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Article

Comparative Evaluation of Human Whole-Body Vibration in Electric and Diesel Articulated Buses

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Abstract

Whole-body vibration (WBV) represents a significant health and comfort concern in modern public transportation systems. This study compares vibration exposure in two types of articulated city buses — diesel-powered and fully electric— under real operating conditions in one of European city (1 million inhabitants). Measurements were conducted at three seating positions (front, middle, rear) across four surface types: smooth asphalt, mixed asphalt-rail, cobblestone, and idle. Triaxial accelerometers recorded accelerations processed according to ISO 2631-1. The frequency-weighted root mean square (RMS) served as the principal comfort indicator, while FFT spectra provided spectral insight. Results show up differences in vibrations, and therefore passenger comfort, in both buses powered by different energy sources (the research was conducted in the period May - July 2025). The article highlights additional inconveniences resulting from operating the buses on roads.

Keywords: whole-body vibration (WBV); ISO 2631-1; RMS; electric bus; diesel bus; vibration comfort; passenger health

1. Introduction

The Mechanical vibrations are an inherent component of vehicular operation, affecting both mechanical integrity and human well-being. Whole-body vibration (WBV), transmitted through seats and vehicle structures, can lead to discomfort, fatigue, and long-term health risks. The ISO 2631-1:1997 standard provides the foundation for assessing human exposure to vibration by defining frequency-weighting filters (W_d, W_k) and health guidance caution zones.

In the context of urban public transport, buses are one of the most frequent sources of long-term exposure to WBV. The recent transition to electric propulsion promises not only lower emissions but also potential improvement in ride quality due to smoother torque delivery and reduced drivetrain-induced vibrations. However, comparative data quantifying WBV differences between diesel and electric city buses remain limited.

The main objective of this study is to quantify WBV in real operational conditions for two articulated bus platforms— diesel and electric—and to assess their implications for passenger comfort and health using ISO 2631-1997 standard.

There is a wealth of valuable literature available in the literature, including studies on vibrations (and even their potential impact on passenger discomfort) in various vehicles equipped with engines with different power supply methods [1–8].

Thamsuwan O., et al. [1] conducted a large-scale field study on WBV exposure in urban bus drivers, showing significant health risk classification under ISO thresholds, especially on cobbled surfaces. Their findings underscore the role of road profile in WBV exposure. Similarly, Ittianuwat R., et al. [2] evaluated different seat suspension systems and found that vertical WBV amplitudes can be reduced with optimized passive dampers.

Patel, Gohil and Borhade [3] compared vibration exposure across various urban road profiles and speeds, establishing that asphalt-rail transitions induce frequency spikes in the 2–8 Hz range, which directly affect lumbar resonance. In another key study, Jagiełło, Wołek and Bizon [4] contrasted WBV between diesel and electric buses, revealing that e-buses demonstrate lower weighted RMS values due to smoother drivetrain profiles.

From a biomechanical standpoint, Alin et al. [5] modelled human-seat dynamics under vertical and multi-axis excitation. Their simulation validated ISO thresholds and indicated that the spine is most sensitive to oscillations below 6 Hz. This aligns with findings by Bai [6], who compared active and passive bus seats, noting a marked reduction in exposure under active damping conditions.

Multibody dynamics have also been applied. Portela and Zannin [7] simulated seated human response in vehicle cabins and identified yaw-induced WBV peaks near articulation joints. Fernandes [8] proposed an optimization framework for suspension design, validated with ISO metrics, reducing exposure zone classification from “Caution” to “Acceptable”.

The particularly valuable literature presenting the results of tests of vehicle components (active and passive) on vibration potential [9–12]. Horvath and Feszty [9] reviewed gear waviness and NVH in EVs, emphasizing that high-frequency vibrations in EVs are more dominant compared to ICE vehicles, affecting perceived comfort. Sangeetha and Ramachandran [9] focused on PMSM-based electric drives, showing that torque ripple is a significant source of passenger discomfort, especially at low speeds. García-Tárrago et al. [10] explored vibration transmission through rubber mounts, highlighting how different impedance behavior in ICE and EV configurations affects isolation efficiency. Fiedler et al. [11] compared interior noise and vibration levels in premium ICE and EV vehicles, noting that EVs tend to have improved low-frequency profiles but introduce high-frequency challenges due to electric drivetrain harmonics. Gad et al. [12] evaluated magnetorheological damper seats in both ICE and EV platforms. The study found measurable improvements in vibration suppression under real-world uncertain driving conditions, offering benefits in both types of vehicles.

Taking into account the subject of the article, it is also necessary to cite publications concerning vibration research in the light of their impact on the human body [14–17]. Whole-body vibration (WBV) occurs when mechanical oscillations are transmitted through a vehicle's structure to its occupants. This type of exposure is common in transportation environments, particularly among professional drivers and frequent commuters. Numerous studies have investigated the physiological, neurological, and musculoskeletal impacts of WBV on the human body. Zhang et al. [14] investigated the onset of drowsiness induced by WBV during transportation. Their findings suggest that specific vibration frequencies (particularly in the 1–20 Hz range) can induce fatigue and drowsiness in as little as 20 minutes of exposure, posing significant safety risks in vehicular and public transport contexts. Griffin's foundational work [15] identifies the resonance frequencies of the human body, revealing heightened sensitivity around 4–8 Hz for the spine and internal organs. These frequencies are commonly encountered in road and rail transport, which may contribute to spinal compression, lower back pain, and long-term tissue degradation. Rahmani et al. [16] assessed the physiological strain on bus drivers under WBV conditions, noting increased heart rates and muscle fatigue, particularly in the lumbar region. These effects were correlated with reduced reaction time and performance accuracy, suggesting operational risk escalation in professional driving scenarios. Li et al. [17] explored the effect of WBV in high-speed magnetic levitation (maglev) trains, comparing it with traditional rail vehicles. The study revealed that although maglev systems eliminate some vibrational sources, failures in levitation units can introduce unique WBV patterns with similar health implications.

2. Methodology

The study was conducted over a three-month period on a regular public transport bus route. These vehicles are very popular across Europe, with over 50,000 diesel vehicles sold and 2,500 electric

vehicles sold. The average age of the vehicles studied was five years. The table below compares the key parameters of the two articulated bus models studied.

Table 1. Comparison of methodologically significant parameters of the tested articulated buses.

Specification	Bus 1 (diesel) (Euro-5)	Bus 2 (electric)
Length (m)	18.13	18.13
Power Output (kW)	220–260	440 peak
Gross Weight (kg)	28,000	29,000
Passenger Capacity	163	146
Production period (years)	1997 - 2006	2019 - present

Both vehicles operated in (this same) line in European city, along identical routes and traffic conditions, covering asphalt, cobblestone, and mixed surfaces (tram-rail section). Measurements were taken at three seat locations: front (behind driver), middle (articulated joint), and rear (above engine/electric axle).

WBV was measured using triaxial accelerometers, mounted on the seat bases to capture vertical (z), lateral (y), and longitudinal (x) accelerations. Sensors were connected to a data acquisition system offering 24-bit resolution and 10 kHz sampling rate per channel [18]. Table 2 contains the most important parameters of the sensor and acquisition system used.

Table 2. Parameters of the vibration sensor used. [19].

Specification	Value
Model	356B41
Manufacturer	PCB Piezotronics
Type	Triaxial ICP® Accelerometer
Sensitivity (±10%)	100 mV/g
Measurement Range	±50 g
Frequency Range (±5%)	0.5 to 1000 Hz
Resonant Frequency	⇒27 kHz
Transverse Sensitivity	≤5%
Output	Voltage, single-ended
Weight	272 grams
House Material	Hermetic

All devices were calibrated prior to measurements. The measurement protocol followed ISO 2631-1 guidelines, ensuring correct sensor orientation, surface fixation, and route repeatability.

The objective of the experiment was to obtain comparable seat-vibration data in two city buses (diesel-powered and an electric). The study was organized as a two-factor design with repeated trials. The independent variables were: (i) pavement/operating condition with four levels - asphalt, mixed (asphalt with tram tracks which is very often for bus ride, because trams and buses share the same "bus lane"), cobblestone, and idle (bus at standstill) - and (ii) seat location with three levels - front, middle, and rear. All other conditions were kept constant as far as practicable; in particular, the same route segments, instrumentation, and parameter settings were used throughout. The complete measurement structure for both buses is shown in Figure 1 (diesel) and Figure 2 (electric). For each bus and each seat location, the vehicle was driven over three fixed route segments representative of the pavement types (asphalt / mixed / cobblestone). In addition, an idle condition

was recorded with the bus stopped. Each condition was measured in two independent repetitions (×2). In total this yields 4 conditions × 3 seats × 2 repetitions = 24 runs per bus and 48 runs overall.

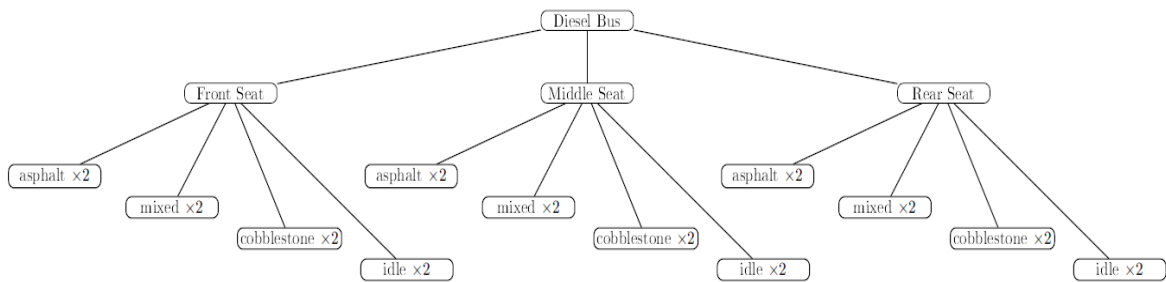


Figure 1. Structure of vibration measurements for diesel-powered bus.

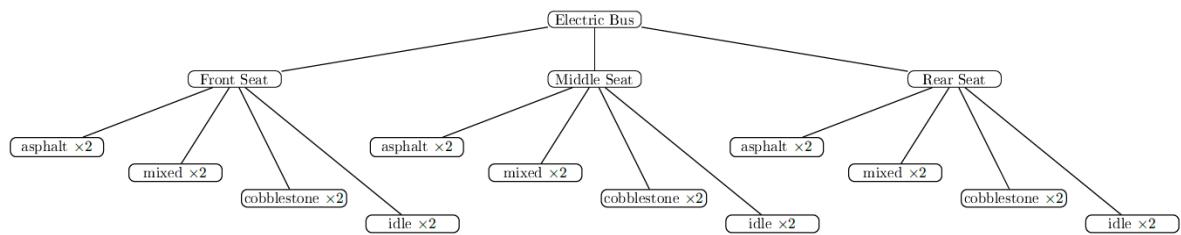


Figure 2. Structure of vibration measurements for electrical-powered bus.

- The following vibration parameters are calculated for each channel and seat position:
- RMS (Root Mean Square) - quantifies the average vibration level and is directly linked to long-term health effects (shows the average vibration level);
 - VDV (Vibration Dose Value) - measures cumulative vibration exposure, sensitive to transient shocks (tells how strong the total vibration exposure was);
 - Peak acceleration - the highest instantaneous acceleration recorded during the session;
 - Crest Factor - the ratio of peak to RMS, indicating the sharpness or impulsiveness of the signal (checks if the vibration had sharp peaks or was smooth);
 - Dominant Frequency - the frequency component with the highest energy (after weighting), related to human resonance;
 - Peak Time - the moment at which peak acceleration occurs, useful for correlating with route events.

Before analysis, the raw acceleration signals are filtered using ISO-defined weighting curves (Wd, Wk, etc.) based on the axis of measurement [20]. This ensures the signal reflects the actual perception and physiological impact of vibration on the human body. A key part of the methodology is the synthesis of a combined vector magnitude (VM) from the three orthogonal axes (X, Y, Z), which allows evaluation of total-body exposure. Based on the combined RMS and VDV values, each measurement is classified into ISO-defined exposure zones (e.g., safe, borderline, or hazardous).

3. Results

This study compared the exposure to whole-body vibration in two articulated city buses: a diesel-powered and a fully electric bus (Table 1). Measurements were conducted under identical operating conditions across various seat positions and road surface types. All data were analyzed according to ISO 2631-1 standards, focusing on frequency-weighted RMS values, VDV, crest factor, and spectral characteristics.

Seat location was the main factor determining the level of WBV. The front seat consistently provided the lowest exposure, while the middle and rear seats had higher amplitudes, especially on

uneven surfaces. Spectral analysis also confirmed that the electric drive effectively eliminates mid-frequency components (20–30 Hz), which are typically associated with oscillations of the combustion engine drivetrain at idle [21,22]. In other situations, vibration exposure in the articulated electric bus is higher than in the diesel bus (Figures 3 and 4).

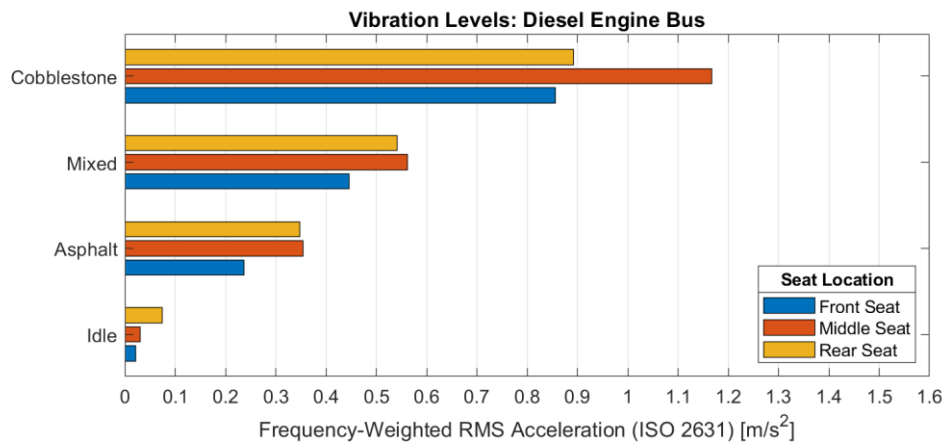


Figure 3. Average RMS vector value, diesel bus.

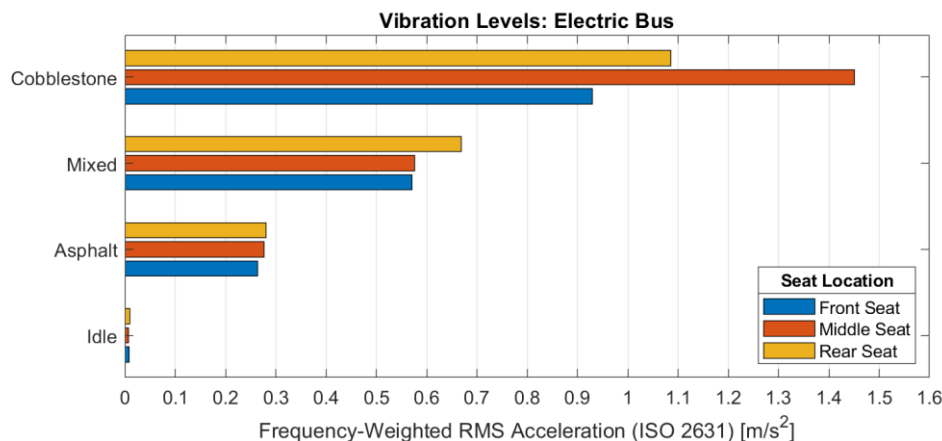


Figure 4. Average RMS vector value, electric bus.

The above data pertain to the combined cycle, in terms of the vehicle's driving surface. However, a more precise distinction between the surface (asphalt and cobblestone) reveals a slight reduction in vibrations in the articulated electric bus for the seats located in the middle and at the front of the vehicle, when driving on asphalt. These small differences do not affect the final conclusion of a higher average vibration exposure in the electric vehicle.

The summary of measurements and their analysis in relation to the ISO 2631-1 standard indicates detailed numerical values:

- Asphalt: $aw \approx 0,24-0,35 \text{ m/s}^2$ across seats. This places the front seat in not uncomfortable and some middle/rear cases in a little uncomfortable. Diesel and Electric are close; Electric is lower at the middle seat. FFTs are dominated by very low frequencies with modest levels, hence small weighted RMS.
- Mixed (asphalt + tram tracks): $aw \approx 0,45-0,67 \text{ m/s}^2$, i.e. mostly fairly uncomfortable (with some front-seat Diesel cases at a little uncomfortable). Electric tends to be higher at the front and rear seats. FFTs show broadened energy in the 3-20 Hz band, which is strongly weighted by Wk.
- Cobblestone: $aw \approx 0,86-1,45 \text{ m/s}^2$ at all seats, i.e. firmly uncomfortable. The

Electric bus is typically higher at the middle and rear seats. FFTs present elevated broadband content with a hump in $\sim 4\text{-}12\text{ Hz}$, the range most influential for seated vertical WBV per ISO 2631-1, explaining the high aw.

- Idle: $aw \approx 0.008\text{-}0.074\text{ m/s}^2$ (not uncomfortable) for all seats. Diesel exhibits a narrow low-frequency line (engine idle), but absolute levels remain low; Electric is uniformly lower in idle.

Figure 5 illustrates the frequency spectrum analysis performed using Power Spectral Density (PSD) calculated via Welch's method. The results are focused on the 0-80 Hz band, as this range was identified to contain the dominant spectral content. The Total PSD represents the cumulative power across all three axes (X, Y, Z).

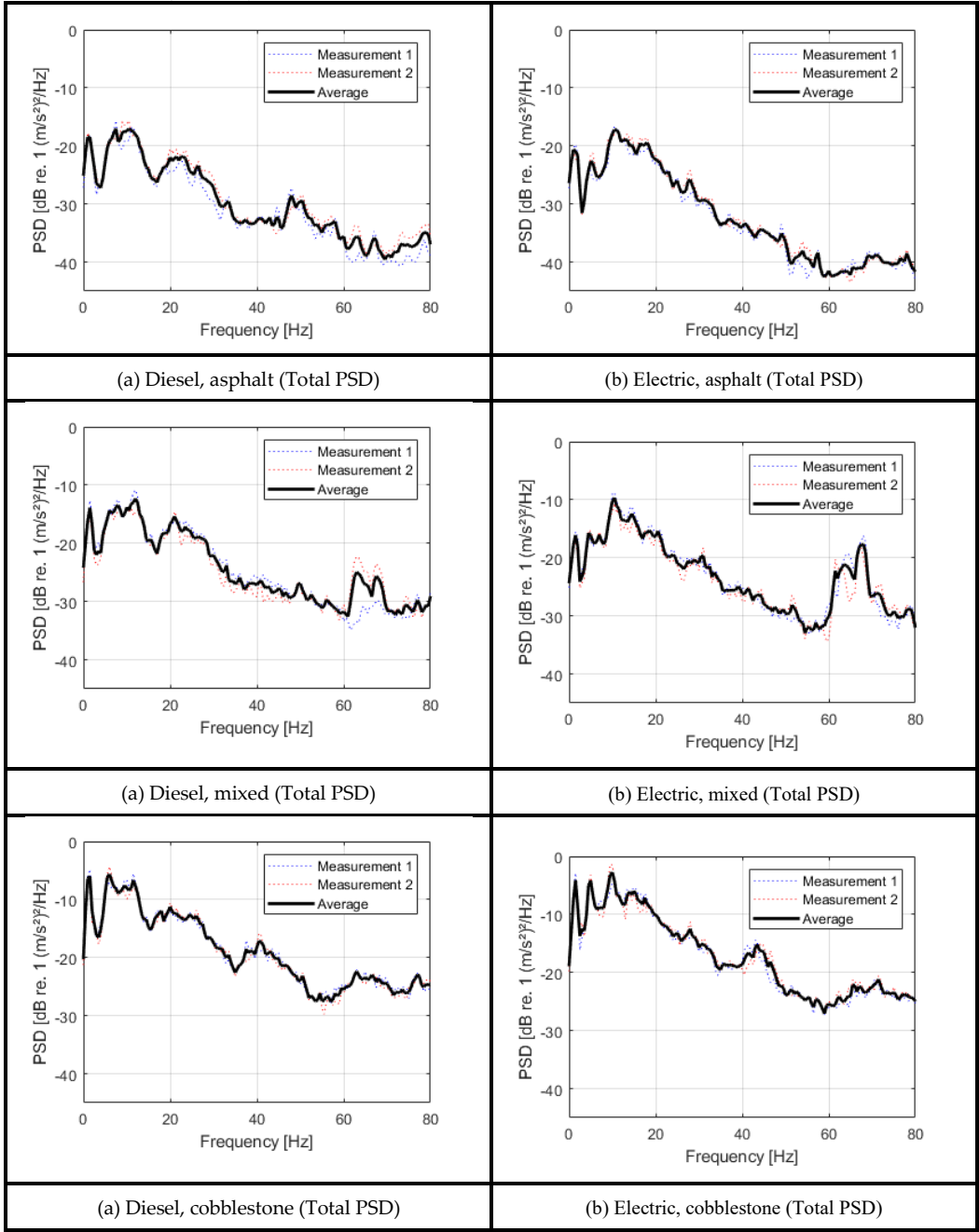


Figure 5. Comparison of the averaged Total Power Spectral Density (PSD) (power sum of X, Y, Z axes) measured at the middle seat for a diesel bus (left) and an electric bus (right) on an asphalt, mixed and cobblestone surface.

At the sample measurement location (middle seat) and for both mixed and cobblestone surfaces, the maximum PSD values within this range were significantly higher for the electric bus. This observation is corroborated by the frequency-weighted RMS results. Furthermore, these distinct

differences in the waveforms persist across all tested surface types, suggesting that this vibrational signature is primarily attributable to the bus's intrinsic mechanical characteristics rather than the road-surface interaction.

It's important to note that not only high amplitude but also frequency variability can lead to micro-injuries, preclinical changes, and psychomotor fatigue [23]. This also highlights the importance of harmonizing vibration risk measurement methods.

For studies with a large number of variables (surface type, power supply method, passenger seat), it was decided to summarize the research results in the form of a heatmap. Figure 6 shows the aforementioned map for the OZ direction.

Based on the research carried out and its analysis, the following general conclusions can be drawn:

- No universal winner between vehicle types. The relative ranking of diesel vs. electric depends on surface and seat. The Electric bus is consistently lower in idle and is sometimes lower on asphalt, whereas on mixed and cobblestone it often shows higher Wk-weighted RMS at the middle and rear seats.
- Comfort is governed by energy in the ISO-sensitive band. Elevated FFT content in ~ 4-12 Hz (where Wk applies the strongest weights for a seated person in the vertical direction) is the primary driver of increases in mixed and cobblestone sections concentrate energy in this band, which explains the shift toward higher discomfort classes.
- Seat location matters. On rougher surfaces (mixed, cobblestone) the middle and rear seats typically exhibit higher aw than the front seat, consistent with the time domain envelopes and the low and middle frequency elevation in the FFTs.
- Surface dictates comfort class; asphalt - not to a little uncomfortable; mixed – pre dominantly fairly uncomfortable; cobble- stone - uncomfortable at all seats; idle – not uncomfortable.
- Engine signature in idle is visible but negligible for aw. Diesel idle shows a narrow low-frequency line in the FFT (engine order), yet absolute levels are small; electric idle remains uniformly low. Both yield very low weighted RMS in idle.

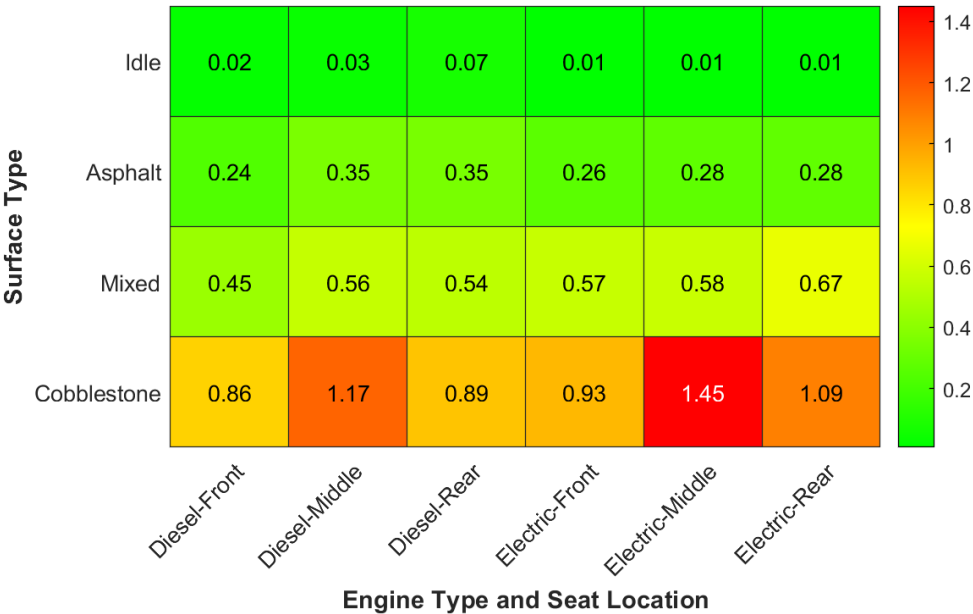


Figure 6. Heatmap of Wk-weighted RMS aw (z-axis) by surface and seat.

It should be noted that the above studies were conducted (over a three-month period) on real vehicles (articulated buses), both electric and diesel-powered, operating on a fixed route. The tested vehicles (Table 1) have very similar parameters (except for the power supply method) and are extremely popular in public transport in Europe. The obtained results appear to result from the weight distribution of these vehicles (articulated electric buses have batteries located on the roof). Each subsequent generation of batteries increases their capacity, but also their weight, as demonstrated in the literature [24,25].

Taking into account the average time of use of public transport buses in Europe (diesel 12-15 years, electric 10-14 years, which corresponds to 500,000-800,000 km), the tests should be repeated periodically, based on subsequent generations of introduced buses. The research did not take into account another variable reported by electric bus drivers, i.e. significant surface degradation caused by electric buses, which must have a direct impact on vibration exposure.

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Abbreviations

The following abbreviations are used in this manuscript:

Aw	Weighted Root Mean Square Acceleration (m/s²), as per ISO 2631-1
EV	Electric Vehicle
FFT	Fast Fourier Transform
ICE	Internal Combustion Engine
ISO	International Organization for Standardization
LD	Linear Dichroism
MDPI	Multidisciplinary Digital Publishing Institute
NVH	Noise, Vibration, and Harshness
PMSM	Permanent Magnet Synchronous Motor
RMS	Root Mean Square
TLA	Three Letter Acronym
VDV	Vibration Dose Value
VM	Vector Magnitude
WBV	Whole-Body Vibration
Wd	Frequency weighting filter for horizontal direction (per ISO 2631-1)
Wk	Frequency weighting filter for vertical direction (per ISO 2631-1)

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