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# Characterisation of Vibrations of a Precast Reinforced Concrete Bridge:
## *The Case of Kangundo Road Bridge on Outering Road, Nairobi, Kenya*

***Clive Mukiria Muita, Simpson N. Osano and Sylvester O. Abuodha**

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**Abstract**

*The Kangundo Road bridge in Nairobi, Kenya, shows permanent mid-span deflections that may alter its dynamic behaviour and affect user comfort. This study assessed bridge vibrations using ADXL355 and MPU9250 accelerometers, collecting acceleration data at five soffit-mounted points. Acceleration, the most perceptible vibration parameter to humans, was analysed and compared to International Standards Organisation (ISO) 2631, Wright & Walker (1972), and American Institute of Steel Construction (AISC) Design Guide 11 comfort limits. T-test results showed that the measured peak accelerations significantly exceeded the ISO and Wright & Walker thresholds by up to 110%, while the AISC limits were only marginally surpassed. Heavy goods vehicles (HGVs) caused uncomfortable vibrations, while small vehicles remained within acceptable limits. Permanent deflections increase dynamic amplification, increase tensile stress and may cause fatigue damage. The study supports the use of stricter vibration limits in urban areas and confirms the effectiveness of low-cost sensors in monitoring bridge performance and vibration-related serviceability.*

**Keywords:** AISC Design Guide 11, bridge vibration, dynamic amplification, ISO 2631, Kangundo Road Bridge, low-cost accelerometers, Wright and Walker

## INTRODUCTION

The Kangundo Road Bridge in Nairobi, Kenya, has developed permanent mid-span deflections that are inconsistent with the initial design, as shown in **Figures 1** and **2**. Such deformations are likely to alter the bridge's dynamic behaviour. While visual inspections can identify physical defects, they do not, however, quantify dynamic performance or user experience. In Kenya, there is limited data on bridge vibration levels and compliance with established worldwide comfort limits. Additionally, the effectiveness of affordable, off-the-shelf accelerometers in monitoring real-world bridge vibrations remains underexplored. The paper investigates bridge vibrations through the lens of acceleration measurements, exploring their role in characterising vibration levels and comparing them with worldwide best practices.

## THEORY

Vibration refers to a structure's response to dynamic forces. Long and light structures are more prone to experiencing large-amplitude vibrations compared to shorter, sturdier structures due to differences in mass and stiffness. The source of dynamic forces can originate from pedestrian and vehicular traffic, machinery within a building, wind, and seismic action. Velocities, displacements, and accelerations are parameters that measure the magnitude of a structure's vibration response (Lazi et al., 2022; Saidin et al., 2022). Md. Robiul Awall et al. (2016) highlights that human beings are more sensitive to accelerations and changes in acceleration than to other vibration parameters, such as velocity and displacement.

Karimi et al. (2022) observed that the relationship between displacement and the first bending natural frequency led to the development of live load deflection limits with dynamic amplification factors (DAF) in design codes such as the American Code AASHTO LFRD:2009, the Canadian Code CSA S6-19, the Indian Code IRC 112-2011, and the Australian Code AS5100.2:2017. These limits

**Corresponding author:*
***Clive Mukiria Muita** student (MSc. Structural Engineering) Kenya Urban Roads Authority, Kenya*
*Email: clivemukiria@gmail.com*

**FIGURE 1**
Deflection profile of the Kangundo Road bridge
**Source:** Field survey, 2025


**FIGURE 2**
Deflection profile of the Kangundo Road bridge
**Source:** Field survey, 2025

aim to control excessive vibrations by relating the live load displacement to the natural frequency of a bridge. The assumption in these codes is that the designer has accurately assessed the expected deflections from other actions, such as permanent loads and time-dependent deformations, to ensure a uniform road profile where these provisions apply. Kużawa et al. (2022) observed that a bridge with permanent deflections on its span had the highest impact on the increase of dynamic properties when compared to a non-deformed one with similar geometric properties and using the same vehicle speed. The research was based on a numerical simulation of the interaction between vehicles and a bridge with damage in the form of permanent deflections. Permanent deflections forced vibration of the vehicle, which led to increased vibration of the bridge-vehicle structure interaction system, thereby increasing the DAF of the vehicle. For reinforced concrete bridges, the increase in DAF results in increased tensile stresses at the girder soffit. Increasing tensile stresses can lead to the development and propagation of cracks due to the significant variation between the maximum and minimum stress values, ultimately reducing the fatigue life of the bridge. The rate of fatigue reduction can be accelerated in situations where there is inadequate enforcement of axle loads.

ISO 2631 addresses whole-body vibrations and shocks in buildings that affect the comfort and annoyance of occupants. Xia et al. (2025) highlighted that in ISO 2631, 0.315 $m/s^2$ was the threshold value for uncomfortable vibrations.

Wright and Walker (1972) observed that human responses to vibration on a bridge depend on the characteristics of the bridge's vertical motion. They developed an acceleration-response relationship shown in **Table 1**. Their recommended threshold limit for transient peak acceleration on a bridge was 0.254 $m/s^2$. The value was determined because they observed that when motion, which is unexpected and suspected to indicate structural inadequacy, is perceived singly, it can be disturbing. The value was approximately 2.6 times the acceleration of gravity. Their work was adopted and incorporated into the Canadian Highway Bridge Design Code, CSA S6-19, and the Australian Bridge Design Code, AS 5100:2004 (Le & Hwang, 2017;Tahmasebinia et al., 2023). The American Institute for Steel Construction (AISC) design guide 11 recommends that the maximum acceleration allowed on outdoor pedestrian bridges be 5% of gravity, which is 0.491 $m/s^2$ for bridges with minimum natural frequencies between 4 Hz and 8 Hz (Soliman, 2022).

## RESEARCH METHODS

### Research Area

The Kangundo Road R-o-R (Road-Over-Rail) bridge is a 23.66m span reinforced concrete structure located on the Outer Ring Road in Nairobi, Kenya, as shown in **Figure 3**. In March 2017, shortly after the bridge was opened, road users reported that it vibrated uncomfortably when one lane experienced stationary traffic while the other lane had moving traffic. Observable permanent deflections at the midspan are present on the bridge superstructure, leading to run-off ponding during the rainy season. The bridge was selected because it had been recently commissioned, and given that bridges usually have a design lifespan of 100 years, the deflection and vibration issues were likely to impact its service life. The bridge under study has the following UTM coordinates: N 98 5891.82, E 26 4312.15. It is a simply supported bridge with reinforced concrete substructures. **Figures 4** and **5** illustrate the bridge dimensions and sensor layout during data collection.

### Research Tools and Data Collection

ADXL 355 and MPU9250 accelerometers were used in the research. These sensors measured acceleration in the three principal directions: x, y, and z (TDK InvenSense, 2025; Analog Devices, 2021). The data was sampled at 20 Hz (samples per second). As shown in **Figure 6**, the ESP32

**TABLE 1**
Peak acceleration for human response to harmonic vertical vibration

| Human response | Peak acceleration, $m/s^2$ | |
|---|---|---|
| | Transient | Sustained |
| Imperceptible | 0.127 | 0.0127 |
| Perceptible to some | 0.254 | 0.0254 |
| Perceptible to most | 0.508 | 0.0508 |
| Perceptible | 1.27 | 0.127 |
| Unpleasant to a few | 2.54 | 0.254 |
| Unpleasant to some | 5.08 | 0.508 |
| Unpleasant to most | 12.7 | 1.27 |
| Intolerable to some | 25.4 | 2.54 |
| Intolerable to most | 50.8 | 5.08 |

**Source:** Wright & Walker,1972


**FIGURE 3**
Location map of the research area
**Source:** Field survey, 2025

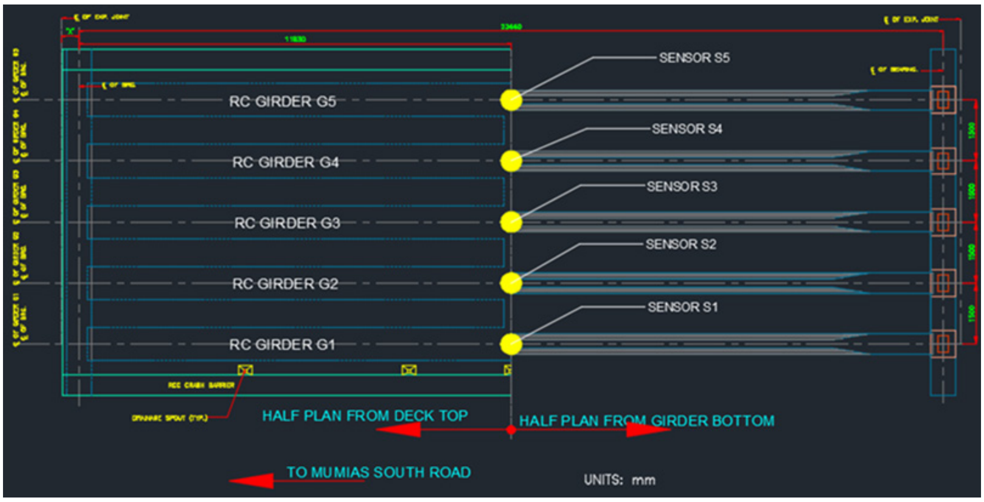


**FIGURE 4**
Location map of the research area
**Source:** Field survey, 2025

microcontroller acted as the processor for each sensor. Each girder of the bridge had a sensor attached at mid-span to the girder soffit, and the sensors were numbered S1 to S5, as shown in **Figure 5**. Using a timestamp, a high-resolution camera recorded traffic flow and was synchronised with the sensors. These sensors and micro-processors are low-cost and readily available.

### Data Analysis Method

The literature review identified accelerations as the preferred parameters to measure, as they define the perceivability threshold and the comfort level of the bridge for humans. Due to the large volume of data collected from the high sampling rate, Pandas and Matplotlib (Python libraries) were used to load and visualise the acceleration data in a graphical chart.

### Hypothesis Testing using the T-Test

A two-tailed t-test was used to statistically compare the measured acceleration data with

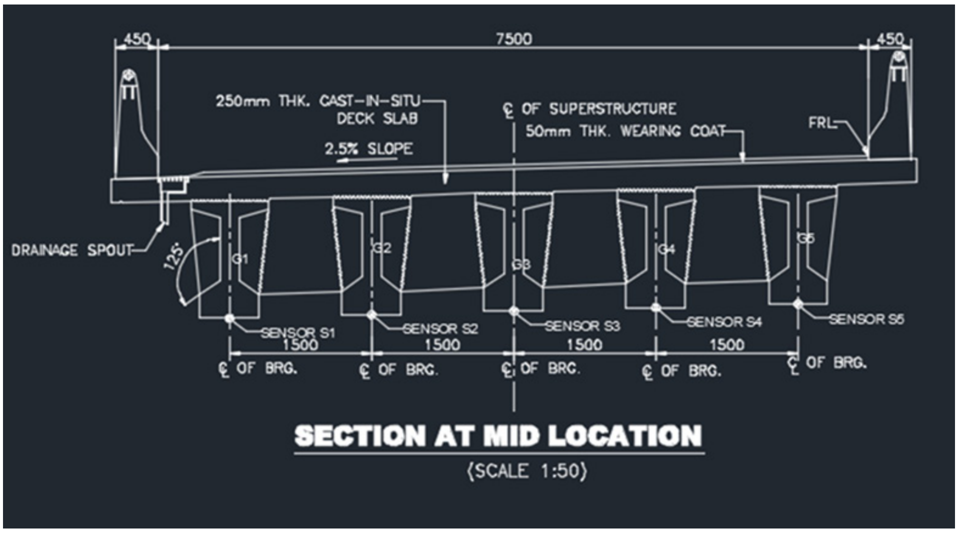


**FIGURE 5**
Cross-section dimensions of the bridge
**Source:** Field survey, 2025

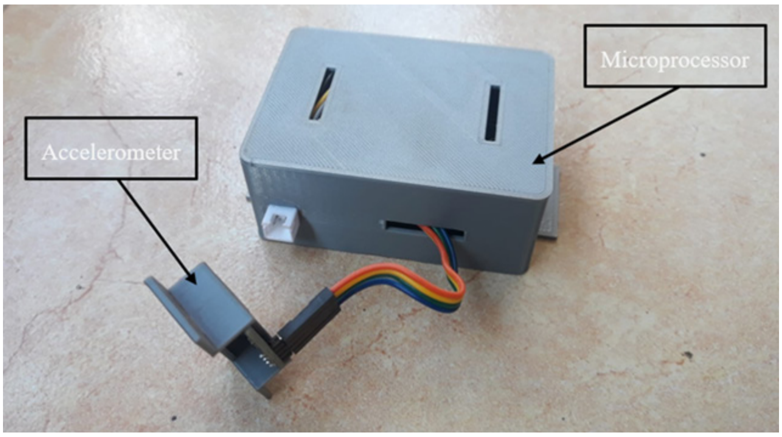


**FIGURE 6**
Accelerometer and microprocessor unit
**Source:** Field survey, 2025

established best practice limits, specifically those outlined in ISO 2631, AISC, and Wright & Walker thresholds. The t-test was chosen due to the small sample size ($n < 30$) and the pairwise nature of the comparisons between observed values and comfort criteria (Bevans, 2020). Each reference standard was evaluated separately against the measured data to determine whether any statistically significant differences existed. The analysis was conducted using Microsoft Excel® (Microsoft, 2025).

**Research Limitations**

Security at the site was inadequate, exposing the sensors to potential vandalism if left unattended. To mitigate this risk, research assistants were assigned to guard the equipment during the data collection periods. This precaution limited data acquisition to daytime hours only, thereby excluding vibration responses that may occur at night. Additionally, budgetary constraints restricted data collection to areas accessible by ladder. Accessing elevated sections of the bridge would have required renting aerial work platforms, which was not feasible within the available funding.

## RESULTS

**Hypothesis Test Results**

The T-test was carried out at a 95% confidence level with a 5% significance level. The results of the analysis are shown in **Table 2**.

The analysis shows that the difference between the measured peak acceleration data and the various

**TABLE 2**
T-test statistics between measured data and various comfort criteria limits

| Measured accelerations vs Reference values | p-value | Threshold p-value | Inference |
|---|---|---|---|
| Measured accelerations and ISO 2631 Limits | 0.000050712 | 0.05 | P-value < 0.05, the difference is statistically significant in the study. |
| Measured accelerations and AISC Limits | 0.093385799 | 0.05 | P-value > than 0.05 indicates that the difference is statistically insignificant to the study. |
| Measured accelerations and Wright &Walker Limits | 0.000017604 | 0.05 | P-value < 0.05, the difference is statistically significant in the study. |

**Source:** Field survey, 2025

comfort criteria limits is significant at a 95% confidence level. However, the confidence level for comparing measured accelerations with AISC is below 95%.

**Acceleration measurements**

Five sensors were mounted on the soffit of the bridge beams at ½ span, from S1 to S5, as illustrated in **Figures 4** and **5**. Acceleration measurements were recorded for 143 minutes, utilising the in-situ traffic as the source of vibration excitation. Data was collected on the x, y, and z axes. The research presents the accelerations along the z-axis, as these were the most significant of the three axes. Subsequently, the acceleration data was plotted using Python libraries for visualisation. The acceleration measurements are shown in **Figures 8** to **12**. The in-situ acceleration measurements and video recordings were conducted on 3rd February 2023. The peak accelerations caused by the HGV, as shown in **Figure 7**, were plotted as a bar graph against the various comfort criteria limits reviewed in this study and are presented in **Figure 13**.


**FIGURE 7**
Four-axle HGV during ambient traffic testing
**Source:** Field survey, 2025

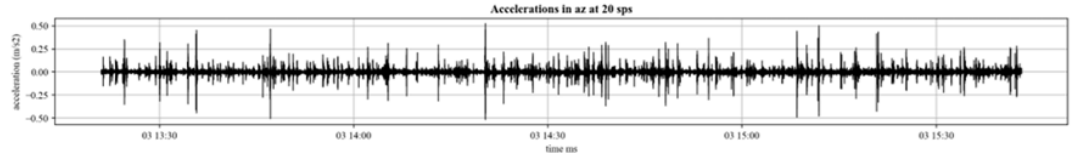


**FIGURE 8**
Acceleration measurements at sensor S1
**Source:** Field survey, 2025

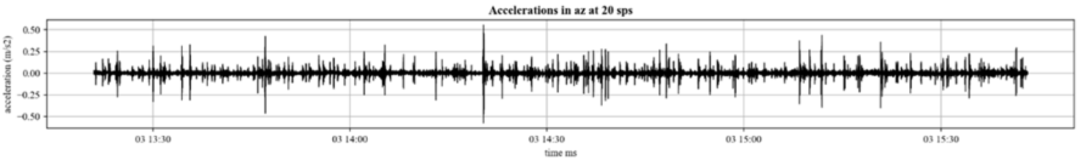


**FIGURE 9**
Acceleration measurements at sensor S2
**Source:** Field survey, 2025

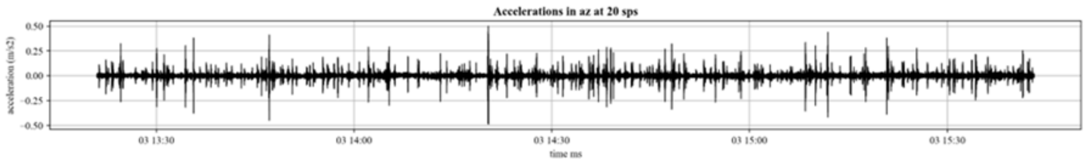


**FIGURE 10**
Acceleration measurements at sensor S3
**Source:** Field survey, 2025

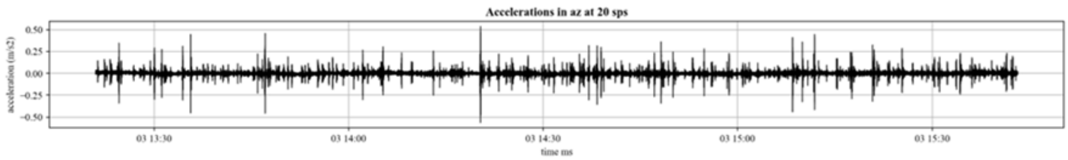


**FIGURE 11**
Acceleration measurements at sensor S4
**Source:** Field survey, 2025

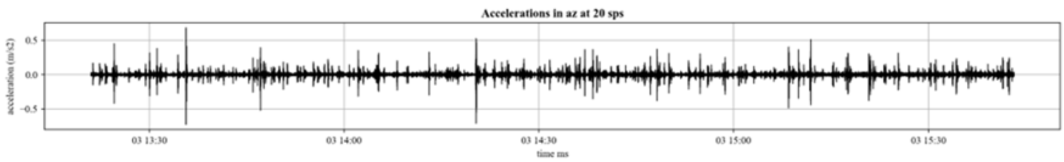


**FIGURE 12**
Acceleration measurements at sensor S5
**Source:** Field survey, 2025

During the vibration test period, accelerations in the z-direction were the most significant compared to those in the x and y directions. It was observed that the threshold of perceivable accelerations was exceeded in the z-axis for each identified peak, with the threshold value of perceivable accelerations being 0.254 m/s². Across all five sensors, a four-axle HGV in **Figure 7** caused accelerations that were 87% to 110% above the threshold recommended by Wright and Walker. The vibrations from the HGV surpassed the ISO 2361 comfort limits for all sensors by between 49% and 73%. Similarly, sensors S1 to S5 exceeded the AISC threshold of 0.491 m/s² by between 4% and 18%, as shown in

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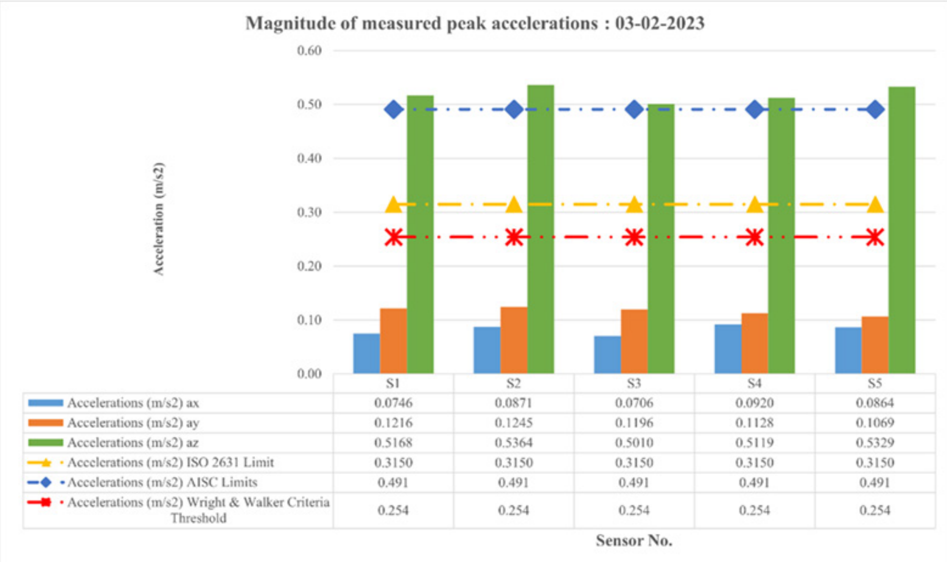


**FIGURE 13**
Comparison of the magnitude of measured accelerations
**Source:** Field survey, 2025

**Figure 11**. Peak accelerations in the plots were mainly caused by a truck crossing the bridge, as confirmed by comparing the timestamps of the peaks with the video recording.

The highest peak acceleration occurred when a 4-axle HGV crossed the bridge at 14:20 hrs. Small cars were observed to produce accelerations on the bridge of less than 0.1 m/s², which are not imperceptible according to the Wright and Walker criteria and fall below the discomfort zones specified by the AISC and ISO 2361 standards. The presence of permanent deflection has altered the bridge's road profile, leading to increased resistance from vehicle suspension systems as they attempt to stabilise under the uneven conditions. This increased resistance results in greater dynamic interaction between the vehicles and the bridge deck, manifesting as high-amplitude acceleration vibrations transmitted to the structure.

T-test p-values comparing measured data with those of Wright & Walker and ISO 2631 are below 0.05, as shown in **Table 2**, indicating statistically significant differences. This is because the measured peak accelerations exceed the comfort values by more than 50%. For ISO 2631 limits, the percentage difference between measured accelerations and the limits ranged from 51% to 70%, as shown in **Tables 3** and **5.**

T-test p-values comparing measured data with those of AISC limits are above 0.05, as shown in **Table 2**. This indicates that the difference between the measured accelerations and the criteria limit is not statistically significant. However, this does not imply that the data is invalid; rather, it indicates that the difference between the comparisons is

**TABLE 3**
Comparison of measured accelerations and ISO 2631

| Sensor No. | Measured Accelerations (m/s²) | ISO 2631 Limits (m/s²) | % Difference |
|---|---|---|---|
| S1 | 0.5168 | 0.351 | 64% |
| S2 | 0.5364 | 0.351 | 70% |
| S3 | 0.4756 | 0.351 | 51% |
| S4 | 0.5119 | 0.351 | 63% |
| S5 | 0.5329 | 0.351 | 69% |

**Source:** Field survey, 2025

converging towards zero, but the data remains informative. **Table 4** illustrates this well, as the difference between the measured accelerations and AISC limits ranges from -3% to 9%. The AISC limits are 5% of the gravitational force, while the Wright & Walker limits are observed to be 2.6% of the gravitational force. The AISC limits provide a higher threshold level for vibrations than the other two comfort criteria limits, thereby yielding a high p-value.

## CONCLUSION

The acceleration measurements indicate that perceivable vibrations are present on the Kangundo Road R-o-R bridge under HCV traffic. The presence of HGV traffic on the bridge causes vibrations that are both perceptible and uncomfortable to humans under the three criteria limits reviewed. The vibrations measured exceed the Wright & Walker limits of perception by between 87% to 110% for the five sensors, which have the lowest comfort criteria limit reviewed. The amplitude of accelerations resulting from small vehicle traffic is below the perceivable threshold and does not cause discomfort to humans.

Permanent deflections on the deck cause increased dynamic deflections in the bridge superstructure, which can raise tensile stress levels at the soffit, potentially leading to cracking. Repeated loading and unloading can lead to the growth of tensile cracks, significantly reducing the bridge's service life due to early fatigue.

The Wright & Walker limits appear to be more stringent. They may be more suitable in urban situations where passengers or maintenance crews spend more time on bridges due to traffic congestion or similar issues, compared to the AISC limits for exterior footbridges, where the user is in a state of continuous motion. Acceleration measurements in the x and y directions were not significant and were therefore ignored. The ADXL355 and MPU9250 accelerometers are appropriate for measuring accelerations on road bridges.

## RECOMMENDATIONS

Based on the findings, the study recommends;

i. Adopt Strict Vibration Thresholds in Urban Bridges
   The Wright and Walker (1972) limits, being more conservative, are better suited for urban bridges where pedestrians, stationary

**TABLE 4**
Comparison of measured accelerations and AISC

| Sensor No. | Measured Accelerations ($m/s^2$) | AISC Limits ($m/s^2$) | % Difference |
|---|---|---|---|
| S1 | 0.5168 | 0.491 | 5% |
| S2 | 0.5364 | 0.491 | 9% |
| S3 | 0.4756 | 0.491 | -3% |
| S4 | 0.5119 | 0.491 | 4% |
| S5 | 0.5329 | 0.491 | 9% |

**Source:** Field survey, 2025

**TABLE 5**
Comparison of measured accelerations and Wright &Walker Limits

| Sensor No. | Measured Accelerations ($m/s^2$) | Wright & Walker Limits ($m/s^2$) | % Difference |
|---|---|---|---|
| S1 | 0.5168 | 0.351 | 103% |
| S2 | 0.5364 | 0.351 | 111% |
| S3 | 0.4756 | 0.351 | 87% |
| S4 | 0.5119 | 0.351 | 102% |
| S5 | 0.5329 | 0.351 | 110% |

**Source:** Field survey, 2025

passengers, and maintenance crews may spend extended periods. These thresholds should be considered in the design and assessment of bridges to enhance user comfort and safety,

ii. Incorporation of Acceleration Monitoring in Routine Inspections
Acceleration should be integrated as a key parameter in bridge health monitoring, particularly for structures that exhibit permanent deflection. Its sensitivity to human perception makes it a critical measure of serviceability,

iii. Use of Low-Cost Accelerometers for Structural Monitoring
The ADXL355 and MPU9250 sensors demonstrated reliable performance in capturing bridge vibrations. Their affordability and ease of deployment make them ideal for continuous or periodic monitoring in resource-constrained environments, and

iv. Enforce Axle Load Limits Strictly
Overloaded vehicles amplify dynamic effects and accelerate fatigue-related damage. Strengthening axle load enforcement will help prolong the service life of bridges.

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