

Measuring Pavement Deflection Variance at Highway Speeds

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ABSTRACT: A new method for testing pavement condition combines laser/inertial profilometry of unloaded pavement with vibration measurements in a full loaded heavy truck at highway speed. Three types of results are obtained. 1: Truck wheel, frame and cab vibration, as well as driver seat vibration to be compared with exposure guidelines in ISO 2631-1 and limits in directive 2002/44/EC. 2: Three-dimensional road surface geometry data for simulation of ride and calculation of roughness indices. 3: Locations of potential pavement "soft spots". The latter is possible since large pavement deflection variance under the heavy truck cause a quite different vehicle vibration pattern than the pattern excited from the measured unloaded road surface profile. A tentative accuracy experiment has been done at 4 sites. Recorded seat vibration levels were very high, thus exceeding the EU Action Value in all test runs. The soft spot indications show reasonable repeatability, as well as reproducibility between different driving speeds and between spring time and autumn. Trueness is the most difficult accuracy feature to estimate, since no ideal reference method is at hand neither for variance of local deflection under truck wheel, nor for global deflection under the entire truck. By comparison with FWD, coring and ground penetrating radar results, trueness seems promising. During the tests, a virtual tyre footprint sensor was used for road profiling. Evaluation showed it to bring a large improvement to profiling accuracy. The new high speed measurement method brings excellent opportunities for further research on the entire chain pavement-truck-ride quality interaction.

KEY WORDS: Ride, soft spots, truck, vibration.

1 PAVEMENT DEFLECTION VARIANCE AND HEAVY VEHICLE RIDE

In-vehicle vibration has a negative effect on vehicle driver and passenger health, as well as on traffic safety. European limits for the maximum exposure of professional drivers to vibration are set in directive 2002/44/EC, and these limits are adopted in each EU member state national laws before 6 July 2005.

Forsén (1999) showed that heavy vehicle cab vibration are primarily influenced by road condition and velocity, secondary by vehicle properties such as sprung / unsprung masses, stiffness, damping et c.

Heavy vehicles perceive not only the static surface roughness, but also a dynamic roughness component when the road has "soft spots". Pavement deflection is typically less than two millimetres under a moving heavy vehicle. This magnitude is comparable with road wearing course texture. The texture however, is smoothed by the tyre's "enveloping effect".

The mentioned two mm is smaller than typical road roughness amplitudes. So, when comparing to static profile heights, ride quality impact of deflections seems neglectable. But is this really true?

The ISO 2631-1 (1997) standard for evaluation of human exposure to vibration tells that ride comfort is associated with vehicle cab motion in terms of vibration acceleration and vibration velocity, rather than vibration displacement. This makes sense; otherwise a stiff sports car would be considered more comfortable than a soft luxury car when riding on bumpy roads.

As seen in Figure 1, the time domain vehicle vertical vibration acceleration is associated with space domain excitation from road roughness profile slope variance, rather than roughness profile height. Of course speed and suspension properties contribute due to attenuation or amplification, but the basic excitation follows the relations given in Figure 1.

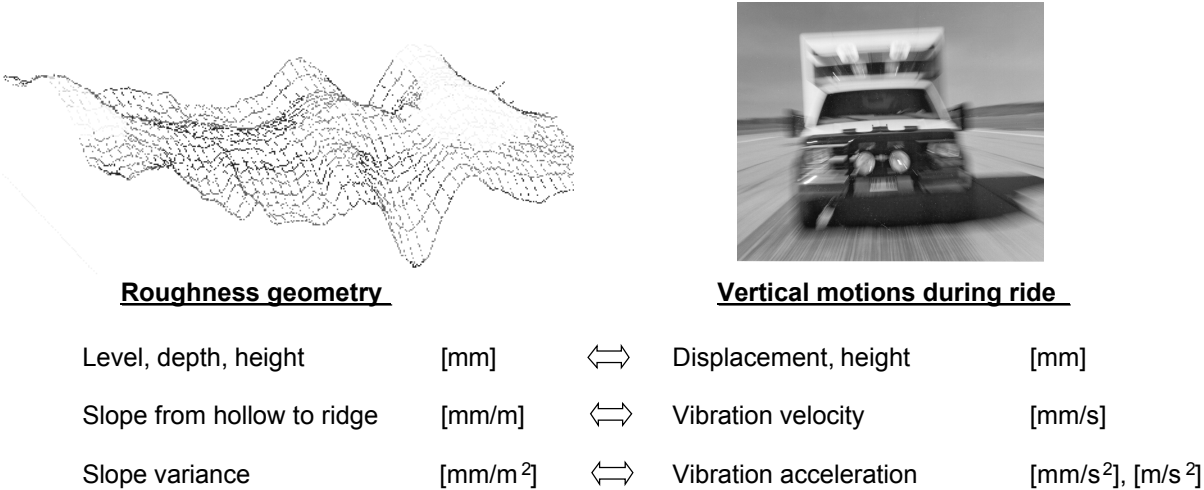


Figure 1: Relating road roughness to vehicle vertical vibration during ride¹

So, even if pavement deflection under heavy vehicles with few exceptions would not be larger than about one or two millimetres, significant vehicle vibration acceleration may occur if the deflection profile varies rapidly in terms of large slope variance.

Ahlin, et al. (2000) made an unexpected observation when comparing road roughness with ride vibration in ambulances and heavy trucks. As can be seen in Figure 2, when surface roughness drops to zero, significant seat vibration remains in heavy trucks while stretcher vibration drops to almost zero in ambulance cars. In the trucks, the threshold of the weighted vibration acceleration was as high as 0.2 m/s² rms. This value is to be compared with the Action Value of 0.5 m/s² rms over 8 hours, stated in directive 2002/44/EC. Clearly, other factors than surface roughness can bring as much as 0.2 / 0.5 = 40 % of the allowed truck seat vibration.

Some possible causal factors behind the 0.2 m/s² threshold truck vibration in Figure 2 are wind load, excentric tyre stiffness, heterogeneous tyre/rim geometry, combustion pulses from the powerful truck engine and unbalance in the power train. However, the hypothesis in this study states that the 0.2 m/s² rms threshold partially relates to pavement deflection profile slope variance (dynamic roughness; soft spots).

¹ Photo from SRA publication 2000:31E

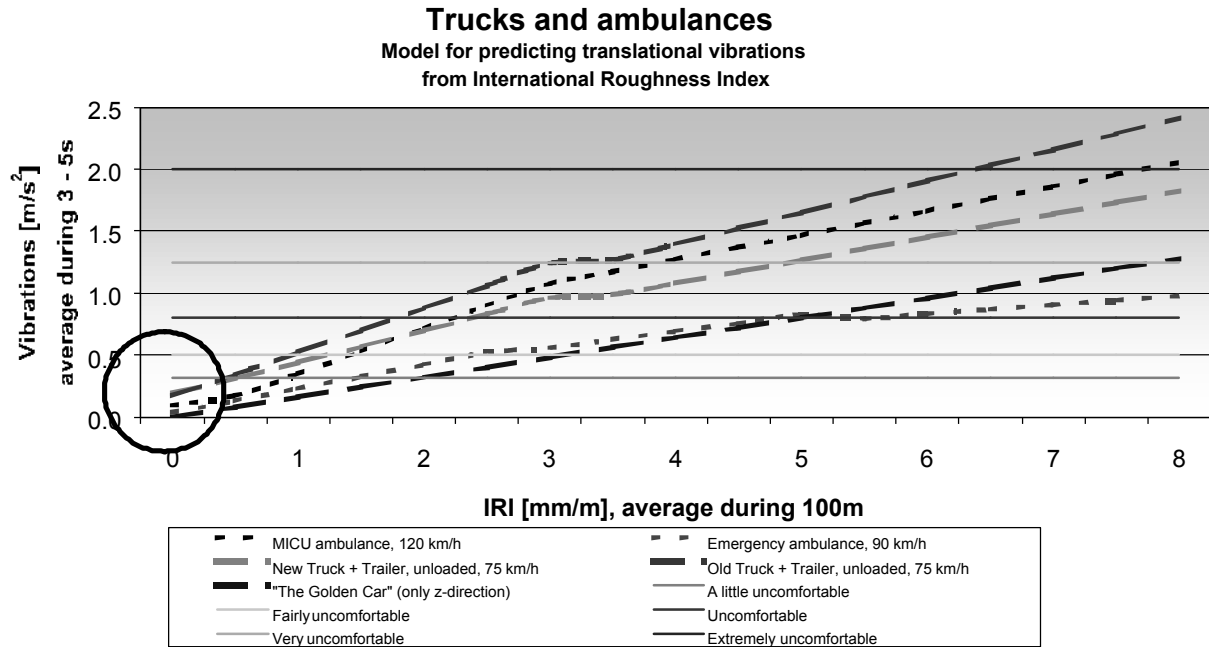


Figure 2: Relation between surface roughness and ride quality domain vibration.

Soft spots and other dynamic roughness under heavy vehicles are expected where:

- the pavement bearing capacity is poor,
- subgrade stiffness changes drastically from soft soil to solid rock et c,
- blocks have due to frost activities moved up to just beneath the asphalt course,
- spring thaw bring large pore water pressures inside the pavement, thereby reducing the inter-particle friction and effective stress,
- the asphalt bound top layers are severely cracked.

2 OBJECTIVES

The paper objective is to present results from a tentative accuracy experiment with the new pavement condition measurement method.

One objective in the accuracy experiment was to test the hypothesis that previously observed threshold truck cab vibration partially relate to pavement deflection profile slope variance (dynamic roughness; soft spots).

If the patented soft spot measurement method turns out to have enough trueness and precision, the only equipment needed would be a heavy truck with full payload, instrumented with a laser/inertial profilometry system.

A major risk factor for the development of the new measurement method is that the profiling method, or the vehicle simulation models, might not be accurate enough. That would affect correlation quality significantly. If this would be the case, such a finding would pinpoint an urgent need for better profiling practices and/or vehicle simulation models also in order to perform traditional road surface condition assessment. Thus, regardless the risk of not succeeding with the new method, this research will give input to improved pavement management in total.

3 BASIC PRINCIPLE OF THE NEW MEASUREMENT METHOD

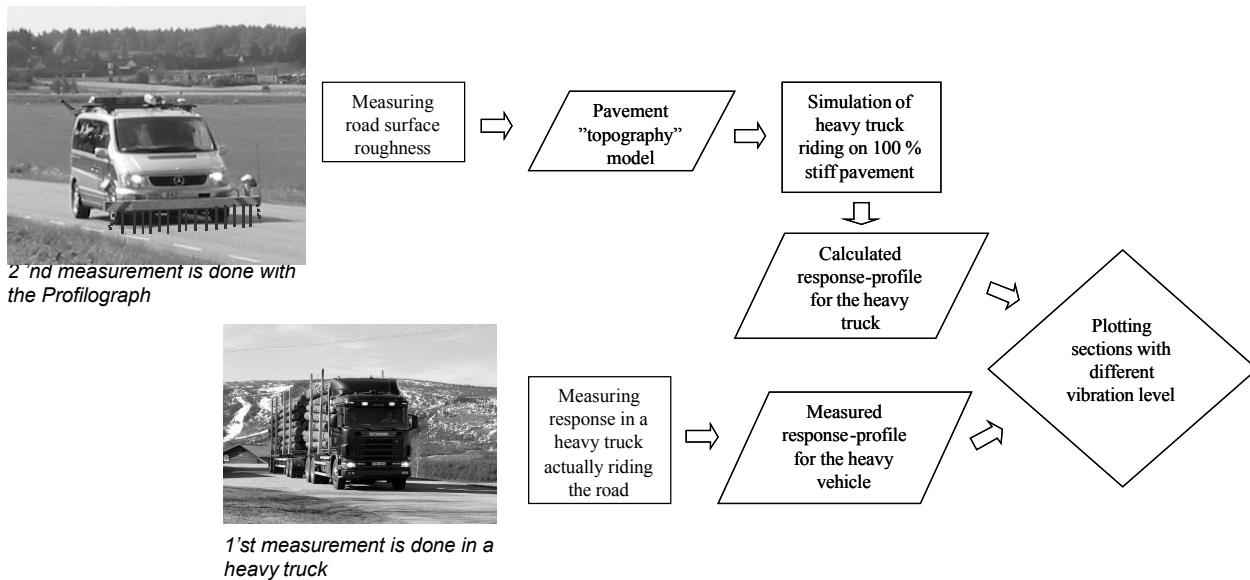


Figure 5: Flow chart for the new method to measure dynamic road roughness¹

A flow chart describing the method is presented in Figure 5.

During the first step, vibration and speed of a loaded heavy truck, travelling the road in question, are recorded and stored.

Secondly, road roughness profiles in the truck wheel paths are measured (in unloaded state) with a high speed laser / inertial Profilograph. These profiles are used as input for a computer simulation of the truck ride. Simulation set-up includes data about speed during the real truck ride, as well as mechanical parameters (measured and derived weights, suspension damping, stiffness etc.) for the actual truck. When doing the simulation, the road profiles are assumed to be 100 % stiff.

Third, measured and simulated vibration data series are adjusted with a new algorithm, making a running synchronization of the inevitable distance position drift. This drift is caused by variance in truck speed, differences in lateral position through curves etc.

Finally, the vibration series are compared, and sections with significant discrepancies are noted. Such sections are surmised to be “soft spots”, exciting vehicle vibration that is very different in reality, than indicated from ride simulations based upon profile data for the unloaded pavement.

4 TEST SITES

Field measurements were done at two test sites located in the western and two test sites in the northern region of Sweden. The sites were from 8 to 32 km long.

The sites were ranked in administrative papers to have full bearing capacity, but in practice they have modest and varying bearing capacity.

All the sites had a paved bound wearing course, while the site AC 600 also had one long section of dirt road.

¹ Photos by Mats Wendel, SRA and Scania Media Services

5 INSTRUMENTS AND METHODS

5.1 Truck vibration

Actual vibration was measured in a loaded heavy truck, while travelling the test sections. Vibration was recorded in a (x, y, z) system, where x is longitudinal, y transversal and z vertical direction. The speed and travelled distance were measured with an odometer, connected to the vibration recording computer.

Vibration measurements were done at:

- front axle, right side wheel (z) and left side wheel (z),
- cab floor, right side (z) and left side (z),
- driver's seat (x, y, z),
- frame, rear end right side (z) and left side (z)
- frame, front end right side (z) and left side (z)

The measurement plan included runs at 30, 50 and 70 km/h. The 70 km/h runs were cancelled at two of the sites, due to safety reasons associated with riding these poor roads.

5.2 Road roughness profilometry

Lane 3-D roughness mapping was done with SRA CS's laser/inertial GE Profilograph P16 seen in Figure 5.

5.3 Reference pavement condition testing

Pavement and subgrade material thickness were mapped with ground penetrating radar (GPR). Material thickness and classification were done using core samples and road laboratory testing. Falling Weight Deflectometer (FWD) testing was done in accordance with the SRA (1998, 2000) standard methods 112 & 114.

6 ANALYSIS OF FIELD DATA FROM TEST SITES

6.1 Hazardous heavy vehicle seat vibration

At several occasions it turned out that it was impossible to safely drive the heavy truck faster than 30 km/h, due to the truck response to the very severely damaged pavement.

Also at the low speed of 30 km/h, the truck driver was occasionally exposed to "extremely uncomfortable" vibration at the two northern region test sites, see Figure 6. At all 4 test sites, the EU Action Value 0.5 m/s^2 were exceeded already when driving at 30 km/h. This means that after 6 July 2005, it will be illegal to have an employed driver to spend the full working days driving a truck at speeds of 30 km/h or more, on roads in this poor condition without taking technical or organisational provisions to minimise vibration exposure.

On average, test site BD 374 had lower International Roughness Index (IRI) than test site O 1996. Still, BD 374 gave much higher seat vibration average level, and almost twice as high transient "shock". Average IRI surface roughness values are obviously poor descriptions of truck ride quality and health risk at the 8 to 32 km long test sections.

Seat vibration @ 30 km/h

IRI = 3,95 mm/m was much worse than IRI = 4,13 mm/m

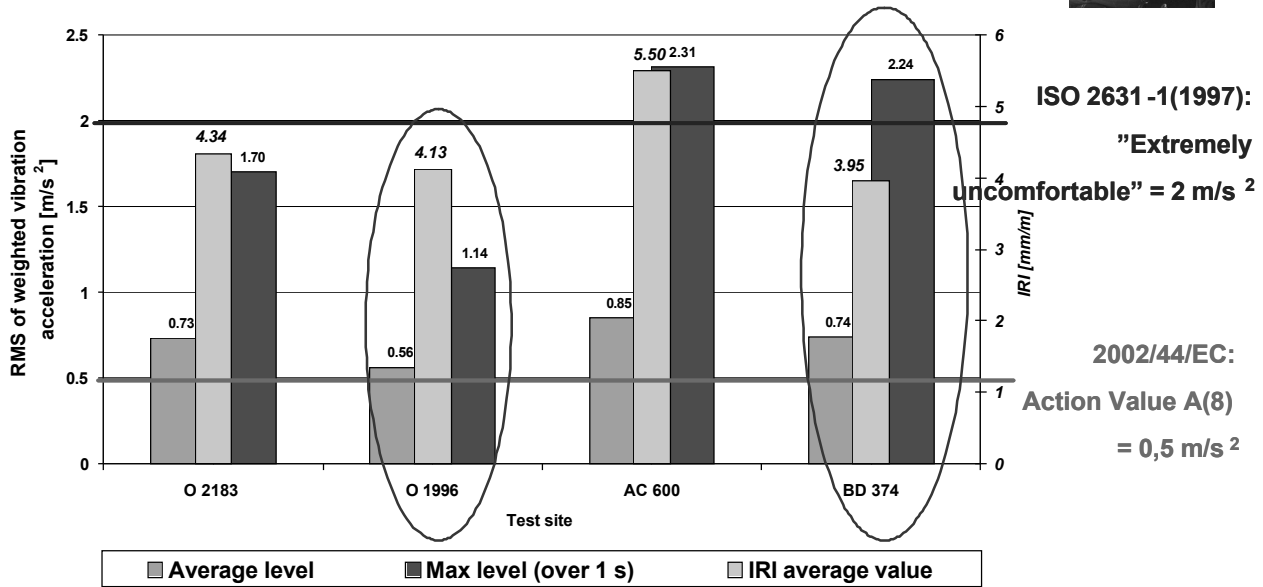


Figure 6: Site average surface roughness (IRI) and vibration level on truck driver's seat

6.2 Comparison of measured and simulated truck vibration

In order to minimize influence on the comparison from other vibration sources than from the road, the receiving point should be as close to the road as possible. The first receiver is the tyre footprint, but its vibration is very difficult to measure. A more reasonable receiving point can be found at the unsprung mass rigid parts. It is reasonable that its vibration should be very little affected by wind load, engine combustion pulses, power train unbalance etc. Thus, the unsprung mass (the strut) was selected as reference receiving point, where measured and simulated vibration becomes compared.

The simulation was made with a quarter vehicle model. The truck parameters were determined by applying the least-square method on the difference between measured and modelled transmissibility, i.e. the quotient between Power Spectral Density (PSD) for truck wheel vibration and PSD for road profile. Details are given in Ahlin et al (2004).

Laser/inertial profilometers typically record 1 mm wide profiles. Such a narrow profile does not give ideal fit with 3 - 4 dm wide truck tyre footprint perceived roughness. To overcome this problem, a virtual tyre footprint profile sensor was used in this project. The accuracy of the profile, as evaluated in terms of vehicle perceived roughness, was improved with about 10 to 15 % compared to a normal profilometer recorded profile, see Ahlin et al (2004).

At first glance, simulated and real vibration showed very poor likeness. As expected, this was due to the small but unavoidable differences in position of the data series. These differences originate from speed variation in the real truck, and from different lateral positioning through horizontal curves etc.

The positioning problem was solved by using a tailored algorithm for "Dynamic Space Warping". The warping makes it possible to adjust the two vibration series extremely carefully to each other, not to loose correlation in position with more than a number of decimetres.

Examples of resulting likeness between the two wheel-vibration series are shown in Figure 7. The graphs show reasonable overall likeness, while some sections show significant lower likeness. Such sections potentially have large pavement deflection variance.

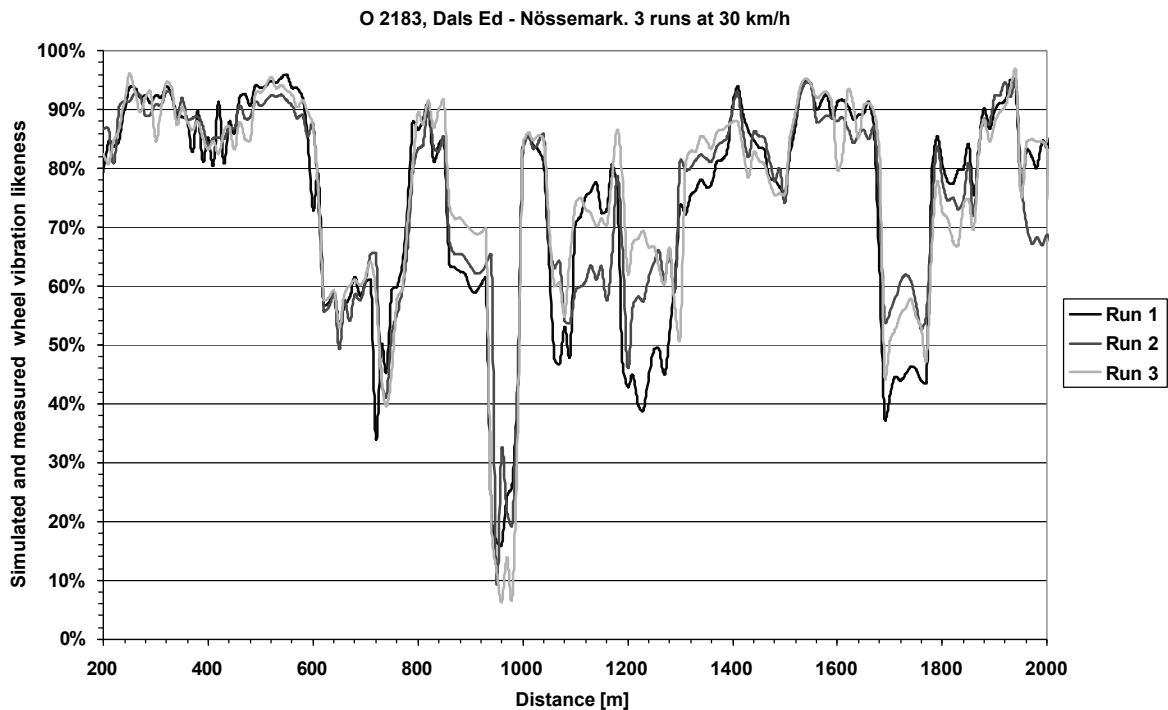


Figure 7: Repeatability results for three truck runs, test site O 2183

Where the warping has worked as intended, accuracy is as described from the examples below. However, at some sections, the warping has gone “out of the track”. The algorithm has been continuously improved during the project, but it is not perfected yet. Thus, an upcoming development work is perfecting the warping algorithm.

The method repeatability is reasonable; the 3 runs in top of Figure 7 show 4.2 % average standard deviation.

Reproducibility over time is reasonable as well; spring and autumn runs at site BD 374 showed 4.8 % average standard deviation. Certain deviation is due to the thaw process, whereas likeness is lower during the spring time. Thus, the method may be useful for detection of spring thaw related pavement problems?

Reproducibility between different speeds also seems reasonable; four 5 km long runs at 30 and 50 km/h recorded at test site AC 600 show 3.7 % average standard deviation. At different speeds, the interaction between pavement structure (resonances with soil layers eigenfrequencies and so on), surface and vehicle dynamics become different. This explains deviations and must be recognized when drafting the final test method. This knowledge could perhaps become utilized to measure pavement dynamic properties in more detail, by comparing results from runs at different driving speeds.

6.3 Comparison of potential soft spots with ground penetrating radar (GPR) results

The truck wheel vibration likeness varied between 3 and 40 % for section 4700 to 5000 m at test site AC 600. By georadargram, the pavement layers were revealed as thin and having large thickness variance. Between 4760 and 4840 m, the pavement layers show poor integrity at depths below 0.2 m, likely due to frost fatigue.

Similar agreements were found at many, but not all, identified potential soft spots. Also when comparing GPR results with FWD testing, the agreement on sections with structural problems was not totally uniform. This confirms the complex nature of pavement engineering, and different pavement test methods should be seen as valuable complements to each other and to the engineer's visual inspection, when making a pavement condition assessment.

6.4 Comparison of potential soft spots with core samples

Core sampling was not done intensively enough to support any stronger conclusions. At site AC 600, 15 cores were taken. Average total pavement thickness was 35 cm. Average wheel vibration likeness was 70 % among sections where coring showed 35 cm or thicker pavement. The likeness was only 50 % among sections with less than 35 cm thickness. This indicates that pavement deflection variance is likely to be larger at sections with thinner pavement thickness, which makes sense.

6.5 Comparison of potential soft spots with results from FWD evaluation

The FWD analysis was done in accordance with the SRA evaluation standard method 114 (2000).

During the spring thaw period FWD-test, large deflections and deflection variance were observed in the data recorded. FWD centre deflections of up to over 4 mm was observed at dirt road sections, and over 2 mm at paved sections. Centre deflections varied up to 3.6 mm between adjacent samples at dirt road sections, and up to 1.5 mm at paved sections.

Potential soft spots are identified by lower-than-usual likeness between simulated and measured wheel vibration.

Examples of agreement between potential soft spots and FWD results are showed in Figure 8 and Figure 9. As seen in Figure 8, wheel vibration likeness shows reasonable fit with calculated subgrade E-module. Bearing Capacity Index is defined in SRA method 114. In Figure 9, this index shows a reasonable fit with wheel vibration likeness.

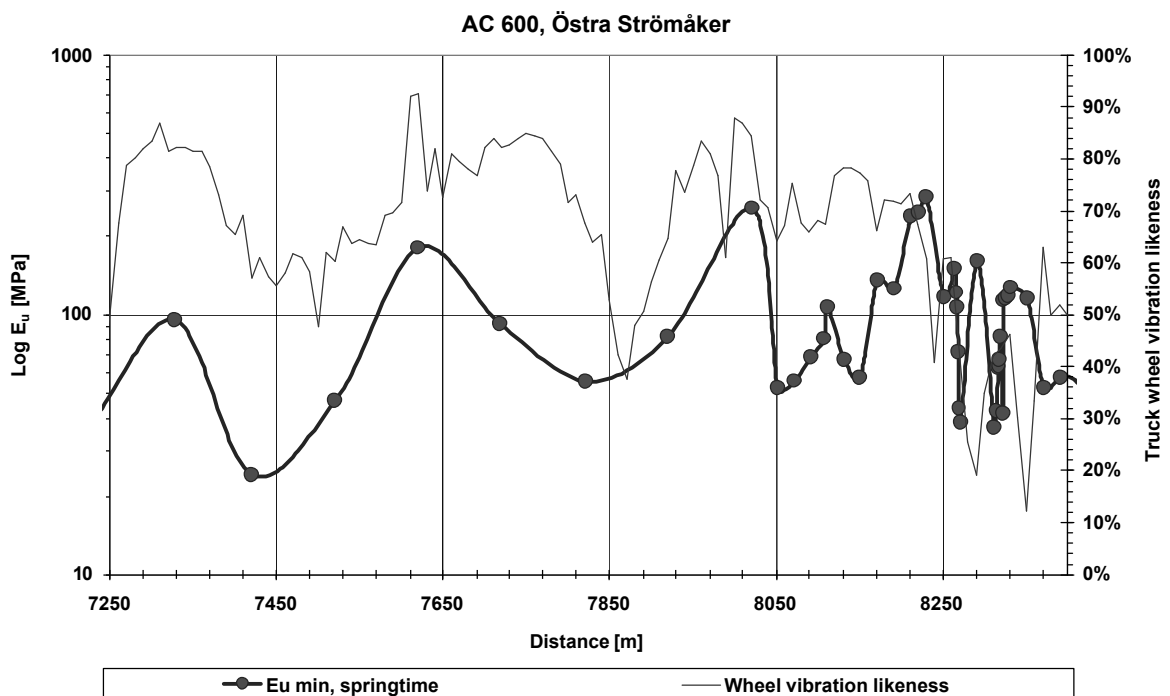


Figure 8: Subgrade stiffness versus soft spot identifications

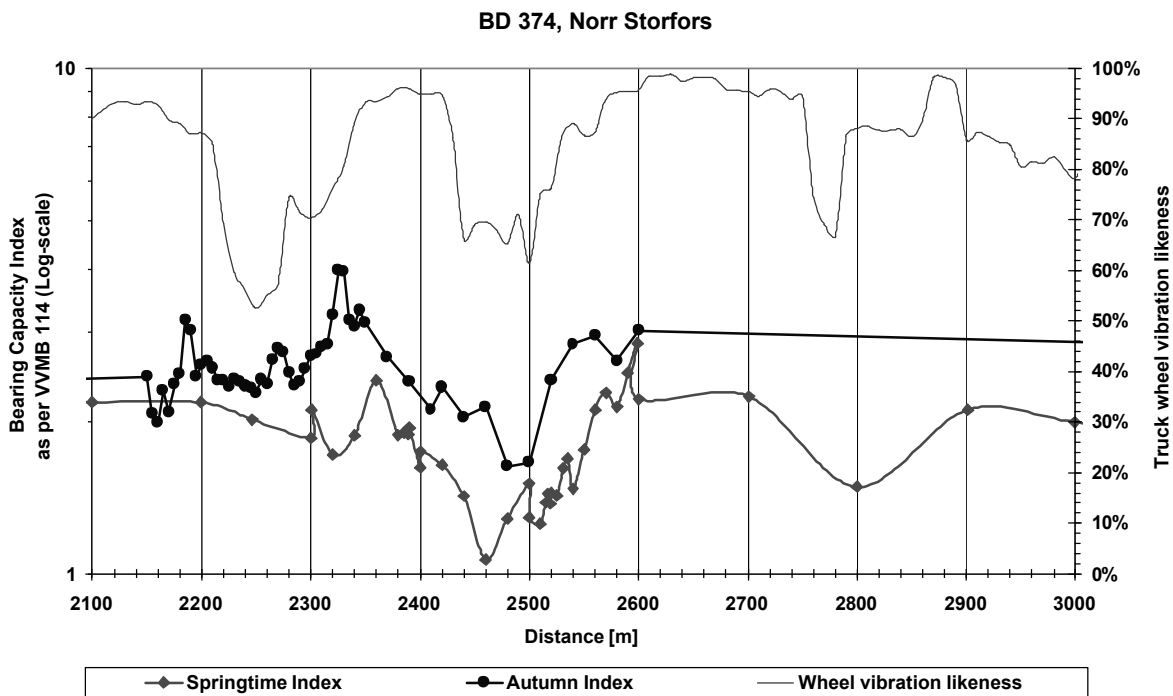


Figure 9: Bearing capacity index versus soft spot identifications

7 CONCLUSIONS

Results from the accuracy experiment do not support a rejection of the hypothesis; previously observed threshold truck cab vibration is partially related to pavement deflection profile slope variance (dynamic roughness; soft spots). Thus, the new and patented method shows a potential for measuring pavement deflection variance at highway speed with existing profiling equipment.

The most studied test site, BD 374, yielded an average likeness of 85.3 % between real and calculated heavy vehicle vibration. At some sections, the collated vibration data show very poor likeness. Such sections are presumed to have high pavement deflection variance.

The likeness increased much when using road profile data collected with a virtual tyre footprint profile sensor instead of a single laser sensor, see Ahlin et al (2004).

Repeated truck runs show reasonable precision in likeness between simulated and measured wheel vibration.

Reproduced runs at spring time and autumn also show reasonable likeness precision, with a bias where spring time likeness is significant lower at certain sections. Those sections are presumed to have spring thaw related problems. Reproduced runs at different speeds also show reasonable precision.

Comparison with results from traditional pavement condition tests (FWD, GPR and coring) show promising trueness. Soft spot indications have been correlated reasonably well with subgrade stiffness as well as with Bearing Capacity Index.

The next step to come is perfecting the warping algorithm, used for dynamic space domain adjustment of simulated and measured vibration series. After that, a standard method should be formalized, and its performance evaluated in a new accuracy experiment.

Truck driver's vibration exposure already at 30 km/h exceeded the new EU Action Value at all test runs. At the roughest (northern region) sites, the ride occasionally became "extremely uncomfortable" already at 30 km/h. This shows that roads with condition similar

to the test sites bring an unacceptable hazardous work environment to professional truck drivers.

Test site BD 374 had lower surface roughness index IRI than test site O 1996, but much higher seat vibration. This means that IRI is not a very accurate indicator for truck ride quality. Indicators with better trueness are truck cab vibration and driver seat vibration.

8 ACKNOWLEDGEMENT

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8.1 Co-operative consultants

Measurements with GPR and basic analysis of GPR-data were done by Radar Väg Analys AB (western sites) and Raycon AB (northern sites).

Vehicle vibration measurements and analysis, including the concept of “Dynamic Space Warping” has been done in cooperation with Axiom EduTech AB.

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