Pavement Life-Cycle Assessment Symposium 2017
Champaign, IL | April 12-13, 2017

Impact of PCC Pavement Structural Rolling Resistance on Vehicle Fuel Economy

Danilo Balzarini, Imen Zaabar, and Karim Chatti

Department of Civil & Environmental Engineering
Michigan State University

Acknowledgements

- This study was conducted in collaboration with **Dr. John Harvey** (University of California, Davis) and Dr. Erdem Coleri (Oregon State University).
- The authors would like to acknowledge the financial support of the **California Department of Transportation**.

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

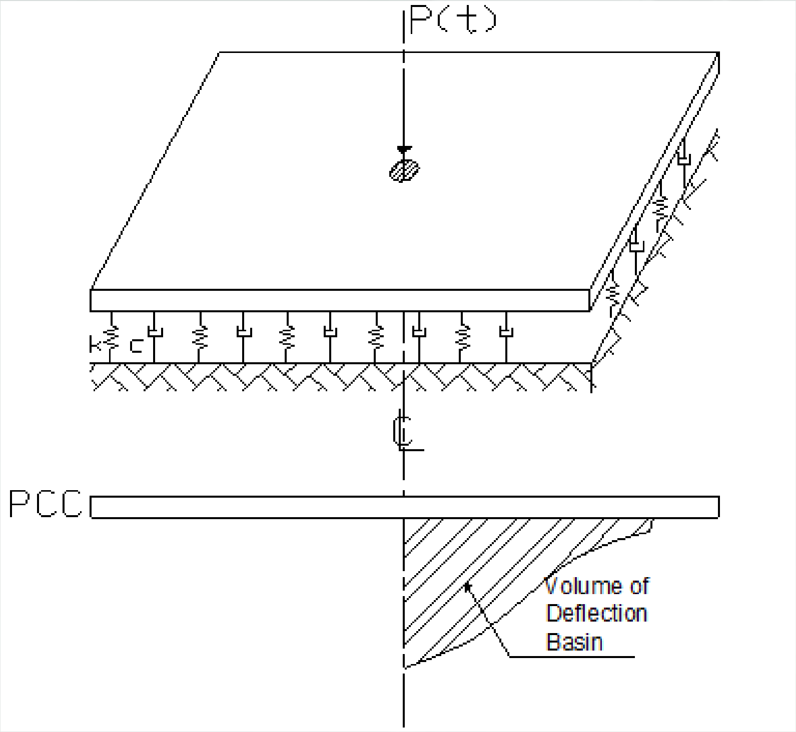
↓

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

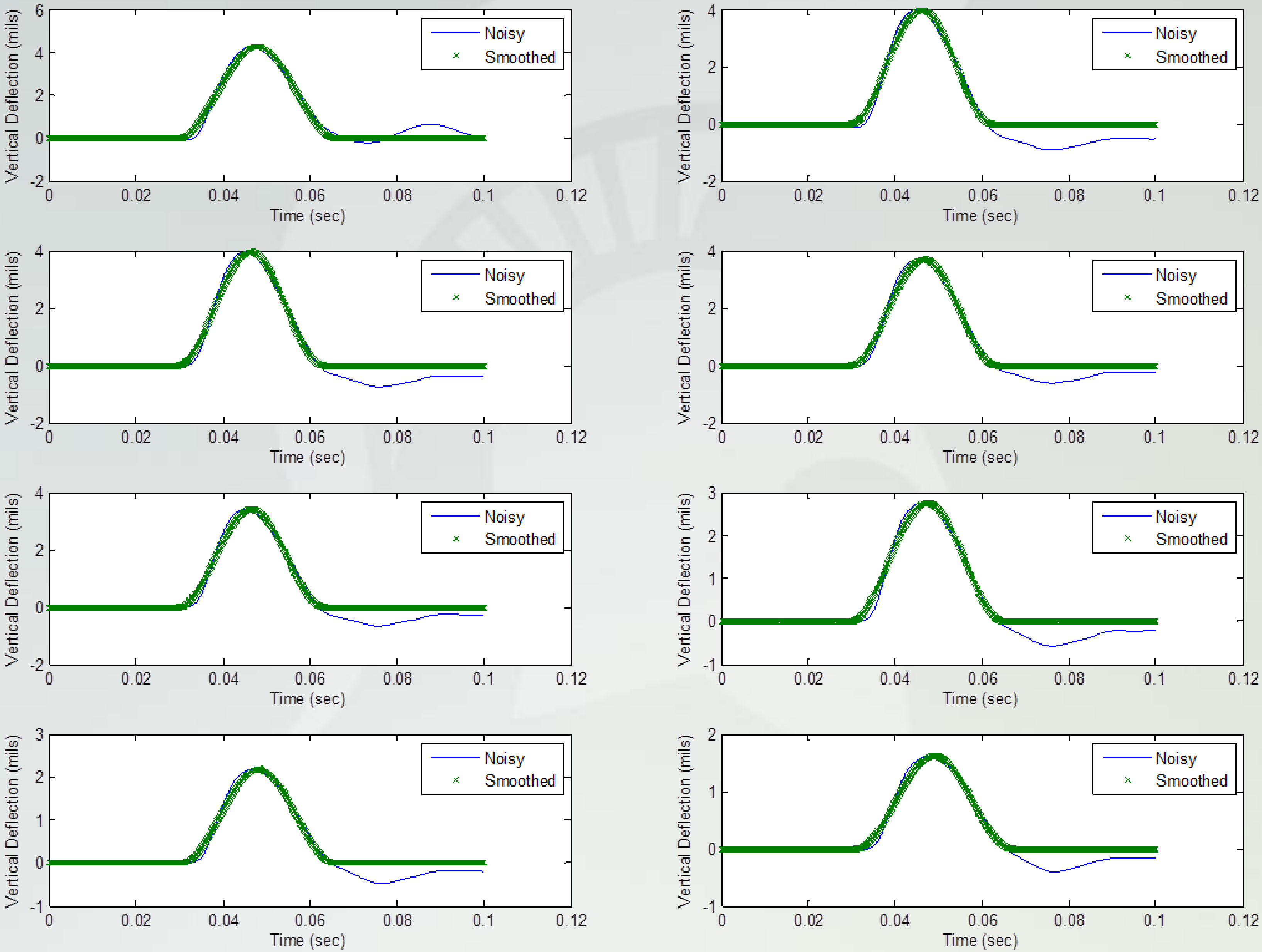
Dynamic Backcalculation
(Chatti, 1992)



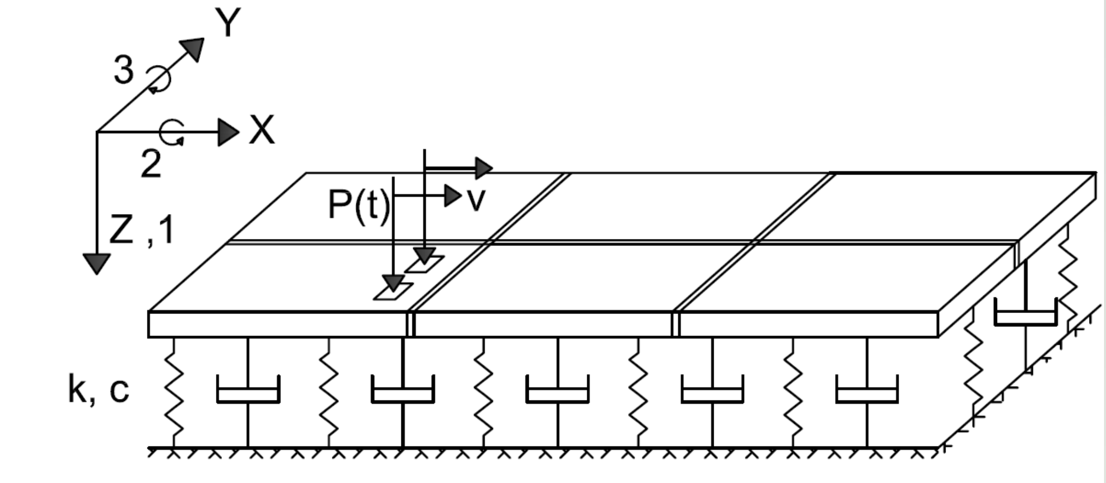
$$k = \frac{\mathrm{Re}(P_0)\int_A \mathrm{Re}\,U\,dA + \mathrm{Im}(P_0)\int_A \mathrm{Im}\,U\,dA}{\left(\int_A \mathrm{Re}\,U\,dA\right)^2 + \left(\int_A \mathrm{Im}\,U\,dA\right)^2} + \omega^2\rho$$

$$c = -\frac{1}{\omega}\,\frac{\mathrm{Re}(P_0)\int_A \mathrm{Im}\,U\,dA - \mathrm{Im}(P_0)\int_A \mathrm{Re}\,U\,dA}{\left(\int_A \mathrm{Re}\,U\,dA\right)^2 + \left(\int_A \mathrm{Im}\,U\,dA\right)^2}$$

FWD Deflection Time Histories



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

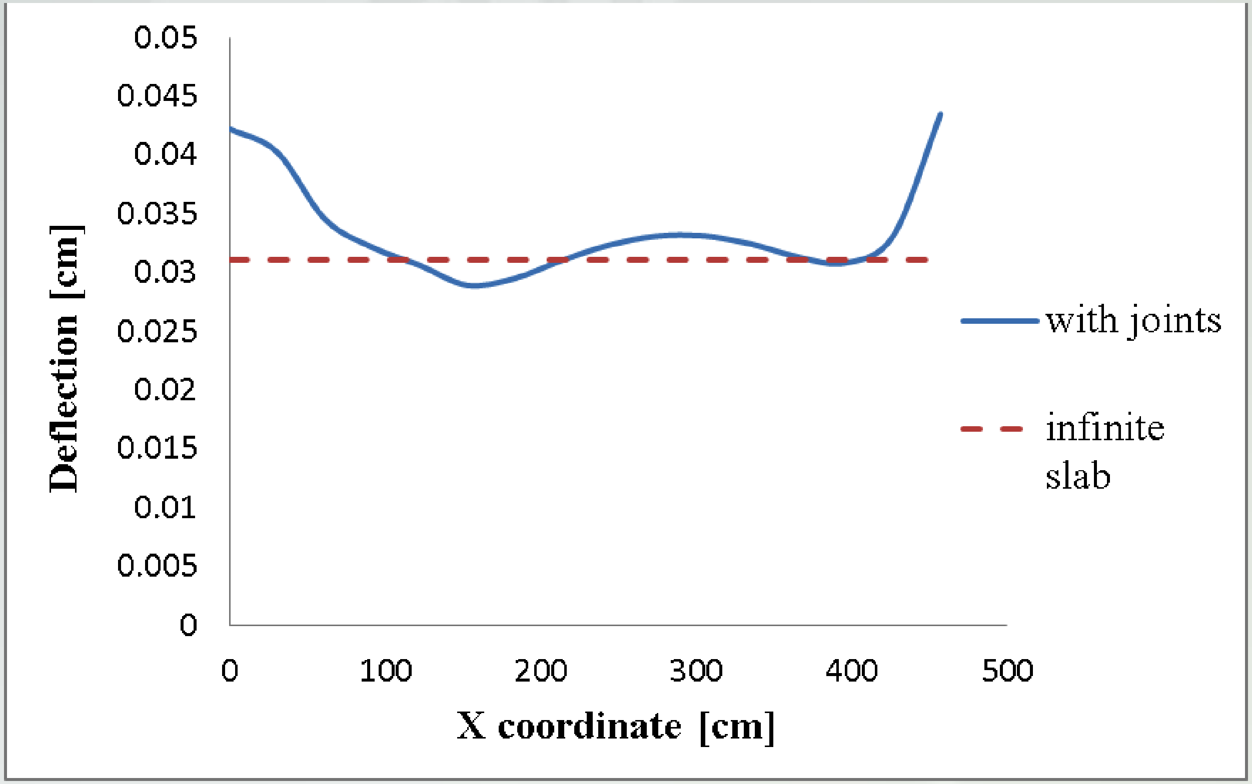
$$LTE(\%) = \frac{\Delta_{i+1}}{\Delta_i} \cdot 100$$

Sensitivity analysis to correlate K_{AGG} and C_{AGG} to the LTE of the joints

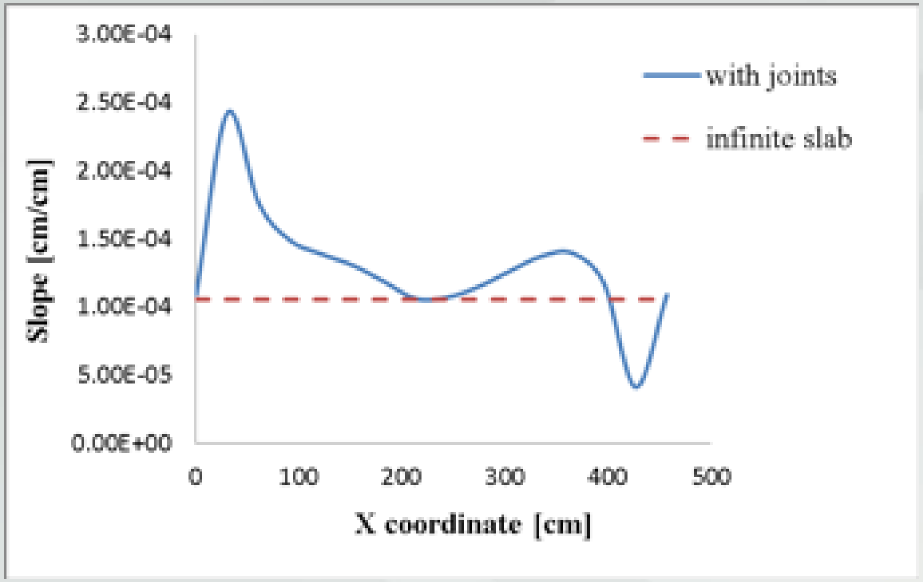
LTE sensitive to K_{AGG}, not sensitive to C_{AGG}

Even when LTE=100% joints have an impact on the pavement response

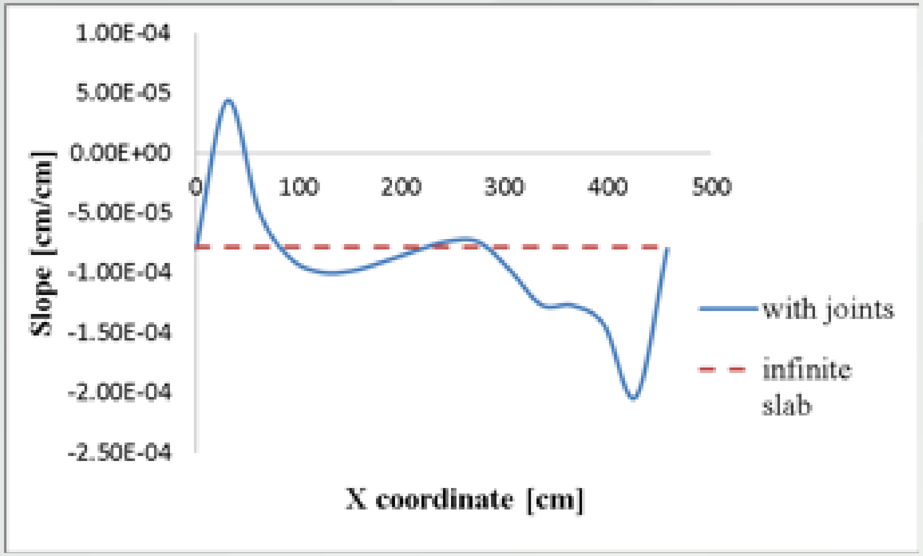
Deflection as Seen by a Moving Vehicle



Slope as Seen by a Moving Vehicle



Front wheels of Tandem axle



Rear wheels of Tandem axle

Vehicle Energy Loss

$$P_{RR}^{str} = \int_S p \frac{dw(x,y,z,t)}{dt} dS$$

$$W_{RR} = \sum_{i=1}^{n} p_i S_i \sum_{j=1}^{m} \left\langle \frac{dw(x_j, t_j)}{dx} \right\rangle \cdot \Delta x$$

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

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 Δx

Calculation of Fuel Consumption

Fuel consumption due to structural rolling resistance

$$Fuel_{RR} = \frac{W_{diss}}{\xi_b}$$

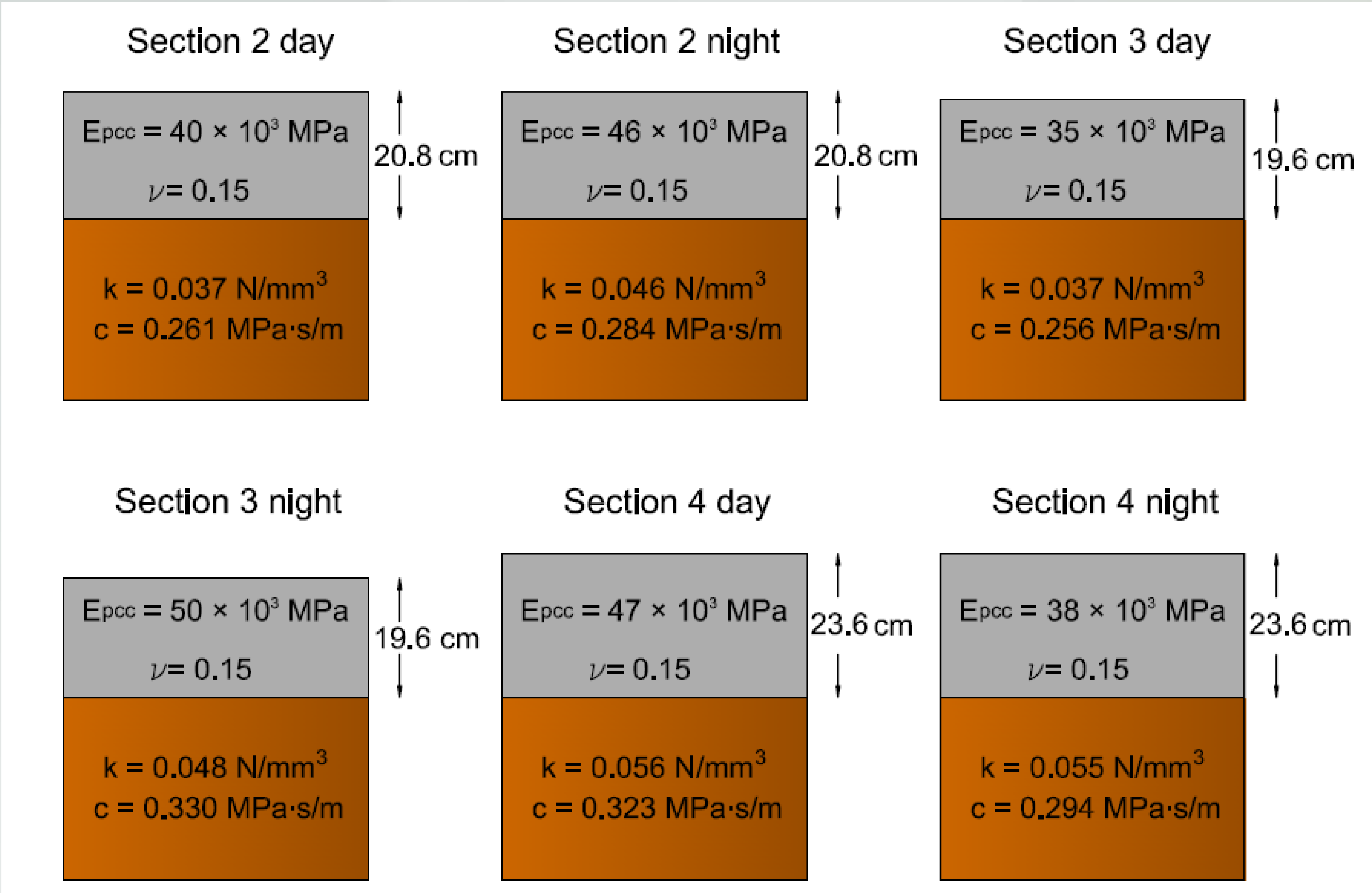
ξ_b is the calorific value of the fuel.

Type of engine	ξ_b [MJ/L]
Gasoline	10.5
Diesel	16

Percent fuel consumption excess (due to SRR)

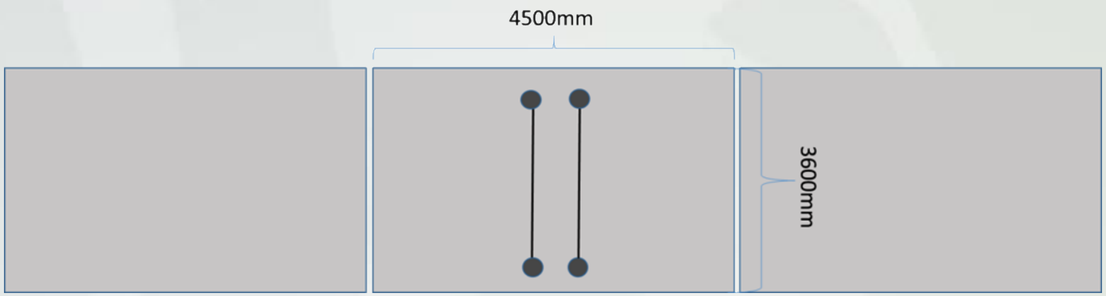
$$Fuel_{excess} = \frac{Fuel_{RR}}{Fuel_C} \cdot 100 = \frac{W_{diss}}{\xi_b \cdot Fuel_C} \cdot 100$$

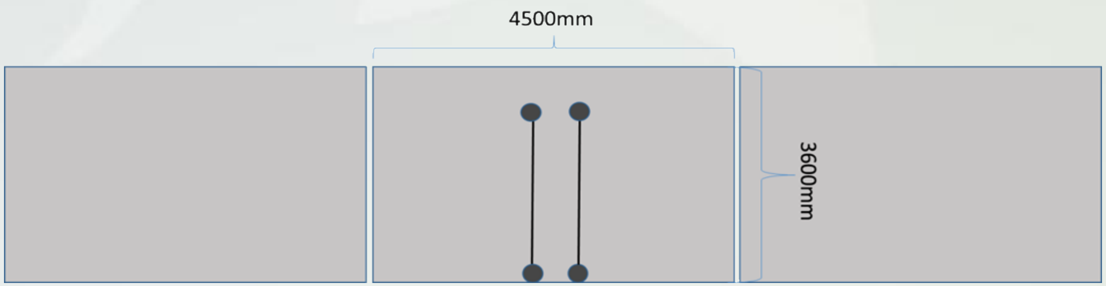
Pavement Sections



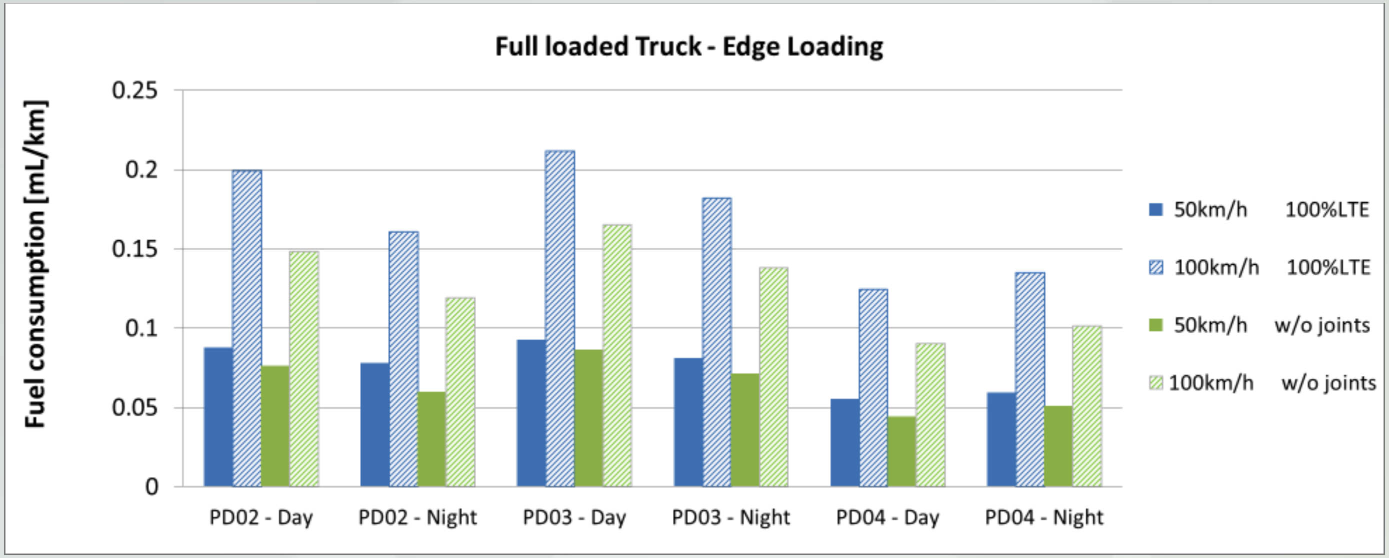
Vehicle Characteristics and Positions

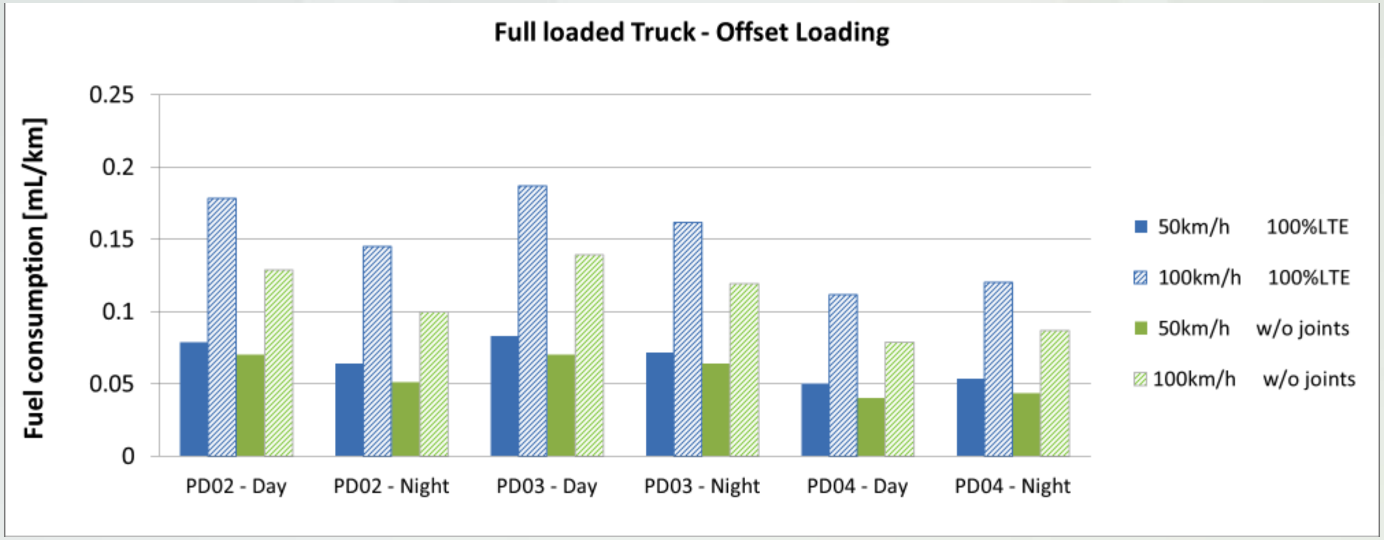
Vehicle Class	Vehicle Characteristics			
	Number of axles	Number of tires	Load per Axle [kN]	Load per Tire [kN]
Medium Car	2	4	7.15	3.58
SUV	2	4	12.25	6.13
Loaded Truck	1	4	151.41	37.85



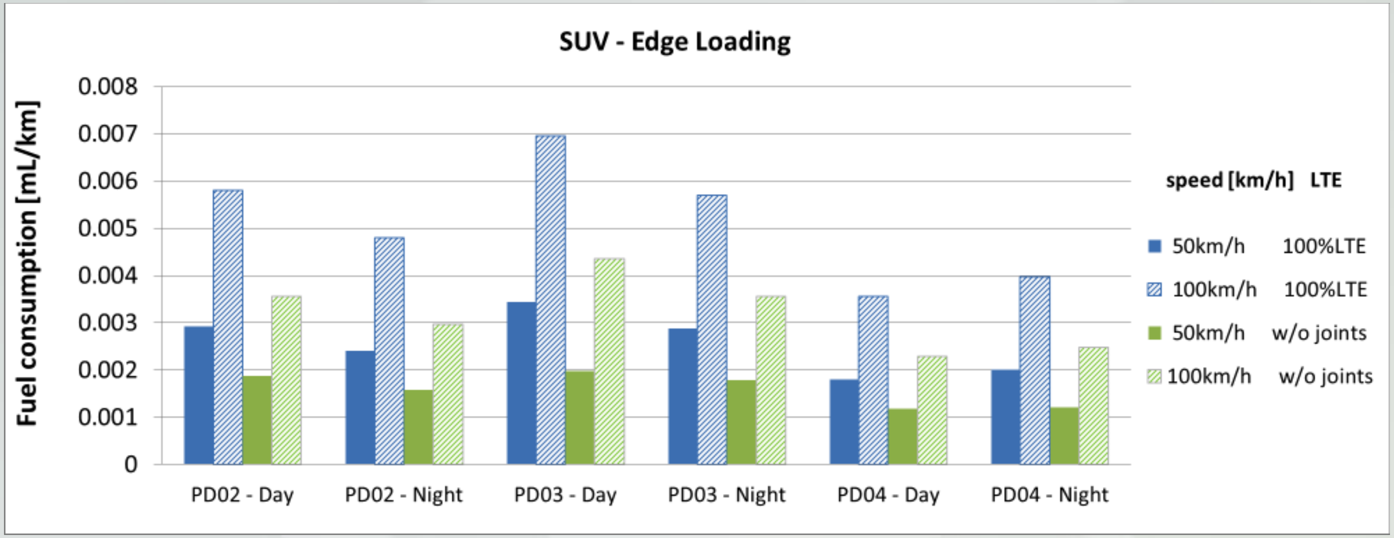


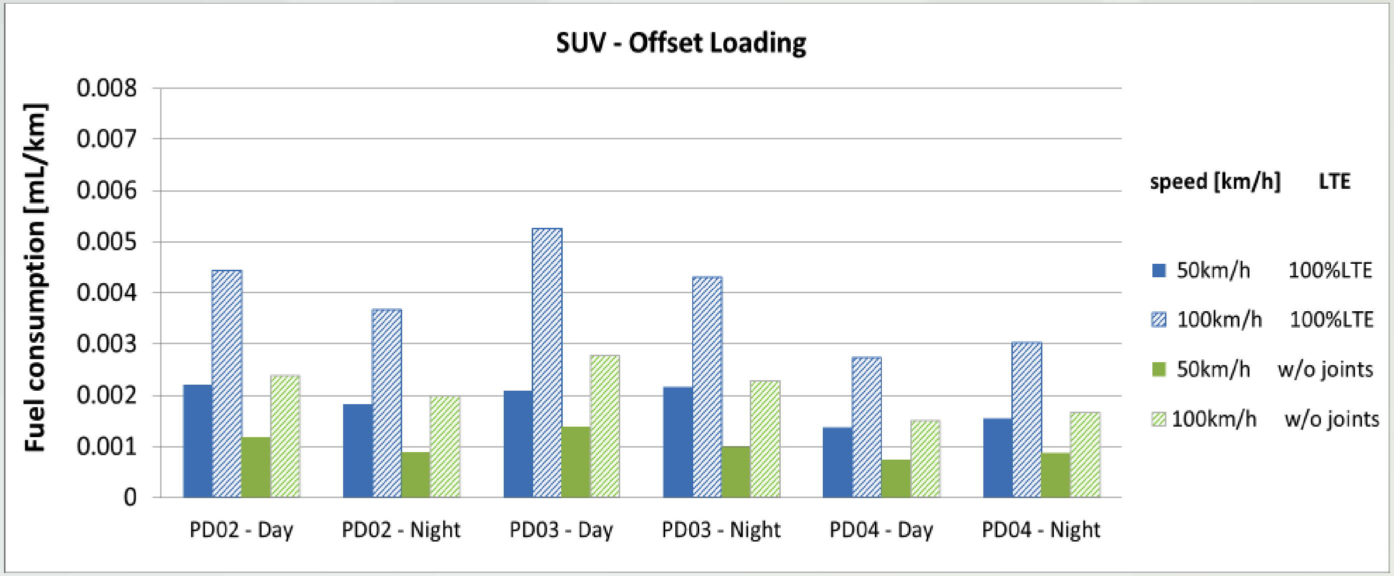
Excess Fuel Consumption Results – Truck Tandem Axle



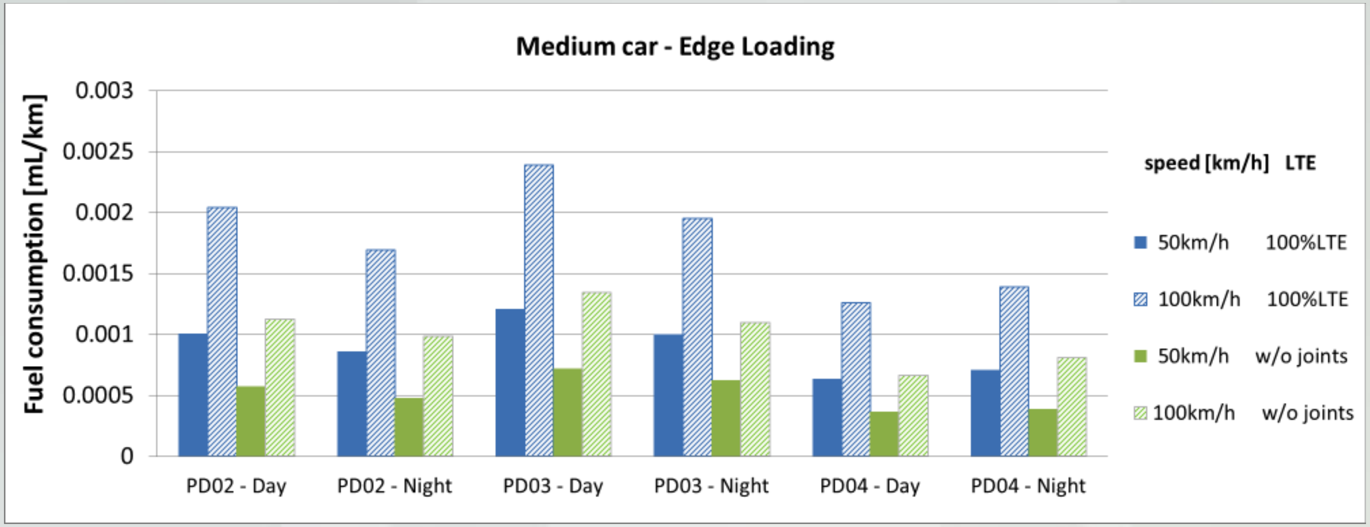


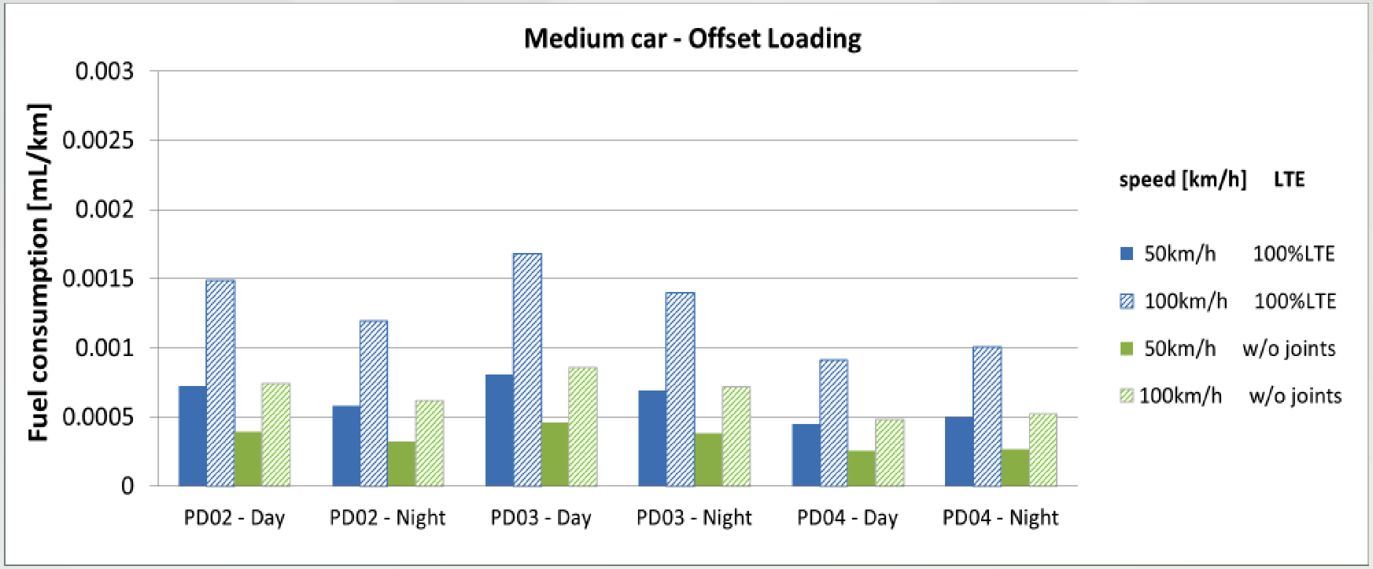
Excess Fuel Consumption Results - SUV





Excess Fuel Consumption Results - Car





Contribution of Rolling Resistance to Fuel Consumption

	F_C [mL/km] (using NCHRP720 model)		% FC due to SRR Edge Loading		% FC due to SRR Offset Loading	
	50 km/h	100 km/h	50 km/h	100 km/h	50 km/h	100 km/h
Medium Car	70.0	95.6	0.002	0.002	0.001	0.002
SUV	78.7	120.9	0.004	0.006	0.003	0.004
Loaded Truck	273.4	551.7	0.072	0.081	0.064	0.072

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?