Impact of PCC Pavement Structural Rolling Resistance on Vehicle Fuel Economy

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Outline

- Introduction
- Objective
- Approach
- Calculation of the fuel consumption due to the structural rolling resistance
- Results
- Conclusion
Factors Affecting Fuel Consumption

- **Vehicle**
  - Thermodynamic efficiency of the engine
  - Aerodynamics
  - Weight
  - Technological characteristics of the tire:
    - Inflation Pressure
    - Temperature
    - Design, materials, dimensions

- **Pavement**
  - Geometry
  - Surface characteristics
  - **Structural behavior of the pavement**
Objective

Evaluate the effects of concrete pavement structural characteristics on rolling resistance (SRR) and fuel consumption using a mechanistic approach.
Approach

Backcalculate PCC slab modulus and subgrade foundation parameters for concrete pavement sections

Simulate different vehicles at various speeds and positions on the slab

Calculate the energy dissipation and fuel consumption due to SRR
Backcalculation

- Eliminate the noise from the FWD time histories
- Use FFT algorithm to decompose the deflection signal of each sensor into a series of harmonic motions
- Use a closed form solution for the dynamic backcalculation of the effective $k$ and $c$ values for the base/subgrade
- Use the best fit method to get the static $k$ value and the elastic modulus of the concrete slab
- Compare the static and dynamic $k$ values
Dynamic Backcalculation (Chatti, 1992)

\[
k = \frac{\text{Re}(P_0) \int A \text{Re} UdA + \text{Im}(P_0) \int A \text{Im} UdA}{\left( \int A \text{Re} UdA \right)^2 + \left( \int A \text{Im} UdA \right)^2} + \omega^2 \rho
\]

\[
c = -\frac{1}{\omega} \frac{\text{Re}(P_0) \int A \text{Im} UdA - \text{Im}(P_0) \int A \text{Re} UdA}{\left( \int A \text{Re} UdA \right)^2 + \left( \int A \text{Im} UdA \right)^2}
\]
DYNASLAB
(Chatti, 1992)

- 2D Dynamic FE model with moving loads
- Elastic slabs on damped Winkler foundation
- Load transfer across joints modeled by a Kelvin-Voigt model (vertical spring $K_{AGG}$ and dashpot $C_{AGG}$ in parallel)
Load Transfer Efficiency

\[ LTE(\%) = \frac{\Delta_{i+1}}{\Delta_i} \times 100 \]

**Sensitivity analysis** to correlate \( K_{AGG} \) and \( C_{AGG} \) to the LTE of the joints

LTE sensitive to \( K_{AGG} \), not sensitive to \( C_{AGG} \)

Even when LTE=100% joints have an impact on the pavement response
Deflection as Seen by a Moving Vehicle
Slope as Seen by a Moving Vehicle

Front wheels of Tandem axle

Rear wheels of Tandem axle
Vehicle Energy Loss

\[ P_{RR}^{str} = \int_{S} p \frac{dw(x, y, z, t)}{dt} dS \]

\[ W_{RR} = \sum_{i=1}^{n} p_{i} S_{i} \sum_{j=1}^{m} \left( \frac{dw(x_{j}, t_{j})}{dx} \right) \cdot \Delta x \]

\[ W_{diss} [MJ / km] = W_{RR} \cdot \frac{1000}{L} \]

Assumptions:

- quasi-static regime
- non-dissipative tires

To take into account the dependency of the slope on time and on the location of the load, the slab is divided into \( m \) intervals of length \( \Delta x \).
Calculation of Fuel Consumption

Fuel consumption due to structural rolling resistance

\[ \text{Fuel}_{RR} = \frac{W_{diss}}{\xi_b} \]

\( \xi_b \) is the calorific value of the fuel.

Percent fuel consumption excess (due to SRR)

\[ \text{Fuel}_{excess} = \frac{\text{Fuel}_{RR}}{\text{Fuel}_C} \cdot 100 = \frac{W_{diss}}{\xi_b \cdot \text{Fuel}_C} \cdot 100 \]

<table>
<thead>
<tr>
<th>Type of engine</th>
<th>( \xi_b ) [MJ/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>10.5</td>
</tr>
<tr>
<td>Diesel</td>
<td>16</td>
</tr>
</tbody>
</table>
Pavement Sections

Section 2 day

\[ E_{pcc} = 40 \times 10^3 \text{ MPa} \]
\[ \nu = 0.15 \]
\[ k = 0.037 \text{ N/mm}^3 \]
\[ c = 0.261 \text{ MPa}\cdot\text{s/m} \]

Section 2 night

\[ E_{pcc} = 46 \times 10^3 \text{ MPa} \]
\[ \nu = 0.15 \]
\[ k = 0.046 \text{ N/mm}^3 \]
\[ c = 0.284 \text{ MPa}\cdot\text{s/m} \]

Section 3 day

\[ E_{pcc} = 35 \times 10^3 \text{ MPa} \]
\[ \nu = 0.15 \]
\[ k = 0.037 \text{ N/mm}^3 \]
\[ c = 0.256 \text{ MPa}\cdot\text{s/m} \]

Section 3 night

\[ E_{pcc} = 50 \times 10^3 \text{ MPa} \]
\[ \nu = 0.15 \]
\[ k = 0.048 \text{ N/mm}^3 \]
\[ c = 0.330 \text{ MPa}\cdot\text{s/m} \]

Section 4 day

\[ E_{pcc} = 47 \times 10^3 \text{ MPa} \]
\[ \nu = 0.15 \]
\[ k = 0.056 \text{ N/mm}^3 \]
\[ c = 0.323 \text{ MPa}\cdot\text{s/m} \]

Section 4 night

\[ E_{pcc} = 38 \times 10^3 \text{ MPa} \]
\[ \nu = 0.15 \]
\[ k = 0.055 \text{ N/mm}^3 \]
\[ c = 0.294 \text{ MPa}\cdot\text{s/m} \]
# Vehicle Characteristics and Positions

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Vehicle Characteristics</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of axles</td>
<td>Number of tires</td>
<td>Load per Axle [kN]</td>
<td>Load per Tire [kN]</td>
</tr>
<tr>
<td>Medium Car</td>
<td>2</td>
<td>4</td>
<td>7.15</td>
<td>3.58</td>
</tr>
<tr>
<td>SUV</td>
<td>2</td>
<td>4</td>
<td>12.25</td>
<td>6.13</td>
</tr>
<tr>
<td>Loaded Truck</td>
<td>1</td>
<td>4</td>
<td>151.41</td>
<td>37.85</td>
</tr>
</tbody>
</table>

![Diagram of vehicle characteristics and positions](image)
Excess Fuel Consumption Results – Truck Tandem Axle

Full loaded Truck - Edge Loading

Full loaded Truck - Offset Loading
Excess Fuel Consumption Results - SUV

**SUV - Edge Loading**

**SUV - Offset Loading**
Excess Fuel Consumption Results - Car
### Contribution of Rolling Resistance to Fuel Consumption

<table>
<thead>
<tr>
<th></th>
<th>$F_c$ [mL/km] (using NCHRP720 model)</th>
<th>% FC due to SRR Edge Loading</th>
<th>% FC due to SRR Offset Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 km/h</td>
<td>100 km/h</td>
<td>50 km/h</td>
</tr>
<tr>
<td>Medium Car</td>
<td>70.0</td>
<td>95.6</td>
<td>0.002</td>
</tr>
<tr>
<td>SUV</td>
<td>78.7</td>
<td>120.9</td>
<td>0.004</td>
</tr>
<tr>
<td>Loaded Truck</td>
<td>273.4</td>
<td>551.7</td>
<td>0.072</td>
</tr>
</tbody>
</table>

SRR contribution to FC is less than 0.1%
Conclusion

The excess fuel consumption of a vehicle travelling on concrete pavements due to the SRR is a very small quantity: less than 0.1% of the total fuel consumption of the truck.

While this excess fuel consumption due to the structural rolling resistance is very small, it has been shown that:

- Increasing the speed increases the fuel consumption due to SRR.
- The fuel consumption due to SRR increases as the wheel is closer to the slab edge.
- A stronger foundation (base and subgrade) reduces the fuel consumption due to SRR.
Future Studies

- Study the effect of shoulders/adjacent lanes and LTE less than 100%
- Consider the curling and warping effects
- Compare the results with simulations on asphalt and composite pavements

Thank you for your attention!
Questions?