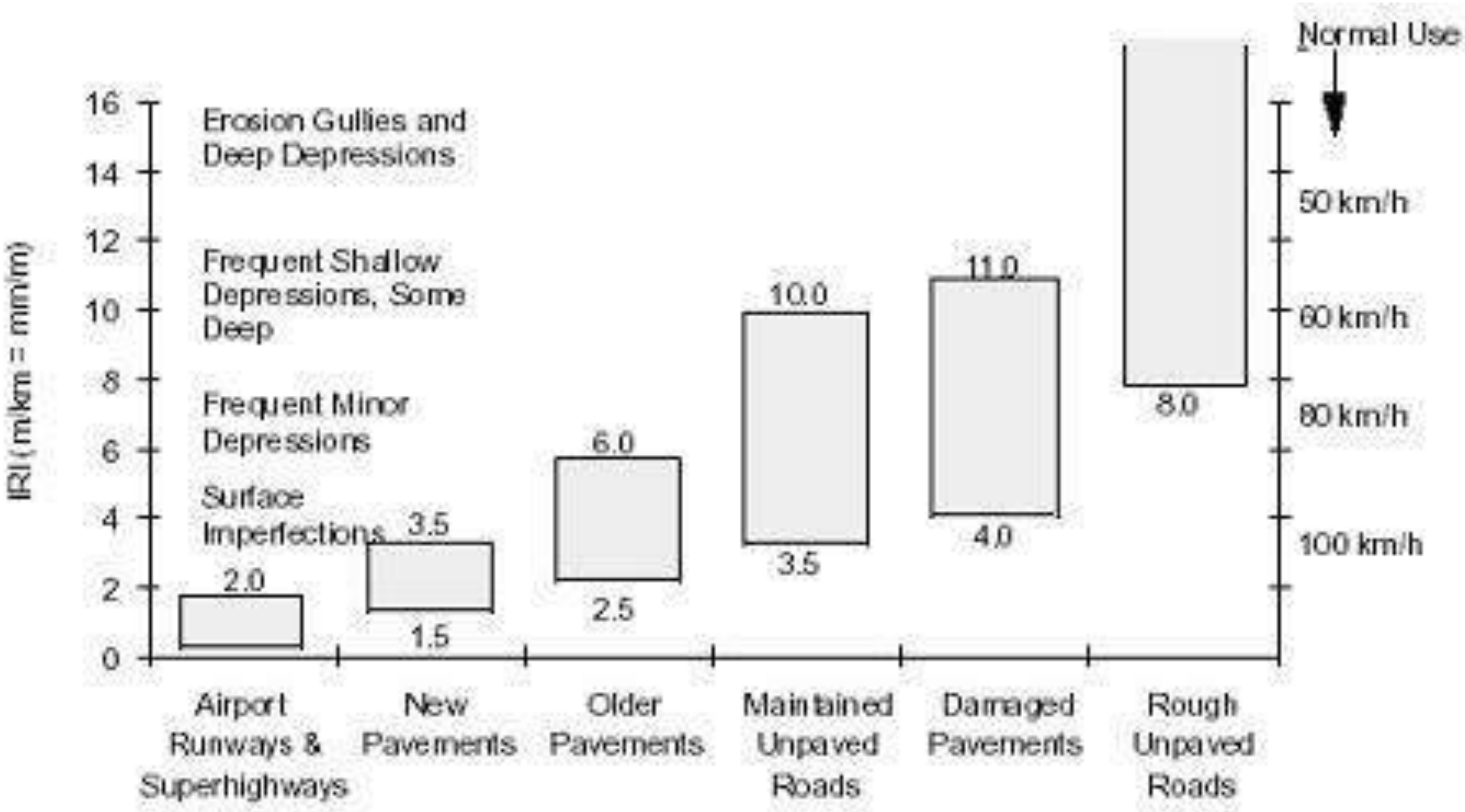
Source: American Association of State Highway and Transportation Officials (2008).

Modeled progress of IRI from Pavement-ME outputs for two scenarios



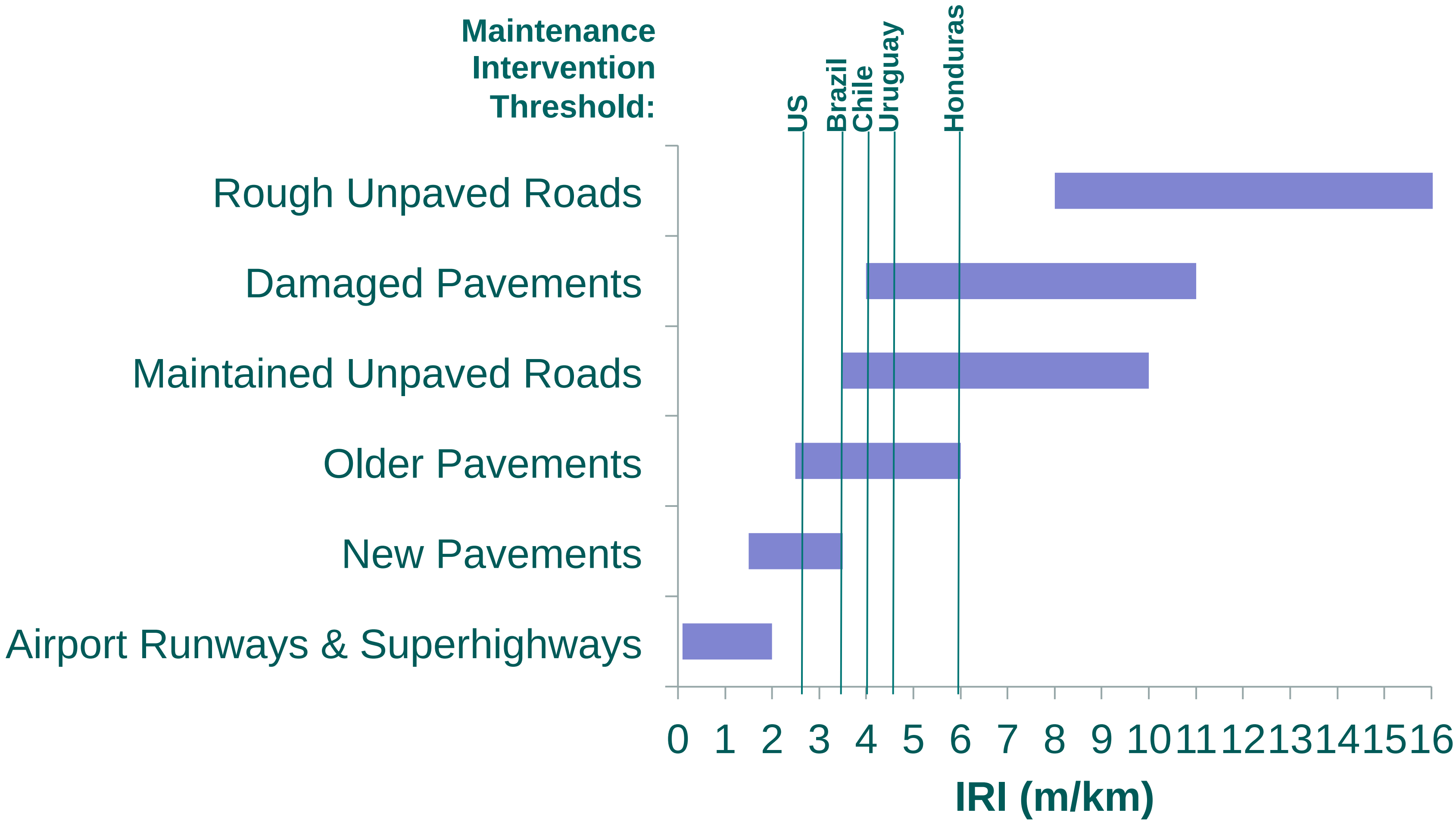
- IRI is modeled to evolve differently in the two climates
- Rate of deterioration is sensitive to climate and design

Typical IRI for different pavement types



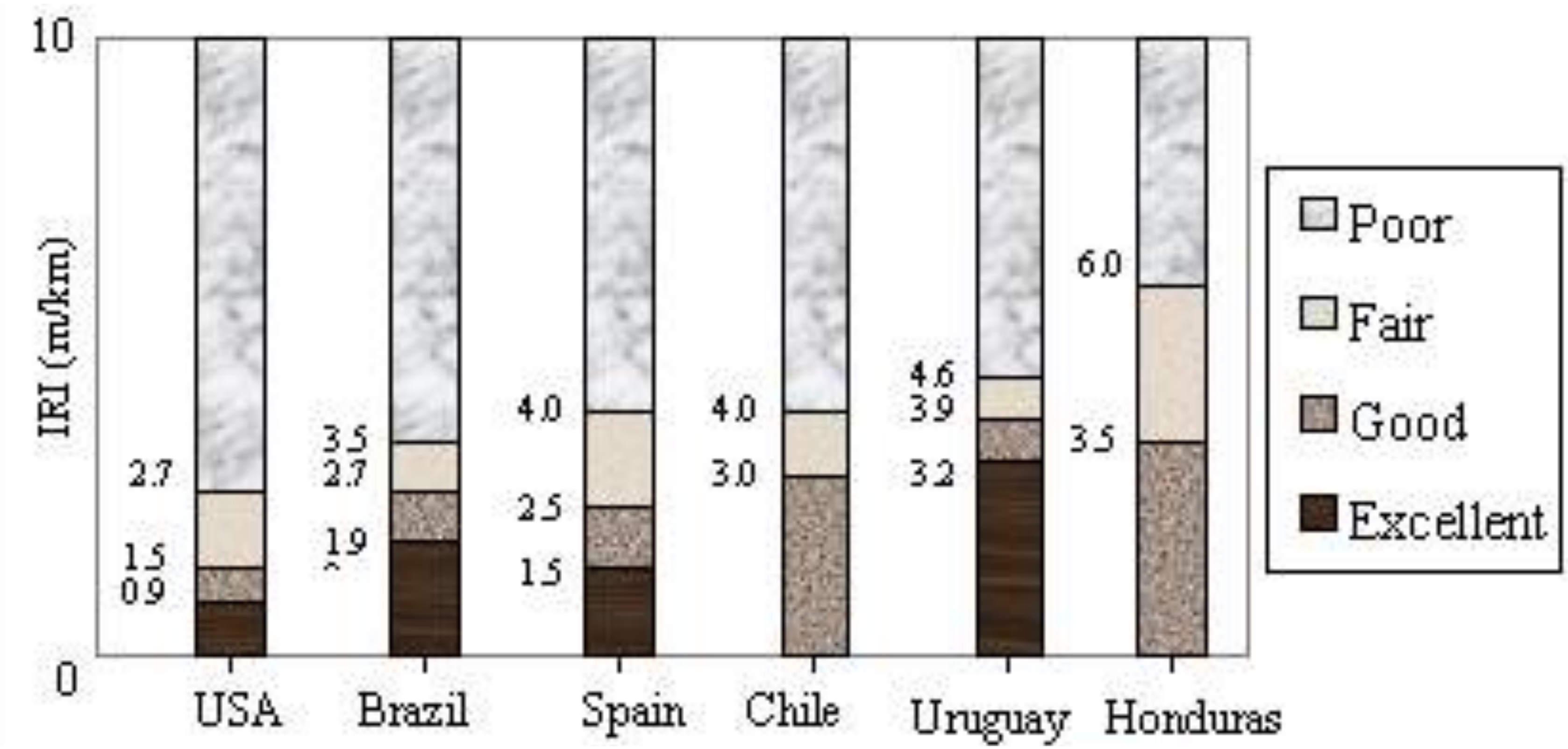
Pavement Interactive replotting of Sayers et al. (1986). World Bank Technical paper 46

Typical IRI for different pavement types



Pavement Interactive replotting of Sayers et al. (1986). World Bank Technical paper 46

IRI Maintenance Intervention Thresholds



*Source: De Souza et al. 2006, Improving Pavements With Long-Term Pavement Performance: Products for Today and Tomorrow.

Roughness measurement: Portable Profiler

INTERNATIONAL CYBERNETICS
Where technology meets the road

Model inputs for excess fuel from roughness

- Pavement and context:
  - IRI: Reference and Current
  - Grade and superelevation of pavement
  - Temperature
- Vehicles:
  - Traffic volume
  - Distribution of vehicle types
  - Vehicle fuel efficiency

Key drivers of rolling resistance & PVI

- **Pavement Texture**:
  - Relevant to vehicle control and safety
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- **Roughness**:
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- **Deflection:**
  - Related to pavement design: stiffness, thickness matter
  - Speed and temperature dependent

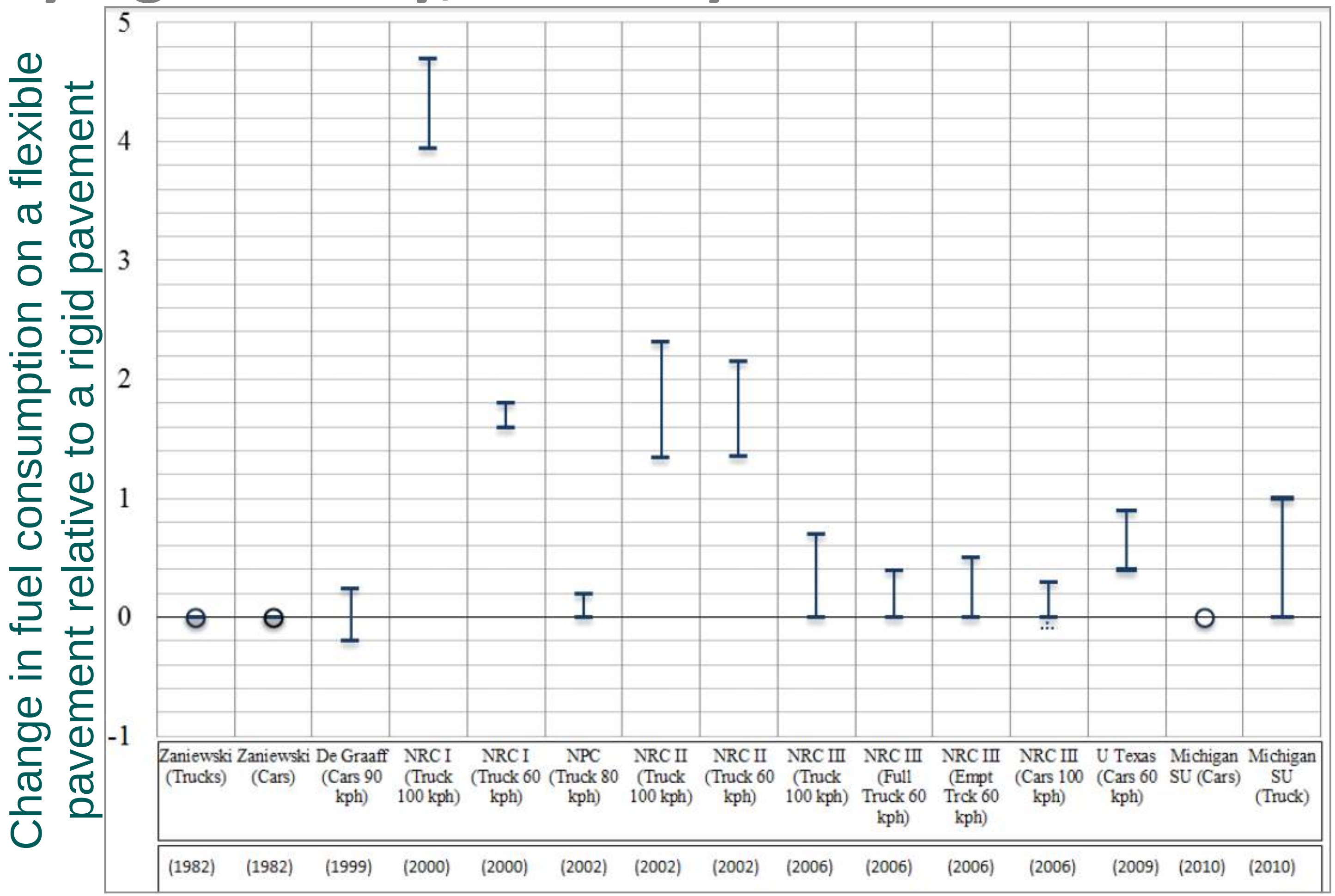
Deflection analogy:
Walking or running on pavement vs. sand

Walking on sand requires **2.1–2.7** times more energy expenditure than does walking on a hard surface;
Running on sand requires **1.6** times more energy expenditure than does running on a hard surface.*

*Source: Lejeune et al., Mechanics and energetics of human locomotion on sand, The Journal of Experimental Biology 201, 2071–2080 (1998)

More deflection =
more energy dissipation

Results of excess fuel consumption experiments vary significantly, few fully account for deflection



Source: Akbarian, SM thesis, Massachusetts Institute of Technology, 2012

Limitations of deflection-induced excess fuel consumption experiments

- High uncertainty in each experiment
- High variability across all experiments
- Binary material view: asphalt vs. concrete
- No structural consideration (top layer only)

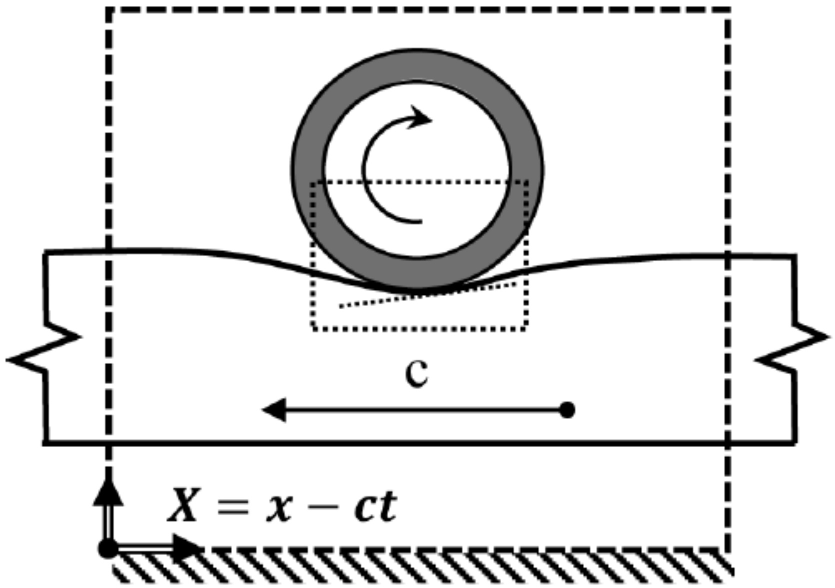
This makes it difficult for engineers and policy-makers to incorporate deflection-induced PVI into pavement designs

Need model to relate fuel consumption to deflection based on materials and structure

Deflection: pavement-specific energy dissipation and excess fuel consumption

MIT Mechanistic Model*

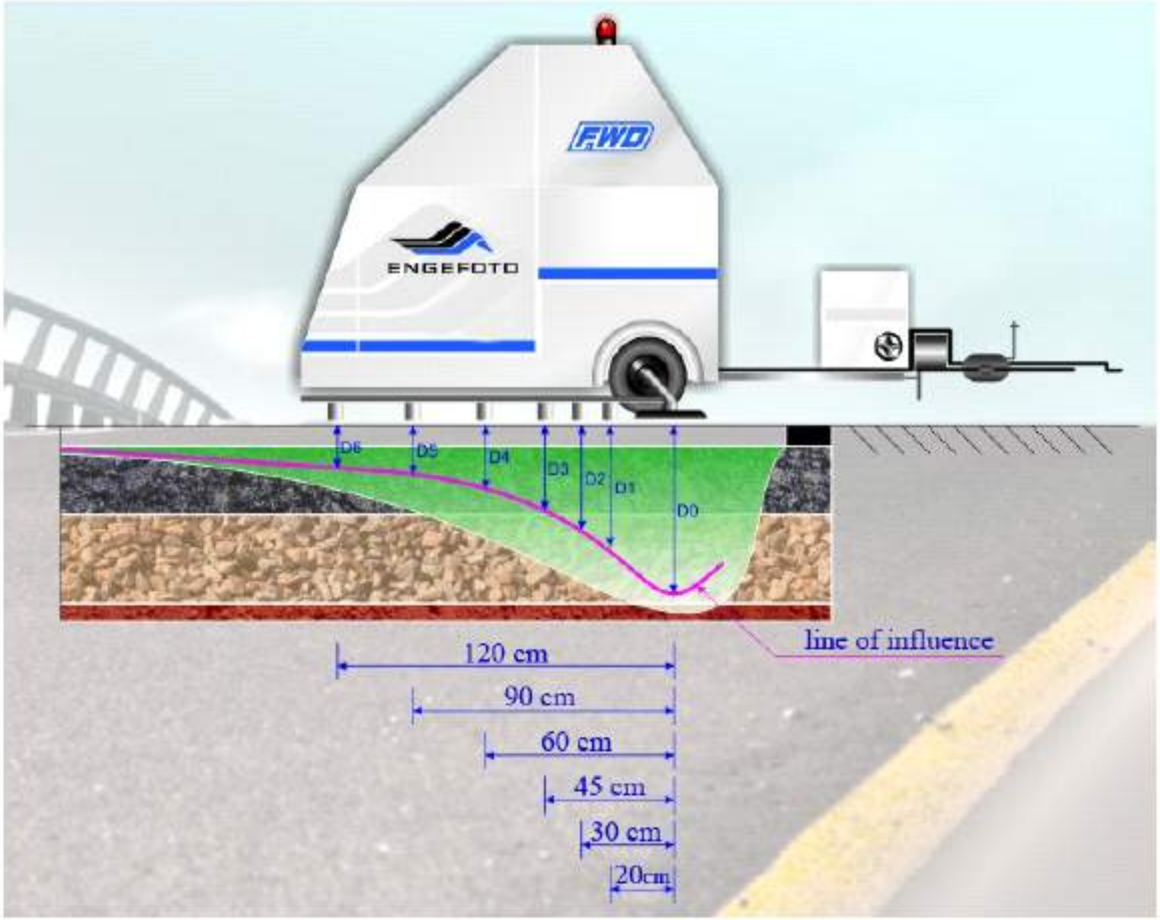
- Pavement Inputs:
  - Pavement stiffness
  - Pavement thickness
  - Substrate stiffness
- Approach:
  - Calibrate and validate with FHWA deflection data
  - Calculate excess fuel consumption from Gradient Force



Always driving slightly uphill

* Akbarian et al., Mechanistic Approach to Pavement-Vehicle Interaction and Its Impact in LCA - *Journal of the Transportation Research Board 2306*, 2013.

Deflection measurement:
Falling Weight Deflectometer device



Model inputs for excess fuel from PVI

	Input	Roughness	Deflection
Pavement & Context	IRI (International Roughness Index)	X	
	Pavement stiffness, thickness, and substrate thickness		X
	Temperature	X	X
Vehicle	Vehicle fuel efficiency	X	
	Vehicle weight and axles		X
	Traffic volume	X	X
	Traffic speed	X	X
	Distribution of vehicle types	X	X

More ↑ or Less ↓ excess fuel from PVI

	If this input is increased…	Roughness	Deflection
Pavement & Context	IRI (International Roughness Index)	↑	
	Pavement stiffness, thickness, and substrate thickness		↓
	Temperature	-	↑
Vehicle	Vehicle fuel efficiency	↓	
	Vehicle weight and axles		↑
	Traffic volume	↑	↑
	Traffic speed	↓*	↓
	Distribution of vehicle types		

Translate Excess Fuel into Cost and GWP Impact

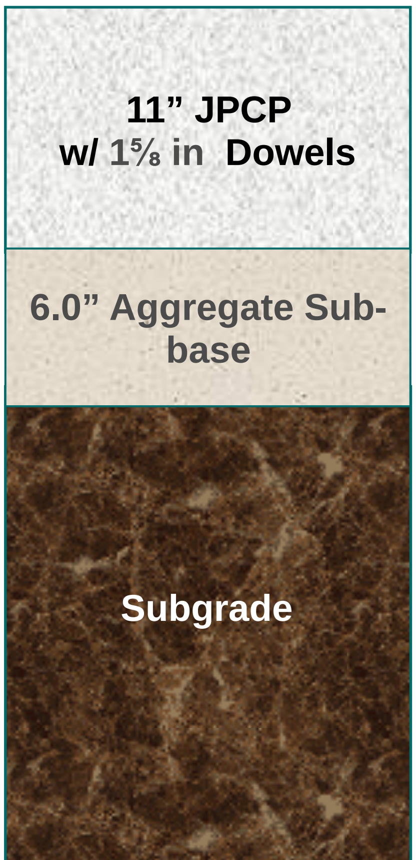
Quantify pavement and vehicle properties → Calculate excess fuel consumption → Estimate excess cost and environmental impact

Excess Fuel × Cost per Liter = Total Cost

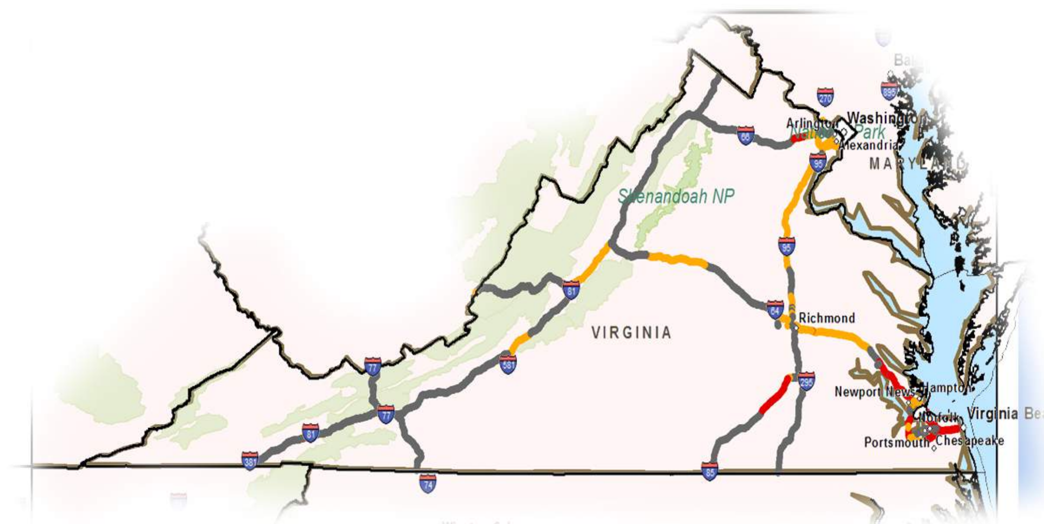
Excess Fuel × GWP Factor per Liter = Total GWP Impact

Model-based approach enables excess fuel consumption and GHG emission analyses

Individual pavements



Pavement networks



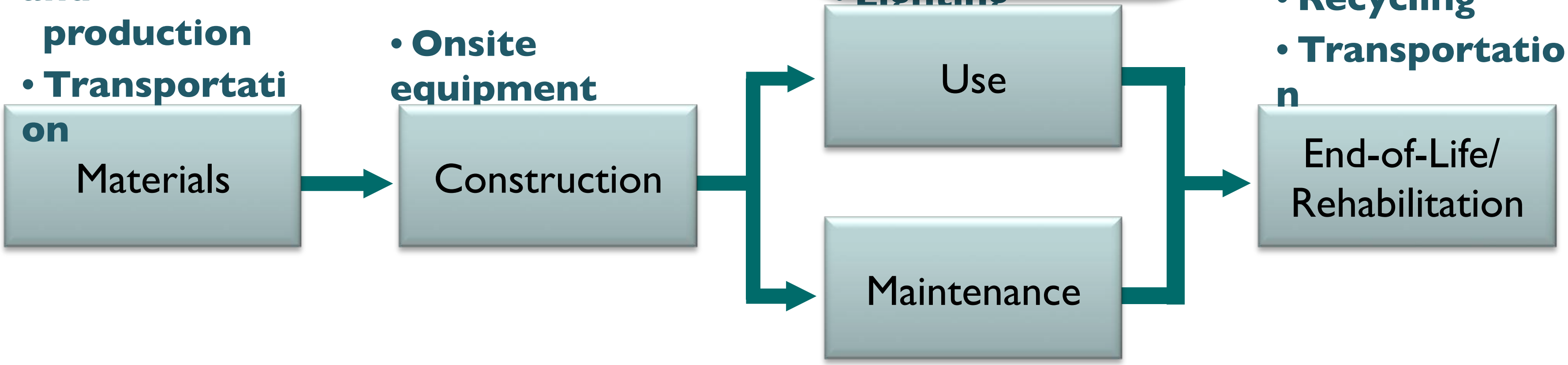
Individual pavement environmental impacts analyzed using life cycle assessment (LCA)

Scope includes all effects <u>attributable to the pavement design</u>.

- **Pavement-Vehicle Interaction**
  - **Roughness**
  - **Deflection**
- **Albedo**
- **Carbonation**
- **Lighting**

- **Extraction and production**
- **Transportation**

- **Onsite equipment**



- **Excavation**
- **Landfilling**
- **Recycling**
- **Transportation**

- **Materials**
- **Constructio**

Analyzed Global Warming Potential scenarios

Pavements

Flexible or Rigid

Analysis Period

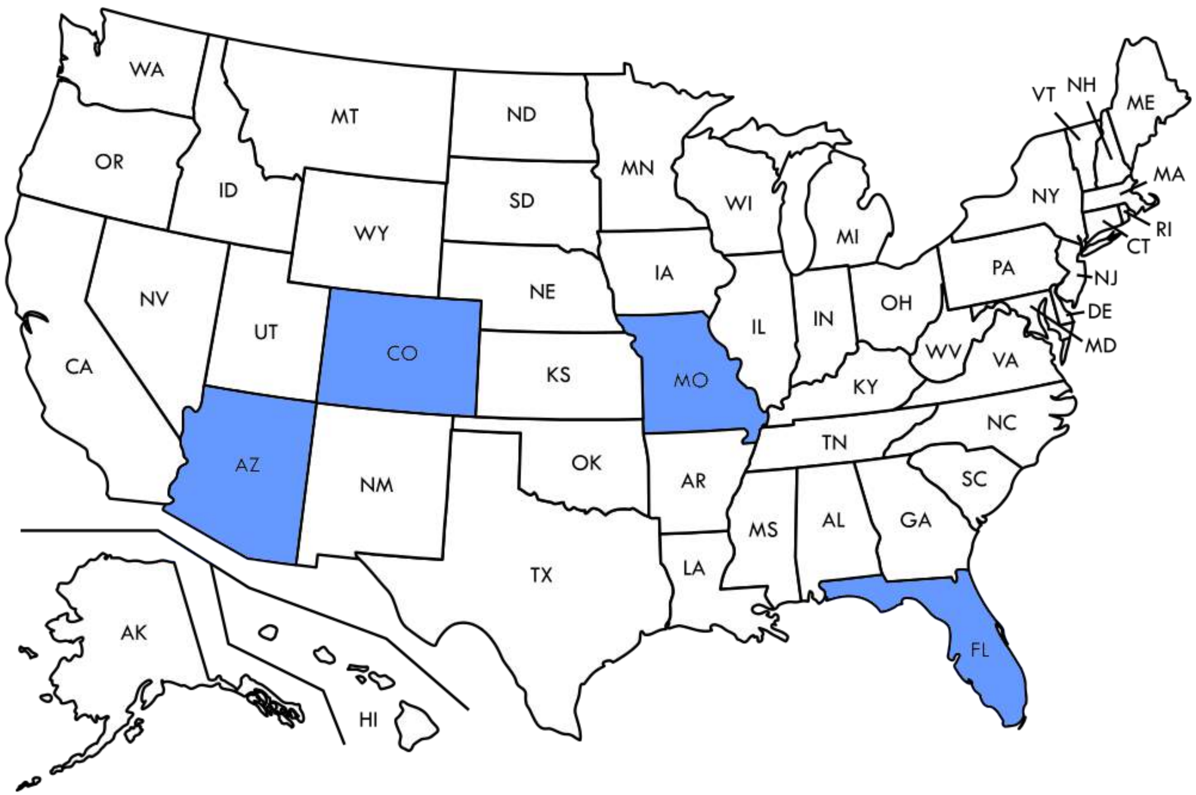
30 years

Traffic

300 – 8,000 AADTT

Maintenance Schedule

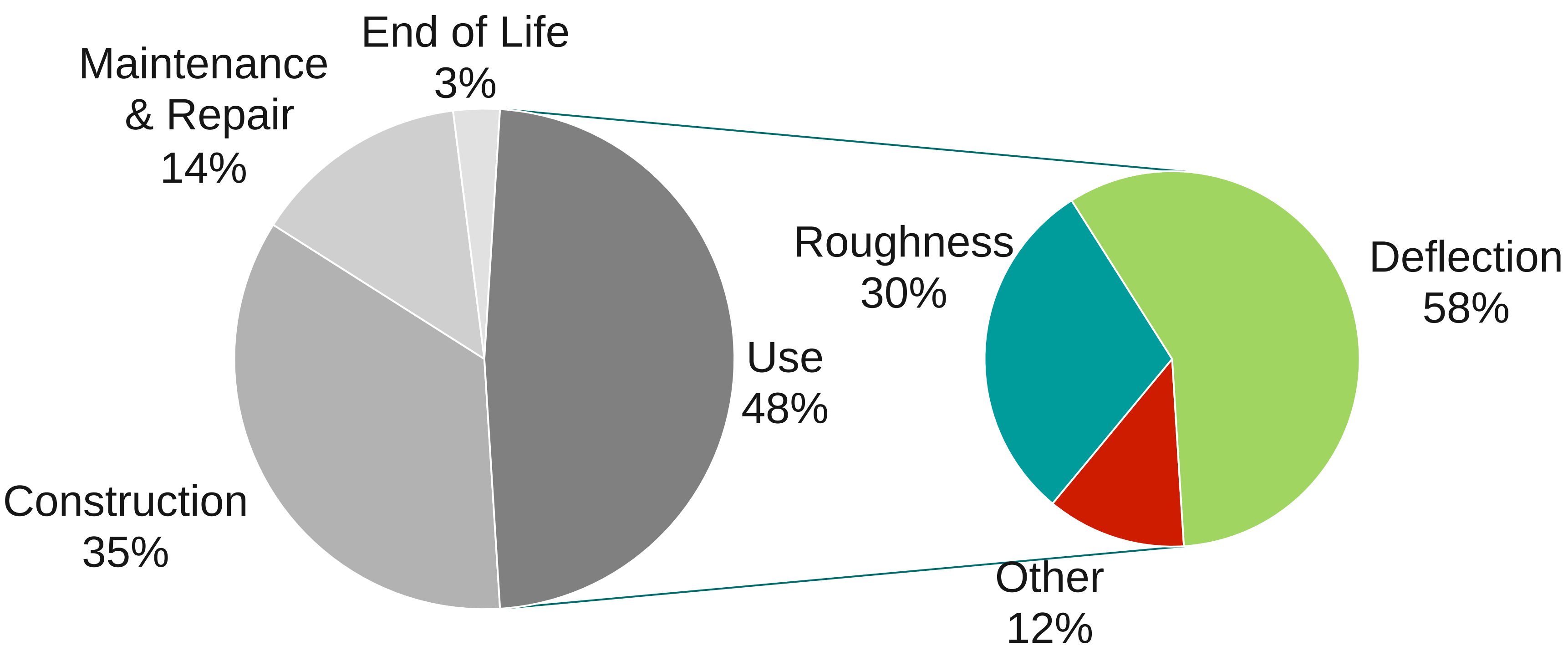
MEPDG



Use phase can be a significant fraction of pavement environmental impact

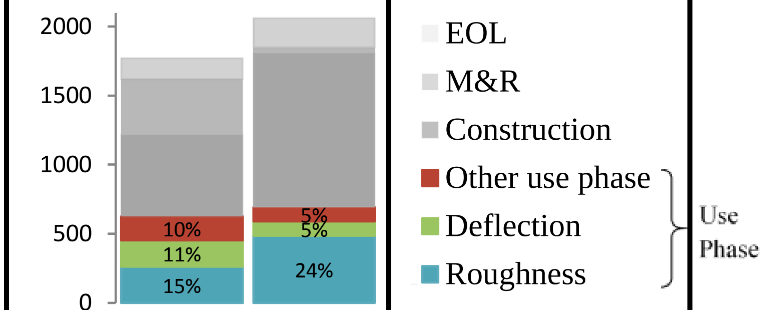
Example:

Life cycle greenhouse gas emissions of an urban interstate pavement in Missouri

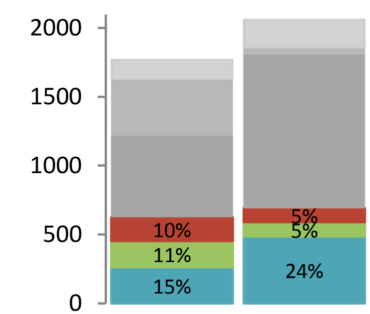
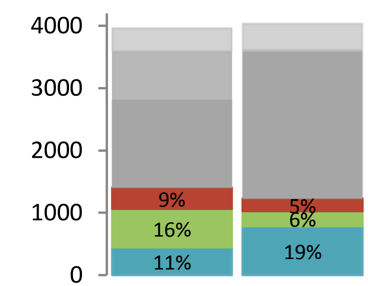
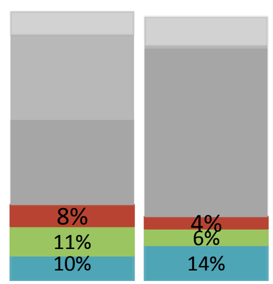
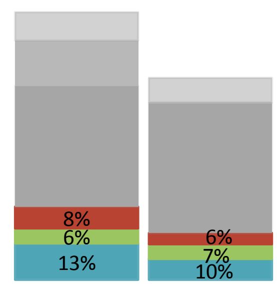
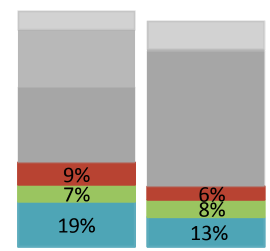


*Other: Lighting - Carbonation

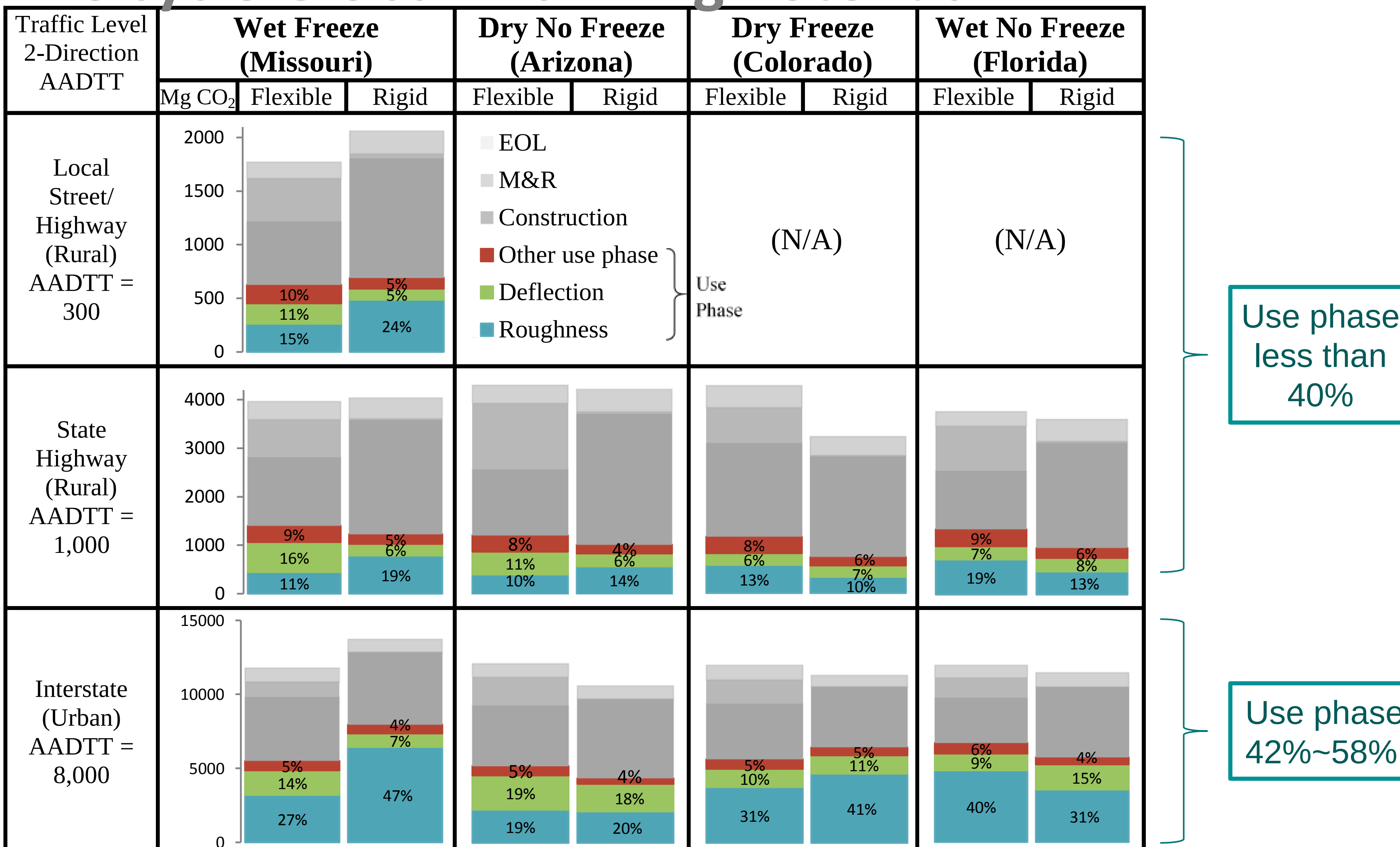
Life cycle Global Warming Potential

Traffic Level 2-Direction AADTT	Wet Freeze (Missouri)		Dry No Freeze (Arizona)		Dry Freeze (Colorado)		Wet No Freeze (Florida)	
	Flexible	Rigid	Flexible	Rigid	Flexible	Rigid	Flexible	Rigid
Local Street/ Highway (Rural) AADTT = 300					(N/A)		(N/A)	
State Highway (Rural) AADTT = 1,000								
Interstate (Urban) AADTT = 8,000								

Life cycle Global Warming Potential

Traffic Level 2-Direction AADTT	Wet Freeze (Missouri)		Dry No Freeze (Arizona)		Dry Freeze (Colorado)		Wet No Freeze (Florida)	
	Mg CO_2 Flexible	Rigid	Flexible	Rigid	Flexible	Rigid	Flexible	Rigid
Local Street/ Highway (Rural) AADTT = 300			EOL M&R Construction Other use phase Deflection Roughness Use Phase		(N/A)		(N/A)	
State Highway (Rural) AADTT = 1,000								
Interstate (Urban) AADTT = 8,000								

Life cycle Global Warming Potential

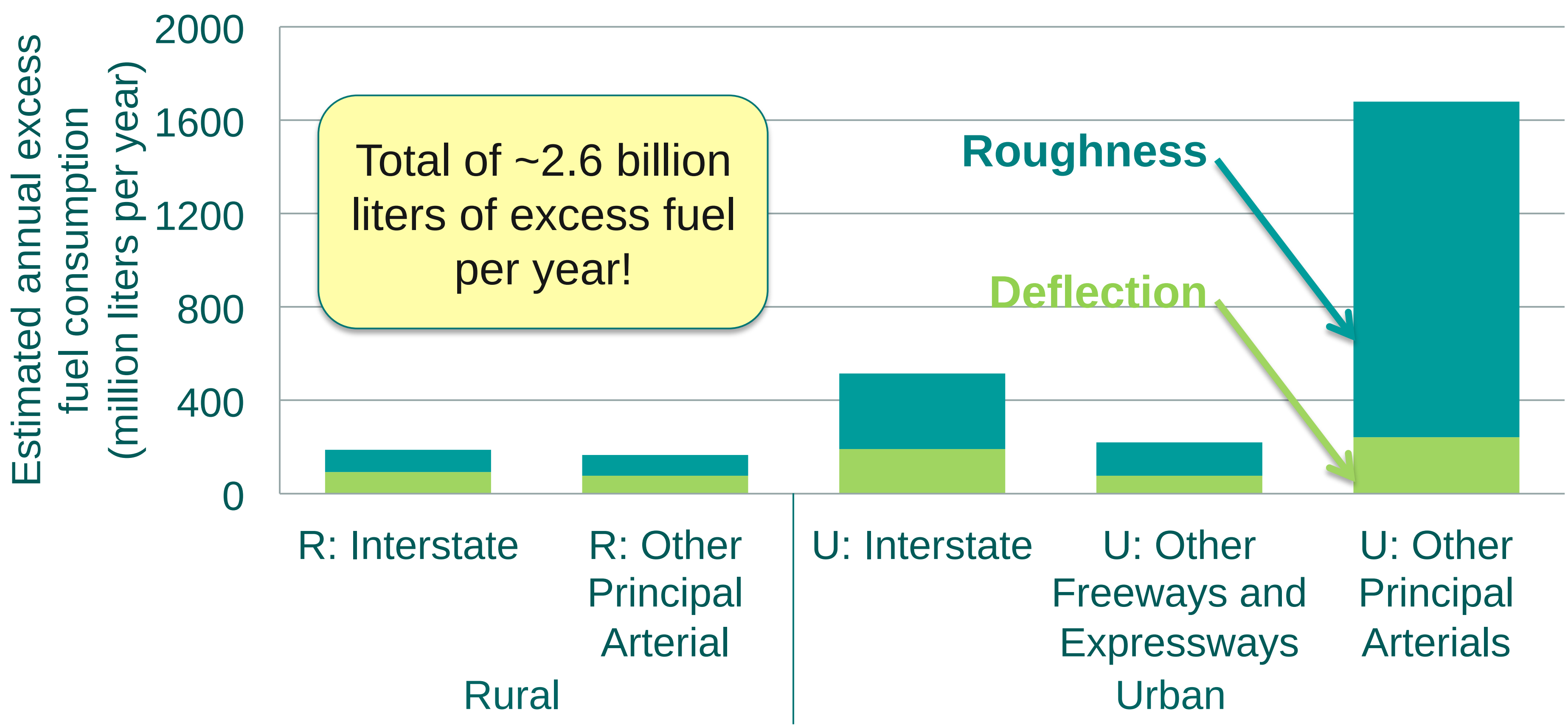


PVI network analyses

FHWA Long-term Pavement Performance Study Sections

Network analyses can help agencies support pavement management decisions and meet greenhouse gas reductions targets

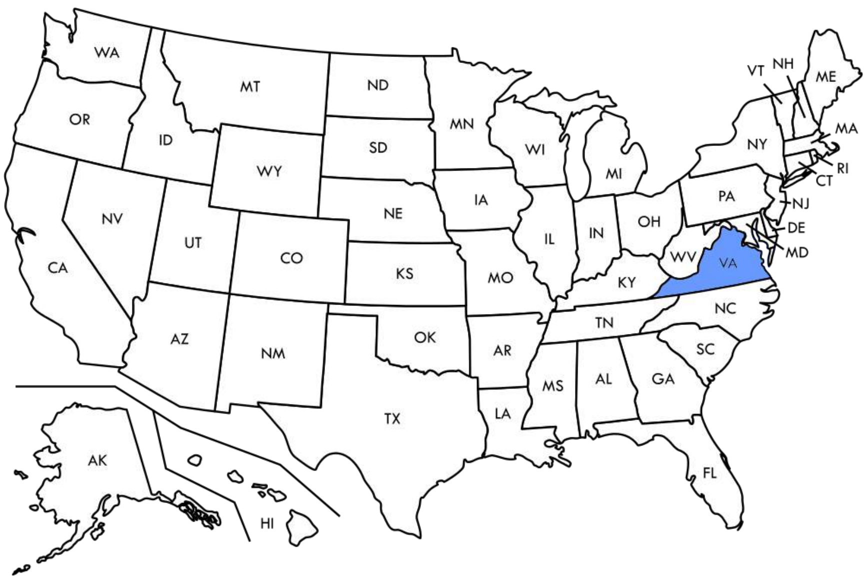
Excess fuel consumption from PVI for US road network is significant



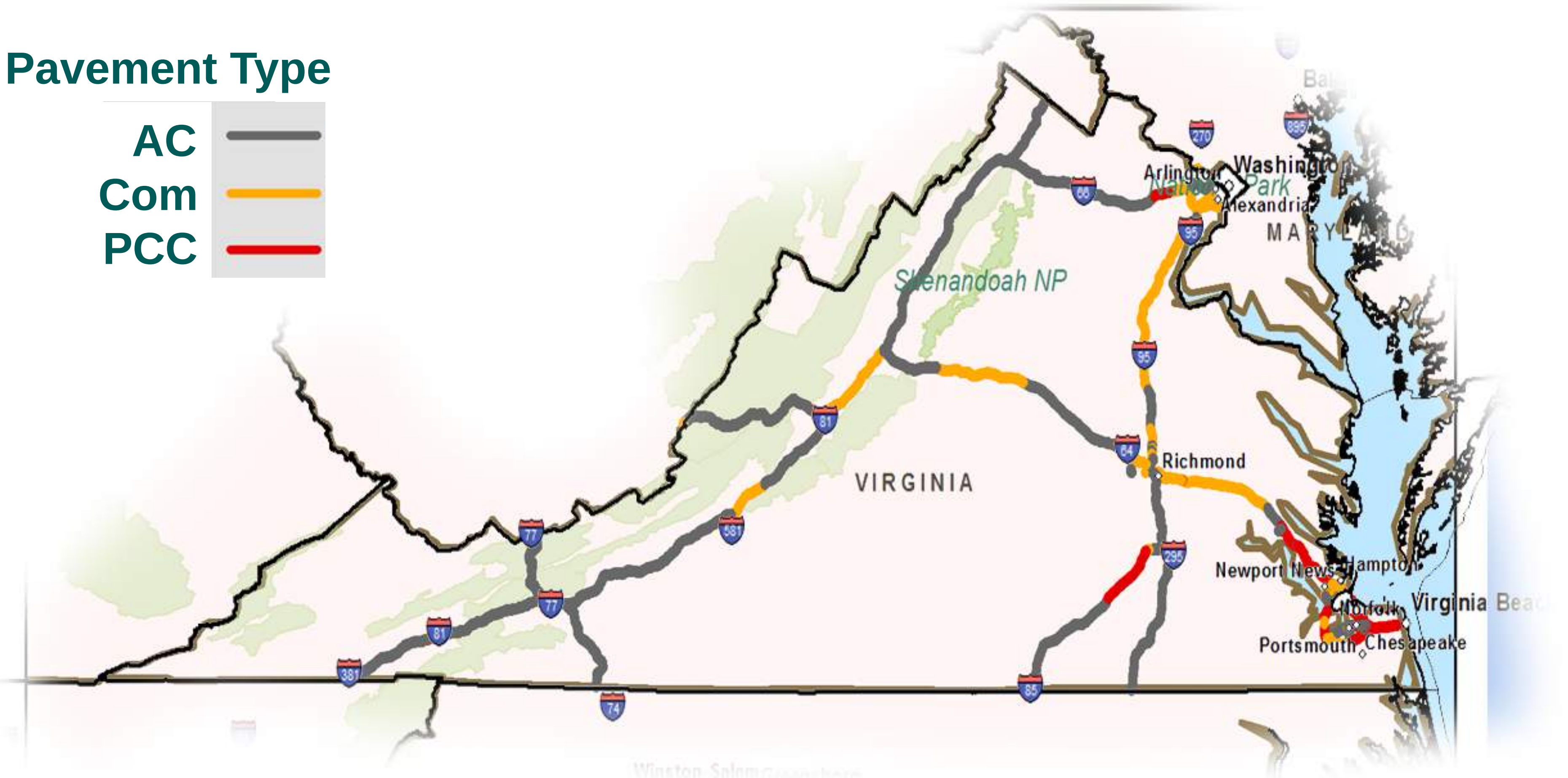
PVI in Interstates: the case of Virginia

Data provided:

- 15 interstates, 2 direction
- Years: 2007-2013
- Section ID and milepost
- AADT, AADTT
- Layer thicknesses
- Material properties (2007)
- IRI over time



Type of Pavements in Virginia Interstates



Excess Fuel Consumption: PVI Roughness

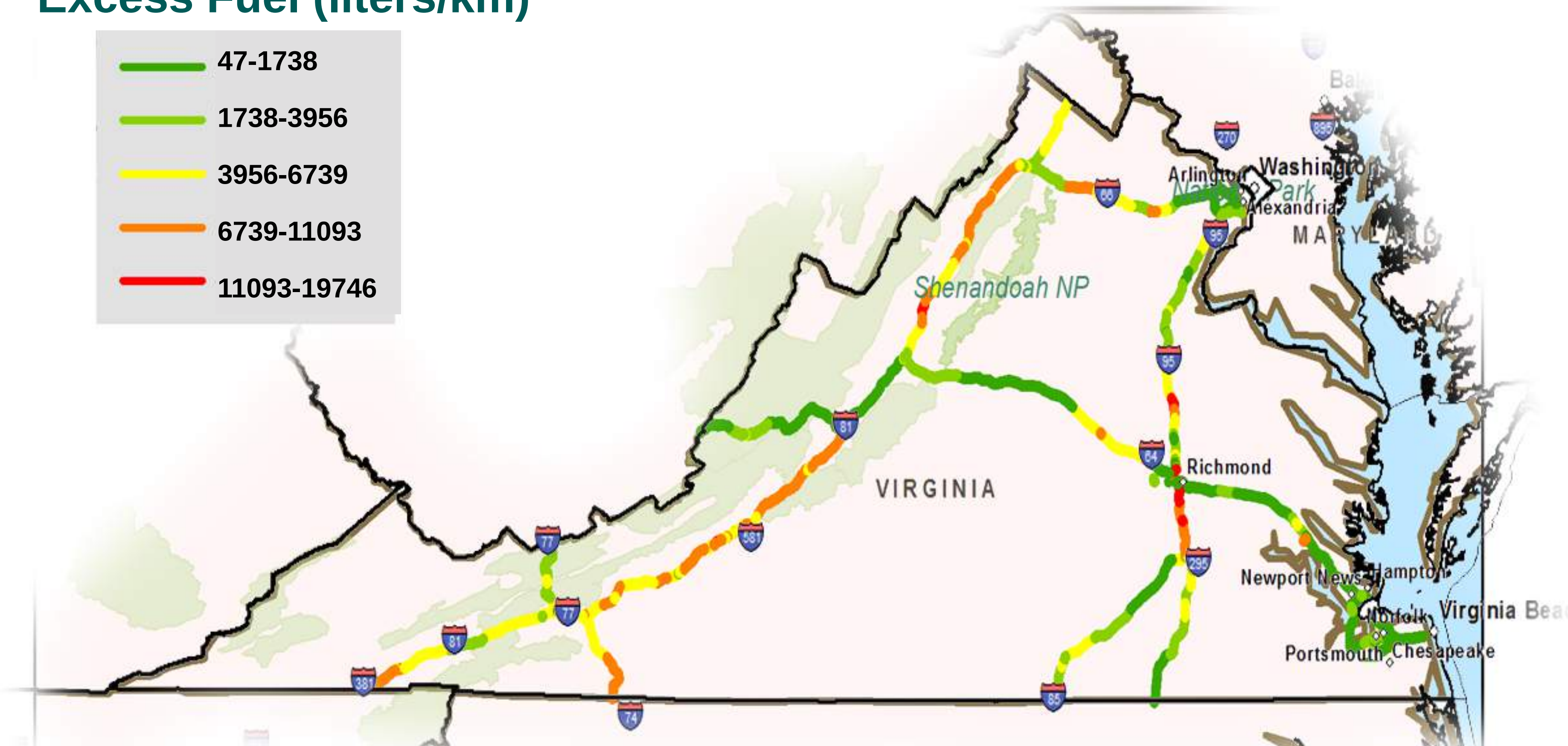
Excess Fuel (liters/km)

2013 data

c= 100 km/h=62.6 mph; T= 16 C/61 F

Excess Fuel Consumption: PVI Deflection

Excess Fuel (liters/km)

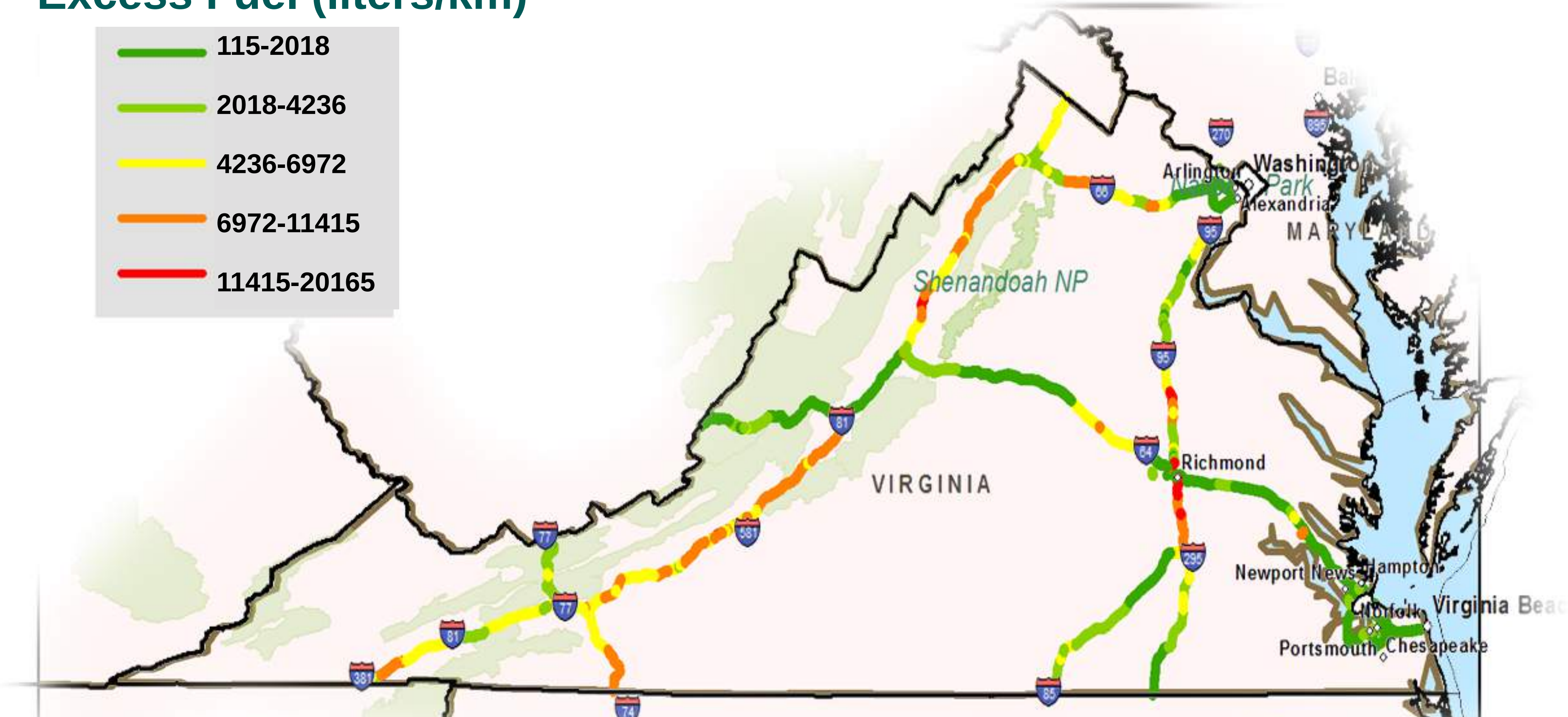


2013 data

c= 100 km/h=62.6 mph; T= 16 C/61 F

Excess Fuel Consumption: PVI Total

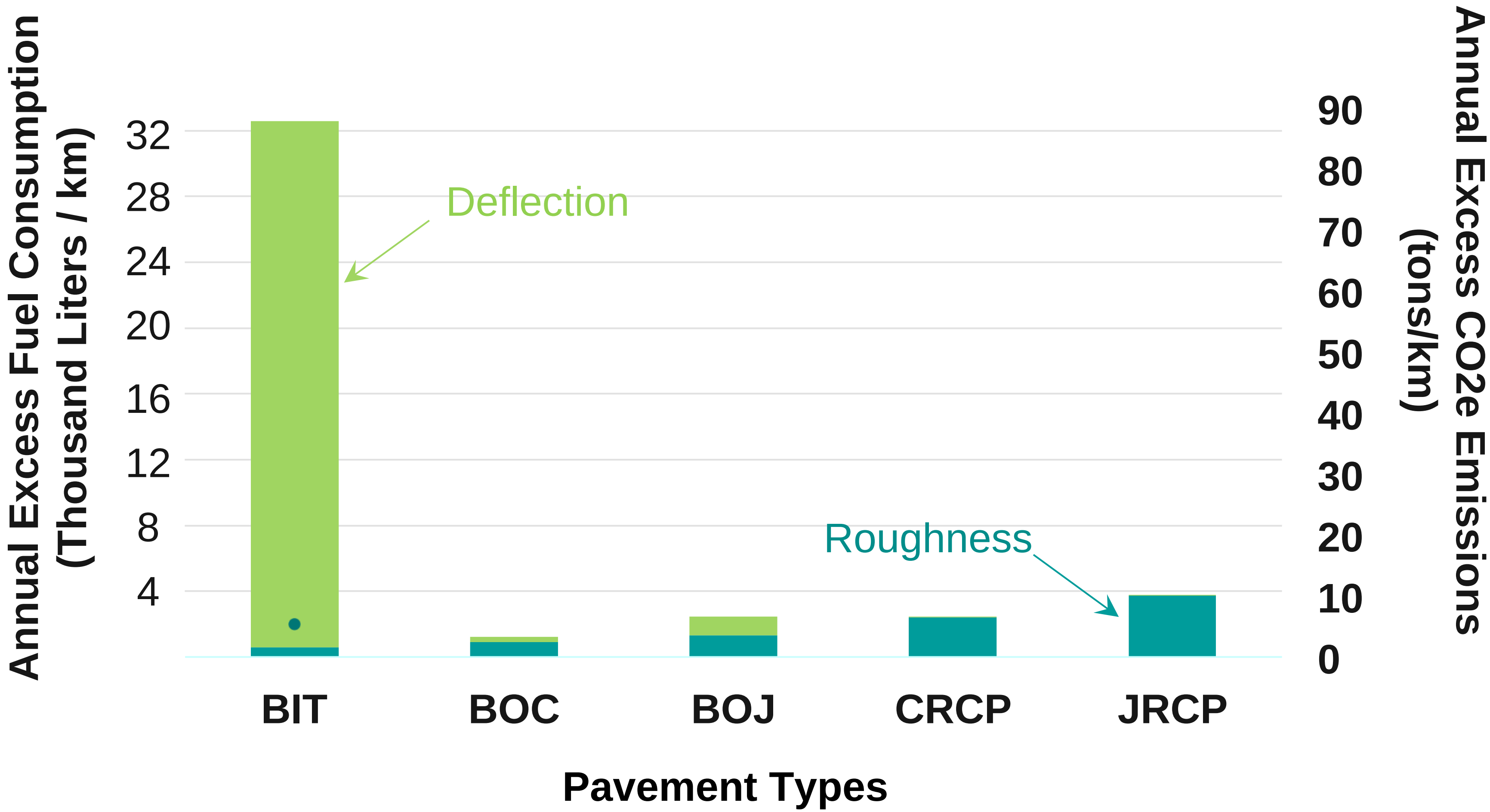
Excess Fuel (liters/km)



2013 data

c= 100 km/h=62.6 mph; T= 16 C/61 F

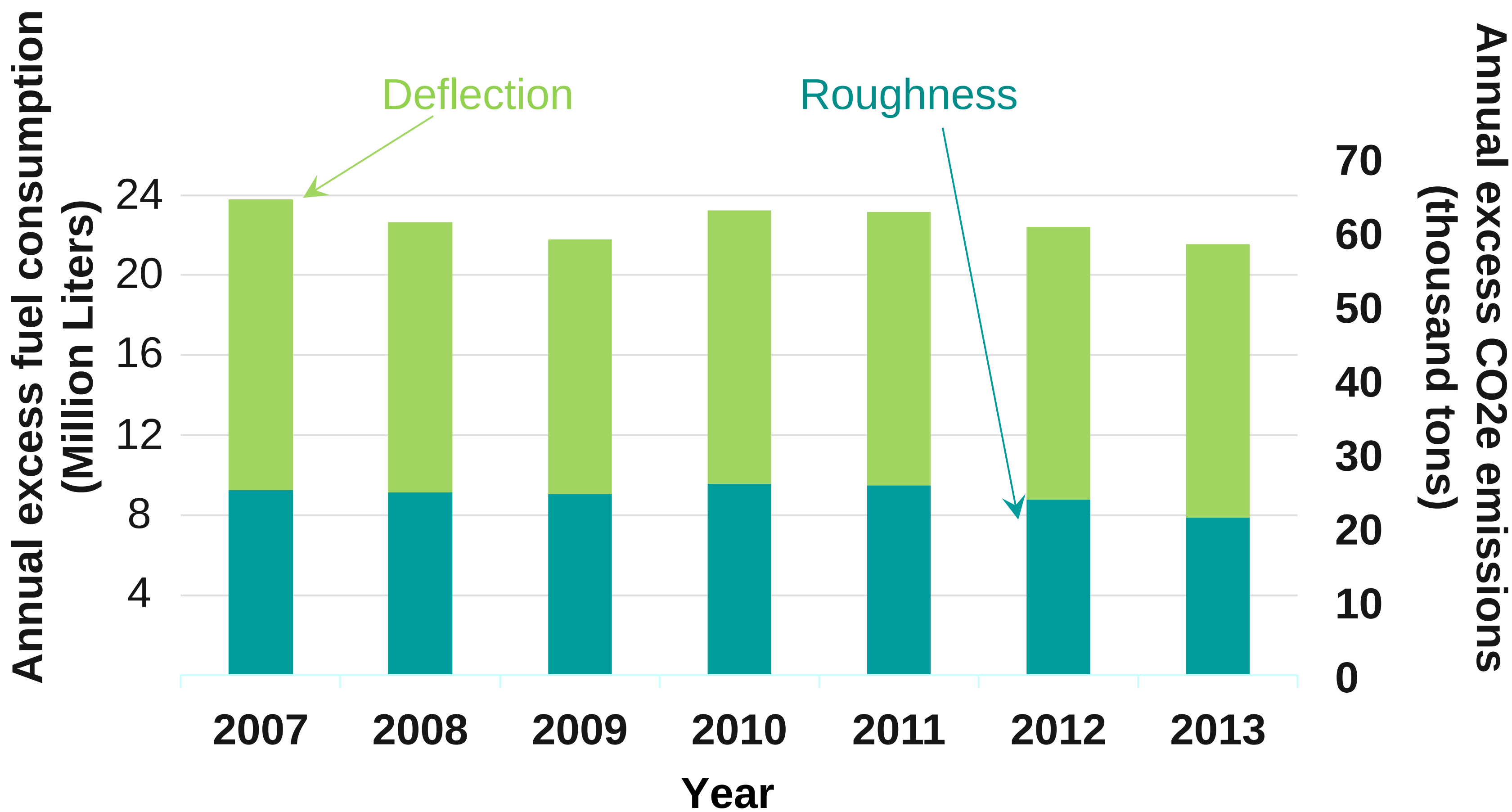
Excess Fuel Consumption: 2013 by Pavement



2013 data

c= 100 km/h=62.6 mph; T= 16 C/61 F

Excess Fuel Consumption: 2007-2013 Totals



c= 100 km/h=62.6 mph; T= 16 C/61 F

The future of PVI-fuel consumption research

- Assessment of PVI mechanistic models
  - UC Pavement Research Center-led effort with collaboration of multiple institutions
- Improved excess fuel consumption experiments
- Continued partnerships with DOTs

Resource for in-depth model details

Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements

April 2012

Mehdi Akbarian
Franz-Josef Ulm

Conclusion: PVI can be an important element of transportation carbon management

- Infrastructure funding remains significantly below what is required to improve conditions and performance
  - "Inter-American Development Bank is recognizing the lack of funding for project financing and preparation as a major bottleneck for the **much-needed scaling up of infrastructure investment in Latin America and the Caribbean (LAC).**"
  - *Incentivize innovation in infrastructure design*
- Model-based approaches enable designers and policy-makers to incorporate PVI into decisions
  - Pavement design and management
  - Individual and network level

For more information:

Reed Miller
trmiller@mit.edu

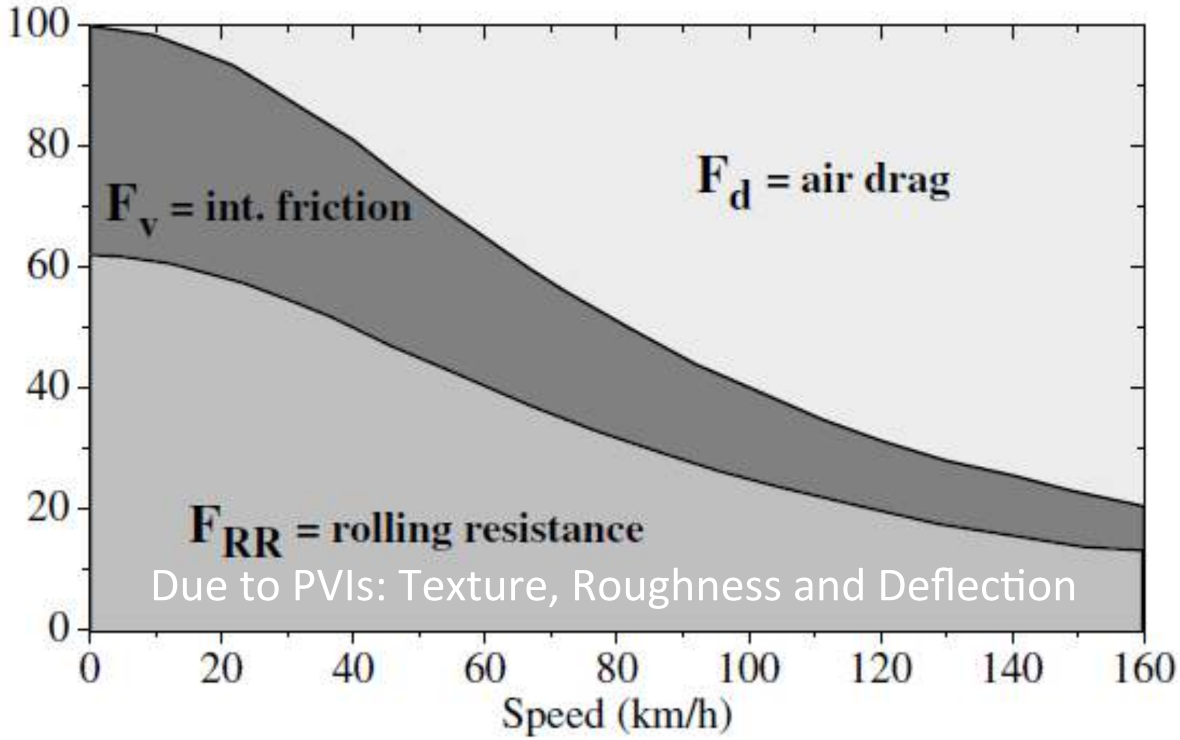
http://cshub.mit.edu/

Additional research collaborators:
Arash Noshadravan, Xin Xu, Omar Swei,
Jeremy Gregory, Randolph Kirchain

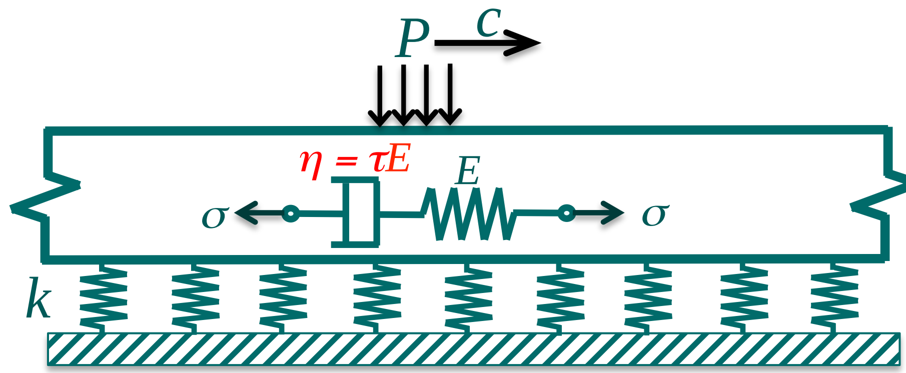
Back-up slides

Context: Rolling Resistance

- Force Distribution in a passenger car vs. speed as a percentage of available power output (Beuving et al., 2004; cited in Pouget et al. 2012)



MIT Model Gen II: Viscoelastic Top Layer



Relaxation Time

$$\tau = \tau_0 (T_0) \times a_T (T)$$

– Bituminous Materials*

$$a_T = \exp\left(-C_1 (T - T_{ref}) / C_2 + (T - T_{ref})\right)$$

– Cementitious Materials**:

$$a_T = \exp\left(U_c \left[1/T - 1/T_{ref}\right]\right)$$

Winkler Length $\ell_s = \sqrt[4]{EI/k}$; $c_{cr} = \ell_s (k/m)^{1/2}$

$$\delta E = -P \frac{dw}{dX} = \frac{c_{cr}}{c} \times \frac{\mathbf{P^2}}{bkl_s^2} \mathcal{F} \left(\Pi_1 = \frac{c}{c_{cr}}; \zeta = \frac{\tau c_{cr}}{l_s} \right)$$

Temperature dependence

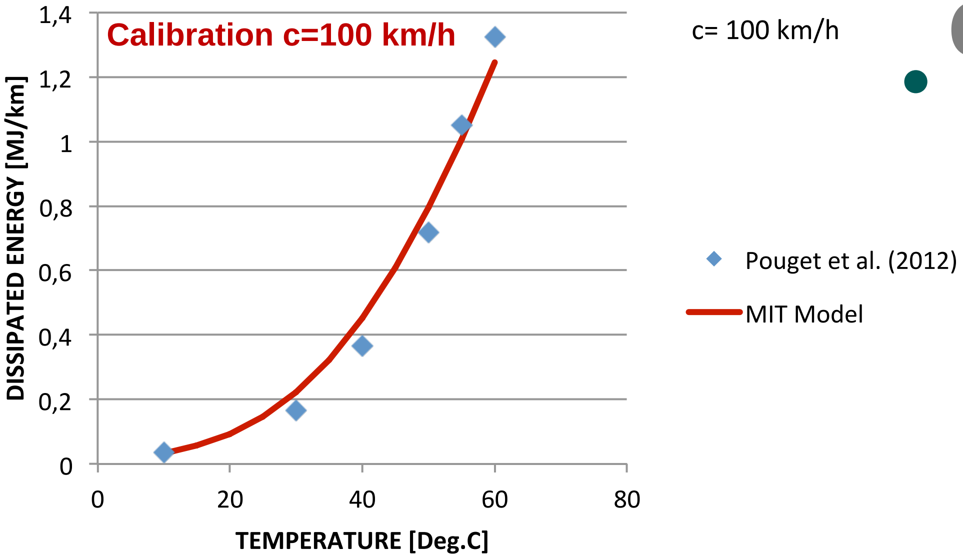
Speed Dependence

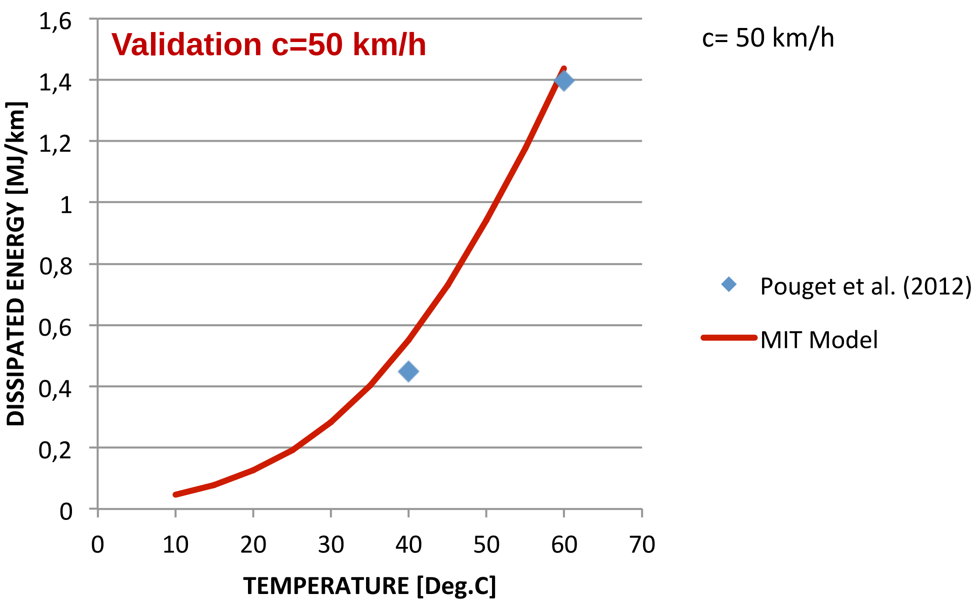
* Pouget et al. (2012); William, Landel, Ferry (1980)
** Bazant (1995)

Consideration of Top-Layer Viscoelastic behavior, including temperature shift factor:

Calibration/Validation

- Model-Based Simulations





$$\delta E = \frac{c_{cr}}{c} \times \frac{P^2}{b k \ell_s^2} F(c/c_{cr}; \zeta = \tau$$

$$\tau(T) = \tau_0(T_0) \times a_T(T)$$

c = Vehicle speed
$P = 32.4$ ton truck (distribution of loads according to HS 20-44)
$b = 3.6$ m (lane width)
E, k, h = 40,264 MPa, 35 MPa/m, 0.22 m
$\tau(T_0 = 283\ \mathrm{K}) = 0.015$ s

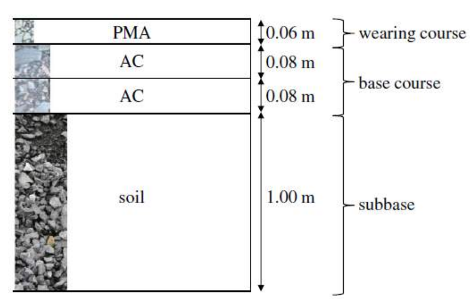
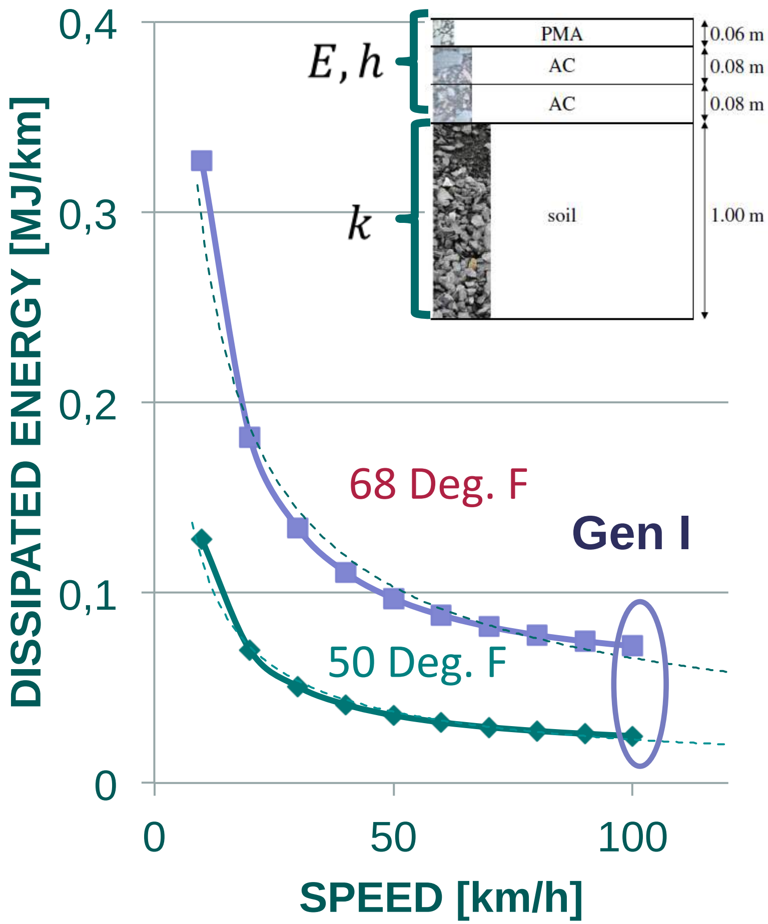


Fig. 3. Pavement structure considered for the calculations

New Feature: Temperature and Speed Dependence



(Example taken from Pouget et al. (2012)

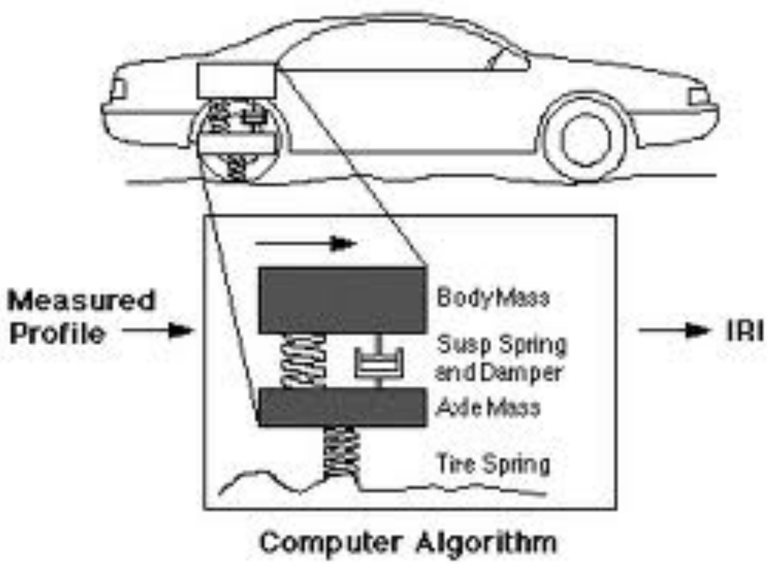
- Model-Based Simulations

$$\delta E = \frac{c_{cr}}{c} \times \frac{P^2}{bk\ell_s^2} \times F\left(\frac{c}{c_{cr}}; \zeta = \frac{\tau(T) c_{cr}}{\ell_s}\right)$$

- Engineering Input:
  - P = weight of vehicle
  - c = vehicle speed
  - $\ell_s = \left(\frac{E}{k} \times \frac{h^3}{12}\right)^{1/4}$
  - $\tau(T)$ = relaxation time.

SUMMARY: PVI-MODELS

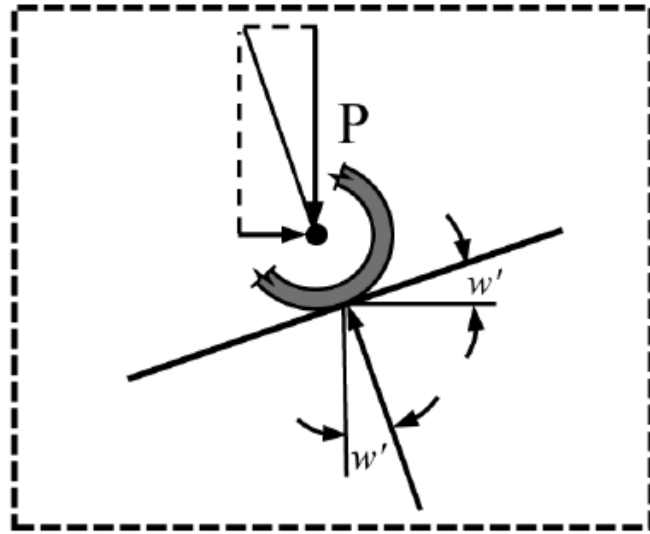
ROUGHNESS/ IRI



- Vehicle Specific.

$$\delta E = \%E_{0} \langle IRI - IRI_{0} \rangle$$

DEFLECTION

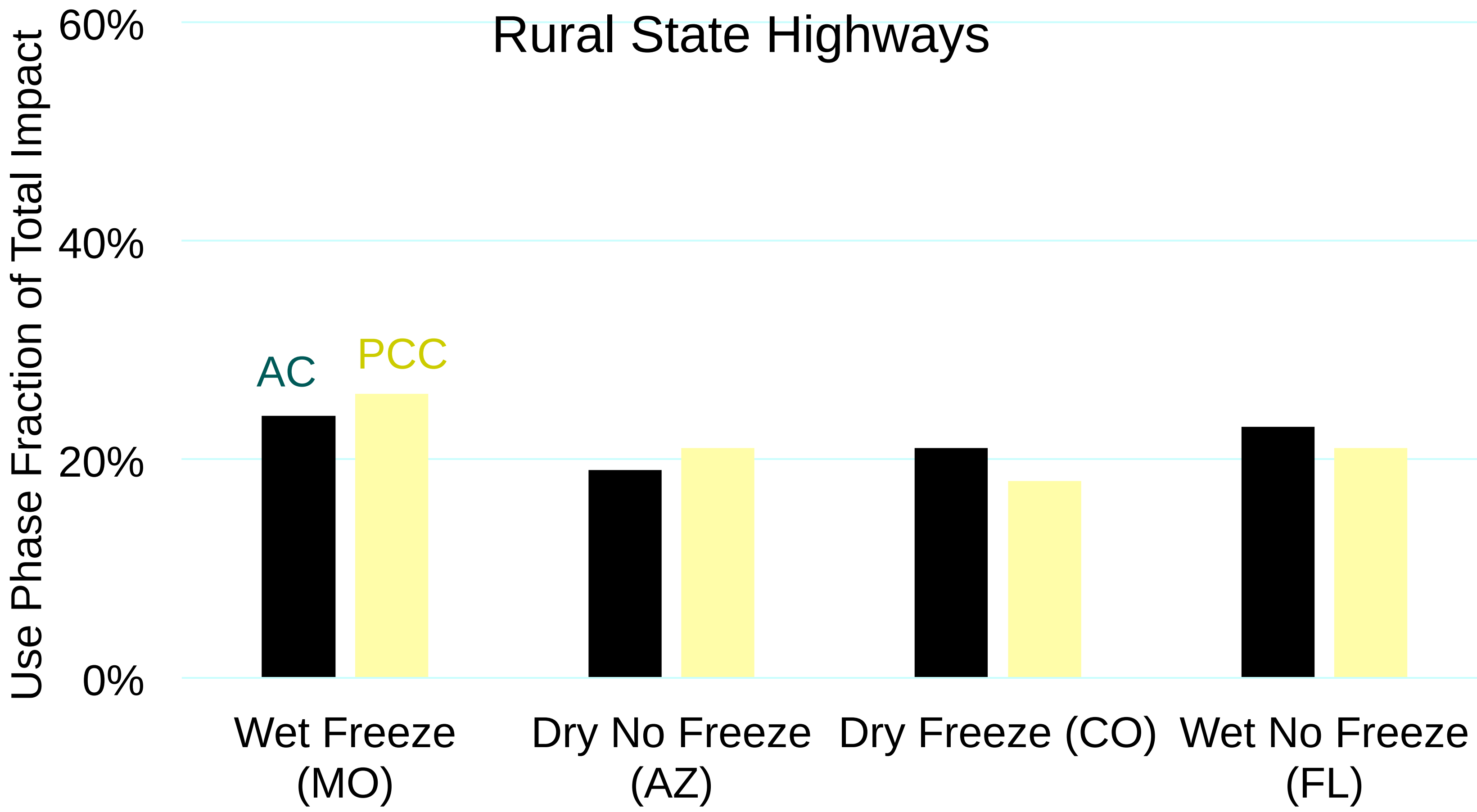


- Pavement Specific.

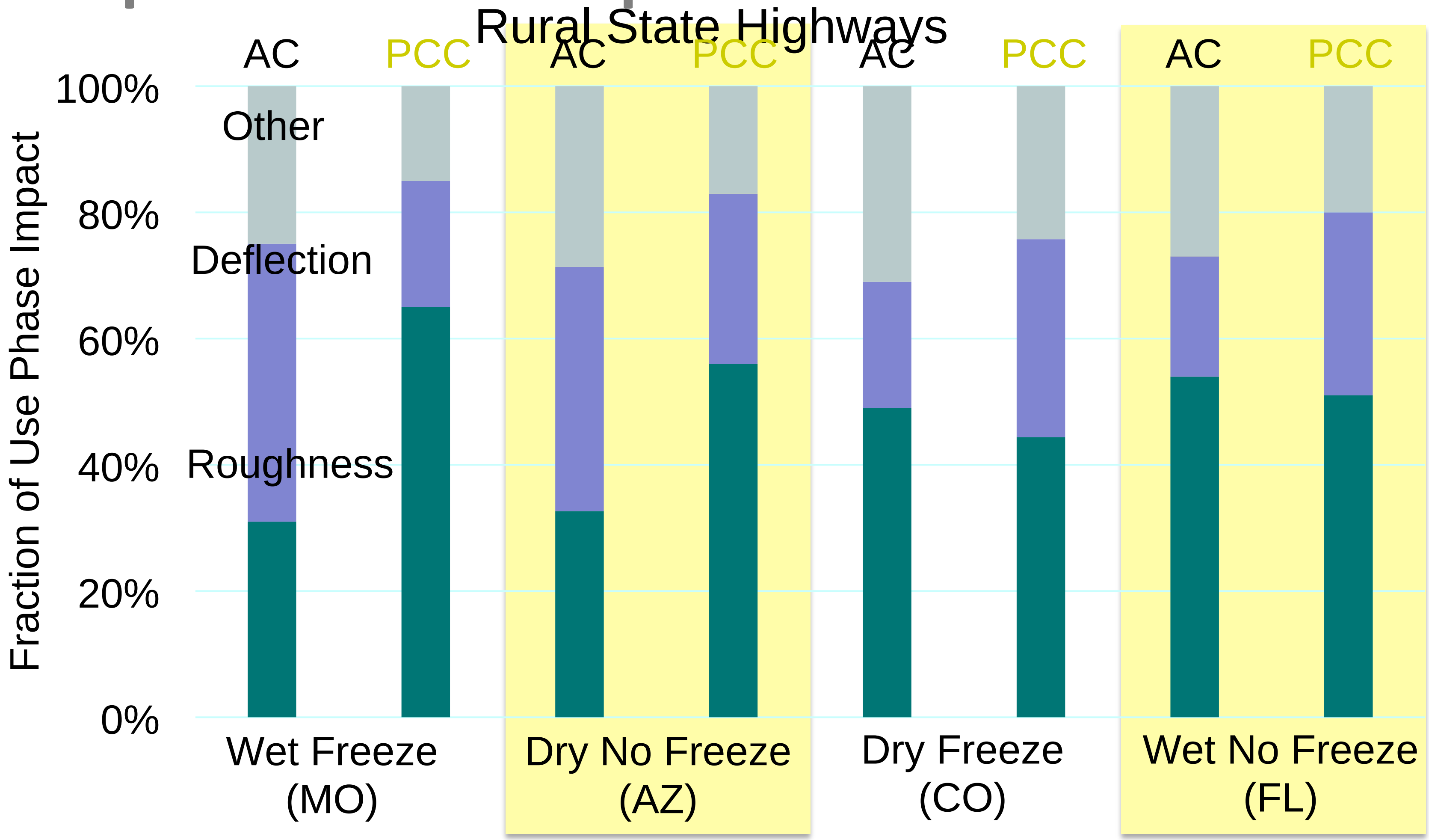
$$\delta E = c_{cr}/c \times P^{2}/bk\ell_{s}^{2} \times F(c/c_{cr};\zeta=\tau$$

Both lead to excess Fuel Consumption – But How much?

Use phase contribution depends on context



Use phase drivers depend on context



Use phase should be important consideration in reducing pavement life cycle impact

Materials Production

- Use recycled materials
- Lower energy use

Design & Construction

- Use less (i.e., stronger) material
- Create longer-lasting designs

Use

- Buildings: lower energy consumption
- Pavements: lower fuel consumption

End-of-Life

- Enable material recovery

This may require trade-offs with burdens of other life cycle phases