The case for reviewing laboratory-based road transport simulations for packaging optimisation

The Case for Reviewing Laboratory-based Road Transport Simulations for Packaging Optimisation.

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ABSTRACT

Today, there exists a number of standards designed to assist packaging engineers with implementing suitable laboratory testing regimes for road transport. However, these standards generally focus on translational vibrations and do not include other motions that may affect survival rates during transport (e.g. pitch and roll). The standards also do not account for the significant variations in vibration (root mean square) levels that are clearly evident during transport. Further, the analysis and interpretation of vibration frequency spectra typically ignore the possible presence of harmonics or shocks. Most standards also advocate some form of time-compression to reduce testing duration by artificially amplifying the simulated vibrations. Each of these individual approaches combine to render the simulated vibrations currently in use unrepresentative of what occurs during transport, thereby making it difficult to optimise packaging systems. This article focuses on road transport shocks and vibrations and highlights the shortcomings of proposing and making changes to test methods based on limited data obtained from specific transport scenarios. It argues that only once all the evidence, taking into account a broader set of scenarios from multiple studies, has been collected and the correct scientific analysis applied, should changes to test protocols be proposed and implemented. The paper includes specific recommendations for further evidence collection and analysis for each of the main issues associated with road transport vibrations namely: spectral shape; rms levels and test duration; non-vibratory events such as shocks and multi-axis vibrations.

Keywords: Road transport simulation, optimised packaging, laboratory simulation, vibration spectra, rms distributions, shocks, simulation, rms level.

1. INTRODUCTION

As the magnitude of the problems associated with packaging and product waste are becoming increasingly evident, it is critical that packaging systems are designed using environmentally responsible materials and optimised such that the least amount of material is used without compromising product integrity. This is critical if the ambitious targets related to waste set by leading organisations such as the United Nation's sustainable development goals [1], the Ellen Macarthur Foundation vision for the New Plastics Economy [2], the Australian National Waste Policy Action Plan 2019 [3] and the Australian Packaging Covenant's 2025 National Packaging Targets [4] are to be met. Aside from addressing the management of packaging-related waste material, one clear way to address the packaging waste issue is to minimise the amount of packaging used in the first place by applying engineering optimisation and risk management principles. A compromise between the costs associated with excessive packaging and those associated with product damage needs to be carefully balanced. For this to occur, damage rates for various packaging scenarios must be accurate and this can only be achieved by ensuring that realistic representations of distribution environments can be reproduced using laboratory-based simulation.

In most distribution chains, shocks and vibrations from transport vehicles are considered one of the most important causes of product damage as, unlike mechanical handling, they are seen as difficult to control. Furthermore, products are usually exposed to transport for significant periods. Because of this, laboratory transport trials are often undertaken to validate packaging systems to ensure that products reach their destination undamaged. This is usually achieved by following protocols prescribed in a variety of standards. These standards have been developed over a number of years and usually represents a compromise between the latest scientific knowledge, current industrial capabilities and cost. Today, they tend to focus on translational vibrations (mostly heave) and typically do not account for the variations in vibration (rms) levels that are evident during most journeys. Further, the analysis and interpretation of spectral information (frequency spectra) does not include the possible presence of harmonics or shocks which can occur in all modes of transport. Due to challenges associated with identifying shocks and harmonics buried in random vibration signals, they are often ignored [5,6]. In addition, artificial amplification of the simulated vibrations, sometime called time-compression, is often advocated in test protocols (ASTM D4728 for instance) to reduce laboratory test to practical durations [6]. As a result of these simplifications and modifications, the simulated vibrations are not (statistically) representative of the original vibrations and shocks encountered during transport.

In the main, current approaches to simulating transport vibrations under controlled conditions in the laboratory have been in place for at least three decades. These have and continue to be useful for validating the effectiveness of packaging systems for transport without having to resort to expensive, uncontrollable and unrepeatable field trials. However, only a few relatively minor modifications have been implemented over the years. Over the last two decades or so, some argument for more radical changes to the approach have been proposed and argued by a number of researchers. Broadly, these include:

- Varying the vibration root-mean-square (rms) levels
- The superposition of (random) shocks for road vehicles
- Alternative methods for designing accelerated testing
- Including vibratory motions in alternative axes

These initiatives have been introduced sporadically and have not always included sufficient evidence-based arguments to support their adoption. All too often, proposals for a new simulation approach are accompanied with a single study or limited experiments on a single specific material or product type thus lacking in rigour and applicability to a broader range of materials or product types.

Although laboratory-based vibration simulation relates to all modes of transport, by far the most popular is road transport. This is mainly due to the generally larger magnitudes of vibrations produced by road vehicles compared to air, rail and maritime transport [7,8] as well as greater (and often unavoidable) reliance on road transport in the majority of supply chains [9,10,11]. Therefore, this paper will limit its focus on road transport and the important considerations for realistic road transport vibration simulation namely: 1) spectral shape, 2) rms levels and test duration, 3) non-vibratory events such as shocks, and 4) multi-axis testing. It is not the aim of the paper to provide an exhaustive review on each of these topics, but rather, propose recommendations for implementing updates to current vibration simulation methods and to promote further research aimed at producing revised vibration test protocols.

2. POWER DENSITY SPECTRUM (PDS) SHAPE

The Power Density Spectrum (PDS) is used to describe the distribution of vibratory energy, measured as Power Spectral Density (units squared per Hertz) as a function of frequency and forms an essential element for synthesizing random vibrations. All vibration simulation protocols use the PDS to define various tests and these are usually defined as ‘breakpoints’ or Power Spectral Density – frequency coordinates. When used to synthesize vibrations, the PDS inherently yields random vibrations that conform to the Gaussian distribution with a constant rms (where the rms is defined by the square-root of the integral of the PDS). In reality, road vehicle vibrations (RVV) are usually complex and often contaminated with transients (shocks) and harmonics of varying frequencies that can affect the way a PDS is calculated. Furthermore, dynamic coupling between the various motion modes (degrees-of-freedom) of road vehicles (such as pitch and roll) can significantly affect the heave vibrations (hence its spectrum) depending on the location of the vibration sensor. It is also important to stress that the shape of the PDS is primarily a function of the vehicle’s dynamic parameters (suspension characteristics) including payload, whereas speed and road roughness are overwhelmingly responsible for the level of the vibrations and, if linear or near linear behaviour is assumed, typically have little influence on the shape of the PDS.

2.1. Literature review

There exists a clear evolutionary path when it comes the characterisation and simulation of transport vibration which has improved with technological advancements in measurement and recording devices. One of the first test spectra developed, shown in Figure 1, was an envelope of maximum acceleration values as a function of frequency for vibration measured to evaluate the transportation of military equipment on highways [12].

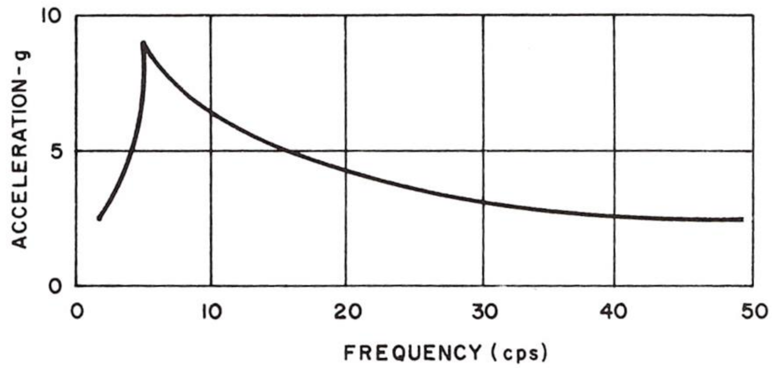

Figure 1. Early vibration frequency spectrum specification for truck transport of military equipment [12].

Ostrem and Rumerman [13] and Schock and Paulson [14] produced a comprehensive literature review of existing information describing shocks and vibrations for the main modes of transport (road, rail, air and sea). The paucity of data precluded statistical analysis, however, the authors produced envelope PDS (peak) for trucks travelling on rough and paved (smooth) roads taken from a variety of roads and vehicle types as shown in Figure 2. These spectra were derived by visual inspection of the oscillography to determine frequencies and amplitudes.

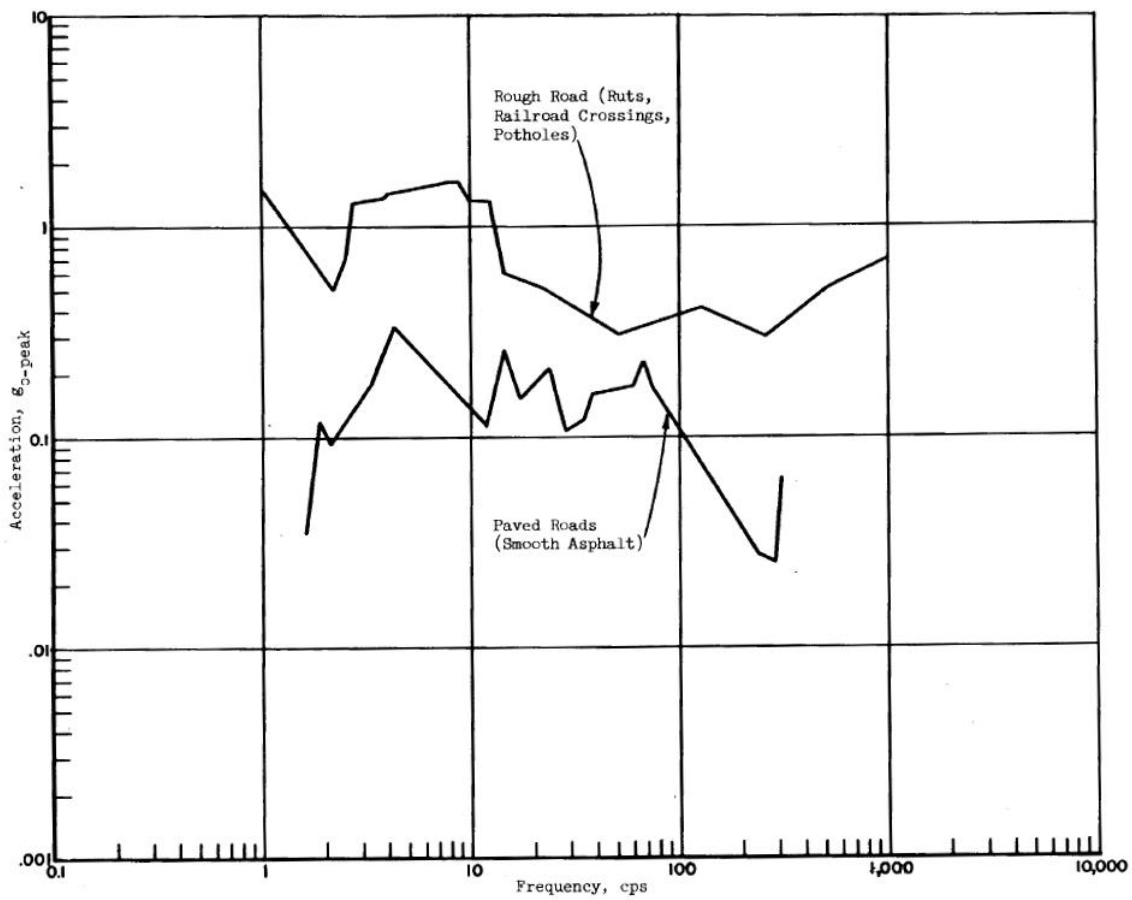

Figure 2. Proposed truck vertical vibration frequency spectra for rough and paved roads [13].

Hanlon and Kelsey [15] (p 18-19) suggested that a typical test procedure would entail "*vibrating a filled package at 250 cycles per minute (or 1 g) for 45 minutes*". This statement is clearly flawed as no amplitude is provided for the cyclic signal. When laboratory transportation trials (used mainly to validate the ability of a package / product to withstand the rigours of transportation) moved from single frequency / constant displacement test machines (so-call transport simulators) to single-axis programmable vibration test systems, the overall (mean) rms vibration level and the corresponding frequency spectrum in the form of the PDS were used to specify the type and level of vibrations to be simulated. Soon thereafter came the introduction of test standards specifying the shape of the PDS, overall rms level and test duration for a variety of scenarios (vehicle types, payloads and assurance levels (safety factor). Today, there are numerous vibration test protocols which have been widely adopted and continue to be used across the globe. A number standards, ASTM D4728-17 for example, recommend the use of measured PDS shapes from specific field trails; however, given the costs associated with direct measurements of route, the PDS shapes listed in standards or related publications are often used.

The published PDS used for synthesizing vibrations were initially constructed from limited environmental data, using approximations to facilitate the setting of the spectral shapes into Random Vibration Controllers (RVCs) to establish standards. These standards are used primarily to ensure that the packaged product will survive the rigours of transport and use conservative vibration levels and simplified PDS shapes that rarely resemble the measured PDS on which they are based [16,17].

Ostrem and Godshall [16] were one of the first to publish information of the PDS of road vehicle vibrations and proposed the use of a ‘vibration envelope curve’ generated by simply joining the spectral peaks (on logarithmic scales) that appears to indiscriminately encompass all frequencies present in the measured data as illustrated in Figure 3 and Figure 4.

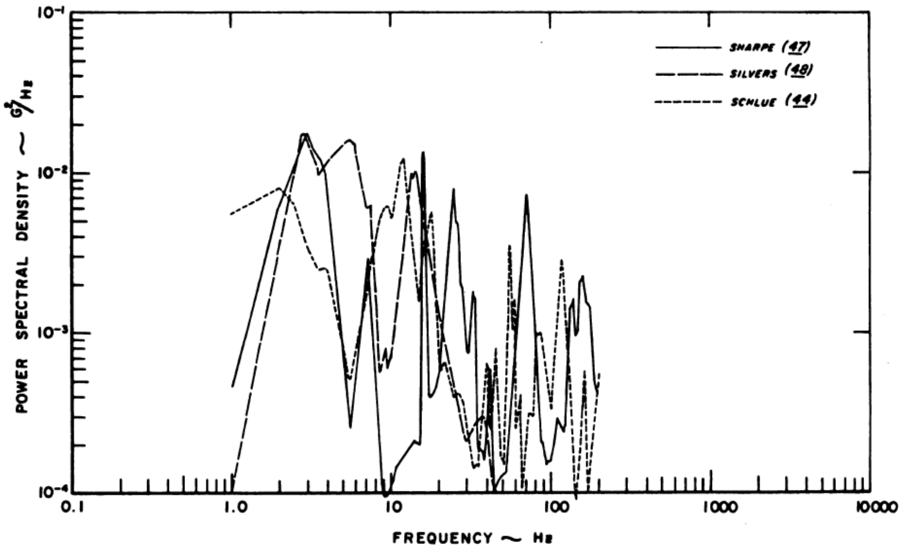

Figure 3. Typical truck frequency spectra (PDS) for three scenarios as published by Ostrem and Godshall [16].

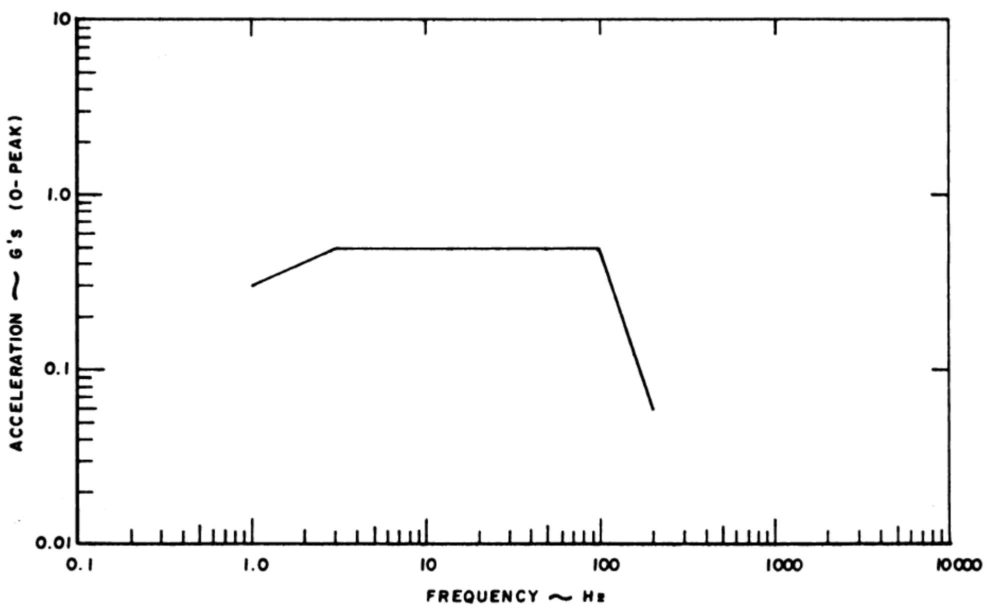

Figure 4. Truck frequency spectra (amplitude) envelope as proposed by Ostrem and Godshall [16]. Note the significant differences to the measured spectra shown in Figure 4.

Ostrem and Godshall [16] suggested that the spectrum in Figure 4 was considered “representative of most trucks”. Rouillard [17] described this approach as highly flawed (but, possibly, deemed necessary at the time) as simplifying the spectrum in this way effectively spreads the vibratory energy across a wide frequency band thus reducing the concentration of vibratory energy in specific frequency bands where resonances exist. When used to evaluate the vibration resistance of packaged products which, more often than not, exhibit multiple resonances, it is difficult to justify this approach. Despite these limitations, simplistically joining spectral peaks to create spectral breakpoints has repeatedly been employed by standard organisations (ASTM at first, then others such as ISO and ISTA) without questioning its validity and appropriateness. The many test spectra published in these standards - illustrated in Figure 5 – have continued to be used around the globe.

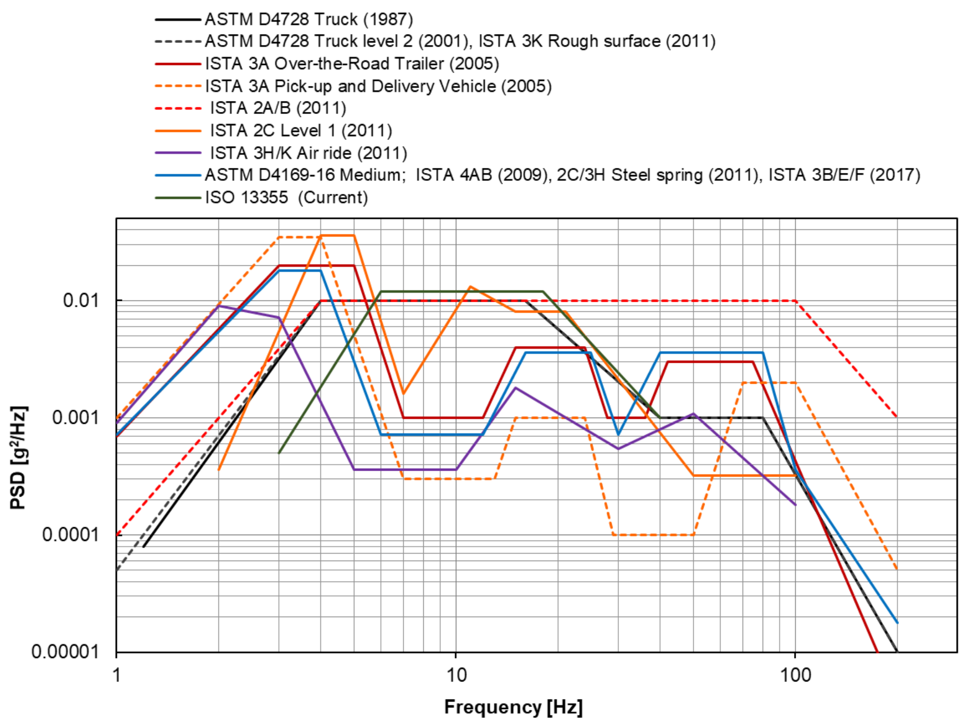

Figure 5. A selected range of Truck PDS including from the original release of ASTM standard D4728 in 1987.

Interestingly, ASTM D4728-01 does not recommend a shape but does provide examples "*for informational purposes only*" which "*do not purport to accurately describe a specific transportation mode or distribution environment*" but, are claimed to have "*evolved from a compilation of field measurements made by several organizations over a period of time*". In all cases, argument for alternatives or changes in the shape of the PDS remain absent or are based on very limited data. For instance, the new PDS specified in 2016 under ASTM D4169 provides no justification for the changes and fails to make clear reference to the data set(s) to validate the changes.

The majority of the numerous studies that have been published on the topic clearly show that measured PDS vary significantly from what standard organisations recommend [16,18,19,20,21,22,23 and 24]. Only a few, isolated examples involving specific vehicle types indicate some similarities to the standard spectra [25,26,8,27,28 and 29]. Understandably, given the difficulties associated in undertaking such vibration surveys, all such studies focus on a specific geographic locations and include a limited number of vehicle types. Their outcomes remain isolated and there appears to have been no concerted effort to undertake a comprehensive comparative study to bring together the wealth of information that has been published over the years.

Despite the strong evidence on the variability of vibration spectra, conservative, simplistic and generic test spectra continue to be the norm in laboratories around the world. Coupled with the propensity to implement 'time compression' or accelerated testing (discussed in the following section), there is a strong argument to suggest that this often leads to over-packaging. The time is ripe to undertake a thorough study of the frequency spectra of measured RVV data that includes analysis using established techniques for dealing with statistical variations in the signal such as harmonics and transients with the aim of producing a range of vibration spectra that are truly representative of the RVV encountered during transport.

2.2. Summary and Recommendations

Despite numerous studies into vibration PDS from road transport vehicles, there has, to date, been no formal attempt to compare the shape of the PDS and relate it to the various types of vehicles and payload conditions. One study by Rouillard et al. [30] published preliminary results showing PDS obtained for a selected range of RVV data covering a broad range of routes and vehicle types (Figure 6). However, no formal comparison was undertaken.

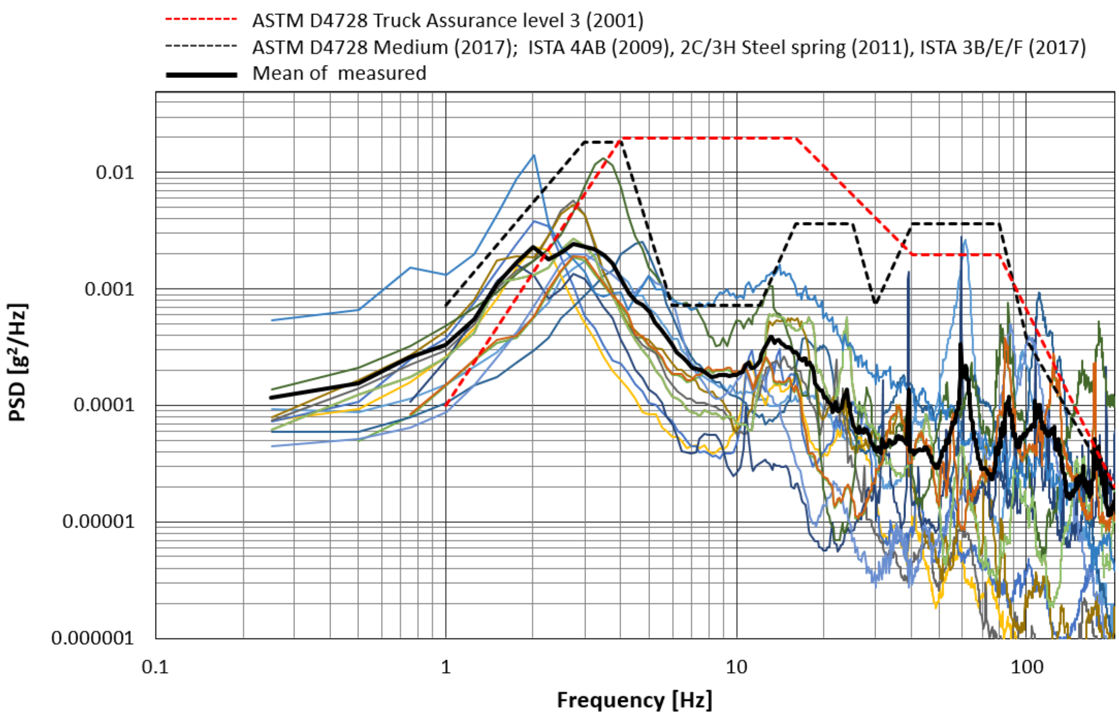

Figure 6. PDS from a variety of measured RVV along with the overall mean and two generic spectra.

Little attention has been paid to issues related to contamination by transients (shocks) and harmonics of varying frequencies. In addition, the effects of dynamic coupling between the various degrees-of-freedom on heave vibration that is dependent on the location on the vehicle have not been properly addressed. It is important to establish the extent to which heave PDS are affected by these issues. Recommendations for further research include:

- Establishing the level to which transients (shock) and varying frequency harmonics affect the calculation of the PDS of random vibration.
- Undertaking a broad survey of road vehicle vibrations for a variety of vehicle types and payloads to establish variations of spectral shape and any relationship with vehicle types and payload. Some preliminary results related to this are presented in Figure 6 although these represent the PDS of raw RVV heave vibration data with no special steps taken to isolate any transients or harmonics or to categorize based on vehicle/route type.
- Explore and validate methods for combining PDS from various scenarios as an alternative to creating test PDS using envelope breakpoints or the simple arithmetic mean.
- Propose updated spectral shapes for laboratory simulation of road vehicle vibrations for testing and validating product and packaging survivability during road transport.

3. TEST (RMS) LEVEL AND DURATION

Given that the vibrations produced by road transport vehicles are random (due to the inherent randomness of the road surface), the main parameter used to describe severity is the rms. Although the overall rms is useful in describing the average severity of vibration along a particular journey, it does not offer any information on the significant variations in vibration severity that occurs throughout the journey. This is essential as a significant proportion of damage caused to products can be attributed to the occasional high rms vibration events that normally occur along road journeys. Despite this, most vibration test protocols continue to use solely the mean rms to specify the severity of the test. Rouillard and Sek [31] gave a typical illustration (Figure 7) of the difference between measured vibration data and those synthesized from the same average PDS. In such cases, the simulated vibrations lack the variations in vibration level that are clearly evident in the measured data.

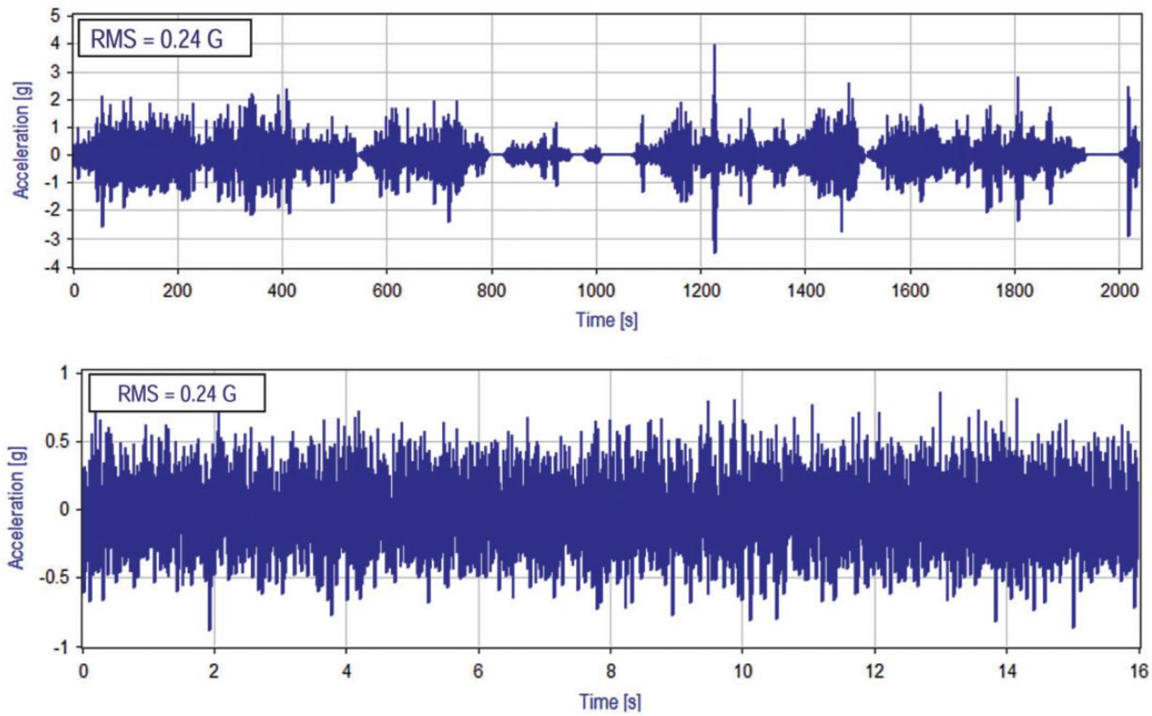

Figure 7. Original, measured vibrations (top) and laboratory-generated vibrations (bottom) from the same PDS (hence same rms). Reproduced from [31].

3.1. Literature review

It has long been recognised that the level of road vehicle vibrations are a function of vehicle type (dynamic characteristics), road roughness, and vehicle speed as shown by Schlue and Phelps [32] who conducted a vibration study to analyse the influence of road roughness, and vehicle loading conditions. This study and many like it [16,33] presented their data as PDS for various statistical levels of occurrences. As recognition that RVV were best described statistically took hold, test protocols to synthesize random vibrations that were similar to the motion of transport vehicles were published by ISO, ASTM and ISTA among others and adopted by the distribution packaging industry [5]. These test protocols using constant rms levels in laboratory-based transportation trials are still widely used to this day. Importantly, these test levels are not based on a specific statistic (such as the mean or median) of vibration levels encountered during typical road journeys but employ artificially-elevated rms levels based on an adaptation of the Basquin model [34] for cyclic fatigue. This approach has long been used for the generation of fatigue curves for engineering materials such as steel; however, it remains unclear whether it is rightly applicable to packaged products in general as the mode of failure is known to vary considerably from one product type to the next. As pointed-out by Shires [6], "… *their applicability to the responses of packaged products to vibration merits question: Many packaging materials are non-metallic; Many failure modes seen in packaged product distribution are not the result of fatigue; The transmissivity of vibration through an assembly of packages may be non-linear with input amplitude (especially near structural resonances); Some failure mechanisms (for example, surface scuffing or closure back-off) may have an endurance limit – i.e. there will be a magnitude of stress cycle below which failure will not occur regardless of the number of stress cycles endured*". Moreover, it is stated in ASTM D4728 (all issues) that "*Test levels are often increased over the actual field data to shorten test time. Any attempt to do so should be done with caution. Use of 'equivalence' techniques of this type may assume linearity of specimen response to test input which is, in fact, not likely*". Convenience and economics demand that laboratory transport trials durations not be excessive so as to be practical. This has been the main driver for applying time-compression techniques to vibration test protocols. This is achieved by calculating the test duration using:

$$t_t a_t^k = t_j a_j^k \qquad (1)$$

where:

t_t and t_j are the test and journey durations respectively,

a_t and a_j are the test and journey rms vibration levels respectively,

k is the Basquin constant which, for fatigue tests, is the slope of the $log(a)$ vs $log(t)$ curve and is dependent on the material (or product) being tested.

Shires [6], who studied the effects of time-compression on broadband random vibration tests, quotes Young [35] and Kipp [36] who claim that, for package testing, the ratio t_j / t_t

is limited to five. However, neither Young nor Kipp give justifications for this limit. Shires concluded that "*the potential error in test severity can be very large if* k *is incorrect*". Shires also states that "*It can be argued that packaging responses to vibration are accumulative in nature and develop more rapidly under more intense vibration; however, it is not known how well these responses are described by the Basquin and Miner–Palmgren equations.*".

Two studies have been presented that suggest that the Basquin model is suitable. The first was presented by Huart et al. [37] who proposed to measure the Basquin constant for prestressed, empty, corrugated cardboard boxes. For the particular box studied, the results suggest that the model is suitable and the method capable of predicting failure times within 8% of the actual measured failure time. More recently, Wang et al. [38, 39] presented a technique for accelerated vibration testing based on the stress response PDS (which they equate to acceleration cycles) of the component in question. The authors claim that this approach, which uses the acceleration rms – life curve of components, represents a broader range of damage mechanism than the Basquin model for fatigue damage. In this case, the time scale (life) is determined by the zeroth and second spectral moment of the component response acceleration spectrum. Their approach is limited to linear packaging systems and was validated using the response acceleration at three arbitrary locations on an unpackaged desktop computer as a test product. The authors acknowledge that more work is required to deal with nonlinear materials and where the excitation is non-Gaussian such as the occurrence of shocks and impacts. This approach was subsequently applied to a paperboard box [40] excited with Gaussian random vibrations. From this the authors showed that the rms – life curve of the corrugated paperboard box could be obtained experimentally and described by both the Basquin model and an exponential function.

To-date, apart from two specific examples as well as some anecdotal testimony, there is no clear objective evidence that time-compression or accelerated vibration testing is universally equivalent to actual transport vibrations and does not lead to over-packaging.

With the availability of powerful and easy-to-use vibration data recorders in the early 1990s, a significant number of studies were undertaken by numerous researchers to characterise various distribution environments using various vehicle and route types. In the early days, the majority of publications reported PDS and overall rms values with no real attempt at analysing the variation in rms level along particular routes [18,41,19 and 8]. More recently, a number of studies have attempted to take into account the random fluctuation in rms level along specific journeys by reporting rms distributions in various forms [42,43,44,45,46,47,48,49,50,51,52,53 and 54]. A review of these papers (among others) was undertaken by Rouillard and Lamb [55] who concluded that these studies all independently report results for very specific vehicle types and routes and do not include comparisons or critique of results from other authors.

Rouillard and Sek [31] recognised the nonstationary nature of RVV by showing how the (local) rms level varied during journey and proposed a strategy for generating artificial nonstationary vibrations by creating a sequence of Gaussian vibrations of varying rms levels and segment lengths. This was followed by a more thorough procedure for decomposing RVV into constituent Gaussian segments as well as a method for synthesizing nonstationary vibrations that better mimic the random fluctuations in rms levels that occur naturally in RVV [56]. Griffiths et al. [57] recognised the nonstationary nature of RVV and proposed a method to produce a decomposed vibration signal comprising a sequence of stationary signals for pre-shipment testing of packaging using the wavelet transform.

The most broad-based results to date are those reported by Rouillard and Lamb [55] who developed a statistical model for rms levels based on a modified version of the Weibull distribution. Despite the increasing recognition of the variation in rms levels during road transport, a universal approach to implement these within test protocols and standards is still lacking and most laboratories today employ the artificially-elevated constant rms, time-compression approach. One exception is the updated version of ASTM D4169 (2016) which recommends a three-level approach (0.4, 0.54 and 0.7 g_{rms} to be generated for 40, 15, and 5 minutes respectively), however, there is no clear evidence to justify the selection of these specific levels and durations nor the sequence in which the different rms levels are produced [58]. The specified rms levels appear still excessive high when compared with rms levels measured during typical (modern) transport routes [55].

3.2. Summary and Recommendations

There is a strong for an evidence-based review of the rms levels and durations used for validation tests and optimising packaging systems for road transport. This is especially the case for situations where information on the route and vehicle types to be used is known and expected vibration levels are statistically low. This opens-up the opportunity for more customised design, testing and validation protocols for specific routes and supply chains leading to truly optimised packaging and a corresponding reduction in packaging waste. In particular, research to investigate the following is recommended:

- The feasibility of using a risk-based statistical approach to quantify and simulate vibration levels for particular route types based on their nominal roughness and vehicle speeds.
- Investigate the effectiveness of simulating non-stationary vibrations (statistical vibration synthesis and elevated kurtosis) by comparing damage rates with those obtained from stationary (Gaussian) vibration tests.
- Undertake a thorough evaluation and influence of accelerated (time-compression) vibration tests by comparing damage rates.
- Explore the applicability and any advantages associated with continually evaluating damage progression rates during simulated vibration tests. This might afford a means by which various vibration simulation schemes could be compared - possibly using real-time (un-scaled) replication as a control.

- The development, validation and calibration of a non-discriminating (in the frequency sense) damage progression index to enable direct comparison of various vibration simulation schemes with a baseline created by testing products using real-time (unscaled) replication of measured RVV signals.
- Generate independent evidence that damage rates achieved under simulated conditions in the laboratory are reproducible.

4. VEHICLE-BORNE SHOCKS (SHOCK-ON-RANDOM)

Interactions between a vehicle and road surface aberrations and defects, as well as features such as kerbs, rail crossings, roundabouts, to name a few, occasionally occur during a journey and are manifested by transient vibrations or shocks. Despite the fact that these shocks can be the difference between shipments reaching their destination unscathed or in a damaged condition, they are rarely included in laboratory-based transport trials as evidenced by standard methods published by ASTM, ISO, and ISTA. This can be attributed mainly to the difficulties associated with identifying shocks buried within (superimposed onto) random vibration signals [16], the challenges associated with extracting the relevant information (such as shape, duration and magnitude) about the shocks and, finally, the difficulties associated with faithfully reproducing shock-on-random vibrations for laboratory-based simulations. One additional difficulty is the reproduction (synthesis) of shocks of varying shape and character using existing laboratory equipment.

The impulse-like character of shocks often contains a wide range of frequencies and, as such, are likely to provoke significant response in the product. The high magnitude of the shocks may also exceed not only the product's fragility but the design range of any protective packaging system [59, 60 ,61 ,62]. Shocks are also likely to provoke different damage mechanisms from random vibrations; the high magnitude may cause plastic deformation, fracture or compression failure (e.g., bruising) to the product, while random vibrations are more likely to cause fatigue failures, product disassembly (e.g., loose fasteners) and surface abrasion. Unlike random vibrations, shocks cannot be adequately described with the average PDS. Furthermore, the PDS of a random signal that contains shocks and transients can sometimes be affected depending on the number of shocks present as well as their amplitude. Therefore, reliance on using the PDS alone for laboratory simulation results in the loss of these important high magnitude events. In a packaging optimisation context, the inclusion of transport-related shocks, namely shock-on-random vibration testing, in laboratory field trials is essential if fit-for-purpose packaging is to be implemented.

4.1. Literature review

Because shocks and random vibrations (and harmonic vibrations for that matter) cannot be analysed using the same statistical methods, the shocks must first be separated from the underlying vibrations. This task is challenging because both events are measured with the same sensor (usually an accelerometer) and are manifested within one common signal. A number of attempts have been made at detecting shocks during road transport [63,64] presenting the results as Shock Response Spectra (SRS). Sharpe et al. [65], on the other hand, made the assumption that the statistical extremes within synthesized random vibrations will account for the higher amplitude shocks. Bruscella [66] applied a moving crest factor technique for detecting shocks within road profile signals; however, the work was applied to measured road profile (elevation) data only and no independent validation was undertaken. Kipp [67] recognised the importance of defining both the magnitude of the shocks as well as their frequency of occurrence within a particular distribution cycle. This definition, however, depends on a reliable method for not only detecting the shocks and transients buried within RVV signals but also for extracting salient information relating to the shocks. Rouillard and Richmond [68] suggested the use of intrinsic mode functions to separate high frequency shocks from the underlying (lower frequency) vibration produced by railcars. However, when it comes to road vehicles, it is not always the case that the frequency content of shocks are composed of higher frequencies than those of the underlying vibration signal. Lepine et al. [69] undertook a significant review of the various methods used for detecting shocks within road vehicle vibration signals and identified the crest factor method as the most commonly-used. However, the crest factor method has an important shortcoming as it depends on the data window duration used to compute the moving rms value [70]. Lu et al. [71], studied the causes of shocks during road transport by manually extracting shock-like events from the recorded data and correlating them with various surface aberrations observed from video footage of the road surface. They concluded by stressing the importance of studying shocks and vibrations separately for laboratory simulation. More sophisticated approaches using time-dependant frequency analysis tools such as wavelets [72,73,74] and the Hilbert-Huang transform [75,76,77,78] have also been used to identify shocks buried within random vibration signals.

The review undertaken by Lepine et al. [69] showed that, to date, there is no single method which can reliably identify the various components of RVVs. Lepine undertook a comparative evaluation of various methods including the crest-factor, the wavelet transform [72] and the Hilbert-Huang transform [76] to show the limitations of each of theses techniques when applied individually. These limitations include false positives and missed detections. Lepine [79] reviewed a Machine Learning application for the detection of shocks by Mednis et al. [80] and developed an enhanced Machine Learning approach that combined 36 processed signals (predictors) using the crest factor, rms, kurtosis, the wavelet transform, and the Hilbert-Huang transform to yield promising detection performances (precision, accuracy and recall). Lepine [79] subsequently tested the accuracy of the new Machine Learning shock detection algorithm on field data using a four-wheeled vehicle travelling on a test track containing a number of carefully positioned obstacles. This yielded encouraging results (especially in the detection of larger, more significant, shocks) but revealed that further enhancement of the algorithms are required to reliably detect smaller shocks from multi-wheeled vehicles. More recently, further applications of Machine Learning to detect shocks have been undertaken [81, 82, 83] but remain to be thoroughly validated for transport vehicles.

When it comes to simulating shock-on-random vibrations for laboratory trials of packaged products, limited information is available. Rouillard and Richmond [68] proposed a method to randomly superimpose shocks onto an underlying random signal controlled by an ordinary Random Vibration Controller but their method was not validated. Zhou and Wang [84] attempted to overcome the limitations of laboratory-simulated Gaussian vibrations by exploiting their shock extraction method (based on the moving crest factor) that produces vibrations as a sequence of Gaussian vibration segments followed by a series of extracted shocks. They compared their results with alternative simulation methods (single level PDS, three-way split spectra and wavelet decomposition) by comparing the resulting accelerations distributions, extrema, rms and kurtosis with those obtained from the original measured signal. They concluded that their shock extraction method is successful in producing vibrations that more closely match the statistical structure of the original measured signal. However, the authors offer no evidence to validate the reliability of their shock detection algorithm.

4.2. Summary and Recommendations

Due to the many challenges associated with the automated and reliable detection of shocks within RVV signals, a limited amount of work has been undertaken in this area. Despite this, detecting and simulating road transport shocks remains crucial, especially if protective packaging systems are to be optimised to reduce the adverse environmental impact of packaging waste. Further work is required to validate current shock detection methods as well as to develop alternative methods to yield improved detection reliability. Once this is achieved, characterisation of the shock 'profile' of various distribution environments would need to become standard practice. In addition, shock-on-random simulation techniques should be developed to enable improved simulation of the hazards associated with road transport. Specifically, further research should include:

- Validation of alternative shock detection validation algorithms using the synthetic shock-on-random signal method developed by Lepine [79] and illustrated in

Figure 7. This will afford a reliable performance comparison of different techniques and avoid difficulties associated with setting-up known shocks on road surfaces and measuring the response using real vehicles.

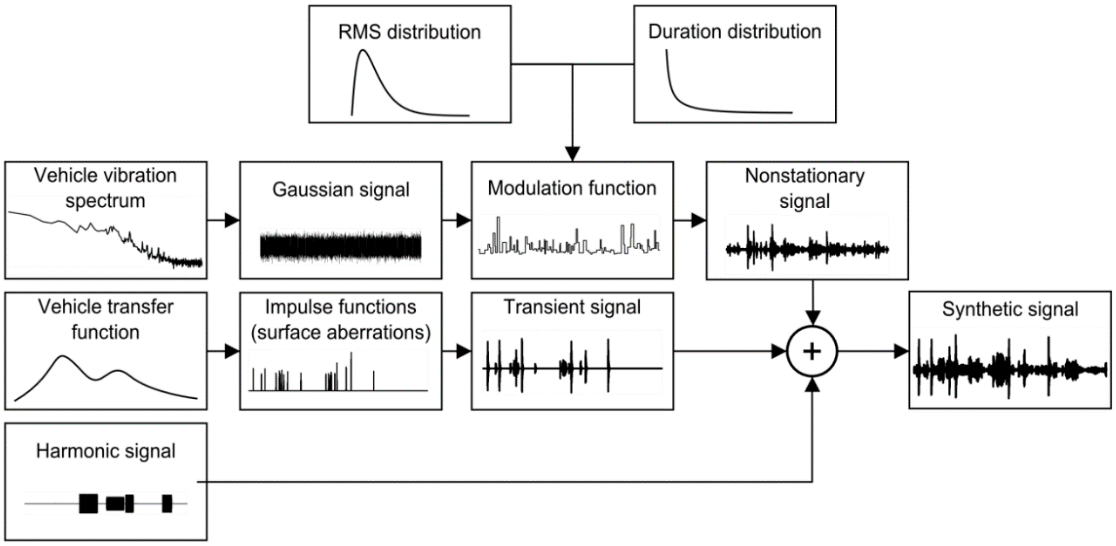

Figure 8. Proposed scheme for the artificial generation of shock-on-random vibration signals [79].

- Controlled field trials to validate shock detection algorithms using a variety of real transport vehicles.
- Application of an effective shock detection algorithm(s) to measured field data to characterise shock parameters and statistics for range of vehicle types and distribution routes
- Development of shock-on-random simulation techniques and protocols. This should include statistical distributions to describe salient shock characteristics such as the shock magnitude, duration and interval. Once identified, these distributions can be used to synthesize shock time-histories that can then be superimposed onto simulated random vibrations as described in Figure 9.

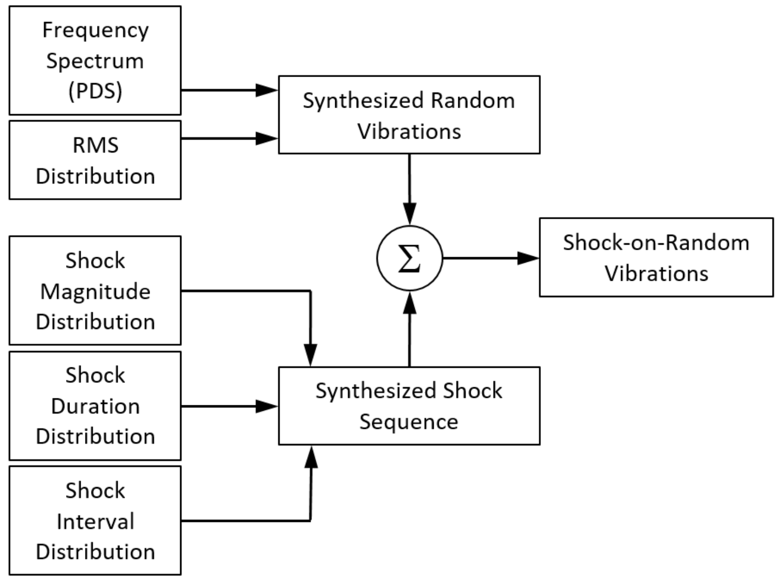

Figure 9. Flowchart for the generation of shocks-on-random vibration from statistical characteristics of shocks.

5. MULTI AXIS TESTING

During normal operation, road vehicles impart multi-directional motion onto the payload in including vertical (heave) vibrations that are widely accepted as the most severe. Vehicle manoeuvring such as accelerating, braking, cornering and swerving can produce significant lateral and longitudinal acceleration events whereas road unevenness can cause the vehicle to experience pitch and roll vibrations. In some packaging contexts, such as when stretch and shrink films are used to contain tall unitised loads that are inherently unstable, these lateral and angular accelerations can induce damage and eventual failure of the packaging and load restraint systems. As a result, it is necessary to consider multi-axial motion when undertaking tests on any stacked or laterally/longitudinally susceptible packaging units.

5.1. Literature review

Testing packaging systems for load stability under vehicle manoeuvring, has received limited attention. One existing test method from EUMOS [85] recommends subjecting the load to a constant horizontal acceleration of up to 2 g for at least 0.3s to quantify the rigidity of the load by measuring the resulting lateral displacement of the load unit. The standard offers no reasoning for the duration of the acceleration pulse although it does not purport to reproduce in-service conditions. Information on the acceleration levels of vehicles during normal driving conditions is available [86] but does not seem to have been used to develop the test standards for load stability. Gracia-Romeu Martinez and de la Cruz Navarro [87] investigated the difference between braking on real vehicles and laboratory-based simulated braking tests using response spectrum analysis. They showed that a maximum of 200 ms time constant jerk duration followed by a steady acceleration at a minimum duration of 300 ms achieved the equivalent load response as produced in a real emergency braking for unit loads with horizontal natural frequencies greater than 1.2 Hz.

In terms of vibration, only the vertical component of the vehicle's vibrations is generally considered relevant as it represents the highest energy component of the overall acceleration signal [88]. For example, Sharpe et al. [65] reported that the lateral acceleration is generally half the vertical accelerations. A later study by Singh [41] showed that below 10 Hz, the level of lateral and longitudinal vibration in truck shipments is far less than the vertical components; however, the levels of lateral acceleration varied with positioning within the stack (i.e. as a result of roll and pitch motion). Singh [41] also showed that, at frequencies above 20 Hz, the contributions of each component of acceleration were similar in magnitude. Despite the comparatively lower magnitudes of the lateral and longitudinal accelerations, Batt [89] showed significant differences in load stability (even when stretch wrap and strapping were used) between vertical only and multi-axis vibration testing. They found that no observable instability was experienced when excitation was applied in the vertical orientation only; however, with low level lateral and longitudinal vibrations and the same vertical vibration, significant box misalignment was observed. This highlights potential problems with stacked unit vibration modes and resonance, and the need to consider non-vertical motion.

At locations away from the vehicle's rotation axis, the translational motions are amplified by contributions from pitching and rolling motion [90]. Bernad et al. [88] investigated the relevance of vibratory motion in all six degrees of freedom, with respect to packaging testing by measuring the vibratory motion of two road trailers. Results from the investigation show that the energy neglected by testing using vertical vibrations alone can be significant. Furthermore, the results showed that, although lateral and longitudinal translational accelerations can cause bending-like modes to appear, their effect is small when compared to that caused by the rotational accelerations (pitch and roll). Bernad et al. [91] extended their work on multi-axial motion and described their methodology used to replicate the motion of different trailer types for a single 1,000-km route using time-compressed laboratory testing. Their study identified the nonstationary nature of the measured multi-axial data, with the probability density functions suggested to have Weibull-like distributions. The importance of considering the nonstationary nature of the vibrations was highlighted by the finding that the peak accelerations can reach as much as 40 times the overall rms value for the journey. The tests were undertaken using time replication techniques as it was argued that a PDS-based (synthesized vibration) test would not maintain the (phase) relationships between the vibration axes. This inability to perform multi-axial based tests using a PDS-based approach identifies the importance of understanding the correlation between the vibration axes which was studied by Long et al. [92] and later Rouillard and Lamb [93]. By comparing the results of their laboratory tests with those from real distribution trials, Bernad et al. [91] suggested that their test method can distinguish between poor and good packaging designs but is not comprehensive and requires further work.

In a more recent study, Gomez-Tabanera and Navaro-Javierre [94] investigated the impact of angular motion on a five-layer palletised load using stretch film as the containment system. Tests were undertaken using two vibration testing configurations, one with heave-only excitation and one which included heave, pitch and roll. The vibratory excitation was based on a transportation record measured between Shanghai and Pekin (1,250 km trip). The analysis was focused on measuring the permanent horizontal distortion of the multi-layer load after the completion of the test. The results show that the average residual overhang was increased by more than 70% with the addition of the angular motion.

Each of the studies on multi-axial motion has shown that tests which rely on vertical excitation alone ignore a significant contribution of the other components of motion. This is particularly the case for the angular vibratory motions (pitch and roll) which induce significant bending modes in stacked packaging units [88]. However, similar to the studies on heave vibrations, each study has a tendency to focus on a specific geographic location and only include a limited number of vehicle types. Their outcomes remain isolated and a concerted effort at undertaking a comprehensive comparative study to bring together the information that has been published is required. Rouillard and Lamb [93] made an initial step towards achieving such a comparison by investigating the PDS shape for heave, pitch and roll vibration, the nonstationarity of the pitch and roll motion and the relationship between the vibration levels of the three modes for a range of small delivery vehicles across a variety of routes. However, the research is limited by vehicle types and further investigation is still required.

The development and validation of test protocols for load stability under vehicle manoeuvring, has been neglected and further investigation related to developing suitable standards is required. The amount and breadth of data on the character and levels of angular vibrations from road transport vehicles is also very limited. Despite this, the available research has shown that pitch and roll motion should be included for any tests on packaging systems that are susceptible to horizontal excitation. The proposed target PDS shapes introduced by Rouillard et al. [30] are shown in Figure 10 and Figure 11. These spectra were produced from a limited set of vibration data [93] involving three different vehicles travelling at ambient speed on mostly urban roads. Also included in the Figures 10 and 11 are the pitch and roll spectra published by Gomez-Tabanera and Navaro-Javierre [94]. The similarity in the spectral shape for all cases for both pitch and roll is worth noting.

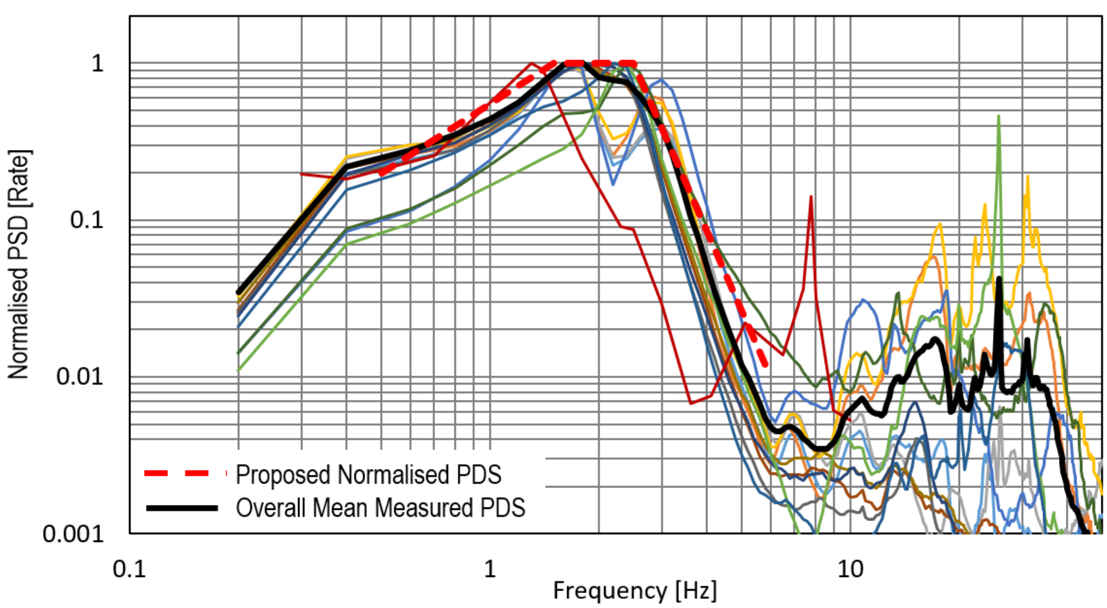

Figure 10. Proposed target PDS shape for pitch angular velocity (rate) along with measured normalised PDS.

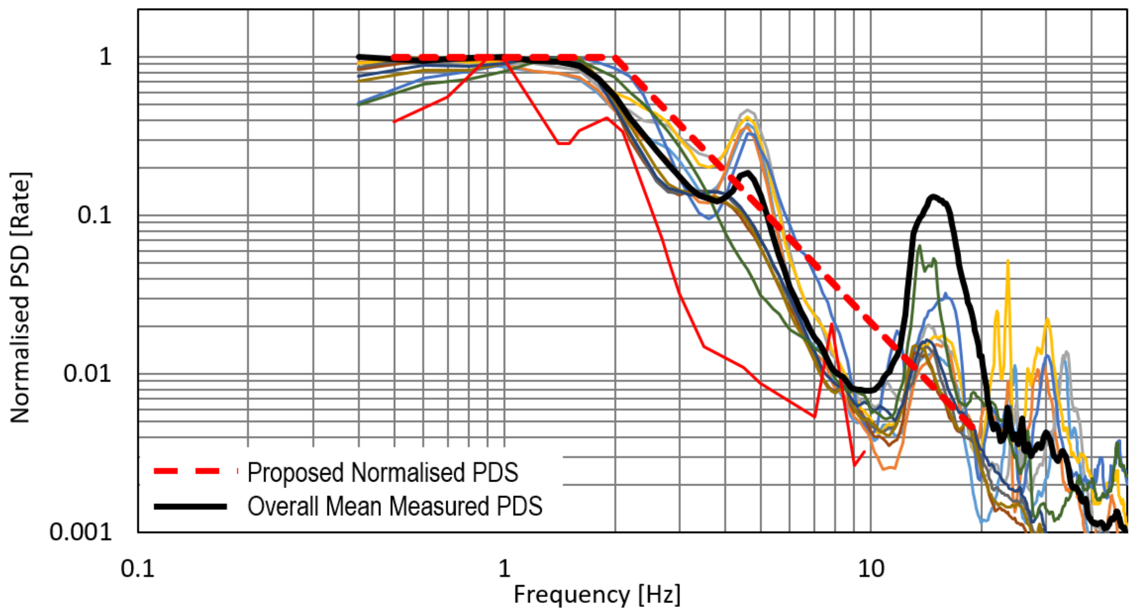

Figure 11. Proposed target PDS shape for roll angular velocity (rate) along with measured normalised PDS.

Rouillard and Lamb [93] also provided a range of probability density functions to show the nonstationary nature of the vibration intensity (rms) of each of the modes. The results showed that the vibration intensity of each mode is nonstationary and that the overall relationship between the angular velocity moving rms (pitch, $\underline{\dot{p}}$, and roll, $\underline{\dot{r}}$) and that of the heave acceleration, $\underline{\ddot{h}}$, can be adequately modelled using a simple linear function that uses both the overall slope, M and the standard deviation, σ, of the joint rms distributions with respect to heave acceleration for pitch and roll respectively:

$$\underline{\dot{p}} = M_{\underline{\dot{p}\ddot{h}}}\,\underline{\ddot{h}} + \aleph(S_{\underline{\dot{p}\ddot{h}}}\,\underline{\ddot{h}}) \quad \& \quad \underline{\dot{r}} = M_{\underline{\dot{r}\ddot{h}}}\,\underline{\ddot{h}} + \aleph(S_{\underline{\dot{r}\ddot{h}}}\,\underline{\ddot{h}}) \qquad \text{(2a, 2b)}$$

Where:

- $M_{\underline{\dot{p}\ddot{h}}}$ and $M_{\underline{\dot{r}\ddot{h}}}$ are the slopes of the joint distributions for pitch and roll with respect to heave

- $S_{\underline{\dot{p}\ddot{h}}}$ and $S_{\underline{\dot{r}\ddot{h}}}$ represent the corresponding gradients between $\sigma_{\underline{\dot{p}}}$ and $\underline{\ddot{h}}$ and $\sigma_{\underline{\dot{r}}}$ and $\underline{\ddot{h}}$.

These relationships can be used to generate normally-distributed random values (denoted by $\aleph$) that provide the necessary fluctuation in rms levels for the purposes of laboratory simulation. Results from Rouillard and Lamb [93] established typical values for the four parameters (Table 1).

Table 1. Empirical joint distribution parameters for multi-axis vibrations [93].

Parameter	**Value**
$M_{\underline{\dot{p}\ddot{h}}}$ and $M_{\underline{\dot{r}\ddot{h}}}$	$1.5 \pm 0.5\ ^{o}s^{-1}/ms^{-2}$
$S_{\underline{\dot{p}\ddot{h}}}$	$0.3 \pm 0.2\ ^{o}s^{-1}/ms^{-2}$
$S_{\underline{\dot{r}\ddot{h}}}$	$0.4 \pm 0.2\ ^{o}s^{-1}/ms^{-2}$

5.2. Summary and Recommendations

The work of Rouillard and Lamb [93] presents a practical method for exploiting the capabilities of multi-axis vibration tests systems for reproducing realistic RVV under controlled conditions. The work sets a starting point for the development of a new standard for multi-axial vibration testing, however, further research is recommended prior to implementing such an approach. Specifically, future research on multi-axial testing should be focused on:

- Development and review of test protocols for evaluating load stability during vehicle manoeuvring.
- Measurement and evaluation (PDS and rms distribution functions) of the multi-axial motion of a wider variety of transport vehicles, particularly heavy vehicles.
- Synthesis of nonstationary, multi-axial vibration for laboratory testing.

6. CONCLUSIONS AND RECOMMENDATIONS

The paper has identified a number of shortcoming with the current approaches to laboratory simulation of transport vibrations. Broadly, these relate to the shape of the PDS used for laboratory simulation; the vibration (rms) levels used for laboratory testing; the duration of laboratory tests; lack of inclusion of shocks and harmonics and, finally, the general exclusion of vibratory motion in all orientations bar the vertical. The paper makes the case that the current approaches, although useful for ensuring product survivability during transport, are no longer adequate in a setting where the impetus for reducing packaging waste through optimisation is becoming prevalent. The paper makes a number of recommendation for further study toward understanding how transport shocks and vibrations are analysed and processed to create improved laboratory simulation protocols. Furthermore, future work should be extended to improve the characterisation and simulation of other modes of transport.

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