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# Pavement performance levels causing human health risks

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Original scientific paper

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## Pavement performance levels causing human health risks

This study investigates performance thresholds of hot mix asphalt pavements in terms of health risks from vibrations affecting drivers of passenger cars on urban roads. The whole-body vibration values in vertical direction are measured at various riding speeds at some pavement sections that are on the pavement condition index (PCI) rating scale proposed by the PAVER system, while the vibration values (VDVz) are calculated. Evaluation results reveal that pavement performance levels have to be at least "fair" (PCI scale range between 55 and 70) to ensure that the health of human body is not negatively affected at 50 km/h riding speed during a daily 8-hour driving.

Key words:
pavement performance, PCI, VDV, riding speed, health risk

Izvorni znanstveni rad

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## Razine svojstava kolničkih konstrukcija rizičnih za ljudsko zdravlje

U radu se analiziraju granična svojstva asfaltnih kolnika, odnosno djelovanje vibracija uslijed kretanja vozila na zdravlje vozača osobnih automobila koji prometuju po gradskim cestama. Ukupne vrijednosti vibracija u vertikalnom smjeru mjerene su kod različitih brzina prometovanja na dionicama kolnika kojima je indeks stanja kolnika određen prema sustavu PAVER, a vrijednosti vibracija (VDVz) su izračunane. Rezultati procjene pokazuju da razine karakteristika kolnika trebaju biti barem "dovoljne" kako ljudsko zdravlje ne bi bilo ugroženo kod brzine kretanja vozila 50 km/h tijekom osmosatne vožnje u jednom danu.

Ključne riječi:
svojstva kolnika, PCI, VDV, brzina prometovanja, zdravstveni rizik

Wissenschaftlicher Originalbeitrag

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## Ebenen der Fahrbahneigenschaften, die für die menschliche Gesundheit riskant sind

In der Abhandlung analysiert man die Grenzeigenschaften der asphaltierten Fahrbahnen beziehungsweise die Auswirkung der Vibration aufgrund der Bewegung von Fahrzeugen auf die Gesundheit von Pkw-Fahrern, die auf den Stadtstraßen fahren. Die Gesamtwerte der Vibrationen in vertikaler Richtung wurden bei unterschiedlichen Verkehrsgeschwindigkeiten auf Fahrbahnabschnitten gemessen, deren Index des Fahrbahnzustandes gemäß dem PAVER-System bestimmt wurde, und die Vibrationswerte (VDVz) wurden berechnet. Die Bewertungsergebnisse zeigen, dass die Ebenen der Fahrbahneigenschaften zumindest "ausreichend" sein sollten, um die menschliche Gesundheit bei Fahrgeschwindigkeiten von 50 km/h während einer achtstündigen Fahrt an einem Tag nicht zu gefährden.

Schlüsselwörter:
Fahrbahneigenschaften, PCI, VDV, Verkehrsgeschwindigkeit, Gesundheitsrisiko

## 1. Introduction

Pavement serviceability is a concept developed using numerical values that describe the level of comfort for drivers and passengers on highways. The serviceability level of a pavement section discretely considers the principles of smoothness, comfort, and safety [1, 2]. Ride (driving) quality is the degree to which the whole experience (including the motion, environment, and other factors) of a journey by a vehicle is perceived and rated by drivers and passengers [3]. Therefore, as the pavement management system theory has begun to develop over recent years, it is acknowledged that pavement serviceability can be determined from the panel rating based on the ride quality evaluation by pavement experts [1].

It is well established that pavement distress adversely affects both drivers and passengers of vehicles [1]. Many studies report that, among these adverse effects, the foremost ones are the vibrations that are formed within the vehicle. It is known that the main causes of vertical vibrations are the mechanical structure of the vehicle and the surface distress on the road on which the vehicle is travelling. The ride quality is explained by ride comfort and safety parameters in a short-term trip; however, human health, and thus the exposure of the body to vibration, emerges as a component when long-term journeys are considered [3].

Vibrations adversely affect many employees. Bovenzi reported that 4 to 7 % of all employees in the U.S., Canada and some European countries are exposed to potentially harmful vibration [4]. Twelve percent of the transport, storage and communication sectors and fourteen percent of the wholesale and retail trade, repair of motor vehicles, motorcycles and household goods sectors are under threat from the negative effects of vibration [4]. Construction, mining, agriculture, and transportation industries workers are often subject to harmful levels of vibration. In the transportation industry, vibration is known to adversely affect the drivers of heavy commercial vehicles. It is understood from the literature that the negative effects of vibration on the drivers of passenger cars used for commercial purposes are ignored.

In the literature, there are only a limited number of studies in numerical terms attempting to describe ride quality – or in other words, the human sensitivity to vibrations during a ride – that take into consideration the comfort, human health risk, and safety. In general, ride quality and vibration limits that adversely affect human health are determined using the ISO 2631 and BS 6841 international standards, which describe the methods used to assess whole-body vibration (WBV).

Many studies assess ride quality by using the root-mean-square acceleration ($a_w$) and vibration dose value (VDV), which are determined based on the frequency-weighted analysis of measured vertical vibrations [5, 6]. The importance of ride comfort and safety on pavements with high operating speeds (or speed limits) has been known for many years; however, studies conducted in recent years have shown that ride quality linked to pavement conditions also significantly affects road safety and human health on pavements with low speed limits [7, 8].

Studies indicate that the relationship between pavement performance and WBV for the driver and passenger is generally evaluated by measuring only vertical vibrations, rather than the vibrations on all other axes. Cantisani and Loprencipe investigated the relationship between the international roughness index (IRI), which indicates pavement performance and the frequency weighted vertical acceleration ($a_{wz}$), according to the ISO 2631 standard. In this study, IRI and vibrational measurements were conducted on a pavement section at a speed of 80 km/h and the results were used in the calibration of a full car model [5]. Pradena and Houben have explained IRI thresholds that can be used in urban road networks so that pavements can serve vehicles, drivers and passengers without harmful effects (in relation to the vertical vibration) [9]. Lakusic et al. in their study, they have investigated the relationship between surface distresses, IRI, and vibrations that vehicles are exposed to, and have proposed a decision support system that can be used in pavement treatments on urban roads [10].

It is clear from some studies that pavement performance (low serviceability level) adversely affects human health during long-term travel [3, 11]. n addition, many studies demonstrate that the use of the VDV component, which is the duration of exposure in the vibration analysis and also includes an analysis of extremes in the acceleration measurement, gives more accurate results to express the quantitative impact of vibration on health risks [12]. Some studies have compared the exposure to vibration in vehicles used on the undulating terrain (e.g. armed forces, agriculture, construction) and their effects on human health, using the ISO 2631-1 and ISO 2631-5 standards [13, 14]. Long-term WBVs can generate adverse health hazards for the lumbar spine. However, they are generally sufficiently powerful to establish a dose–effect relationship between exposure to WBV and the risk of lumbar disorders [15]. As is the case of all other objects in nature, the organs of the human body also emit natural frequency vibrations. Consequently, the resonance that results from the conflict between the vibration signals to which the human body is exposed, and the natural vibrations of the organs, leads to discomfort within the body during long-term exposure [3].

Some studies presented in literature have attempted to explain the concept of WBV based on relative personal perceptions and interpretations. For this purpose, there are noteworthy studies that have measured heart rate and evaluated human response to exposure to various vibrations, via vehicle suspension systems created in the laboratory [16, 17]. Likewise, there are also studies that have investigated ergonomic structure of the driver seat and suspension systems of construction equipment (trucks, tractors, rollers, etc.) and analysed driver exposure to WBV according to the terrain conditions in which these vehicles and machinery were operated [18, 19]. Other studies have also compared the results of the statistical analysis of vibration data with pavement performance indicators, and described the relationship between the unevenness of the standard deviation in the longitudinal direction, root mean square, and skewness [20].

Various pavement performance indicators, accepted by many authorities, have become worldwide standards [21]. It should be noted that there is a lack of research investigating the comparable pavement performance thresholds that constitute a health risk between performance indicators and vibration exposure, for vehicles travelling on pavements. In this study, performance thresholds of asphalt pavements have been evaluated in terms of health risks to drivers travelling by passenger cars, according to the globally recognized ergonomic constraints taken into account for the purposes of vibration. Hot mix asphalt (HMA) roads, which are the most preferred paved roads in the urban roads network, were examined. To this end, to explain seven performance ranges, pavement sections that are on the pavement condition index (PCI) rating scale proposed by the PAVER system were selected. At these pavement sections, WBV data in vertical direction were measured on the driver seat (directly beneath the driver) at the riding speeds of 20, 30, 40, and 50 km/h, and the vertical vibration dose values ($VDV_z$) defined in the ISO 2631-1 were calculated. With the help of these data, potential vibration exposure values ($VDV_z$) were estimated for each riding speed at 1, 2, 4, 6, 8, 10, and 12-hour travel times at pavements exhibiting various performance levels. The results were evaluated using graphs, based on PCI rating scale average ranges for each riding speed. In this way, thresholds of pavement performance as related to human health risk were identified with different performance levels of pavement sections on urban roads over long-term trips. In particular, important information for understanding the pavement performance levels that adversely affect human health was obtained for passenger car drivers, who account for a significant part of daily traffic (taxi drivers, etc.).

## 2. Materials and methods

### 2.1. Pavement performance evaluation

The PAVER system is an evaluation procedure that is used to assess current performance of pavement by evaluating data gathered according to the identification guide from ASTM D 6433-11 in sample areas of 225 ± 90 m$^2$, chosen randomly in line with distribution principles. In these assessments, a coefficient was obtained by determining the ratio between the sample area size and the data for 20 different pavement distress types, with low (L), medium (M) and high (H) severity levels. With the aid of this coefficient, deduct values were obtained from performance level tables prepared according to the deterioration type. Subtracting the obtained deduct values from 100 gives the PCI value, which defines the performance of the pavement with a numerical value between 0 and 100 in ASTM D 6433-11 [22]. The PCI value of 100 denotes pavement on which there is no distress and that is in the best condition, while a value of 0 indicates pavement that is completely corrupted and cannot be used. The PCI is an index that shows the current performance

**Table 1. Distress classification for asphalt concrete pavement according to ASTM D 6433-11 [22]**

| Code | Distress | Unit of measure | Defined severity levels | Cause | Code | Distress | Unit of measure | Defined severity levels | Cause |
|---|---|---|---|---|---|---|---|---|---|
| **1** | Alligator cracking | m$^2$ | Yes | Load | **11** | Patching | m$^2$ | Yes | Other |
| **2** | Bleeding | m$^2$ | Yes | Other | **12** | Polished aggregate | m$^2$ | No | Other |
| **3** | Block cracking | m$^2$ | Yes | Climate | **13** | Potholes | Broj | Yes | Load |
| **4** | Bumps and sags | m | Yes | Other | **14** | Railroad crossings | m$^2$ | Yes | Other |
| **5** | Corrugation | m$^2$ | Yes | Other | **15** | Rutting | m$^2$ | Yes | Load |
| **6** | Depression | m$^2$ | Yes | Other | **16** | Shoving | m$^2$ | Yes | Other |
| **7** | Edge cracking | m | Yes | Load | **17** | Slippage cracking | m$^2$ | Yes | Other |
| **8** | Joint reflection crac. | m | Yes | Climate | **18** | Swell | m$^2$ | Yes | Other |
| **9** | Lane/shoulder drop-off | m | Yes | Other | **19** | Ravelling | m$^2$ | Yes | Climate |
| **10** | Long. and trans. crac. | m | Yes | Climate | **20** | Weathering | m$^2$ | Yes | Climate |

of the pavement, and is based on an evaluation of the common components of the distress type, distress quantity, and distress severity on pavement surface [23]. PCI components and the rating scale are shown in Figure 1.

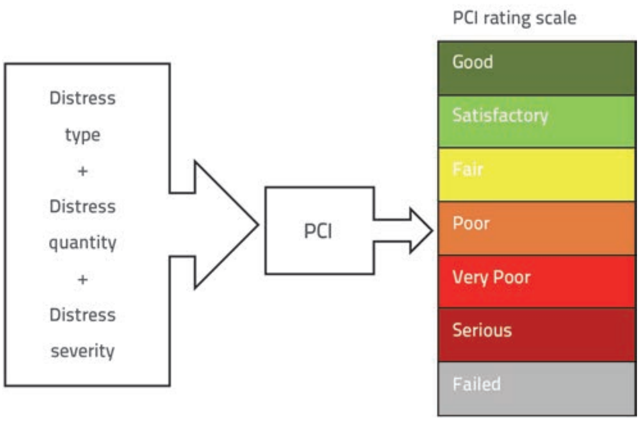


**Figure1. Pavement Condition Index (PCI) ranges in ASTM D 6433-11 [22]**

The rating scale concept describing pavement performance is used in the PAVER system to describe the current status of pavement by means of various colours. Simultaneously, pavement performance was also defined as "good" or "satisfactory" with verbal expression in this PCI rating scale. With the PAVER system used as a base, the distress classification used for HMA coated roads and parking lots - defined in the standard ASTM D 6433-11 code - is shown in Table 1.
In this study, the pavement distress data from 23 different urban road pavement sections were obtained in the Turkish city of Samsun. The pavement sections were HMA coated and presented different serviceability levels, as defined in the ASTM D 6433-11 standard adopted by the PAVER system. The surface distress data were gathered from 88.8 % of the originally identified areas to assess surface degradation according to the requirements of the PAVER system; however, surface assessments were also made on a number of sample units, to ensure the precision of the project level, according to the definition of the PAVER system, at all investigated road sections.

## 2.2. Vibration measurement (ISO 2631) and evaluation

It has been reported that WBV has acute detrimental effects on visual acuity equilibrium and manual dexterity [24]. This situation leads to muscle fatigue and muscle fatigue is among the major causes of traffic accidents. Several factors - grouped into organizational factors (length of route, travel time, rest breaks), workplace factors (ergonomics, physical factors in cab), external factor (traffic volume, weather) and personal factors (age, health) - affect how safely drivers perform in road traffic [25]. Acknowledged adverse effects of WBV on human body can be listed as follows: gastrointestinal tract problems, spinal degeneration, lower-back pain, autonomic nervous system dysfunction, neck problems, and headaches [14]. Studies have shown that the negative effect limits of vibrations on the whole body can be considered as a mathematical expression [11, 13, 19]. Principal factors for explaining the WBV, which are necessary to determine acceptable level of exposure of the human body, are described in ISO 2631-1 [26]. Four possible effects of vibration on the human body include degraded health, comfort, perception, and motion sickness. In ISO 2631-1, the frequency ranges of these effects are 0.5 - 80 Hz for degraded health, comfort, and perception.
The ISO 2631-1 standard recommends using the Butterworth filtering technique to evaluate acceleration signals in the frequency limits of the 1/3 octave band. In this context, vibration signals are evaluated using low-pass and high-pass filters, as well as digital filtering, which convert these signals into relevant frequencies. To be able to assess WBVs based on the definitions contained in ISO 2631-1, the accelerometer in a particular elastic pad must be placed directly beneath the driver (to ensure full interaction between the device and the driver).
Based on separation according to the 1/3 octave band frequencies, by multiplying the acceleration frequency gain by the weights defined in the standard, it becomes possible to determine the frequency-weighted acceleration values ($a_w$) obtained for all directions separately by the following equations. According to ISO 2631-1, the $a_w$ component is considered to be a fairly suitable parameter for explaining the acceleration transferred, as felt by the affected person [26]. The $a_w$ is computed with equation (1):

$$a_w = \left[\sum_i (w_i a_i)^2\right]^{\frac{1}{2}} \quad (1)$$

where, $a_w$ is the configured frequency vertical acceleration, $w_i$ is the weight factor that defines the related factor, and $a_i$ is the vertical RMS value for the 1/3 octave band interval. If one crest factor value of vibration measurements is above 9, this level indicates that the fourth power vibration dose method (VDV) should be considered, particularly when predicting health risks [26]. According to ISO 2631-1, the VDV can provide more accurate results than $a_w$ parameter in the evaluation of the peak acceleration data. For this reason, at a given time interval, the VDV assessment is made on the fourth power of acceleration measurements instead of the second power. The unit of VDV parameters is m/s$^{1.75}$, although it is calculated using the following equation (2) [26]:

$$VDV = \left\{\int_0^T \left[a_w(t)\right]^4 dt\right\}^{\frac{1}{4}} \quad (2)$$

where, $a_w(t)$ is the instantaneous frequency weighted acceleration and $T$ is the duration of measurement. When the vibration exposure consists of more than one time intervals (i) of different magnitudes, the VDV for total exposure should be calculated using the equation (3) [26]:

$$VDV_{total} = \left( \sum_i VDV_i^4 \right)^{\frac{1}{4}} \tag{3}$$

As can be understood from the mathematical expression, the VDV parameter value increases with an increase in measurement time. For this purpose, the VDV parameter can be used to express the effects of vibration and daily exposure duration over a certain period of work or travel, as specified in ISO 2631-1. In other words, exposure time can be taken into account because the VDV component is a very useful indicator for evaluating vibration in terms of health risk. In addition, the following approach (eq. 4) is recommended for calculating the potential VDV values to which individuals are exposed during long-term vibrations based on representative VDV measurement taken for shorter periods [27]:

$$VDV = VDV_{part} \cdot \sqrt[4]{\frac{T}{t}} \tag{4}$$

where, $VDV_{part}$ is the VDV measured over a representative period, while t and *T* is the length of the full shift.

In this study, the vertical vibration values measured at the driver seat on road sections, specified PCI values, and VDV values ($VDV_z$), were established according to the method described in ISO 2631-1. Only vertical vibration data were measured and examined since the study evaluated only the vibration effects caused by the current pavement performance level, as determined by surface distresses. Using a vibration measurement set, comprising vertical accelerometers designed for the measurement of vibration (±4g, sensitivity 500±15 mV/g), a GPS antenna and a data logger, the vibration values were recorded in vertical direction on the roads on which a PAVER evaluation was made. The vertical acceleration data and GPS data were collected and transferred to the computer instantly as 1000 pcs accelerations per second and as one location and one speed per second during measurement, respectively. Following the directions given in ISO 2631-1 and ISO 8041, an accelerometer in an elastic pad was placed under the driver, to enable the most accurate quantitative determination of the WBV in the human body [28]. The vibration values were evaluated using software developed in the MATLAB program, by means of the analysis method described in ISO 2631-1, and $VDV_z$ values and measurement duration of the sections (determined before PCI values) were obtained. The vertical vibration value measurements were performed using a passenger car belonging to "segment C" (lower-middle) category according to the Euro Car segment classification, which corresponds to a car length interval of 4100 to 4600 mm. The driver is a 36 years old and 172 cm tall person, weighing 85 kg.

The aim of this study is to investigate performance thresholds of pavements that affect vibration-induced health risks on human body inside a passenger car at 20, 30, 40, and 50 km/h riding speeds, which are the typical speed limits in urban areas. For this reason, it is necessary to evaluate the longitudinal profile


**Figure 2. a and b) Vibration measurement set; c) vibration evaluation software; d) sample of test roads**

of the road based on vibrations measurements. Therefore, the principles of longitudinal profile measurement defined in the ASTM E 950 [29], E 1082 – 90 [30], and E 1926 – 08 [31] standards were accepted during the vibration measurements. Considering the general approach of these standards, the measurement of the same traffic lanes, and a minimum constant vehicle speed of 20 km/h, were recognized as the measurement criteria. The vibration measurement set used for field surveys, vibration evaluation software, and sample of the test roads, are shown in Figure 2.

In many countries around the world, the maximum speed limit on urban roads is usually in the region of 50 km/h. For this reason, vibration measurements were performed and evaluated at constant speeds of 20 km/h, 30 km/h, 40 km/h, and 50 km/h. Vibration measurements were made at 23 different pavement sections for each riding (measurement) speed. In roads with more than one traffic lane, vibration measurements were made separately for each lane, and $VDV_z$ values were determined accordingly for the individual lanes. The $VDV_z$ value was calculated to reflect the overall section by taking the average of these values.

When determining the sections at which vibration measurements are to be performed, the principle that at least one data measurement (pavement PCI value) should be taken from each of the seven ranges specified in the PCI rating scale (see. Figure 1) was taken into account. In this way, it was possible to express the PCI rating scale range for all evaluated data.

Vibration data measured at the same pavement section at different riding speeds were reciprocally assessed with their raw state. It was observed that the vibration data can also be meaningful even if un-weighted, because the large amplitudes are generated when passing over the pavements with vehicles, especially at low performance levels. In general, it appears that the vibration amplitudes are increasing as the performance of pavements decreases and as the riding speed increases. In terms of being an example, the un-weighted vibration data measured at good, poor, and failed performance levels of pavements are shown in Figure 3.

A similar evaluation was made by taking the power spectral density (PSD) of the data to understand how much energy the vibration signals have in each frequency component. PSD evaluations at some pavement sections, for the good, poor and failed performance levels, are shown in Figure 4. It is known that the spectral densities do not change much in the low frequency vibrations the human body is subjected to, even though there

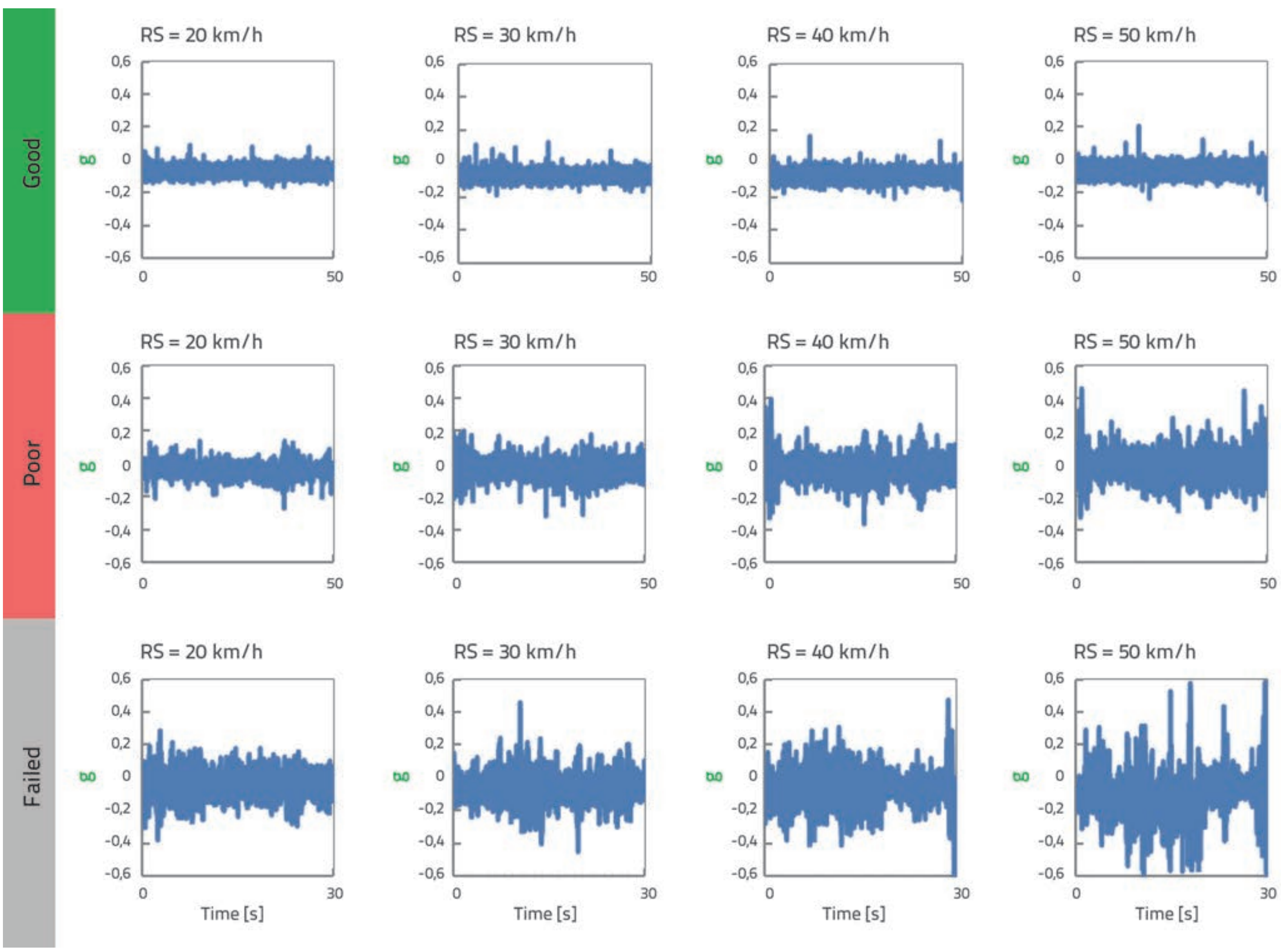


**Figure 3. The un-weighted vibration in vertical (z) direction for some pavement performance ranges at different riding speeds (RS)**

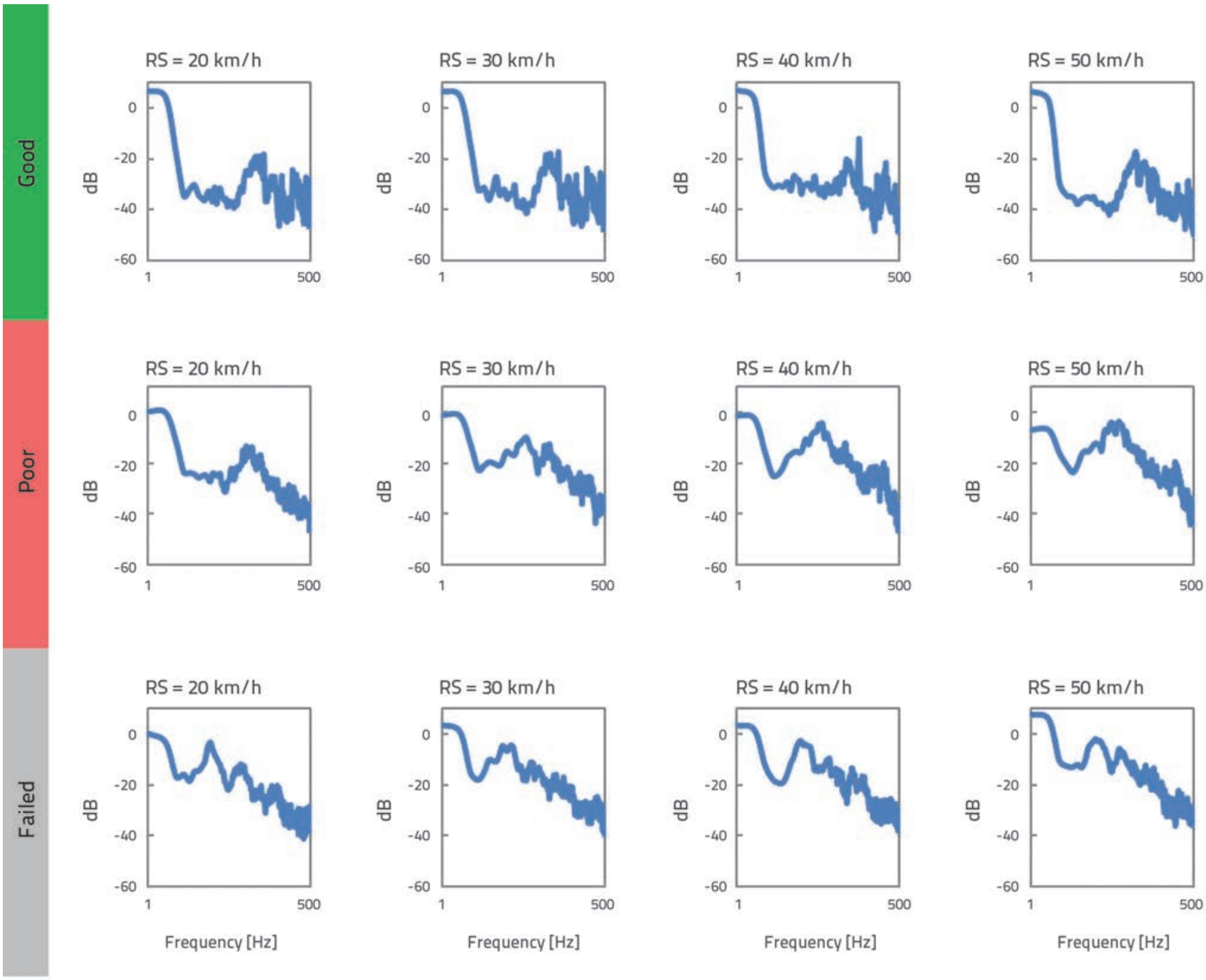


**Figure 4. The un-weighted power spectral densities of some pavement performance ranges at different riding speeds (RS) (the x-axis is a scale of log base 10)**

are significant differences in the amplitudes [3, 11, 13]. This situation is shown in Figure 4.

It is believed that the two most important factors affecting ride quality in a passenger car at straight road sections without slope are the speed of the vehicle, and the current performance indicator of the pavement. Methods for predicting the health risk arising from exposure to WBV (0.5 - 80 Hz) at work are typically based on two parameters: the acceleration transmitted to the part of human body in contact with the vibration source, and the duration of exposure [32]. As described earlier, $VDV_z$ values and the measurement duration of sections were obtained by making vibration measurements in the vertical direction at riding speeds of 20, 30, 40 and 50 km/h, on HMA coated roads with various performance levels. By using mathematical approaches (4), potential vibration values ($VDV_z$) revealed in the vehicle were obtained for each riding speed at 1, 2, 4, 6, 8, 10, and 12 hours travel time on pavements with various performance levels.

In the evaluation, the PCI values of pavements were expressed for each of the seven scale ranges, defined according to the PAVER rating scale, so as to establish the road sections to be measured. In this context, it was expected that the average PCI value of the test sections selected from each scale range would be close to the average of the limit values of the scale. The average values shown in Table 2 indicate that the average PCI values of the sections for which pavement performance was determined were very close the PCI scale average values. Since the upper limit threshold value does not only include those in the scale range that are labelled as "good", vibration parameters were calculated on the road sections in which the PCI value was 100. Using the same approach, the $VDV_z$ value, measured and analysed for pavements with various PCI values and mean values, was obtained according to the corresponding PCI scale interval. A single $VDV_z$ acceptable value expressed by the scale interval was thus determined. As an example, an eight-hour exposure of driver ($VDV_z$ values) to various riding speeds and various PCI scale ranges is shown in Table 2.

**Table 2. Averages of interval scale and averages of $VDV_z$ ($m/s^{1.75}$) components of pavement sections during eight hours of travel exposure**

| PCI rating scale | Average of rating scale range limits | PCI average of measured sections | 20 km/h | 30 km/h | 40 km/h | 50 km/h |
|---|---|---|---|---|---|---|
| Good | 93 | 100 | 3.0915 | 3.4116 | 3.0067 | 2.7449 |
| Satisfactory | 78 | 77 | 4.7759 | 6.3631 | 6.3436 | 7.1976 |
| Fair | 63 | 64 | 5.0332 | 6.7696 | 7.4656 | 9.0546 |
| Poor | 48 | 49 | 5.4668 | 7.1967 | 8.1802 | **9.5966** |
| Very Poor | 33 | 34 | 6.7999 | 8.6802 | **10.3964** | **11.3581** |
| Serious | 18 | 21 | 7.7099 | **9.9420** | **11.6310** | **12.4978** |
| Failed | 5 | 5 | 8.6847 | **10.9806** | **13.1556** | **13.7561** |

In a number of approved technical standards and regulations, there are VDV parameter limits that are considered to adversely affect human health. The European Union Physical Agents (Vibrations) Directive recommends adoption of an exposure action value of 9.1 $m/s^{1.75}$ and an exposure limit value of 21 $m/s^{1.75}$ following eight hours of exposure to vibration effects [33, 34]. In other words, at a VDV value of 9.1 $m/sn^{1.75}$ and exposure to a travel time in excess of eight hours, human health can be affected, resulting in permanent damage to the body. Likewise, the ISO 2631-1 standard specifications for the range of vibration exposure by which human health may be adversely affected are given in Table 3 [34].

**Table 3. Human health exposure limits [34].**

| VDV [$m/s^{1.75}$] | Description |
|---|---|
| < 8.5 | Health risks have not been objectively observed |
| 8.5 – 17 | Caution with respect to health risks is indicated |
| > 17 | Health risks are likely |

## 3. Results

The WBV is defined as vibration felt by a person as a result of direct contact with vibrating surfaces [3]. Therefore, according to ISO 2631-1, the VDV component can provide more accurate results than the $a_w$ evaluation in extreme points, for which the largest and smallest acceleration data are selected as evaluation parameters.

Acceptable thresholds defined by authorities are described below, taking into account the nature of the human body, although somewhat different values of acceptability for the sensitivity and strength of vibration can individually be determined. In sum, an increase in VDV values above the limit value of 8.5 $m/s^{1.75}$ is considered to have negative health effects on the human body. At the same time, it is possible to say that an increase above the 9.1 $m/s^{1.75}$ limit following 8 hours of exposure to vibration is also a parameter for negative effects on human health. In the light of this information, the $VDV_z$ values for various vibration exposure times, and various riding speeds, are graphically shown for each of the seven intervals of the PCI rating scale. The graphics were created using the colour coded system as suggested by the PAVER system at the PCI rating scale ranges. Each graph shows the threshold of adversely affected human health (8.5 $m/s^{1.75}$) by limit line and the eight-hour equivalent exposure action value (9.1 $m/s^{1.75}$) by point. The $VDV_z$ changes, obtained by measuring the same pavement sections at riding speeds of 20, 30, 40, and 50 km/h, and the mean values determined in the PCI scale range, are shown in Figures 5, 6, 7, and 8.

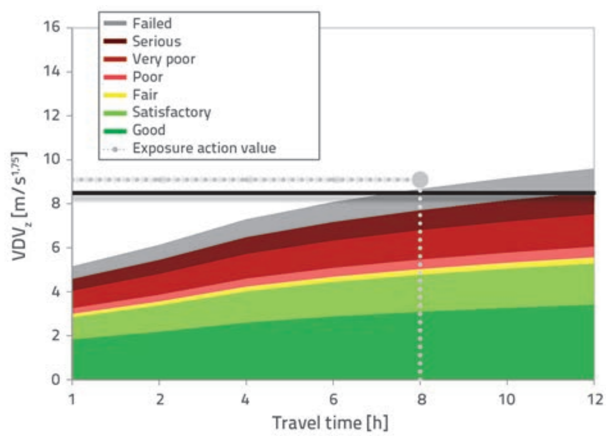


**Figure 5. $VDV_z$ changes at a riding speed of 20 km/h**

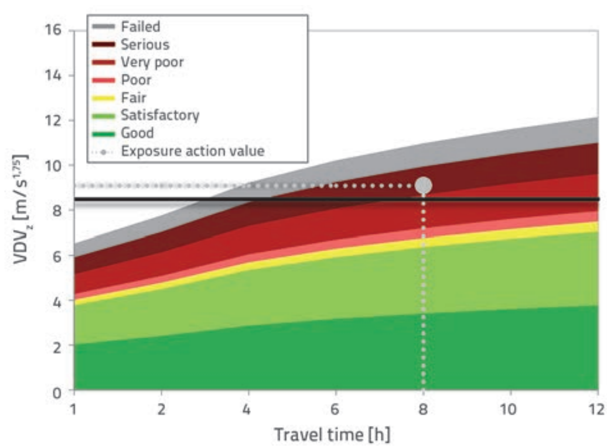


**Figure 6. $VDV_z$ changes at a riding speed of 30 km/h**

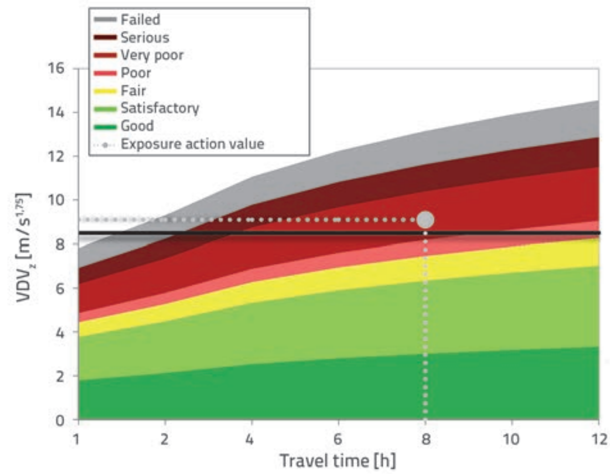


**Figure 7. VDV$_z$ changes at a riding speed of 40 km/h**

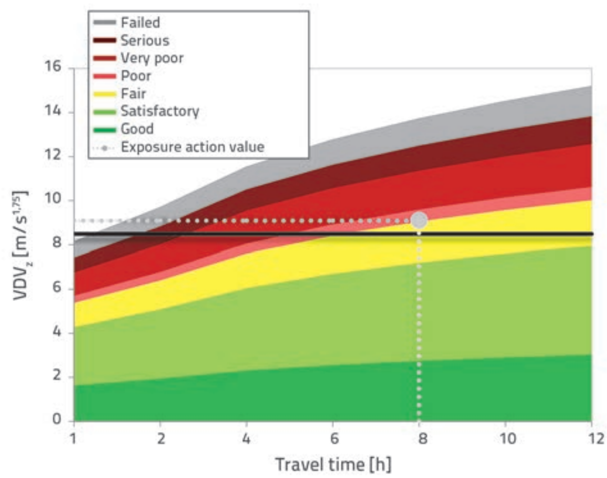


**Figure 8. VDV$_z$ changes at a riding speed of 50 km/h**

As shown in graphics (Figure 5, 6, 7, and 8), the exposure of human body to vibration increases with the increase in riding speed. Figure 5 shows that the exposure action value cannot be reached in any way during eight hours of travel at a riding speed of 20 km/h. After the 8$^{th}$ hour, negative vibrational limits for human health were reached only at roads with "failed" pavement performance. As shown in Figure 6, at a riding speed of 30 km/h, the exposure action value was reached on pavements with "serious" pavement performance, while negative vibration limits for human health were reached in three hours for roads with "failed" pavement performance, in four hours for roads with "serious" pavement performance, and in seven hours for roads with "very poor" pavement performance. In addition, as shown in Figure 7, at a riding speed of 40 km/h, the exposure action value was reached in roads with "very poor" pavement performance, while negative vibration limits for human health were reached in one hour and 30 minutes for roads with "failed" pavement performance, in two hours for roads with "serious" pavement performance, in four hours for roads with "very poor" pavement performance level, and in eight hours for roads with "poor" pavement performance level. Finally, Figure 8 demonstrates that at a riding speed of 50 km/h, the exposure action value was reached for roads at the border between "poor" and "fair" pavement performance levels. On the other hand, pavement performance levels from the worst to the best approached the negative vibration limits for human health quickly at a 50 km/h riding speed and slightly more than one-hour travel time. At this speed, the negative vibration limit for human health reached a "fair" performance level at the end of approximately six-hour travel.

These assessments show that, in addition to travel comfort and security, pavements with poor pavement performance can also negatively affect the health of drivers and passengers in terms of vibration-induced disorders during long-term travel. In other words, this evaluation demonstrates that the driver health can be negatively affected if he/she uses a vehicle for approximately six hours at an average speed of 50 km/h on pavements with a performance level lower than "fair" (PCI range: 70 to 55). The situation will be quite similar for a driver using a car for more than eight hours at an average speed of 40 km/h, on pavements with a performance level lower than "poor" (PCI range: 55 to 40).

## 4. Discussion

It is known that in the pavement management concept the ride comfort and structural condition are influential in determining limit values for making decisions on the maintenance, repair and renewal of pavements [1]. However, the long-term effects of pavement on the drivers are ignored in these evaluations. Especially on urban roads, the effects on passenger car users for commercial use of pavements for a long time are not considered under any circumstances.

The limit at which drivers begin to be adversely affected by vibration is set at 8.5 m/s$^{1.75}$ in the ISO standard. Taking this into consideration, the required performance levels on pavements are shown in Table 4 so that the drivers are not adversely affected by vibrations they are exposed to during long day trips, by resting in short intervals when riding along urban road networks.

**Table 4. Pavement performance levels at which drivers begin to be adversely affected at different riding speeds and travel times**

| Travel time [h] | 20 km/h | 30 km/h | 40 km/h | 50 km/h |
|---|---|---|---|---|
| 1 | No | No | No | Failed |
| 2 | No | No | Failed | Serious |
| 4 | No | Failed | Serious | Very poor |
| 6 | No | Serious | Very poor | Poor |
| 8 | Failed | Very poor | Very poor | Fair |
| 10 | Failed | Very poor | Poor | Fair |
| 12 | Serious | Very poor | Poor | Fair |

When the results are examined, it can be seen that no adverse effects are observed for 6 hours at 20 km/h, 2 hours at 30 km/h, and 1 hour at 40 km/h. It is also understood that during short travel times, the drivers are not adversely affected by vibration at low pavement performance levels. Therefore, the pavements should be at "fair" performance level for 8 hours of travel per day at a riding speed of 50 km/h. This result is in line with the minimum pavement performance level that should be found in the urban roads, as proposed by the PAVER system [23]. This suggests that the proposal of the PAVER system is also appropriate for the protection of human health from vibration.

It is also a known fact that drivers who travel long distances in urban roads are exposed to vibrations in transverse and longitudinal directions originating from road geometry and traffic. Considering that an average person has to travel for many years during their lifetime, it seems inevitable that they are negatively affected by the vibration caused by deterioration of road pavements.

## 5. Conclusions

Many aspects of both the driver and passenger, particularly comfort factors, including human health and safety, are negatively affected by exposure to whole-body vibration in vehicle during travel. The VDV parameter is an extremely useful component for expressing the vibration exposure effect during a certain period of work or travel. This study used VDV parameters to investigate the relationship between duration of exposure to vibration, which adversely affects human body in terms of health, and pavement performance. Pavements were determined by expressing the performance range based on the PCI rating scale. Then the vibration data were measured at speeds of 20, 30, 40, and 50 km/h, and the VDV values were calculated in vertical direction. Based on vibration data measured on pavement sections, the potential vibration values were obtained using the measurement time and $VDV_z$ values at different riding speeds for long-term exposure to vibration in a vehicle. Graphics were generated and results were evaluated using these $VDV_z$ values for each riding speed based on the average range of the PCI rating scale.

The analysis of results revealed a general increase in the effect of vibration exposure with an increase in riding speed. Although human body was not negatively affected by the impact of vibration at any pavement performance level at a speed of 20 km/h, it was observed that adverse effects occurred at higher speeds over an eight-hour travel time. It was determined that in order to prevent drivers, who travel for an average of eight hours a day on urban roads, from being physically affected and having negative health outcomes as a result of vibrations to which they are exposed, pavements should at the very least have a "very poor" performance level at a riding speed of 40 km/h. In addition, at a riding speed of 50 km/h, it was determined that pavements need to have a performance level on the border between "poor" and "fair". In addition, it is known that by travelling in excess of the maximum speed limit, drivers are frequently exposed to momentary vibrations during the stop-start movement of urban traffic. It is therefore considered that the performance levels of pavement should be extremely high for vehicles so that the vibration exposure does not adversely affect human health. This study is intended to serve as an important and useful tool for agencies responsible for the management (including maintenance and repair) of pavements, and to help in identifying the ride-related satisfaction levels of drivers using the road networks administered by such agencies.

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