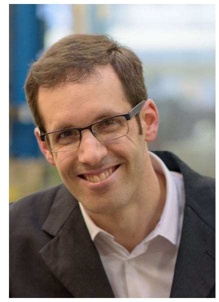
Novel Insights into Pavement-Vehicle Dynamics and Rolling Resistance Coefficients of Heavy Vehicles.





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Abstract
Rolling resistance is a key factor in heavy vehicle energy consumption and greenhouse gas emissions. Standard laboratory methods often fail to replicate real driving conditions, limiting their applicability. This study uses a novel measurement system with high accuracy (±0.1 kg/tonne) to evaluate the rolling-resistance coefficient of semi-trailer suspensions in real-world scenarios. By measuring forces and displacements between the suspension and its frame, the system provides new insights into pavement-vehicle interactions. The study identifies translational axial oscillations in semi-trailer axles at wheel rotation frequencies, likely caused by pavement cross-slopes. Thermal cracking on flexible pavement increased rolling resistance by 0.8 kg/tonne, while slab faulting on rigid pavement caused a 0.3 kg/tonne variation. These findings reveal the significant impact of pavement conditions on rolling resistance, overlooked in laboratory tests. The results underscore the need for further research to enhance understanding of pavement-related energy losses and improve road sustainability.

Keywords: Rolling resistance, pavement-vehicle interaction, road roughness, instrumentatio

1. Introduction

Assessing the rolling resistance of heavy vehicles under real driving conditions is widely studied, but paradoxically not well understood as many underlying phenomena still require further clarification and quantification. Standardized rolling-resistance performance testing under laboratory conditions have been introduced in recent years (Official Journal of the European Union, 2020) with the aim of promoting tires with lower rolling resistance, and reducing greenhouse gas emissions from the transportation sector (European Tyre and Rubber Manufacturers' Association., 2018, 2021). However, there is significant evidence in the scientific literature that the laboratory methods on which these standards are based do not accurately reflect real-driving conditions:

- **The curvature of steel drums** deforms tires in a manner unrepresentative of flat surfaces. Although authors have developed formulas to compensate for this effect (Freudenmann et al., 2009), these formulas rely on several simplifications that are currently under debate (Ejsmont et al., 2022).
- **Key pavement characteristics**, such as macrotexture, road roughness, and structure-induced rolling resistance, are absent in steel drum testing (Levesque, Bégin-Drolet, et al., 2023a).
- **Tire temperature** significantly influences the coefficient of rolling resistance, and existing standards do not necessarily represent real driving conditions (Ejsmont et al., 2022, 2024). This discrepancy is particularly relevant for winter tires, which are tested and optimized at the same air temperature as summer tires (25°C) (Ejsmont et al., 2024).
- **Transient tire conditions** play a critical role in realistic speed profiles, as reaching steady-state thermal conditions requires considerable time (Hyttinen et al., 2023).
- **Tire aging** substantially impacts rolling resistance. Tread depth reduction leads to a nonlinear decrease in rolling resistance, and artificial wear used in laboratory measurements has been found inadequate for mimicking on-road wear with respect to the evolution of the coefficient of rolling resistance (Luchini et al., 2001).

These points collectively underscore the necessity of measuring rolling resistance under real driving conditions to ensure that relevant policies effectively reduce greenhouse gas emissions in the transportation sector. This need is constrained by two primary challenges:

1. The actual energy consumption of a vehicle depends on **numerous interrelated factors**, making tire and pavement-related rolling resistance data noisy, diluted, and challenging to isolate (Levesque et al., 2024).
2. Interpreting rolling resistance in real driving conditions demands **expertise across diverse fields**, including tire engineering, vehicle dynamics, and pavement engineering.

This paper leverages an advanced measurement system capable of evaluating the on-road rolling resistance coefficient of a semi-trailer suspension with a very high accuracy of $\pm$ 0.1 kg/tonne. This system has been presented and used in the context of previous work (Levesque, Bégin-Drolet, et al., 2023b; Levesque et al., 2024), and one of the main conclusions was that pavement type alone was not a sufficient parameter to predict pavement-related rolling resistance. This paper represents an initial attempt to address the second difficulty identified above.

2. Methodology

Typical and widely used methods to evaluate pavement conditions have low interpretability and are independent of how real-world vehicles interact with it. For example, road roughness is typically measured using laser-based profilometers, following these steps (Sayers & Karamihas, 1998):

1. Measure the road surface and simplify it into a one-dimensional profile.
2. Filter the road profile using a mobile averaging window of 250 mm.
3. Simulate a quarter-car model traversing the profile with standardized vehicle parameters.
4. Calculate the mobile average of the absolute value of simulated suspension speed, which yields the International Roughness Index (IRI).

Conceptually, the IRI is the amplitude of the simulated vehicle response under the effect of road roughness, but this common approach necessitates to greatly simplify the pavement surface and the vehicle dynamics.

Some conventional methods to evaluate pavement structural capacity typically rely on measuring its deflection under a controlled load (Nielsen, 2019; F. Xiao et al., 2021). This approach provides a single value representing the pavement's structural capacity, which limits its interpretability as many aspects should be considered such as cracking, rutting, etc (Stephanos et al., 2007).

The low interpretability of the methods aforementioned is problematic since pavement conditions can have a significant effect on the rolling resistance of heavy vehicles (Levesque, Bégin-Drolet, et al., 2023a). This cannot be considered with laboratory measurements that aim to quantify the rolling resistance coefficient (C_{RR}) as follows:

$$C_{RR} = \frac{F_{RR}}{F_V} \tag{1}$$

Where:

F_{RR}: is the rolling resistance force [N or kg]
F_V: is the weight of the vehicle [kN or tonne]

The C_{RR} enables the calculation of mechanical power loss due to rolling resistance, which can then be adjusted for vehicle efficiency to estimate the power required from the power unit (e.g., internal combustion engine or electric motor). In essence, C_{RR} is a very useful information to have as it provides universal applicability across different vehicles. This is why there is a need to measure C_{RR} under real driving conditions.

As demonstrated in prior research, the novel measurement system used in this study quantifies forces and displacements between a semi-trailer suspension and its frame (Levesque, Bégin-Drolet, et al., 2023b; Levesque et al., 2024). The measurement system is illustrated in Figure 1.

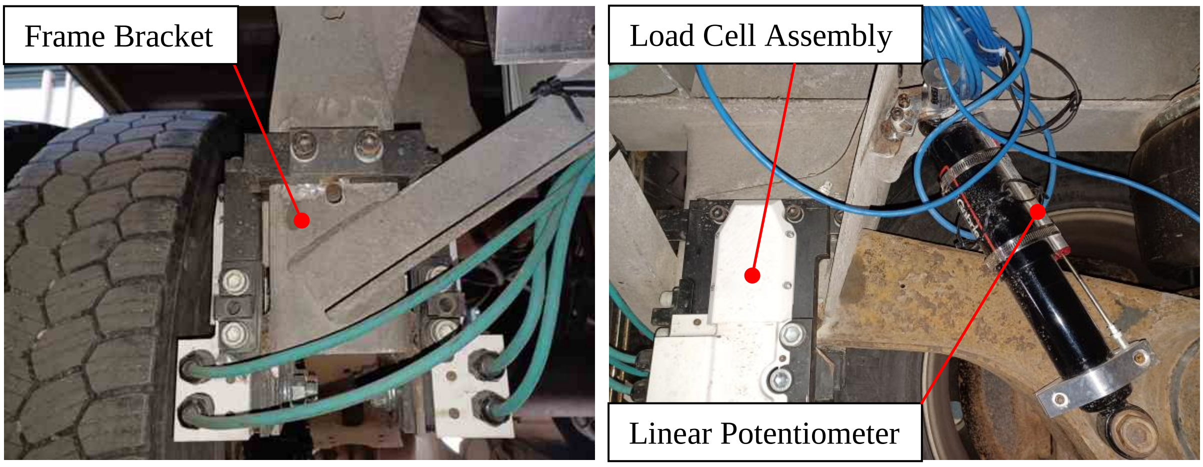

Figure 1: Measurement System Capturing Forces and Displacements between a Semi-trailer Suspension and its Frame for Rolling Resistance Evaluation under Real Driving Conditions.

The measurement system illustrated in Figure 1 has been used on 174 km of highway at constant speed and pavement type has been found to be an inconsistent predictor of pavement-related rolling resistance. From this conclusion, this study aims to explore the following questions:

- Which pavement conditions serve as reliable indicators of pavement-related rolling resistance for heavy vehicles, and how should the term "pavement conditions" be defined in this context?
- How do such pavement conditions influence the measurements of forces and displacements in the instrumented suspension?

To address these questions, a comprehensive analysis was conducted by utilizing displacement and force measurement data from the suspension. Specifically, a pavement-vehicle interaction analysis was conducted to infer pavement conditions and establish a correlation with the on-road rolling-resistance coefficient. This was achieved by comparing the frequency content of suspension speed across various road segments. The conceptual difference between the usage of laser-based profilometers for road roughness evaluation and the suggested approach is summarized graphically in Figure 2.

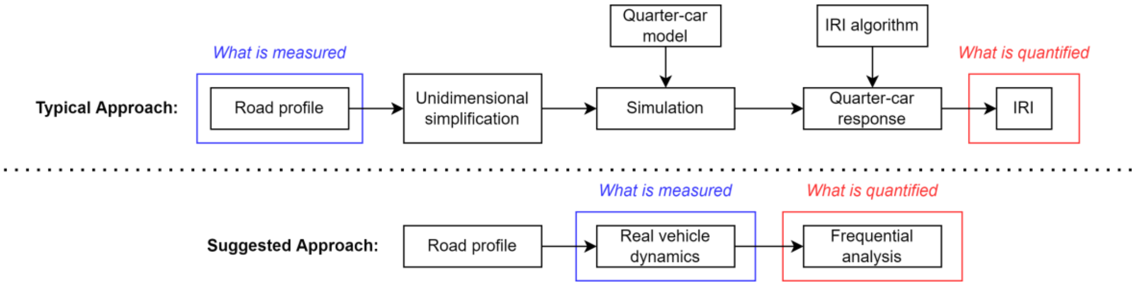

Figure 2: Comparison between the Conceptual Approach used for Assessing Road Roughness and the Suggested Approach Using the Novel Measurement System.

One advantage of the suggested approach is the fact that various forms of pavement distress (*e.g.* cracking), which excite the suspension, may indicate underlying structural issues. Consequently, the frequency response of the instrumented suspension captures insights into both road roughness and pavement structural capacity, which is not the case for laser-based profilometers.

3. Results and Discussion

3.1 Typical Pavement-Vehicle Interaction

To understand how a pavement interacts with a semi-trailer suspension, it is insightful to analyse the force signals obtained from the load cells assemblies presented in Figure 1. This is illustrated in Figure 3. Following the defined sign convention, it can be seen in the force signals that the forces on the right side of the frame brackets are higher than the left sides. This is particularly true for the right frame bracket.

The prediction and modelling of the expected longitudinal forces at the four load cell assemblies is not a trivial task because the suspension could be defined as a pseudo-hyperstatic system, which means there are more constraints than strictly necessary and the force equations cannot be solved purely from static equilibrium. The difference between left and right side of each frame bracket can be explained by the cross slope of the pavement. When a semi-trailer travels on the right side of the road, the pavement's cross-slope induces an anticlockwise moment at the kingpin due to the semi-trailer's weight. This moment must be counterbalanced by transverse forces at the tire-pavement contact patches. Nonetheless, the average forces of 266 N and 332 N attributable to rolling resistance, which are the sum of two load cell assemblies, were consistent with expectations. It is, however, necessary to average this value over a longer road segment (*e.g.* 2.5 km) in order to mitigate sufficiently the effect of road gradient and obtain the actual rolling resistance (Levesque et al., 2024).

It is interesting to note that the tires on the left side of the suspension were marketed as “fuel efficient” or “round-year traction”, and the tires on the right side of the suspension were marketed as “for deep snow and mud traction” and “perfect tire for high scrub and rough road conditions”. The exact service life of the tires during the measurements is not known, but they were retreated at least once. The tires were still relatively cold with an operating temperature of about 40°C. Finally, it can be specified that the diagram in Figure 3 is not exactly a free body diagram since the blue and orange arrows are the longitudinal forces that suspension applies on the frame, rather than the longitudinal forces that the frame applies on the suspension.

Data collected from multiple road segments were used to calculate the power spectrum density (PSD) of the suspension speed from the data obtained with the linear potentiometer identified in Figure 1. The first natural frequency of the pneumatic suspension was expected to be approximately 1.6 Hz, as reported by the manufacturer (Hendrickson, n.d.). Additionally, a second natural frequency (*i.e.* unsprung mass) around 15 Hz was anticipated to be present, and broader due to greater damping (Smith & Swift, 2011). To confirm these assumptions, a PSD analysis from a 22.7 km road segment of flexible pavement is shown in Figure 4.

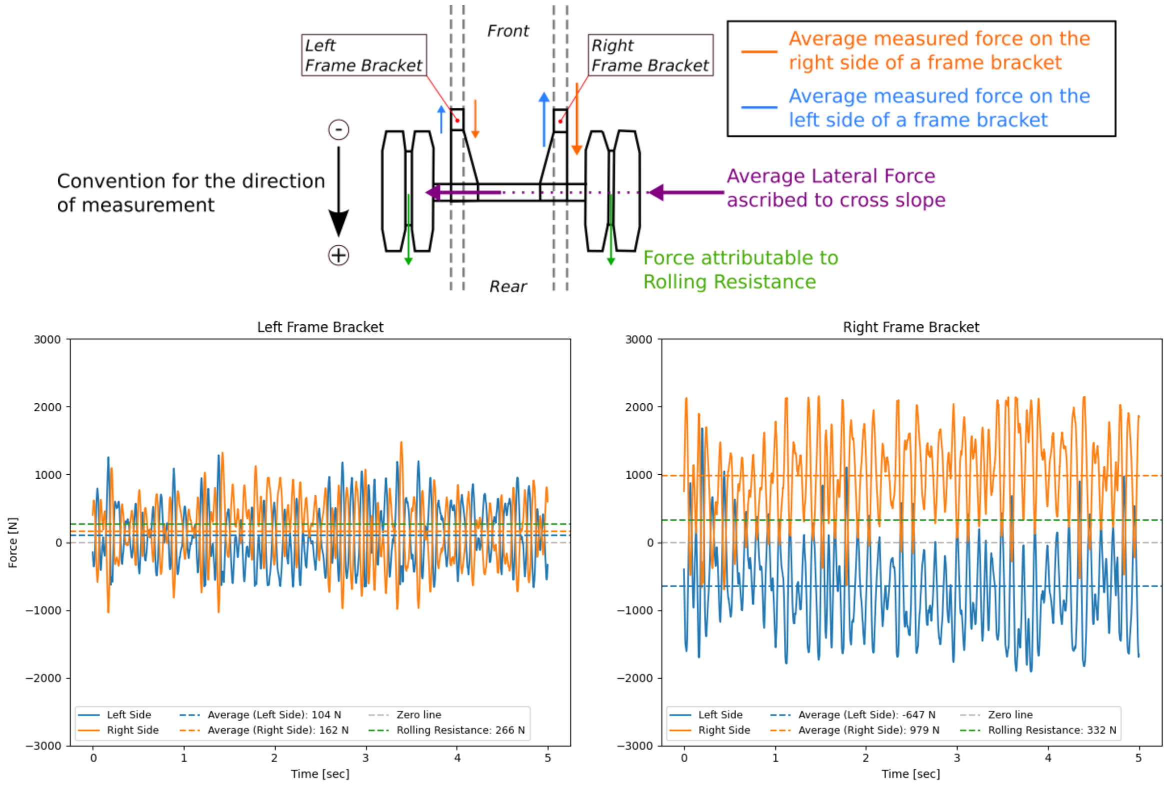

Figure 3: (Top) Forces that the Pavement Applies on the Suspension and Direction of Measurement at the Frame Brackets; (Bottom) Force Signals Measured by the Load Cells.

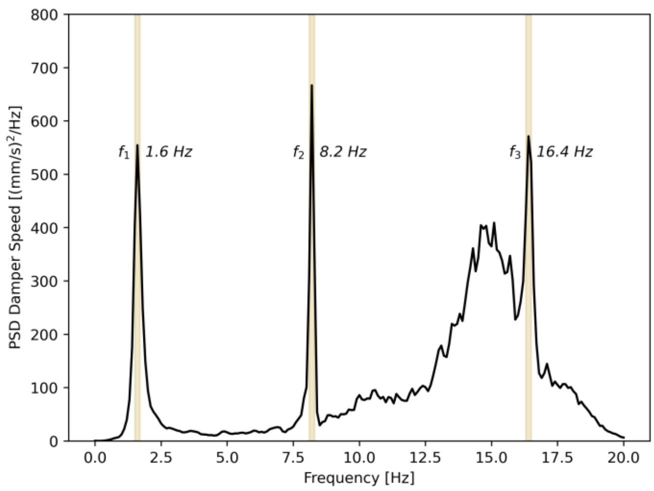

Figure 4: Typical Power Spectrum Density of Suspension Speed Measured on a 22.7km Flexible Pavement.

Figure 4 demonstrates that the first natural frequency of the suspension (f_1) aligns with the expected 1.6 Hz. Similarly, the broad, damped peak near 15 Hz matches predictions from existing models (Smith & Swift, 2011). However, unexpectedly narrow, high-frequency peaks at 8.2 Hz (f_2) and 16.4 Hz (f_3) were observed. Given the vehicle's speed of 95 km/h, these correspond precisely to the first and second harmonics of wheel rotation.

Initially, these frequencies were suspected to result from wheel imbalance. However, it can be seen by visual inspection of the measured force signals presented in Figure 3 that there was a very important 8.2 Hz frequency with a 180° phase difference between left and right side of each frame bracket. This observation indicates that the semi-trailer axle undergoes translational axial oscillations at the wheel rotation frequency.

To the best of the authors' knowledge, this phenomenon has not been previously measured and documented clearly in the literature. While its significance to rolling resistance remains unclear, the data indicates it may have implications absent in laboratory testing conditions.

3.2 Rolling Resistance and Thermal Cracking

The frequencies of interest in the PSD of Figure 4 are relative to vehicle dynamics. This would suggest that pavement conditions primarily influence the amplitude of these frequencies, a common and implicit assumption in various model-based studies on road roughness using in-vehicle sensors (Fares & Zayed, 2023). To investigate further, the PSD of suspension speed is shown for another 20.5 km flexible pavement segment in Figure 5.

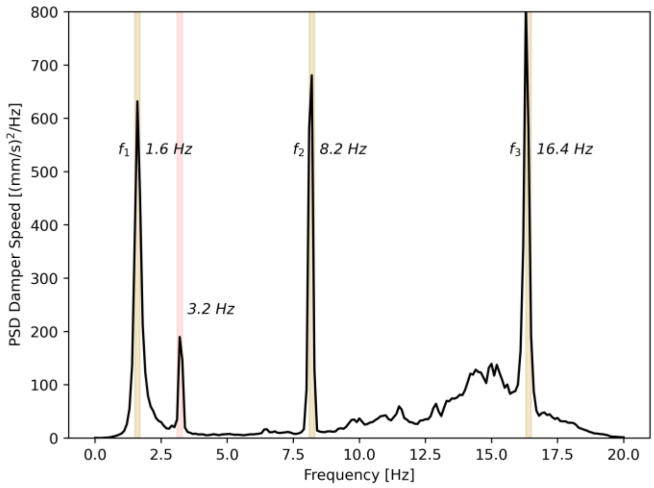

Figure 5: Power Spectrum Density of Suspension Speed Measured on a 20.5km of Flexible Pavement on which there is Thermal Cracking.

Figure 5 reveals an additional frequency at approximately 3.2 Hz. Given the vehicle's speed of 95 km/h, this corresponds to a wavelength of 8.2 m per cycle. Unlike the previously discussed frequencies, this does not correlate with vehicle dynamics. This specific frequency appeared only on this segment, indicating that the pavement's condition had degraded to the extent of exciting the suspension at this frequency.

The measurements were conducted in Quebec, Canada, a region with occasionally harsh winter conditions. Such climates cause significant pavement challenges, including seasonal road roughness variations and various distress phenomena (Fradette et al., 2005). One such phenomenon, thermal cracking, involves cracks in flexible pavements spaced equally due to thermal stress exceeding the asphalt material's tensile strength (Rajbongshi & Das, 2009). According to the literature, the regular spacing of thermal cracks typically ranges between 5 m and 10 m (Li et al., 2005; Rajbongshi & Das, 2009).

It is hypothesized that thermal cracking caused the additional frequency observed in Figure 5, suggesting that the instrumentation system can detect this condition. This is significant because the type of pavement cracking provides critical insights into the root causes of pavement deterioration (Nieminen, 2024).

To examine this hypothesis further, it is helpful to convert frequencies into spatial wavelengths, as the 3.2 Hz frequency applies only at a vehicle speed of 95 km/h. Pavement cracking should be analyzed spatially rather than temporally. Additionally, observing variations in wavelengths across the road segment can determine whether this phenomenon is localized. These analyses are presented in Figure 6.

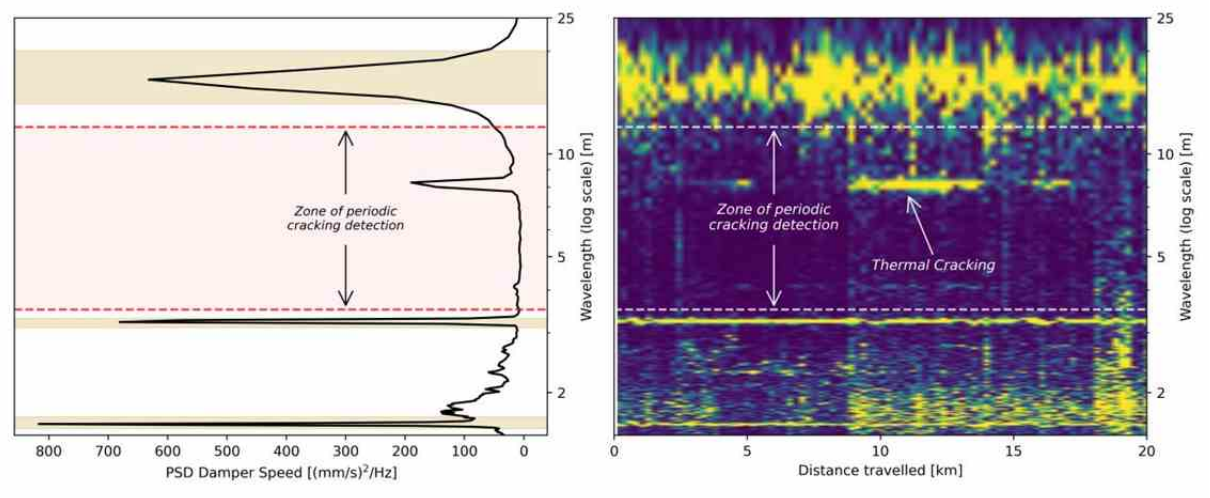

Figure 6: For the 20.5 km Flexible Road Segment: (Left) Power Spectrum Density of Suspension Speed as a Function of Pavement Wavelength. (Right) Spectrogram of the Power Spectrum Density of Suspension Speed (Brightest colour set at 150 $(mm/s)^2/Hz$).

Figure 6 shows that the 8.2 m wavelength linked to thermal cracking begins distinctly at the 8.85 km mark and persists for exactly 5 km, ending at the 13.85 km mark. Beyond this point, thermal cracking appears less intense, but higher-frequency wavelengths continue to dominate the suspension response, contrasting with the segment preceding the 8.85 km mark. The road segment is therefore divided into two zones: "before cracking" (prior to the 8.85 km mark) and "during cracking" (after the 8.85 km mark).

Current methods, such as laser-based profilometers or AI-powered camera detection systems, face challenges in detecting cracking accurately due to the lack of international standards (Nieminen, 2024). Moreover, the quarter-car model used for IRI calculations may not effectively detect thermal cracking because the 250 mm mobile average window filters out narrower cracks. Visual inspection of the suspension speed signal at the 8.85 km transition revealed no clear indications, suggesting that IRI-based algorithms would miss significant pavement condition details. For these reasons, the spectrogram in Figure 6 is highly insightful for evaluating pavement conditions.

The final step involves comparing the two identified zones (before and during cracking) to determine whether thermal cracking correlates with changes in the rolling resistance coefficient. The results are illustrated in Figure 7.

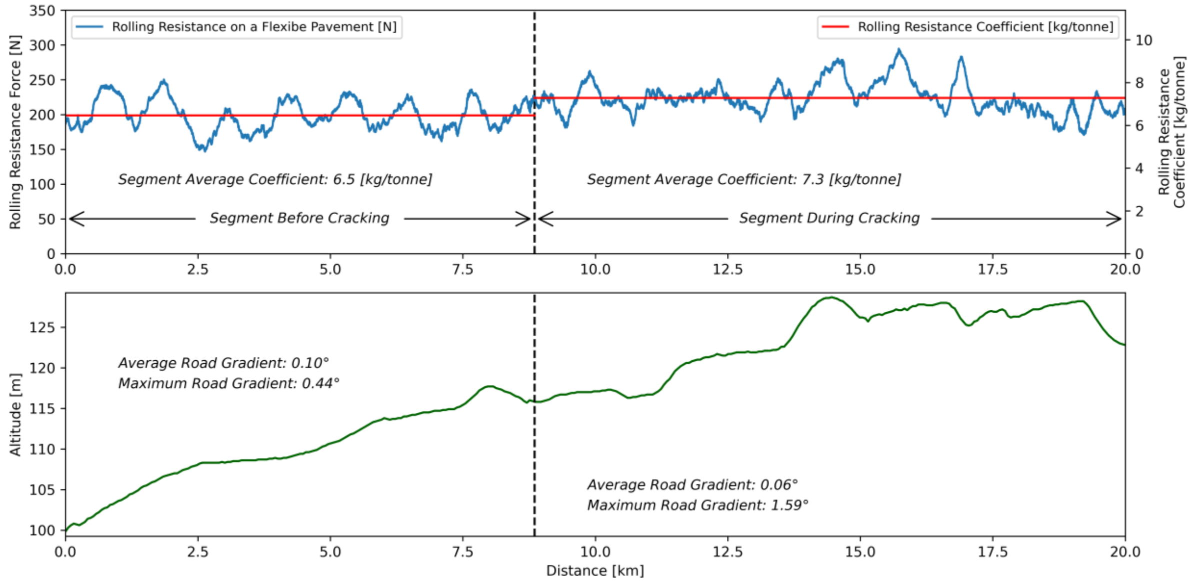

Figure 7: Evolution along the 20.5 km Flexible Road Segment for: (Top) Rolling Resistance; (Bottom) Altitude in Respect to Sea Level.

Figure 7 indicates that the average rolling-resistance coefficient increases from 6.5 kg/tonne in the "before cracking" zone to 7.3 kg/tonne in the "during cracking" zone. The road gradient difference between these zones is approximately 0.4°, a variation within the system's uncertainty of ± 0.1 kg/tonne (Levesque et al., 2024). Additionally, tire temperature was only 1 °C higher in the cracking zone, and a warmer tire reduce rolling resistance (Hyttinen, 2023). Thus, the observed 0.8 kg/tonne increase in rolling resistance during the cracking zone cannot be attributed to either tire temperature or road gradient changes.

An increase of 0.8 kg/tonne is significant for a heavy vehicle. Indeed, European tire labels for rolling resistance performance evaluation that are provided by tire manufacturers consist of letters (*i.e.* A, B, C, etc.) that each exist in a range of ± 0.5 kg/ton (Official Journal of the European Union, 2020). This means that a heavy vehicle equipped with "A" tires could effectively perform as if equipped with "B" tires on a pavement with thermal cracking. In addition, it is reasonable to assume that the significant increase in the rolling resistance coefficient presented in Figure 7 is reflected somehow in every heavy vehicle circulating on this road segment. This represents thousands of heavy vehicles per day (in one direction). This insight has substantial implications for road network management and optimization (Levesque, Samson, et al., 2023). However, additional research under various meteorological conditions is necessary to apply these findings broadly.

3.3 Rolling Resistance and Faulting

Jointed rigid pavements are commonly used in Quebec, and several road segments with this pavement type were tested. The spectrogram of suspension speed for a 12.9 km rigid pavement segment is shown in Figure 8.

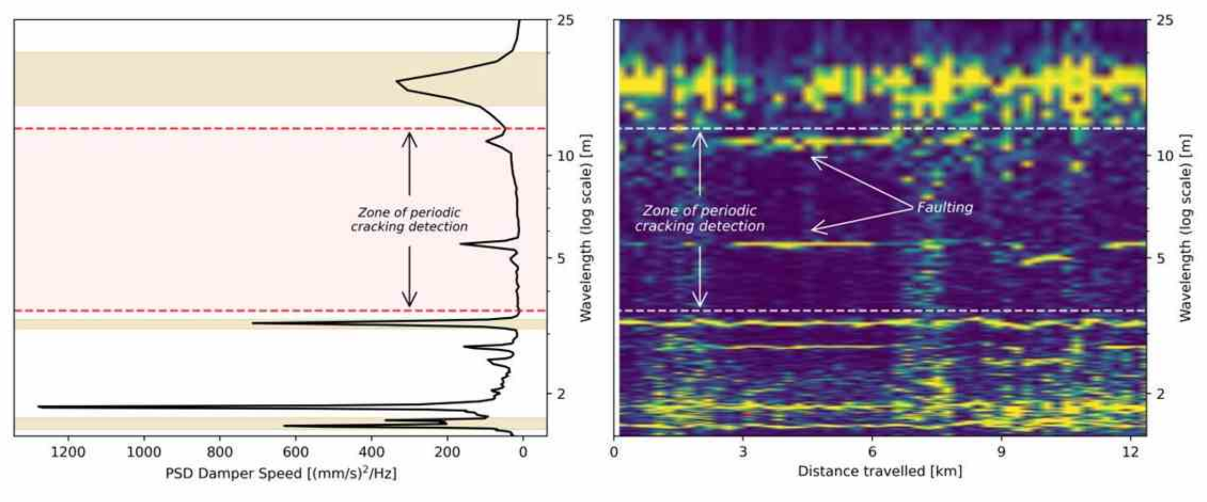

Figure 8: For a 12.9km Rigid Road Segment: (Left) Power Spectrum Density of Suspension Speed as a Function of Pavement Wavelength. (Right) Spectrogram of the Power Spectrum Density of Suspension Speed (Brightest colour set at 200 $(mm/s)^2/Hz$).

Figure 8 reveals a prominent wavelength of 5.5 m, particularly before the 6 km mark. This wavelength aligns with the length of individual slabs, suggesting a connection to slab faulting—a phenomenon involving vertical displacement of slabs as they deteriorate (W. Xiao et al., 2023). The spectrogram also shows harmonics of the 5.5 m wavelength, as well as a subharmonic at twice this length (11 m). To evaluate the influence of faulting on rolling resistance, the rolling resistance force measurements are displayed in Figure 9.

Figure 9 demonstrates that faulting correlates with changes in the rolling resistance coefficient. Specifically, the coefficient is 6.5 kg/tonne before the 6 km mark and 6.2 kg/tonne afterward. This finding is significant because rigid pavements are designed for decades of use, and slab faulting is a defect that progressively worsens. However, it is unclear whether the effects of faulting on rolling resistance vary with meteorological conditions.

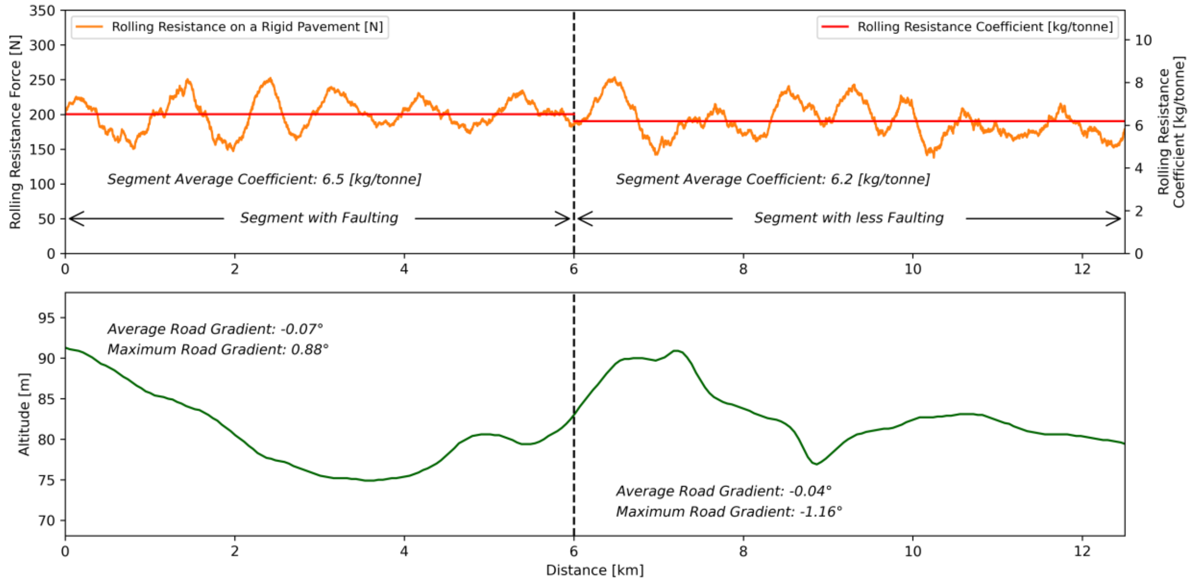

Figure 9: Evolution along the 12.9km Rigid Road Segment for: (Top) Rolling Resistance; (Bottom) Altitude in Respect to Sea Level.

4. Conclusion

This paper leverages a novel measurement system that allows for evaluating the rolling resistance coefficient of a semi-trailer suspension under real driving conditions with a very high accuracy of ± 0.1 kg/tonne. This system, which consists of measuring all the forces and displacement between a semi-trailer and its frame, can be used to make connections between seemingly unrelated fields of expertise such as tire engineering, vehicle dynamics and pavement engineering. The key insights and hypotheses from suspension speed spectral analysis can be summarized as follows:

- Semi-trailer axles exhibit significant translational axial oscillations at the wheel rotation frequency, likely due to pavement cross-slope causing lateral forces at the tire-pavement interface. The effect of this phenomenon on rolling resistance remains unclear.
- Thermal cracking was detected on a 20.5 km flexible pavement segment, increasing the rolling resistance coefficient by 0.8 kg/tonne.
- Slab faulting was detected on a 12.9 km rigid pavement segment, increasing the rolling resistance coefficient by 0.3 kg/tonne.

Further research under diverse meteorological conditions will refine these findings and enhance understanding of pavement-vehicle interactions.

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