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HUMAN COMFORT IN BUILDINGS: AUTOMATION OF THE VIBRATION DOSE VALUE METHOD

Smart buildings, as dynamic ecosystems, integrate cross-dependent sensors to enhance structural serviceability, optimize efficiency, and improve safety. This research employs a custom-designed sensor prototype to explore the feasibility of developing an automated system for evaluating building sensitivity to traffic-induced vibrations. The methodology involves collecting acceleration data from a full-scale structure subjected to traffic vibrations, processing it through an automated algorithm, and categorizing buildings qualitatively based on vibration levels and human perception, as defined by the Vibration Dose Value (VDV) method in the BS 6472-1 standard. Comparative analyses reveal the method's sensitivity to signal duration and amplitude variations, highlighting its potential for integration into real-time smart monitoring systems.

Keywords: traffic-induced vibrations, vibration dose value, vibration measurement, human comfort, acceleration amplitude, smart monitoring systems.

1. INTRODUCTION

In modern urban environments, vibrations caused by traffic — both from road and railway systems — are a common issue that can significantly impact building structures and occupant comfort. Vibrations in buildings often lead to negative effects, including cracks, plaster detachment, and in extreme cases, structural damage. In addition, the simultaneous presence of noise and vibrations can further disrupt occupant comfort, affecting both acoustic and visual well-being. According to studies such as [16], human perception of vibrations is influenced by factors like resonance frequencies, which are critical for understanding how building occupants experience these disturbances.

Numerous studies have analyzed traffic-induced vibrations, focusing on their measurement and impact in high-traffic urban areas [1], [2], [10], [11]. These investigations emphasize the importance of minimizing dynamic loading to meet the threshold levels set by various standards, such as the British

Standard BS 6472-1 and ISO standards [8], [9]. Measures proposed to mitigate vibration effects include retrofitting buildings with appropriate insulation [13], [15], and using in-situ measurements to assess ground-level vibrations, which are then incorporated into structural design models [12], [7], [14]. These approaches ensure that structures meet serviceability requirements and safeguard occupant comfort.

Various standards, including the ISO and British standards, focus on evaluating the sensitivity of buildings to vibrations and their impact on occupant comfort. These guidelines are primarily based on the calculation of a weighted acceleration value derived from measured time records. Other standards, such as the NBC 2005, provide specific recommendations for maximum acceleration limits based on the type of building [4]. The European Standard EN 1990, which addresses the dynamic effects of vibrations, suggests that the natural frequency of a structure be limited to prevent exceeding the serviceability limit state, with further detailed assessments available through ISO standards [5], [6].

This paper investigates the vibration levels in a building exposed to traffic-induced vibrations, analyzing the effects on occupants based on recorded acceleration signals. Specifically, it examines the British Standard BS 6472-1 [3] and the robustness of the Vibration Dose Value (VDV) method for vibration assessment. Two key factors are studied: (1) the impact of signal duration and (2) the influence of peak amplitude on vibration perception. The findings offer valuable insights into the potential for automating the analysis within real-time smart monitoring systems.

The prototype sensor used in this study could be further developed into a "smart" sensor, capable of monitoring a range of environmental factors such as temperature, humidity, and vibrations. This advancement would enhance the role of such sensors in "smart" buildings, ultimately improving structural serviceability, efficiency, and occupant safety.

2. OVERVIEW OF THE BRITISH STANDARD BS 6472-1 METHODOLOGY

The British Standard BS 6472-1 [3] offers a systematic approach for predicting and assessing human responses to vibrations within the frequency range of 0.5 Hz to 80 Hz. By categorizing vibration time histories, the standard accommodates diverse scenarios:

- Continuous vibrations – sustained vibrations over extended periods, such as those caused by consistent traffic flow.
- Periodic vibrations – vibrations occurring at regular intervals, often associated with industrial machinery.
- Occasional vibrations – irregular or infrequent vibrations, such as those caused by sporadic construction activities.

Traffic-induced vibrations are typically classified as continuous, characterized by fluctuating amplitudes throughout the measurement period.

To account for human perceptual sensitivity, the standard [3] incorporates frequency-dependent weighting factors. These factors adjust recorded acceleration signals to reflect the human body's differential sensitivity to vibrations. For vertical movements, the Wb factor is applied, emphasizing the range of 4 to 12.5 Hz. For horizontal movements, the Wd factor is used, capturing sensitivity within 1 to 2 Hz. These adjustments, presented in one-third octave bands, align with the physiological perception thresholds of vibration. Their linear values are graphically represented in Figure 1.

The primary parameter for assessing the effects of vibrations on occupants is the Vibration Dose Value (VDV). This parameter considers the cumulative effect of vibration amplitude over time and is particularly sensitive to peak amplitudes due to its reliance on a fourth-power calculation. The VDV is defined as:

$$\mathrm{VDV}_{\mathrm{b/d,day/night}} = \left(\int_0^{\mathrm{T}} \mathrm{a}^4(\mathrm{t})\mathrm{dt}\right)^{0.25} \qquad (1)$$

Here, $\mathrm{VDV}_{\mathrm{b/d,day/night}}$ represents the vibration dose value for the specified weighting and time period (day or night), expressed in m/s$^{1.75}$ for translational vibrations or rad/s$^{1.75}$ for rotational vibrations; $\mathrm{a(t)}$ represents the weighted acceleration as a function of time, expressed in m/s^2 for translational vibrations or rad/s^2 for rotational vibrations; T represents the duration of a measurement period during which vibration can occur, expressed in s.

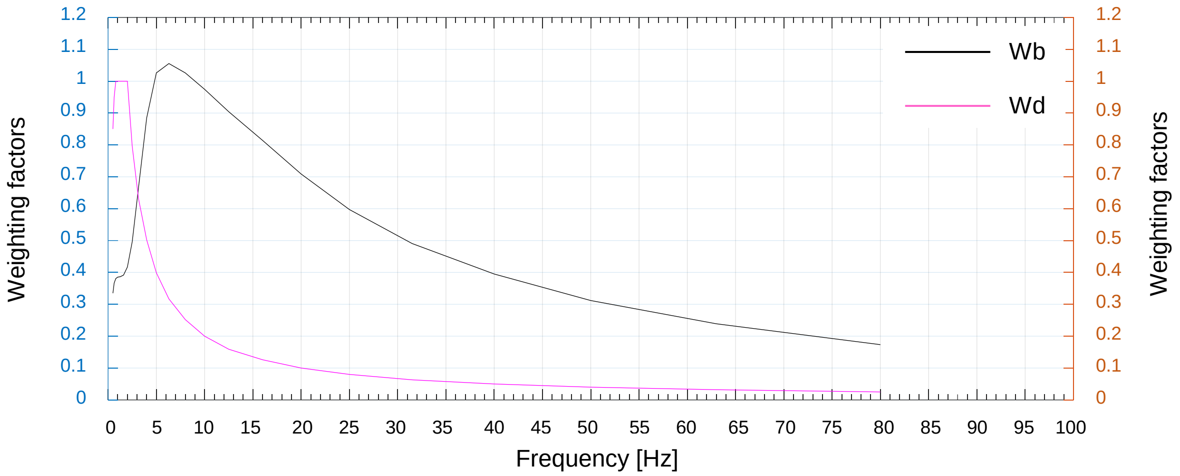

Figure 1. Weighting factors according to BS 6472-1

If the vibration signal consists of multiple intervals with varying durations (e.g., traffic-induced vibrations), the total VDV is calculated as:

$$\mathrm{VDV}_{\mathrm{b/d,day/night}} = \left(\sum_{\mathrm{n=1}}^{\mathrm{N}} \mathrm{VDV}_{\mathrm{t_n}}^{4}\right)^{0.25} \qquad (2)$$

where N represents the total number of time intervals; $\mathrm{VDV}_{\mathrm{t_n}}$ represents the vibration dose value for the time interval $\mathrm{t_n}$, expressed in $\mathrm{m/s^{1.75}}$ for translational vibrations or $\mathrm{rad/s^{1.75}}$ for rotational vibrations; $\mathrm{t_n}$ represents the duration of $\mathrm{n_{th}}$ time interval, expressed in s.

The process of calculating the VDV is outlined in the accompanying block diagram (Figure 2).

Once the VDV is calculated, the standard [3] provides threshold values to interpret its significance. These thresholds categorize the likelihood of adverse comments from building occupants. Lower VDV values indicate minimal risk of negative feedback, while higher values suggest a higher probability of dissatisfaction. The variability in human sensitivity and expectations accounts for the broad ranges specified in the standard, which inherently limits the precision of the assessment.

By integrating these guidelines, the British Standard BS 6472-1 provides a robust framework for quantifying and mitigating vibration effects on building occupants. This study leverages its methodology to assess the sensitivity of an exposed structure, with implications for advancing automated monitoring systems.

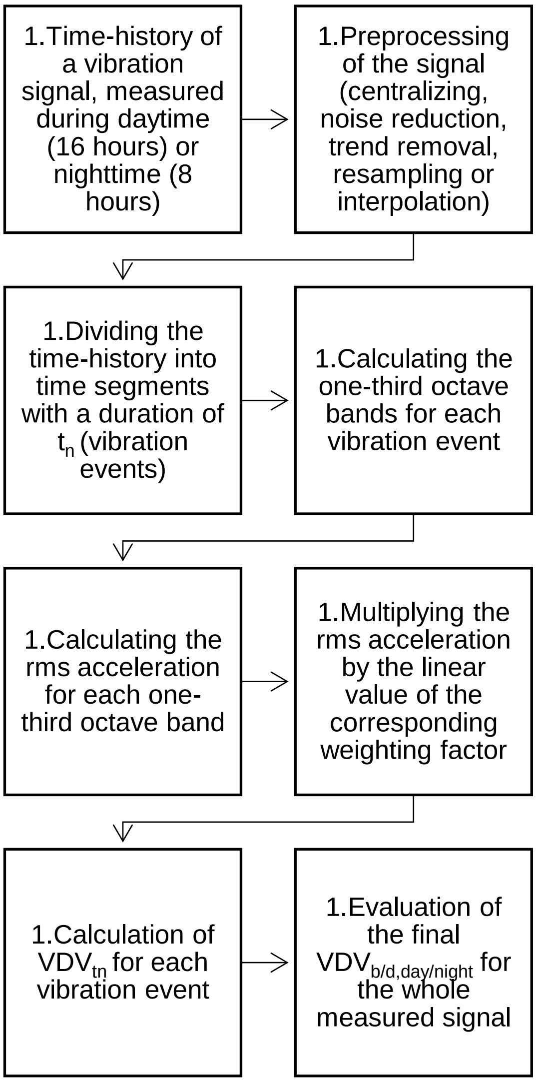

Figure 2. Step by step methodology

3. EXPERIMENTAL CASE STUDY ON BUILDING VIBRATION RESPONSE TO TRAFFIC STIMULI

3.1. CONCEPT DEVELOPMENT

This concept, which forms part of the SmartBuild research project supported by the University of Ss. Cyril and Methodius in Skopje, explores the development of methodologies for utilizing sensor technology in the smart monitoring of various environmental parameters, including temperature, humidity, and vibration levels in buildings. Such a methodology aims to enhance insights into building performance and facilitate data-driven decision-making through real-time monitoring and analysis.

The vibration-based monitoring system proposed in this study focuses on creating a methodology for an automatic system that is triggered when vibration amplitudes surpass predefined acceleration threshold values. Upon activation, the system would record the corresponding vibration events, storing the acceleration histories. These recorded signals would be automatically processed through an algorithm that estimates the Vibration Dose Value (VDV) and provides the user with a qualitative assessment of the vibration levels. The procedure is outlined schematically in Figure 3, and can be divided into four primary phases: (1) measuring of vibrations and time-history acquisition; (2) preprocessing of the signal and preparing the raw data for more detailed analysis; (3) processing of the signal in time domain and frequency domain; (4) obtaining of final results and evaluation. This algorithm could be fully automated via a programming platform, allowing users to adjust input parameters such as the duration of time intervals (t_n) or the acceleration amplitude cut-off threshold. Additionally, constants could be used for values such as one-third octave bands' frequencies, linear weighting factors, and the limit values for qualitative evaluation.

3.2. DESCRIPTION OF THE EXPERIMENTAL SETUP

The experimental setup in this study involved the use of a custom-designed prototype by Digitex Systems [17], representing a smart structural monitoring system composed of two main components.

The first component is the measuring instrument – a prototype three-axis accelerometer called Pulse (Figure 4). This device features three channels, two for horizontal axes and one for the vertical axis. The accelerometer has a sensitivity of 900 mV/g and is equipped with an analog low-pass anti-aliasing filter to reduce band noise and limit the bandwidth. This filter provides a fixed 3 dB bandwidth of approximately 1 kHz (selectable). The Pulse device requires electrical power, which is supplied via a USB connection.

The second component of the system is Voyager, a cloud-based software platform for data collection and processing (Figure 4). Voyager facilitates real-time data collection, management, and analysis from all sensor units connected in the monitoring system. Data communication between Pulse and Voyager is established via Wi-Fi, ensuring continuous data transfer and remote monitoring.

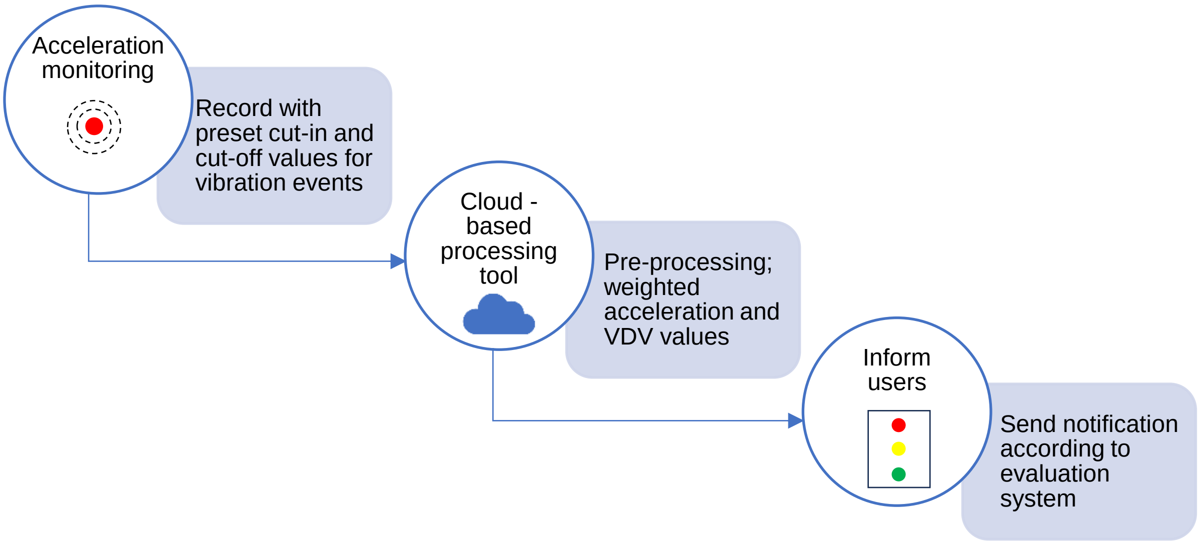

Figure 3. Concept for the automated algorithm for calculating the VDV parameter

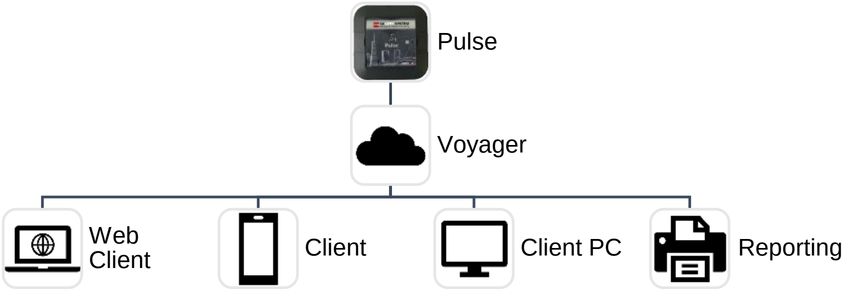

Figure 4. Pulse - Voyager system (adopted from [17])

Following the guidelines outlined in the British Standard [3], the accelerometer was positioned at floor level within a room of the building exposed to traffic-induced vibrations (Figure 5). The building is located along a boulevard with high traffic frequency. The sensor was placed directly on the floor (without being fixed) and connected to the cloud-based software via Wi-Fi for real-time data transmission. During the monitoring period, the building was unoccupied and not in use.

Figure 5. Placement of measuring instrument

To assess the sensitivity of the applied methods and tools regarding measurement duration and exposure time, a 16-hour daytime period was selected based on the recommendations from the standard [3]. In total, 96 acceleration time histories, each lasting 10 minutes, were collected. The recording frequency was set to 200 samples per second, allowing for the extraction of frequencies below 100 Hz. The recorded data was subsequently processed using a custom algorithm developed in the MATLAB programming environment.

3.3. IMPACT OF TIME DURATION AND SIGNAL AMPLITUDE ON VIBRATION ANALYSIS

Determining how the length and amplitude of the measured acceleration signal affect the estimated VDV parameter is crucial for an effective autonomous algorithm, especially in defining the threshold values for cut-in and cut-out amplitude levels that determine vibration events (step 3 of the proposed methodology in Figure 2).

Regarding the time length of the vibration events t_n, three different analyses were conducted for each direction, using signals that include the identified peak acceleration amplitude. The durations analyzed were: 600 seconds (the duration of the entire 10-minute signal), 100 seconds, and 20 seconds. For clarity, only the results from the X and Z directions will be presented here. In the results shown in Figure 6, the three vibration events correspond to the periods during which the maximum acceleration amplitude (from the entire 16-hour signal) occurs.

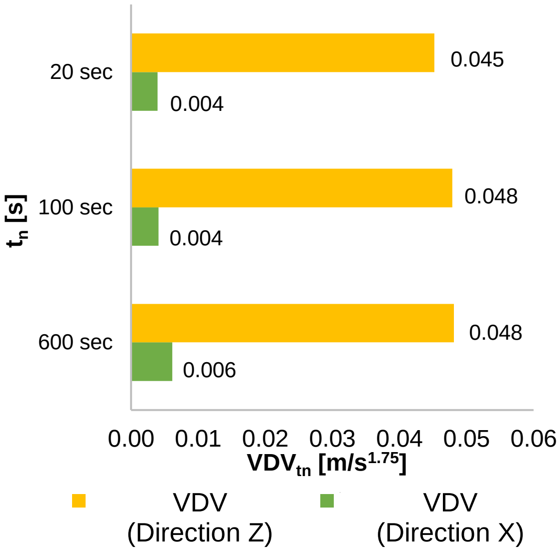

Figure 6. Results for parameter VDV_{tn} depending on direction and time of integration

The linear values of the applied weighting factors (compared to those proposed in the ISO standards), along with the frequency domain representation of the signal, are shown in Figure 7 for direction X and Figure 8 for direction Z.

A possible simplification is to automatically preset the algorithm to assess time slots with identified absolute maximum accelerations within a 16-hour monitoring period. To examine how the magnitude of the amplitude affects the VDV_{tn} parameter in relation to the length of vibration events, all 10-minute records from the 16-hour measurement period were assessed using the three time-lengths: 600 seconds, 100 seconds, and 20 seconds, each of which included the maximum peak occurring in the corresponding record. The graphical representations of these results are shown in Figures 9 and 10, where the maximum VDV_{tn} values are also marked.

The linear trendlines show that, generally, the VDV_{tn} values increase as the maximum acceleration in the vibration event increases. However, it is noteworthy that in some pairs of adjacent amplitudes on the graphs, the VDV_{tn} value is lower when analyzing the time record with the larger amplitude (as observed in the X direction, the maximum VDV_{tn} value is calculated for a vibration event in which the maximum acceleration is lower than the greatest peak in entire signal). This occurs because other significant peaks are present in the time segment of the analyzed record, in addition to the one with the greatest value. These additional peaks have considerably high acceleration values, which contribute significantly to the final integration of values when determining the VDV_{tn} value.

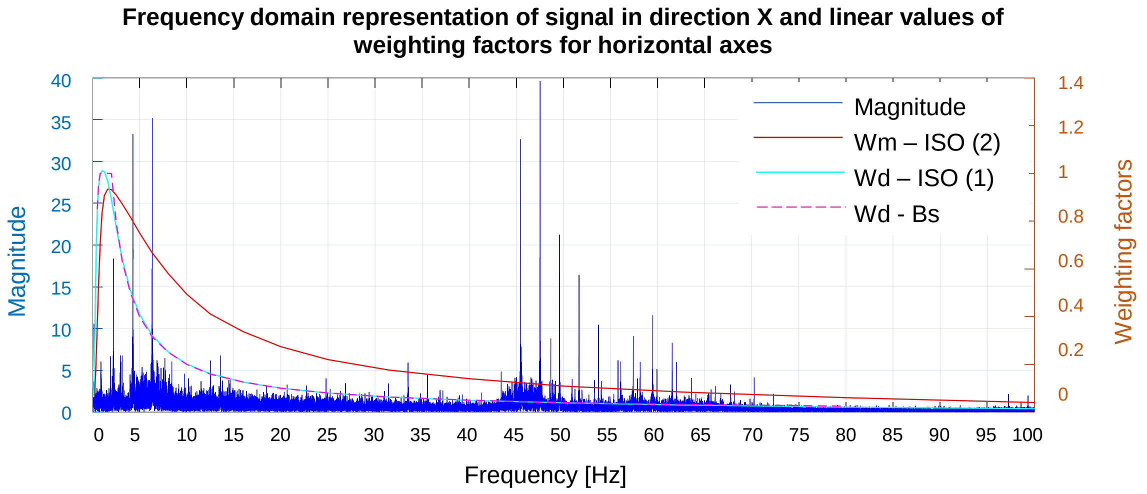

Figure 7. Linear values of weighting factors for horizontal axes and frequency domain representation of signal in direction X

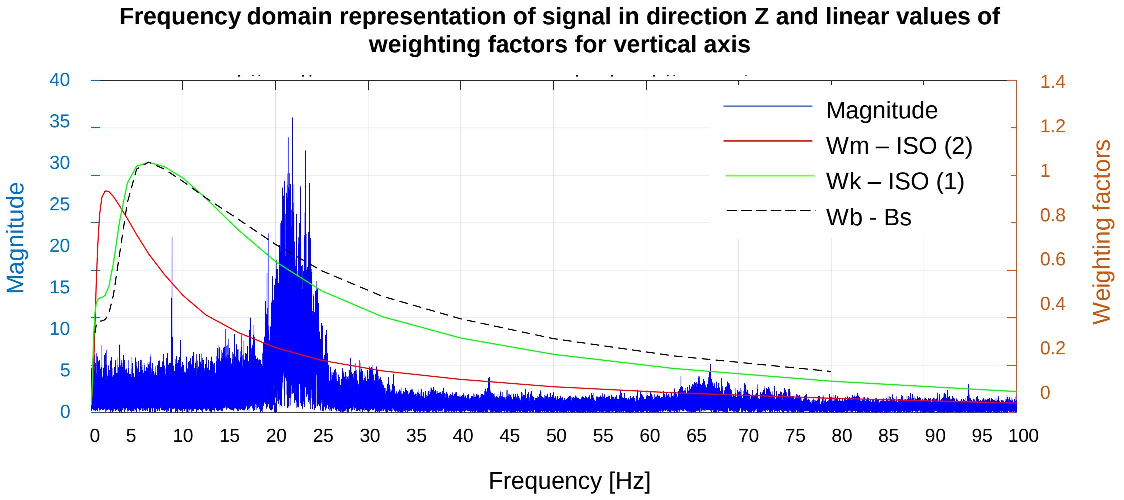

Figure 8. Linear values of weighting factors for vertical axis and frequency domain representation of signal in direction Z

Thus, although the records may contain accelerations that are slightly lower than the maximum, the final result shows a higher VDV_{tn} value compared to cases where only one amplitude is considered, accompanied by much lower accelerations.

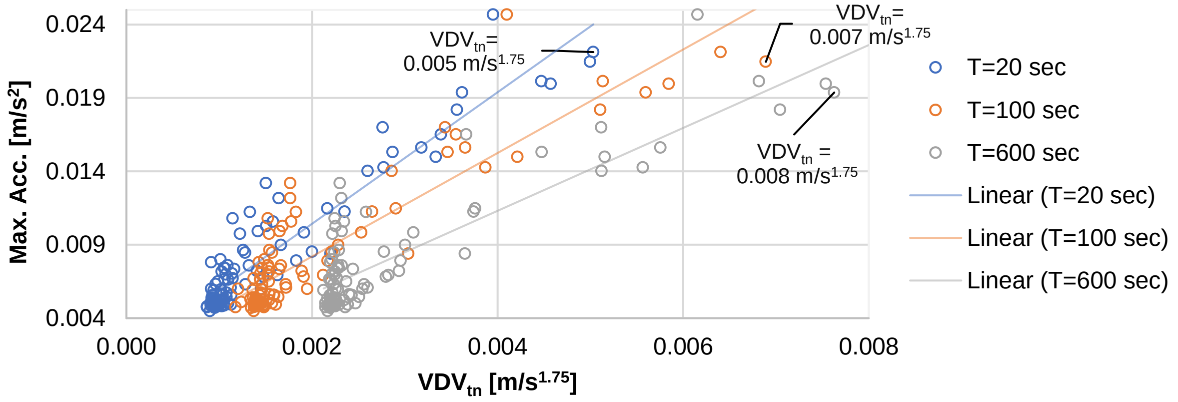

Figure 9. Impact of the length and the amplitude of the time signal on the VDV_{tn} value, direction X

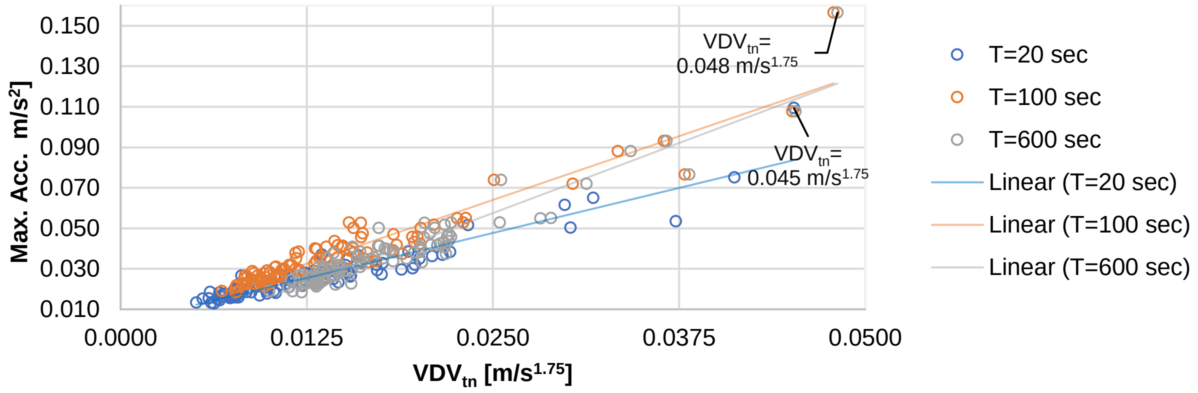

Figure 10. Impact of the length and the amplitude of the time signal on the VDV_{tn} value, direction Z

3.4. IMPACT ASSESSMENT BASED ON PROBABILITY OF ADVERSE HUMAN RESPONSE

Based on the calculated VDV_{tn} values for t_n=600 s (which produced the highest values compared to the shorter time slots), and applying equation (2), a final evaluation of the results for the 16-hour daytime exposure period is provided in Table 1.

This shows that according to the standard [3], no negative effects occur from the examined stimulus.

Table 1. Evaluation according to BS 6472-1

Direction	X	Z
Place and period of measurement	Residential buildings, 16 hours-daytime	Residential buildings, 16 hours-daytime
Calculated VDV	0.013 $m/s^{1.75}$	0.071 $m/s^{1.75}$
Lowest limit value	0.2 $m/s^{1.75}$	0.2 $m/s^{1.75}$
Effect	No adverse comments expected	No adverse comments expected

4. CONCLUSIONS

This study investigates the application of the British Standard BS 6472-1 for assessing the impact of traffic-induced vibrations on buildings, with a focus on developing an autonomous monitoring methodology. Using a prototype triaxial accelerometer, a 16-hour monitoring period was conducted on a building floor exposed to vibrations from nearby traffic. The measured time histories were analyzed to calculate the Vibration Dose Value (VDV) for various vibration events of different durations.

The results demonstrated that the VDV values were not significantly influenced by the various duration of the vibration events, suggesting that the methodology robust across different time intervals. The final assessment indicated no adverse effects from the vibrations, with all values falling below the prescribed limits in the standard. This supports the potential of the proposed methodology for assessing human response to building vibrations in real-time.

Future work will expand on this concept by incorporating multiple accelerometers for more comprehensive data collection, long-term monitoring to build a larger dataset, and controlled traffic exposure to better simulate real-world conditions. Additionally, the development of a refined algorithm with pre-set thresholds for automatic detection of vibration events will further enhance the efficiency and accuracy of the system.

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