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INVESTIGATION OF THE EFFECT OF BODY WEIGHT AND VEHICLE SPEED ON THE MEASUREMENT OF VIBRATIONS USED IN HIGHWAY PAVEMENT EVALUATION

KARAYOLU ÜSTYAPI DEĞERLENDİRMESİNDE KULLANILAN TİTREŞİMLERİN ÖLÇÜMÜNDE VÜCUT AĞIRLIĞI VE TAŞIT HIZI ETKİSİNİN İNCELENMESİ

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ABSTRACT

The study delved into investigating the impact of body weight on the determination of vibration parameters, as outlined in the ISO 2631 standard, which elucidates the evaluation concept of Whole Body Vibration. First of all, the ride speed component, which significantly affects the amplitude of the vibration experienced in the vehicle, was determined. In this context, vibration data were recorded at three different points in the vehicle at 20, 30, 40, and 50 km/h ride speeds on a road section whose roughness can be considered homogeneous. Measurements were repeated with drivers weighing 58, 80, and 113 kg to determine the effect of driver weight on vibration parameters. The vibration parameters produced due to the analyses were evaluated with both parametric and non-parametric statistical methods. In the urban road network with bituminous hot mixture pavement, it has been determined that the most appropriate ride speed for passenger car-type vehicles to evaluate the service level of the pavement is 40 km/h. In the last stage, the differences between the averages of the measurements made with three different weight drivers at the determined ride speed were evaluated statistically. Through analysis of three distinct data recording points within the vehicle, it has been established that the driver's weight exerts no discernible influence on any of the vibration parameters.

Keywords: Whole-body vibration, ride speed, body weight

ÖZET

Bu çalışmada Tüm Vücut Titreşiminin değerlendirilmesi kavramını açıklayan ISO 2631 standardında tanımlanan titreşim parametrelerinin belirlenmesinde vücut ağırlığının etkisi araştırılmıştır. Öncelikle taşıt içerisinde maruz kalınan titreşimin genliğini önemli derecede etkileyen sürüş hızı bileşeni belirlenmiştir. Bu kapsamda düzgünsüzlüğünün homojen olduğu kabul edilebilen bir yol kesiminde 20, 30, 40 ve 50 km/sa sürüş hızlarında taşıt içerisinde üç farklı noktada titreşim verileri kaydedilmiştir. Sürücü ağırlığının titreşim parametreleri üzerindeki etkisini tespit edebilmek için ölçümler 58, 80 ve 113 kg ağırlığındaki sürücüler ile tekrarlanmıştır. Analizler sonucu üretilen titreşim parametreleri parametrik ve parametrik olmayan istatistik analiz yöntemleri ile değerlendirilmiştir. Bitümlü sıcak karışım kaplamalı kentsel yol ağında, binek araç türü taşıtlarda üstyapının hizmet seviyesinin değerlendirmesini yapabilmek için en uygun sürüş hızının 40 km/sa olduğu tespit edilmiştir. Son aşamada, belirlenen sürüş hızında üç farklı ağırlıktaki sürücü ile yapılan ölçümlerin ortalamaları arasındaki farklar istatistik olarak değerlendirilmiştir. Taşıt içerisinde veri kaydedilen üç farklı noktada tüm titreşim parametreleri üzerinde sürücü ağırlığının etkisiz olduğu tespit edilmiştir.

Anahtar Kelimeler: Tüm vücut titreşimi, sürüş hızı, vücut ağırlığı

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INTRODUCTION

In the years when the theory of the Pavement Management System (PMS) began to be developed, it is known that the service capabilities of highway pavements were made by panel evaluations based on riding comfort (Haas, Hudson, & Zaniewski, 1994). In these evaluations, the service capability of the pavements to the driver and passengers is measured by the experts' perception of comfort during travel. The vibration parameter is the most critical component in grading this perception in experts' brains. The exposure to whole-body vibration (WBV) experienced while traveling in vehicles has various adverse effects on human health, safety, and overall comfort, particularly impacting drivers and passengers in multiple ways (Griffin, 2012).

Ride comfort is often assessed in numerous studies by evaluating the square mean (a_{wz}) derived from frequency-weighted analysis of the vertical vibration measurements. Cantisani and Loprencipe (2010) explored the correlation between the International Roughness Index (IRI), a measure of pavement performance, and a_{wz}, which quantifies whole-body vibration following the ISO 2631 standard. The studies reveal that extended travel on low-performing pavements has an adverse impact on human health. In addition, in many studies, it is seen that the Vibration Dose Value (VDV) component, which includes the time exposed to vibration in the analysis and gives more sensitive results in the analysis of acceleration measurements at extreme points, is used to express the effects of vibration on human health numerically (S. Wang, Zhang, & Yang, 2010; Turner & Griffin, 1999). A study compared the impacts of vibrations on human health in vehicles utilized by the US armed forces, employing the ISO 2631-1 and ISO 2631-5 standards for assessment (Alem, 2005).

Furthermore, the literature has explored the topic of assessing the present condition of pavements using accelerometers. From the publications on this subject, it is clear that researchers mainly focus on comparing the surface distress data and roughness data of the pavement with the vertical vibration data of the vehicle. It is evident that with the help of the standard developed with the ASTM E 950 code and explaining how IRI measurements should be made, it will provide convenience to institutions/organizations trying to establish their PMS to make surface deterioration assessments with the help of accelerometers. In studies, it is seen that researchers use acceleration data as calibration data in vehicle dynamics models or to investigate their correlations with surface distress data and roughness data. In the evaluation of vehicle vibration, it was seen that the researchers created simulation models and mechanisms that can be considered the last point in PMS engineering. Put differently, when all PMS studies are evaluated, it is seen that the service level of the road can be determined before the road is built, with the distress that will occur over time in a pavement that will be manufactured after its design using today's latest technology and the effects of these distresses on the road users (Bolling et al., 2011; Muniz de Farias & de Souza, 2009; González, O'Brien, Li, & Cashell, 2008; Liu, Zhang, & Ji, 2008; Ahlin & Granlund, 2002; Kropáč & Múčka, 2005).

Significant attention should be drawn to the abundance of studies in the literature that delve into the correlation between vehicle-induced vibrations and pavement performance metrics. The studies analyzed ride comfort using dynamic vehicle models that respond to signal stacks representing macrotexture depth. In other words, they rely on profile inputs that can quantitatively describe the road surface (C. Zhang & Guo, 2023; J. Zhang, Wang, Jing, Wu, & Li, 2020; Cantisani & Loprencipe, 2010; Hou, Liang, Ma, & Hua, 2009). Furthermore, research examining ride comfort by employing synthetic road profiles corresponding to the road classifications outlined in the ISO 8608 (Du, Li, Ning, & Sun, 2020; ISO, 1995) standard is a notable focus in the literature (Agostinacchio, Ciampa, & Olita, 2013; Múčka, 2015; Nguyen, Lechner, Wong, & Tan, 2019). Similarly, investigations have explored the connections between pavement performance and vibration measurements conducted on road sections of specific lengths with superimposed pavement distress (Múčka, 2017, 2021; Abudinen, Fuentes, & Carvajal Muñoz, 2017; F. Wang & Easa, 2016). The studies highlight those vibrations recorded in passenger car-type vehicles of various sizes, particularly at urban speed limits, exhibit minimal variation irrespective of the car's brand and model (Múčka, 2020, 2021; Duarte & de Melo, 2018). In studies concerning this topic, it is evident that the impact of road surface-induced vibrations experienced within a vehicle on ride comfort is frequently assessed using performance index components that reflect the pavement's current condition.

When the literature is examined in detail, it is seen that although many parameters, such as differences between vehicles, differences between compared indexes, and so on, are evaluated in the measurements made to determine the comfort level and even the profile of the road, the body weight taken into account during the measurement is not considered.

The prevailing consensus is that the primary factors contributing to vibrations in the vertical axis direction are the vehicle's mechanical structure and the road surface deformations encountered during travel. The study investigated the effects of driver weights on the determination of vibration parameters accepted in the ISO 2631-1 (1997) standard. In this context, numerous measurements were conducted with drivers weighing 58 kg, 80 kg, and 113 kg at measurement speeds of 20, 30, 40, and 50 km/h on a road section with well-documented pavement performance, from which vibration parameters were derived. Whole-body vibrations affected by the driver's seat and the changes in the vehicle's vibrations at driving speeds of 20 to 50 km/h and specified driver weights were examined graphically. Similarity inquiries were made with statistical analyses between the determined many measurements and the vibration parameters produced from these measurements, and the results were examined. Vibration measurements were completed on a newly made pavement section to eliminate the possibility of vehicles overreacting due to vehicle mechanics due to significant level differences on the road surface.

MATERIALS AND METHODS

ISO 2631 Standard

The study evaluated the change between driver weight and driving speed changes, which is considered to affect these vibrations in the vehicle, and the vibration data in the vertical direction. The evaluation in question was conducted following the standard guidelines of ISO 2631-1, which pertain to Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration (ISO, 1997). The standard, last published by the International Organization for Standardization (ISO) in 1997, establishes criteria for assessing the comfort and health impact on individuals exposed to whole-body vibration in various vehicle types. Additionally, it outlines the principles for calculating and evaluating these effects. The first part of the ISO 2631 standard (ISO 2631-1) covers the evaluation of periodic, random, and discontinuous vibration movements about people's health, perception, and comfort responses. Regarding their impact on the human body, this standard categorizes vibrations into two frequency ranges: 0.5 Hz to 80 Hz, where vibrations may lead to discomfort, fatigue, and health issues, and 0.1 Hz to 0.5 Hz, which can induce motion sickness.

The ISO 2631-1 standard asserts that the a_w component is the most suitable parameter for describing the acceleration transmitted to an individual exposed to vibrations and, consequently, the sensations experienced by that person (ISO, 1997). The ISO 2631-1 standard suggests organizing vibration signals based on 1/3 (one-third) octave band frequency limits using the Butterworth filtering technique. The acceleration values filtered in the one-third octave band are multiplied by the gain coefficients defined in the frequency weight filters, and the weighted total values (a_w) in the direction of the relevant axis are obtained. To clarify, the weighted acceleration values are obtained by multiplying the acceleration frequencies, divided into one-third octave band frequencies, with the corresponding weights specified in the standard. Equation (1) shows the parameter's mathematical expression. In this context, a_w represents the frequency-weighted acceleration, w_i denotes the corresponding frequency-defined weighting factor, and a_i stands for the Root Mean Squared (RMS) acceleration value for the i^{th} one-third octave band. Besides, random shock vibrations transmitted to road users can also be defined in the standard with the help of partial analysis of the entire vibration data stack recorded in a specific time interval, made in short time intervals. The weighted square mean ($a_w(t_0)$) value, which occurs in a time interval recommended as 1 second in the standard but recommended to be determined by the operator performing the analysis, is determined. The weighted square mean value is expressed in equation (2).

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

$$a_w(t_0) = \left\{\frac{1}{\tau}\int_{t_0-\tau}^{t_0} [a_w(t)]^2 \, dt\right\}^{\frac{1}{2}} \tag{2}$$

Within this equation, $a_w(t)$ signifies the instantaneous frequency-weighted acceleration value, τ denotes the moving average period, t represents the measurement variable, and t_0 corresponds to the measurement time. To reiterate, it is recommended to choose 1 second as the time frame of the moving average in the ISO 2631-1 standard. In light of this information, the maximum transient vibration value (MTVV) is expressed in equation (3).

$$MTVV = \max[a_w(t_0)] \tag{3}$$

According to the ISO 2631-1 standard, the fourth power vibration dose method (VDV), which can give more accurate results than the a_w parameter in the evaluation of the most significant acceleration data during the accepted measurement period, is made by taking the 4th floor instead of the 2nd floor of the acceleration measurements made in the time interval. Even though the unit of the VDV parameter is designated as $m/s^{1.75}$, its calculation is performed using equation (4).

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

Within this equation, $a_w(t)$ represents the instantaneous frequency-weighted acceleration value, while T denotes the total measurement time.

Acceleration Data Measurement Kit

The study collected data through a vibration measurement set consisting of three accelerometers (with a measurement range of ±4g and sensitivity of 500±15 mV/g), one GPS antenna (with an accuracy below 3 meters), and a data logger. Vibration data were captured in the vertical direction to assess the correlation between the flexible pavement surface and whole-body vibration. The acceleration measurement set operates in conjunction with the computer, enabling simultaneous collection of vertical acceleration and GPS data. During the study, vertical vibration data were gathered at 1000 intervals per second, while GPS data were collected at one-second intervals and promptly transferred to the computer. Vertical vibration measurements were carried out on an automobile belonging to the lower middle-class C segment, with a length ranging between 4100-4600 mm, according to the Euro NCAP car segment classification.

In order to assess whole-body vibration following the definitions outlined in the ISO 2631-1 standard, an accelerometer should be positioned directly beneath the driver to capture the interaction with the passenger accurately. The accelerometer, which determines the driver's WBV values, is positioned on a rubber pad. The accelerometer is fixed since the driver sits on this pad during measurements. The other two accelerometers (over the middle axle and right front seat points) were placed and restrained in a light bed (using a towel) that did not allow free horizontal movement. The mentioned measuring point is shown in Figure 1. Throughout the measurements, the accelerometers were positioned at three distinct locations: the driver's seat (with the driver seated), the right front seat (without any passengers), and the middle axle (at foot level). The mentioned acceleration measurement points are shown in Figure 2. The researchers analyzed the measured vibration values utilizing both the analysis method developed in the MATLAB® interface and the analysis method prescribed in the ISO 2631-1 standard. Figure 3 displays the vibration measurement set employed for field surveys along with the software designed to assess vibration data.

Figure 1. Position of Accelerometer According to ISO Standard (Point 2)

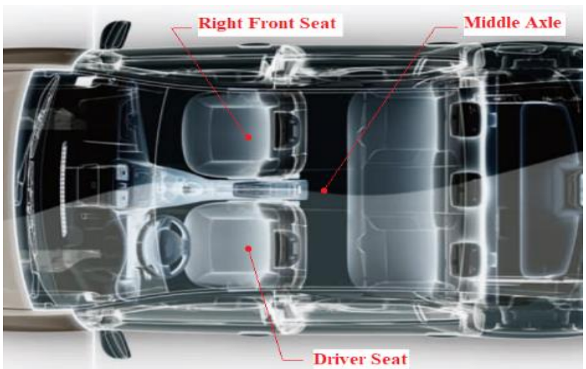

Figure 2. Location of Accelerometers Placed Inside the Vehicle

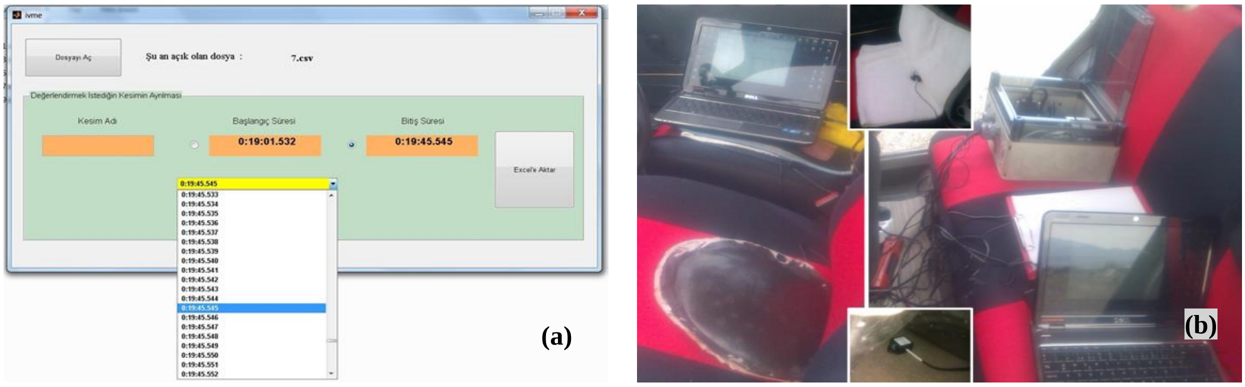

Figure 3. a. Analysis Program and **b.** Vibration Measurement Set Used in the Study

Measured Road Pavement Section

The pavement of the road section used in vibration evaluation is Bituminous Hot Mixed Asphalt (HMA). In the pavement design, a 25 cm crushed stone subbase, 20 cm crushed stone base, 6 cm binder course, and 5 cm surface course are envisaged. The section foreseen in the design was applied in place. All vibration measurements were made above the surface course. The longitudinal slope of the measured road is 0, and its length is 960 m. The roughness index of the section measured after manufacturing was determined to be approximately 1.2 m/km, and the pavement performance status (PCI) was about 100. The “Soiltest CT-444 electronics roughness indicator” device was used to determine the roughness values. Values ranging from 1,152 to 1,247 m/km were measured during the roughness measurements made on the surface layer. The standard deviation of the measurements was found to be ±0.03 m/km.

Marshall design method was used to determine the optimum bitumen content in the binder and surface layers designed as a bituminous hot mixture. The mixture design determined that 4.25% by-weight bitumen with a 70-100 penetration value should be used for the binder layer, and 4.65% by-weight bitumen with a 50-70 penetration value should be used for the surface layer. Additionally, due to the high peeling rates of the aggregate, it is envisaged to add 0.5% anti-stripping Diamine HBG additive to the 50-70 penetration bitumen in the wearing layer. It was implemented at the foreseen manufacturing site.

RESULTS AND DISCUSSION

Vibration Change According to Driving Speed

The study investigated whether the driver's weight affects the evaluation results in the vibration measurements made with the driver on the driver's seat, which the standard defines as the most suitable measurement place. As stated in the previous section, field measurements were made on a newly constructed flexible pavement section where the surface roughness characteristic can be assumed to be homogeneous. To evaluate only the effects of driver weights on vibration parameters, a flexible pavement section with a pavement condition index value of 100 was determined as the road section to be measured. Namely, numerous measurements were made on the route at measurement speeds of 20, 30, 40, and 50 km/h with the same drivers weighing 58 kg, 80 kg, and 113 kg in a flexible pavement section with a pavement condition index value of 100. Measurements were completed at different speeds on the same route, and vibration parameters were calculated.

In this study, vertical vibration data were recorded at three different points in the vehicle at 20, 30, 40, and 50 km/h speeds with drivers weighing 58, 80, and 113 kg on the same pavement section and analyzed according to the principles of ISO 2631-1 standard. At least six measurement data were recorded for each speed and driver weight. By evaluating the vibration data, a_w, MTVV, and VDV vibration parameter values were obtained at different speeds and driver weights. During the measurements, vibration data were measured in the vertical direction to see only the changes caused by the vehicle, and the vibration parameters produced from these data were named a_{wz}, $MTVV_z$, and VDV_z. Evaluation data stacks were created by averaging the data obtained at each driver's weight and measurement (driving) speed. The a_{wz} parameter changes of these produced vibration parameters at three different vibration measurement points according to the driving speeds and driver weights are shown in Figure 4, the $MTVV_z$ parameter changes in Figure 5, and the VDV_z parameter changes in Figure 6.

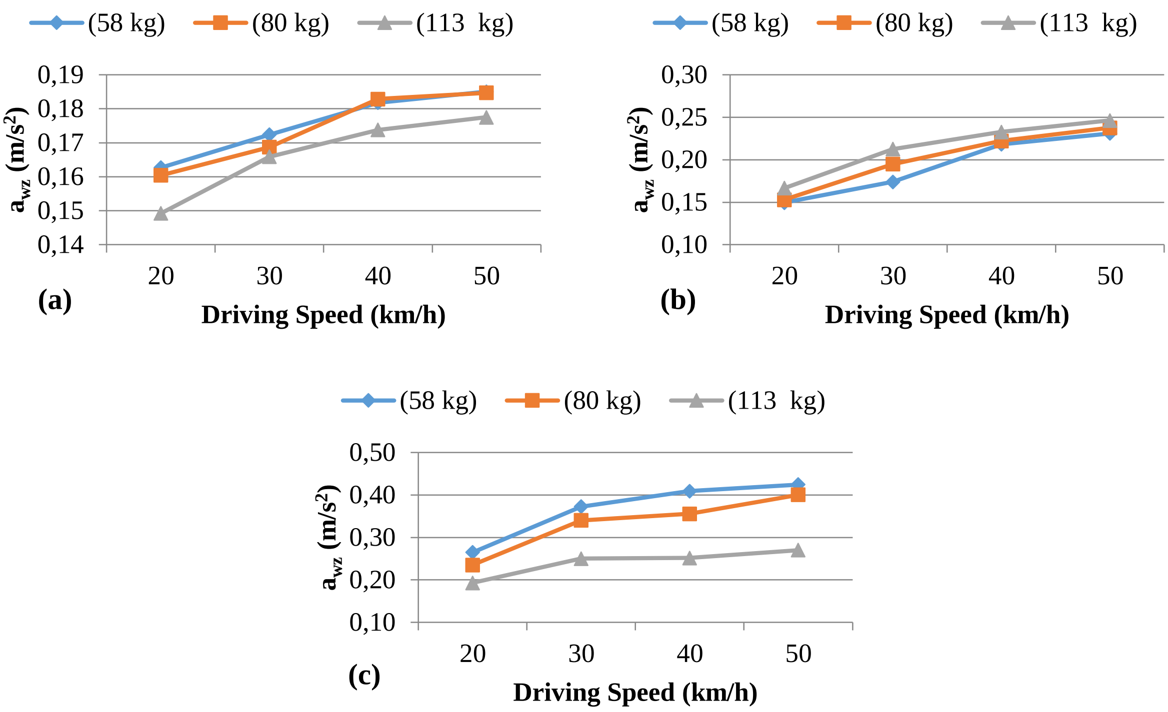

Figure 4. a_{wz} Changes According to Driving Speed in **a.** Driver Seat, **b.** Over Middle Axle and **c.** Right Front Seat Points

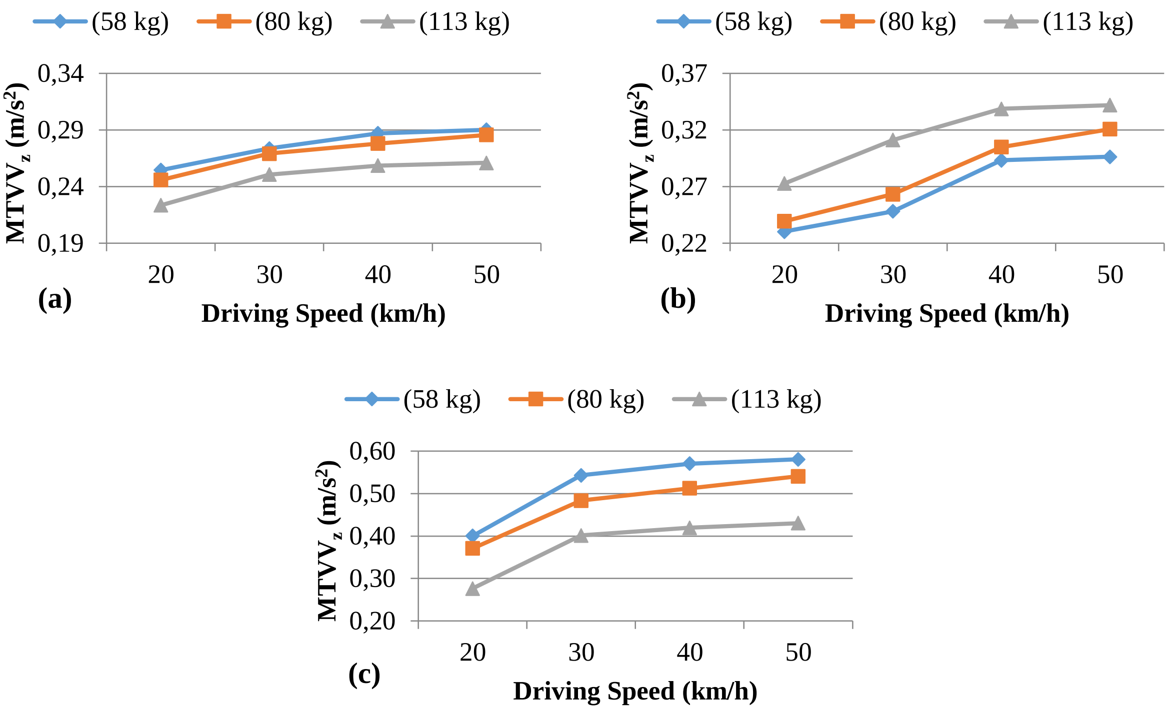

Figure 5. $MTVV_z$ Changes According to Driving Speed in **a.** Driver Seat, **b.** Over Middle Axle and **c.** Right Front Seat Points

As can be seen from the graphs created as a result of the analysis, as the driving speed increases, the vibration parameter values in the vehicle increase. According to all measurement parameters, relatively large vibration values in the measurements on the seat (driver and right front seat) occur in the measurements made with the driver weighing 58 kg. In comparison, the measurements made with the driver weighing 113 kg in the measures on the mid-axle show high vibration values. Thus, due to the suspension effect, less driver weight increases the vibration amplitude on the seat, while more driver weight increases the vibration amplitude on the vehicle floor. However, in general, it is seen that there are no significant numerical differences between vibration parameters according to different driver weights.

It is seen in Figure 5 that there are similar results in the $MTVV_z$ parameter, which expresses the maximum vibration values in the one-second interval in vibration measurements, in other words, the instantaneous shock value. The pavement section where the measurements were made was made recently, and since the surface roughness was homogeneous and at minimum values, the $MTVV_z$ parameters, i.e. instantaneous shock values, did not reach significant values. Similarly, in the evaluations made according to the VDV_z parameter, which more precisely reflects the change in vibration amplitude, no difference is observed in the order of the driver's weight versus the measurement point (seen in Figure 6).

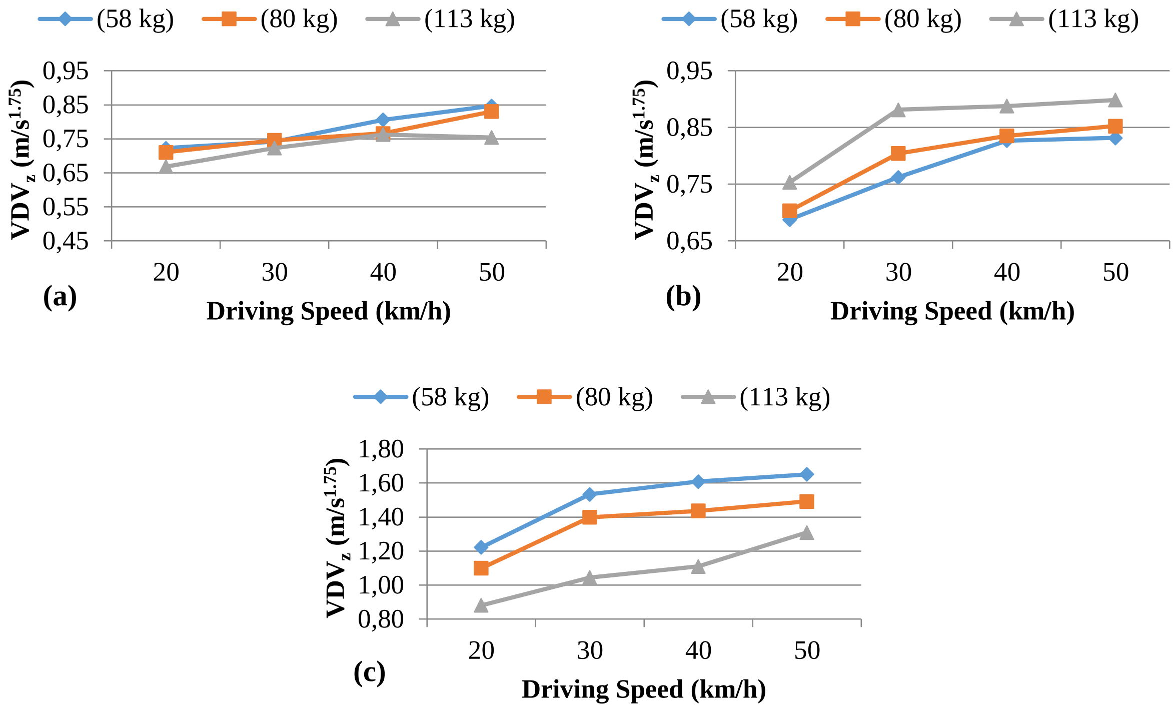

Figure 6. VDV_z Changes According to Driving Speed in **a.** Driver Seat, **b.** Over Middle Axle and **c.** Right Front Seat Points

Correlation between Driver Weight and Vibration Parameters

These vibration parameters obtained were evaluated with both parametric and non-parametric statistical methods, and it was investigated whether there was a statistically significant difference between the values. The SPSS package program was used in all statistical evaluations. Primarily, evaluation was made with non-parametric methods. In this sense, the Kruskal-Wallis H Test was used to compare the measurements of more than two groups with non-parametric data. Measurements made at different driver weights of 58, 80, and 113 kg and speeds of 20, 30, 40, and 50 km/h were evaluated statistically for each of the measurement points of the driver's seat, on the middle axle and right front seat. The statistical significance values (p) found as a result of the evaluation made using the SPSS program are shown in Table 1.

Table 1. Kruskal-Wallis H Test Statistical Significance Values

Speed (km/h)	Driver Seat			Middle Axle			Right Front Seat		
	a_{wz}	$MTVV_z$	VDV_z	a_{wz}	$MTVV_z$	VDV_z	a_{wz}	$MTVV_z$	VDV_z
20	0.033	0.526	0.030	0.001	0.018	0.008	0.000	0.001	0.000
30	0.147	0.687	0.034	0.004	0.037	0.025	0.001	0.034	0.001
40	0.056	0.190	0.066	0.085	0.118	0.172	0.000	0.000	0.000
50	0.090	0.263	0.069	0.593	0.125	0.162	0.001	0.001	0.001

In the statistical evaluation, the parameters that the H_1 hypothesis is fulfilled, that is, the statistical significance value is more significant than 0.05, are shown with grey fill in the table. That is, the table shows cases where the differences between the vibration parameters measured and calculated in gray filled cells, with 95% accuracy, at 58, 80, and 113 kg driver weights, are statistically insignificant compared to the driver's weight. As a result of the evaluation, it was determined that the differences in the vibration parameters produced in the measurements made only at 40 and 50 km/h speeds at the measurement points on the driver's seat and on the middle axle were statistically insignificant.

Another evaluation was made using the independent sample one-way Analysis of Variance (ANOVA) test, which compares the measurements of more than two groups from parametric methods. As it is known, to make parametric evaluations in statistical evaluations, the conditions for the data to be homogeneous and to comply with the normal distribution are sought. Therefore, the values found as a result of the evaluation made according to the variance test homogeneity are shown in Table 2. According to the evaluation, it was observed that the vibration parameters produced from the measurements made on the driver's seat and the middle axle at 40, and 50 km/h speeds were homogeneous. It has been emphasized that another condition for parametric statistical evaluations is that the data should be by the normal distribution. As a result of the evaluations, statistical significance values of the parameters of the measurements made on the driver's seat, on the middle axle, and the right front seat at 20, 30, 40, and 50 km/h speeds for each vibration parameter were found for drivers weighing 58, 80 and 113 kg. Evaluation results for a_{wz}, $MTVV_z$, and VDV_z parameters are shown in Tables 3, 4, and 5, respectively. In the tables, cells, where the difference between the data is statistically insignificant are shown with grey fill. As a result of all these evaluations, it has been determined that each vibration parameter is by the normal distribution.

Table 2. Variance Homogeneity Evaluation Statistical Significance Values

Speed (km/h)	Driver Seat			Middle Axle			Right Front Seat		
	a_{wz}	$MTVV_z$	VDV_z	a_{wz}	$MTVV_z$	VDV_z	a_{wz}	$MTVV_z$	VDV_z
20	0.121	0.005	0.918	0.055	0.003	0.098	0.002	0.281	0.001
30	0.568	0.010	0.195	0.204	0.100	0.952	0.003	0.049	0.005
40	0.206	0.093	0.258	0.623	0.063	0.113	0.033	0.427	0.047
50	0.129	0.069	0.062	0.036	0.107	0.095	0.342	0.053	0.225

Table 3. The Statistical Significance Values of The a_{wz} Parameter Conforming to The Normal Distribution

a_{wz}	Driver Seat			Middle Axle			Right Front Seat		
	58 kg	80 kg	113 kg	58 kg	80 kg	113 kg	58 kg	80 kg	113 kg
20	0.965	0.813	0.972	0.877	0.967	0.999	0.980	0.700	0.518
30	0.979	0.764	1.000	0.996	0.805	0.712	0.826	0.877	0.976
40	0.867	0.953	0.786	0.890	0.820	0.766	0.715	1.000	0.952
50	0.999	0.316	0.981	0.976	0.993	0.638	0.988	0.731	0.998

Table 4. The Statistical Significance Values of The $MTVV_z$ Parameter Conforming to The Normal Distribution

$MTVV_z$	Driver Seat			Middle Axle			Right Front Seat		
	58 kg	80 kg	113 kg	58 kg	80 kg	113 kg	58 kg	80 kg	113 kg
20	0.994	0.933	0.828	0.872	0.478	0.839	0.655	0.117	0.651
30	0.999	0.999	0.152	0.997	0.986	0.990	0.782	0.972	0.908
40	0.937	0.949	0.293	0.837	0.450	0.999	0.995	0.809	0.937
50	0.731	0.641	0.401	0.975	0.974	0.906	0.966	0.992	0.853

Table 5. The Statistical Significance Values of The VDV_z Parameter Conforming to The Normal Distribution

VDV_z	Driver Seat			Middle Axle			Right Front Seat		
	58 kg	80 kg	113 kg	58 kg	80 kg	113 kg	58 kg	80 kg	113 kg
20	0.574	0.641	0.875	0.991	0.690	0.979	0.779	0.578	0.822
30	0.993	0.974	0.359	0.951	0.992	0.896	0.724	0.943	0.569
40	0.831	0.240	0.999	0.953	0.998	0.940	0.772	1.000	0.894
50	0.868	0.100	0.957	0.832	0.754	0.950	0.997	0.933	0.856

It has been determined that the vibration parameters of the measurements made on the driver's seat and the middle axle at 40 and 50 km/h speeds generally meet the mentioned criteria. After this conformity assessment, the ANOVA test was applied and investigated whether the difference between the parameters of the vibration data measured at different driver weights was statistically significant. The results of the evaluation are shown in Table 6.

Table 6. ANOVA Test Statistical Significance Values

Speed (km/h)	Driver Seat			Middle Axle			Right Front Seat		
	a_{wz}	$MTVV_z$	VDV_z	a_{wz}	$MTVV_z$	VDV_z	a_{wz}	$MTVV_z$	VDV_z
20	0.027	0.368	0.029	0.000	0.000	0.012	0.000	0.116	0.000
30	0.125	0.568	0.156	0.001	0.026	0.020	0.000	0.013	0.000
40	0.051	0.079	0.292	0.065	0.083	0.086	0.000	0.000	0.000
50	0.544	0.100	0.108	0.202	0.061	0.121	0.000	0.000	0.000

The cases where the differences between the vibration parameters measured and calculated at 58, 80, and 113 kg driver weight with a 95% accuracy are statistically insignificant compared to the driver weight are shown in Table 6 with grey-filled cells. As a result of the ANOVA analysis, which is a parametric statistical evaluation method, it was determined that the differences in the vibration parameters produced in the measurements made at 40 and 50 km/h speeds at the measurement points on the driver's seat and on the middle axle, as in the result of the non-parametric statistical analysis Kruskal-Wallis H Test, were found to be statistically insignificant.

It has been emphasized before that there is no statistically significant difference according to the hypothesis tests performed in the results, with a statistical significance value of $p > 0.05$ at the 95% confidence interval. In this evaluation, when we evaluated the data obtained from the vibration measurements made according to 58, 80 113 kg driver weights with both parametric and non-parametric methods, it was determined that the difference between the data was insignificant only at 40 and 50 km/h speeds on a highway where the pavement roughness is considered homogeneous. In other words, from statistical evaluations, it can be accepted that the driver's weight is insignificant only at speeds of 40 and 50 km/h. When a certain speed is exceeded, it is understood that the mechanical vibrations created by the rotational forces arising from the vehicle movement are homogeneously distributed in the vehicle body, and the driver's weight becomes meaningless with the increasing vibration value.

In addition, these statistical evaluations determined that the differences between the vibration parameters produced from the measurements made on the right front seat were statistically significant in both parametric and non-parametric evaluations. In the study, the statistically significant difference between the vibration parameters was found as a result of the measurements made in the right front seat, even in a superstructure where the vertical vibration values are minimal; in other words, the PCI value is accepted as 100, is taken as an indication that the measurements made at this point are not reliable.

Then again, it was determined that the differences between the parameters produced from the measurements made on the driver's seat and the middle axle were statistically insignificant only in the measurements made at 40 and 50 km/h speeds. Therefore, as a result of all statistical evaluations, 20, 30, 40, and 50 km/h speed values of 40 and 50 km/h were found to be acceptable measurement speed values. It has been determined that the speed limits allowed, especially in urban residential areas, are pretty low, and 40 km/h driving speed would be the most appropriate choice in vehicle measurements to determine pavement performance due to the difficulties arising from urban road geometries.

In addition, vertical vibration measurements were evaluated regarding driver weight in all sections to be considered in the study. The similarities of the vibration parameter set produced at each driver weight at the 40 km/h measurement speed with the others were investigated. To rephrase it, whether the vibration parameters produced at any driver weight reflect the general was statistically evaluated. In this sense, a single sample t-test was performed for each measurement point. As a result of the t-test for each driver weight and vibration parameter, it was seen that the H_1 hypothesis was correct since the significance values of the t-distribution were more significant than 0.05 in the evaluation. To reiterate, the average values accepted as calibration parameters for the 40 km/h measurement speed were determined to reflect the set of parameters. As an example of the evaluation, the statistical significance evaluation results, which were found due to the comparison of the 80 kg driver's weight with the other driver's consequences, are shown in Table 7.

Table 7. t Test Statistical Significance Values

	Driver Seat	Middle Axle	Right Front Seat
a_{wz}	0.137	0.091	0.443
$MTVV_z$	0.241	0.051	0.500
VDV_z	0.794	0.352	0.573

One of the primary sources of vibration experienced while driving is the roughness of the road surface. Although it is impossible to predict the IRI, which expresses the condition of the road, with high accuracy with acceleration measurement data, it is possible to comment on the IRI status of a road according to the acceleration values obtained. The IRI is a standardized measurement used to assess the roughness or smoothness of a road's surface. It is typically determined by analyzing vehicle response to road surface irregularities, often using vertical displacement and acceleration data.

CONCLUSION

It is known that road pavement distress adversely affects vehicle drivers and passengers. It is seen in many studies that vibrations in the vehicle are at the beginning of these adverse effects. The study investigated the changes in the vibrations occurring in the vehicle and the whole-body vibrations affected by the driver's seat at different driving speeds and driver weights. The acceleration data measured for vibration evaluation were analyzed according to the evaluation principles specified in the ISO 2631-1 coded standard. In the study, the analyses were made as a result of the measurements, and the results were evaluated with the help of graphics.

In addition, the effects of rider weight were analyzed in whole-body vibration studies. In this sense, statistical similarities between the data were investigated by applying the Kruskal-Wallis H Test, one of the non-parametric tests, and the Independent Sample One-Way Analysis of Variance, one of the parametric tests. It was determined that the difference between the vibration parameters measured on the driver's seat and the middle axle at speeds of 40 km/h and above was statistically insignificant. To put it differently, it was concluded that the driver's weight is not essential in evaluating the vibrations measured on the driver's seat and the middle axle at 40 km/h and above.

Many authorities accept that the most challenging step in the operation of pavement management systems is to determine the current performance levels of pavements. Today, it is known that the most effective method, especially in determining the pavement performance of urban roads, is the relative evaluations made by experts. These evaluations can be made by experts trained in the field by visual analysis of the pavement surface, collecting surface distress data, and evaluating the driving comfort in the vehicle. In this study, it was concluded that the speed of the vehicle should be at least 40 km/h so that the pavement evaluation specialist can decide on the pavement comfort without being affected by his weight; in other words, to obtain the correct expert opinion in the pavement performance evaluations made with the driving comfort in the vehicle. Instead, considering the pavement roughness evaluation standards, it is recommended that the superstructure performance evaluations with the driving comfort evaluation principle should be done at a constant speed and a minimum speed of 40 km/h.

It is thought that repeating similar measurements with different vehicle types, such as minibuses and buses, in the further stages of the study and mutually evaluating these results will provide significant gains to the literature. On the other hand, simulating the results of the measurements with mechanical models that consider the human body-vehicle interaction will also allow the mutual evaluation of test sections with deterioration on the road surface.

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REFERENCES

Abudinen, D., Fuentes, L. G., & Carvajal Muñoz, J. S. (2017). Travel Quality Assessment of Urban Roads Based on International Roughness Index. *Transportation Research Record: Journal of the Transportation Research Board, 2612*, 1-10. https://doi.org/10.3141/2612-01

Agostinacchio, M., Ciampa, D., & Olita, S. (2013). The vibrations induced by surface irregularities in road pavements – a Matlab® approach. *European Transport Research Review, 6*(3), 267-275. https://doi.org/10.1007/s12544-013-0127-8

Ahlin, K., & Granlund, N. O. J. (2002). Relating Road Roughness and Vehicle Speeds to Human Whole Body Vibration and Exposure Limits. *International Journal of Pavement Engineering, 3*(4), 207-216. https://doi.org/10.1080/10298430210001701

Alem, N. (2005). Application of the New ISO 2631-5 to Health Hazard Assessment of Repeated Shocks in U.S. Army Vehicles. *Industrial Health, 43*(3), 403-412. https://doi.org/10.2486/indhealth.43.403

Bolling, A., Jansson, J., Hjort, M., Lidström, M., Nordmark, S., Sehammar, H. k., & Sjögren, L. (2011). An Approach for Realistic Simulation of Real Road Condition in a Moving Base Driving Simulator. *Journal of Computing and Information Science in Engineering, 11*(4), 041009. https://doi.org/10.1115/1.4005450

Cantisani, G., & Loprencipe, G. (2010). Road Roughness and Whole Body Vibration: Evaluation Tools and Comfort Limits. *Journal of Transportation Engineering, 136*(9), 818-826. https://doi.org/10.1061//ASCE/TE.1943-5436.0000143

Du, H., Li, W., Ning, D., & Sun, S. (2020). *Advanced Seat Suspension Control System Design for Heavy Duty Vehicles* (1st Edition ed.). London, UK: Academic Press.

Duarte, M. L. M., & de Melo, G. C. (2018). Influence of pavement type and speed on whole body vibration (WBV) levels measured on passenger vehicles. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40*(3), 150. https://doi.org/10.1007/s40430-018-1057-0

González, A., O'Brien, E. J., Li, Y. Y., & Cashell, K. (2008). The use of vehicle acceleration measurements to estimate road roughness. *Vehicle System Dynamics*, *46*(6), 483-499. https://doi.org/10.1080/00423110701485050

Griffin, M. J. (2012). *Handbook of human vibration*. London, UK: Academic press.

Haas, R., Hudson, W. R., & Zaniewski, J. P. (1994). *Modern Pavement Management*. Malabar, Florida, USA: Krieger Pub. Co.

Hou, X., Liang, X., Ma, S., & Hua, W. (2009, 5-9 August). *The Analysis of the Correlation between International Roughness Index and Body Ride Comfort.* Paper presented at the Ninth International Conference of Chinese Transportation Professionals (ICCTP), Harbin, China.

ISO. (1995). Mechanical vibration - Road surface profiles - Reporting of measured data. In *ISO 8608*. Geneva, Switzerland: ISO.

ISO. (1997). Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration, Part 1: General Requirement. In *ISO 2631-1*. Geneva, Switzerland: ISO.

Kropáč, O., & Múčka, P. (2005). Be careful when using the International Roughness Index as an indicator of road unevenness. *Journal of Sound and Vibration, 287*(4-5), 989-1003. https://doi.org/10.1016/j.jsv.2005.02.015

Liu, Z., Zhang, E., & Ji, Z. (2008). Simulation and Experimental Study of Human Riding Comfort in Dynamic Man-Automobile System. In *Intelligent Robotics and Applications* (pp. 577-587): Springer.

Múčka, P. (2015). Sensitivity of Road Unevenness Indicators to Distresses of Composite Pavements. *International Journal Pavement Research Technology, 8*(2), 72-84. https://doi.org/10.6135/ijprt.org.tw/2015.8(2).72

Múčka, P. (2017). Road Roughness Limit Values Based on Measured Vehicle Vibration. *Journal of Infrastructure Systems*, *23*(2), 04016029. https://doi.org/10.1061/(asce)is.1943-555x.0000325

Múčka, P. (2020). Vibration Dose Value in Passenger Car and Road Roughness. *Journal of Transportation Engineering, Part B: Pavements*, *146*(4), 04020064. https://doi.org/10.1061/jpeodx.0000200

Múčka, P. (2021). International Roughness Index Thresholds Based on Whole-Body Vibration in Passenger Cars. *Transportation Research Record, 2675*(1), 305-320. https://doi.org/10.1177/0361198120960475

Muniz de Farias, M., & de Souza, R. O. (2009). Correlations and Analyses of Longitudinal Roughness Indices. *Road Materials and Pavement Design, 10*(2), 399-415. https://doi.org/10.1080/14680629.2009.9690202

Nguyen, T., Lechner, B., Wong, Y. D., & Tan, J. Y. (2019). Bus Ride Index – a refined approach to evaluating road surface irregularities. *Road Materials and Pavement Design, 22*(2), 423-443. https://doi.org/10.1080/14680629.2019.1625806

Turner, M., & Griffin, M. J. (1999). Motion sickness in public road transport: passenger behavior and susceptibility. *Ergonomics, 42*(3), 444-461. https://doi.org/10.1080/001401399185586

Wang, F., & Easa, S. (2016). Analytical Evaluation of Ride Comfort on Asphalt Concrete Pavements. *Journal of Testing and Evaluation, 44*(4), 1671-1682. https://doi.org/10.1520/jte20140339

Wang, S., Zhang, J., & Yang, Z. (2010). *Experiment on Asphalt Pavement Roughness Evaluation Based on Passengers' Physiological and Psychological Reaction*. Paper presented at the 10th International Conference of Chinese Transportation Professionals—Integrated Transportation Systems: Green, Intelligent, Reliable, Beijing, China.

Zhang, C., & Guo, L.-X. (2023). Analysis of lumbar spine injury with different back inclinations under whole-body vibration: A finite element study based on whole human body models. *International Journal of Industrial Ergonomics, 95*. https://doi.org/10.1016/j.ergon.2023.103447

Zhang, J., Wang, L., Jing, P., Wu, Y., & Li, H. (2020). IRI Threshold Values Based on Riding Comfort. *Journal of Transportation Engineering, Part B: Pavements, 146*(1), 04020001. https://doi.org/10.1061/jpeodx.0000144