Calculation of Reference Ride Quality, using ISO 2631 Vibration Evaluation

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Abstract

Every road authority targets good ride quality in their pavement management. Ride quality depends strongly on the experienced vibrations, induced by road roughness. International Roughness Index, IRI, is the most common way to describe road roughness. But there exist no commonly accepted limits for IRI. ISO 2631 defines how to measure human whole body vibration (WBV), as experienced by vehicle occupants during the ride. Criterions for discomfort and health justifies vibration limits in the ISO 2631 standard. Calculated WBV could therefore be useful to create relevant limits for road roughness, to be used in our pavement management systems. IRI is defined by means of a quarter car model, and the same model is here used to 1) calculate WBV as defined in ISO 2631, and 2) to get a relation between IRI-values and WBV. A software Ride Quality Meter™ has been developed to calculate WBV from laser/inertial measured road profiles, without involving IRI at all.

Average suspension stroke in a passenger car; International Roughness Index

People early became interested in the causes of road roughness, how roughness affect vehicle motion, and how these motions affect ride quality and highway safety.

Early test cars were equipped with pantograf-type systems, in order to plot resulting "average suspension stroke" [mm/m, inch/mile] between wheel axle and car body. See figure 1.

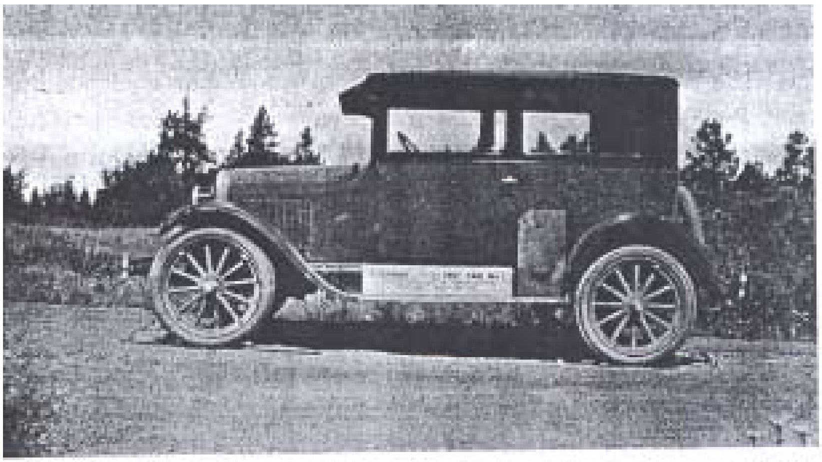

Figure 11. View of Highway Washboard Test Car of the Engineering Experiment Station, Car Is Shown with High Pressure Tires.

Figure 1. 1927 test car, measuring average suspension stroke [mm/m]. Dana (1933).

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Mechanical properties, as well as different test speed, gave significant measurement problems over time (wear and ageing of components in the test cars etc) and when comparing different road stretches.

In 1986 the International Roughness Index, IRI, was defined by the World Bank in order to solve these problems.

IRI became defined as the accumulated suspension stroke in a mathematical car model, divided by the distance traveled by the model. The calculation is based on a simulated ride, at the reference speed 80 km/h, on the measured road roughness profile.

Road roughness profiles are measured by profilometers using combinations of laser and inertial technology. A profilometer with 17 parallell 16 kHz lasers and a complex inertial unit is shown in figure 2. The figure also contain a 3-D plot of 17 parallell roughness profiles in a measured road lane. (Traffic goes to the right in the plot). Operating speed for measurement of profile roughness data relevant for ride evaluation, is limited by vehicle performance (over 160 km/h) and public speed restrictions. The resulting profiles are not dependant to the used operating speed of the Profilograph, unless it has been very low (parking speed) during a rather long sequence.

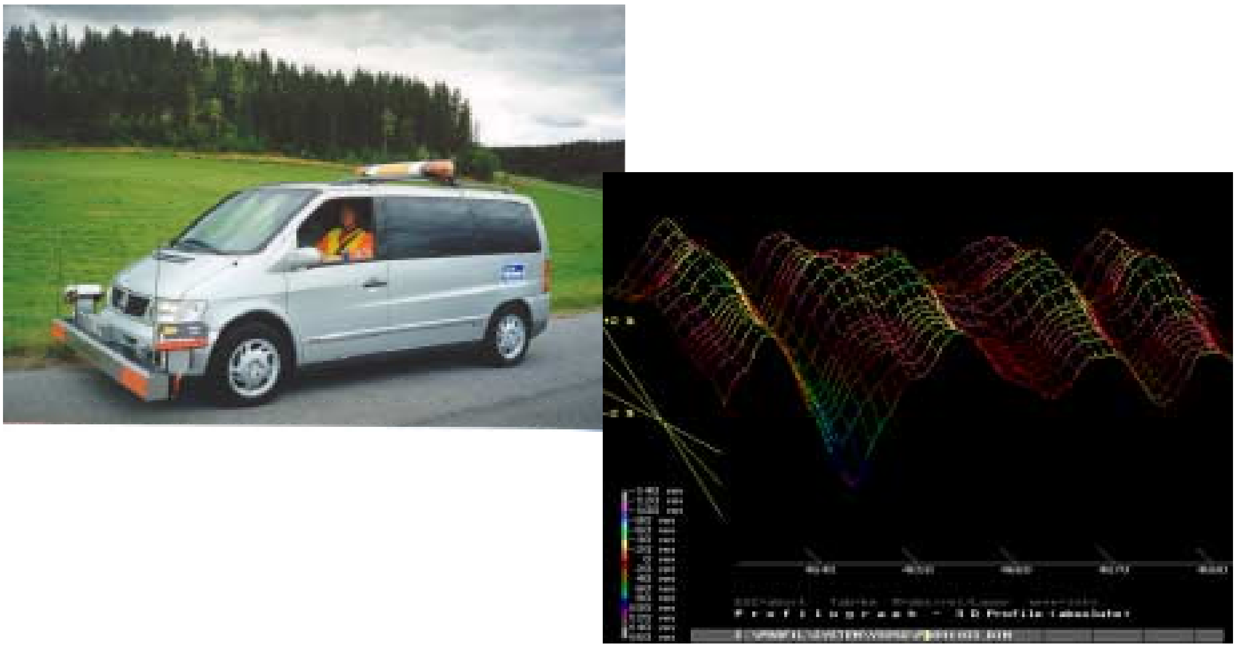

Figure 2. Vägverket Konsult Profilograph P16 laser-inertial road roughness profiler.

If the accumulated stroke in the mathematical reference vehicle is measured in millimetres and the traveled distance in metres, we get the unit [mm/m] for IRI. In the USA the unit is [inch/mile].

The mathematical model is a quarter car model, see figure 3.

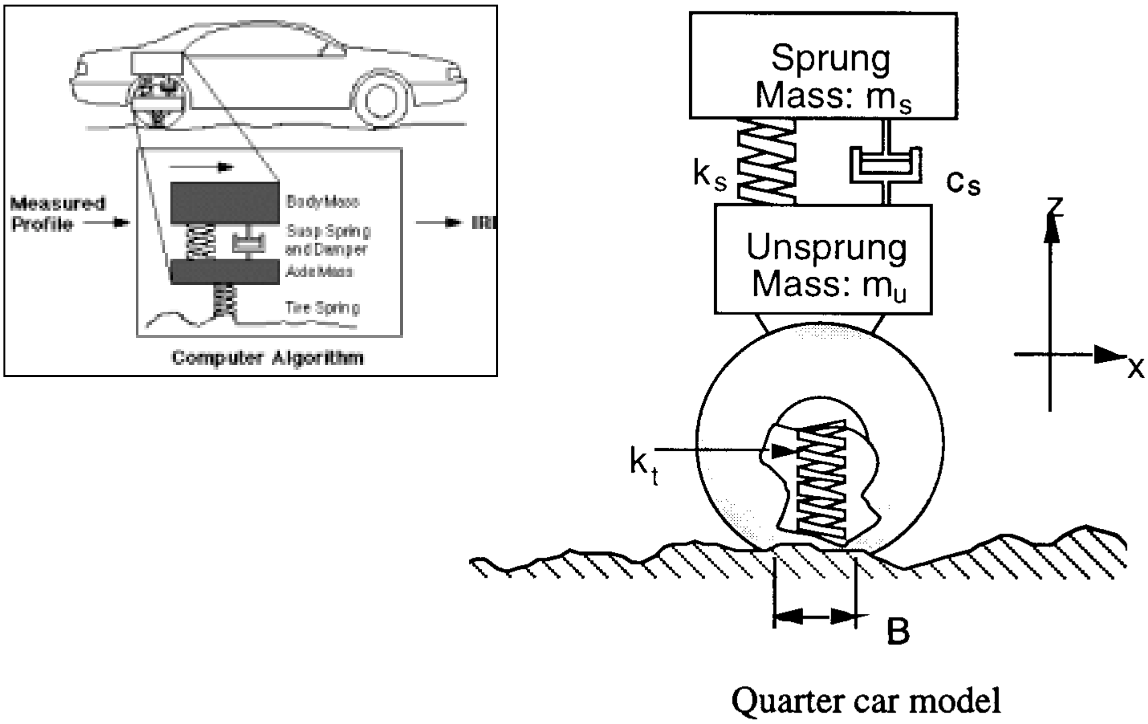

Figure 3. Quarter car model, Karamihas & Sayers (1996).

The (normalized to m_s = 1) parameters for the model are defined by ”the Golden Car”:

$c_s = 6.$	[1/s]
$k_t = 653.$	[1/s^2]
$k_s = 63.3$	[1/s^2]
$m_u/m_s = 0.15$	

The simulated speed v is set to 80 km/h. The equations of motion for the model are:

$$\left(M \cdot s^2 + C \cdot s + K\right) \cdot \begin{pmatrix} z_s \\ z_u \end{pmatrix} = \begin{pmatrix} 0 \\ k_t \cdot h \end{pmatrix} \tag{1}$$

where h is the road profile and z_s and z_u is the vertical motion for the sprung and unsprung mass, respectively. The Golden Car parameters define the matrices M, C and K.

The accumulated suspension stroke d is calculated as:

$$d = \int_0^T \left|\dot{z}_s - \dot{z}_u\right| dt \tag{2}$$

where T is the measurement time.

to get IRI we divide by the distance L, which is:

$$L = v \cdot T \tag{3}$$

and we get

$$IRI = \frac{1}{v \cdot T} \int_0^T \left| \dot{z}_s - \dot{z}_u \right| dt \tag{4}$$

We find that IRI is the time average of the absolute value of the relative velocity between m_s and m_u, divided by the speed v. [(mm/s)/(m/s)] = [mm/m].

The transfer function from road profile h in [mm] to the relative velocity between the two masses is shown in figure 4.

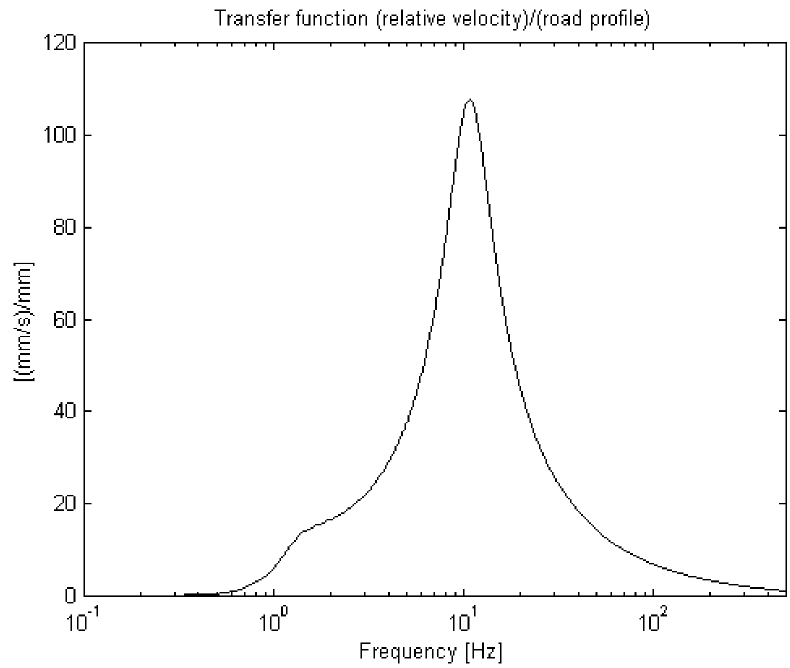

Figure 4. Transfer function (relative velocity)/(road profile)

The profile slope from road roughness bottom to peak (figure 5) can roughly be estimated as

Slope = 2*A/(λ/2) = 4*A/λ (5)

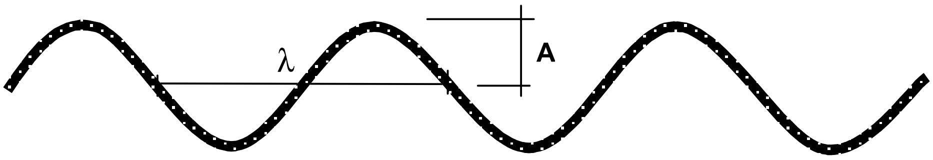

Figure 5. Road roughness wavelength and amplitude

If one consider the contribution to the roughness profile slope from a certain amplitude (i.e. 1 mm) at different roughness wavelengths / frequencies (at 80 km/h), Figure 4 can be re-plotted as in figure 6, a plot that is recognized by pavement engineers familiar with the IRI.

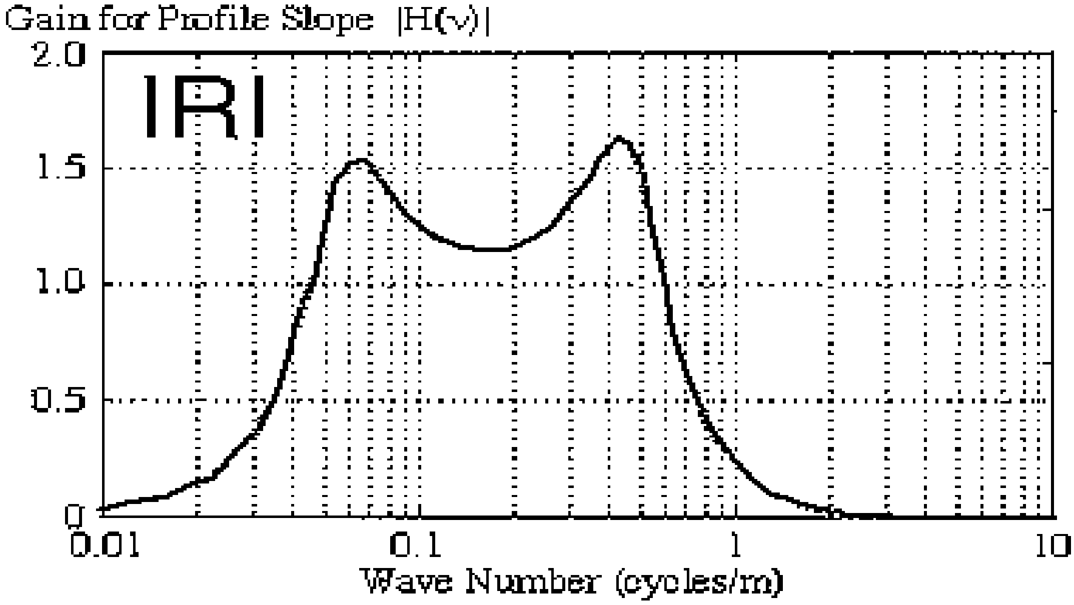

Figure 6. Transfer function (suspension stroke at 80 km/h - IRI)/(road profile slope), Karamihas & Sayers (1998).

ISO 2631 whole body vibration

The vibrations - for instance in a vehicle body - that have influence on the human in terms of comfort, activities and health are treated in ISO 2631-1 (1997). It is measured as the r.m.s. value of a frequency-weighted acceleration. In the quarter car model, the vertical vibration affecting the vehicle occupants corresponds to the vibration of the sprung mass m_s, weighted with the ISO filter W_k (which is designed to match vibration impedance of the human body and its organs). The transfer function from road profile to frequency-weighted acceleration of m_s is given in figure 7.

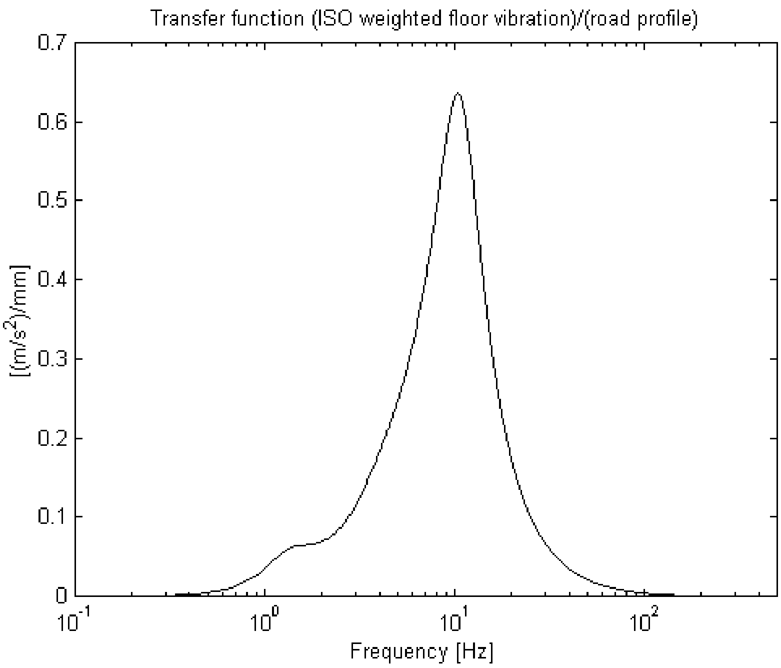

Figure 7. Transfer function (ISO weighted floor vibration)/(road profile)

Relation between floor vibration and IRI for sinusoidal road roughness profile

To get a first relation between IRI and floor vibration in the car body we start with a sinusoidal road roughness profile. We may then compute the quotient between floor vibration and IRI as a function of the wavelength of the road profile and the vehicle speed. The IRI computation is standardized to a speed of 80 km/h, but when we calculate the ISO floor vibration we must allow any vehicle speed. One way to present the result is given in figure 8. A common wavelength is 5 meters, and we find that at 80 km/h the quotient is 0.16.

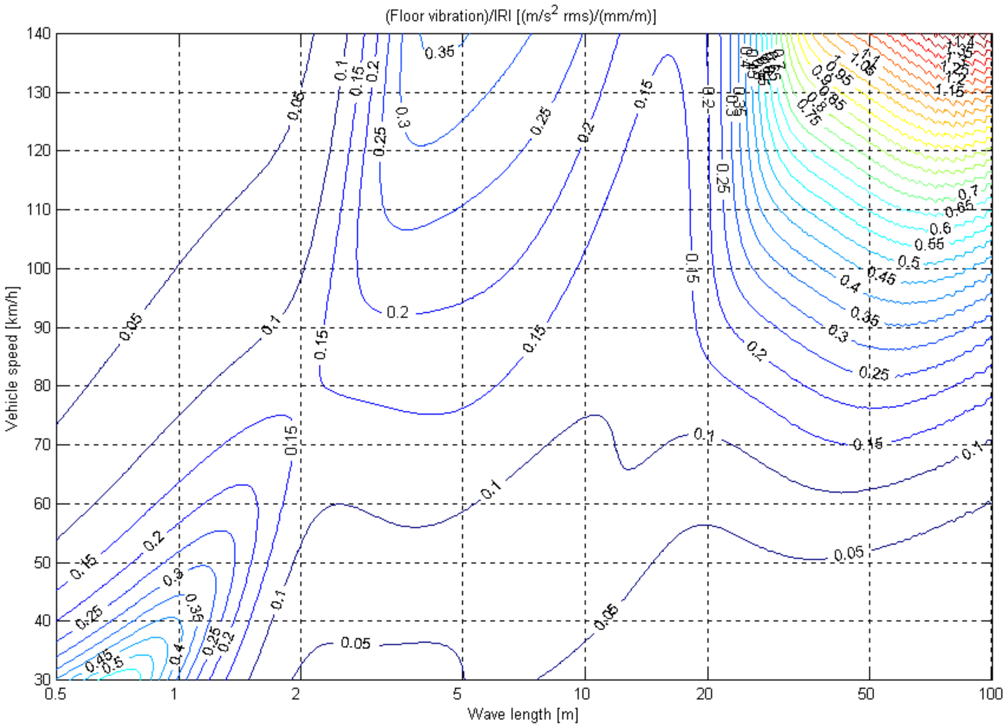

Figure 8. (Floor vibration, ISO frequency-weighted)/IRI as a function of road profile wavelength and vehicle speed

Relation between floor vibration and IRI for roughness profile given by power spectral density

To get a relation that is valid for more complicated road roughness profiles, a Power Spectral Density, psd, model for the road roughness may be used. A common model for the psd is:

$$pk(k) = P_0 \cdot \left(\frac{k}{k_0} \right)^{-n} \quad [m^2/(c/m)] \tag{6}$$

where k is the wave number [cycles/m]. The exponent n has a value around 2.

When you travel across a road profile with psd pk(k) with a vehicle speed v [m/s], you will get a psd pf as a function of frequency f:

$$pf(f) = \frac{1}{v} \cdot pk\left(\frac{f}{v}\right) = \frac{1}{v} \cdot P_0 \cdot \left(\frac{f}{k_0 \cdot v} \right)^{-n} \quad [m^2/Hz] \tag{7}$$

We may now apply this simple spectral model with different exponents to the quarter car model and calculate IRI and ISO frequency-weighted floor vibration. We plot the quotient between floor vibration and IRI as a function of vehicle speed for different exponents. The result is given in figure 9.

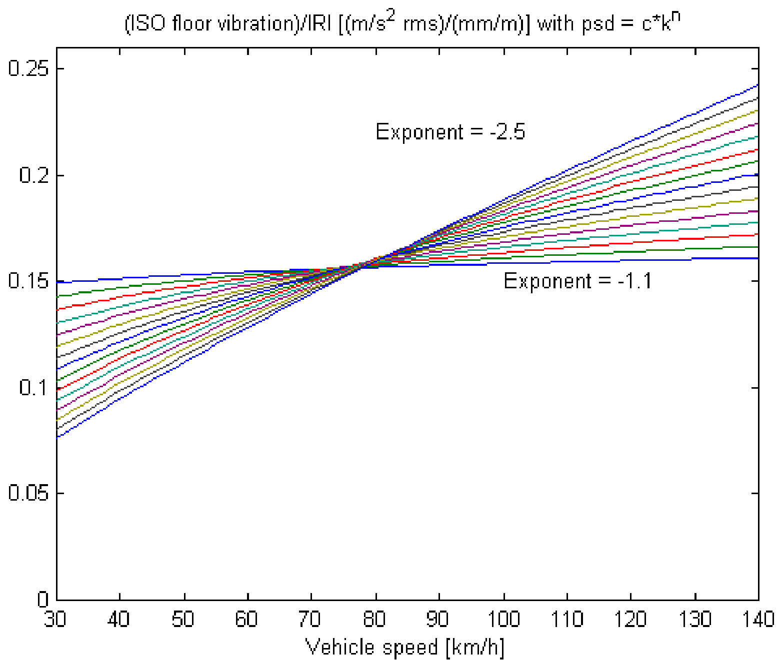

Figure 9. Relation between floor vibration and IRI with psd model

We once again find the value 0.16 at a vehicle speed of 80 km/h. For the curves in figure 9 we find with good approximation:

$$\frac{floor\ vib}{IRI} = 0.16 \cdot \left(\frac{vs}{80} \right)^{\left(\frac{n-1}{2} \right)} \tag{8}$$

where vs is the vehicle speed in [km/h].

We now use 0.8 m/s^2 as a limit for the (ISO frequency-weighted) vibrations, corresponding to ”uncomfortable” ride according to ISO 2631 . From equation (8) we may then derive a relation between ”comfortable vehicle speed”, cvs [km/h], and IRI [mm/m]:

$$cvs = 80 \cdot \left(\frac{IRI}{5} \right)^{\left(\frac{2}{1-n} \right)} \tag{9}$$

A diagram for different psd exponents is given in figure 10.

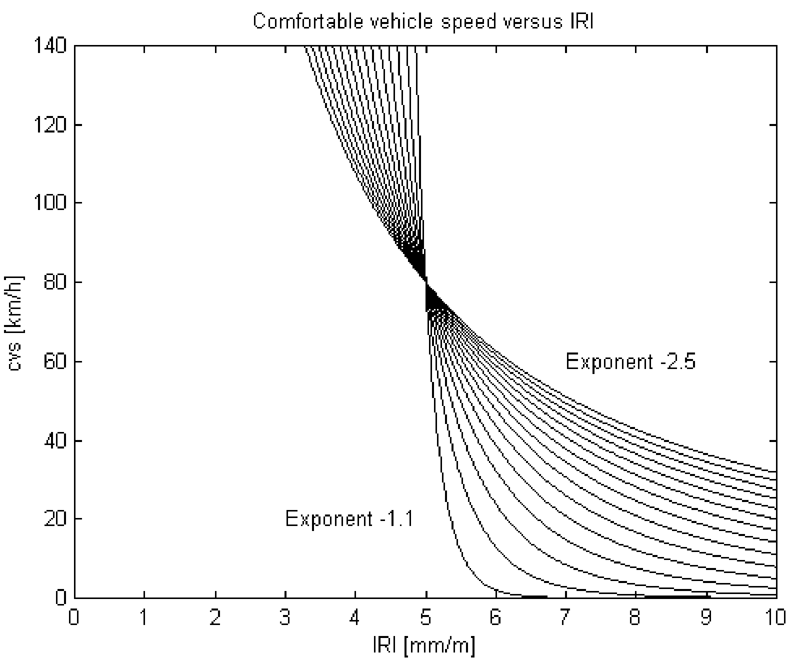

Figure 10. ”(Un)comfortable vehicle speed” as a function of IRI.

Reference Ride Quality for real road roughness profiles

The effect from real road roughness upon ride quality depends strongly of interaction between various roughness components. In the left side of figure 11, there are two different road humps/roughness. Even though the geometries are quite similar, the resulting car body vertical peak accelerations differ with approx. 30-50 %. In the right side of the figure there are two road roughness profiles that gives quite different ride, but that may be rated as equal profiles by several common road profile measurement and analysing methods.

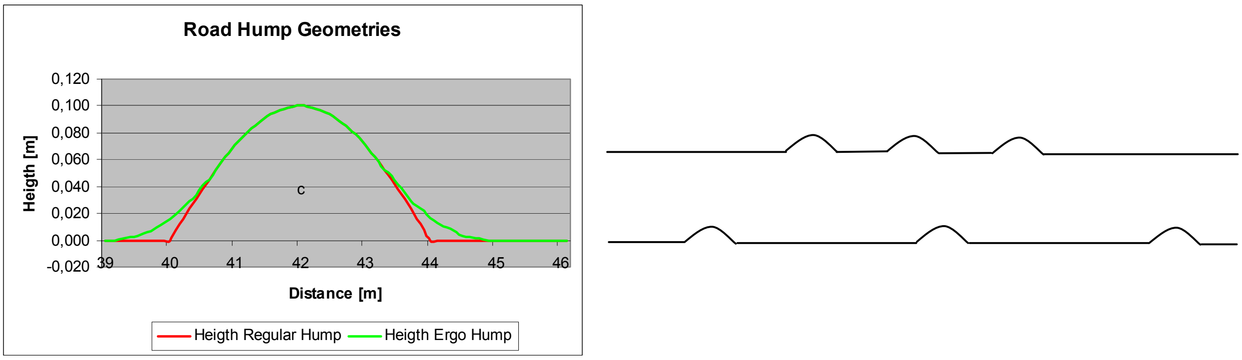

Figure 11. Examples of road roughness geometries, Granlund (2001).

Real road roughness have certain causes, which in turn affects the roughness properties, see table 1. Some important factors are pavement type, age, condition, climate, vehicle type and speed.

Table 1. Some common ride-affecting road damages and their causes

Damage cause	**Frequency [Hz]**	**Typical resulting wavelength λ [m] at varius speed [km/h]**						
		Undependent of speed	***30***	***50***	***70***	***90***	***110***	***130***
Frost actions		1 – 3 (1 - 30)						
Traffic load	1 (7 – 12)		8	14	19	25	31	36
Settlements	(0,1 – 0,63)	10 - 200						
Increased speed – increased superelevation	(0,1 – 0,63 with lower level at the drivers side of the car)	30 – 300						

In cold climate roads often become damaged by frost actions. This typically creates roughness with wavelengths about 1 - 3 meters, but also other wavelengths can occur.

Roads with poor bearing capacity become damaged by dynamic loads from the body bounce and the axle hop of heavy vehicles. The bodies have eigenfrequencies around 1 Hz. (This is the same frequency as rocking chairs, childrens rocking beds etc – these motions are obviously also a safety hazard, due to impact on driver sleepiness). Accelerating 400 kg unsuspended mass with 2 g, Newtons second law (F = m * a) suggest a dynamic load of 8 kN/wheel. This is a load that quickly dampens. Accelerating a suspended mass of 5000 kg/wheel with 0,3 g, Newtons second law suggest a dynamic load of 15 kN/wheel. The bounce load will be apperent for a rather long time, damaging a long road section. In pavement engineering the load-to-damage relation normally follows the power of 4. Obviously, body bounce add much damage to the roads, creating 10 – 30 m roughness wavelength and increasing the risk for tiredness-related accidents.

The average speed is increasing over time. On roads with poor curvature design this has been compensated by adding on the superelevations when repaving the roads. This increases the low frequency movements - known to cause motion sickness - that car suspension cannot reduce at all. The vertical motion is lower at the drivers side of the car, since that side in closest to the centerline of the road. The profile at the centerline is very little affected by superelevation. (As a consequence: Stretches in ambulances should preferably be placed behind the drivers seat, in the UK on the right hand side of the car).

The road managers want information about the overall road network condition, about certain routes, about repair projects and also about the individual road damage. On many roads real rides (such as ambulance transportation) normally occur at other speeds than the IRI reference speed 80 km/h. To comply with these kind of aspects (with an exception of motion sickness aspects), a new software Ride Quality Meter™ was developed.

Example of output from Ride Quality Meter™ is presented in figure 12. The roughness profile in the bottom reads on the right scale. Car body accelerations (peak and running rms) during high speed ride reads on left scale. The accelerations are frequency-weighted with the ISO-filter W_k and can be compared to limits in ISO 2631-1 (1997).

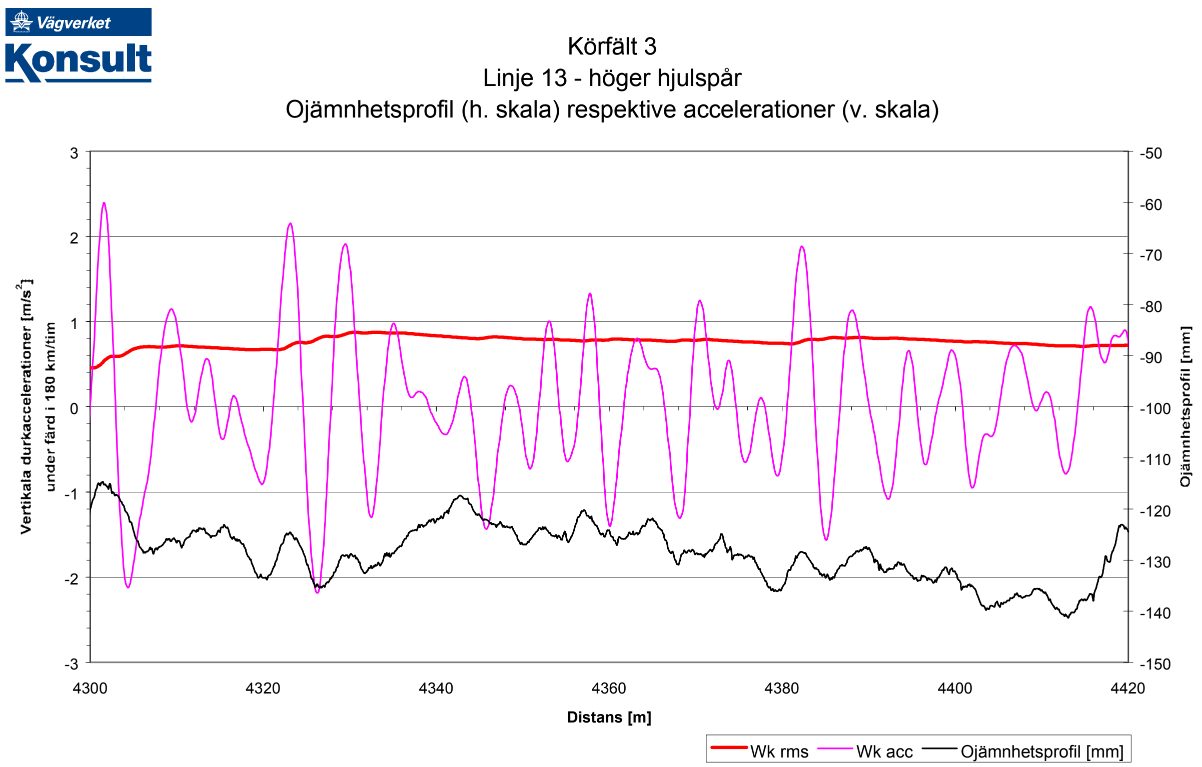

Figure 12. Example of output from Ride Quality Meter™.

Conclusions

Through inter-disciplinary scientific work we have established a model for predicting vertical human whole body vibrations in a typical passenger car, using data from any measured road roughness profile. The model can be used as part of the foundation of road roughness management policies. However any such policy must also consider the needs in more demanding situations of road use. Examples are the high speed transportation of injured patients in heavy ambulances of ”Mobile Intensive Care Unit” type, and occupational exposure of professional drivers in heavy vehicles. In both cases the vibration gain is much higher than in passenger cars, while also the acceptable vibration peak level and cumulative dosis is lower than for the common road user (Ahlin et al, 2000). The model does neither consider horizontal or rotational vibrations, nor the low frequency vertical vibrations 0,1 – 0,63 Hz known to cause motion sickness etc. Calculations with the model are efficiently made with the software Ride Quality Meter™. The calculations can be made for real road roughness profiles measured with a laser/inertial Profilograph, as well as for theoretical profiles such as different road repair layouts or different road hump layouts.

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