Sensors, standards and analysis techniques for road transport vibration: A systematic review

Emmanuel Kefas Bwade, Bashir Aliyu, Yakubu Ibrahim Tashiwa

1Department of Agricultural and Bio-Environmental Engineering Technology, Federal Polytechnic, Mubi-650231, Adamawa State, Nigeria
2Department of Agricultural and Environmental Engineering, Modibbo Adama University, Yola- 640261, Adamawa State, Nigeria

*Corresponding Author email: bwade.pub@gmail.com

ABSTRACT

This comprehensive review paper analyzes 20 published articles focused on the instrumentation and analysis of road transport vibrations. The study encompasses the distribution of articles based on databases, journals, and publication years, revealing trends in research sources. The examination of sensors and standards emphasizes the critical role of vibration sensor selection and the application of standards, with a focus on accelerometer designs and the prevalence of ASTM D4169-16. The paper delves into various analytical methods, highlighting the frequent use of power spectral density (PSD) and the application of these methods in understanding vibration frequencies and their effects on different transportation conditions. The review identifies key areas for future research, emphasizing the need for refined instrumentation methodologies, standardized standards, and exploration of advanced analytical techniques, considering the dynamic nature of real-world vibrations and emerging technologies in the road transport landscape. Additionally, the review suggests future investigations into optimizing packaging designs and developing innovative materials with vibration-damping properties to enhance the safety and efficiency of road transportation systems.

Keywords: Road Vibration; Sensor Selection; ASTM Standards; Accelerometer; PSD

1. INTRODUCTION

The past few decades have witnessed an unprecedented increase in the human population, globally. A study by Crist et al. (2022) predicted that, by 2050 and 2100, the population will have grown from 7.9 billion in 2022 to 9.7 billion and 10.9 billion, respectively. Several issues, including food insecurity, have been brought about by population growth, prompting the launch of numerous initiatives. These initiatives include increasing crop yields worldwide, creating novel fruit, vegetable, and crop cultivars, and figuring out why agricultural materials lose their quality after harvest (Battersby & Watson, 2018; Wijeratna-Yapa & Pathirana, 2022). Some of the key factors linked with the increased postharvest loss are infestations by pests and diseases, storage conditions (temperature and relative humidity), and handling/transport-related problems. Agriculture and biological scientists have studied disease, pests, and storage conditions in great detail; however, the effects of environments and transportation facilities on food and agricultural material losses are a relatively new area of study.

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Significantly, mechanical shock and vibration emerge as primary culprits causing damage to fresh agricultural materials during transit (Fernando et al., 2019; Park et al., 2020). As road transport vehicles navigate through material shipments, factors such as cargo characteristics, road ride quality, truck specifications (payload capacity, suspension system type), travel speed, and cargo type collectively contribute to varying levels of shock and vibration intensities (Park et al., 2020; Ranathunga et al., 2010; Zhou & Wang, 2018). To comprehend and assess these intensities, several standards have been developed, including ASTM D4169-79 through ASTM D4169-16, ASTM D4728-01, ISTA 3A, ISTA 3H, ISTA 4AB, ISO 13355, and the International Roughness Index (IRI) (Chaiwong et al., 2021; Park et al., 2020; Singh et al., 2017; Zhou et al., 2015). These standards offer procedures and specifications for testing the ability of packaged products and shipping containers to withstand shocks, vibrations, and compression in real or laboratory transport environments. However, despite the existence of these standards, findings from previous studies exhibit inconsistencies. While some studies report consistency in vibration profiles and levels between local roads and established standards (Lu et al., 2010; Park et al., 2020; Paternoster et al., 2018), others present divergent results. For example, studies in Korea (Singh et al., 2007) and India (Vasudevan et al., 2020; Zhou et al., 2015) reported higher lateral, longitudinal and vertical vibration profiles than those suggested by ASTM D4169.

Accelerometers, including AS-10GB, SAVER 3X90, Brue & Kjaer, ADXL 337, and DTS-50 (Barchi et al., 2002; Berardinelli et al., 2003; Chaiwong et al., 2021; Park et al., 2020; Singh et al., 2007; Zhou & Wang, 2018), play a crucial role in assessing vibrations in the road transport environment. Although accelerometers have been used quite widely among vibration researchers and material handlers, but not without limitations. For instance, their effectiveness diminishes when the frequency of interest exceeds 1/5th of the accelerometer’s resonant frequency. Piezoelectric accelerometers also face limitations in low-frequency measurements (Park et al., 2020; Shahbazi et al., 2010). Additionally, non-wireless accelerometers with long cables may introduce errors due to cable capacitance at high frequencies (Lu et al., 2008; Seydim & Dawson, 1999). When handling vibration data obtained through field sampling, a significant amount of complexity arises due to the sheer volume of generated data. Analyzing the large volumes of data generated in field vibration studies presents another challenge (Vursavuş & Özgüven, 2004). While simple statistical tools like mean and standard deviation are commonly applied (Aba et al., 2012; Park et al., 2020), other studies employ more advanced techniques such as probability density function (PDF), cumulative frequency distribution (CDF), power spectral density (PSD), and the Welch method (Garcia-Romeu-Martinez et al., 2008; Garrido et al., 2023; Paternoster et al., 2018; Ranathunga et al., 2010; Zhou et al., 2015).

The application of diverse vibration sensors/accelerometers, testing protocols/standards, methodologies, and analysis techniques poses a considerable challenge for direct result comparisons. In light of these considerations, this study seeks to address questions regarding the types of standards, sensors, and analysis techniques utilized by researchers in the realm of road transport evaluation.
2. METHODOLOGY

2.1. SEARCH STRATEGY:

For this systematic review, we developed a search strategy to identify relevant literature. This strategy was tailored to two databases: Google Scholar and Research Rabbit. The following search terms were used: Road Vibration Analysis AND "ASTM D4169" OR Vibration Standard. All searches spanned between 1992 and 2023.

2.2. SELECTION CRITERIA:

The selection criteria were based on the documented PRISMA guidelines (Moher et al., 2009). The search span was from 1992-2023. All articles published before 1992 and after 2023 were excluded. The selection process is shown in Fig. 1.

2.3. DATA EXTRACTION:

In the data extraction phase, 20 articles were selected from a total of 248 records identified (Fig. 1) and the characteristics extracted were:

1. Article must be an original paper. Review papers, reports, case studies, patents and textbooks were excluded.
2. The article must be complete paper published in English language.
3. The extracted articles were published between 1992 to 2023.

![Flowchart: Selection process using flowchart](image-url)
3. RESULTS AND DISCUSSION

3.1. CHARACTERIZATION OF ARTICLES

For this study, 20 published articles were chosen based on the criteria outlined in the materials and method section. The distribution of the reviewed articles is presented as follows:

3.1.1. Distribution of articles by database

Two databases were used for sourcing articles for the study (Google Scholar and Research Rabbit). Most of the articles (65.0%) were sourced from Google Scholar while the remaining articles (35.0%) were sourced from the Research Rabbit database (Fig. 2).

![Fig. 2. Articles by database](image)

3.1.2. Distribution of journals by number of cites

The 20 articles used in this study were published in 15 journals and were cited by 858 other articles (858 cites). The distribution of journals by the number of cites per journal is shown in Fig. 3. The Journal of Packaging Technology and Sciences received the highest number of cites (26.0%), this was followed by the Journal of Biosystem Engineering (21.4%) and, the Turkish Journal of Agriculture and Forestry (16.1%). All other journals recorded a low number of cites (0.3 - 7.8%) with two journals recording zero number of citations (Journal of Water Resources and Journal of Packaging Technology and Science).

![Fig. 3. Percentage distribution of journals by number of cites](image)
3.1.3. Distribution of articles by year of publication and database

Fig. 4 presents the distribution of articles by the year of publication and the database used in sourcing the reviewed articles. The figure shows that, across the two databases used, most of the articles (60%) on the subject matter were published in the last decade (2012 – 2023) compared to the year range between 1999 to 2010 which recorded only 40% of the articles reviewed in this study. It also showed that while most of the articles searched between 2010 – 2023 were obtained on the Google Scholar database, Research Rabbit was more beneficial in sourcing articles published before 2010.

![Fig. 4. Articles by database and year of publication](image)

3.1.4. Distribution of articles by study approach/environment

Based on the stated criteria, the study revealed that previous researchers have investigated road transport vibration using four different approaches/environments, namely, field study, laboratory study, a combination based approach (field and laboratory study conducted in sequence) and most recently the use of computer simulation (Fig. 5). Most of the articles (65.0%) adopted field studies for the investigation of road transport vibration. This was followed by the laboratory simulation of the road transport vibration (25.0%) while the computer simulation as well as the combination method represent 5% of each of the articles reviewed in this study (Fig. 5). The widespread adoption of the field study approach may not be unrelated to the high cost of instrumentation associated with the laboratory-based approach (Cardona et al., 2021; Komarizadehast et al., 2021). Nevertheless, a laboratory-based approach provides the opportunity to simultaneously study the effects of multiple levels of factors affecting vibration levels on transported loads (i.e., factorial experiment) (Bernad et al., 2011; Kipp, 2008; Rouillard et al., 2021). Although the costs associated with computer simulations may be comparatively lower, the study indicates low patronage among researchers. The low adoption observed by computer simulations among researchers in the road transport environment may be attributed to the fact that the approach is relatively new and the analysis technique required for computer simulations is complex.
3.2. RESEARCH QUESTIONS (RQ)

To allow for a deeper understanding of the instrumentation and analysis of the road transport environment, three research questions were formulated as follows:

RQ1: what sensors and standards are necessary for the instrumentation of road transport environment?

RQ2: What techniques or analytical tools are necessary for the analysis of vibration data from the road transport environment?

3.2.1. Sensors and standards for road transport vibration

Vibrations in the road-transport environment result from the interaction between the vehicle and the road. While an instantaneous value can be predicted for harmonic excitations, the oscillation process in the road-transport environment is complex and its amplitude at a specific time cannot be accurately predicted (Ishikawa et al., 2009; Zhou et al., 2015). This highlights the need to use an empirical method to determine vibration levels resulting from a given environment (Börocz, 2019). To achieve higher accuracy when measuring vibrations in the road transport environment, the correct choice of vibration sensor is crucial.

This study found consistency in the use of different accelerometer designs for vibration monitoring and evaluation. We identified up to 10 different accelerometer designs that were used to assess vibration levels and their effects on transported loads (Fig. 6). As shown in Fig. 6, only 15% of the 20 articles did not use an accelerometer in their studies. The most preferred accelerometer designs for assessing the road-transport environment are SÄVER 3X 90 (Tri-axial Accelerometer, Lasmont Corp., Monterey, CA, USA) (Aba et al., 2012; Fernando et al., 2019; Seydim & Dawson, 1999; Singh et al., 2017; Tihanyi-Kovács et al., 2023) and Brüel & Kjær, 4393 V (piezoelectric accelerometer) (Barchi et al., 2002; Berardinelli et al., 2003; Paternoster et al., 2018; Zhou et al., 2015), each of which was used by 20% of the reviewed article, respectively. These were followed by DTS -50 (Accelerometer, Shinyei Technology, Japan) (Garrido et al., 2023; Lu et al., 2008), which recorded 10%. All other accelerometer designs were used by 5% of the articles.
Furthermore, the review has also established a wide range of application areas of the vibration sensors which included investigating the effect of vibration levels on shipping containers (Böröcz, 2019), and logistic transportation on fresh agricultural cargoes such as tomatoes bananas, guava, loquat, watermelon and on beer (Aba et al., 2012; Barchi et al., 2002; Chaiwong et al., 2021; Fernando et al., 2019; Paternoster et al., 2018) as well as for studying the effects of transport vibration on the growth rate of microorganisms in transported table water (Tihanyi-Kovács et al., 2023) (Table 1).

**Table 1. Details of vibration sensors**

<table>
<thead>
<tr>
<th>S#</th>
<th>Vibration Sensor/Accelerometer</th>
<th>Application</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SAVER 3X90 (Lansmont Corp, Monterey, CA, USA)</td>
<td>Effects of vibration and acceleration on ISO container shipments</td>
<td>(Aba et al., 2012; Böröcz, 2019; Fernando et al., 2019; Park et al., 2020; Seydim &amp; Dawson, 1999; Singh et al., 2017; Tihanyi-Kovács et al., 2023; Zhou &amp; Wang, 2018)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vibration levels in express logistics transportation</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Vibration levels in Korean truck transport</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact of mechanical agitation on microbial growth in water</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Measurement of vibration and mechanical damage to bananas</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Impact of road conditions on tomato damage during transportation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measurement and analysis of transport vibrations for LTL freight</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Brüel &amp; Kjær, 4393 V (piezoelectric accelerometer, Denmark)</td>
<td>Comparison of measured vibration levels with standards</td>
<td>(Barchi et al., 2002; Berardinelli et al., 2003; Chaiwong et al., 2021; Paternoster et al., 2018; Zhou et al., 2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vibration bruising in ‘Glom Sali’ guava fruit</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Investigation of vibrations during transportation of loquats</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Evaluation of damage to packaged pears during simulated transport</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Investigation of vibrations during beer transportation</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>DTS-50 (Shinyei Tech. Ltd., Japan)</td>
<td>Shock and vibration analysis in truck transport</td>
<td>(Garrido et al., 2023; Lu et al., 2008)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effects of different packaging materials on egg breakage</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vibration and shock analysis of fruit and vegetable transport</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>X-Viber, X-25 (Accelerometer, Switzerland)</td>
<td>Evaluation of watermelon damage during transportation</td>
<td>(Shahbazi et al., 2010)</td>
</tr>
<tr>
<td>S#</td>
<td>Vibration Sensor/ Accelerometer</td>
<td>Application</td>
<td>Reference</td>
</tr>
<tr>
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</tr>
<tr>
<td>5</td>
<td>LIS302DL MEMS (Steval, tri-axial accelerometer)</td>
<td>Impact of road quality on tomato damage during transportation</td>
<td>(Ranathunga et al., 2010)</td>
</tr>
<tr>
<td>6</td>
<td>ADXL 337 accelerometer</td>
<td>Impact of vibrations on beer transportation</td>
<td>(Paternoster et al., 2018)</td>
</tr>
</tbody>
</table>

Zhou et al. (2018) utilized SAVER 3X90 accelerometers to investigate transport vibrations in South China. Park et al. (2020) used an identical accelerometer to investigate the degree of agreement between the vibration profiles of the sampled roads in Korea and those of the International standards analyzed based on the Power Spectral Density (PSD). Borocz (2019) assessed transport vibration in Hungary, underscoring the importance of considering road conditions and speed. Whereas all of these researchers (Böröcz, 2019; Park et al., 2020; Singh et al., 2017; Zhou & Wang, 2018) used identical accelerometers for their respective studies (SAVER 3X90) they reported different findings. The findings by Park et al. (2020) reported the difference in vibration level between the investigated roads, Borocz (2019) underscored the contributions of road condition and vehicle speed on the resulting vibration levels during transportation. Zhou et al. (2018) documented values for vertical axis vibration. Singh et al. (2017) on the other hand examined the vibration characteristics of a vehicle but paid more attention to the effects of payload capacity on the vibration levels of the vehicle during transport.

The application of Bruel and Kjaer 4393 V in transport vibration studies is documented in previous studies (Barchi et al., 2002; Berardinelli et al., 2003; Chaiwong et al., 2021). In Chaiwong et al. (2021), vibration testing on guava peel revealed that acceleration, particularly at 8.826 m/s², significantly influenced vibration bruising, with optimized treatment conditions identified. Barchi et al. (2002) measured vibrations in a semi-trailer during loquat transportation and found position-dependent power spectral density (PSD) with a characteristic peak at 16 Hz. Additionally, insulating sheets reduced fruit damage by 20–40%. Berardinelli et al. (2003) simulated medium-long transportation for packaged pears and observed vibro-pressure damage in different cultivars, with no significant differences among acceleration levels but variations in damage dimensions based on floor position. While all studies employed the identical accelerometer (Bruel and Kjaer 4393 V), differences in fruit types, transportation conditions, and damage characteristics contributed to distinct findings, with none of the articles reporting the limitation/setback experienced due to the usage of the selected vibration sensor.

On the other hand, Lu et al. (2008) employed the AS-10GB accelerometer to analyze shock and vibration during truck transport in Japan, revealing non-random vibrations with sporadic shocks caused by road conditions. After isolating shocks, they reconstructed the remaining acceleration as continuous vibration, following a normal probability distribution. Though not so widely, the application of X-Viber/ X-25 accelerometer for investigating transport vibration has also been documented (Shahbazi et al., 2010). Their study focused on assessing the effects of vibration parameters and fruit position on watermelon damage, highlighting significant impacts on the modulus of elasticity. While Lu et al.(2008) concentrated on overall transport vibration patterns, Shahbazi et al.(2010) specifically
examined the consequences of vibration on watermelon damage, emphasizing the significance of controlled variables in such assessments.

The application of SAVER 3X90 by a comparably higher number of researchers with diverse research focus (as seen in Table 1) has underscored the adaptability of the SAVER 3X90 for various aspects of transport vibration. The AS-10GB accelerometer, employed by Lu et al. (2008), demonstrated its suitability for analyzing non-random vibrations with sporadic shocks during truck transport in Japan. The Bruel & Kjaer accelerometer (Barchi et al., 2002; Berardinelli et al., 2003) exhibited applicability for assessing vibrations during loquat transportation and damage to pears, although detailed performance assessment was limited. The X-Viber and X-25 accelerometers, utilized by Shahbazi et al. (2010), proved effective in studying vibration parameters related to watermelon damage, emphasizing the importance of considering specific study objectives when selecting an accelerometer for transport vibration analysis.

While each of the reviewed studies seems to highlight the benefits/advantages associated with a vibration sensor they adopted, there is no sufficient information on the relative suitability of these sensors for road transport studies as such most of the individual studies relied on the cost of sensor, ease of application, frequency range and convenience of data analysis as criteria for selecting a vibration sensor.

Selecting and applying an appropriate vibration standard is critical to the accuracy and validity of any vibration instrumentation. This review identified the application of eight categories of vibration standards used to monitor/measure the vibrations resulting from vehicle-road surface interaction (Fig. 7). While several studies relied on one standard, mainly ASTM D4169, to study road vibration (Ranathunga et al., 2010; Tihanýi-Kovács et al., 2023), other researchers used a combination of these standards, e.g. a combination of ASTM D4169, ISTA 3B, 3 H and ISTA 4AB (Zhou & Wang, 2018), ASTM D4728 and ISO (Paternoster et al., 2018). The most widely used vibration standard, as shown in Figure 5, is ASTM (D4169-16) and a combination of ASTM D4169 (Zhou & Wang, 2018) + ISTA (3B, 3H and 4AB), but each of the remaining standards was used by 5% the article (Table 2).

Table 2. Variation of vibration standards with study focus

<table>
<thead>
<tr>
<th>Vibration Standard</th>
<th>The focus of the Study</th>
<th>Limitation/Weakness of the Standard</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM D4169-16 and ISTA 4AB</td>
<td>Vibration levels in express logistics transportation</td>
<td>May not fully encapsulate the real-world range and intensity of vibrations in transportation.</td>
<td>(Zhou et al., 2015)</td>
</tr>
<tr>
<td>ASTM D4169-16 and ISTA 4AB</td>
<td>Vibration bruising in 'Glam Sali' guava fruit</td>
<td>Not stated in the article</td>
<td>(Chaiwong et al., 2021)</td>
</tr>
<tr>
<td>ASTM D4169-16</td>
<td>Measurement of vibration and mechanical damage to bananas as well as microbial growth in water</td>
<td>Not stated in the article</td>
<td>(Fernando et al., 2019; Tihanýi-Kovács et al., 2023)</td>
</tr>
<tr>
<td>IRI</td>
<td>Evaluating the impact of road transportation on the damage inflicted on cargo, specifically tomatoes.</td>
<td>Not stated in the article</td>
<td>(Ranathunga et al., 2010)</td>
</tr>
</tbody>
</table>
It is important to note that Park et al. (2020) specifically examined differences between the ASTM D4169-2016 standard and the vibration profiles observed in the studied truck transport environments in Korea. The study by Park et al. (2020) highlighted the limitations of simulating transportation studies based on the PSD following the methods recommended in the ASTM and suggested developing a more accurate protocol for simulating truck transportation vibrations in Korea. Their focus on comparing domestic transportation vibration levels with international standards suggests a critical examination of the applicability of the ASTM standard to the specific road conditions examined. In contrast, some previous studies (Fernando et al., 2019; Zhou & Wang, 2018) did not observe any differences between the ASTM standard and the vibration profiles of the respective roads examined. Other researchers (Chaiwong et al., 2021; Zhou et al., 2015) used both ASTM D4169 and ISTA 4 AB to study the effects of transport vibrations. Nevertheless, differences were observed in their research focus, methods and the materials studied. While Chaiwong et al. (2021) studied the vibration damage to guavas during transportation, Zhou et al. (2015) focused on studying the fluctuations of vibration levels in China. The time discrepancy between the studies, which were carried out in 2021 and 2015, raises the possibility of further developments or changes in the test methods. While the general use of ASTM D4169 provides a basis for comparison, variations in the type of goods examined, response variables, and test parameters may contribute to disparities in observed vibration effects. The potential use of ISTA 4AB standards was observed in their methodology, but none of the studies demonstrated how vibration levels were affected by the inclusion of ISTA 4AB in the methodology; This makes it difficult to assess its impact on comparative analysis.

Barchi et al. (2002) used ASTM D4728 to evaluate vibration levels during domestic transportation of loquat from Spain to Italy. Their results showed that vibration levels depend significantly on the type of semi-trailer and road conditions. In particular, the study recommended packaging designs that can effectively dampen vibrations and protect loquats from damage. When examining the vibration levels experienced by products transported on both aluminium and steel decks, Singh et al. (2017) used ASTM D4169-2008 and ISTA 3B. Their results showed that aluminium decking has higher vibration levels than steel decking. The study recommended the use of congestion optimization devices and vibration-damping materials to reduce vibrations and protect products during transportation. In the study by Borocz (2019), applying ASTM D4169-2016 and ISTA 3H
standards, the investigation of multimodal container shipping from Hungary to Mexico, India and China found that vibration and acceleration levels were significantly influenced by handling events, racking and stacking systems influenced and transshipments. In particular, extreme accelerations in the vertical (9.37 G) and lateral (4.45 G) directions were observed during handling and transshipment operations, highlighting the need for careful consideration of these factors in packaging design for multimodal container transport. While the studies provide valuable insights, the significant differences in standards, transportation environments, and emphases, as well as potential controversies arising from assumptions and variations in test metrics, underscore the complexity of the topic and the need for further research.

The suitability of ASTM D4169-2016 and ASTM D4169-2008 lies in their comprehensive frameworks for evaluating shipping container performance, including vibration studies. However, these standards may not accurately reproduce the dynamic nature of all transportation scenarios, leading to potential discrepancies. ASTM D4728 is tailored to horizontal vibration effects and is suitable for specific studies, particularly those focused on domestic transportation. However, the limited scope may not allow for a comprehensive assessment of packaging performance in different distribution environments. ISTA 3B and ISTA 3H, developed by the International Safe Transit Association, provide detailed protocols for assessing the impacts of distribution environments on individually packaged products, including vibration in the multimodal shipping context. Despite their usefulness, these standards may not perfectly reflect all aspects of real-world transportation, and specific details related to the handling of events, racking, and stacking systems may not be fully covered. Researchers should carefully consider these limitations and the specific context of their studies when selecting standards for vibration assessments.

Although standards such as ASTM (D4728) provide a random vibration test that is sufficiently accurate to simulate vibrations that occur during the actual distribution and transportation environment, as well as ISO 13355 (2016), which is often used to perform a vertical random vibration test complete, filled transport packaging and loading units under random excitement; however, such standards are purely test methods and cannot be used as stand-alone methods; They must be combined with a set of predetermined requirements, which should include at least the PSD, the duration and the total grams. It is also worthy of note that with the exception of one study (Zhou et al., 2015), who acknowledged a limitation of an adopted road transport standard, none of the reviewed studies reported any limitation/setback associated with using any of the stated standards. Zhou et al. (2018) used ASTM D4169-16 and ISTA 4AB standards and opined that, standards may not fully encapsulate the real-world range and intensity of vibrations in transportation (Table 1).
3.2.2. Vibration Analysis Technique

Vibrations in a real road-transport environment occur in the time domain. Although such signals can provide information about occurrence in the transportation environment, analysis of the recorded signal provides much information about the interaction between vehicle and road profile. The methods used to process such signals have varied among previous researchers. This study identified 10 different methods used in analyzing data from the road-transport environment (Fig. 8). As shown in Fig 8, the observed methods are not entirely different, but some researchers used a combination of several methods to analyze the same vibration data. Based on this study, the most widely used method for analyzing vibration data is power spectral density (PSD), which was used by 45% of the articles examined. This was followed by an analysis of variance (ANOVA) (10%) and a combination of ANOVA and transmissibility ratio (10%). Each of the combination methods was adopted by 5% of the examined articles for vibration analysis. The combination methods observed in this study are fast Fourier transform (FFT), Welch method, cumulative distribution function, CFD; Weibull function; Kurtosis and Skewness (Böröcz, 2019). Others include FFT and CFD (Paternoster et al., 2018); Probability density function (PDF), PSD, kurtosis and skewness (Park et al, 2020), PSD and kurtosis (Zhou et al., 2015), and PSD and PDF (Ishikawa et al., 2009) (Table 3).

Various studies use frequency analysis, particularly power spectral density (PSD), to understand the distribution of oscillation frequencies (Barchi et al., 2002; Ishikawa et al., 2009; Park et al., 2020; Zhou & Wang, 2018). The limitations of PSD are highlighted, including its potential inability to fully represent real-world vibrations. Various studies investigate the effects of transport conditions, speeds, payload sizes and positions within the vehicle on vibration levels (Barchi et al., 2002; Ishikawa et al., 2009; Park et al., 2020). The responses of certain packaging methods to vibration are being studied, with plastic containers, for example, outperforming traditional baskets in reducing pressure damage to tomatoes (Aba et al., 2012). Studies also address the complex interaction of road conditions, truck speed and load mass on vehicle vibrations (Böröcz, 2019; Park et al., 2020; Zhou et al., 2015).
Analytical methods such as fast Fourier transform (FFT), skewness, kurtosis, root mean square (RMS) accelerations, and cumulative distribution functions (CDFs) are used to gain insights into vibration characteristics under various conditions (Böröcz, 2019; Park et al., 2020; Zhou et al., 2015). The effectiveness of different analysis techniques is discussed taking into account the nature of the vibration signal. The limitations of FFT in capturing transient behaviour are pointed out, while power spectral density (PSD) is considered suitable for continuous signals (Chaiwong et al., 2021; Hurley et al., 2013; Jarimopas et al., 2005; Singh et al., 2017).

The combination of analysis techniques is explored to gain benefits from each method simultaneously. About 30% of articles use a combined approach, integrating standards such as ASTM D4169 with statistical tools to provide a comprehensive understanding of vibration data distribution (Aba et al., 2012; Böröcz, 2019; Vursavuş & Özugüven, 2004). Statistical tools such as skewness, kurtosis, CDF, and ANOVA are discussed in the context of their applications in vibration studies. They provide a global overview of the distribution of vibration data, but may not capture localized variations and provide insights into signal dynamics (Böröcz, 2019).

The use of ANOVA and transmission ratio to compare data from different treatments or diseases is highlighted, although challenges such as oversimplification of transmission dynamics and possible nonlinearity are acknowledged. Overall, the knowledge gained from these studies contributes to improving vehicle design, optimizing maintenance schedules and increasing road safety.

Table 3. Vibration analysis techniques

<table>
<thead>
<tr>
<th>S/No</th>
<th>Analysis technique</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power Spectral Density (PSD)</td>
<td>(Barchi et al., 2002; Fernando et al., 2019; Garrido et al., 2023; Grzesica, 2018; Ishikawa et al., 2009; Shahbazi et al., 2010; Tihanyi-Kovács et al., 2023; Zhou et al., 2015)</td>
</tr>
<tr>
<td>2</td>
<td>Power Spectral Density (PSD), Probability Distribution Function (PDF)</td>
<td>(Ishikawa et al., 2009)</td>
</tr>
<tr>
<td>3</td>
<td>Analysis of Variance (ANOVA), Transmissibility ratio</td>
<td>(Aba et al., 2012; Vursavuş &amp; Özugüven, 2004)</td>
</tr>
<tr>
<td>4</td>
<td>Analysis of Variance (ANOVA)</td>
<td>(Berardinelli et al., 2003; Seydim &amp; Dawson, 1999)</td>
</tr>
<tr>
<td>S/No</td>
<td>Analysis technique</td>
<td>Reference</td>
</tr>
<tr>
<td>------</td>
<td>--------------------------------------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>5</td>
<td>Kurtosis, Skewness, Weibull function, Cumulative Function Distribution (CFD)</td>
<td>(Borocz, 2019)</td>
</tr>
<tr>
<td>6</td>
<td>Cumulative Distribution Function (CDF), Fast</td>
<td>(Paternoster et al, 2018)</td>
</tr>
<tr>
<td></td>
<td>Fourier Transform (FFT)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Welch method</td>
<td>(Ranathunga et al, 2010)</td>
</tr>
<tr>
<td>8</td>
<td>Kurtosis, Skewness, Probability Density Function (PDF), Power Spectral Density (PSD)</td>
<td>(Park et al, 2020)</td>
</tr>
<tr>
<td>9</td>
<td>Fast Fourier Transform (FFT)</td>
<td>(Chaiwong et al, 2021)</td>
</tr>
<tr>
<td>10</td>
<td>Spectral analysis (PSD), Kurtosis</td>
<td>(Zhou et al, 2015)</td>
</tr>
</tbody>
</table>

4. CONCLUSION AND RECOMMENDATION

The review paper analyzes 20 articles on road vibration, covering databases, journals and publication years. It studies sensors and finds different accelerometer designs used in different applications. Vibration standards, particularly ASTM D4169-16, play a critical role, although challenges and limitations are acknowledged. Data analysis methods include power spectral density (PSD) and various analysis tools such as FFT, skewness and kurtosis. Studies examine transportation conditions, speeds, payload effects, and packaging methods at the vibration level. The combination of analysis techniques is highlighted for a comprehensive understanding.

Future research on road vibration should prioritize improving instrumentation methods, including sensor selection and standardized standards, to improve the accuracy of vibration assessments. Exploring advanced analytical techniques such as machine learning could provide more nuanced insights while accounting for the dynamic nature of real-world vibrations. Research efforts should also address the impact of new technologies on vibrations in road transport and explore the optimization of packaging designs and innovative materials with vibration-damping properties to improve the safety of fresh agricultural cargoes and the efficiency of road transport systems.

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Conceptualization, E.K. Bwade and B. Aliyu; methodology, Y.I. Tashiwa and B. Aliyu; Writing- original draft preparation, E.K. Bwade; writing-review and editing, B. Aliyu and Y.I. Tashiwa. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest:
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Reference:


