A MECHANISTIC APPROACH FOR PAVEMENT VEHICLE INTERACTION IN LCA

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Outline

Introduction

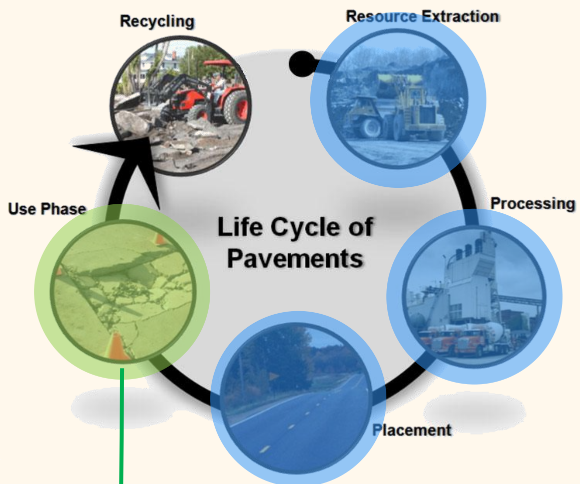
Pavement-Vehicle Interaction

Model

Results: LTPP Network Analysis

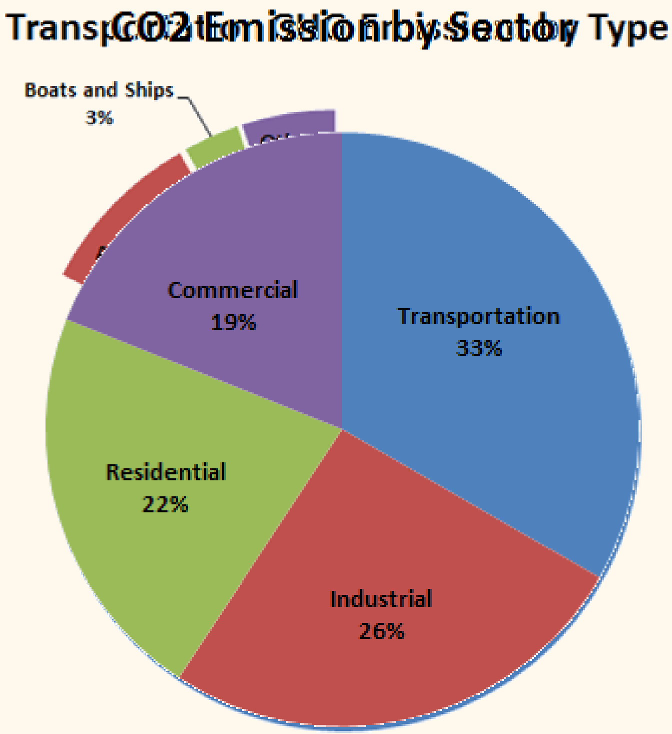
Conclusion and Future Work

Why Bother: Transportation Accounts for 20% of US CO2 Emissions



LCA & LCCA Boundaries

Pavement Vehicle Interaction: 72%



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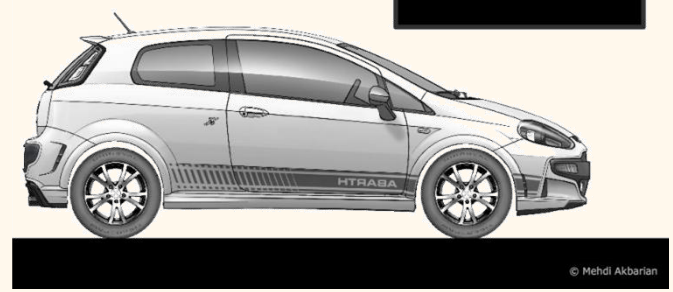
Pavement-Vehicle Interaction

Pavement Roughness*

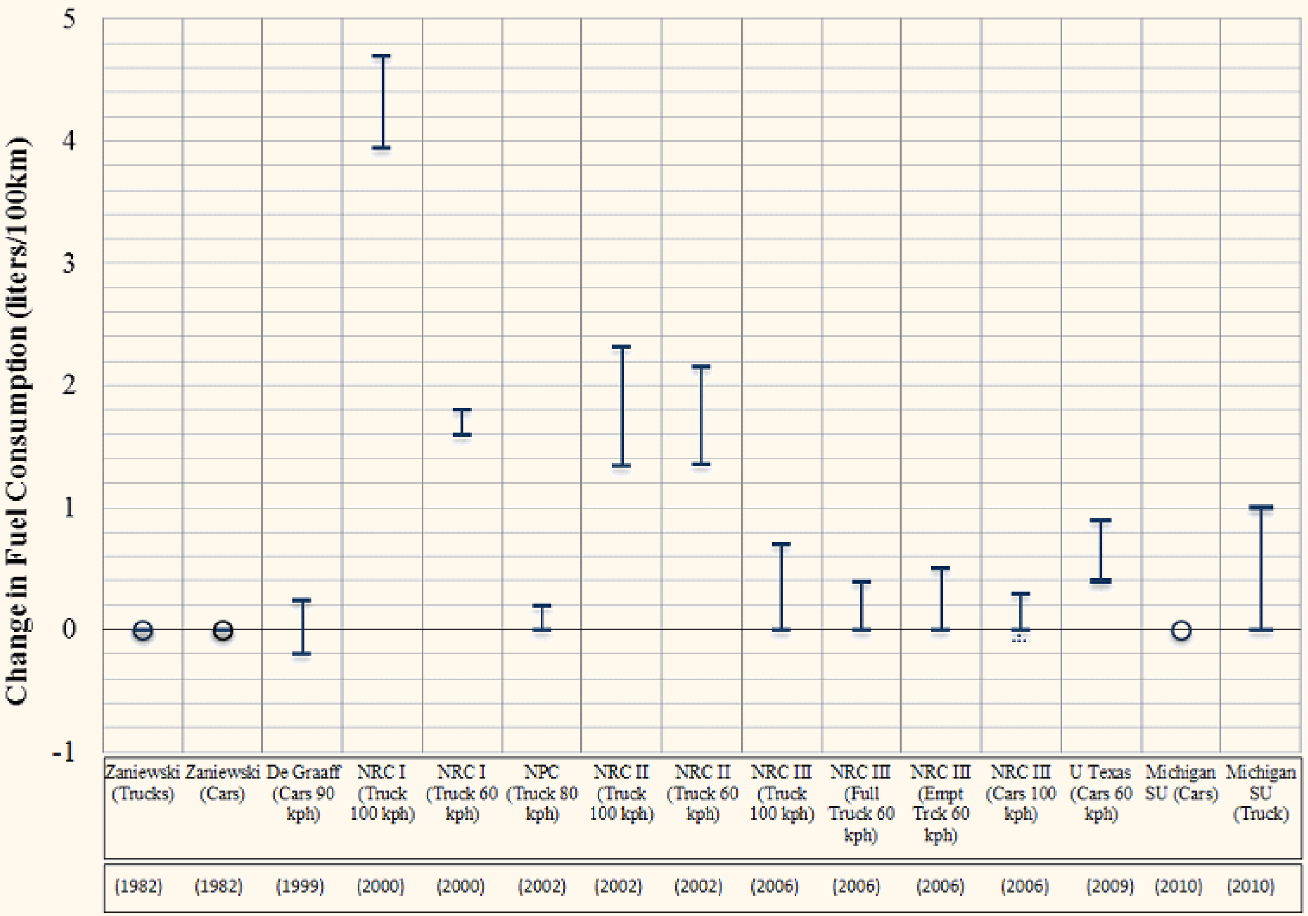


Pavement Deflection

Structure and Material

* Zabaar and Chatti (2010) Calibration of HDM-4 Models for Estimating the Effect of Pavement Roughness on Fuel Consumption for U.S. Conditions

Literature: Empirical Studies on Pavement Deflection



Empirical Database:

- High uncertainty
- High variability
- Question of objectivity
- Binary material view:
  - Asphalt vs. concrete
- No structural consideration

Need:

- Model is missing to relate fuel consumption to:
  - Deflection
  - Structure
  - Material

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PVI Deflection Model

Research Problem:

- Evaluate, in first order, the mechanics behind pavement vehicle interaction

Research Goal:

- Create a model that relates fuel consumption to:
  - Deflection
  - Structure
  - Material properties

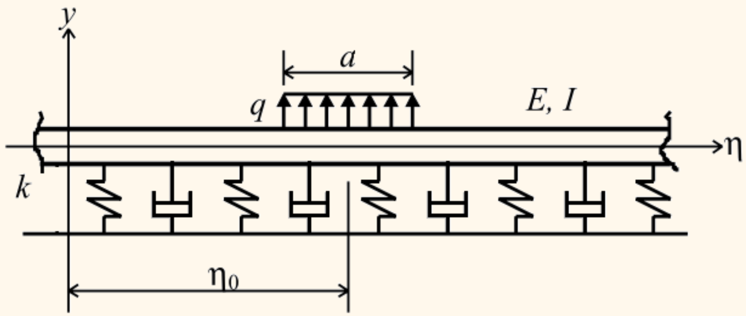
Simplest model:

- Bernoulli Euler beam on viscoelastic foundation
- Calibrate model parameters
- Validate with experimental data

Bernoulli Euler beam on viscoelastic foundation

$$EI\frac{\partial^4 y}{\partial x^4} + m\frac{\partial^2 y}{\partial t^2} + c\frac{\partial y}{\partial t} + ky = q(x,t) \qquad [eq.1]$$

Moving coordinate system: $\eta = x - Vt \qquad [eq.2]$



$$EI\frac{\partial^4 y}{\partial \eta^4} + m\left(\frac{\partial^2 y}{\partial t^2} - 2V\frac{\partial^2 y}{\partial t \partial \eta} + V^2\frac{\partial^2 y}{\partial \eta^2}\right) + c\left(\frac{\partial y}{\partial t} - V\frac{\partial y}{\partial \eta}\right) + ky = q(\eta,t) \qquad [eq.3]$$

ξ (and **Ω** *) are tranformed fields of **η** and **t**

$$y(\eta) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{Q(\xi)}{EI\xi^4 - mV^2\xi^2 + k(1+2i\zeta)}e^{i\xi\eta}d\xi \qquad [eq.4]$$

$$Q(\xi) = q\int_{-a/2}^{a/2} e^{-i\xi\eta}d\eta \qquad [eq.5]$$

(* in the case of periodic load, not considered in what follows)

Input:

E: Elastic Modulus of Top Layer
h: Thickness of Top Layer
k: Elastic Modulus of Subgrade
ζ: Damping Ratio
m: Mass of beam per unit length

Output

$\boldsymbol{y(\eta)}$: Deflection

Model Parameter Study

Inputs:

- ***E:*** Top layer modulus
- ***h:*** Top layer thickness
- ***k:*** Substrate modulus
- ***M:*** Vehicle mass

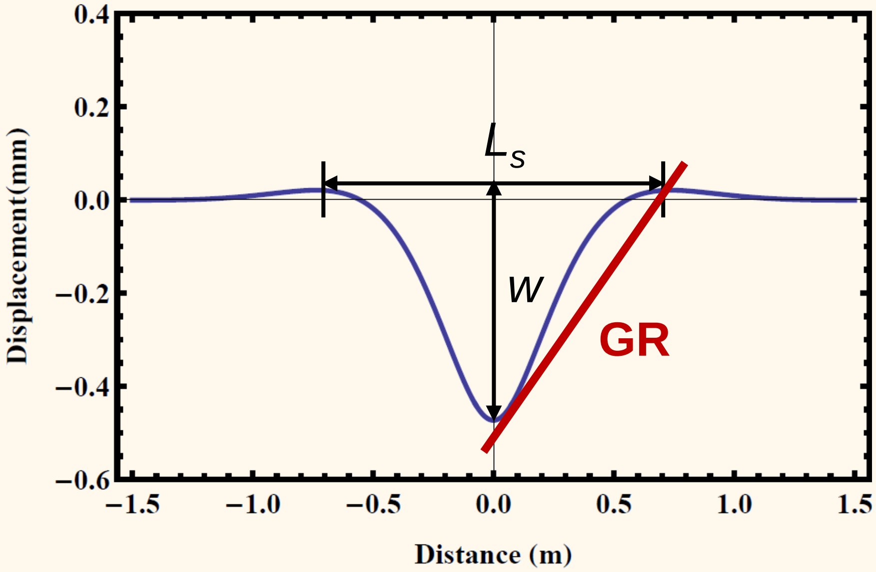
$IFC \sim GR \times M \times \mathrm{g}$: Gradient Force

$GR \sim \frac{w}{L_s}$

$w \sim M^1 \, E^{-1/4} \, k^{-3/4} \, h^{-3/4}$

$L_s \sim E^{1/4} \, k^{-1/4} \, h^{3/4}$

$$IFC \sim M^2 \times E^{-1/2} \, k^{-1/2} \, h^{-3/2}$$

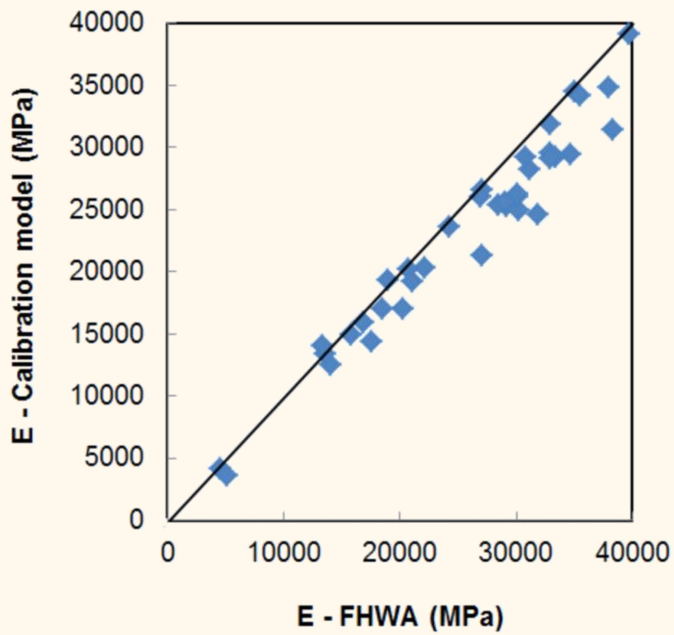


* Mechanistic Approach to Pavement-Vehicle Interaction and Its Impact in LCA - *Journal of the Transportation Research Board*, 2012.

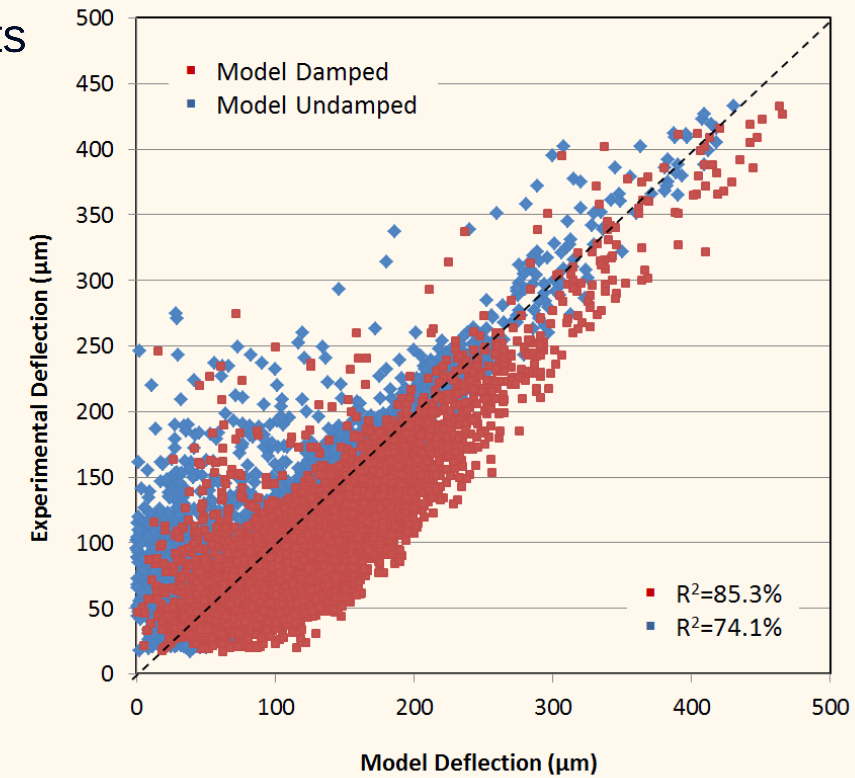
Calibration – validation: FHWA DATA

FWD Time Histories:

1. Calibration: Arrival time of signal
2. Validation: Maximum deflection at offsets

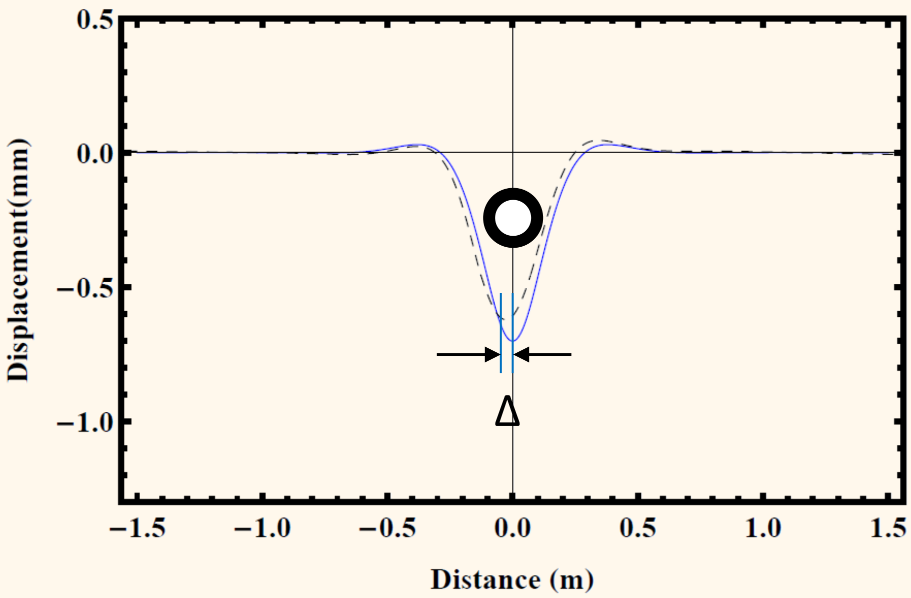


Calibration



Validation

Role of Damping



Effect of damping:

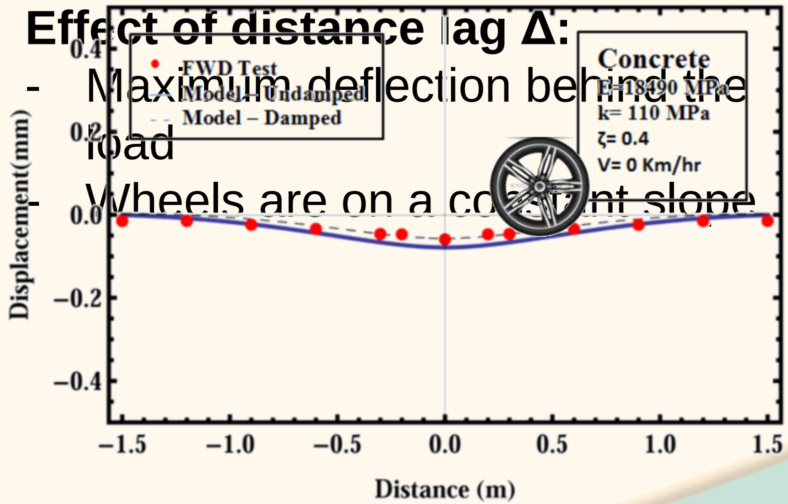
1- Distance lag Δ due to increase in damping.

2- Decrease in maximum deflection.

3- But, second-order effect.

Effect of distance lag Δ:

- Maximum deflection behind the load
- Wheels are on a constant slope.



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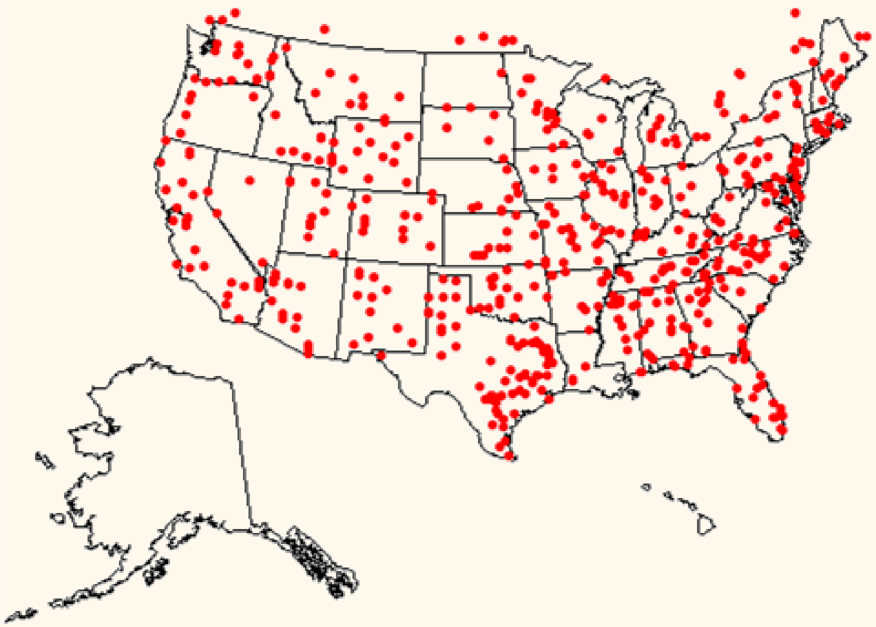
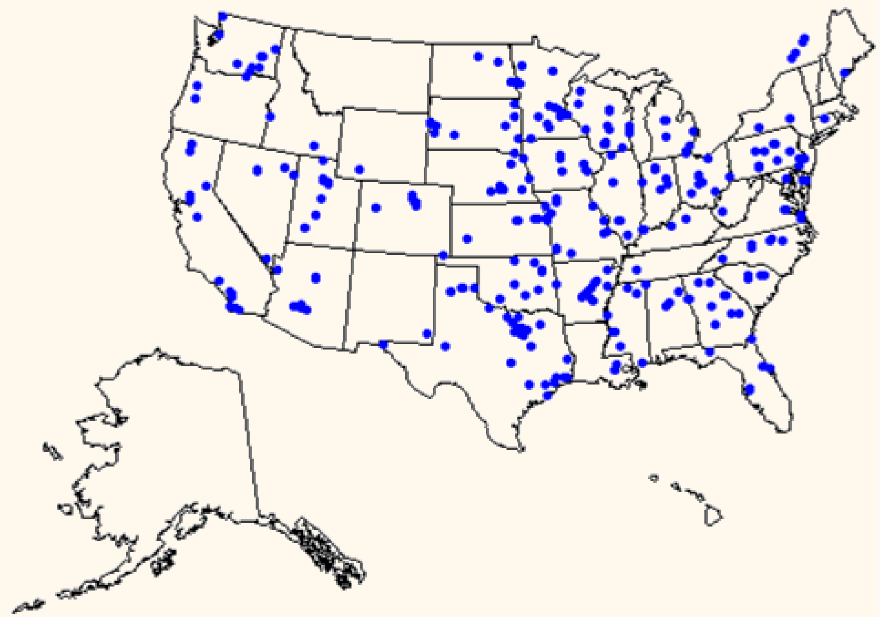
LTPP Monitored Sections

Total of 5643 sections: 1079 rigid, 4564 flexible

Concrete



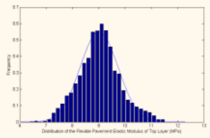
Asphalt



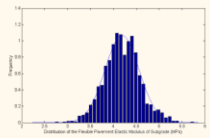
Data used:

- Top layer modulus *E*
- Subgrade modulus *k*
- Top layer thickness *h*
- Loading condition *q*
- Traffic Volume (AADT, AADTT)

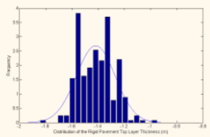
Monte-Carlo Procedure



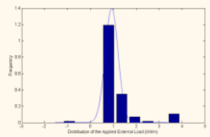
E (μ,σ)



k (μ,σ)



h (μ,σ)



q (μ,σ)

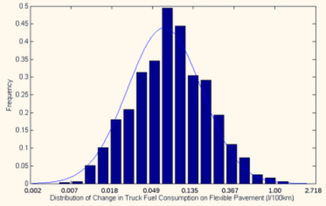
Sample Data (log space)

Calculate Fuel Consumption

Check convergence

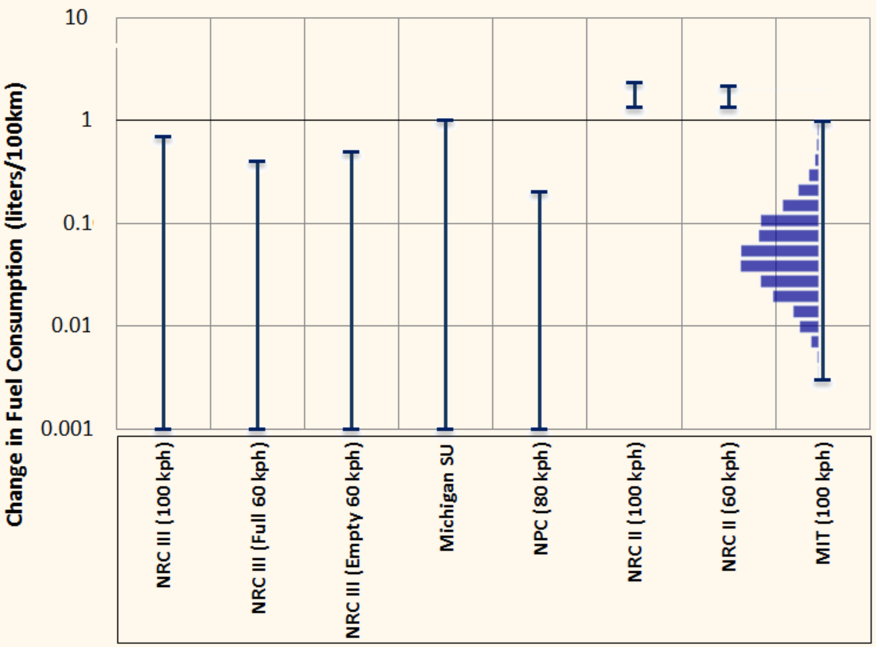
$$\frac{\text{inputs}}{(\mu, \sigma)} \approx \frac{\text{samples}}{(\mu, \sigma)}$$

PVI Deflection Fuel Consumption

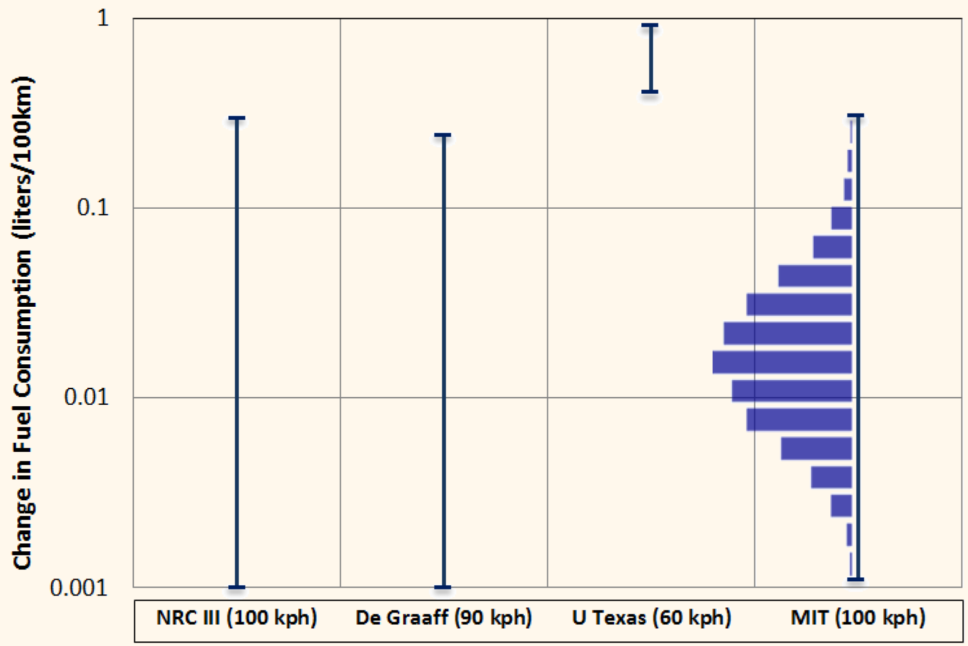


Deflection Induced Fuel Consumption

Trucks:



Cars:



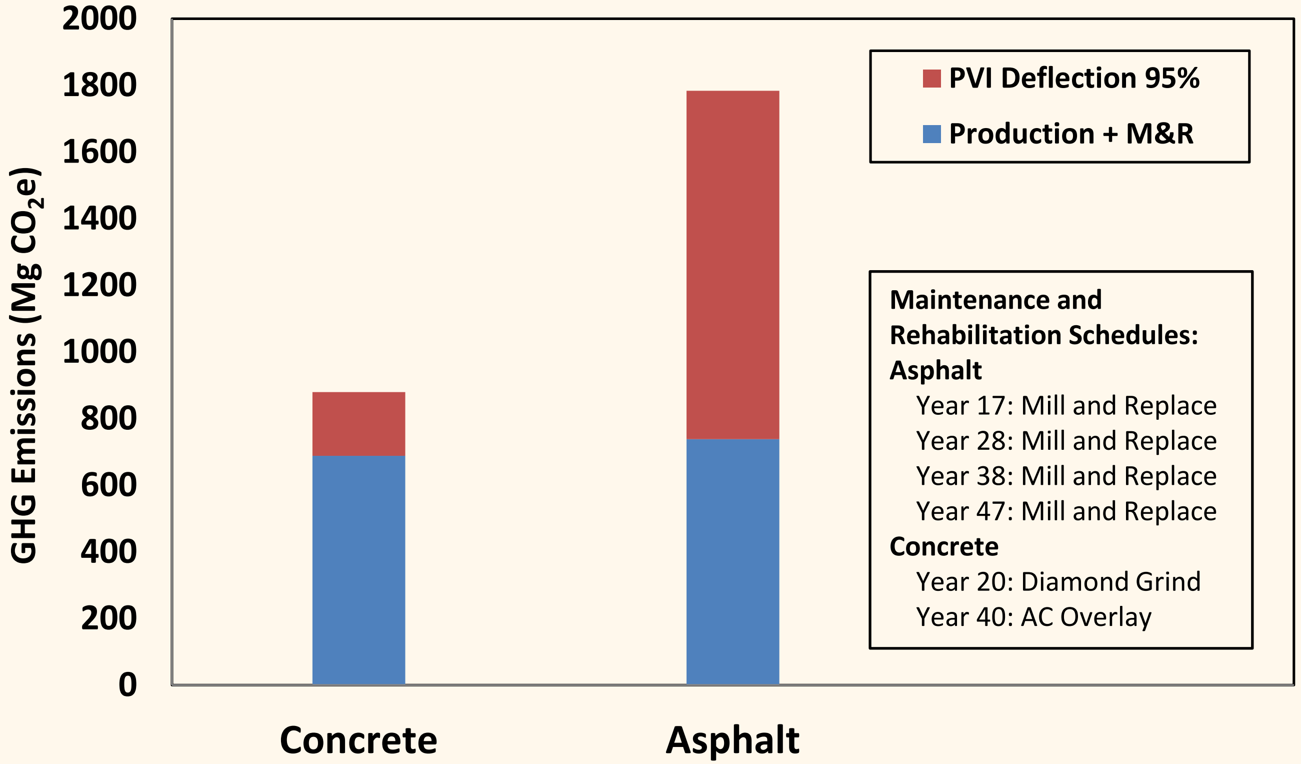
Report:

*Akbarian M., Ulm J-F. 2012. Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements. Concrete Sustainability Hub. MIT

Use in a LCA

50 yr GHG Emissions of Two Pavement Scenarios Relative to a "Flat" Pavement

$$Total\ IFC \sim E^{-1/2}\ k^{-1/2}\ h^{-3/2} \sum_i (N_i\ W_i^{\,2})$$



*Embodied GWP for Canadian High Volume Traffic Scenario : Athena (2006)

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Conclusion

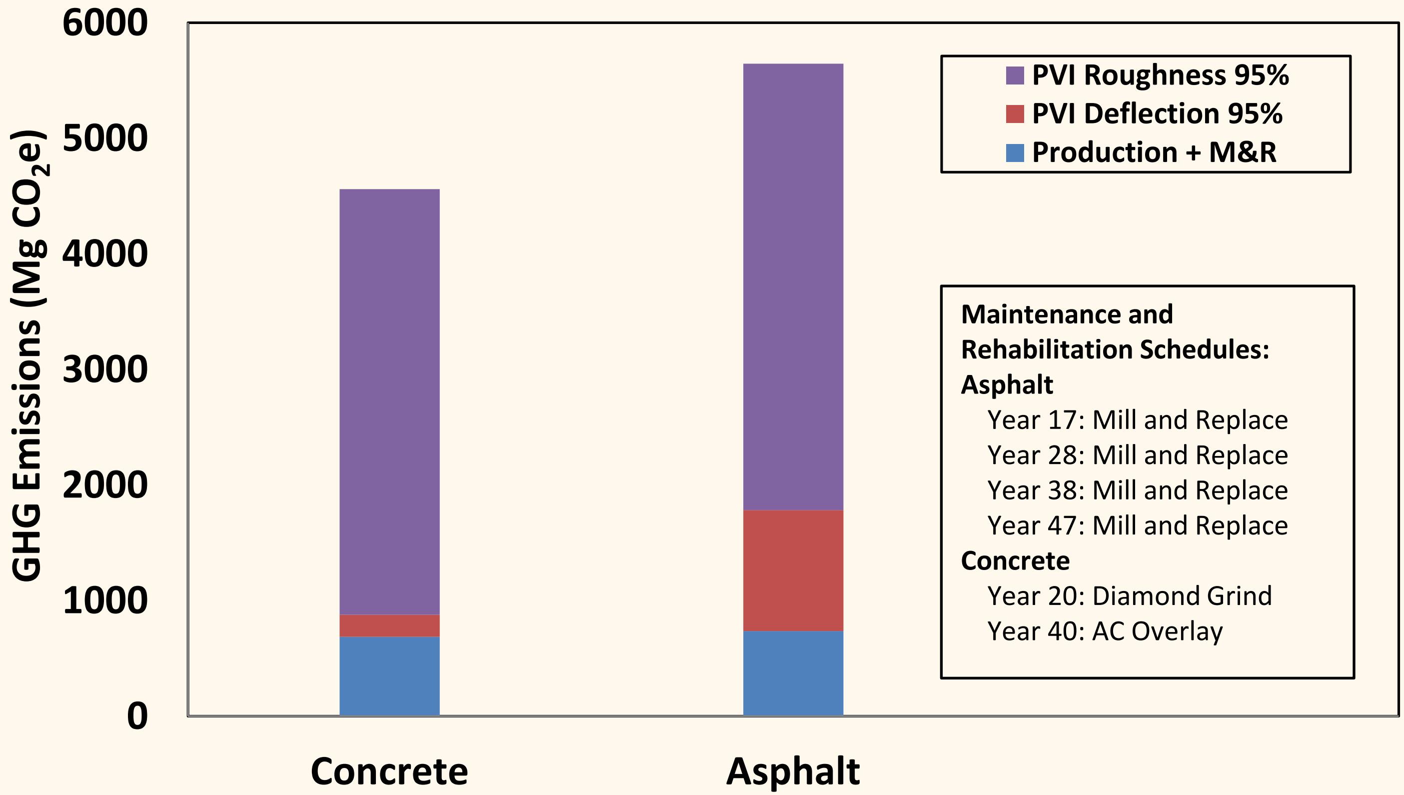
Developed:

- Relationship between material and structural pavement properties with PVI
- Calibration – Validation of model
- Model provides realistic estimates of FC for vehicles and current trends

Future Work:

- More accurate pavement model
- Realistic vehicle model
- Network application

Use in a LCA – with roughness



Embodied GWP for Canadian High Volume Traffic Scenario : Athena (2006)
IRI design criterion = 160 in/mile