Quantifying excess fuel consumption for pavement design and maintenance decisions

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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


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
Pavement-induced fuel consumption research

Deflection Induced PVI

Roughness Induced PVI

Probabilistic PVI Implementation
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
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:

\[
\delta E = -P \frac{dw}{dX}
\]

- Finding key parameters and invariants via dimensional analysis:

\[
\Pi = \frac{\delta E \ell^2_s b k}{P^2} \frac{c}{c_{cr}} = \mathcal{F} \left( \Pi_1 = \frac{c}{c_{cr}} ; \Pi_2 = \frac{\tau c_{cr}}{\ell_s} \right)
\]

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; \(\tau\): Relaxation time; \(P\): Vehicle load; \(E\): Top layer modulus; \(h\): Top layer thickness; \(k\): Subgrade modulus
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
- \( P \): Wheel load
- \( c \): Vehicle speed

**Pavement:**
- \( \tau \): Relaxation time
- \( h \): Top layer thickness
- \( k \): Subgrade modulus
- \( E \): Top layer modulus
Equivalent to 180 miles of road testing with varying: $P$, $c$ and $\tau$, $E$, $h$
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):

\[ \Pi = \frac{\delta E \ell_s^2 b k}{P^2} \frac{c}{c_{cr}} = F \left( \Pi_1 = \frac{c}{c_{cr}}; \Pi_2 = \tau c_{cr} \ell_s \right) \]

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

Dimensionless dissipation (simplified model fit):

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

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

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:

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

- Finding key parameters and invariants via dimensional analysis

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

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

- Scaling relationship of roughness-induced PVI:

\[ E[\delta E] \sim E[IRI]^2 V^{w-2} \]
Mechanistic roughness model calibrated with HDM-4

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

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

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

\[ E[\delta E] \sim E[IRI] \]

Pavement-induced fuel consumption research

Deflection Induced PVI

Roughness Induced PVI

Probabilistic PVI Implementation
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<sub>0</sub>
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.

Monte Carlo Procedure:

- LTPP Distributions
- Sample Data
  - Calculate Fuel Consumption per PM of Section
- PVI Deflection Fuel Consumption
Probabilistic PVI implementation with limited data
Probabilistic roughness model implementation with MEPDG
Probabilistic PVI implementation with MEPDG
AZ case study: contributions of use phase components

Fuel consumption dominates use phase

- Carbonation
- Lighting
- Fuel loss: IRI
- Fuel loss: deflection
- Albedo

GWP (Mg CO2e/ml)

AC PCC AC PCC AC PCC AC PCC

- 95th
- median
- 25th
Identifying drivers of PVI uncertainty - MEPDG
AZ case study: contributions of use phase components

Contribution to variance for GWP
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.
Thank you

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