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Quantifying excess fuel consumption for pavement design and maintenance decisions

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Pavement LCA 2017

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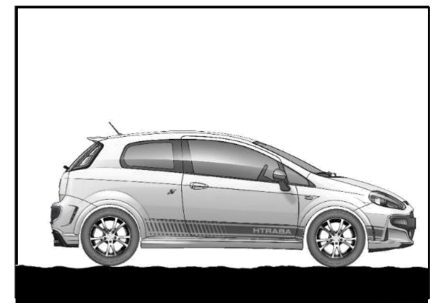
Key Drivers of Excess Fuel Consumption

Surface condition:

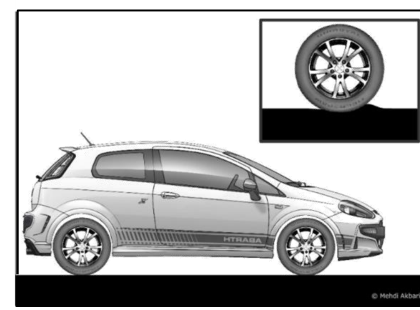
1. Texture-induced PVI*:
   - Mechanism: dissipation in tire
   - Parameters: vehicle type, pavement texture

2. Roughness-induced PVI*:
   - Mechanism: dissipation in suspension
   - Parameters: vehicle type, pavement roughness.



Structural properties:

3. Deflection/dissipation-induced PVI**:
   - Mechanism: dissipation in pavement
   - Parameters: vehicle type, speed, pavement viscoelasticity, stiffness, thickness, temperature



*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.

Pavement-induced fuel consumption research

Deflection Induced PVI

Roughness Induced PVI

Probabilistic PVI Implementation

Key research findings

We can quantify excess fuel consumption due to pavement-vehicle interaction

Probabilistic analysis provides useful estimates even with limited data

Surface and structure matter

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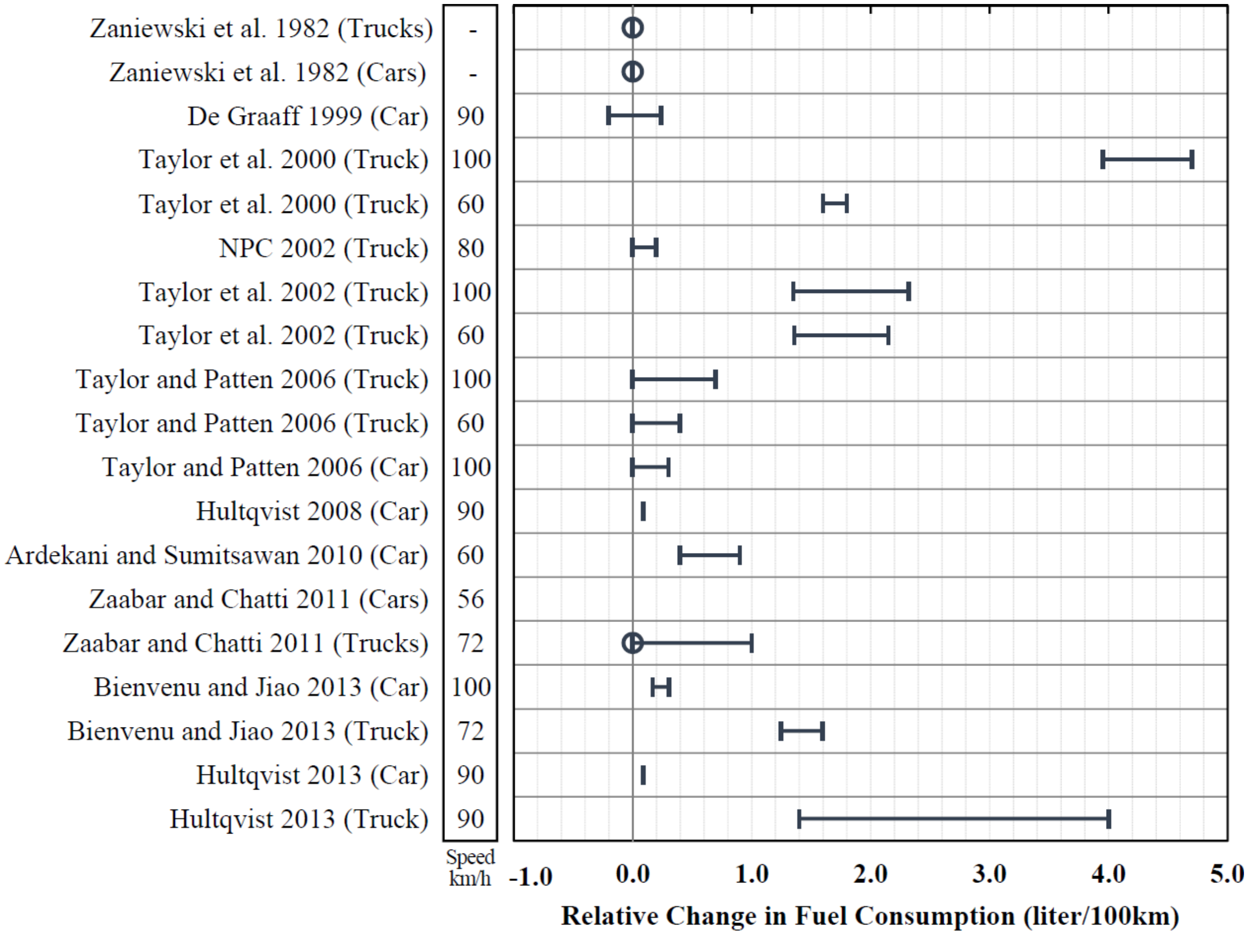
Deflection-induced PVI: empirical studies



Main findings:

- Asphalt is more dissipative than concrete
- Highly influenced by vehicle load, speed, temperature.

Shortcomings:

- High variability in impact
- Binary material view
- No structure and mat.

Deflection-Induced PVI Parameters:
Vehicle load & speed; pavement viscoelasticity, thickness, modulus, temperature

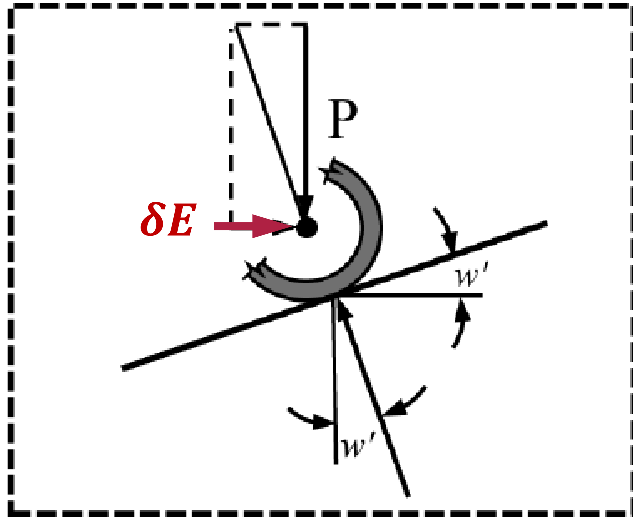
Model

Fuel Consumption

Deflection-Induced PVI: Mechanistic Model

- Dissipated energy due to pavement viscoelasticity results in slope under the wheel and must be compensated by the engine power to maintain a constant speed:

$$\delta E = -P\frac{dw}{dX}$$



(Adapted from Flugge, 1975)

- Finding key parameters and invariants via dimensional analysis:

$$\Pi = \frac{\delta E \ell_s^2 bk}{P^2}\frac{c}{c_{cr}} = \mathcal{F}\left(\Pi_1 = \frac{c}{c_{cr}}; \Pi_2 = \frac{\tau c_{cr}}{\ell_s}\right)$$

Winkler Length $\ell_s = \sqrt[4]{EI/k}$

$c_{cr} = \ell_s (k/m)^{1/2}$

- Scaling relationship of deflection-induced PVI:

$$\delta E \propto (c\tau)^{-1} P^2 E^{-0.25} h^{-0.75} k^{-0.25}$$

c: Speed; τ: Relaxation time; P: Vehicle load; **E**: Top layer modulus; **h**: Top layer thickness; **k**: Subgrade modulus

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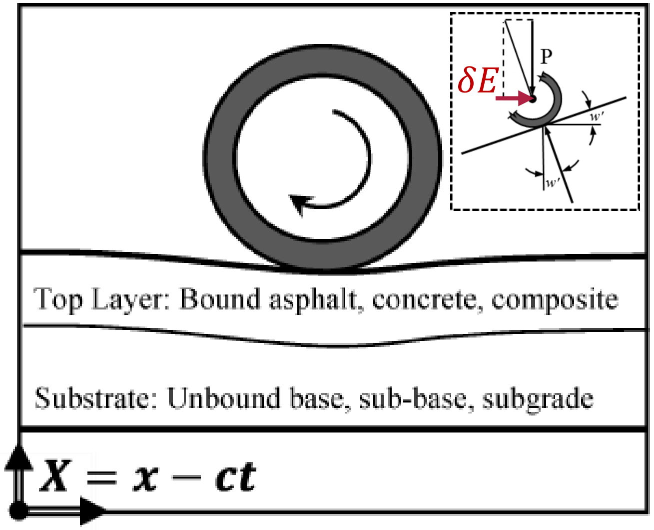
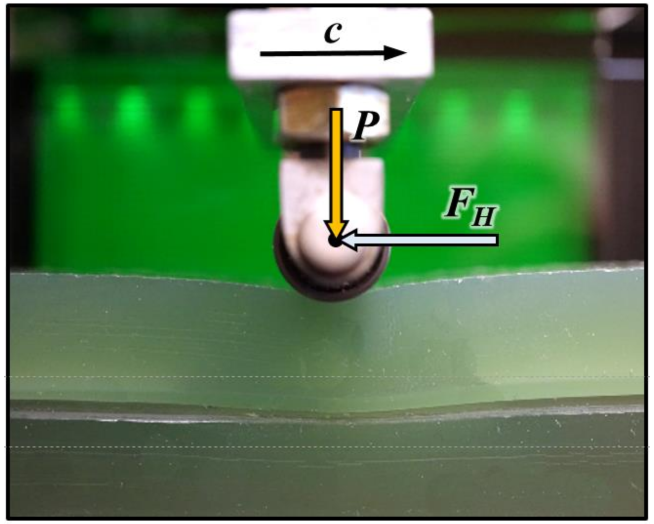
Recreating the deflection-induced PVI mechanism





$$\delta E = -P\frac{dw}{dX} \geq 0$$

$$F_H = -P\frac{dw}{dX} \geq 0$$

$$\therefore \delta E \propto F_H$$

PVI Parameters:

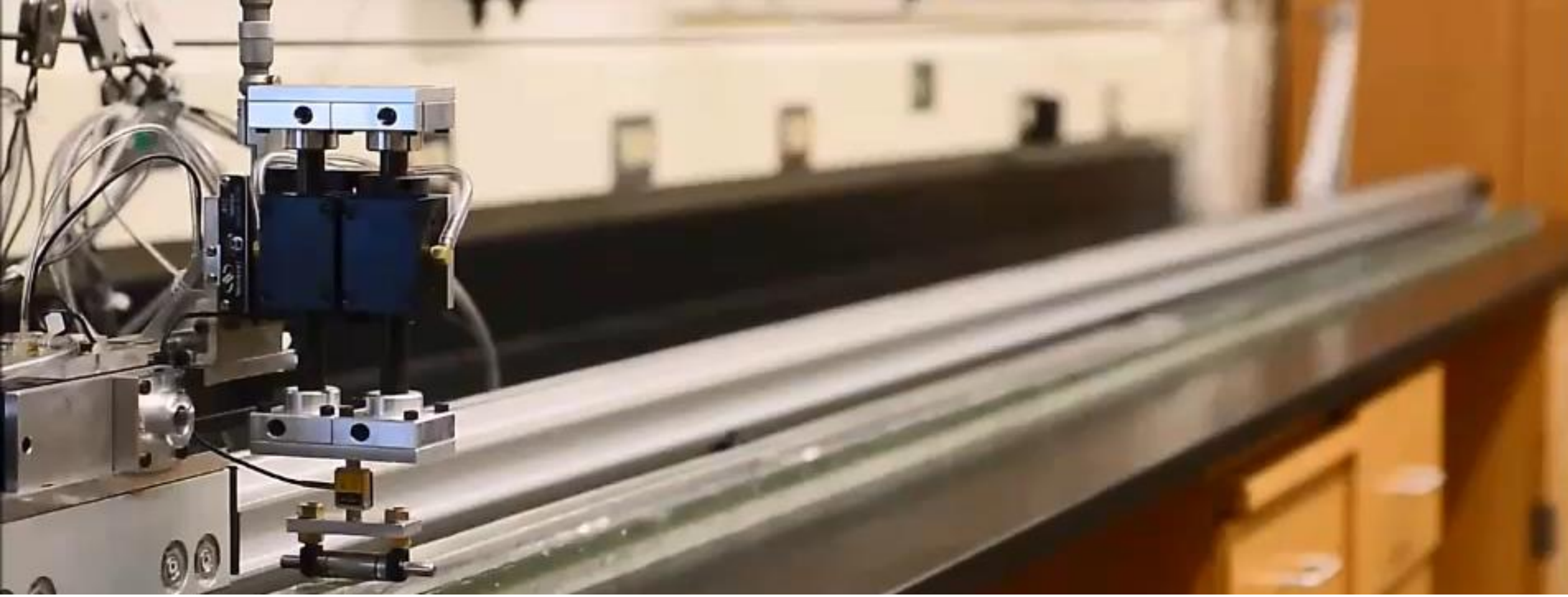
Vehicle:

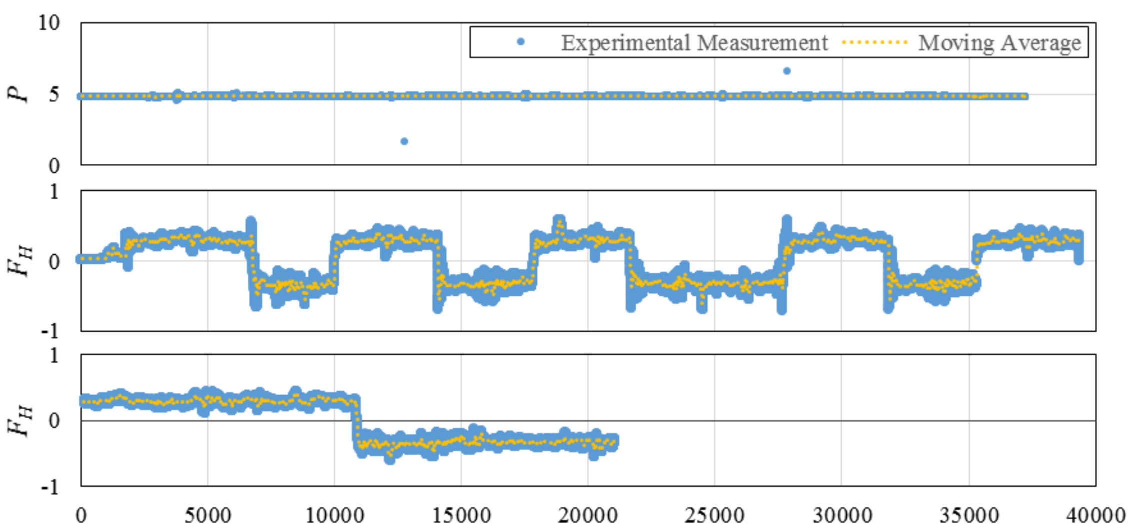
F_H: Horizontal Force $\quad$ P: Wheel load $\quad$ c: Vehicle speed

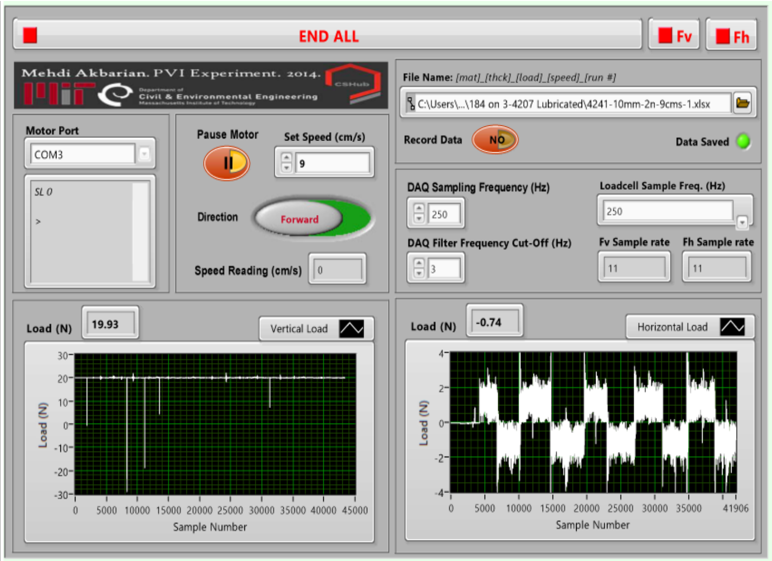
Pavement:

τ: Relaxation time $\quad$ h: Top layer thickness $\quad$ E: Top layer modulus

k: Subgrade modulus

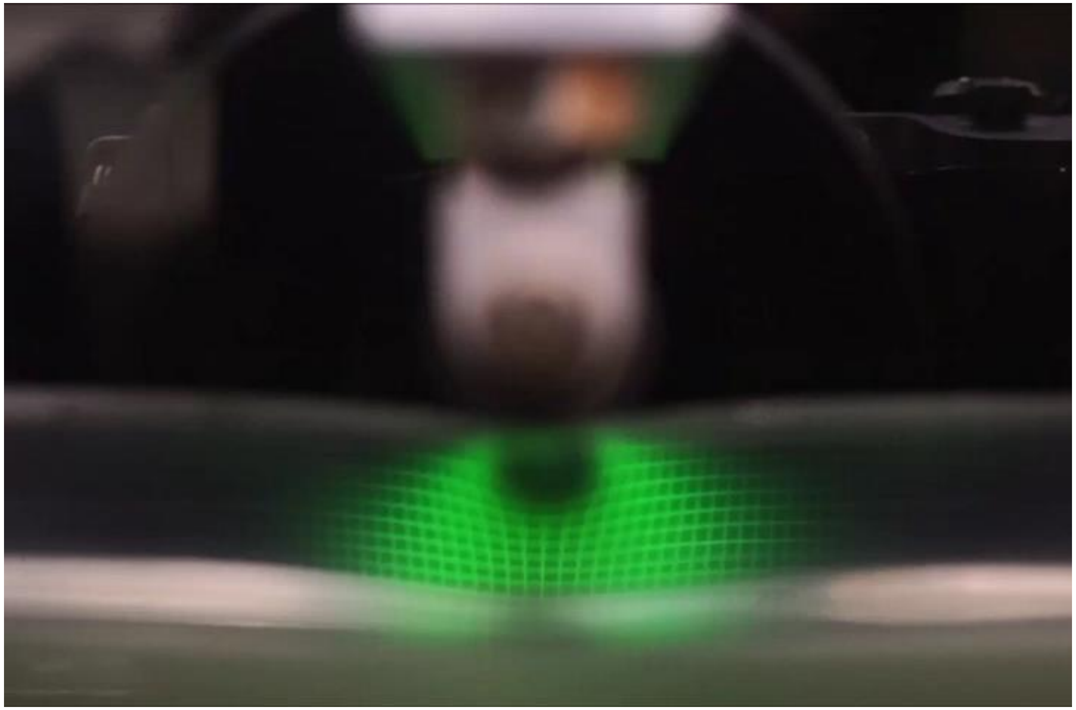


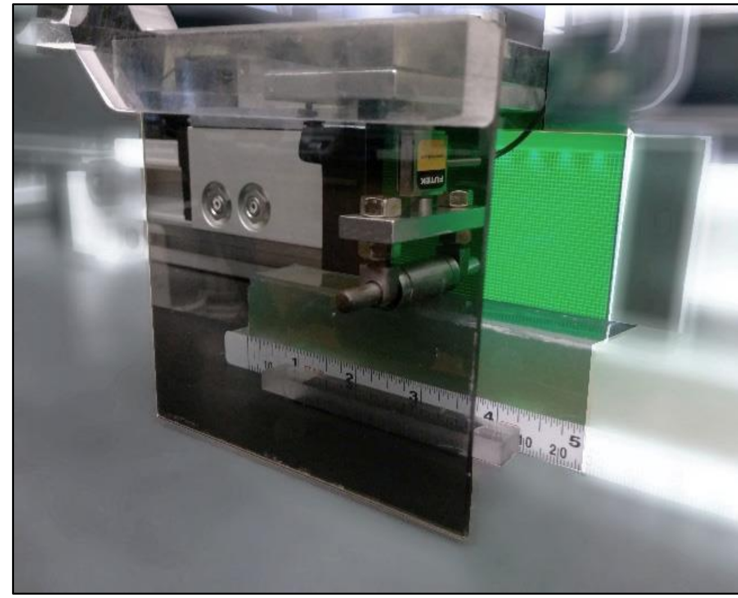




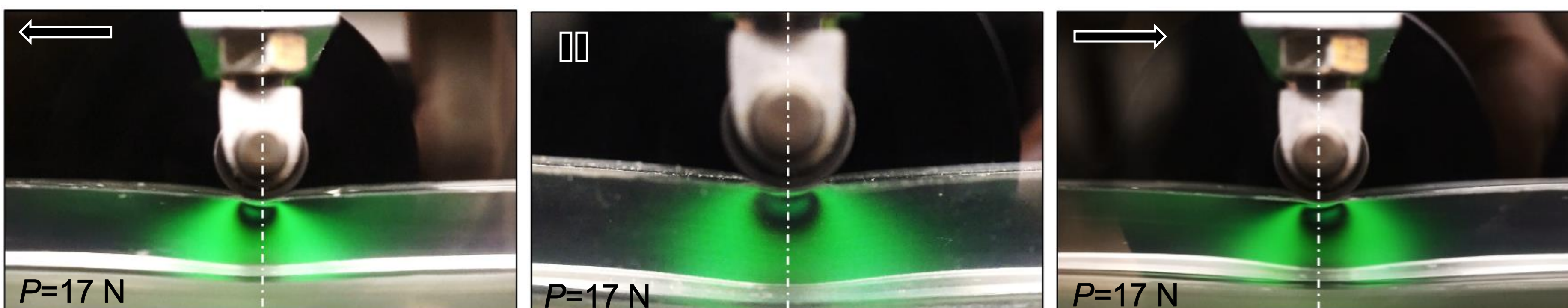
Equivalent to 180 miles of road testing with varying: P, c and τ, E, h

Photo-elasticity: asymmetry of the response

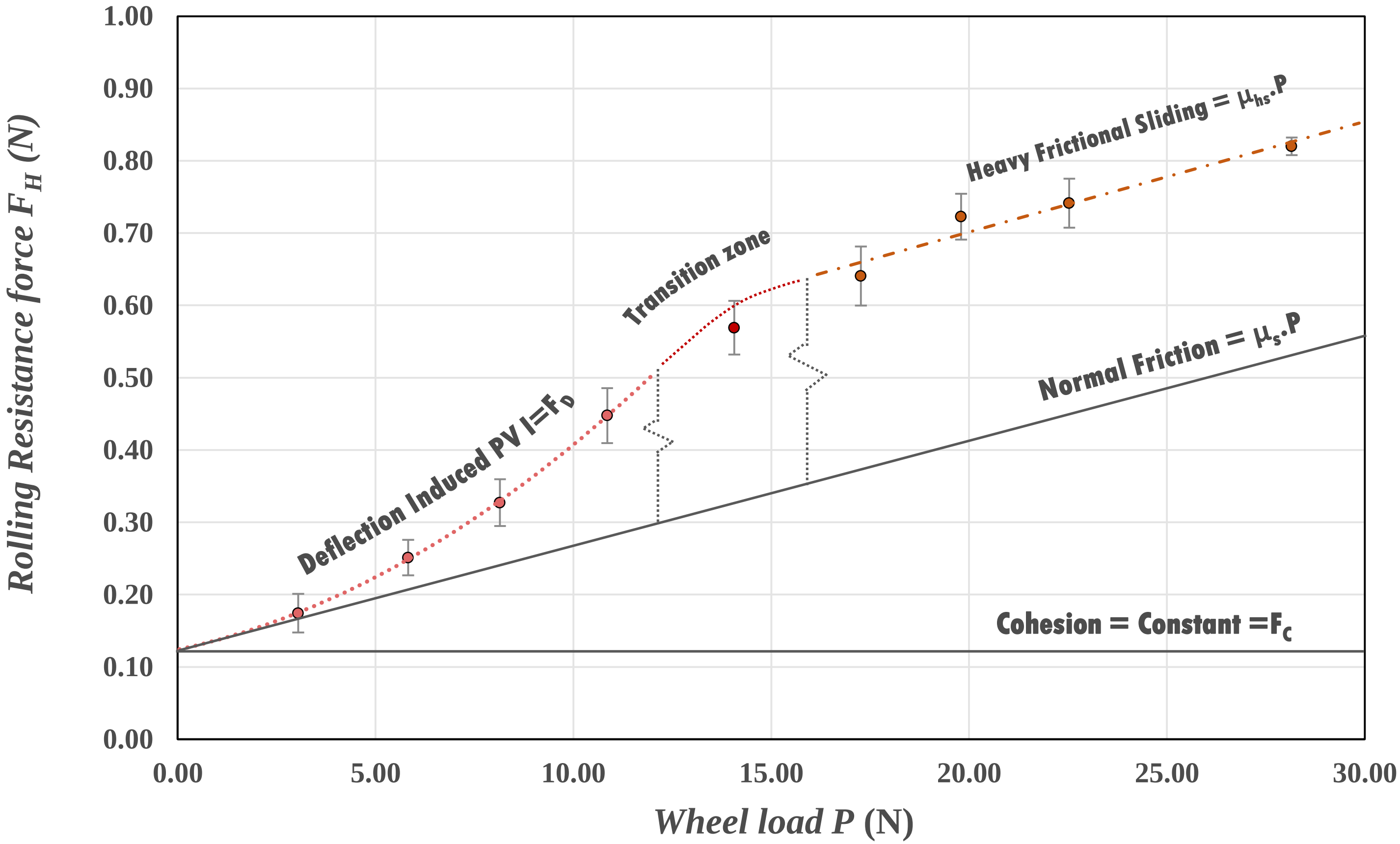


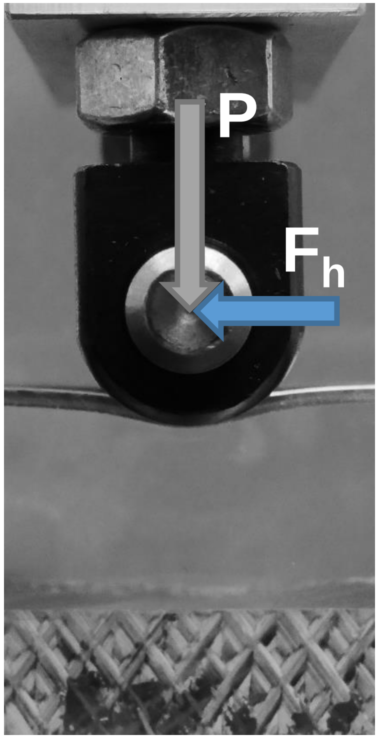


1: Analyzer
2: Quarter Wave-Plate
3: Wheel
4: Polarizer
5: Green Filter
6: Light Source



Experiments validate model behavior





Mechanistic model scaling: $\delta E \propto (c\tau)^{-1} P^{2} E^{-0.25} h^{-0.75} k^{-0.25}$

Experimental validation: $\delta E \propto (c)^{-0.87} P^{2.02} h^{-0.63}$

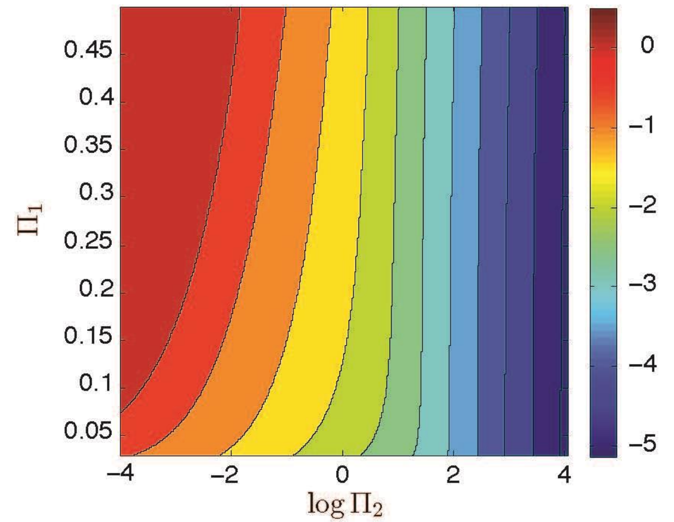
c: vehicle speed; P: vehicle load; h: top layer thickness

PVI deflection implementation-ready model

Dimensionless dissipation (simulation):

$$\boldsymbol{\Pi} = \frac{\boldsymbol{\delta E}\ell_s^2 bk}{P^2}\frac{c}{c_{cr}} = \mathcal{F}\left(\boldsymbol{\Pi_1} = \frac{c}{c_{cr}}; \boldsymbol{\Pi_2} = \frac{\tau c_{cr}}{\ell_s}\right)$$

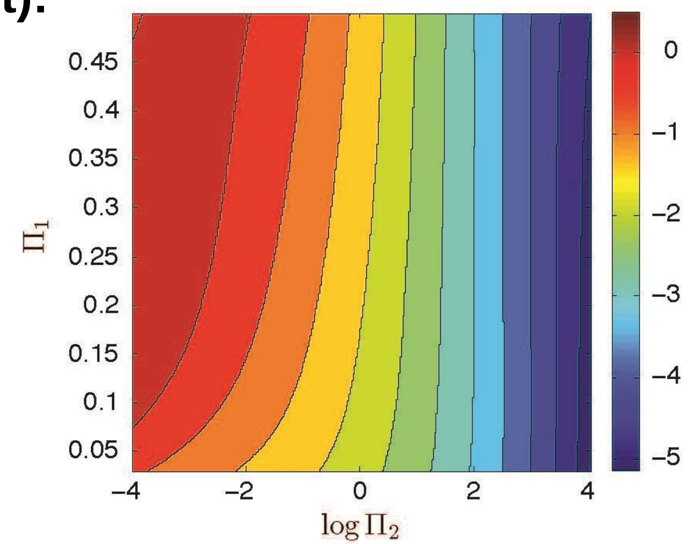
Winkler Length $\ell_s = \sqrt[4]{EI/k}$ $\quad \boldsymbol{c_{cr}} = \ell_s(k/m)^{1/2}$



Dimensionless dissipation (simplified model fit):

$$\log_{10}(\boldsymbol{\Pi}) = \log_{10}\frac{\boldsymbol{\delta E}c\ell_s^2 bk}{P^2 c_{cr}} = \sum_{i=0}^{i=5}\sum_{j=0}^{j=3} p_{ij}\boldsymbol{\Pi_1}^i \times \log_{10}(\boldsymbol{\Pi_2})^{j*}$$

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



* Mechanistic Approach to Pavement-Vehicle Interaction and Its Impact in LCA - *Journal of the Transportation Research Board.* 2014.

Pavement-induced fuel consumption research

Deflection Induced PVI

Roughness Induced PVI

Probabilistic PVI Implementation

Roughness-Induced PVI: Mechanistic Model

- Dissipated energy in suspension due to roughness must be compensated by the engine power to maintain a constant speed:

$$E[\boldsymbol{\delta E}] = \frac{C_s E[\dot{z}^2]}{V} \quad ; \dot{z} = \frac{c}{\sqrt{2/\pi}} E[IRI]$$

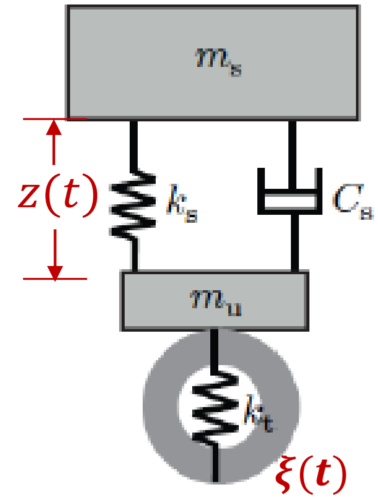
- Finding key parameters and invariants via dimensional analysis

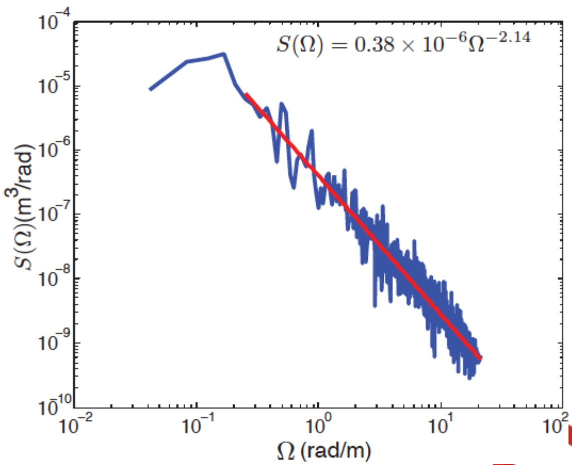
$$\boldsymbol{\Pi} = \frac{\boldsymbol{\delta E}}{m_s \omega_s^{4-w} V^{w-2} c}$$

$$= F\left(\boldsymbol{\Pi_1} = \frac{m_u}{m_s} = \gamma, \boldsymbol{\Pi_2} = \frac{\omega_u}{\omega_s} = \beta, \boldsymbol{\Pi_3} = \frac{C_s}{2\omega_s m_s} = \zeta\right)$$

- Scaling relationship of roughness-induced PVI:

$$\boldsymbol{E[\ \delta E\ ] \sim E[IRI]^2\ V^{w-2}}$$





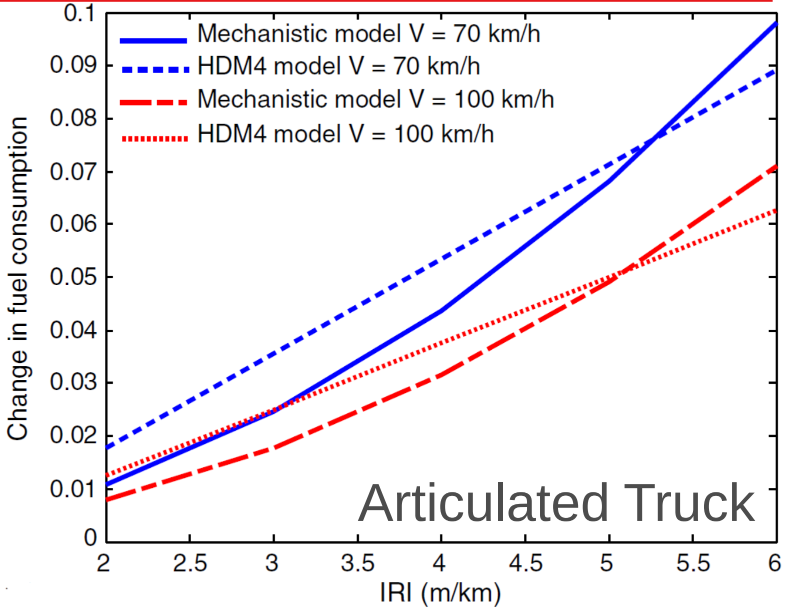
Mechanistic roughness model calibrated with HDM-4

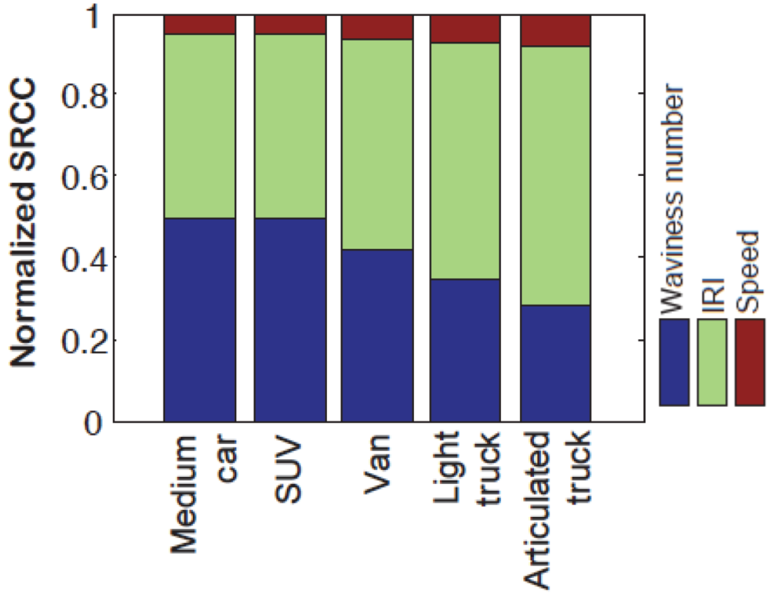
- Mechanistic Model:
  - Two parameter model: *IRI* and *w*
  - Quadratic relationship with *IRI*
  - Dynamic interaction

$$E[\,\delta E\,] \sim E[IRI]^2\, V^{w-2}$$

- HDM-4:
  - One parameter model: *IRI* (*w*=2)
  - Linear relationship with *IRI*
  - Vehicle speed dependency

$$E[\,\delta E\,] \sim E[IRI]$$





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Pavement-induced fuel consumption research

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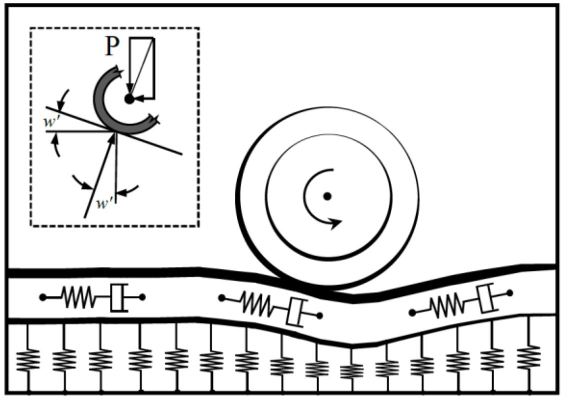
PVI Model Inputs and Uncertainties

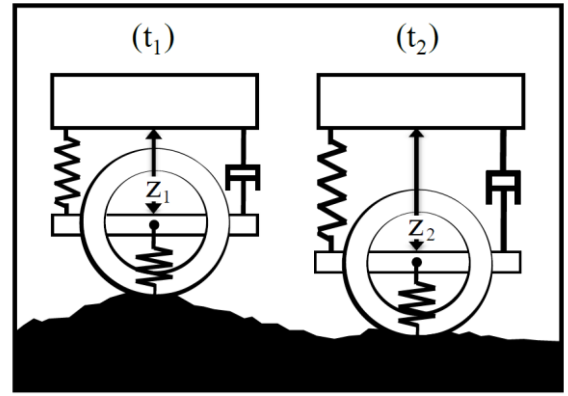
Deflection-induced PVI



Input:

1: Top layer modulus
2: Top layer thickness
3: Top layer relaxation time (AC/PCC)
4: Subgrade modulus
5: Vehicle load
6: Vehicle speed
7: Temperature

Roughness-induced PVI



Input:

1: IRI(t)
2: Reference IRI_0
3: Vehicle type
4: Vehicle speed

Probabilistic deflection model implementation with limited data

1- Top layer modulus:
LTPP distributions for similar material and traffic condition.

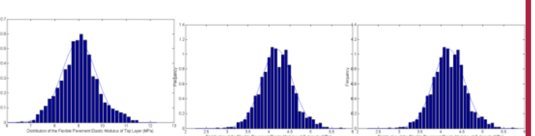
2- Top layer thickness:
LTPP distributions for similar material and traffic condition.

3- Subgrade modulus:
LTPP distributions for similar regional condition.

Long Term Pavement Performance (LTPP) Program Climate Zones

Monte Carlo Procedure:

LTPP Distributions



E (μ,σ) h (μ,σ) k (μ,σ)

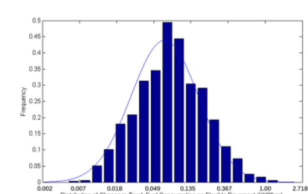
→

Sample Data

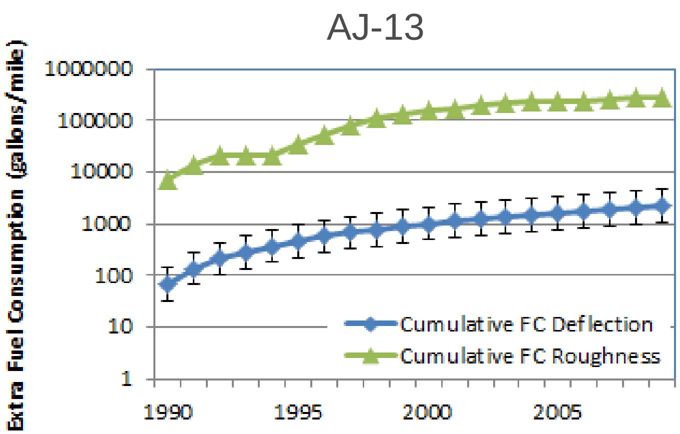
Calculate Fuel Consumption per PM of Section

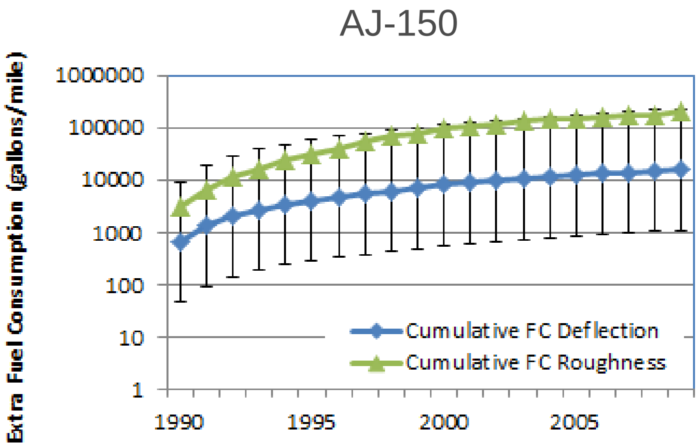
→

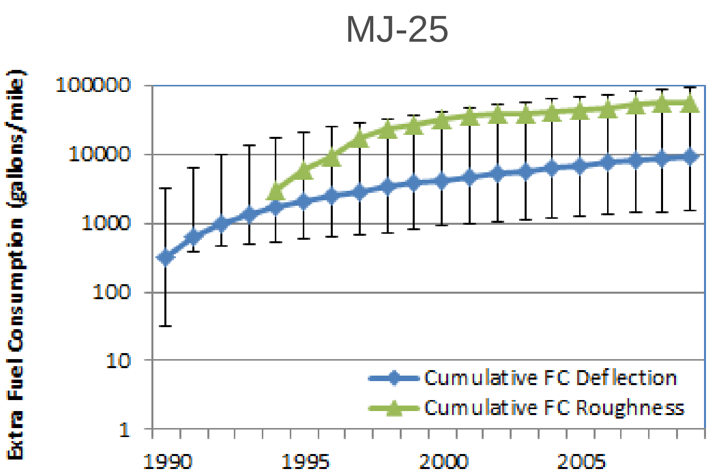
PVI Deflection Fuel Consumption

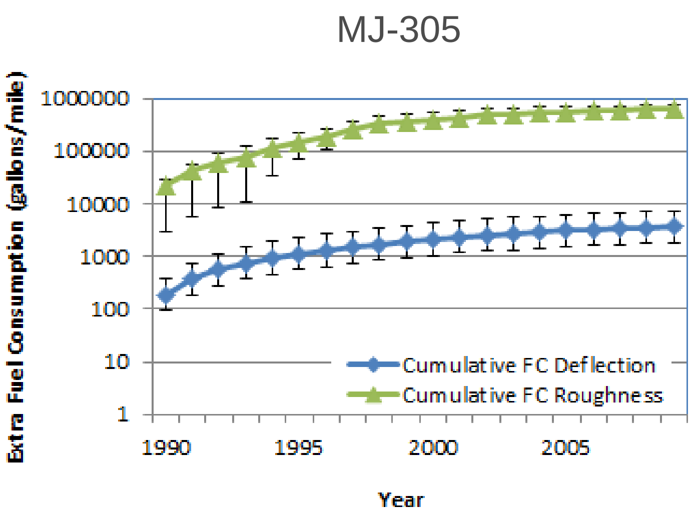


Probabilistic PVI implementation with limited data









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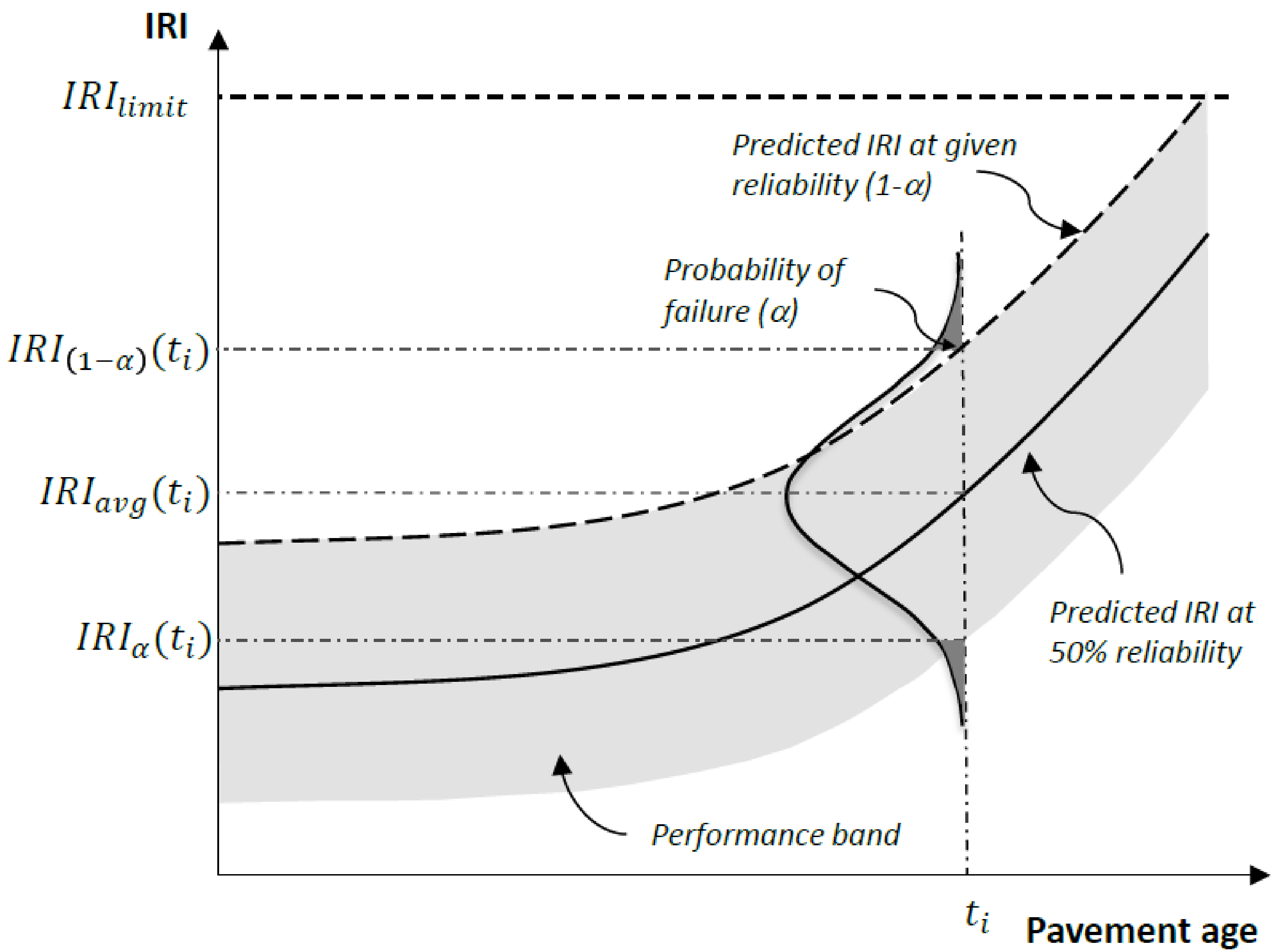
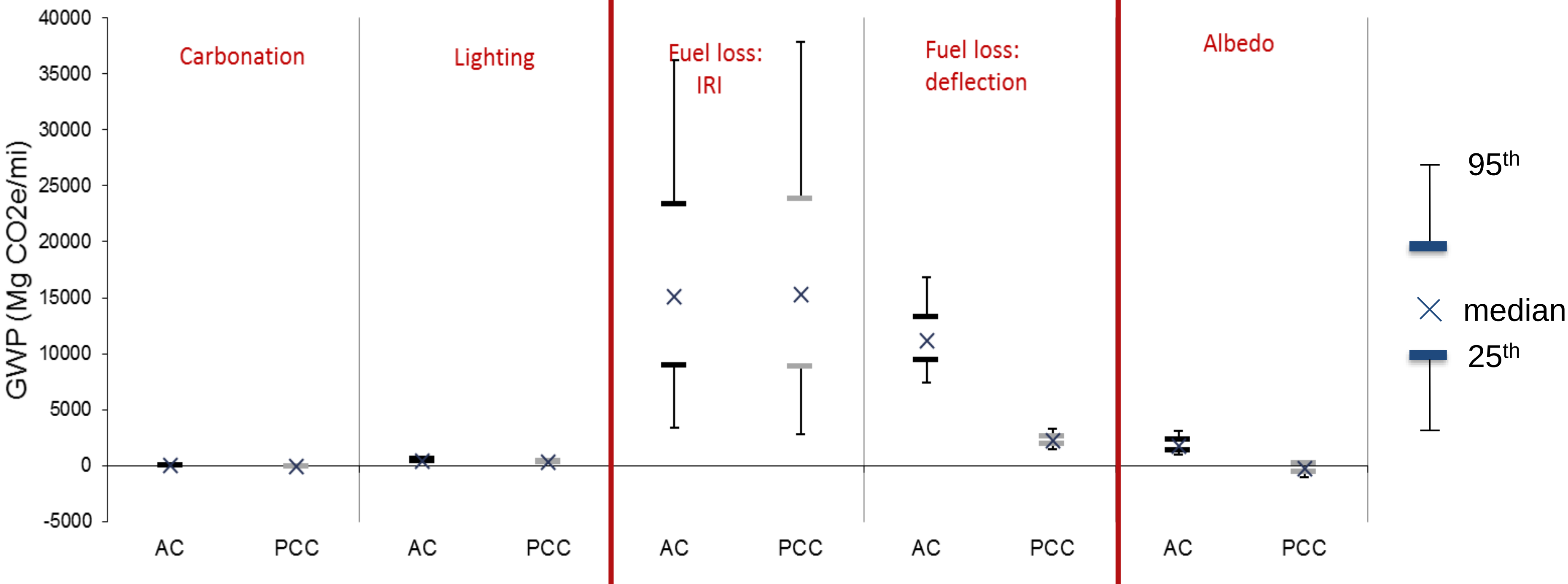
Probabilistic roughness model implementation with MEPDG



Probabilistic PVI implementation with MEPDG

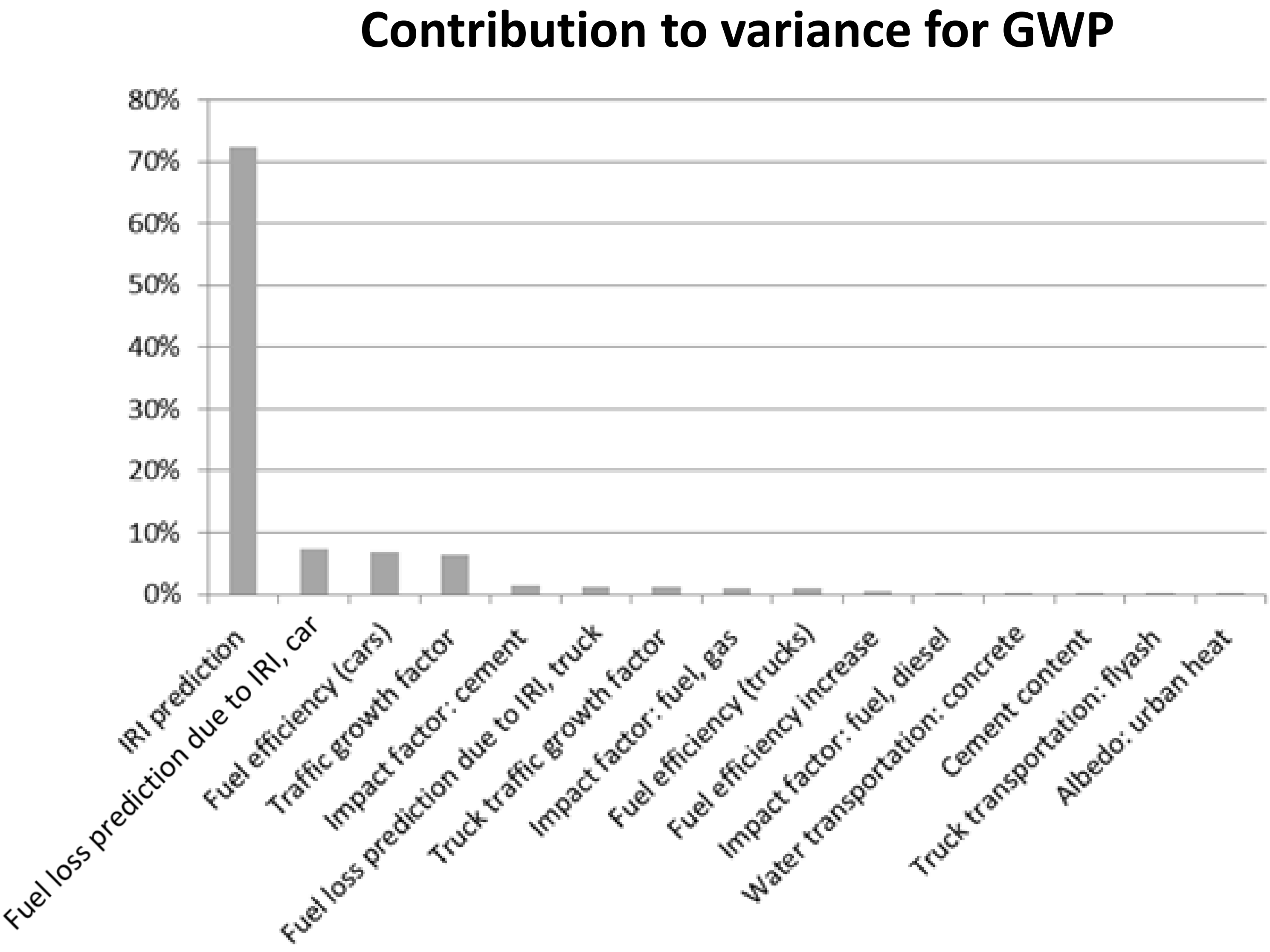
AZ case study: contributions of use phase components

Fuel consumption dominates use phase



Identifying drivers of PVI uncertainty - MEPDG

AZ case study: contributions of use phase components



Key research findings

- We can quantify excess fuel consumption due to pavement-vehicle interaction
- Probabilistic analysis provides useful estimates even with limited data
- Surface and structure matter

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Thank you

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