

Impact of PCC Pavement Structural Response on Rolling Resistance and Vehicle Fuel Economy

D. Balzarini

Michigan State University, East Lansing, Michigan, USA

I. Zaabar

Michigan State University, East Lansing, Michigan, USA

K. Chatti

Michigan State University, East Lansing, Michigan, USA

ABSTRACT: Reduction in vehicle fuel consumption is one of the main benefits considered in technical and economic evaluations of road improvements considering its significance. Surface roughness, texture, and structural response are the main pavement characteristics influencing rolling resistance. This project investigates the increase in vehicle energy consumption caused by the structural response of a cement concrete pavement. The rotation and deformation of the slabs on a viscoelastic subgrade, which is represented as a damped Winkler foundation, cause the vehicle to consume additional energy to overcome the slope formed by the local deflection basin. The structural rolling resistance is calculated on sections with different mechanical characteristics at different speeds, temperature, loading conditions and subsequently converted into fuel consumption excess. The maximum deflection-induced energy consumption is about 0.1% of the total consumption for articulated trucks. Note that the effects of curling and load transfer efficiency (LTE) below 100% were not considered in this study.

1 INTRODUCTION

The theme of sustainable development is of primary importance today. The chance to reduce fuel consumption required by vehicles for their operation and thus to lower energy prices has its effect on consumers, businesses and environment.

To reduce the environmental impact of mobility on the road, one of the objectives is to reduce the energy consumption of vehicles. For this purpose, the EU and the US have set binding emission targets for new fleets of cars and vans, leading all major automobile manufacturers to compete with massive investment in technological development and innovation in the energy sector to reduce emissions throughout the life cycle of the vehicle. However, the search for higher performance engines with lower fuel consumption is not the only way forward. Many factors, beyond the thermodynamic efficiency of the engine, have an impact on the fuel consumption of a vehicle. The main ones are the air resistance and the rolling resistance.

Rolling resistance is a force acting in the direction opposite to that of motion, during the rolling of the tire on the road pavement. It includes mechanical energy losses due to aerodynamic drag associated with rolling, friction between the tire and road and between the tire and rim, and energy losses taking place within the structure of the tire.

The characteristics of the tire that affect the rolling resistance the most are the tire material, shape, width and the inflation pressure. It has been proven that the rolling resistance at the pavement - wheel interface is also significantly affected by the surface of the pavement. A report published by Epa/Eurobitume Task Group (2004) states that different textures of road surfaces influence fuel consumption by up to 10%. The NCHRP 720 study (Chatti & Zaabar 2012) proved from field data that different surface characteristics provide a major contribution to the rolling resistance. Since 2012 more studies have been conducted on the Structural Rolling Resistance (SRR), which can be estimated using two methods:

- Considering the stress-strain history, as the energy dissipated in the hysteresis loop of the viscoelastic material, in a finite volume of pavement (Coleri et al. 2016, Pouget et al. 2012, Shakiba et al. 2016).
- Considering the deflection basin, in terms of the energy required for a rolling wheel to move uphill, facing a positive slope caused by the delayed deformation of the viscoelastic pavement. (Louhghalam et al. 2013, Chupin et al. 2013).

All of these studies assumed the asphalt pavement to be a homogeneous continuous viscoelastic medium, which is a valid hypothesis for asphalt pavements but can't be applied to rigid pavements, due to the discontinuities caused by the joints. The study carried out in this paper investigates the effect of the SRR on rigid pavements, namely the increase of vehicle energy consumption induced by the pavement structural response due to the deformation of subgrade materials and the rotation of the concrete slabs under passing vehicles. This study is part of a research that aims to quantify rolling resistance due only to the structure of the pavement. In parallel with the study shown in the paper, different models are being developed to evaluate the SRR on flexible pavement. The findings of these studies will finally be compared and checked versus field measurements to establish if different types of pavement (rigid or flexible) or different pavement structures could lead to a change in rolling resistance and therefore in fuel consumption. The approach used to estimate the fuel consumption excess of a vehicle caused by the SSR is in three folds:

- (1) Compute the concrete pavement response due to a moving vehicle of three types of vehicles (car, SUV, truck) at different speeds and positions on the slab using a finite element solution (DYNASLAB).
- (2) Calculate the energy dissipated in the pavement, which is equal to the energy needed by the vehicle to overcome the additional traction forces caused by the pavement's deformation.
- (3) Estimate the fuel consumption excess due to such energy dissipation.

2 CONCRETE PAVEMENT RESPONSE

The calculation of the response of the pavement is performed using the 2D finite element software DYNASLAB (Chatti 1992). The program can analyze pavements with one or two layers resting on a damped frequency-dependent Winkler foundation, modeled by uniformly distributed springs and dashpots. The concrete slab is modeled by rectangular medium-thick plate elements. Each node contains three degrees of freedom: a vertical translation in the *s*-direction and two rotations about the *x* and *y* axes, respectively. The program can also analyze multiple slabs with variable load-transfer mechanisms across cracks and joints: a bar element to represent dowel bars or a vertical Kelvin-Voigt element (spring and dashpot connected in parallel) to represent the aggregate interlock. The moving load is simulated using finite-element shape functions at successive time-dependent positions of the vehicle.

In this paper, three different concrete pavements sections located in I-5 and US-50 near Sacramento were used (Figure 1). Their mechanical characteristics were backcalculated from falling weight deflectometer tests, which have been conducted during daytime and nighttime, so that the effects of daily temperature change could be accounted for.

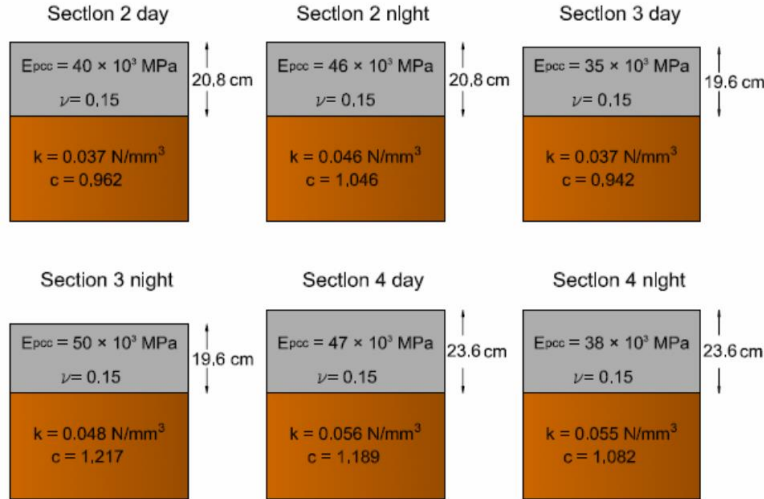


Figure 1. Pavement sections

2.1 Effects of the joints

Any concrete pavement requires joints. Through the joints, the bending and shear stresses are transferred between slabs. When a slab is loaded, the adjacent slabs also deflect, and the Load transfer efficiency (LTE) is defined as

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

where Δ_i is the deflection on the edge of the loaded slab and Δ_{i+1} is the deflection on the edge of the adjacent slab. In this study the joints are modeled by a Kelvin-Voigt element, consisting of a spring and dashpot connected in parallel. DYNASLAB does not allow entering the LTE value as an input, therefore a sensitivity analysis has been conducted to establish the relation between the k , c values of the spring and dashpot and the load transfer efficiency. FWD tests have been simulated in DYNASLAB using different values of k and c , and the LTE associated with each of those values was calculated. The sensitivity analysis showed that LTE is highly sensitive to the stiffness but not sensitive to the damping coefficient (Fig. 2).

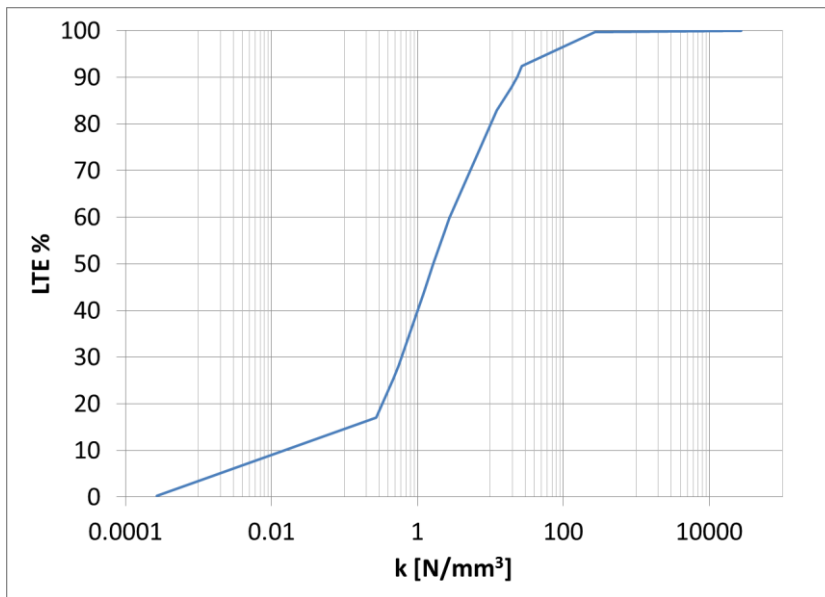


Figure 2. Relation between LTE and spring stiffness

The joints have a major impact on the structural behavior of the pavement. While asphalt pavements can be assumed to be represented as a continuous medium, PCC pavement cannot be considered as a semi-infinite in the longitudinal or in the transversal direction. Joints have a significant impact on the response and even more on the energy dissipation, since relative rotation between two consecutive slabs is allowed even when the deflection is continuous along the pavement (LTE=100%). From the point of view of a load moving along a semi-infinite slab, the deflection basin would be the same for the entire duration of travel; the maximum deflection would be constant and located under the load. Instead, considering a finite length slab, the deflection basin would depend on the position on the slab. At any different location of the load on the slab the rotation parameter changes, and so does the deflection basin. Figure 3 shows the deflection of both jointed and infinite PCC pavement under the front axle of a truck pavement without joints. When the load is closer to the edges ($x=0$, $x=450$) the rotation of the slab is maximum, and thus the deflection is higher.

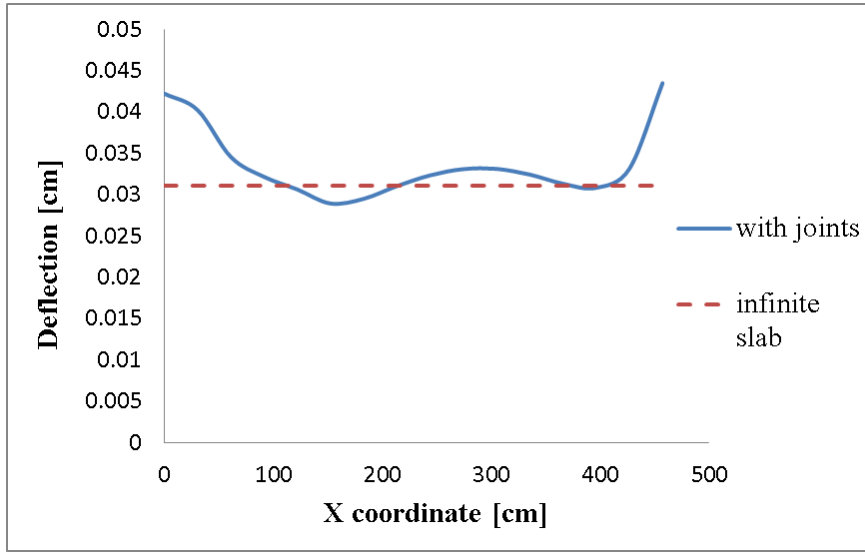


Figure 3. Effects of the joints on the value of the deflection under the tire

3 CALCULATION OF THE ENERGY LOSS OF THE VEHICLE

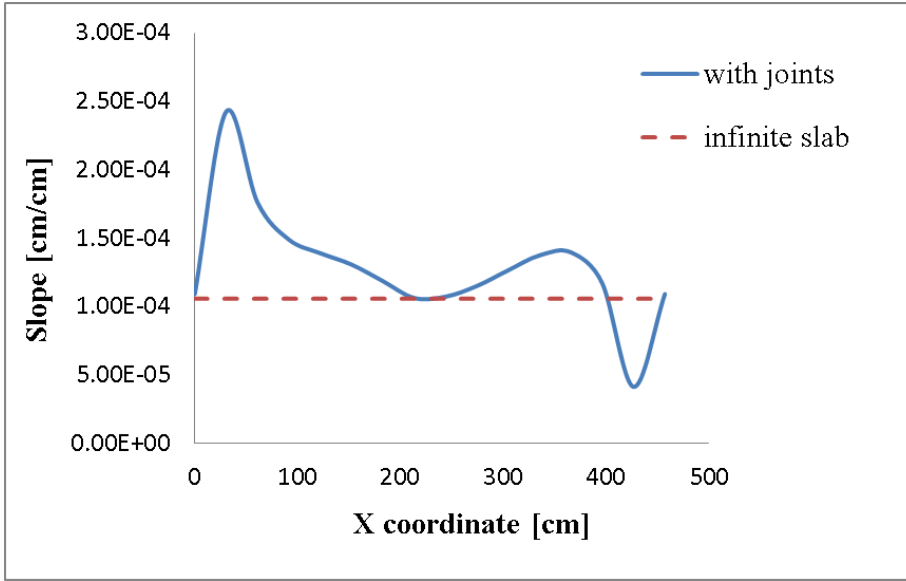
It has been shown that, with the assumptions of a quasi-static regime, and non-dissipative vehicle tires, the power dissipation of a wheel due to the structural rolling resistance can be evaluated as (Chupin et al. 2013):

$$P_{RR}^{str} = \int_S p \frac{dw(x, y, z, t)}{dt} dS \quad (2)$$

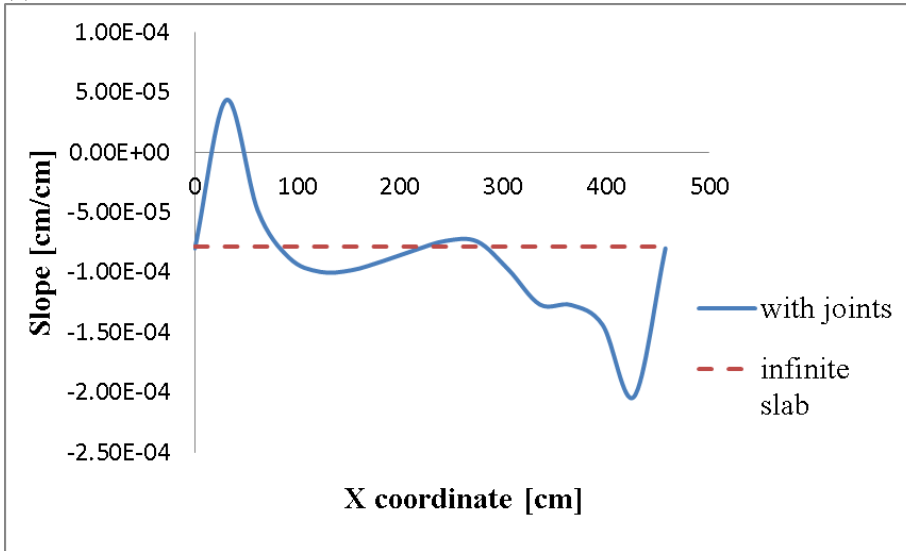
Where p is the pressure applied on the pavement, S is the area of the tire print and $w(x,y,z,t)$ is the deflection of the pavement.

As well as the deflection basin, also the average slope under the tire depends on the position of the wheels on the slab. In Figure 4a the slope as seen by the wheels of the front of a trailed tandem axle moving at 100 km/h is shown. The slope is maximum at the moment the tire print is entirely on the slab ($x=30$), while it is minimum as the wheel is leaving the slab. The rear axle surmounts the slab when the front axle is in $x=152$, and it can be noted that the slope does not change significantly, however, when the LTE is lower than 100%, the slope has a sudden increase. Figure 4b shows that the slope as seen by the rear axle is negative for most of the time. It is due to the fact that the maximum deflection of the slab is generally located between

the two axes. There is no gain of energy, since the effects of the two axes cannot be decoupled.



(a)



(b)

Figure 4. Slope as seen by the front (4a) and back wheels (4b) of a trailed tandem axle of a loaded truck at 100 km/h, central loading.

To take into account the dependency of the slope on time and the position on the slab, the slab (of length L) is divided into m intervals of length. The energy dissipated on the slab is calculated as

$$W_{RR} = \sum_{i=1}^n p_i S_i \sum_{j=1}^m \left\langle \frac{dw(x_j, t_j)}{dx} \right\rangle \cdot \Delta x \quad (3)$$

The total energy dissipated by the vehicle per mile can be calculated as

$$W_{diss} [MJ / km] = W_{RR} \cdot \frac{1000}{L} \quad (4)$$

Where L is the length of the slab.

4 ESTIMATION OF THE FUEL CONSUMPTION EXCESS

The fuel consumption excess caused by the dissipation of energy can be evaluated as following:

$$Fuel_{RR} = \frac{W_{diss}}{\xi_b} \quad (5)$$

The factor ξ_b is the effective calorific value of the combustible, and is a function of the engine technology. According to Baglione (2007), the maximum efficiency of Gasoline engines is about 25-30% while it is about 40% for Diesel engines; those percentages represent the energy released by the Gasoline and Diesel engines that will be available to move the vehicle. Since the calorific value of Diesel is about 40 MJ/L and the one of Gasoline is about 34 MJ/L, the value used for ξ_b is 16 MJ/L for a Diesel engine and 10.5 MJ/L for a Gasoline engine.

5 RESULTS

Typical slab length (4.50 m, 15 ft.) and width (3.6 m, 12 ft.) are considered in the simulation. Three types of vehicles are simulated moving along the sections (medium car, SUV and the trailed tandem axle of a loaded truck) at two different speeds: 50 km/h and 100 km/h. For the truck, only one tandem axle has been considered; the other axles do not affect the response significantly since different axles are never located on the same slab at the same time. The characteristics of the loading for each type of vehicle used are shown in Table 1. For each vehicle two simulations are made with a different position of the wheels on the slab, as shown in Figure 5.

Table 1. Characteristics of the vehicles and their fuel consumption

Vehicle	Vehicle Characteristics				Fuel Consumption			
					Fc [ml/km]		Max Fuel _{excess} [%]	
	Number of axles	Number of tires	Load per Axle [kN]	Load per Tire [kN]	50 km/h	100 km/h	50 km/h	100 km/h
Car	2	4	7.15	3.58	70.0	95.6	0.002	0.002
SUV	2	4	12.25	6.13	78.7	120.9	0.004	0.006
Truck	1	4	151.42	37.85	273.4	551.7	0.072	0.081

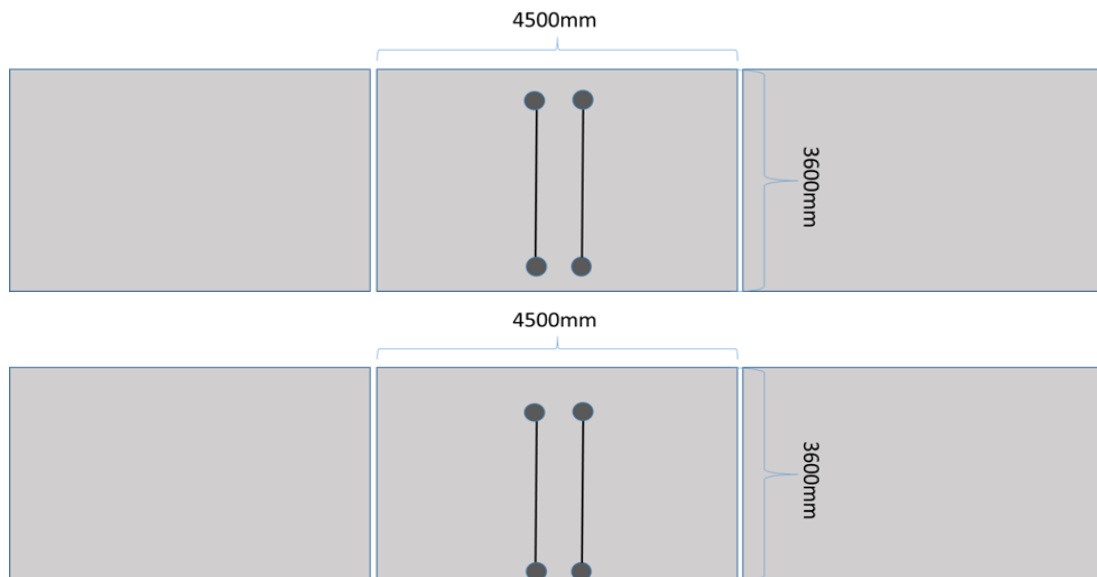


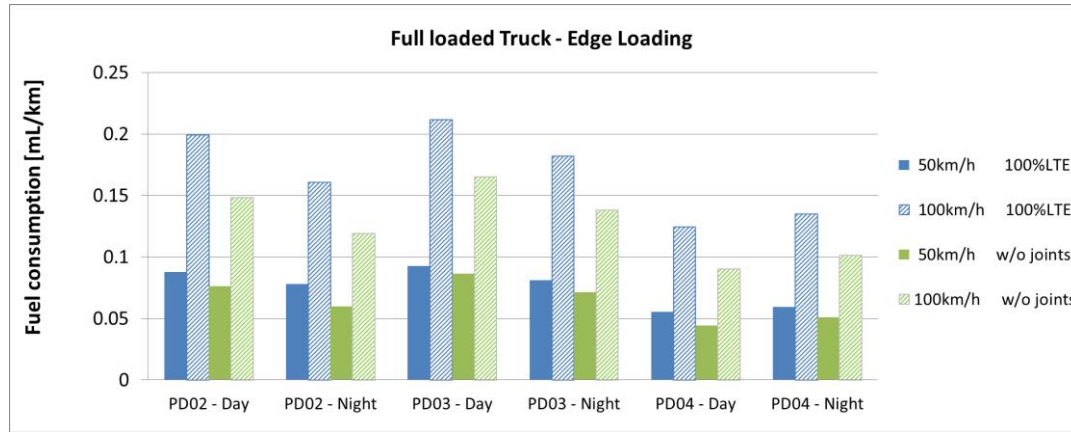
Figure 5. Offset and edge loading.

The fuel consumption excess is calculated as a percentage of the consumption ($Fuel_C$) of the vehicle calculated using the HDM4 Model (Chatti & Zaabar 2012):

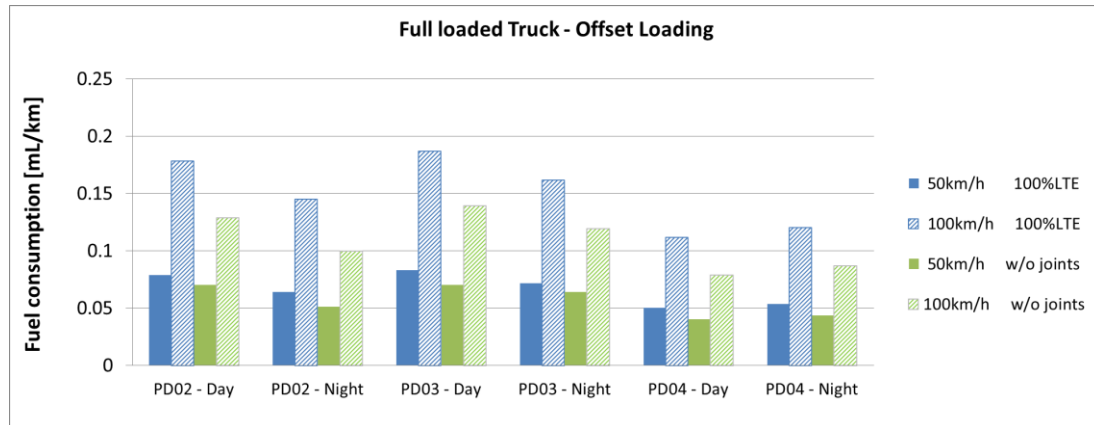
$$Fuel_{excess} = \frac{Fuel_{RR}}{Fuel_C} \cdot 100 = \frac{W_{diss}}{\xi_b \cdot Fuel_C} \cdot 100 \quad (6)$$

The model provides an estimation of the fuel consumption of a vehicle at different speeds based on the power required to overcome the traction forces P_{tr} (which include rolling resistance), the power required for engine accessories P_{accs} (e.g. fan belt, alternator etc.) and the power required to overcome internal engine friction P_{eng} . The F_c value used in the paper was obtained using standard parameters for the vehicles to account for P_{accs} and P_{eng} ; no grade, curvature or acceleration were considered and the road surface is in good condition (IRI=1 m/km, 0.5 mm texture).

The estimations of the fuel consumption of the vehicles are shown in Figures 6-8. The results are shown for the sections with and without joints. Although it is not realistic to consider concrete pavement without joints (except for continuously reinforced concrete pavements), the comparison points out how the joints increase the energy dissipation due to the structural rolling resistance.



(a)



(b)

Figure 6. Comparison between fuel consumption excess due to structural response of a jointed concrete pavement with 100%LTE and an infinite slab to a moving tandem axle at different speeds.

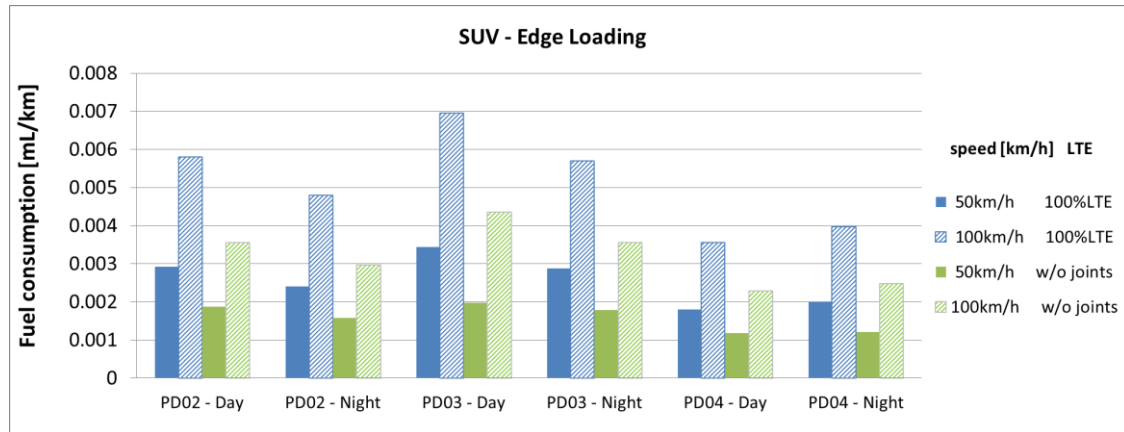
The fuel consumption is directly proportional to the speed. Although the deflection is higher at lower speeds, the slope seen by the wheels increases with the velocity. For an increase of 100% of the velocity of the vehicle, the fuel consumption excess increases of 83-129%, where the higher increase occurs for heavier loads.

The position of the wheels on the slab also affects the fuel consumption excess: for the pavement with joints the difference between edge and offset loading is 9-12% for a truck, 23-25% for the SUV and 27-33% for the medium car.

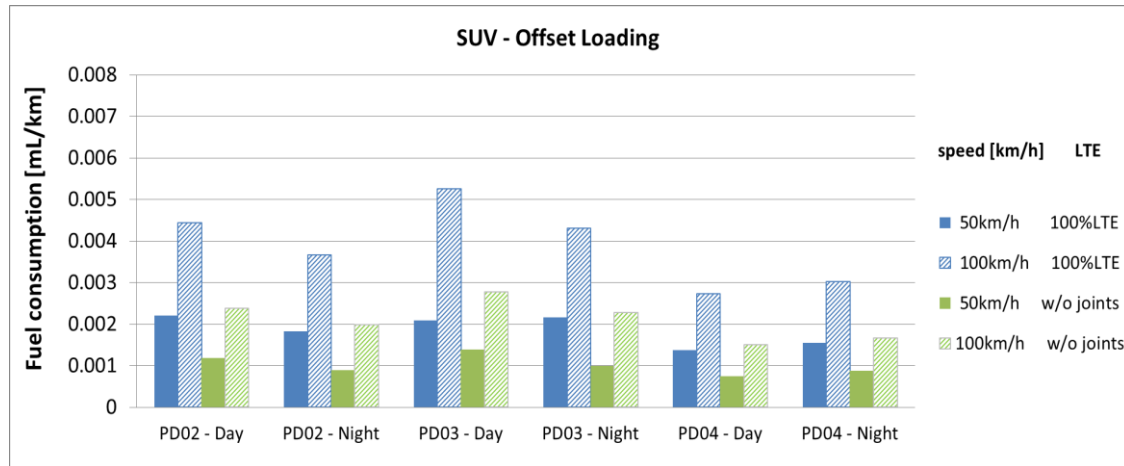
The temperature does not seem to be affecting the structural rolling resistance significantly. The difference in fuel consumption between day and night is small and does not show a specific trend, for sections 2 and 3 the fuel consumption is higher during daytime, while for section 4 it is higher during nighttime.

The section that shows the least structural rolling resistance is section 4, which has a thicker concrete slab and higher values of the Winkler foundation parameters k, c when compared to the other sections.

In general the results show that the fuel consumption excess due to the structural rolling resistance on a rigid PCC pavement does not exceed 0.22 mL/km per axle for a truck, which, when compared to the consumption of the entire vehicle, corresponds to a $Fuel_{excess} \cong 0.08\%$ (see table 1), which is a very small quantity.

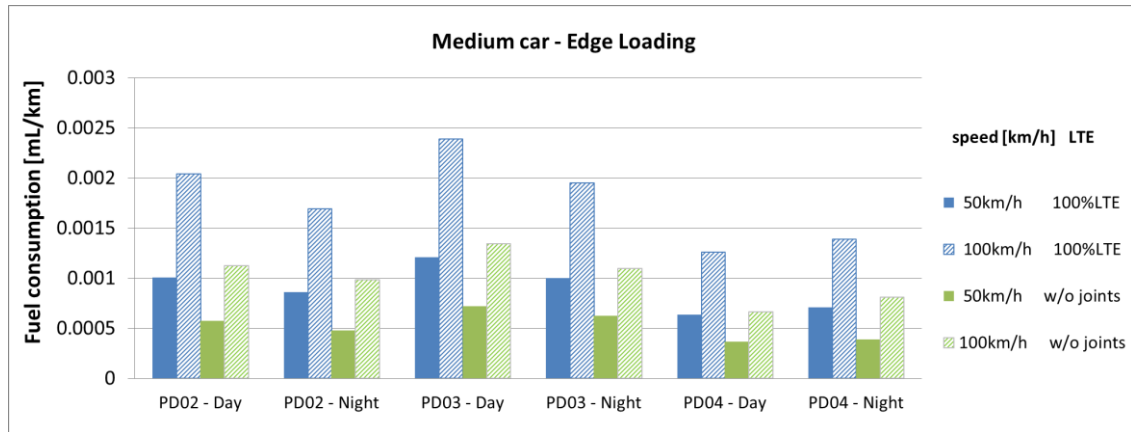


(a)

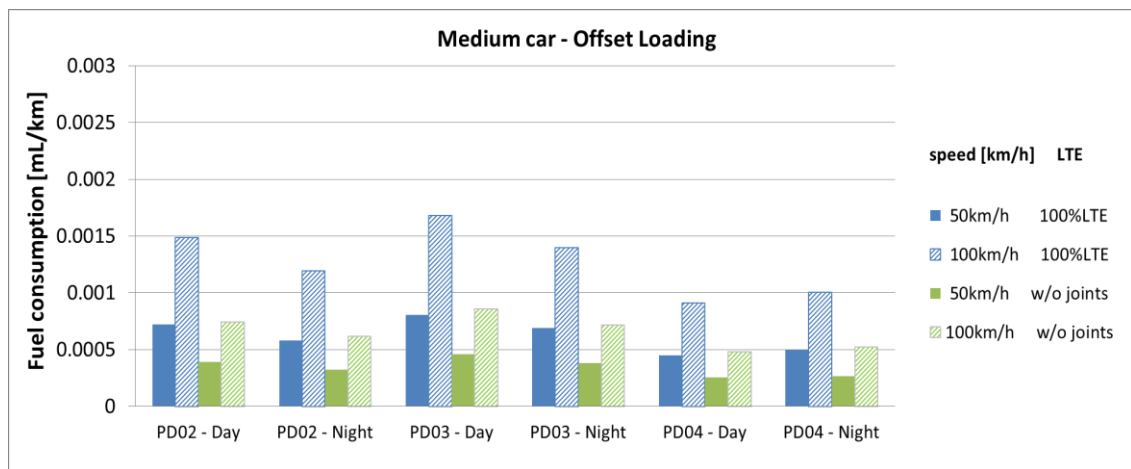


(b)

Figure 7. Comparison between fuel consumption excess due to structural response of a jointed concrete pavement with 100%LTE and an infinite slab to a SUV at different speeds.



(a)



(b)

Figure 8. Comparison between fuel consumption excess due to structural response of a jointed concrete pavement with 100%LTE and an infinite slab to a medium car at different speeds.

6 CONCLUSIONS

This paper presented a methodology to calculate the deflection-induced fuel consumption excess of trucks, SUVs, and cars travelling on concrete pavements. Using the finite element model DYNASLAB, different types of vehicles moving along sections with different mechanical properties are simulated at different speeds and load positions on the slab. The response of the pavement was used to calculate the dissipation of energy and fuel consumption caused by the structural rolling resistance.

The results show that the excess of 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, the paper showed that:

- By increasing the speed, the fuel consumption excess increases.
- The position of the vehicle on the slab has an effect on the results. The fuel consumption increases as one of the wheels is closer to the edge of the slab. This increment is amplified as the velocity of the vehicle increases.
- The effects of temperature do not follow a specific trend. The differences in fuel consumption related to temperature changes are very small if compared to the effects of the other factors. Note that the effects of temperature on curling were not considered in this analysis.
- The structural rolling resistance is lower for sections with thicker concrete slabs.

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