Advances in Materials and Pavement Performance Prediction II – Kumaret al. (eds) p.220-224,
©2021 Taylor & Francis Group, London, ISBN 978-0-367-46169-0

Measurement of structural rolling resistance at two temperatures

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ABSTRACT: In this study, we investigate how an increase in road temperature influences the structural rolling resistance of a heavy vehicle. The structural rolling resistance (SRR) is defined as the dissipated energy due to pavement deflection under a moving load. It is measured using a newly proposed method, which is based on the relationship between SRR and the slope of the deflection basin underneath the load. Using the Traffic Speed Deflectometer technology, we measured SRR on the same road under two different road temperatures, 18°C and 35°C respectively. On average, an increase in SRR of 59% was observed, with some areas of the road having up to 400% increase. This indicates that under warm road conditions SRR might have a significant effect on the overall rolling resistance of a heavy vehicle.

1 INTRODUCTION

When a pavement is subject to a moving load, it will deform underneath it. If the pavement is viscoelastic, the time delay in the deflection makes the maximum deflection appear behind the load. This results in an asymmetric deflection basin, as illustrated on Figure 1a. Consequently, the load experiences an uphill deflection slop (Fig. 1b) and has to do work in order to maintain a constant speed (Flügge, 1975). The excess energy consumption due to deflection of the pavement is dependent on the pavement structure, and we will refer to it as structural rolling resistance (SRR). SRR can be calculated directly from the asymmetric deflection basin (Balzarini et al. 2018, Chupin et al. 2013).

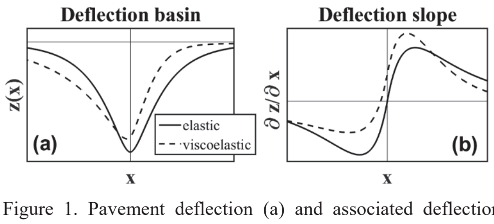


Figure 1. Pavement deflection (a) and associated deflection slope (b) of an elastic and viscoelastic pavement. Viscous properties make the deflection basin asymmetric, which results in a positive deflection slope underneath the load (x=0).

Estimates of SRR are often derived by simulating the pavement response to a moving load with constant speed. The pavement parameters used in these simulations are obtained from either back-calculated falling weight deflectometer measurements or laboratory measurements on the pavement materials (Pouget et al. 2012, Akbarian et al. 2012 ,Balzarini et al. 2017). Moreover, indirect measurements of SRR have been conducted (Zaabar & Chatti 2014). However, it has been proven difficult to develop accurate and robust methods for measuring SRR directly.

In Nielsen et al. (accepted) we presented a new method for direct measurements of SRR, using the Traffic Speed Deflectometer (TSD) technology. The method is based on the relation between SRR and the slope of the deflection basin underneath a moving load. Using the TSD has the advantage that it mimics a full-size trailer and thus it measures the pavement deflection slope under realistic driving conditions. The method proved to be robust and measure SRR with high accuracy when repeated measurements where compared. Furthermore, it has the clear advantage that it does not require a model or prior knowledge about the pavement in order to calculate SRR.

The influence of temperature on SRR has been investigated in literature, by use of numerical simulations (Pouget et al. 2012, Shakiba et al. 2016). The magnitude of the found temperature effect differs between the studies is dependent on the applied pavement models. To the authors knowledge no direct measurements of the temperatures influence on SRR for heavy vehicles exist.

In this paper, we investigate the effect of road temperature on SRR. We expect that a higher road temperature will lead to a softer asphalt layer and an increased pavement response to the moving load. In addition, within the investigated temperature range we expect the viscoelastic damping of the asphalt to increase with increasing temperature (Pouget et al. 2012, Shakiba et al. 2016). Consequently, we expect that an increase in road temperature will lead to a higher SRR.

2 TRAFFIC SPEED DEFLECTOMETER DATA

2.1 *TSD principle*

The Traffic Speed Deflectometer (TSD) continuously measures the vertical velocity (v_d) of the pavement underneath the right rear-end trailer tires, while the truck is moving. This is done by means of Doppler lasers positioned between the tire set both in front and behind the axle. From this, the pavement deflection slope ($dz(x_n)/dx$) for each position (x_n) is obtained by dividing with the driving speed (v),

$$\frac{dz(x_n)}{dx} = \frac{v_d(x_n)}{v}. \tag{1}$$

The principle is explained in more depth in Nielsen (2019).
Having measurements on both sides of the load enable us to determine the asymmetry in the deflection basin arising from viscoelastic properties in the pavement.

2.2 *Raw data*

For this study, two sets of measurements were made at a road section near Copenhagen, Denmark. The measurements were made on two days (15 months apart), where the pavement temperature was 18°C and 35°C respectively. Each set of measurements were repeated three times and a good reproducibility was seen with median standard deviations of 9% (18°C) and 5.5% (35°C). The TSD truck was at maximum axle load (10 tonnes) and driving speed was between 50-60 km/h, with the exact driving speed recorded continuously during the measurement rounds.

In Figure 2a, a plot of the measured deflection slope data in the beginning of the ~10 km measured road section is shown. The measured deflection slope for each sensor is an average over 10 m. An example of the deflection slopes at 2 km, as a function of distance from the load, is seen in Figure 2b. The center of the axle is at x=0. The deflection slope curve is characterized by a minimum located behind the load and a maximum in front of the load. The standard deviations are illustrated with error bars in Figure 2b. In some cases, the error bars are smaller than the markers and thus not visible.

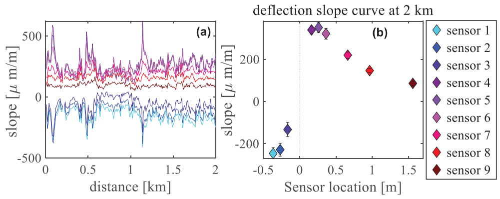


Figure 2. Example of raw data at 18°C. (a) Measured deflection slope for all sensors in the beginning of the measured road. (b) deflection slopes as a function of distance from the load. Standard deviations are shown with error bars.

3 SIMPLE METHOD FOR ESTIMATING THE STRUCTURAL ROLLING RESISTANCE

This method was presented for the first time in Nielsen et al. (accepted). In the simplest approach, we assume that the applied load is a point load, located at the center of the tire (x=0) with magnitude F_L. The dissipated energy in the pavement (P_{SRR}), can be calculated from the vertical pavement velocity underneath the load and the applied load,

$$P_{SRR} = F_L v_d(x=0) = F_L v \frac{dz}{dx}(x=0), \tag{2}$$

where the last expression comes from Equation 1. In the case of a perfectly elastic pavement the deflection slope under the load is zero, and therefore the dissipated energy is also zero, $P_{SRR} = 0$. On the other hand, if there is some damping in the pavement, the slope underneath the load will be larger than zero. In this case, energy is dissipated in the pavement i.e. $P_{SRR} > 0$. Equation 2 requires knowledge of the deflection slope exactly underneath the load (x=0). However, due to the presence of the axle, it is not possible to measure in that point. Therefore, we have to estimate the slope at x=0 based on the surrounding data points. The simplest approach is to make a linear interpolation between the two sensor points closest to the load (sensor 3 and 4). Doing this we have that

$$P_{SRR} = F_L b v, \tag{3}$$

where b is the intersection at x=0 for the linear interpolation. From this, we obtain the expression for the structural rolling resistance force, $F_{SRR}=P_{SRR}/v$. We can also derive the structural rolling resistance coefficient, defined as the ratio between the rolling resistance force and the applied load,

$$C_{SRR} = \frac{F_{SRR}}{F_L} = b. \tag{4}$$

4 RESULTS

4.1 *The influence of temperature on the structural rolling resistance coefficient*

Using two sets of deflection slope data measured at the road temperatures 18°C and 35°C, we study the influence of road temperature on SRR. The temperatures were measured at the surface using an infrared temperature sensor through all measurements. In Figure 3 C_{SRR} is plotted versus distance on the ~10 km measured road segment. In this plot, the mean C_{SRR} values after three repeated measurements are shown. There is a systematic increase in C_{SRR} as the road temperature increases. The median of the standard deviations in C_{SRR} are $0.13 \cdot 10^{-4}$ (9%) for 18°C and $0.2 \cdot 10^{-4}$ (5.5%) for 35°C. Thus, the calculated C_{SRR} values have a good precision.

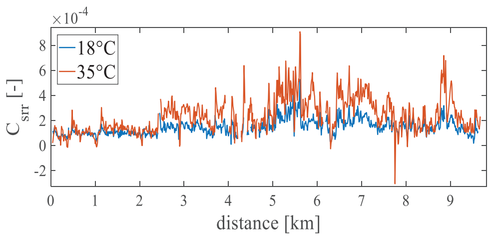


Figure 3. Calculated C_{SRR} at warm (35°C) and cold (18°C) road temperature. The median of the standard deviations are $0.13 \cdot 10^{-4}$ (9%) for 18°C and $0.2 \cdot 10^{-4}$(5.5%) for 35°C. Note that the C_{SRR} values are negative in some points at 35°C, which is unphysical. This behavior is commented on in section 4.2.

In Figure 4, a histogram of the measured C_{SRR} values is shown. Here, we see that the mean C_{SRR} over the entire road increases from $1.4 \cdot 10^{-4}$ to $2.3 \cdot 10^{-4}$ when the temperature is increased. Furthermore, the distribution of C_{SRR} becomes broader with higher temperature. This means that the calculated C_{SRR} for 35°C varies more along the road. The total rolling resistance of a truck is typically on the order of 1% of the load. Based on this, the mean C_{SRR} found in this study are 1.4% (cold) and 2.3% (warm) of the typical total rolling resistance.

C_{SRR} varies considerably throughout the measured distance (from 0.01% of the load to 0.06%). This variation is completely reproducible within the three repeated measurement runs, and we see that spatial variations are similar for the two temperatures. A notable increase in C_{SRR} is seen around 2.5 km. There is no visible change in the asphalt in this area, and thus the change is due to a structural change in the underlying layers. The varying C_{SRR} values reflect the fact that the road measured on is not a homogeneous road, but a real road with varying pavement structure. Most likely the thickness of the asphalt layer and possibly also the type of asphalt differs along the road. As a result, SRR and its temperature dependence will also differ along the road. The method shows a good ability to reproducibly capture these changes in C_{SRR}, even in areas where C_{SRR} changes dramatically.

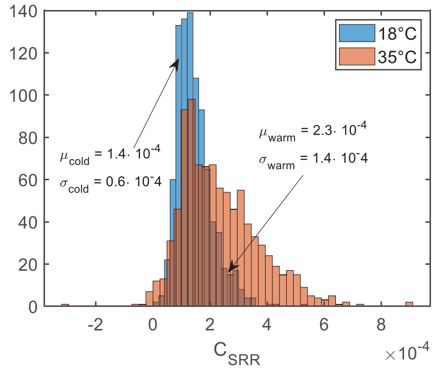
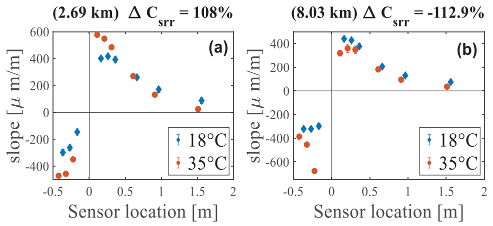


Figure 4. Histogram of measured structural rolling resistance coefficients for cold (18°C) and warm (35°C) road conditions. We see an increase in the mean (μ) C_{SRR} value, when the road temperature is increased. Furthermore, the distribution of measured values is broader under warm conditions (increased σ).

4.2 *Influence of temperature on the deflection slope curves*

By looking into some representative sets of deflection slopes, we can qualitatively investigate the change caused by increased road temperature. Figure 5a illustrates the most commonly encountered influence that the increased road temperature has on the deflection slope curves. Either the maximum deflection slope increases, the minimum deflection slope decreases or both effects occur at the same time (as seen in Figure 5a). An increase in maximum deflection slope value means that the deflection basin gets steeper in front of the load. This often leads to the deflection slope value underneath the load being increased (thus higher P_{SRR}). A decrease in the minimum deflection slope value means that the deflection basin becomes steeper behind the load. Furthermore, we often see that the minimum deflection slope is moved to the left (away from the load) in the warm data. This corresponds to the maximum deflection moving further behind the load, something which is associated with an increased effect of viscous damping.

In Figure 3, the calculated C_{SRR} is negative in a few places, which is unphysical. In Figure 5b, an example of such a deflection slope curve in a place with negative C_{SRR} is plotted. Here, a plot of the deflection slope values at 8.03 km is shown for both temperatures. The relative change in C_{SRR} from cold to warm data is -112.9%, as in the warm situation, we calculate a negative C_{SRR} when using linear interpolation. Note that the shape of the deflection slope curve changes dramatically around the minimum, when temperature is increased. Furthermore, for the warm data we see that the magnitude of the deflection slope is higher



behind the load than in front of the load. This behavior indicates that using linear interpolation to find the deflection slope underneath the load, in some cases is too simple to capture the actual slope assess.

Figure 5. Representative sets of deflection slope curves. The relative change in C_{SRR} is listed for each plot as ΔC_{SRR}. Standard deviations are indicated with error bars (not visible when these are smaller than the markers). It should be noted that in between the two sets of measurements the sensor locations have been changed slightly. We only expect this to have a minor effect on the results of the analysis.

5 SUMMARY AND CONCLUSION

In this study, we have presented measurements of structural rolling resistance of a ~10 km road section, measured at two different road temperatures (18°C and 35°C). The method shows good reproducibility between the repeated measurements, with small standard deviations. Furthermore, it was also able to capture the spatial changes in C_{SRR}, which occur in data at 18°C and 35°C.

The found SRR values have a magnitude which is comparable with results found in empirical and numerical studies on the subject (Akbarian et al. 2012, Chupin et al. 2013, Zaabar & Chatti 2014, Pouget et al. 2012). On average, C_{SRR} increased with 59% over the measured distance when temperature increased, in some areas even up to 400% increase, showing that for warm weather conditions SRR have an effect on the overall energy consumption for heavy vehicles.

An increase in SRR with temperature was expected based on studies in the literature and our physical intuition. We observed a difference in the degree of which temperature influenced SRR, depending on which area of the measured road we looked at. This result in a broadening of the distribution of C_{SRR} for increasing road conditions. The general trend is, that the magnitude of the deflection slope maximum and minimum increases (separately or together) which shows that the deflection basin gets steeper and deeper. This is consistent with our expectation, that the asphalt layer becomes softer at higher temperatures. Furthermore, the maximum deflection moves further behind the load, indicating that the role of viscous damping in the pavement becomes greater.

Some unexpected behavior in the deflection slope curves was also observed. In some areas, the magnitude of the slope becomes bigger behind the load than in front of the load, when the temperature is increased. This odd behavior was fully reproducible within the three repeated measurements. We speculate that this behavior is due to a situation where the asphalt layer becomes much softer than usual. In this case, there will be a compression of the top layer in addition to the usual bending of the top layer. This leads to a non-intuitive behavior of the overall deflection basin, and thus an odd signal in the deformation slope. A better understanding of the temperature influence on the pavement response requires a model study, giving a more detailed insight into road temperatures effect on the structural behavior.

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