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

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Motivation: carbon management in the transportation sector

US transportation sector consumed 190 billion gallons of fuel in 2012. This represents approximately 1/3 of US greenhouse gas emissions.

- Fossil Fuel Combustion: 92%
- Residential: 6%
- Other Sources: 8%

Sources of US Fossil Fuel GHG Emissions (2012)
- Electricity Generation: 40%
- Transportation: 34%
- Industrial: 15%
- Commercial: 4%
- Other: 1%

1% reduction in transportation = 17 million metric tons of CO₂ eq. saved

Sources: EIA, EPA
Engineering strategies for transportation carbon management

- Improve energy efficiency
- Improve aerodynamics
- Reduce rolling resistance, including pavement-vehicle interaction
Policy strategies for transportation carbon management

The Washington Post February 18, 2014

“Obama to tighten fuel efficiency standards for big trucks”

What about fuel efficiency standards for pavements?
Key drivers of rolling resistance & PVI

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

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

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

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Deflection analogy: Running on pavement vs. sand

Walking on sand requires 2.1–2.7 times more energy expenditure than does walking on a hard surface at the same speed; while running on sand requires 1.6 times more energy expenditure than does running on a hard surface.*

More deflection = more energy dissipation

PVI relationship to fuel consumption

Quantify pavement properties
- Roughness (m/km)
- Deflection (mm)

Quantify excess fuel consumption
- Δ fuel consumption (l/km)

Accomplished for roughness and deflection using:
- Experimental results
- Empirical models
- Mechanistic models
Results of deflection-induced excess fuel consumption experiments vary significantly.

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
MIT approach: model-based assessment of PVI

Pavement Deflection
MIT Model
Structure and Material
Deflection & Roughness

Pavement Roughness
MEPDG+HDM4
Excess Fuel consumption
Environmental Impact
Deflection: **pavement-specific energy dissipation and excess fuel consumption**

**MIT Mechanistic Model***

**Input:**
- Pavement stiffness $E$
- Pavement Thickness $h$
- Substrate stiffness $k$

**Approach:**
- Calibrate/FHWA
- Validate/FHWA
- Excess Fuel Consumption from **Gradient Force**

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

*(Adapted from Fluegge, 1975)*

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**Roughness: vehicle-specific energy dissipation and excess fuel consumption**

Roughness measurement: Quarter-car model*

Excess fuel consumption: HDM-4 Model**:

\[ \delta E = \% E_0 (\text{IRI} - \text{IRI}_0) \]

Vehicle Specific

Reference IRI-Value

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>IRI-Value</th>
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<tbody>
<tr>
<td>Articulated Truck</td>
<td></td>
</tr>
<tr>
<td>Light Truck</td>
<td></td>
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<tr>
<td>Medium Car</td>
<td></td>
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<tr>
<td>SUV</td>
<td></td>
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<tr>
<td>Van</td>
<td></td>
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<tr>
<td>Average Light Duty Vehicle</td>
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</table>

Roughness measured at \(c=80 \text{ km/h}\)

\(C_S\) = Damping of Suspension System (Vehicle Specific)

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

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

Individual pavements  Pavement networks

11” JPCP w/ 1% in Dowels
6.0” Aggregate Sub-base
Subgrade
Individual pavement environmental impacts analyzed using life cycle assessment (LCA)

Scope includes all effects attributable to the pavement design.

- Extraction and production
- Transportation
- Onsite equipment
- Use
- Maintenance
- End-of-Life/Rehabilitation

- Pavement-Vehicle Interaction
  - Roughness
  - Deflection
- Albedo
- Carbonation
- Lighting
- Excavation
- Landfilling
- Recycling
- Transportation

Incorporating use phase in pavement LCA is a recent innovation.
LCA uses model-based assessment of PVI

Pavement Deflection

MIT Model

Pavement Roughness

MEPDG+HDM4

Structure and Material

Deflection & Roughness

Excess Fuel consumption

Environmental Impact
Use phase can be a significant fraction of pavement environmental impact

**Use** 48%
- **Construction** 35%
- **End-of-Life** 3%
- **M&R** 14%

**Fuel loss:**
- **deflection** 30%
- **roughness** 58%
- **Other*** 12%

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

*Other: carbonation & lighting
Use phase contribution depends on context

Urban Interstates

Use Phase Fraction of Total Impact

- Wet Freeze (MO)
  - Design A
  - Design B

- Dry No Freeze (AZ)
  - Design A
  - Design B
Use phase drivers depend on context

Urban Interstates

- **Design A**: 100% Roughness, 20% Deflection, 0% Other
- **Design B**: 100% Roughness, 0% Deflection, 0% Other

- **Wet Freeze (MO)**
- **Dry No Freeze (AZ)**
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

Total of ~700 million gallons of excess fuel per year

Annual excess fuel consumption (million gallons per year)

R = Rural
U = Urban

Estimate of US road network excess fuel consumption from PVI based on statistical analysis using FHWA LTPP data, MIT deflection model, and HDM-4 roughness model
PVI in a state DOT: the case of Virginia

Data:
- 15 interstates, 2 direction
- Years: 2007-2013
- Section ID
- Section milepost
- AADT, AADTT
- Layer thicknesses
- Material properties (2007)
- IRI (t)
Annual Excess Fuel Consumption: PVI Deflection

*2013 data

\[ c = 100 \text{ km/h} = 62.6 \text{ mph}; T = 16 \text{ C}/61 \text{ F} \]

FC (gallon/mile)

- Green: 20 - 739
- Light Green: 739 - 1682
- Yellow: 1682 - 2865
- Orange: 2865 - 4716
- Red: 4716 - 8395
Excess Fuel Consumption: PVI Roughness
*2013 data

FC (gallon/mile)

- <64
- 64-153
- 153-268
- 269-498
- 498-878
PVI Total Impact: Roughness and Deflection

*2013 data: Trucks

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

FC (gallon/mile)

- 49 - 858
- 859 - 1800
- 1801 - 2964
- 2965 - 4853
- 4854 - 8573

Map of Virginia showing different FC values with various colors.
Network: Annual PVI Truck* – excess FC per mile

*2013 data

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

Impact reduction through enhanced pavement design and management
Network: Annual PVI Truck – Total FC

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

### Annual excess CO2e emissions (tons)

<table>
<thead>
<tr>
<th>Year</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
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<td>0.0</td>
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<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>7.0</td>
</tr>
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### Annual excess fuel consumption (Gallons)

- **Deflection**
- **Roughness**
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
  – Florida International University
  – UCPRC?

• Continued partnerships with state DOTs
Conclusion: PVI can be an important element of transportation carbon management

- Infrastructure funding remains significantly below what is required to improve conditions and performance
  - Highway Trust Fund forecast to go bankrupt next year
  - Congress should consider GHG and cost savings from improved pavement design and management when debating a new long-term transportation bill
  - *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
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