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On the Parameters that Influence Road Vehicles Vibration Levels

M.J Lamb (PhD.)[a]* and V. Rouillard[b] (PhD.)

[a,b] Engineered Packaging and Distribution Research Group,

Victoria University, Melbourne, Australia

PO Box 14428, MCMC 8001 Melbourne, Australia

[a]*Corresponding Author Email: matthew.lamb@vu.edu.au

ABSTRACT

It has long been recognised that the level of road vehicle vibrations are mainly a function of vehicle characteristics, road roughness, and vehicle speed. With the introduction of easy-to-use vibration data recorders, significant amounts of data have been recorded and numerous studies on the rms levels of truck vibrations have been published. However, the results available to date are typically from specific scenarios and do not provide comprehensive comparisons with similar published work. In addition, most of the publications only report the mean rms level with no indication of how the rms varies throughout the journey nor statistical information on the likelihood of particular rms levels being exceeded. This paper brings together the available information on road transport vehicle vibration levels for analysis. It does so by first collating published mean vibration rms values for a broad range of scenarios, and supplements them with additional mean rms values recorded by the authors. The collated results were analyzed statistically to reveal the influence of important parameters, namely suspension type, road type, payload and vehicle type. Results from the statistical analysis are used to quantify the influence of each parameter and to allow for the prediction of expected rms levels based on the transport scenario. This introduces a risk-based approach to laboratory testing which allows the analyst to set the test rms levels based the road transport scenario and the accepted level of risk.

Keywords: Transport, vibration, rms, road, Weibull distribution

INTRODUCTION

As the magnitude and significance of the problems associated with excessive packaging and waste is 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 Nations (Sustainable development goals) [1], the Ellen Macarthur Foundation (Vision for the new plastics economy) [2] and the

Australian Government's Department for Agriculture, Water and the Environment (National waste policy action plan 2019) [3] are to be met. Aside from addressing the management of packaging-related waste material, one clear way to limit the impact of packaging waste 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 related with product damage needs to be carefully balanced. For this to occur, the prediction of 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 predicted and reproduced using laboratory-based simulation. Further to this, if the significance of the parameters influencing the vibration levels is better understood, it will be possible to make informed decisions with regards to the types of vehicles and the delivery routes that are used to transport goods.

Vibrations from road transport vehicles are one of the most common causes of product damage. This is mainly due to the typically larger magnitudes of vibrations produced by road vehicles compared to air, rail and maritime transport [4,5] and the greater reliance on road transport in the supply chain [6,7,8]. The root causes of road vehicle vibrations (for example road surface conditions and vehicle speed) are not always predictable and are, therefore, difficult to control. Furthermore, as distribution networks expand, so does the exposure of products to vehicle vibrations. Today, the main approach taken to design and validate packaging systems for distribution relies on various vibration test protocols such as those published in standards including ASTM D4169 and ISTA 2, 3 and 4 series. These protocols specify average vibration rms levels and corresponding durations which the product is to withstand. In the vast majority of cases, this is accomplished by subjecting samples of the product to simulated vibrations under controlled laboratory conditions and inspecting for signs of damage once the test is complete. However, rms levels for specific road transport scenarios (vehicle type, suspension, road type etc.) are not always known and, in such cases, the generic rms values published in standards are used. With the exception of the latest release of ASTM D4169 (which publishes three specific mean rms levels to be simulated in an increasing sequence), all published standards for testing the survivability of products during transport specify mean values for vertical (heave) vibrations only and make no reference to the variations in vibration rms levels that often occur in transit.

Since the introduction of standard methods for vibration testing of products and package systems, numerous studies aimed at quantifying the vibration characteristics of road transport vehicles with respect to various factors such as vehicle type, suspension type, payload, road type and vehicle speed have been undertaken. The broad approach has been to mount accelerometers onto road transport vehicles and record vertical vibrations either continuously or sporadically to accommodate the memory restriction of the recording devices. Usually, three recording modes have been employed: 1) continuous recording, 2) where data is recorded repeatedly and regularly for a pre-set duration at regular time intervals (broadly known as time trigger) and 3) where data is recorded for a pre-set duration whenever the acceleration level exceeds a pre-set threshold (broadly known as level trigger). The latter two approaches produce a sample of the vibrations and the influence of the sample size on the results has been evaluated and discussed by Rouillard & Lamb [9, 10].

A number of road transport studies make recommendations as to the vibration frequency spectra and rms levels to be used to characterise specific road transport conditions. To date, however, there is no evidence of a concerted attempt to combine the data from these independent studies in an endeavour to take a broader perspective in analysing the results. This paper seeks to address this gap in the research by collating and analysing the vibration levels (mean rms) reported in the literature with the aim of presenting an overarching assessment of road transport vibration levels. In undertaking the study, data available from the literature is supplemented by unpublished vibration data collected by the authors over the years thereby producing the most comprehensive set of information on road vehicle rms vibration levels available to date. By evaluating the available data, the paper seeks to identify the important parameters (such as suspension type, road type, payload and vehicle type) that influence vibration rms levels and to quantify their impact using a statistical approach.

LITERATURE REVIEW

As shown by Schlue and Phelps [11], who conducted a vibration study to analyse the influence of road roughness and vehicle loading conditions, the level of road vehicle vibrations is a function of vehicle type (dynamic characteristics), road roughness, and vehicle speed. Some of the first identifiable efforts at quantifying road transport vibration levels were undertaken by Ostrem and Rumerman [12], Schock and Paulson [13] and Foley [14] who published reports on the influence of road quality (roughness), payload levels (empty and full) and suspension systems (air ride and steel spring). However, no rms levels were reported and, instead, acceleration magnitude spectra were published. This was followed in 1979 by a comprehensive study by Osterm and Goodshall [15] aimed at quantifying the main hazards during transport.

Again, data was presented as frequency spectra with a proposed "*summary envelope spectrum*" and an rms level of 0.15 g.

Since the introduction of powerful and easy-to-use vibration data recorders in the early 1990s, a significant number of studies have been undertaken to characterise specific distribution environments using various vehicle types and configurations and road types [16 - 45]. These works, all focus on various aspects of road vehicle vibrations and report a variety of findings including the vibration spectra and the rms levels specific to the conditions of their research. Due to the sheer number of publications, a thorough review of each of these publications is beyond the scope of this manuscript. Instead, these papers were examined to extract reported vertical rms vibration levels and pertinent associated information (i.e. vehicle type, suspension type, payload, vehicle weight capacity and road type) with the aim of collating the most comprehensive set of published road vehicle vibrations rms values as possible.

Many early works focused on comparing vibration levels for different types of larger vehicles and the two main suspension types, namely, leaf spring and air ride. In many cases, vibrations measurements were short [16, 17, 18, 19] and were undertaken on US and European roads. A more comprehensive study was undertaken by Singh et al. [20] to compare vibration levels for fully-loaded trucks with leaf spring and air ride suspension using data from 14 trips (totalling 5,711 km) across a variety of interstate routes in the USA.

A number of later studies focused on a broader range of vehicle types including smaller trucks and delivery vehicles carrying a range of payloads across various routes including minor (sometimes unsealed) and major roads [21, 22, 23, 24, 25, 26, 27, 28, 29] in Asia, Australia and Brazil. These studies contain important information on vibration levels for minor roads and, in one case [28], for a fully-loaded semi-trailer and one over-loaded (150% weight capacity) rigid truck (both with leaf spring suspensions) on intercity roads in China.

Other studies have focused on the influence vehicle speed coupled with other parameters such as suspension or road surface type on the rms level [30, 31]. Vibration rms values were reported as a function of vehicle speed for a number of scenarios.

In some cases, the research included the measurement and analysis of multi-axis vibrations from a variety of vehicle and route types. These include a less-than-truckload trailer travelling on various road types [32], a rigid truck and a truck with pup trailer, both with air ride suspension, travelling on good quality roads (motorways and highways) [33]; three air-ride suspension semi-trailers on motorways and highways (1,000 km long route) [34]; a fully-loaded rigid truck with steel suspension travelling between Shanghai and Beijing in China [35] and two small vehicles travelling on country roads (highways) at constant speed [36]. In all these cases, mean rms levels were reported for heave vibrations.

Uncovering the statistical character of road vehicle vibrations was the main motivation for a number of more recent studies. These involved continuous and time-triggered measurement of vibrations for significant periods on a variety of typical transport vehicles travelling over a range of road types and the reporting of mean rms values along with various statistical distributions [37, 38, 39, 40, 41, 42, 43] and included data from multiple locations on fully-loaded B-double (9 axles) trailers with air suspension travelling on a 3,300 km long interstate in Australia [44].

From careful examination of all of the above-mentioned publications, mean rms values for a variety of conditions were retrieved and only rms acceleration data that was accompanied with reasonably clear information related to vehicle type, suspension type, payload and route type or road condition was collated. In all, 138 rms values were retrieved and are listed in the appendix. Given the biasing effect of data recorded using level-trigger conditions [9], only rms values computed from continuous or time-triggered data were collated.

In all cases, the publications contained enough information to describe the broad type of vehicle used; however, potentially important information such as gross and tare masses and number of axles was inconsistently published.

Without exception, the type of suspension involved was clearly reported although no information on the condition of the suspension system was published.

Sensor location was rarely reported. Consequently, sensor location will not form part of the subsequent analysis.

Vehicle speed was rarely clearly reported but sometimes the speed limit or average was published. Consequently, the influence of vehicle speed was not investigated further. Routes and road types were sometimes reported but information on road quality or class (roughness) was rare. Furthermore, in some cases, vibration rms levels were reported for journeys involving a broad mix of road types.

The duration of the recorded signals from which the rms values were calculated was generally available and, where not, could be estimated from the published journey length, average vehicle speed and data capture regime. This is not seen as critical as the data upon which the mean rms was calculated was sufficiently long in all cases to be taken as a statistical representation of the entire journey [9].

ANALYSIS METHODOLOGY

In addition to published mean rms levels, 32 values from vibration data previously measured but unpublished by the authors were added to the set making a total of 170 mean rms values representing the broadest range of road transport conditions collated to date. The additional 32 records are summarised below:

- Four continuously-measured vibration records (380 minutes each) from fully-loaded road-trains (air ride) travelling on mixed highway and motorways in Australia.
- Twelve continuously-measured and two using level trigger (with 0.2 g threshold) sampling vibration records totalling 37 hours from fully-loaded semi-trailers (air ride) travelling on mixed highway and motorways in Australia. In the two latter cases, the trigger level was considered sufficiently low [10] to be included in the data set.
- Four continuously-measured vibration records (44 minutes total) for two utility trucks with steel suspension loaded between 25 and 70% weight capacity travelling on a mix of urban roads and highways in Australia.
- Five continuously-measured vibration records (average duration: 137 mins.) from a rigid truck (air ride) with various payloads travelling on urban roads in Australia.
- Seven continuously-measured vibration records (average duration: 164 mins.) from a small transport van (steel suspension) with various payloads travelling on urban roads and highways in Australia.

The set of mean rms values extracted from the published data along with the 32 new mean rms values was treated as a random sample that is statistically representative of mean rms vibration levels for road transport in general.

Data classification

To allow for the analysis of parameters which may influence road transport vibration levels, the mean rms data set was categorised into four groups:

- Payload: Due to a lack of detailed information in some publications, payload was grouped as a proportion of weight capacity in two halves.
- Suspension type: Two broad suspension groupings were used (where suspension type at the front and rear of the vehicle differed, the rear suspension type was used):

- Steel leaf
  - Air.
- Road type: Two broad road types were used (records with mixed major/minor roads were not included):
  - Minor roads: Metropolitan and minor roads.
  - Major roads: Main roads, arterial roads, highways and motorways.
- Vehicle type: Four groupings were used:
  - Heavy articulated: Semi-trailer and B-double (road trains were not included in this group to removing a biasing effect resulting from all of the recorded road trains travelling on the same road type)
  - Rigid commercial: Small trucks (utilities), vans and rigid body truck
  - Light commercial: Small trucks (utilities) and vans
  - Heavy commercial: Semi-trailer, B-double, rigid body truck, road train and large truck-trailer combinations

Analysis Method

Once the rms values were categorised, a statistical analysis process to characterise the rms levels was established. This process was based on the work of Rouillard and Lamb [45] who demonstrated that the probability density function describing the statistical distribution of the vibration levels of vehicles travelling on sealed roads can be adequately defined using a three parameter Weibull function (density) with the shape parameter set to two (1):

$$p(x) = \frac{2}{\eta^2}(x - x_0) \cdot \exp\left[-\left(\frac{x - x_0}{\eta} \right)^2 \right] \quad \forall \begin{cases} x \in \mathbb{R} \\ x_0 \le x < \infty \\ \eta \in \mathbb{R}^+ \end{cases} \qquad (1)$$

, where: *p(x)* is the probability density, η is the scale parameter and x_o is the location parameter.

The Weibull function was chosen because it had previously been successfully applied to describe the distribution of road vehicle rms vibrations [30, 34, 45]. The authors [45] were also able to establish relationships between the mean heave acceleration rms of the vibration records and the scale and location parameters as shown in Figure 1.

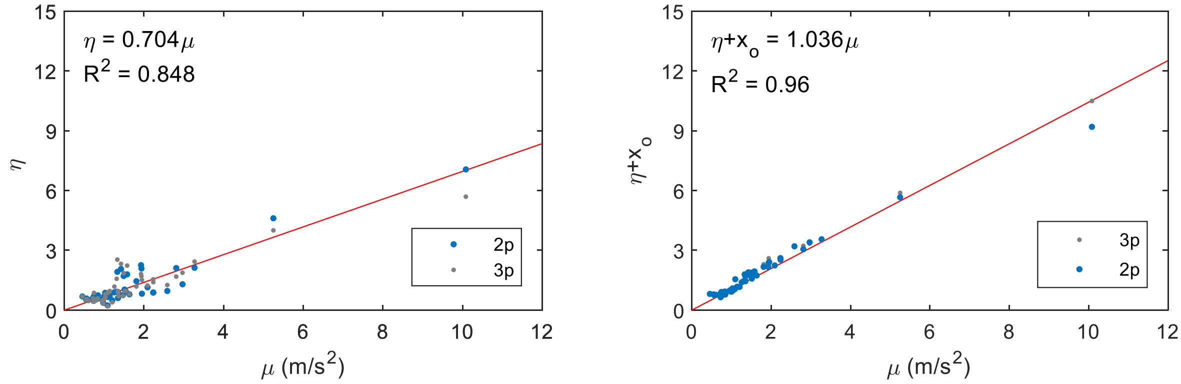

Figure 1. Relationships between the Weibull scale parameter (left) and the scale + location parameters and the mean rms with the Weibull shape parameter set to 2 [45].

Given a known mean rms, these relationships allow for the prediction of the overall rms distribution which enables the maximum rms level to be estimated. This is useful in instances when only the mean rms is available (e.g. when only average power density spectra are stored).

In this study, the Weibull distribution is again used to describe the statistical distribution of rms levels. Specifically, it is used to analyse the entire mean rms data set as well as mean rms data sets based on the aforementioned categories. Probability distribution and cumulative distribution functions were used to establish the mean vibration rms levels at specific percentiles of interest considering a risk-based approach. Each of the cumulative distribution functions were described mathematically using the cumulative Weibull distribution (2). The Weibull parameter values were obtained by finding the curve of best fit which allowed each data grouping to be compared at specific values of probability.

$$P(x) = 1 - \exp\left[-\left(\frac{x - x_0}{\eta}\right)^{\beta}\right] \quad \forall \begin{cases} x \in \mathbb{R} \\ x_0 \le x < \infty \\ \eta \in \mathbb{R}^{+} \end{cases} \tag{2}$$

where β is known as the shape parameter [45].

Following this analysis, the relationships established by Rouillard and Lamb [45] were used to predict the rms distribution associated with a particular combination of transport parameters (suspension type, road type, payload and vehicle type) and risk level.

RESULTS

The results are presented as the probability of occurrence (%) and the cumulative probability of occurrence (%). Figure 2 presents the statistical evaluation of all reported mean rms values. Results are also presented separately for the various categories of suspension type, road type, payload and vehicle type. For the categorized results, there is an additional plot which shows the ratio of the Weibull fit of the cumulative distribution function (2) of the categorized data set to the cumulative distribution function of all data. The results are highlighted for the 50th, 75th, 90th and 95th percentiles (P50, P75, P90 and P95, respectively) to show the rms correction factors that need to be applied to the results presented in Figure 2 to account for the specific parameter being studied. The percentiles were selected to provide estimates for the full range of the data above the mean. Estimates below the 50th percentile were not considered as meaningful as they would not reasonably be used for design purposes in practice.

Overall results

The distribution of mean rms vibrations for the entire data set - Figure 2 (a) - shows that for the vast majority of cases, the mean rms level is contained within the range 0.2 – 3.5 m/s^2. Mean rms values above 3.5 m/s^2 are rare with two notably extreme cases above 10 m/s^2. The first of these specific cases corresponds to a small utility vehicle with no load and poorly-maintained steel leaf suspension (resulting in low damping and unknown stiffness character) travelling on two very rough roads in an industrial area (Melbourne, Australia) [22]. The second was from a moderately-loaded semitrailer with steel-leaf suspension travelling at reasonably high speed (70 – 100 km/h) on poor roads in Brazil [24].

The cumulative distribution of the mean rms level for the entire set is shown in Figure 2 (b) along with the best-fitting 3-parameter Weibull distribution (x_o = 0.20, η = 0.97 and β = 1.43). This cumulative Weibull distribution can be used to estimate the expected mean rms level for any specific probability level. Such a risk-based approach is aimed at encouraging the pro-active management of vibration levels during distribution and promote the allocation of responsibility and liability if expected or agreed levels of vibrations are exceeded. Transport organisations can use this probabilistic approach to manage the level of vibrations associated with their services while those responsible for product and protective packaging design can, correspondingly, plan for the agreed expected vibration levels.

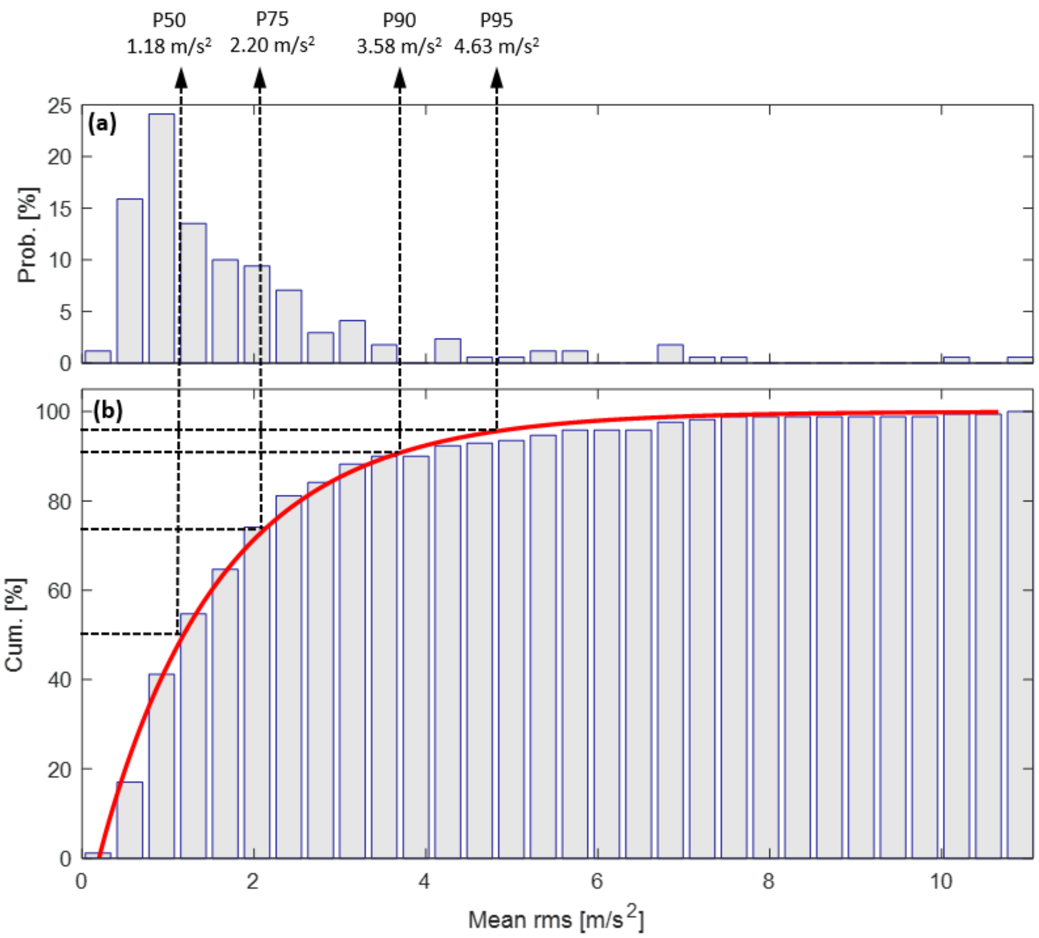

Figure 2: (a) Probability density, (b) cumulative distribution along with the best-fitting Weibull model (red line) of the mean rms vibration level from the entire data set.

Influence of suspension type

There exists two main types of suspension for commercial vehicles, steel leaf and air ride [46]. Both systems are designed to achieve the most appropriate combination of natural frequency and damping. However, for some commercial vehicles, the natural frequency and effective damping ratio are not independent parameters in a practical sense and it can be difficult to achieve both a suitably low natural frequency and a suitably high damping ratio [47]. This is further complicated by the range of loads which may be placed on the vehicle. For example, results from Fancher [46] show that the unsprung mass to sprung mass ratio varies from 0.06 for a fully loaded trailer to as high as 0.27 for an unloaded trailer. Air suspension systems have an advantage in this sense as their stiffness can be adjusted to accommodate for variations in payload, and in doing so can minimize the variation in natural frequency. The natural frequencies of typical air suspended systems are listed in [47] which suggests that air suspended systems generally have vertical sprung mass natural frequencies of approximately 1.5 Hz compared with steel systems which are closer to 3 Hz. Gillespie [48] writes that 1 Hz is the optimized heave natural frequency of the sprung mass of highway vehicles. Further to this, the need to limit the heave natural frequency is evident when considering the shape of the road roughness acceleration spectrum which increases in amplitude with frequency. If the heave natural frequencies are appropriately low, the increased road roughness acceleration at higher frequencies is attenuated by the decreased gain of the vehicle's transmissibility function which creates moderate attenuation between the sprung and un-sprung mass natural frequencies and rapid attenuation thereafter [48]. Given the relatively lower sprung natural frequencies that can be achieved with air suspension, it affords a significant advantage in heavy vehicles. However, a quantified measure of this advantage over a broad range of vehicles is not available in the literature with the most detailed study to date provided by Singh et al. [20].

For this study, mean rms values from the data set were categorized based on suspension type and the statistical distributions evaluated as shown in Figure 3. These were compared with the overall distribution (middle) and a correction function (bottom) calculated using the ratio of the cumulative distributions between the selected data and the entire data set. These correction functions illustrate how suspension type influences mean rms levels as a function of probability of occurrence. For example, using a 50% probability level for the mean rms, a factor of 0.73 can be applied to the overall expected mean rms when using air-ride suspension compared with a factor of 1.55 when using steel leaf suspension. This demonstrates an effective 53% reduction in mean rms level when goods are transported on air suspended trucks as opposed to vehicles with steel leaf suspension. The effect is amplified at higher mean rms probability levels. For instance, at the 90% mean rms probability level, the factors are 0.47 and 1.38 for air and leaf suspensions respectively. This equates to a reduction of 66% for air suspension relative to leaf suspension. These values are comparable to previous results presented by [20] who used composite [sic] results to show that, for the selection of trailers tested, those which were steel suspended had 60-65% higher heave rms acceleration than the air suspended trailers. The results from [20] also showed that the higher variations occurred at the more extreme vibration levels, matching the finding presented here.

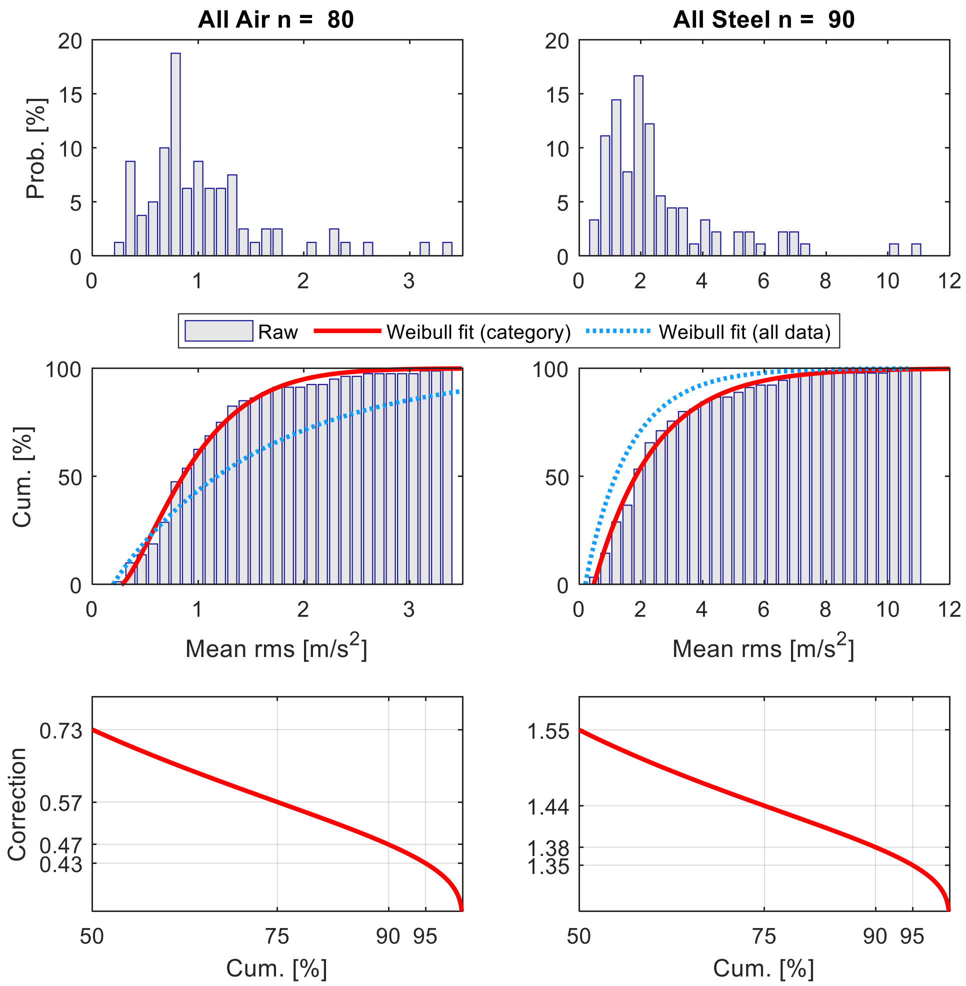

Figure 3: Mean rms probability distribution (top), cumulative distribution (centre) and correction factor (bottom) for all vehicles with air ride (left) and steel leaf (right) suspension.

Influence of payload

For suspensions with fixed stiffness (as is the case for leaf spring suspensions) a reduction in load results in an increase in heave natural frequency hence an increase in overall rms level. In modern air suspension systems, this is mitigated by the automated adjustment of suspension pressure, hence stiffness, to accommodate variations in payload. The influence of payload is studied here by separating the mean rms data set in two halves; low load (0 – 50% weight capacity) and high load (50 – 100% weight capacity). The resulting statistical distributions are shown in Figure 4. The shift in the mean rms distribution is clear and, when compared with the cumulative distribution for the entire data set, the benefits of heavier payloads on the mean rms levels is plainly evident. The correction factors for high and low load bands do not vary significantly with mean rms level. The results are, of course, affected by the coarse grouping of the data but, nonetheless, affords a useful means for quantifying the influence of payload on the mean rms level. On average, the benefit of carrying heavier loads equated to a reduction of approximately 37% in mean rms level compared to the overall average. Analysis of finer load groupings was not possible with the limited data available.

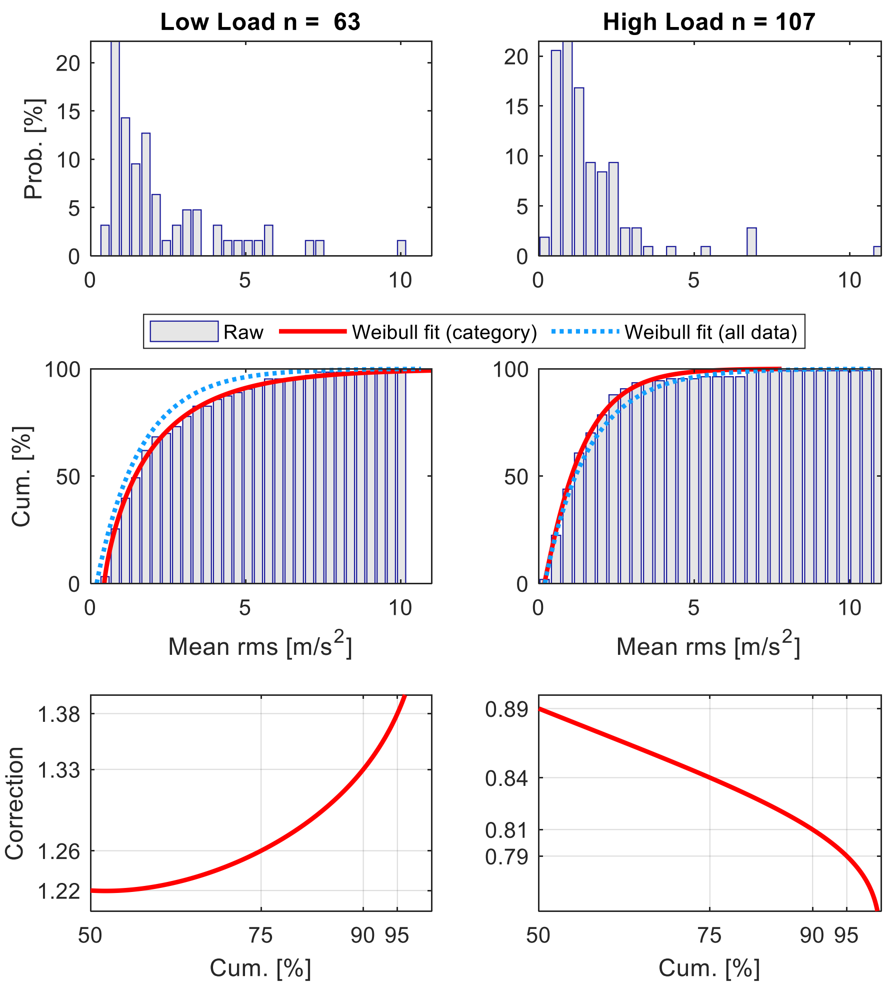

Figure 4: Mean rms probability distribution (top), cumulative distribution (centre) and correction factor (bottom) for all vehicles with low payloads (left) and high payloads (right).

Influence of road type

Given the same vehicle, an increase in speed or road roughness will generally directly increase the heave response. On rough roads this will often be managed by the driver who will adjust the vehicle's speed to suit the rough conditions, whereas, on well-maintained highways and motorways, mean heave rms will be regulated by the speed limit. Due to a lack of detailed information on road roughness and vehicle speed, the mean rms data set was separated into two groups of sealed roads: minor roads (including metropolitan roads) and major roads (incorporating main roads, highways and motorways). Any rms level that was associated with a mix of minor and major road types were excluded from the analysis. Such coarse categorization is bound to contain some overlap but the statistical distributions of the mean rms shown in Figure 5 show the overall influence of road type on the mean rms level. In general, the reduction in mean rms level on major roads when compared to minor roads varies between 51 % (P50) and 61% (P90). These are not insignificant values and should be sufficient to promote the avoidance of minor roads or, alternatively, take appropriate action (such as speed reduction or selecting vehicles with well-maintained air-suspension) where possible.

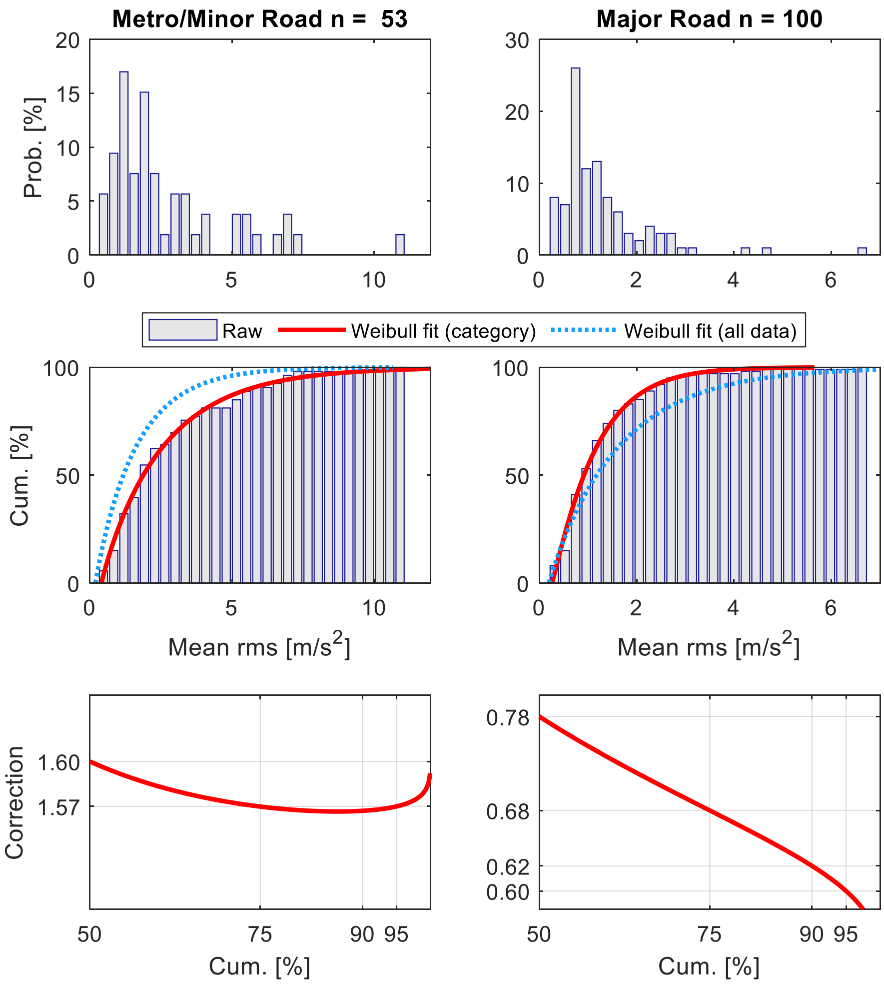

Figure 5: Mean rms probability distribution (top), cumulative distribution (centre) and correction factor (bottom) for all vehicles travelling on minor roads (left) and major roads (right).

Influence of vehicle type

The results presented in Figure 6 are from the analysis of large rigid vehicles and articulated commercial vehicles, specifically semi-trailers and B-doubles. For both sets of results, the corrections required to the mean rms of the overall distribution are small (less than 15%) for mean rms probability levels above 50%. This suggests that the vehicle type alone has little influence on the vibration rms level. This is not unexpected given that commercial vehicles, irrespective of size and configuration, are designed to have particular vertical natural frequencies and a damping ratio that optimizes ride quality.

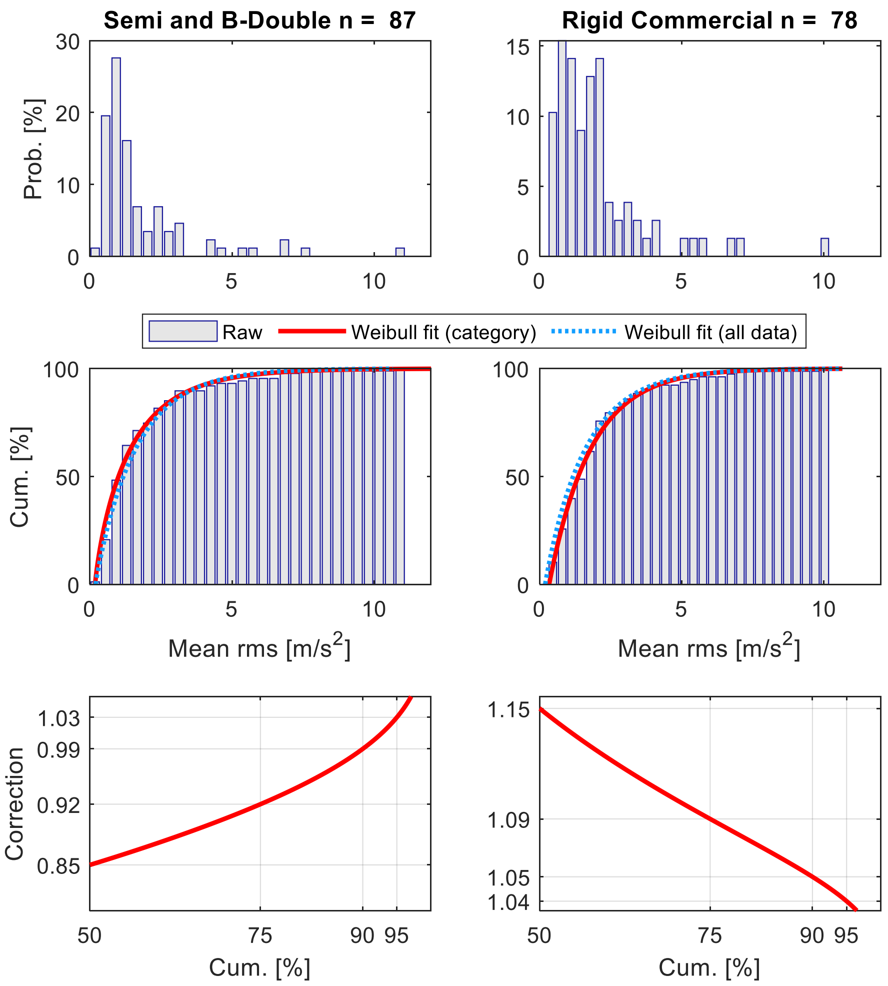

Figure 6: Mean rms probability distribution (top), cumulative distribution (centre) and correction factor (bottom) for all heavy articulated vehicles (left) and all heavy rigid vehicles (right).

The influence of vehicle size was also examined by defining small vehicles as vans and utility vehicles with a weight capacity of 2,000 kg or less. The mean rms distributions for the two vehicle size classes are shown in Figure 7. The limited amount of data for small vehicles is likely to introduce a bias in the results and does not allow for further statistical analysis. Further, the type of road on which the vehicles were driven and the speed at which they were driven are likely to confound the results given that small vehicles are more likely to be driven at lower speeds on minor roads and urban areas, where road roughness is generally less well managed, whereas large vehicles are more likely to be used for long hauls over better maintained main roads and freeways.

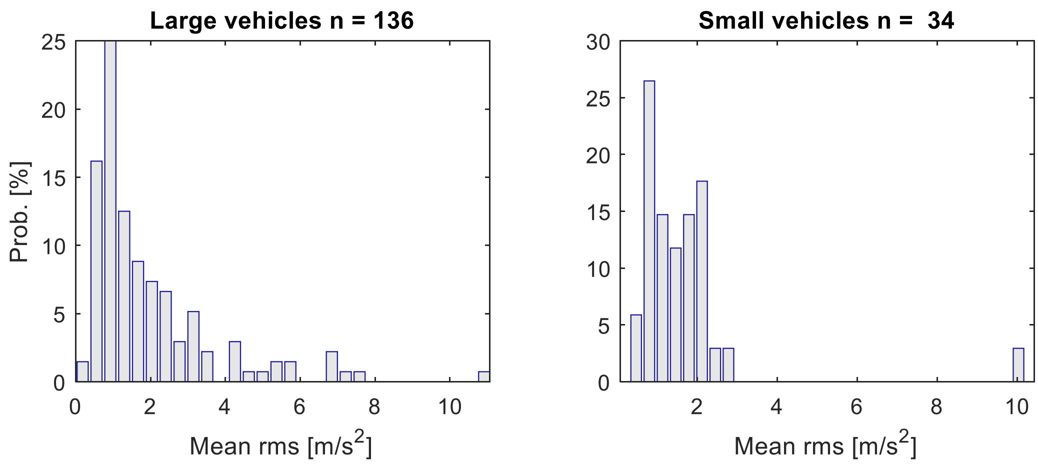

Figure 7: Mean rms probability distribution for all large vehicles (left) and small vehicles (right).

DISCUSSION

The influence of suspension type, road type and payload was quantified using the ratio of the Weibull fit of the cumulative distribution function of the categorized data set to the cumulative distribution function of all data. This yielded correction factors based on probability level that can be applied to the statistical distribution of the mean rms level for the entire data set to estimate the combined effect of a variety of transport parameters. Figure 8 summarizes these correction factors and Table 1 details all possible scenarios for four probability levels and shows how the individual correction factors are combined to calculate the corrected mean rms level for the selected probability levels.

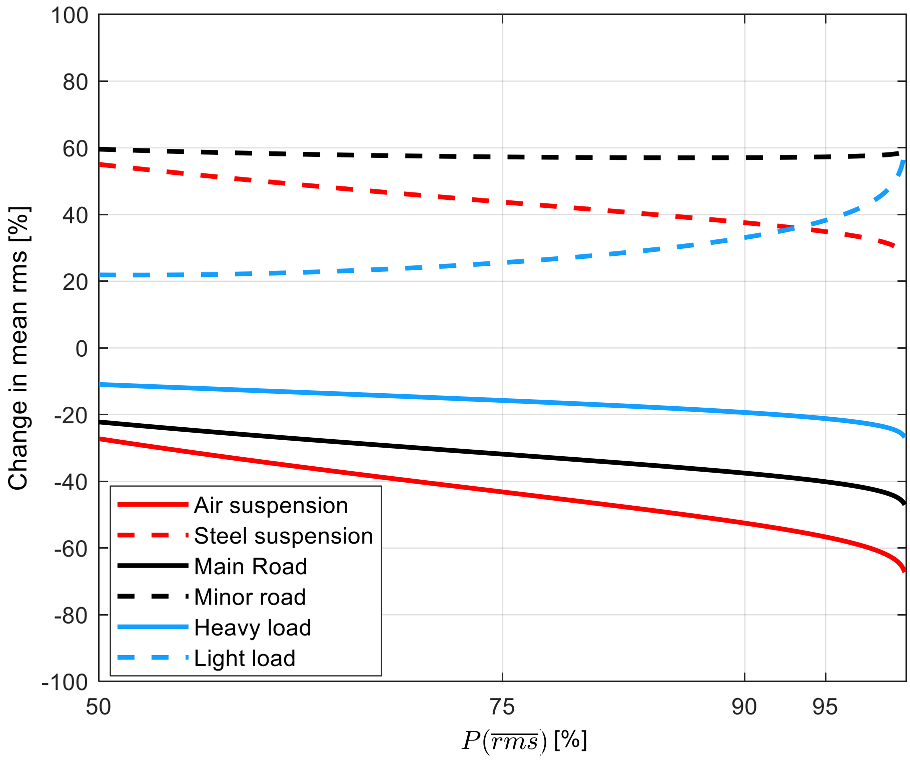

Figure 8: Summary of correction factors to be applied to the statistics of the full data set.

Using the results, a risk based approach for laboratory based vibration testing is recommended as follows:

[1] Select the probability percentile and record the corresponding expected mean rms based on the entire data set
[2] Select suspension type
[3] Select the road type
[4] Select the payload level
[5] Use Table 1 to find the combined correction factor.

For example (following the highlighted values in Table 1), for a percentile level of 90% (P90), leaf steel suspension, major road and low payload level, the combined correction factor is 1.14. That is, the expected mean rms level is 1.14 times the expected, P90, mean rms level of the entire data set resulting in a new mean rms of 4.07 m/s^2.

Table 1: Application of correction factors to obtain corrected mean rms values.

	Mean rms [m/s²]	Suspension Type		Road		Payload		Combined Correction Factor	Corrected mean rms [m/s²]
P50	1.18	Steel leaf	1.55	Minor	1.60	Low (< 50%)	1.22	3.03	3.57
						High (> 50%)	0.89	2.21	2.60
				Major	0.78	Low (< 50%)	1.22	1.47	1.74
						High (> 50%)	0.89	1.08	1.27
		Air ride	0.73	Minor	1.60	Low (< 50%)	1.22	1.42	1.68
						High (> 50%)	0.89	1.04	1.23
				Major	0.78	Low (< 50%)	1.22	0.69	0.82
						High (> 50%)	0.89	0.51	0.60
P75	2.20	Steel leaf	1.44	Minor	1.57	Low (< 50%)	1.26	2.85	6.27
						High (> 50%)	0.84	1.90	4.18
				Major	0.68	Low (< 50%)	1.26	1.23	2.71
						High (> 50%)	0.84	0.82	1.81
		Air ride	0.57	Minor	1.57	Low (< 50%)	1.26	1.13	2.48
						High (> 50%)	0.84	0.75	1.65
				Major	0.68	Low (< 50%)	1.26	0.49	1.07
						High (> 50%)	0.84	0.33	0.72
P90	**3.58**	**Steel leaf**	**1.38**	Minor	1.57	Low (< 50%)	1.33	2.88	10.32
						High (> 50%)	0.81	1.75	6.28
				Major	**0.62**	**Low (< 50%)**	**1.33**	**1.14**	**4.07**
						High (> 50%)	0.81	0.69	2.48
		Air ride	0.47	Minor	1.57	Low (< 50%)	1.33	0.98	3.51
						High (> 50%)	0.81	0.60	2.14
				Major	0.62	Low (< 50%)	1.33	0.39	1.39
						High (> 50%)	0.81	0.24	0.85
P95	4.63	Steel leaf	1.35	Minor	1.57	Low (< 50%)	1.44	3.05	14.13
						High (> 50%)	0.79	1.67	7.75
				Major	0.60	Low (< 50%)	1.44	1.17	5.40
						High (> 50%)	0.79	0.64	2.96
		Air ride	0.43	Minor	1.57	Low (< 50%)	1.44	0.97	4.50
						High (> 50%)	0.79	0.53	2.47
				Major	0.60	Low (< 50%)	1.44	0.37	1.72
						High (> 50%)	0.79	0.20	0.94

Once a mean rms value is estimated for the specific journey, the relationships established by Rouillard and Lamb [45] can be applied to estimate the distribution of the rms. Direct application of these relationships resulted in a slight under estimate (approximately 4%) of the mean rms. In this study, the gradients of each trend (Figure 1) are adjusted to correct for the difference. The resulting equations (3) and (4) were used to estimate the scale and location parameter which can then be used in equation (1) to estimate the overall rms distribution.

$$\eta = 0.735 \cdot \overline{rms} \tag{3}$$

$$x_o = 1.082 \cdot \overline{rms} - \eta \tag{4}$$

As an illustration, four scenarios for the 90th percentile – P90 – are given in Figure 9. The four scenarios (taken from Table 1) represent:

- Air ride suspension with high payload on major roads (0.85 m/s^2 mean rms)
- Air ride suspension with high payload on minor roads (2.14 m/s^2 mean rms)
- Steel suspension with low payload on major roads (4.07 m/s^2 mean rms)
- Steel suspension with low payload on minor roads (10.32 m/s^2 mean rms)

Such distributions can be used to make risk-based decisions as to the maximum rms level expected for a particular road transport scenario and its probability of occurrence. In practical terms, costs associated with protective packaging (material, transport volume, disposal costs etc.) can be optimized against the costs associated with product damage. It is acknowledged that there may be some variation in the roughness associated with major and minor roads from different regions in the word and minor adjustments to the mean rms may be required. For these instances Múčka [49] has compiled a valuable reference for comparing the roughness levels of various road types around the world.

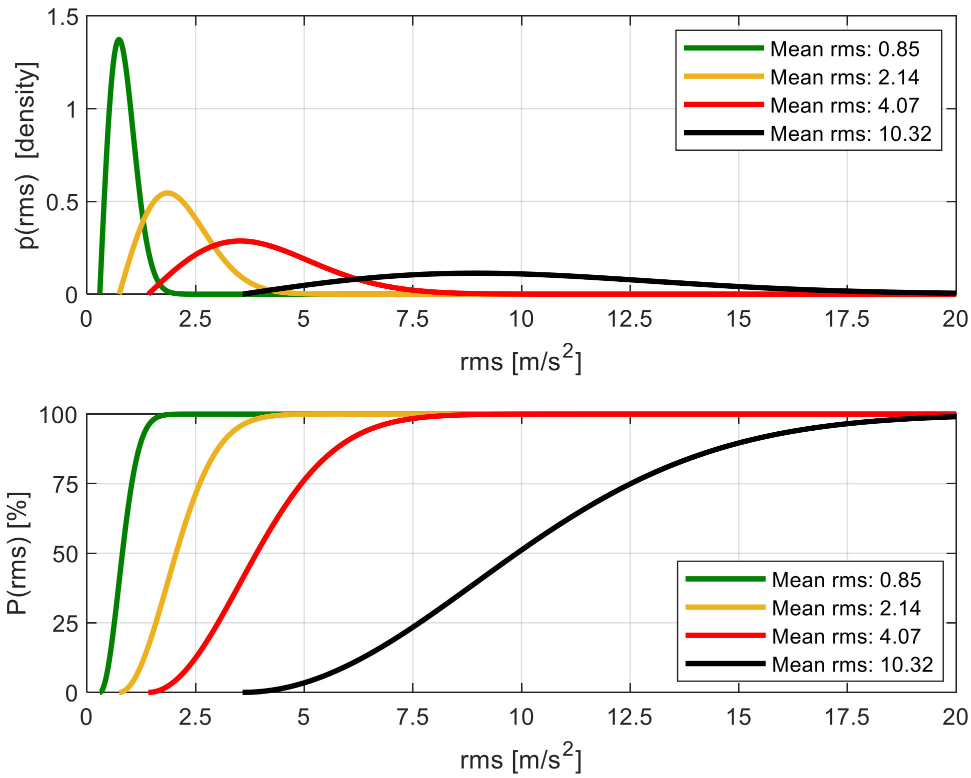

Figure 9: Probability density function (top) and cumulative distribution (bottom) for a range of mean rms values corresponding to the percentile level of 90% (see Table 1).

CONCLUSIONS

Mean rms vibration levels for road transport vehicles were collated from all accessible publications and combined with mean rms values from field surveys undertaken by the authors. These mean rms values (170 in total) were analysed statistically to reveal the influence of some important parameters namely, suspension type, road type, payload and vehicle type. This analysis was achieved by separating the data into subsets based on information reported in the literature. For each subset, the three-parameter Weibull distribution was used to characterize the cumulative distribution functions which were subsequently used to calculate correction factors as a function of mean rms probability level. It was found that driving on minor roads (including urban roads) has the greatest influence in raising the mean rms level (close to 60% on average) whereas the use of vehicles with air suspension had the greatest positive influence (reductions of between 25% and 60%). Driving on major roads reduced the mean rms level by between 22% and 40% and the use of vehicles with steel leaf suspension increased it by between 35% and 55%. Payload as a proportion of weight capacity has some influence on mean rms levels with lower payloads (<50% weight capacity) increasing the mean rms by approximately 30% and heavier payloads (>50% weight capacity) decreasing the mean rms by around 15%. These results are significant as they not only confirm what has long been suspected but, importantly, use actual published data to quantify the influence of these parameters and allow the prediction of mean rms levels by combining the correction factors associated with each of the parameters as a function of probability level.

The results from the statistical analysis enable the application of a risk-based approach to estimating the mean rms level for any road transport scenario. Finally, to account for the fact that the mean rms vibration is not, by itself, sufficient to completely describe vibration levels during road transport, the range of rms level expected to exist is predicted using a model based on the three-parameter Weibull distribution as a function of mean rms level. This model can be used to determine the expected maximum rms level to occur for any specific road transport scenario thus enabling the optimisation of protective packaging.

Further work on collecting more road transport vibration data will enable deeper study into the interaction of the transport parameters to evaluate their combined effect. These future data collection efforts should focus on the vehicle type, suspension type, payload (as a percentage of weight capacity), vehicle speed, location in vehicle (sensor location) and road type (including roughness) rather than geographic location.

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Appendix: Table 2

Table 2. Summary of published road vehicle vibration rms data.

Source	Measurement conditions	Vehicle type(s)	Route(s) description	RMS levels reported / extracted
1992. Marcondes et al. [16]	Continuous recording at three nominal speeds.	loaded tractor semi-trailer with steel leaf suspension	20 short sections of highway pavements of varying roughness levels	3
1992. Singh et al. [17]	Continuous recording.	two tractor-trailers with leaf spring suspensions with light and heavy loads	concrete expressways in average condition	2
2002. Barchi et al. [18]	Five minute records at the centre of the load tray for 22 different road sections.	Fully-loaded air suspended semi-trailer.	Mostly on highways and motorways in Spain, France and Italy travelling at ambient speeds.	22
2003. Berardinelli et al. [19]	Five minute records at three locations along the load tray (forward, centre and rear).	Three air suspended trucks with varying payloads.	Typical routes between production plants and markets in Italy.	9
2005. Jarimopas et al. [21]	Vibration level data was reported as power density values for and could not be used to estimate overall rms vibration level.	Variety of commercial vehicle types and vehicle speed	Typical commercial shipments in Thailand	0
2006. Singh et al. [20]	Vibration using both timer-trigger and level-trigger configurations.	Fully-loaded trucks with leaf spring and air ride suspension.	14 trips (totalling 5,711 km) across a variety of interstate routes in the USA	14
2007. Rouillard [22]	Continuous records for a total of 281 minutes.	Number of different transport vehicle types with a variety of payloads	Variety of route types (motorway, main roads and minor roads)	8

2007. Zhou et al. [23]	Time-trigger sampling at the front and rear of the load tray for a total of 5.3 minutes.	Fully-loaded small truck with steel leaf suspension	Between orchard and wholesale market in China (500 km) comprising unsealed roads, tertiary and secondary roads, arterial roads and highways.	4
2008. Garcia-Romeu-Martinez et al. [30]	Data was collected using both time and level trigger (0.5 g threshold).	Two large semi-trailers with both steel spring and air ride suspensions with zero and high payloads.	Four trips of approximately 370 km along intercity highways and motorways in Spain.	4
2008. Rissi et al. [24]	Collected vibration data using time-trigger sampling.	Rigid trucks and semi-trailers with various payloads.	13 trips (6,114 km in total) on metropolitan and inter-city roads in Brazil.	13
2008. Singh et al. [25]	Vibration records (16.7 mins. each) were measured using time and level (1 g threshold) trigger configurations.	Semi-trailer and a pup trailer (leaf spring suspensions) with less-than-truckload shipments.	City streets, highways, parking areas, terminals and unpaved roads.	3
2009. Chonhenchob et al. [25]	Vibration levels in truck shipments between packing houses and retail distribution centres. Used time and level-trigger (2.4 g threshold) sampling.	Four fully-loaded, rigid-body trucks	Three routes of 80, 700 and 15 km in length on roads ranging from very poor (unsealed and poorly maintained) to good quality highways in Thailand.	3
2010. Bernad et al. [33]	Vibrations were measured continuously.	Rigid truck and a truck with pup trailer both with air ride suspension with no payload.	Two routes of 15 and 220 km on good quality roads (motorways and highways).	2
2010. Lu et al. [31]	Vibrations were measured continuously and rms vibration levels were reported as a function of vehicle speed.	A single unloaded air suspended rigid body truck.	various local roads (400 km) and highways (400 km) in Japan.	1

2011. Garcia-Romeu-Martinez and Rouillard [37]	Continuously measured vibrations records of 43 mins each.	Steel-suspended and air-ride semi-trailers with a variety of payloads.	Highways and motorways in Spain.	4
2011. Otari et al. [38]	Vibrations were recorded using a time-trigger configuration.	Small delivery van (unloaded)	Country road (240 mins. record) and a motorway (240 mins. record) in France	2
2012. Bernad et al. [34]	Vibrations recorded using a time trigger configuration.	Three air-ride suspension semi-trailers (near full load).	Motorways and highways (1,000 km long route) in Spain.	3
2012. Chonhenchob et al. [27]	measured vibrations using both time and level (0.5 g threshold) trigger for a total of 70 hrs.	Small and medium-sized vehicles (vans, utility and trucks)	Single parcel delivery routes in Thailand and the USA.	4
2012. Ainalis [39]	Vibrations were measured continuously.	Two typical rigid trucks (small and large) both with air ride suspension and no payload.	39 km-long motorway in Spain.	2
2013. Griffiths et al. [40]	Continuously-measured vibrations.	Unloaded box (delivery) van.	Mix of road types (32 km) in the UK.	1
2015. Zhou et al. [28]	Vibrations were sampled with a time-trigger configuration for two 60 minute journeys.	One fully-loaded semi-trailer and one over-loaded (150% capacity) rigid truck (both with leaf spring suspensions).	Intercity roads in China.	2
2016. Long [36]	Continuous vibration measurements with vehicles travelling on at constant speed.	Two small vehicles (utility and van) with a variety of payloads.	Country roads (highways), totalling 92 km in length.	4
2017. Borocz and Singh [42]	Vibrations were measured using time trigger.	Two courier delivery vans (with leaf springs) loaded to 30% capacity.	Six typical courier delivery routes (totalling some 1,676 km) around urban areas in Hungary.	6

2017. Zhou et al. [29]	Measured vibration data (using time trigger) - 10 records of 16 minutes duration on average.	Heavy truck, a light truck and a small van. All with steel leaf suspension and a variety of payloads.	A range of urban roads and highways in China.	10
2018. Bonin et al. [41]	Vibration measured using a time trigger configuration.	Rigid truck with steel leaf suspension and no payload.	Route comprised city roads (15 km), country roads (45 km) and motorways (50 km).	1
2019. Gomez-Tabanera and Navarro-Javierre [35]	Vibration measured continuously from a travelling	Fully-loaded rigid truck with steel suspension.	Intercity and Motorway between Shanghai and Beijing in China.	1
2019. Borocz [43]	Vibration recorded using time and level (0.5 g threshold) trigger.	Near fully-loaded semi-trailers with air ride suspension.	Major roads between Gyor in Hungary and Dunajska Streda in Slovakia (60 km), Veracruz and San Jose Chiapa in Mexico (280 km) and between Mumbai and Aurangabad in India (411 km).	6
2019. Fernando et al. [44]	Collected vibration data (continuously) from multiple locations on vehicle. Vibration sensors were placed on both ‘fifth wheels’, rear of trailers and centre of B trailer.	Fully-loaded B-double (9 axles) truck with air suspension	3,300 km long interstate in Australia.	5