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REDUCING THE VIBRATION LEVEL: AN ESSENTIAL FACTOR IN OPTIMIZING ROAD FREIGHT TRANSIT

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The paper studies the influence of vibrations on the quality of road freight transit. A method that establishes the weight of the moving vehicles is presented, using wireless sensors that measure the vibration level resulting from the interaction between the vehicle and the road. Also, the paper determins the link between the quality of road freight transit and road characteristics. We present the equations that establish the connection between the vibrations recorded in the vehicles during the road freight transit and the deformations of the road, a method of classifying this deformation and the pattern of obtaining it.

Keywords: vibration, longitudinal roughness, friction, cross slope, quarter car model

List of Abbreviations:

IRI - International Roughness Index;
WBV - Whole Body Vibration;
A(8) - The daily vibration exposure for a truck driver in 8 hours of driving;
WSN - Wireless Sensor Network;
ADC - Analog-to-digital convertor;
MEMS - Micro-Electro-Mechanical Systems;
LAN - Local Area Network;
WAN - Wide Area Network;
ITS - Intelligent Tansport Systems;
WIM - Weigh In Motion;
E-screening - Electronic screening;
AP - Access Point;
PTZ - Pan tilt zoom

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1. Introduction

The optimization of road freight transit has the main purpose of ensuring the health and safety of the driver, but also the integrity of the vehicle and the goods carried. This goal can be achieved using ITS systems.

A wide range of various technologies called intelligent transport systems provide answers to many of the road freight transit issues. ITS systems are based on a set of technologies specific to data processing, communications, control and electronics.

ITS systems are transport systems that use informations, communications and control technologies to improve the operation of transport networks. The tools offered by ITS systems, called "Telematics in Transport", are based on three fundamental features - *information, comumunications and integration* - wich helps operators and travelers make better and more coordinated decisions. These tools are used to save time, money and lives, improve the quality of life and the environment, and increase the productivity of business. These objectives are common to all regions of the world, with their priority varying from one region to another.

ITS systems and services refer to any system or service that makes the move of people and goods more efficient and more economical, therefore "smarter". ITS systems contain a wide range of new tools for the management of transport networks and passenger services. Collecting, processing, integrating and providing information is at the center of ITS systems, providing real-time information on current network traffic conditions through online travel planning. The tools offered by the ITS systems allow authorities, operators and travelers to be better informed and make more coordinated and "smarter" decisions.

ITS systems can make every trip more dynamic, more comfortable, less stressful and safer. The fulfillment by a national system of the need to be effective, both economically and environmentally, requires a new way to address and solve transport problems.

Accidents and congestion caused by traffic have an important impact on life, decrease productivity and diminish energy. ITS systems offers people and goods the opportunity to move more efficiently and safely within the current multimodal transport system.

A fundamental technique for optimizing road freight transit is the electronic screening of vehicles. One of the technologies used within the electronic screening, WIM, is very important when it comes to optimizing road freight transit. This technology consists of measuring the approximate weight of the axles while the vehicle passes over some sensors mounted in the road, contributing to the determination of the total weight of the vehicle and to the classification of vehicles according to axel weight and spacing. The detection of vehicles loaded above traffic law is a necessity because they are difficult to handle and the braking distances for these vehicles are much higher. These vehicles represent a real danger both for the rest of the road users and to their own drivers. In addition, due to overloading, these vehicles seriously and irreparably damage the quality of the road.

2. Estimating the weight of vehicles using road vibrations

There is a relatively inexpensive solution for estimating the weight of moving vehicles, a solution based on a network of wireless sensors and using vibrations measured on the road.

The Wireless Sensor Network

In this section, we present a wireless sensor network that can estimate the weight of moving trucks from measured road vibrations. Figure 1 is a general depiction of the system. Multiple wireless sensors are embedded in road to detect vehicles, and to measure vehicle speed and the corresponding pavement acceleration and temperature. Since the system measures actual pavement response, it can also be used for structural health monitoring of pavements.

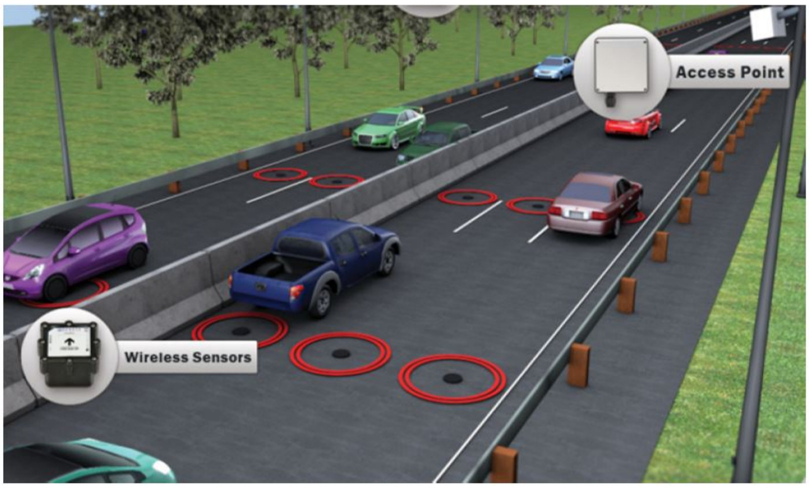

Fig. 1. Image showing a general setup of the system.

The wireless sensor network is used for detecting on-going vehicles and measuring corresponding pavement acceleration and temperature. We start by describing the WSN components: vehicle detection sensors, vibration sensors, and the access point. The low-noise vibration sensor was built specically for this project and we present that in more detail. Fig. 2 shows a general setup of the sensor network. The system is comprised of wireless sensor nodes that are embedded in the pavement, and an access point installed on the roadside. The sensor nodes are synchronized in time with the AP, and report data for vehicle detection, pavement acceleration and temperature. The AP controls the nodes and records the incoming data coming from the sensors and other optional peripherals such as a PTZ camera.

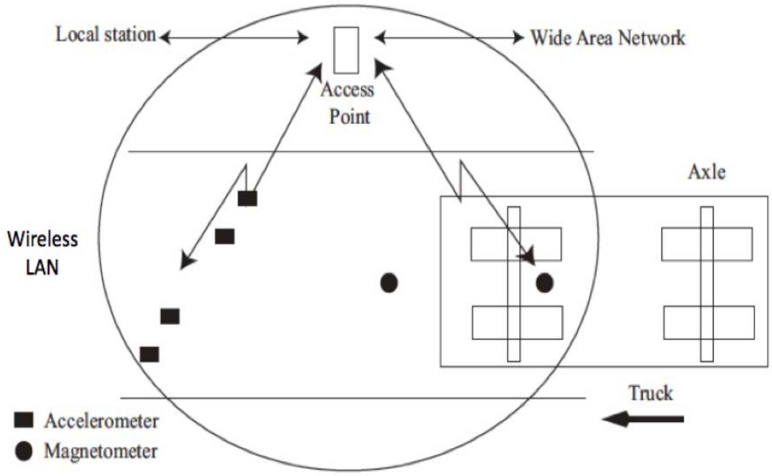

Fig. 2. Image showing a general setup of the system.

Sensor network components

Wireless sensor nodes

A wireless sensor node consists of 3 main components: a sensor, a microprocessor, and a wireless transceiver (or radio). Figure 3 shows the block diagram for a typical wireless sensor node. The sensor converts physical quantity like temperature, acceleration, magnetic field into an analog voltage signal. This signal is passed through an analog filter (signal-conditioning stage) and sampled using an analog-to-digital converter, typically available on microprocessors. The sampled data is transmitted wireless using an on-board wireless transceiver.

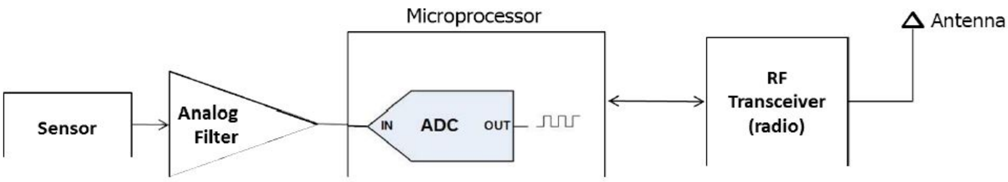

Fig. 3. Block diagram for a typical wireless sensor node.

There are two different types of wireless sensors in our system: vehicle detection sensors that detect the presence of a vehicle using a magnetometer, and vibration sensors that measure the vertical acceleration of the road pavement.

The vehicle detection sensor measures changes in the local magnetic field to infer the presence of a vehicle. The sensors have been shown to be very accurate for vehicle detection and have a lifetime of 10 years.

The vibration sensor

The vibration sensor is needed to measure the vertical acceleration of the pavement but has many unique design challenges: sensor needs to have a very low noise level in order to measure the ultra-low road vibrations; the sensor needs to sample fast enough to capture the transient pavement vibrations and yet have low power consumption for a long lifetime; the vibrations due to truck engines and other sounds should have a minimal effect on sensor readings; the sensor must be well coupled to the pavement and be strong enough to withstand tire forces from heavy vehicle traffic. Figure 4 shows a picture and the block diagram of the sensor. The MEMS accelerometer converts mechanical vibrations to an analog voltage signal. This signal is filtered to reduce noise and sound interference and amplified to increase the sensor sensitivity. The filtered signal is then sampled by a 12-bit analog-to-digital convertor and the samples are transmitted via a radio transceiver. The accelerometer also includes a temperature sensor whose output can be sampled by the ADC. The accelerometer and analog filter are powered by a 2.5 V supply voltage that can be turned off by the microprocessor when needed. The specifications for the vibration sensor were obtained using simulations done in previous tests on a highway. It was found that the sensor needs to have a resolution of 500 µg at 50 Hz bandwidth, and a range of ± 200 mg.

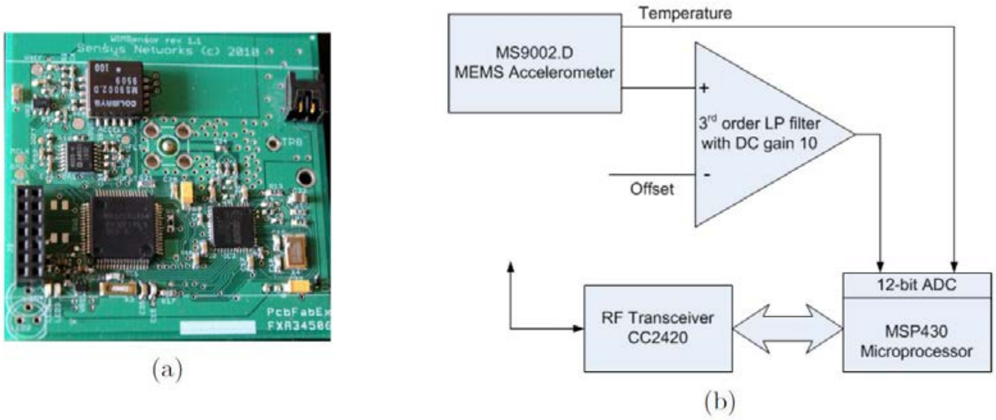

Fig. 4. Wireless vibration sensor. (a) Picture of the sensor board. (b) Block Diagram of WIM Sensor.

Fig. 5 shows a block diagram for the access point. This equipment provides remote control and observation of the WSN. The AP contains: (i) a processor with attached radio transceiver and 2 TB hard drive storage; (ii) a power controller that controls power to each connected device; (iii) an ethernet hub through which a local area network is setup for devices to communicate with each other; (iv) a 3G modem that acts as a gateway to the wide area network and enables remote access to the system; (v) a Wi-Fi bridge and an ethernet data port for local access to the system; and (vi) an optional pan-tilt-zoom camera for taking roadside images. Once a remote computer is connected to the AP, it can communicate with any of the connected devices through the LAN. It can, for instance, use the power controller to turn on/off individual components in the box, send commands to the sensors via the radio, change the settings of the PTZ camera, and start collecting video and sensor data remotely.

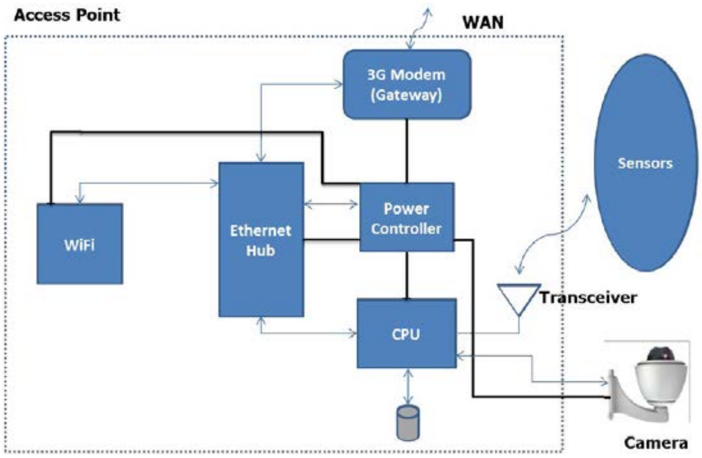

Fig. 5. Access point.

Sensor calibration

The idea of the calibration procedure is to use gage blocks of different heights to change the inclination of the sensor, thus changing the component of gravity (g) along its sensing direction. Figure 6 shows the calibration setup.
We record the accelerometer output for approximately 10 seconds at each height, and calculate the mean and standard deviation of the recorded signal for each height. The mean value is used for sensitivity estimation while the standard deviation is used to estimate the sensor resolution as described below.

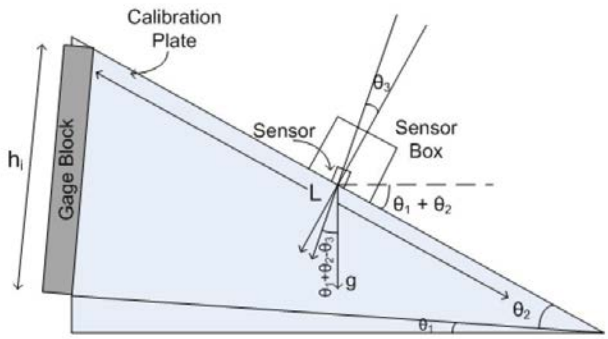

Fig. 6. Calibration setup for vibration sensors.

3. Relating ride to road standard

Most national public road administrations worldwide are surveying the condition of roads in their road network, with respect to criteria such as Road durability, Winter operations, Noise, Debris, Mobility, Road safety, Ride Quality, Wear and Tear and Energy Consumption. See the headers of the vertical columns in Figure 7.

Each criterion is affected by several road properties, as seen in the horizontal rows of the figure. Longitudinal roughness causes ride vibration. Due to its large impact on criteria such as Road durability, Mobility, Road safety, Ride quality, Wear and tear as well as Fuel consumption, the by far most important is the longitudinal roughness having most red-marked cells in Fig. 7. When considering normal conditions, megatexture (waves 50 – 500 mm), friction between tyre and road, macrotexture (waves 0.5 – 50 mm), edge deformation, water pooling and bearing capacity are secondary in importance. Rut depth, crack index and other parameters are third in importance; having mainly yellow, green or even white (no importance) marked cells in Fig. 7.

For road safety and ride quality, the focus aspects of this report, the most important road properties are longitudinal roughness, megatexture, edge deformation, water pooling and friction. Cross slope has been given a low rank in the matrix. If it had been combined with horizontal curvature and speed limit as well as longitudinal grade, or together with the mentioned properties been transformed into “Need for side friction” and “Drainage gradient”, it would surely been top ranked for road safety (as reflected in road design manuals world-wide).

	Criteria										
								Wear and tear			
Road property	Road durability	Winter operations	Noise	Debris	Mobility	Road Safety	Ride Quality	Vehicle	Tyre	Goods	Fuel consumption
Bearing capacity	3				3						
Surface stiffness			1								2
Longitudinal roughness	3	2	2	1	3	3	3	3	2	3	3
Megatexture	2	2	3	1	2	2	3	3	2	3	3
Macrotexture	2	2	3	1		2	1	1	3		3
Cross slope	2			1	1	2	1	1	1		1
Edge slump	3	2	1		3	3	3	2	1	2	1
Rut depth	3	2	1	2	2	2	2	1	1	1	1
Water pooling	1	1	1	3	2	3	2				1
Friction		3	1		3	3	2		3		3
Retroreflection					2	2	2				

Importance	
Large	3
	2
	1
Small	0

Fig. 7. Influence of road properties on road durability, safety, road user costs etc

4. Comparing vehicle driver vibration to IRI-values

The overall single most important road property of the matrix in Figure 7 is longitudinal road roughness. There are several available scales for road roughness. The most used scale globally is the International Roughness Index. This index is calculated with a computer-based “quarter car model” as illustrated in Figure 8. IRI was defined by the World Bank in 1986 and describes the vertical motion between the suspended vehicle body and the unsuspended wheel mass, when driving at the reference speed 80 km/h. When calculating IRI, a set of reference parameters for stiffness, damping and mass are used. These parameters define the “Golden car” used for the IRI calculation.

IRI may be computed from road profile data achieved by various methods, including static rod and level. However road profile sampling must be made at maximum 3 dm long steps and with very high vertical accuracy. For practical reasons, road condition measurements are normally made with mobile high-speed laser/inertial profilometers as per the ASTM E 950 standard.

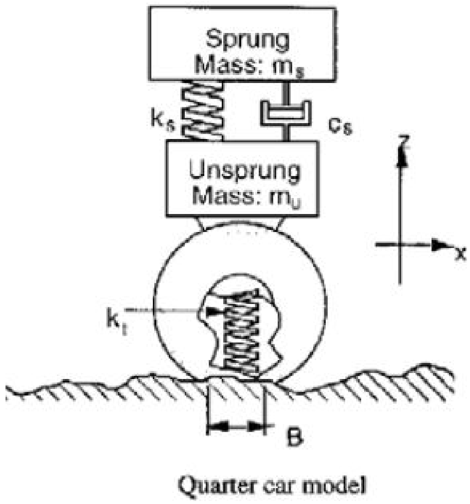

Fig. 8. Quarter car model used for calculation of IRI

Since many road agencies are measuring and managing the condition of their road network based on the IRI-scale, it is relevant to relate truck drivers' exposure from whole-body vibration to IRI-values / road quality.

4.1 Passenger car driver vibration

Most studies have resulted in linear relationships between ride vibration in passenger cars and road roughness on the IRI-scale, as (1):

$$a_w \left[\frac{m}{s^2}\right] = a + b \times IRI\ [\frac{mm}{m}] \quad (1)$$

The review of car studies showed ranges for the intercept "a" of 0 < a < 0.0768 and for the slope factor "b" of 0.0665 < b < 0.27. Ahlin and Granlund (2002) derived the physical relationship between IRI and cab floor vertical acceleration in the "Golden car" reference model for the IRI computation. The derived relationship in Equation 2 concerns the vehicle model´s "driving speed" *v* and the waviness w of the road profile elevation. Typical values for waviness are 1.6 < w < 2.4. For v = 80 km/h and w = 2, the slope factor "b" equals 0.16. The intercept a-value was 0 (zero). Note that this study did not include the effect of megatexture waves, which is a likely cause to why the intercept was a = 0.

$$a_w \left[\frac{m}{s^2}\right] = 0.16 \times (\frac{v}{80})^{(\frac{n-1}{2})} \times IRI[\frac{mm}{m}] \quad (2)$$

4.2 Driver vibration in heavy trucks with trailers

Ahlin et al (2000) measured seat vibration (as per the ISO 2631 standard) in timber logging trucks and collated the drivers' vibration exposure at 75 km/h to road roughness on the IRI-scale. The collation was carried out using a linear relationship as per Equation 1.

Exploratory data analysis showed that there were greater variances in seat vibration at road roughness levels above IRI = 3 mm/m. This may be explained by the fact that while modest road roughness is difficult to see, severe road damages are more visible. Hence most truck drivers try to avoid traversing the worst roughness by changing the truck´s lateral position on the carriageway (even to the extent of driving on the wrong side of the road), and by braking to lower the speed in order to reduce vibration. Another explanation is that rough road sections with IRI > 3 mm/m cause much more rotational vibration in roll and pitch modes, with associated lateral and fore-aft vibration.

Regardless of the exact reason why there is a breakpoint for WBV (x, y, z vector) at IRI = 3 mm/m, the exploratory data analysis led to the conclusion that different regression analysis had to be made for IRI above and below 3 mm/m. Results from Ahlin et al (2000) are given in (3), (4) and Fig. 9.

$$WBV\ \left[\frac{m}{s^2}\right] = 0.18 + 0.30 \times IRI\ [\frac{mm}{m}] \tag{3}$$

$$WBV\ \left[\frac{m}{s^2}\right] = 0.35 + 0.22 \times IRI\ [\frac{mm}{m}] \tag{4}$$

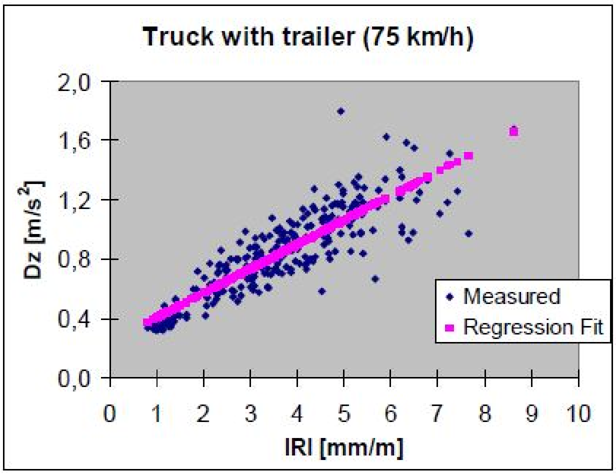

Fig. 9. Truck drivers WBV (vertical direction only) as function of IRI.

Note that according to Eq. 3, and assuming an 8 hour daily driving time, the truck drivers exposure to WBV exceeded the EU Action Value of A(8) = 0.5 m/s^2 with as little as an IRI slightly above 1 mm/m. Roads with IRI = 1 mm/m are considered by typical passenger car occupants to be in good condition and give a very smooth ride. Note also that a significant part of the truck seat vibration is related to the equation´s a-term (the intercept), rather than to the b-term (the slope factor) associated with road roughness reflected by the IRI-scale. With the a-value being as high as 0.18 (not to mention the 0.35 in Eq. 4), the intercept makes a great proportion of the EU Action value. If the intercept can be lowered, a higher IRI-value (rougher roads) can be accepted without exceeding the EU Action Value for truck driver´s exposure to whole-body vibration during the truck operation.

Experience from several other studies show that the factors a & b in Equation 1 vary between road sections and between trucks. Typical ranges are for the intercept "a" of $0.1 < a < 0.35$ and for the slope factor "b" of $0.2 < b < 0.3$. Bad roads and bad trucks results in higher factors.

A very important question is*: Why does the seat vibrate significantly despite no road roughness being present? Why isn´t the intercept a = 0 (zero) at IRI=0?*

It was shown by Ahlin & Granlund (2002) that a = 0 for the idealized "Golden car". When studying real cars however, the intercept ranged up to a = 0.08 for passenger cars. This may possibly be explained by the fact that IRI does not reflect megatexture waves < 0.5 m at all, while megatexture causes vibration in cars. Hence tendencies of washboarding, ravelling and pothole formations may be present and cause ride vibration despite low IRI-values in both cars and heavy trucks.

For heavy trucks, there are several other possible explanations why the intercept is not at zero:

• On weak roads, especially during the spring thaw period, "soft spots" in the road can give high variance in pavement deflection under a heavy truck wheel (as indicated by falling weight deflectometer testing of pavements). This causes ride vibration but is not measured by IRI, as IRI is calculated assuming a 100 % stiff road profile.

• Truck wheels may suffer from severe unbalance, caused by geometric and stiffness
eccentricity. While wheel unbalance is more or less impossible to become unaware of in any modern passenger car, the resulting vibration in a heavy truck may be masked by other vibration and may hence not be easily discovered.

• Truck frames are flexible compared to stiff car bodies. Long wave road unevenness may
cause vibration due to “frame beaming”, while IRI is not sensitive to these long waves.

• The truck engine´s powerful combustion pulses may not be efficiently isolated from the
frame, cab and driver seat.

4.3 Relating truck driver WBV to IRI-values

Data from two adjacent sections of road 331 (a test road between the Swedish inland forest area and the coast) recorded in the very same truck at constant speed are presented in Figure 10. While the slope factor b is similar for both road sections (0.25 and 0.26), the intercept a-factor differs by a factor close to 2 (0.12 versus 0.21). This indicates a large difference in road properties. The section with IRI of 1.0 to 1.5 mm/m and intercept a-factor 0.21 had been fairly recently resurfaced but has probably low and varying pavement stiffness due to being built on a subgrade of soft soil.

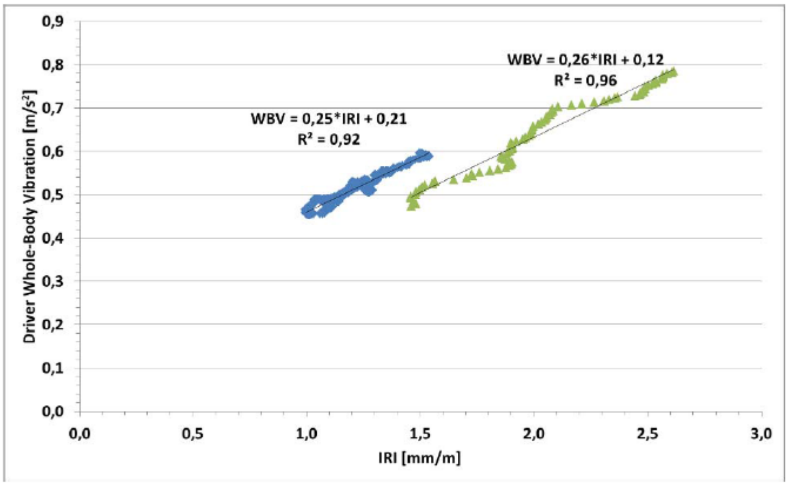

Fig. 10. Truck drivers WBV (weighted x,y,z vector) as function of IRI.

4.4 Using IRI to estimate truck ride vibration

This section offers an example on how to use IRI to estimate truck ride vibration. The road section example is from Highway 21 in Finland, heading Northbound for Kilpisjärvi. Data in the Finnish PMS show that this section had IRI = 1.81 mm/m. The example vehicle is a grocery truck. It is of a comfortable premium model, but old and worn. To reflect this, ”low mid-range” values for a &

b-factors have been inserted into Eq. 1, resulting in WBV ≈ 0.18 + 0.23 * IRI, i.e. WBV ≈ 0.18 + 0.23 x 1.81 = 0.60 m/s2.

In reality, the measured truck driver WBV was 0.58 m/s² for this case, so the estimate was very close the measured value. The author of this report is convinced that *with a fair selection of a & b when using Equation 1, IRI can give WBV typically within some 15 %* (for truck speed far below 80 km/h, IRI may overestimate ride vibration at rather long waves; this makes it unsuitable to use IRI for estimating truck ride quality at undulating secondary/tertiary low speed roads.).

The final step in assessing the daily A(8) vibration exposure is to use the UK HSE A(8) calculator to normalise the WBV-value to daily driving hours.

5. Conclusions

As a result of the tests carried out on the heavy vehicles transporting goods, the following conclusions were reached:

- Several of the root causes to high vibration are man-made. Actions need to be taken to assure that road repairs are effective and not worse than before. It is recommended the road condition (alignment, slopes and surface condition) should always be measured by a certified inspector after the completion of any major road-repair works using an approved ASTM E950 “Class 1” road profiler;
- Improperly banked horizontal curves are a common traffic safety problem, therefore it is recommended the implementation of a method for easy detection of hazardous flat outer curves, as well as banked innercurves;
- Transversal edges of new asphalt overlays should not be placed “layer-on-layer” with the old asphalt but cut down into the same elevation as the surface of the old asphalt. This will require the use of a small milling machine. Such machines are available on the market, but not always implemented in highway pavement maintenance;
- An overall objective for road management should be to keep pavements in such good condition that it is possible to operate normal trucks over normal working days behind the steering wheel, and still keep the A(8) under the EU Action Value 0.5 m/s².
- Truck hauliers should carry out a risk assessment with associated measurements to clarify if actions have to be taken to protect their drivers from health and safety risks caused by ride vibration and mechanical shocks;
- A significant share of the ride vibration problems can be eliminated in a relatively short time by improved road construction and maintenance

practices as they originated from manmade sources, such as culvert trenching transversal joints at bridges and at improperly performed resurfacings.

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