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Whole-Body Vibration in Vehicles on Iraqi Roads

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Abstract: This study investigates whole-body vibration (WBV) exposure in commuters on Iraqi roads. Measurement of vertical, lateral and longitudinal acceleration was obtained on urban arterials, rural two-lane roads and intercity highways using a low-cost measurement setup that incorporates an MPU6050 accelerometer and ESP32 microcontroller. Data was analyzed in accordance with ISO 2631-1, i.e. frequency-weighted root mean square (RMS) acceleration, vibration dose values (VDV) or power spectral density analysis. The results show that vertical vibration (z-axis) predominates in WBV, with maximum energy occurring within the 3–6 Hz frequency range, which is known to correspond to the most responsive frequency range of the human body. The International Roughness Index (IRI), a measure of pavement texture, was highly associated with RMS ($r = 0.66$), with speed having an additional enhancing influence. Cars and SUVs on intercity highways stayed in "comfort" or "light comfort" zones, whereas heavy trucks on rural roads often encountered "uncomfortable" levels, with VDV up to 16.9 $m/s^{1.75}$. These results reveal a growing need for pavement rehabilitation of the Iraqi arterial and rural road networks, better enforcement of axle-load limits and the adoption of WBV monitoring in sensor-based management of road infrastructure. The research outcomes can serve as a useful reference for enhancing transport and occupational health protection policy making in Iraq.

Keywords: Human body vibration; Ride comfort; International Roughness Index; Accelerometer; ISO 2631-1

1 Introduction

Whole-body vibration (WBV) is a major concern for land vehicle occupants when they are subjected to abrupt events which induce travel irregularities; chronic exposure to the phenomenon may lead to discomfort, fatigue, musculoskeletal disorders and a decline in performance [1]. Vertical acceleration especially, and in particular within the 3–6 Hz frequency band, is found to be near human resonance frequencies responding with enhanced physiological and perceptual effects of vibration [2]. ISO 2631-1 describes established methods to assess WBV via root mean square (RMS) and vibration dose values (VDV)-weighted acceleration, as well as comfort boundaries [3].

International WBV field investigations show that exposure levels and dominant frequency content vary markedly across regions due to differences in pavement maintenance, vehicle fleets, and operating conditions. Studies from Europe and North America often report WBV measurements on relatively well-maintained networks or controlled routes, with a strong emphasis on passenger vehicles and comfort-oriented indices. In contrast, studies conducted in developing regions more frequently document elevated WBV exposure for commercial vehicles operating on deteriorated pavements, where roughness-related excitation becomes more pronounced and cumulative measures such as VDV are particularly relevant. These cross-regional differences indicate that WBV should be interpreted as an outcome of combined road–vehicle interaction rather than infrastructure quality alone [4, 5].

Across literature, methodological choices also influence comparability. Some studies rely on seat-pad measurements with standardized ISO frequency weighting, while others adopt chassis-mounted sensors or alternative filtering schemes [6, 7], leading to differences in reported RMS and spectral peaks. Similarly, the magnitude of the reported association between roughness indicators (e.g., IRI) and WBV metrics varies with suspension design, axle configuration, and loading conditions, particularly for trucks. In this context, field data that jointly report WBV metrics together with road roughness and operating speed provide stronger evidence for comparing exposure patterns across vehicle classes and road categories.

The consequences of WBV include not only poor infrastructure maintenance but also increased cost of occupational health programs, besides reduced transport capacity and less efficient operation of transport-dependent sectors [8]. For professional drivers, in particular, prolonged exposure (¿8–10 h daily) to WBV on degraded road networks is a daily reality. This exposure leads to public health related issues and contributes to higher healthcare costs, workers' compensation claims and decreased operational efficiency of commercial transportation fleets [9].

A great deal of evidence is available globally that supports the relationship be-tween road roughness and WBV exposure. Múčka's study, entitled evaluation of WBV and ride comfort in a passenger car [10], investigated vehicle vibration on different road categories at various speeds and discovered a strong relationship between pavement International Roughness Index (IRI), RMS acceleration and perceived ride comfort. The author suggested an IRI threshold definition of passenger car ride comfort and indicated that this threshold was affected by vehicle speed and road condition categories. More recently, De la Hoz-Torres and colleagues reported WBV exposure in heavy equipment vehicle drivers; examining both ISO 2631-1 and the later ISO 2631-5 standards, they concluded that cumulative "shock" exposure as well as posture can affect health risk profiling [11].

Furthermore, tests such as "Assessment of the effect of road roughness and vehicle speed on vibration comfort of school bus drivers' seats based on ISO 2631-1" (2024) showed how vehicle speed influence on WBV in combination with road roughness exposure extends beyond the predictions based upon noise alone. Metro or train drivers [12], for instance, are also found to be exposed to levels of WBV continuously present even on the most "resilient" track sections that exceed comfort and health guidelines at higher speeds or in poorer track conditions. Recent progress in low-cost sensor technology, especially IoT-based accelerometer systems such as ESP32/MPU6050 platforms, opens up new possibilities for broad-based WBV monitoring at only a fraction of the costs of classical equipment [13]. These systems support real-time data generation, wireless communication and fleet-wide coverage across multiple road networks [14]. Contrary to typical vibration measurement systems that require investment running into thousands of dollars, these new generation technologies offer performance similar to that achieved in traffic signal systems, at less than $50 a piece per instance (2database), enabling comprehensive monitoring programs within budgets accessible to developing countries and for research.

Research by the region's scholars on Iraqi road conditions suggests widespread pavement distress. For example, the study "The Pavement Condition Index (PCI) method for evaluating pavement distresses of the roads in Iraq—A case study in Al-Nasiriyah city" [15] found that most of the 13 roads surveyed in the Al-Hadharat Quarter scored in the "fair to poor" and "very poor" categories, with one road even rated "serious", although none rated "failed" under PCI. While this provides a structural and visual distress assessment, these studies do not (in their current published form) measure WBV exposure or IRI and vibration metrics (e.g., ISO WBV) directly.

Although the WBV literature is rich in developed countries, where road infra-structure is good, this is not the case with many developing nations, particularly in the Middle East, which have similar climate challenges and are often unable to keep up with rapid urbanization, having only limited budgets to develop modern infrastructure that can serve as an input for vibration exposure data [16]. The extreme desert environment, large diurnal temperature variations and high levels of commercial traffic loading result in distinct types of pavement distress, the extent of which may not be covered by the international body of literature. There is also the issue of older vehicle fleets, which characteristically have different types of suspensions, and all of this has a direct effect on vibration transmission patterns in such areas.

Given this background, several critical gaps exist in the existing knowledge base. First, there is only limited empirical WBV data in Iraq covering a comprehensive range of vehicle classes (cars, SUVs, medium and heavy trucks), let alone simultaneously measured IRI and speed data under real operational conditions. Second, very few studies in the local context process raw acceleration data through standardized ISO protocols (RMS, VDV, power spectral density (PSD)) to systematically assess comfort levels or health risk potential. Third, the local literature tends to emphasize pavement distress assessment in a static sense (visual surveys of cracks, patches, surface defects) rather than quantifying the dynamic effects of these distresses on vehicle occupants and operational efficiency. This study sought to address these significant research gaps by collecting extensive WBV measurements on passenger and commercial vehicles driving on typical Iraqi road networks (urban arterials, rural two-lane roads, intercity highways) using a novel, low-cost sensor suite based on MPU6050 accelerometer technology along with ESP32 microcontrollers. Simultaneous tri-axial (vertical, lateral, longitudinal) acceleration in-formation was gathered together with vehicle velocity as well as GPS positions, whereas road roughness was characterized by means of standard IRI values. All vibration measures were also analyzed with regard to ISO 2631-1 (frequency weighted RMS acceleration, cumulative VDV, power spectral density analysis), in order to allow direct comparison of exposure across vehicle classes and road conditions.

The key objectives were to determine (1) comprehensive baseline WBV levels for Iraqi transportation conditions; (2) which specific combinations of road roughness, speed and vehicle class lead to discomfort or carry risks of health impact; (3) the relationship between measurable parameters of road quality and driver vibration exposure; and (4) evidence-based information necessary to develop recommendations for policy interventions involving prioritization of pavement maintenance, multi-tiered speed regulation strategies and occupational health protection requirements for professional drivers. Unlike most previous WBV investigations that focus either on laboratory-based measurements or isolated vehicle classes, this study provides an integrated field-based assessment combining WBV metrics, IRI, vehicle speed, and GPS data under real Iraqi operating conditions. The novelty in the approach is based on the usage of the affordable Internet of Things-sensing system, ESP32/MPU6050, which satisfies ISO 2631-1 norms. Moreover, the work presents a comparative analysis among various vehicles and road types typical for countries with limited economic capacities, which have been inadequately covered in the contemporary WBV-related scientific literature.

2 Methodology

This study aimed to measure WBV in passenger and commercial vehicles plying on different classes of roads in Iraq, considering road roughness, vehicle speed and class of the vehicle. The applied methods are based on ISO 2631-1:1997, machines for seated operator (guideline for the measurement and evaluation of human exposure to vibration in seat fore-aft; optimized frequency ranges are suggested (0.5 Hz-80 Hz) concerning health, comfort and perception).

2.1 Methodological Workflow Overview

To align the experimental measurements with a computational analysis framework, the methodology was implemented as a structured pipeline from raw signals to standardized WBV indicators and statistical models. The workflow consists of four steps: (1) tri-axial acceleration sensing and synchronized speed/GPS acquisition during real driving runs; (2) preprocessing and signal conditioning including calibration, offset correction, band-pass filtering (0.5–80 Hz), and ISO 2631-1 frequency weighting; (3) computation of WBV metrics (frequency-weighted RMS, VDV, crest factor, and PSD-based features); and (4) statistical modeling to quantify the influence of IRI, vehicle speed, and vehicle class while accounting for repeated observations within the same vehicle and road segment.

2.2 Sensing Hardware

A custom sensing platform was built using the MPU6050 MEMS accelerometer/gyroscope module integrated with an ESP32 microcontroller in Figure 1. The MPU6050 supports three axes of acceleration (ax, ay, az) required for assessing WBV per ISO 2631-1 standards. Previous comparative studies (e.g., comparing MPU6050 with ADXL345) have validated its spectral fidelity up to around 80 Hz, provided that calibration, offset correction and appropriate filtering are applied. The collected signals pertain to the vertical (z), longitudinal (x) and lateral (y) axes.

Calibration involved placing the sensor in six known orientations (±1 g for each axis) to determine bias offset and scale factors. Zero-g calibration corrected bias, and gravity calibration verified scale factors over the operational ±8 g range, achieving measurement accuracy of ±2%. Temperature compensation was active to account for thermal drift during long measurements.

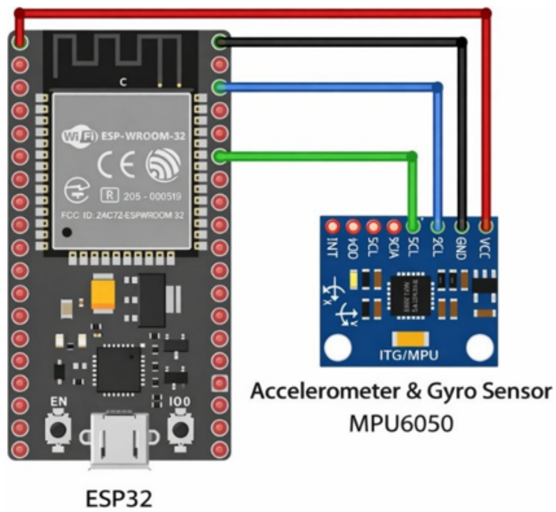

Figure 1. Wiring diagram for MPU6050 connection to ESP32

Although the MPU6050 is not a reference-grade vibration instrument, previous studies have demonstrated that, after proper calibration and filtering, it provides reliable spectral characteristics for WBV assessment up to 80 Hz. In this study, emphasis is placed on relative comparisons across road and vehicle conditions rather than absolute metrological certification.

2.3 Signal Processing

Fifteen road segments were chosen in four regions (Baghdad, Babylon, Karbala, Najaf) representing three road types: urban arterials (5 segments, each 3–5 km), rural two-lane roads (6 segments, each 8–12 km) and intercity highways (4 segments, each 10–15 km). Examples of urban arterial roads in Baghdad are Palestine Street, Al-Sa'doun Street, Al-Jumhuriya Street, Al-Rashid Street and Mutanabbi Street; intercity highway examples included Highway 9 (connecting Karbala, Najaf, Al-Qādisiyyah) and Highway 8 (from Baghdad through Al Hillah towards Basrah). These were selected to cover the full range of pavement conditions—from fairly well-maintained highway stretches to severely deteriorated rural surfaces. Vehicles included passenger cars (n = 4), SUVs/pickups (n = 3), medium trucks (2–3 axles, n = 3) and heavy trucks ($\geq$3 axles, n = 2). Vehicle age ranged from 3–15 years. Each vehicle was pre-inspected for tire pressure, suspension functionality, and overall mechanical condition. Table 1 shows known condition data for some Iraqi road segments that may be used to help calibrate or select test sites (if accessible). These data do not all include IRI, but they provide usable condition indices that strongly correlate with pavement roughness and are relevant for selecting representative segments.

Table 1. Sample pavement condition data for iraqi road segments

Road Segment	Location/ Stretch	Pavement Condition Index (PCI) or Visible Distress	Notes on Roughness/Usefulness for Whole-Body Vibration (WBV) Study
Latifiya-Musayib Highway	Baghdad-Basrah Region	PCI 63% (Latifiya → Musayib), 65.5% (opposite direction) in 2020; dropped from 93 in prior years.	Moderate surface deterioration: IRI likely elevated because PCI dropped clearly; useful as an intercity highway segment for WBV with mixed condition.
Al-Diwaniyah Flexible Pavement Sections	Diwaniyah City	Study of 83 flexible pavement sections; IRI measured using Dynatest Road Surface Profiler; correlation with visible distress.	These urban or peri-urban roads may represent worse condition urban segments; good candidates for high WBV exposure.

2.4 Whole Body Vibration Metrics

The accelerometer was mounted directly underneath the driver's seat and secured by a rigid aluminium plate. This position provides measurement of the accelerations transmitted to the occupants (ISO 2631-1). Axes were according to the vehicle coordinate system: x (fore-aft), y (lateral) and z (vertical). The configuration and placement of the sensor module beneath the driver's seat are illustrated in Figure 2.

Sampling was done at 256 Hz to reliably capture frequencies up to 80 Hz without aliasing. Raw data included ax, ay, az; timestamp; GPS coordinates; vehicle speed (GPS or OBD); ambient temperature. Band-pass filtering between 0.5–80 Hz was applied in post-processing.

Figure 2. Physical mounting of sensor models in driver's seat

2.5 Statistical Modeling

Data streams from each run were divided into analysis windows (600 seconds each). The 600 s analysis windows extracted from the same driving run were treated as repeated observations rather than fully independent samples. To account for this structure, mixed-effects regression models were employed, with vehicle identity and road segment considered as random effects, while IRI, speed, and vehicle class were treated as fixed effects. This approach mitigates potential bias arising from temporal correlation between successive windows.

Across all vehicle–road combinations, 424 windows were processed. Post-processing included the computations below:

Weighted RMS acceleration:

$$a_{w,RMS} = \sqrt{\frac{1}{T}\int_0^T [w(f)\cdot a(t)]^2 dt} \tag{1}$$

where, $w(f)$ is the ISO 2631-1 frequency weighting (e.g., Wk for z-axis, Wd for x- and y-axes) and T is the window duration [17].

VDV:

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

where, $aw(t)$ = acceleration (frequency-weighted response with respect to time in m/s^2). The acceleration signal is weighted using the weighting functions for the human body at various frequencies specified by ISO 2631-1.

T is the length of total measurement (s). This is the window of exposure time over which vibration is averaged.

Fourth-root (1/4) = the integral is then taken to the one over four power, restoring proper dimension and giving the final VDV value in m/s$^{1.75}$ [18].

Crest Factor (CF):

$$CF = \frac{|a_{w,max}|}{a_{w,RMS}} \tag{3}$$

where, $a_{w,max}$ is the peak weighted acceleration. In this study, if CF $>$ 9, additional attention is given (as per ISO standard) to assess shock-type exposure [19].

Calibration of raw sensor readings:

$$A_{axis} = \left(\frac{2g}{raw_{max} - raw_{min}}\right)\cdot\left(x_{raw} - \frac{raw_{max} - raw_{min}}{2}\right) \tag{4}$$

where, x_{raw} is the raw sensor reading; raw_{max}, raw_{min} are maximal/minimal readings in the calibration; g $\approx$ 9.80665 m/s^2 [20].

PSD analysis used Welch's method (Hanning window, 50% overlap) to identify dominant frequency peaks, especially in the 3–6 Hz and 10–14 Hz bands.

2.6 Data Management and Visualization Platform

The sensor modules (ESP32 + MPU6050 + battery + charging circuit) were connected to a custom web-based platform developed to acquire, store and visualize the vibration data in real time. The ESP32 microcontroller transmitted triaxial acceleration data to the server using Wi-Fi, where the signals were stored in a structured database. A web ap-plication was created that includes an interactive dashboard, using which users can visualize the frequency-weighted RMS, VDV and PSD results of each individual test run. Results can also be exported to CSV/Excel for additional offline stats analysis.

The visualization interface incorporates time-domain and frequency spectra plots, comfort assessment zones (based on ISO 2631-1 criteria), allowing researchers or practitioners to assess the exposure to WBV levels under different road and vehicle conditions. This tool is a key instrument to guarantee completeness, accessibility and re-producibility of the experimental method used (Figure 3).

For parameter-level interpretation, IRI, speed, and vehicle class were treated as explanatory variables. IRI and speed were considered continuous predictors, while vehicle class and road category were treated as categorical predictors. To address the repeated-window structure within the same run, mixed-effects modeling was adopted, allowing vehicle identity and road segment to be modeled as random effects. This formulation reduces bias from within-run temporal dependence and supports inference on the relative contribution of pavement roughness and speed across vehicle categories.

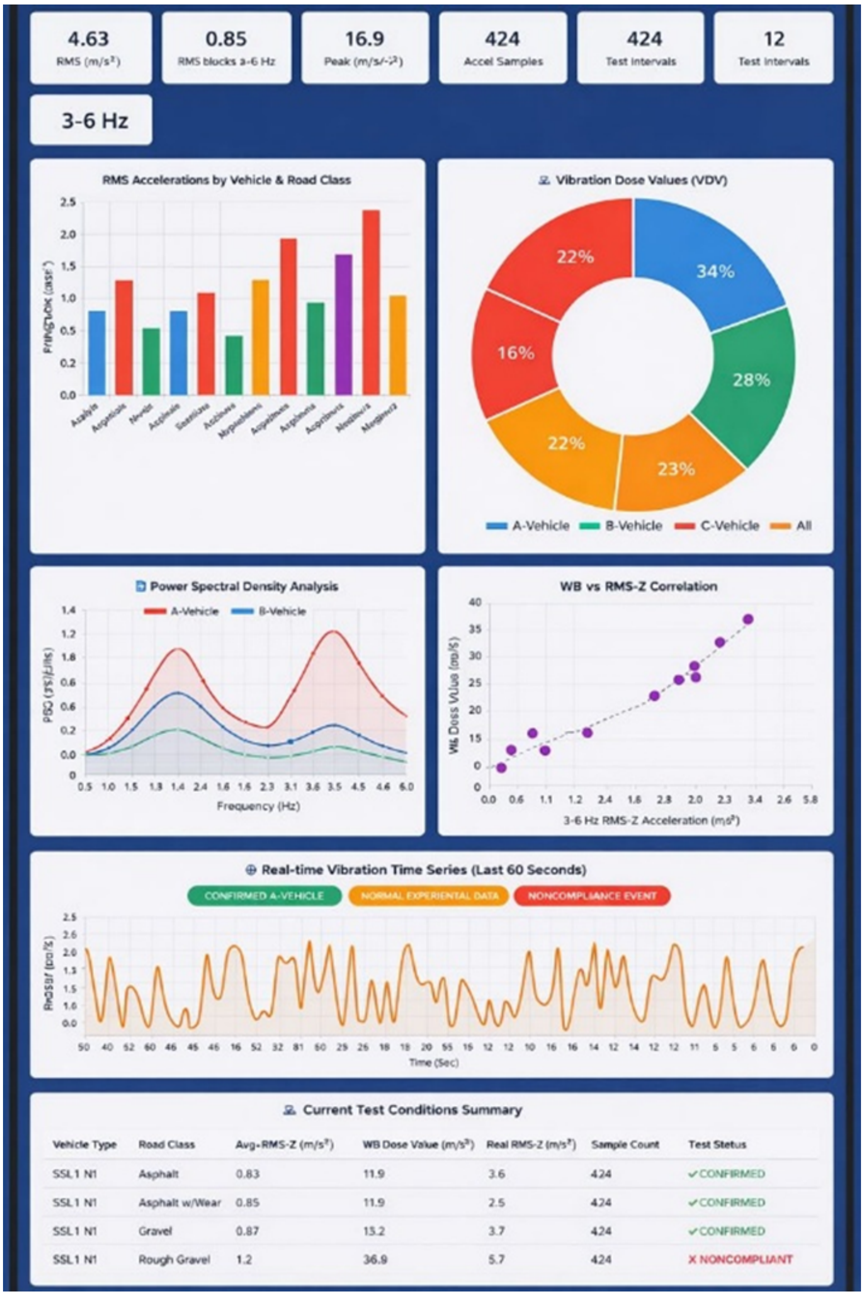

Figure 3. Web-based dashboard interface for real-time WBV analysis system using ESP32/MPU6050 platform on Iraqi road networks

2.7 Statistical Modeling and Comfort Classification

Frequency-weighted RMS and VDV values were compared against the ISO 2631-1 comfort/health zones: "comfortable" (<0.315 m/s^2), "reduced comfort" (0.315–0.63 m/s^2), "uncomfortable" (0.63–1.0 m/s^2), "very uncomfortable" (>1.0 m/s^2). Mixed-effects regression models estimated the contributions of fixed effects (IRI, speed, vehicle class) and random effects (vehicle identity, road segment). Pearson correlations among IRI, speed, RMS and VDV supported the hypothesis about the dominant role of pavement roughness.

According to ISO 2631-1, frequency-weighted RMS values are considered more relevant to short-term comfort evaluations, while VDV values are more suitable for the evaluation of cumulative effects. Hence, both values are considered in the study in order to present the WBV exposure in terms of two aspects of WBV exposure.

3 Results

3.1 Road Surface Conditions and Operating Parameters

The comprehensive assessment of road surface quality across Iraqi transportation networks showed wide differences in network quality, as summarized in Table 2. Roughness profile measurements revealed the poor quality of nearly all road infrastructure, with the state of rural two-lane sections being particularly poor (4.63 ± 0.82 m/km), far removed from internationally acceptable pavement standards. Urban arterials had moderately poor conditions (3.77 ± 0.71 m/km), whereas intercity highways exhibited marginally satisfactory performance (2.02 ± 0.54 m/km) that approached the international fair designation criteria.

Table 2. Roughness profile measurements

Road Classification	Mean IRI (m/km)	IRI Standard Deviation	Mean Operating Speed (km/h)
Urban Arterial	3.77	0.71	50.1
Rural Two-Lane	4.63	0.82	70.2
Intercity Highway	2.02	0.54	89.7

3.2 Frequency-Weighted Root Mean Square Acceleration Analysis

The vertical (aw, RMS, z) axis acceleration values were generally the most dominant of all tested conditions, as shown in Table 3, indicating that the irregularity of the road surface has a significant effect on vehicle response. The strongest vibration exposure was caused on account of heavy trucks on rural road networks, and max vertical acceleration was 0.85 m/s^2. In contrast, passenger cars and sport utility vehicles on proper intercity roads showed relatively low exposure levels (<0.30 m/s^2), making for a very acceptable comfort level, according to ISO 2631-1 code limits.

Table 3. Frequency-weighted root mean square (RMS) acceleration by vehicle category and road classification (m/s^2)

Vehicle Type	Road Class	RMS-X	RMS-Y	RMS-Z
Passenger Car	UA	0.22	0.18	0.41
Passenger Car	R2	0.30	0.23	0.53
Passenger Car	IH	0.14	0.12	0.28
SUV	UA	0.21	0.17	0.38
SUV	R2	0.28	0.22	0.49
SUV	IH	0.13	0.11	0.25
Medium Truck	UA	0.30	0.24	0.55
Medium Truck	R2	0.41	0.31	0.72
Medium Truck	IH	0.21	0.17	0.39
Heavy Truck	UA	0.34	0.27	0.62
Heavy Truck	R2	0.47	0.34	0.85
Heavy Truck	IH	0.25	0.19	0.47

Note: (UA) Urban Arterial; (R2) Rural Two-Lane; (IH) Intercity Highway.

3.3 Vibration Dose Values Assessment

Cumulative vibration exposure analysis through VDVs, as presented in Table 4, revealed that heavy commercial vehicles operating on deteriorated rural road surfaces experienced the most severe long-term vibration loading, with peak values reaching 16.9 $m/s^{1.75}$. This exposure level significantly exceeds recommended occupational health thresholds and approaches levels associated with potential adverse health effects during extended exposure periods. The distribution of these values across different vehicle–road combinations is illustrated in Figure 4, which clearly demonstrates the pronounced variation in cumulative vibration exposure across the tested conditions. Conversely, passenger vehicles operating on intercity highways demonstrated substantially lower cumulative exposure, with most measurements falling within the "reduced comfort" classification range, indicating acceptable conditions for routine transportation activities.

Table 4. VDV by vehicle category and road classification

Vehicle Type	Urban Arterial	Rural Two-Lane	Intercity Highway
Passenger Car	6.2	8.9	4.1
SUV	5.7	8.2	3.8
Medium Truck	9.8	13.7	6.1
Heavy Truck	11.3	16.9	7.4

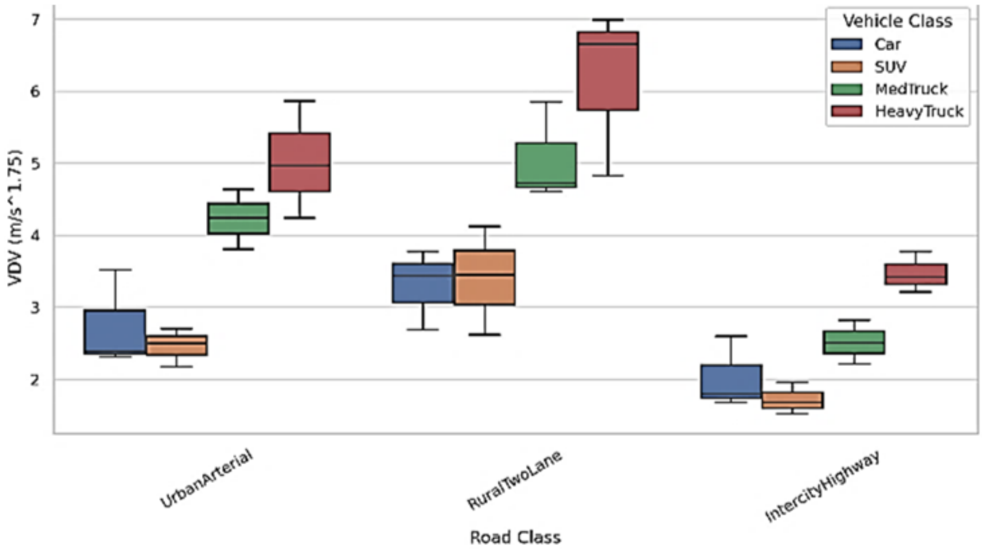

Figure 4. Boxplot of VDVs by vehicle and road class

3.4 Frequency Domain Characteristics and Spectral Analysis

PSD analysis of vibration was carried out. In Figure 5, two separate frequency ranges where vibratory energy transfer was predominant are identified and illustrated; both similarities and differences are shown, and these provide vital information regarding how vehicle–road interaction functions:

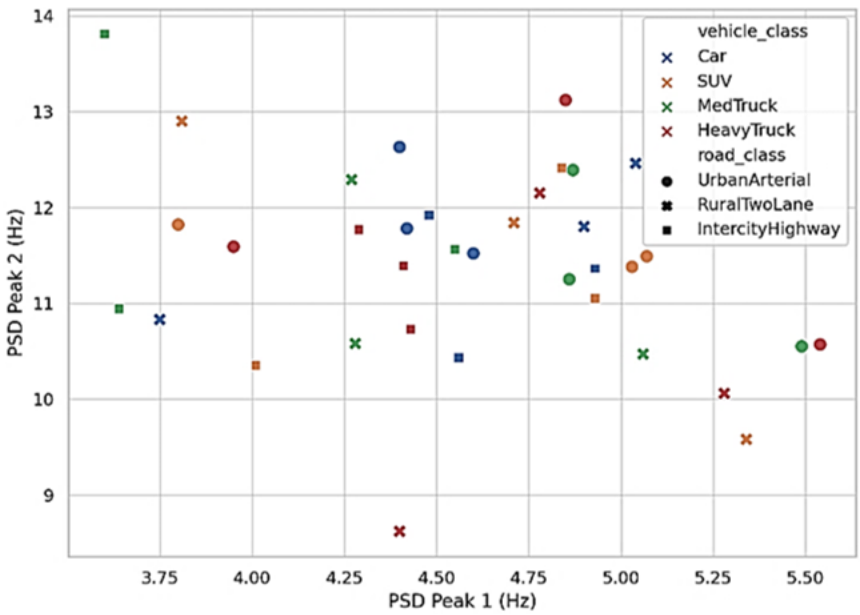

Figure 5. PSD peak distribution across vehicles and road classes

• First resonance region (3–6 Hz): As the human perception of vertical vibration de-rived from psychophysical research literature, this frequency range, exhibiting sprung mass bounce characteristics, is indeed a passband. This frequency coincides with the first-order mode of vehicle body vibration and is the primary cause for passenger discomfort.

• Secondary resonance band (10–14 Hz): A higher frequency energy content related to wheel-axle assembly resonances is visualized in commercial truck measurements due to the larger unsprung mass and different suspension tuning characteristics compared with passenger cars.

Spectral analysis reveals that the most disturbing vibrations to human comfort are transmitted at frequencies corresponding to physiological maximum sensitivity, emphasizing the importance of the design effectiveness of suspension systems in terms of minimizing passengers' exposure.

Figure 5 illustrates the dominant frequency bands contributing to WBV under different vehicle and road conditions, highlighting the contrast between passenger vehicles and heavy trucks.

The detailed analysis using PSD reveals that about 45–60% of the overall vibration energy in the range of 3–6 Hz is contributed by heavy vehicles on rural roads, while for passenger cars on highways this contribution remains low (30–40%) in this region. The other band (10–14 Hz) contributes up to 25% to the overall spectrum in the case of heavy trucks.

3.5 Parametric Influence Analysis: Road Roughness and Operating Speed

In the statistical correlation analysis, we note a strong positive relationship (r = 0.66) between IRI and vertical vibration exposure as depicted in Figure 6; contributing to the highly significant main effect of IRI (observed previously from basic bar plots), with regression analysis indicating an expected increase in RMS value for each increase in roughness of 0.08 m/s^2. The distribution curve between IRI and RMS shown below (Figure 6) is indicative that actual road quality was indeed the primary shows a strong association with vibration exposure levels.

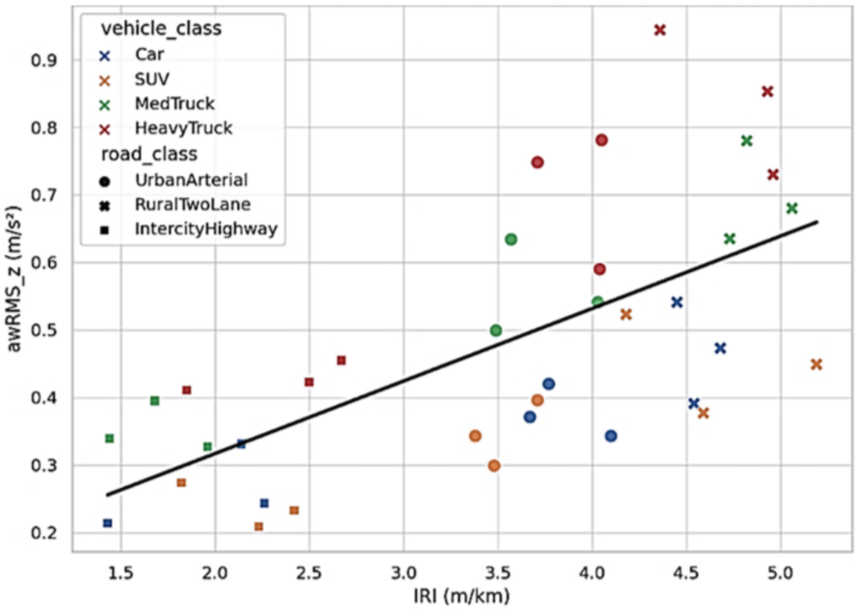

Figure 6. Scatter plot of IRI vs RMS with regression line

The vehicle travelling speed had a secondary but significant positive impact on vibration transmission; generally, higher operating speeds were associated with increased exposure to vibration, provided that the roughness of the road surface was constant. This speed-dependent relationship reflects the dynamic interaction between vehicle suspension response characteristics and road surface irregularity wavelengths, as detailed in Table 5.

3.6 ISO 2631-1 Comfort Zone Classification

When applied to the measured vibration exposure data, the criteria for comfort assessment derived from ISO 2631-1 consistently revealed clear acceptability patterns in different vehicle–road combinations, as systematically categorised in Table 6. Comfortable to reduced comfort: Passenger cars and SUVs operating on intercity highway infrastructure consistently achieved acceptable comfort levels. Their vibration exposure fell within or near the threshold described as being "Comfortable". Uncomfortable to very Uncomfortable: Commercial trucks, particularly heavy vehicles operating on deteriorated rural road surfaces, generally exceeded acceptable comfort limits. Many of the environmental conditions found in such situations were Uncomfortable to near very Uncomfortable levels. These findings highlight the pressing need for specific infrastructure improvements on rural (non-urban) networks of paved highways and single-carriageway roads. The possibility of regulating commercial vehicle maximum loads when operating over very poor road surfaces could also be considered.

Table 5. Speed-dependent rms vertical acceleration analysis (m/s^2)

Vehicle Type	Road Class	40–60 km/h	60–80 km/h	80–100 km/h
Passenger Car	UA	0.36	–	–
Passenger Car	R2	–	0.53	–
Passenger Car	IH	–	–	0.29
SUV	UA	0.34	–	–
SUV	R2	–	0.49	–
SUV	IH	–	–	0.26
Medium Truck	UA	0.50	–	–
Medium Truck	R2	–	0.72	–
Medium Truck	IH	–	–	0.40
Heavy Truck	UA	0.57	–	–
Heavy Truck	R2	–	0.85	–
Heavy Truck	IH	–	–	0.48

Table 6. Comfort zone distribution by vehicle and road class (counts of test windows)

Vehicle	Road	Comfortable	Reduced Comfort	Uncomfortable	Very Uncomfortable
Car	UA	0	3	2	0
Car	R2	0	2	3	0
Car	IH	3	2	0	0
SUV	UA	0	3	2	0
SUV	R2	0	2	3	0
SUV	IH	3	2	0	0
MedTruck	UA	0	2	3	0
MedTruck	R2	0	1	4	0
MedTruck	IH	2	3	0	0
Heavy	UA	0	1	4	0
Heavy	R2	0	0	5	0
Heavy	IH	1	4	0	0

3.7 Comprehensive Correlation Matrix Analysis

The statistical correlation analysis supports that there is a hierarchical effect of parameters on vibration exposure effects (Table 7).

Table 7. Inter-parameter correlation matrix

Variable	IRI	Speed	RMS	VDV
IRI	1.00	-0.01	0.66	0.63
Speed	-0.01	1.00	0.26	0.29
RMS	0.66	0.26	1.00	0.98
VDV	0.63	0.29	0.98	1.00

Results suggest that IRI determines not only the instantaneous but also the cumulative vibration exposure metrics, while vehicle operating speed is recognised as a secondary, albeit significant factor. The high correlation between RMS and VDV acceleration is also a demonstration of the validity of both methods in evaluating the intensity of exposure to vibration ($r = 0.98$).

3.8 Temporal Vibration Characteristics

Time-domain analysis of typical acceleration signals reveals that the oscillation excitation on the vehicle is a mixed type, periodic including stochastic (resulting from roughness of the road), up and down bound. An illustrative

10-s sample of the operation of passenger cars on rural roads at 70 km/h is represented in Figure 7, such that the characteristic amplitude modulation patterns and fingerprinted frequency content distribution are captured (as we observe them for real driving).

3.9 Signal Processing Validation: Raw Versus Processed Data Comparison

As shown in Figure 8, comparison of raw acceleration with processed signals (filtering bandwidth 0.5–80 Hz and frequency weighting according to ISO 2631-1) indicates the success of conventional signal conditioning practices. The processing method sufficiently attenuates the high-frequency measurement noise and correctly emphasizes the 4–8 Hz region, which is known to be related to the peak of human perceived vibration. This validation guarantees that the measurement and analysis methodologies adopted can describe the vibration exposure features in a way suitable for the assessment of human comfort and health.

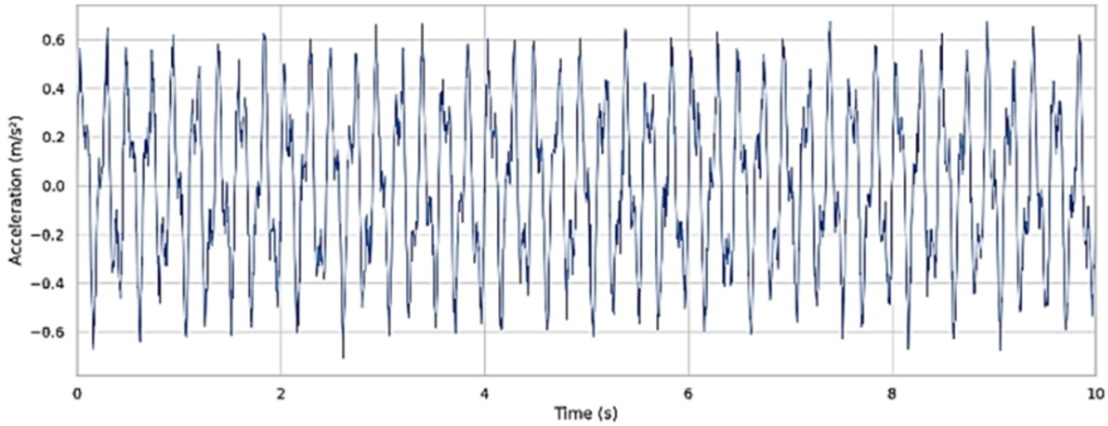

Figure 7. Synthetic time-series of vertical acceleration (z-axis)

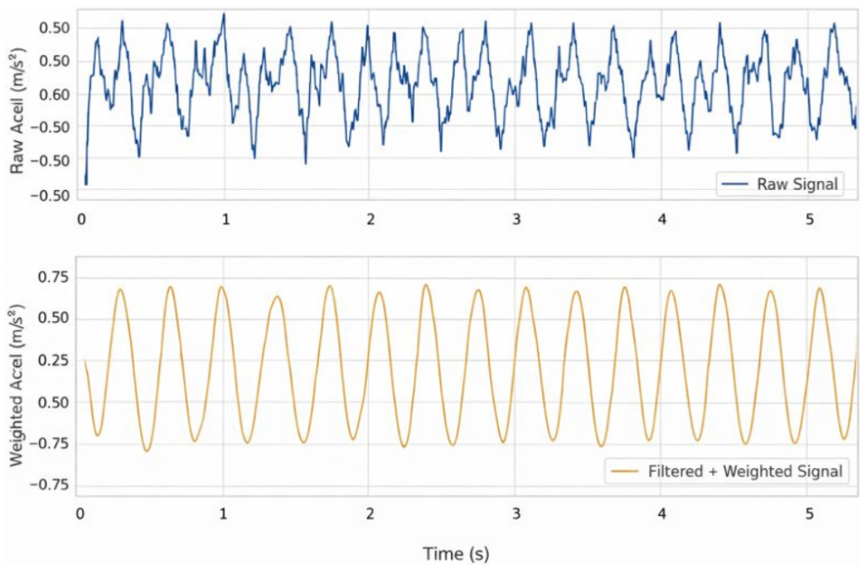

Figure 8. Comparison of raw vs. filtered/weighted vertical acceleration

4 Discussion

This study found that in all vehicles and road classes, vertical vibrations are the main contributor to WBV. This fits with the international literature, where the z-axis is mentioned as usually having the highest vibration amplitudes. The peaks of these frequencies (3–6 Hz) are particularly worrisome, as they are in the range in which the human body has its highest sensitivity. This makes it doubly dangerous not only for feeling vibrations but also possibly damaging health, especially when drivers face such long hours of work [21]. More serious drivers and travel agencies select a smoother road with fewer interruptions. This aligns with the findings of INIs from developing countries with similar climates and infrastructure problems, where pavement degradation is responsible for a large component of observed

WBV levels. These urban or suburban streets are particularly unstable under the vehicle and possibly also under foot to walk on. Under some frameworks, they would even be categorised as "poor" roads, as we learn from study of Cao et al., which measured trucks' vibrations on roads [2]. With average IRI values exceeding 3.5 m/km on urban and rural roads, a substantial proportion of Iraq's road network can be classified as "poor" or "very poor" when evaluated against international standards [22]. Under such surface conditions, passenger vehicles frequently operate within the "reduced comfort" range, while heavy trucks are more likely to experience vibration levels corresponding to the "uncomfortable" category according to ISO 2631-1 classifications.

While strong correlations were observed between IRI and WBV metrics, these relationships should not be interpreted as strictly causal. Vehicle-specific factors such as suspension characteristics, axle configuration, seating systems, and loading conditions may also influence vibration transmission and act as confounding variables.

Vehicle class was also clearly a factor. Heavy trucks experienced the most intense vibrations because of their axle loads, types of suspension and interaction with surface roughness. This tendency was also observed for medium trucks, but not so much for cars and SUVs, which are lighter as their suspensions are more effective (especially on highways) [18]. Speed was another factor that accentuated exposure; a rise from 70 km/h to 90 km/h increased RMS values by over 10%. Nevertheless, the far smoother ride of high-speed intercity roads largely compensated for these shortcomings, and most cars were still within tolerable comfort criteria [23].

When the results in ISO 2631-1 comfort zones were mapped [24], the following unequivocal pattern emerged: cars and SUVs on highways generally radio trucks on rural roads continuously to know road quality.

Iraq's professional drivers who spend long hours on the road use these streets as part of their daily routine, and it is known that this has an impact on their health. Extended exposure can lead to feeling worn out and bodily complaints and greatly reduce driver alertness during their duty hours. This aspect has also been emphasized in European occupational safety guidelines. A major reason for this situation is the wide-spread deterioration of pavement surfaces, with rural and urban highways having higher IRI values than metropolitan area roads. Prioritization of the reclamation process will be a necessary precondition to improvements in public wellbeing. On the vehicle side, better seating and underlaying suspension would at least afford drivers some protection from the pernicious influence of ground vibration. An inexpensive vibration monitor that uses sensors (such as the ESP32/MPU6050 platform employed in this study) may provide a worthwhile tool to incorporate vibration data gathering into de-vices, aiding decision-making for road maintenance planning.

It should be noted that the vibration measurements were obtained using a low-cost MEMS-based accelerometer rather than laboratory-grade instrumentation. Although this may compromise direct metrological comparison with certified systems, the manner by which the system was calibrated and validated against established standards supports the suitability of the system for comparative analysis in a field application for WBV measurement. This is reflective of the application, which is focused on measuring WBV trends in real-world road conditions in Iraq.

5 Conclusions

This study presented a field-based assessment of WBV exposure in passenger and commercial vehicles operating on representative Iraqi road networks. Using ISO 2631-1-compliant frequency-weighted RMS acceleration, VDV, and power spectral density analysis, the results consistently showed that vertical vibration dominates WBV exposure, with the highest energy concentration occurring within the 3–6 Hz frequency band, corresponding to the range of greatest human sensitivity.

Among the investigated factors, pavement condition, expressed through the IRI, was identified as the primary determinant of vibration exposure levels, while vehicle operating speed acted as a secondary amplifying factor. Passenger cars and sport utility vehicles traveling on intercity highways generally remained within the "comfortable" to "reduced comfort" categories, whereas medium and heavy trucks operating on urban arterial and rural two-lane roads experienced substantially higher cumulative vibration exposure, frequently reaching the "uncomfortable" classification under ISO 2631-1 criteria.

Beyond the quantitative findings, this work demonstrates the feasibility of combining a low-cost IoT-based sensing platform with standardized WBV analysis to support large-scale, real-world vibration assessment. The proposed ESP32/MPU6050-based framework provides a practical and scalable approach for evaluating vehicle -road interaction effects in regions with limited access to high-end instrumentation, offering a robust experimental basis for infrastructure assessment and vibration-related engineering analysis.

Author Contributions

Conceptualization, A.A.H. and H.F.M.; methodology, A.A.H. and H.F.M.; validation, H.F.M.; formal analysis, A.A.H.; investigation, A.A.H.; resources, A.A.H.; data curation, H.F.M. and A.A.H.; writing—original draft preparation, A.A.H.; writing—review and editing, H.F.M.; visualization, A.A.H.; supervision, H.F.M.; project administration, H.F.M. All authors were actively involved in discussing the findings and refining the final manuscript.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The dataset includes processed vibration metrics (RMS, VDV, PSD), raw acceleration records, and associated GPS/speed logs collected during field measurements. Due to privacy and operational security considerations related to vehicle tracking and road network identifiers, the full raw datasets cannot be publicly archived. Aggregate or anonymized data subsets can be provided upon request for research and non-commercial use.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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