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Smartphone-based evaluation of urban cycling pavement types and rider comfort

Nicolly Novais Sousa
Universidade Tecnológica Federal do Paraná, Pato Branco, Paraná, Brasil
nicollysousa@alunos.utfpr.edu.br

Igo Brasil Monteiro
Universidade Tecnológica Federal do Paraná, Pato Branco, Paraná, Brasil
imonteiro@alunos.utfpr.edu.br

Giovane Vaz Costa
Universidade Tecnológica Federal do Paraná, Pato Branco, Paraná, Brasil
giovanec@alunos.utfpr.edu.br

Marina Myszak Biedacha
Universidade Tecnológica Federal do Paraná, Pato Branco, Paraná, Brasil
marinabiedacha@alunos.utfpr.edu.br

Vinicius Pegorini
Universidade Tecnológica Federal do Paraná, Pato Branco, Paraná, Brasil
vinicius@utfpr.edu.br

Jesner Sereni Ildefonso
Universidade Estadual de Maringá, Maringá, Paraná, Brasil
jsildefonso@uem.br

Fabio Zanchetta
Universidade de Brasília (UnB), Brasília, Distrito Federal, Brasil
fabio.zanchetta@unb.br

Danilo Rinaldi Bisconsini
Universidade Tecnológica Federal do Paraná, Pato Branco, Paraná, Brasil
bisconsini@utfpr.edu.br

ABSTRACT

The assessment of cycling pavements is vital for promoting comfort and safety in the city, encouraging daily bicycle use as a sustainable mode of transport. This study evaluated ride quality on three urban pavement types: asphalt, Portland Cement Concrete (PCC), and pavers, introducing an objective, low-cost approach utilizing smartphone accelerometer and GNSS data. The methodology comprises field tests where vertical accelerations were recorded at the handlebar and seat for time and frequency analysis. Comfort was classified using an adaptation of ISO 2631-1 and NHO-10 standards to evaluate whole-body and hand–arm vibration. The results indicate that paver generated the highest vibration amplitudes, while asphalt and PCC exhibited significantly lower values. Frequency analysis revealed predominant peaks near 15 Hz. In conclusion, the study confirms smartphones as reliable tools for assessing pavement conditions, providing objective data to support urban infrastructure management.

KEYWORDS: Smart Cities. Urban Mobility. Cycling pavements. Vibration comfort. Urban infrastructure management.

INTRODUCTION

Cycling has gained increasing prominence worldwide as a sustainable mode of urban transportation, recreation, and sport, particularly in cities seeking to reduce emissions, improve public health, and enhance mobility efficiency. As cycling networks expand in urban environments, the quality of cycling infrastructure becomes a decisive factor influencing user comfort, safety, and route attractiveness. Among infrastructure components, pavement surface condition plays a central role, since surface irregularities directly affect vibration levels transmitted to cyclists and may lead to discomfort, fatigue, and reduced control during riding (Olieman et al., 2012; Doria et al., 2021)..

In urban contexts, inadequate cycling pavement conditions represent not only a comfort issue but also a management challenge for cities. Poor surface quality may discourage daily bicycle use and compromise the effectiveness of public investments in active transportation infrastructure. Previous studies have shown that different pavement typologies produce distinct vibration responses, with continuous surfaces such as asphalt generally offering smoother rides, while modular or jointed pavements tend to generate higher vibration amplitudes due to surface discontinuities (Hölzel et al., 2012; Ahmed et al., 2023).

Despite the recognized importance of pavement-induced vibrations for cycling comfort, their systematic evaluation in real urban environments remains limited by methodological constraints. Conventional approaches often rely on laboratory experiments or dedicated external sensors, which are costly, logistically demanding, and challenging to apply at the city scale. In this context, smartphones have emerged as promising tools for assessing cycling infrastructure. Equipped with accelerometers and Global Navigation Satellite System receivers, smartphones enable low-cost, flexible, and widely deployable data collection. Recent studies have demonstrated that smartphone-based measurements can reliably capture vibration signals relevant to cycling comfort, provided that sensor placement and data acquisition parameters are adequately considered (Bíl et al., 2015; Cafiso et al., 2022). This study proposes the use of this tool for evaluating cyclist comfort.

Literature Review

The quality of the riding surface is a crucial factor in determining the comfort and safety of cyclists. Irregular or poorly maintained surfaces generate excessive vibrations, which, when experienced over extended periods, can lead to long-term health issues (Doria et al., 2021). Beyond physical health, surface conditions influence the attractiveness of the mode; inadequate pavements reduce riding comfort and create distractions that compromise stability (Wijerathne et al., 2018).

Research indicates that the relationship between pavement type and vibration levels is significant. Modular or cobbled pavements, such as interlocking concrete blocks (pavers), typically generate higher vibration levels and lower comfort scores compared to continuous surfaces like asphalt or cast concrete (Hölzel et al., 2012; Ahmed et al., 2023). These elevated vibrations are primarily attributed to surface irregularities and joint discontinuities, which are typical of modular systems and may contribute to hand-arm fatigue (Munera et al., 2015; Gao et al., 2018).

The comfort experienced by a cyclist is intrinsically correlated to the vibrations transmitted through contact points. Two international standards are used to quantify these effects: ISO 2631-1 (1997), providing criteria for assessing Whole-Body Vibrations (WBV), typically measured at the bicycle seat (Gao et al., 2018; Cafiso et al., 2022); and ISO 5349-1 (2001) / NHO-10 (2013), defining methods for analyzing Hand-Arm Vibrations (HAV), focusing on the vibrations transmitted through the handlebars.

These standards enable the identification of critical sections that require maintenance and repair. While the International Roughness Index (IRI) is a standard for motorized vehicles, several authors argue it is insufficient for cycling infrastructure. Recent studies (Niska et al., 2022; Sousa et al., 2022) demonstrate that the IRI lacks a strong correlation with cyclists' actual perception, as it was not designed for low-speed vehicles with minimal suspension systems (Cafiso et al., 2022).

Traditionally, pavement conditions are evaluated through visual surveys or subjective assessments, both of which are labor-intensive and dependent on expert judgment. To overcome these limitations, the use of smartphone sensors, specifically accelerometers and Global Navigation Satellite System (GNSS) receivers, has emerged as a cost-effective alternative (Ahmed et al., 2024).

Studies by Grouios et al. (2022) demonstrate that modern smartphone accelerometers are reliable for estimating human body motion and vibration. However, the literature highlights technical challenges that must be addressed, including sensor calibration, sensitivity variations between models, and the impact of smartphone positioning on the bicycle (Vezio et al., 2024; Zang et al., 2018).

To objectively quantify comfort, different parameters derived from acceleration data are utilized. The Root Mean Square (RMS) of vertical accelerations is widely accepted as an indicator of vibration severity (Olieman et al., 2012; Cafiso et al., 2022). Other metrics, such as the Square Root of the Mean Squares (RMQ), crest factor, and shock content quotient, have also been tested for their ability to differentiate hand-transmitted vibrations (Drouet et al., 2022).

A critical debate in the literature concerns the domain of analysis. While time-domain analysis is common, Olieman et al. (2012) suggest that frequency-domain analysis is more insightful, as it reveals harmonic signals hidden in time-series data. However, the reliability of frequency analysis is highly dependent on the sampling rate. Many previous studies relied on low rates, such as 20 Hz to 50 Hz (Bíl et al., 2015; Nuñez et al., 2020; Cafiso et al., 2022), which may limit the reconstruction of high-frequency signals.

From an urban management perspective, smartphone-based sensing opens new possibilities for continuous monitoring of cycling infrastructure and integration with Geographic Information Systems (GIS), supporting maintenance prioritization and network-level analyses (Gao et al., 2025). However, existing studies often lack explicit formalization of research problems and objectives related to urban cycling pavement evaluation, and few investigations jointly analyze vibrations transmitted to both the cyclist's hands and body while linking the results to practical applications in city-scale infrastructure management (Zang et al., 2018)..

In this context, the research problem addressed in this study can be stated as follows: how can cycling pavement comfort in urban environments be objectively assessed using low-cost, widely available tools, while accounting for vibrations transmitted to different contact points between the cyclist and the bicycle? Based on this problem, the central research questions are as follows: How do different urban cycling pavement types influence vibration amplitude and frequency characteristics? Whether vibration levels transmitted to the handlebars and seat differ significantly. To what extent can smartphone-based measurements support the classification of comfort and pavement management in cities?

Accordingly, the objective of this study is to develop and apply an objective smartphone-based methodology for evaluating cycling pavement comfort in urban environments. To achieve this objective, the study performs a comparative assessment of asphalt, Portland cement concrete pavement, and interlocking concrete block pavement, based on the analysis of vertical accelerations measured at both the handlebar and the seat. The evaluation incorporates vibration characteristics in both the time and frequency domains, allowing for a comprehensive characterization of pavement-induced discomfort under real urban cycling conditions.

The justification for this research lies in its contribution to urban infrastructure management, as it proposes a low-cost and replicable approach that overcomes practical limitations commonly reported in literature. Many existing methods for evaluating cycling pavement comfort rely on external sensors or specialized instrumentation, which are often costly, complex to operate, and difficult to deploy at the city scale. By relying exclusively on sensors embedded in smartphones, the proposed methodology reduces technical and financial barriers, enabling broader application under real urban conditions. This approach supports municipalities and planners in identifying priority maintenance sections and improving user experience across cycling networks. Additionally, integrating vibration-based indicators with spatial data provides a practical foundation for incorporating cycling comfort into pavement management systems at the city scale.

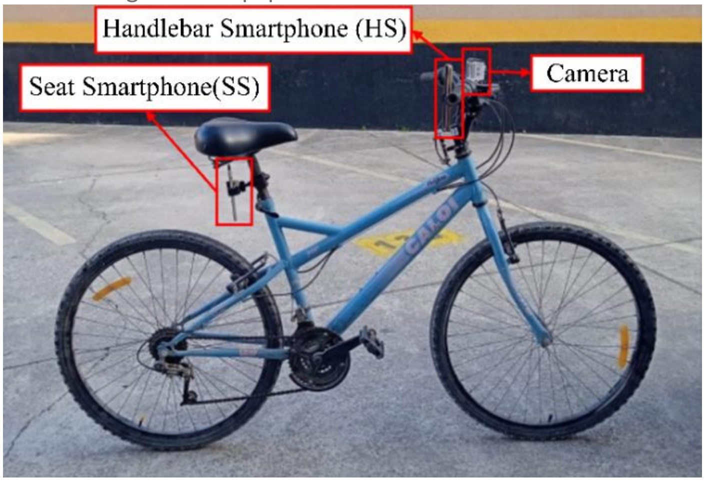
MATERIALS AND METHODS

Definition of tools and experimental sections

For data collection, this study selected the Phyphox application, developed by RWTH Aachen University, due to its versatility in simultaneously recording data from multiple embedded sensors. Two smartphones were employed to capture dynamic and positional data: an Apple iPhone 13 mounted on the handlebars (HS) and a Motorola Moto G22 attached beneath the seat (SS). To ensure high temporal resolution for accurate vibration profile reconstruction, acceleration signals were recorded at the devices' operational limits—100 Hz for the HS and 200 Hz for the SS—while GNSS coordinates were logged at a rate of 1 Hz.

The experiments utilized a Caloi Ultra Feminino bicycle with 26-inch wheels, supplemented by an Eken H9r 4K action camera to provide high-resolution visual records of the routes. All devices were securely mounted in predefined positions to ensure stability and minimize measurement interference caused by vibration coupling. Additionally, the selection of two smartphones with distinct operating systems and sensors was a strategic methodological choice to compare performance between devices, an approach considered relevant by Grouios et al. (2022) and Vezio et al. (2024).

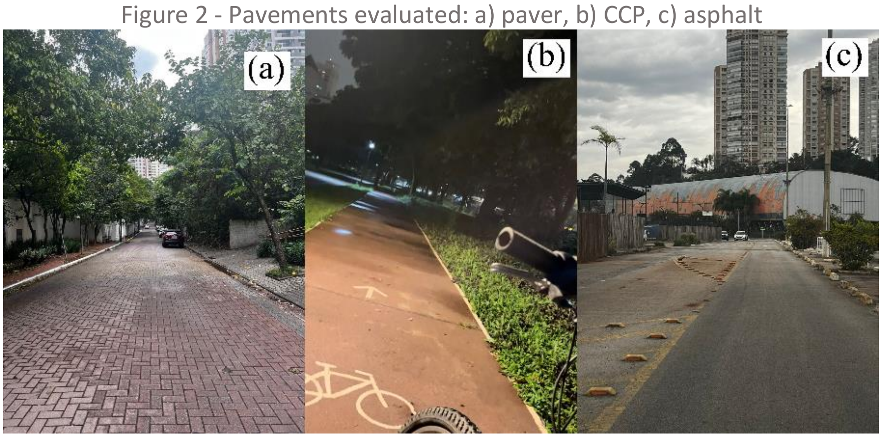
Figure 1 – Equipment used for data collection



Field data collection

Data collection occurred in São Paulo, Brazil, across three 1,000-meter-long sections with different surface types. Section 1, paved with concrete blocks (pavers) (Figure 2a), is located between Fábio Lopes dos Santos Luz Street and Itanhatim Street, in the Vila Andrade district (initial coordinates: -23°37'57"; -46°43'43.826"; final coordinates: -23°37'52"; -46°43'46.913"). Section 2, surfaced with Portland Cement Concrete (PCC) slabs (Figure 2b), corresponds to a segment of the Parque do Povo cycleway (initial and final coordinates: -23°35'19"; -46°41'18.485"). Section 3 features an asphalt surface (Figure 2c) and is located along Avenida da Ligação (initial coordinates: -23°37'33"; -46°43'0.45"; final coordinates: -23°37'35"; -46°42'57.587").

Figure 2 - Pavements evaluated: a) paver, b) CCP, c) asphalt



During data collection, efforts were made to maintain a constant cycling speed; however, no target speed was imposed, prioritizing a safe and comfortable ride for the researcher across all routes. The mean overall cycling speed was 10.92 km/h, with slight variations between sections: 11.97 km/h on the paver pavement, 10.26 km/h on the PCC pavement, and 10.53 km/h on the asphalt pavement.

The choice of not setting a standard speed, maintaining natural and safe driving, followed the approach adopted by Cafiso et al. (2022) and Ahmed et al. (2024), who emphasize that the perception of vibrational comfort can be affected by speed, but should be evaluated under conditions representative of real use. Furthermore, simultaneous collection was intended to provide a robust comparative basis, as indicated by Lee et al. (2025).

Section division

The collected datasets, comprising dates, vertical accelerations, and geospatial coordinates, were organized and formatted for integration with the Roadify processing platform. Within the software, the 1,000-meter test sections were subdivided into 10-meter segments to facilitate high-resolution analysis, a methodology consistent with that of Cafiso et al. (2022). This specific segment length was selected because pavement wavelengths between 1 and 5 meters are most indicative of cyclist discomfort, whereas wavelengths exceeding 10 meters have a negligible impact on perceived ride quality (Benbow et al., 2006; Larsson et al., 2023).

Following segmentation, the platform generated descriptive statistical parameters by averaging acceleration samples within each 10-meter subsection, resulting in 100 characterizing values per test section. The analysis focused exclusively on the vertical acceleration component (y-axis), consistent with the smartphones' mounting orientation. This approach effectively isolates the structural response to pavement surface irregularities by minimizing interference from lateral or longitudinal movements associated with steering, pedaling, and balancing adjustments. The average vertical accelerations for each segment were computed according to Equation 1.

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \qquad (1)$$

Where:
RMS = root mean square (m/s²).
n = number of acceleration samples in each segment.
x_i = vertical accelerations collected in each segment (m/s²).

Before computing the RMS values, a fifth-order high-pass Butterworth filter with a cutoff frequency of 0.5 Hz was applied to eliminate the influence of static gravitational acceleration.

Ride comfort classification

Following the computation of RMS acceleration values for each segment, the results were categorized based on the comfort criteria established in ISO 2631-1 (1997). The original standard defines comfort across six categories, with thresholds set sequentially at < 0.315 m/s² (Comfortable), 0.315 to 0.63 m/s² (Slightly uncomfortable), 0.5 to 1.0 m/s² (Fairly uncomfortable), 0.8 to 1.6 m/s² (Uncomfortable), 1.25 to 2.5 m/s² (Very uncomfortable), and > 2.5 m/s² (Extremely uncomfortable). These thresholds and the descriptive comfort categories were adjusted and simplified to five levels to align with the specific vibration conditions observed in cycling pavements. The modified classification framework, which relaxes the "Comfortable" threshold to < 0.5 m/s² to enhance its applicability to bicycle vibration analysis, is presented in Table 1.

Table 1. Ride comfort classification according to ISO 2631-1 adapted

Parameter for comfort	
RMS (m/s²)	Classification
< 0.5	Comfortable
0.5 – 1.0	Slightly uncomfortable
1.0 – 1.6	Fairly uncomfortable
1.6 – 2.5	Uncomfortable
> 2.5	Very uncomfortable

The adaptation of ISO 2631-1 (1997) in this study was guided by two primary considerations. First, the original version of the standard presents overlapping numerical ranges between adjacent comfort levels, which can hinder the establishment of an unambiguous and reproducible classification. Second, the number of comfort categories was reduced from six to five to produce a more balanced and symmetrical scale incorporating an intermediate comfort class. This refinement facilitates clearer interpretation and supports more straightforward decision-making processes within Pavement Management Systems (PMS). Comparable adjustments to this standard have also been implemented in related research focusing on cyclist vibration comfort (Nuñez, Bisconsini, & Silva, 2020; Bisconsini et al., 2021; Farias et al., 2023). ISO 2631-1 (1997) states that comfort can be assessed by weighting RMS acceleration according to the corresponding frequency bands (Aeq), as expressed in Equation 2.

$$Aeq = \sqrt[2]{\frac{\frac{1}{n}\sum_{i=1}^{n} x_i^2 \times Wk_i}{\sum_i^n Wk_i}} \quad (2)$$

Where:
Aeq = frequency-weighted RMS acceleration for comfort evaluation (m/s²).
x_i = acceleration value in frequency band i (m/s²).
Wk_i = frequency weighting factor for band i — dimensionless.
n — number of frequency bands considered — dimensionless, integer.

In addition to the Whole-Body Vibration (WBV) analysis, the Hand–Arm Vibration (HAV) transmitted through the bicycle handlebar was also evaluated. Continuous exposure to such vibrations for prolonged periods can pose health risks to cyclists (Fundacentro, 2012). Therefore, ISO 5349-1 (2001) — published in Brazil as NHO-10 (2013) — was applied, establishing that acceleration values must be weighted according to a frequency-dependent filter. This weighting is crucial since specific frequency ranges are Zang more harmful to human health (Griffin, 1990; Bovenzi, 2010). Accordingly, the weighting filter Hw was applied as shown in Equation 3.

$$H_w = \frac{(s + 2\pi * 15.915) * 2\pi * 15.915^2}{\left(s^2 + 2\pi * 15.915 * \frac{s}{0.64} + 4\pi^2 * 15.915^2\right) * 15.915} \quad (3)$$

The application of Eq. 3 required an adaptation of the original calculation described in NHO-10 (2013), since the frequencies of the accelerations occurring during a cyclist's ride are not constant. Therefore, a Fourier Transform was performed using the Roadify software based on acceleration and time data. This process yielded the amplitude values associated with each acceleration frequency. The weighted mean frequency was computed to apply a single representative frequency to the filter, with each weight corresponding to its respective amplitude.

Once the accelerations were weighted, ISO 5349-1 (2001) was used to determine the daily exposure value based on a reference duration of 8 hours. This procedure considers both the RMS acceleration and the time interval during which it occurred, as defined in Equation 4.

$$A(8) = \sqrt{\frac{1}{T_0} \sum_{i=1}^{n} a_{hvi}^2 T_i} \quad (4)$$

Where:

A(8) = daily vibration exposure normalized to an 8-hour reference (m/s²).

T_0 = reference duration (8 hours or 28,800 s).

ahvi = frequency-weighted RMS acceleration during exposure i (m/s²).

T_i = duration of exposure I (s).

The use of Eq. 4 was feasible due to the constant data acquisition rate of smartphones, allowing the exposure time to be computed from Equation 5.

$$T_i = {}^{1}/_{f} \quad (5)$$

Where:

f = acceleration data acquisition rate (Hz).

Finally, the resulting A(8) value was compared with the reference limits presented in Table 2, which indicate whether the vibration exposure is acceptable or potentially harmful.

Table 2. Classification for hand-arm vibration

A(8) (m/s²)	Classification
0 a 2.5	Acceptable
2.5 a 3.5	Above action level
3.5 a 5.0	Uncertainty region
> 5.0	Above exposure limit

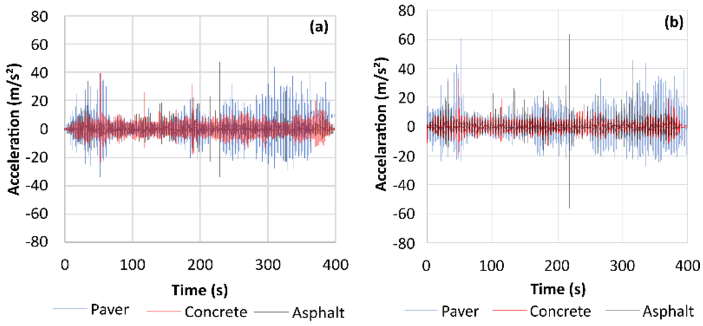
Source: NHO-10 (2013)

According to NHO-10 (2013), exposure levels above the action value require preventive measures, whereas those exceeding the exposure limit demand immediate intervention.

RESULTS AND DISCUSSION

After segmenting the sections and applying the high-pass filter, plots of RMS acceleration ($m \cdot s^{-2}$) versus time (s) were generated. Although the acceleration signals exhibited variable amplitudes, their overall behavior followed a similar pattern over time. Fig 3 illustrates the acceleration-time plots for the three pavement types, with data collected from the smartphone mounted on the handlebar (Figure 3a) and beneath the seat (Figure 3b).

Figure 3 - Accelerations versus time on the handlebars (a) and seat (b)



The RMS acceleration–time plots (Fig 3) reveal distinct vibration patterns for each pavement. The interlocking concrete block surface exhibited the highest amplitude variations, with several pronounced peaks throughout the test, indicating strong dynamic excitation associated with its surface joints and discontinuities. The PCC pavement showed intermediate behavior, with moderate oscillations but lower peak amplitudes, while the asphalt pavement presented the smallest variations and the most stable profile over time. This finding confirms that the smoother asphalt surface produced less dynamic excitation and a more comfortable riding experience.

This consistency in temporal behavior, even with amplitude variations, indicates that the vibration response of each pavement type remained stable throughout the test runs. The amplitude differences are mainly attributed to each pavement's surface texture and roughness characteristics, rather than transient dynamic effects. Similar temporal vibration patterns have also been reported in experimental analyses of cycling comfort using smartphone-based accelerometers (Ahmed et al., 2023).

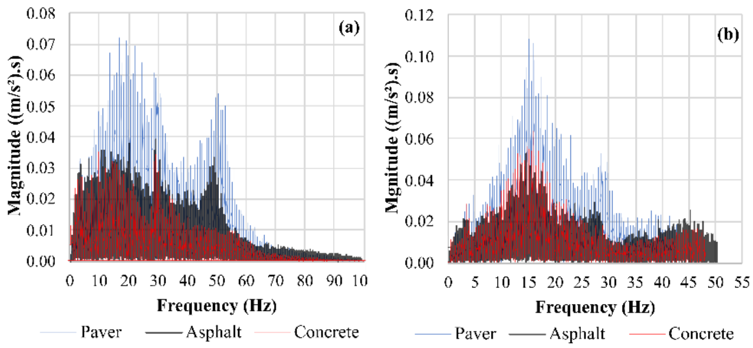
Regarding the position where vibrations were measured, the mean acceleration value recorded on the handlebar was approximately equal to that measured on the seat for the paver, both around 3.4 m/s^2. The difference between the mean acceleration values obtained at the two positions was slight for the asphalt pavement, only 0.1 m/s^2. In contrast, the PCC pavement's mean acceleration measured at the handlebar was 0.5 m/s^2 higher than that measured at the seat. Therefore, no clear trend was observed in the variation of acceleration amplitude between the vibrations transmitted to the hands and arms and those transmitted to the seat.

These results suggest that HAV are comparable to those transmitted to the seat, indicating that vibration measurements can be reliably taken at the handlebar or the seat, with no significant difference in the amplitude of the recorded signals. This observation is unexpected compared with previous studies, which reported different vibration magnitudes between the handlebar and saddle positions during cycling (Olieman et al., 2012; Vanwalleghem et al., 2012).

Frequency-domain signal analysis

Using the Fourier Transform, the spectral analysis of the acceleration signals was performed in the frequency domain. Figure 4 presents the magnitude spectra of the accelerations, expressed as (m/s²) ·s, plotted against frequency (Hz). It was observed that the accelerations recorded on the paver pavement exhibited significantly higher magnitudes compared with those measured on the asphalt and PCC pavements, which showed similar magnitude levels. Conversely, the frequency distribution patterns were comparable across the three pavement types, indicating that although the overall vibration intensity varied with the surface texture, the dominant vibration frequencies remained consistent.

Figure 4 - Frequency of accelerations collected on the seat (a) and handle (b)



The observed similarity in frequency distributions suggests that excitation sources, such as tire–surface interactions and bicycle dynamics, are governed by consistent mechanical behaviors, regardless of the pavement material. However, the irregular geometry of paver sections induces higher-energy vibrations (Núñez et al., 2020). Regarding sensor positioning, signals collected from both the seat and handlebars showed relevant acceleration magnitudes distributed up to approximately 50 Hz, with dominant frequencies concentrating between 10 Hz and 30 Hz. This range aligns with prior studies on human exposure to whole-body vibration (Chiementin et al., 2016; Doria et al., 2021; Núñez et al., 2020), confirming that the most perceptible vibrations originate from the natural frequencies of the bicycle-rider system and interactions with pavement texture.

Unlike motorized vehicles, where suspension systems are designed to attenuate vibrations above 15 Hz and target specific resonance ranges between 1 Hz and 15 Hz (Gillespie, 1992; Sayers & Karamihas, 1998), the results indicate that bicycles fail to attenuate vibrations around the critical 5 Hz range, which causes human discomfort. Furthermore, cyclists are exposed to significant vibrations above 20 Hz, a frequency range distinct from that experienced by occupants of motor vehicles. While Olieman et al. (2012) suggest that vibrations above 10 Hz are less relevant due to natural attenuation by soft tissues, the data confirm that smartphones are valuable tools for characterizing these signals in the frequency domain and evaluating bicycle suspension performance.

However, accurate frequency analysis is constrained by data acquisition rates, as insufficient sampling can lead to aliasing; a distortion occurring when the sampling rate violates the Nyquist theorem by being less than twice the maximum signal frequency (Bisconsini, 2020; Oppenheim & Schafer, 2009). In this study, the HS device was limited to 100 Hz, restricting reliable analysis to frequencies up to 50 Hz and making its signal reconstruction less accurate than that of the SS device. The SS device, operating at 200 Hz, demonstrated superior data acquisition capability, producing a clearer frequency spectrum with a reliable reduction in amplitude beyond 50 Hz.

Despite the higher sampling rate of the SS device, aliasing effects cannot be conclusively ruled out without even higher acquisition capacities. To ensure maximum signal fidelity and prevent the misrepresentation of acceleration peaks, future research should utilize external accelerometers or advanced smartphone models with superior sampling limits. For instance, Bisconsini et al. (2021) demonstrated the efficacy of using devices capable of 500 Hz for longitudinal roughness evaluation, showing that higher acquisition frequencies significantly improve the accuracy and reliability of spectral analyses.

Classification of segments without frequency weighting

The analyses presented in this section are based on unweighted acceleration data, with frequency weighting considered later in Section 3.6. Using the adapted classification derived from ISO 2631-1 (1997), the paver, asphalt, and PCC pavement sections were classified according to their associated comfort levels. Table 4 summarizes the percentage distribution of the 100 analyzed 10-meter segments for each pavement type, based on the acceleration data obtained from the SS smartphone.

Table 4. Comfort classification based on ISO 2631-1 adaptation, using SS data

Classification	Paver	PCC	Asphaltic
Comfortable	0%	4.00%	2.70%
Slightly uncomfortable	0%	21.33%	18.92%
Fairly uncomfortable	34.55%	69.33%	40.54%
Uncomfortable	50.91%	5.33%	32.43%
Very uncomfortable	14.55%	0%	5.41%

The PCC pavement provided the lowest discomfort levels, while the paver surface resulted in the highest. Most PCC segments (69.33%) were only "fairly uncomfortable." In contrast, over half of the paver segments (50.9%) were rated as strictly "uncomfortable," a category which contained nearly one-third of the asphalt segments (32.4%), but only about 5.3% of the PCC segments.

No paver segments were classified as comfortable or slightly uncomfortable, while the PCC pavement presented a combined 25.3% of its segments within these two categories, followed by the asphalt pavement with 21.6%. The percentage of segments classified as comfortable was generally low, with the highest value being 4% for the PCC pavement, which had no segments rated as very uncomfortable.

Consistent with the results presented in Table 4, Table 5 shows the comfort classification of the 10-meter segments based on the data collected from the HS smartphone.

Table 5. Comfort classification based on ISO 2631-1 (1997), using HS data

Classification	Paver	PCC	Asphaltic

Comfortable	0%	1.33%	5.33%
Slightly uncomfortable	9.09%	6.67%	37.33%
Fairly uncomfortable	29.09%	60.00%	26.67%
Uncomfortable	43.64%	32.00%	29.33%
Very uncomfortable	18.18%	0%	1.33%

Regarding hand-arm vibrations (Table 5), the asphalt produced the lowest overall discomfort, followed by the PCC, while the paver surface was the most uncomfortable. The asphalt pavement showed the highest proportion of segments classified as "slightly uncomfortable" (37.3%). In contrast, the predominant categories for the PCC and paver pavements were, respectively, "fairly uncomfortable" (60.0%) and "uncomfortable" (43.6%).

No paver segments were classified as comfortable, and nearly one-fifth (18.1%) were rated very uncomfortable. In sharp contrast, no PCC segments fell into the "very uncomfortable" category, and only 1.3% of the asphalt segments did. Overall, the proportion of comfortable segments remained generally low across all types, with the asphalt pavement showing the highest, yet modest, comfortable rating at 5.3%.

These results confirm that asphalt and PCC surfaces tend to provide lower vibration exposure to cyclists than modular pavements, due to their continuous texture and reduced joint discontinuities, which enhance vibration damping. This interpretation is consistent with the findings of Cafiso et al. (2022), who demonstrated that RMS and frequency-weighted RMS values correlate strongly with surface distress severity and pavement typology. Comparable trends were also observed by Olieman et al. (2012), who found that jointed or rough surfaces generated higher vertical accelerations and reduced perceived comfort.

Nuñez et al. (2020) also used a handlebar-mounted smartphone to assess interlocking, paver, and asphalt pavements. They found that concrete pavements were the most comfortable and interlocking pavements the least comfortable. These results corroborate the findings of the present study regarding paver pavements.

Comfort analysis based on frequency-weighted acceleration

The study included HAV and WBV analyses, utilizing frequency-weighted acceleration signals. The NHO-10 (2013) methodology was used for HAV analysis (Table 6). The analysis first covered the full distance because the actual data exposure time was short (approximately six minutes per section). Additionally, we simulated longer exposure times (30 minutes, 1 hour, and 2 hours) to model typical bicycling scenarios such as commuting or sports.

Table 6 - Comfort classification related to HAV based on NHO-10 (2013)

Pavement	Weighted mean frequency (Hz)	Hw filter	A(8) (m/s²)	A(8) (m/s²) for 30 min	A(8) (m/s²) for 1 h	A(8) (m/s²) for 2 h
Paver	21.07	0.4820	0.152	0.428	0.604	0.855
PCC	20.81	0.4855	0.055	0.616	0.871	1.231
Asphalt	22.34	0.4648	0.106	0.458	0.648	0.916

The weighted mean frequencies ranged between 20 and 22 Hz, indicating that the vibration exposure occurred primarily above the human body's resonance range, typically between 4 and 8 Hz (ISO 2631-1, 1997). Although these frequencies pose a lower health risk, they can still contribute to localized hand and arm discomfort during prolonged rides. The Hw coefficients were similar across pavement types, confirming that the frequency weighting procedure remained consistent. Regarding A(8) values, all pavements showed a natural increase with exposure duration, reflecting the cumulative nature of vibration exposure. The PCC exhibited the steepest growth rate, suggesting a greater transmission of high-frequency vibrations on rigid surfaces. Conversely, the asphalt maintained the most stable response over time, highlighting its better damping capability and overall comfort.

All results indicate A(8) values below the action level limit of 2.5 m/s² (Table 2). Therefore, even when considering longer exposure durations of up to two hours, no health implications related to hand–arm vibrations were observed.

The results of WBV analysis, using Wk filter, are presented in Table 7, including the numerical values and corresponding comfort classifications according to the adaptation proposed in this study (Table 1b).

Table 7 - Comparison between RMS values with and without frequency weighting according to ISO 2631-1

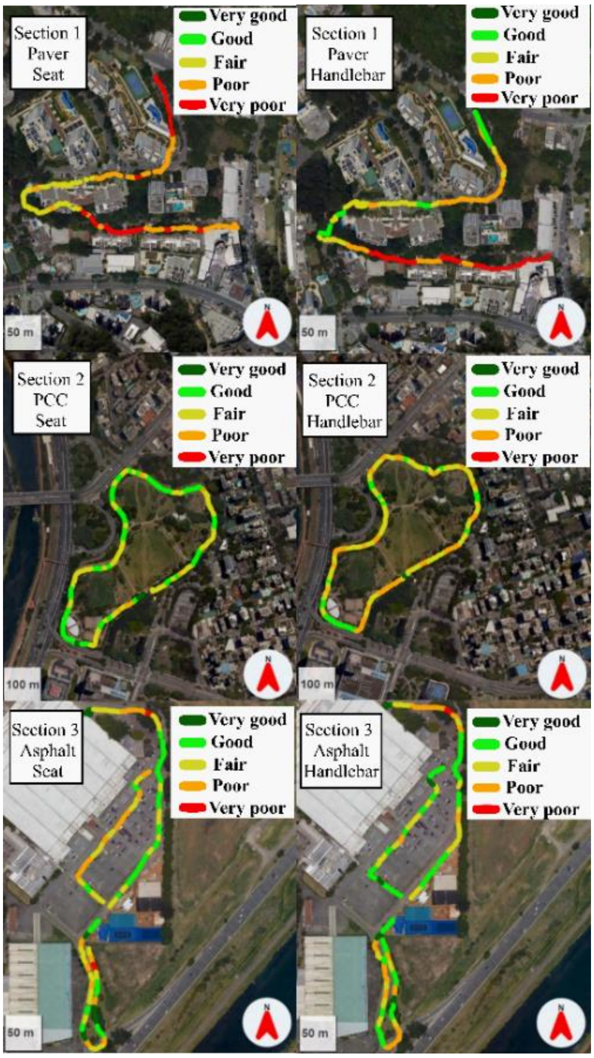
Pavement	Unweighted RMS (m/s²)	Weighted RMS (m/s²)	Unweighted classification	Weighted classification
Paver	2.76	2.22	Very uncomfortable	Uncomfortable
PCC	2.02	1.24	Uncomfortable	Fairly uncomfortable
Asphalt	1.66	1.45	Uncomfortable	Fairly uncomfortable

From Table 7, the weighting based on the Wk filter considerably reduces the acceleration, leading to a milder classification of ride quality and possibly reflecting a more realistic user perception. In this case, the asphalt pavement becomes slightly more uncomfortable than the PCC overall, although both fall within the same qualitative comfort category. This finding indicates that frequency-based weighting, which accounts for dominant frequencies, is an important consideration for accurately evaluating the ride quality of bicycle pavements.

Application of data in a Geographic Information System (GIS)

One of the main advantages of using smartphones in PMS is their ability to provide real-time data on road conditions, which can be integrated into thematic maps through applications linked to GIS platforms. To illustrate this application, Figure 5 presents classification maps generated using the Roadify software.

Figure 5 - Thematic maps of WBV classification based on ISO 2631-1



In Figure 5, the comfort condition of each segment is displayed using a color scale corresponding to the classification categories established by ISO 2631-1 (1997). The color legend ranges from dark green (Very Good) to red (Very Poor). The maps were generated with a 10-meter segmentation interval for both seat and handlebar data. Since the software used in this study does not yet include an option for frequency-weighted acceleration analysis, the maps were produced without applying this weighting. However, although the maps were generated without frequency weighting, future integration of ISO 2631-1 weighting functions would increase the accuracy of the comfort rating by better reflecting human sensitivity to vibration.

The spatial distribution of comfort levels along the analyzed segments reveals that sections with abrupt variations in classification may correspond to localized surface defects that could be prioritized for maintenance, reinforcing the use of GIS as a decision support tool in cycle path management systems. By incorporating these thematic maps into municipal GIS platforms, decision-makers can visualize critical zones in the cycling network and schedule targeted maintenance interventions more effectively.

CONCLUSIONS

This study analyzed the cycling comfort provided by asphalt, Portland cement concrete, and paver pavements using acceleration and GPS data collected through smartphone sensors. Variations in vibration amplitude along the routes and the corresponding spectral frequency were examined based on the vertical accelerations measured at the bicycle's handlebars and seat. An adaptation of ISO 2631-1, which addresses WBV, was proposed to classify the comfort levels of the three pavement types investigated. Each pavement segment was 1,000 meters long and subdivided into 10-meter sections for more detailed analyses.

Differences between handlebar (hand-arm) and seat (whole-body) vibrations were minimal. Paver pavement yielded identical average acceleration values for both positions. Minor discrepancies were found for asphalt (0.1 m/s^2 difference) and PCC (0.5 m/s^2 difference). For the bicycle used, the vibration amplitude transferred to the hands is mainly like that transmitted to the cyclist's spine.

Regarding the frequency of the accelerations, significant magnitudes occurred up to 50 Hz, with a predominant frequency around 15 Hz, particularly for handlebar vibrations, and a similar distribution pattern among the three pavement types, although the paver exhibited higher magnitudes. This result indicates cyclists' exposure to higher-frequency vibrations than road vehicle passengers. Moreover, it highlights the importance of employing sufficiently high data acquisition rates to prevent aliasing and the attenuation of acceleration peaks.

Regarding the proposed classification, based on ISO 2631-1, the paver had most segments classified as "Uncomfortable" for both the seat and handlebar positions. The PCC showed most of its segments classified as "Fairly Uncomfortable" for vibrations at both positions, while the asphalt had most of its segments classified as "Fairly Uncomfortable" for seat vibrations and "Slightly Uncomfortable" for handlebar vibrations. Overall, asphalt and PCC provided similar levels of vibrational comfort and are more suitable for cycling infrastructure than paver.

Considering NHO (2013), the action level of 2.5 m/s^2 was not reached for any pavement types, indicating no significant health risks to the cyclist regarding HAV. Regarding the frequency-weighted acceleration analysis for WBV, a reduction in acceleration values was observed when accounting for the dominant frequencies of each pavement type. As a result, the asphalt became slightly more uncomfortable than the PCC.

In conclusion, the study demonstrates how accessible consumer technology can be appropriate to address urban mobility challenges, bridging the gap between technical monitoring and social needs. The proposed method empowers public managers and citizens with a low-cost solution to digitize infrastructure conditions, directly supporting the promotion of safer and more sustainable and smart cities.

A limitation of this study was the 100 Hz sampling rate of the handlebar smartphone, which restricted the analysis of frequencies above 50 Hz (Nyquist limit). Future research should utilize external accelerometers with higher sampling capacities to further validate smartphone spectral data. Additionally, the study focused on vertical accelerations; incorporating lateral and longitudinal axes could provide a more holistic view of stability.

Future studies will address images to assess additional environmental factors relevant to cycling route quality and other bicycle models to analyze data variations when using suspension systems with different stiffness levels and different riding speeds.

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Correspondência: