A MECHANISTIC APPROACH FOR PAVEMENT VEHICLE INTERACTION IN LCA

Mehdi Akbarian (MIT)
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%

CO2 Emission by Sector Type

- Transportation: 33%
- Residential: 22%
- Industrial: 26%
- Commercial: 19%
- Agriculture: 7%
- Manufacturing: 5%
- Mining & Quarrying: 3%
- Boats & Ships: 3%
- Aviation: 3%
- Other: 1%
Outline

Introduction

Pavement-Vehicle Interaction Model

Results: LTPP Network Analysis

Conclusion and Future Work
Pavement-Vehicle Interaction

Pavement Roughness* 

Structure and Material 

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
Outline

Introduction
Pavement-Vehicle Interaction
Model
Results: LTPP Network Analysis
Conclusion and Future Work
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

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

Moving coordinate system: \( \eta = x - Vt \)  \[ eq. 2 \]

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

\( \xi \) (and \( \Omega^* \)) are transformed fields of \( \eta \) and \( t \)

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

[eq. 4]

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

(* 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
- \( \zeta \): Damping Ratio
- \( m \): Mass of beam per unit length

**Output**
- \( y(\eta) \): Deflection
Model Parameter Study

**Inputs:**

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

\[ IFC \sim GR \times M \times g : \text{Gradient Force} \]

\[ GR \sim \frac{w}{L_s} \]

\[ w \sim M^1 E^{-1/4} k^{-3/4} h^{-3/4} \]

\[ L_s \sim E^{1/4} k^{-1/4} h^{3/4} \]

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

Calibration – validation: FHWA DATA

FWD Time Histories:
1. Calibration: Arrival time of signal
2. Validation: Maximum deflection at offsets
Role of Damping

Effect of damping:
1- Distance lag $\Delta$ due to increase in damping.
2- Decrease in maximum deflection.
3- But, second-order effect.

Effect of distance lag $\Delta$:
- Maximum deflection behind the load
- Wheels are on a constant slope
Outline

Introduction
Pavement-Vehicle Interaction Model
Results: LTPP Network Analysis
Conclusion and Future Work
LTPP Monitored Sections

Total of 5643 sections: 1079 rigid, 4564 flexible

Data used:
- Top layer modulus $E$
- Subgrade modulus $k$
- Top layer thickness $h$
- Loading condition $q$
- Traffic Volume (AADT, AADTT)
Monte-Carlo Procedure

Sample Data (log space)
Calculate Fuel Consumption

Check convergence
inputs \( (\mu, \sigma) \) \( \approx \) \( (\mu, \sigma) \)

PVI Deflection Fuel Consumption

E (\( \mu, \sigma \))

k (\( \mu, \sigma \))

h (\( \mu, \sigma \))

q (\( \mu, \sigma \))
Deflection Induced Fuel Consumption

Trucks:

Cars:

Report:
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)

Outline

Introduction
Pavement-Vehicle Interaction Model
Results: LTPP Network Analysis
Conclusion and Future Work
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

IRI design criterion = 160 in/mile