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Environmental conditions — Vibration and shock of electrotechnical equipment

Part 4: Equipment transported in road vehicles

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National foreword

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A list of organizations represented on this committee can be obtained on request to its secretary.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ENVIRONMENTAL CONDITIONS – VIBRATION AND SHOCK OF ELECTROTECHNICAL EQUIPMENT –

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FOREWORD

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IEC/TR 62131-4, which is a technical report, has been prepared by IEC technical committee 104: Environmental conditions, classification and methods of test.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
104/509/DTR	104/538/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2. A list of all the parts in the IEC 62131 series, under the general title *Environmental conditions – Vibration and shock of electrotechnical equipment,* can be found on the IEC website.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this standard may be issued at a later date.

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ENVIRONMENTAL CONDITIONS – VIBRATION AND SHOCK OF ELECTROTECHNICAL EQUIPMENT –

Part 4: Equipment transported in road vehicles

1 Scope

IEC/TR 62131-4, which is a technical report, reviews the available dynamic data relating to electrotechnical equipment transported by road vehicles. The intent is that from all the available data an environmental description will be generated and compared to that set out in IEC 60721 [25][1].

For each of the sources identified the quality of the data is reviewed and checked for self consistency. The process used to undertake this check of data quality and that used to intrinsically categorize the various data sources is set out in IEC/TR 62131-1.

This technical report primarily addresses data extracted from a number of different sources for which reasonable confidence exists as to the quality and validity. The report also presents data for which the quality and validity cannot realistically be reviewed. These data are included to facilitate validation of information from other sources. The report clearly indicates when utilizing information in this latter category.

This technical report addresses data from a number of data gathering exercises. The quantity and quality of data in these exercises varies considerably as does the range of road (and test track) conditions covered. The vast majority of the road conditions are from Western Europe. It is believed that one of the data sources considered is that used to set the current IEC 60721 severities. However, review of that data indicates the inclusion of some quite old vehicles.

Relatively little of the data reviewed were made available in electronic form. To permit comparison to be made in this assessment, a quantity of the original (non-electronic) data have been manually digitized.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60721-3-2:1997, *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 2: Transportation*

3 Data source and quality

3.1 SRETS road and test track measurements

The Source Reduction by European Testing Schedules (SRETS) study ([1]), part-funded by the European Union, was a collaborative venture undertaken by 10 European agencies and companies. The purpose of the study was to establish new vibration and shock test severities for equipment subject to road transportation. These test severities were destined for a new

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[1] References in square brackets refer to the bibliography.

CEN and ISO test procedure for packaged equipment. The three year study was completed in 1999 and the final report (see ([1]) published by the EU.

The vibration and shock measurement phase of the work focused on two separate exercises (see Table 1).

The first exercise, undertaken in the UK, was to establish the vibration and shock experienced by typical goods in real road conditions. To that end, measurements were made without the knowledge of the vehicle driver at the payload to vehicle interface during transportation of the same goods over similar (550 km) routes on 19 separate occasions, using different vehicles of a similar class (38 tonne articulated HGV's). The vehicles (commercial haulers) and drivers were supplied, the drivers being entirely unaware of the measurement exercise.

By contrast, in the second exercise, the measurements made with the full knowledge of the vehicle driver, used two specific vehicles on controlled German test tracks employing professional test track drivers. This second exercise was aimed at comparing vehicles, trailers, payloads and road surfaces. The second set of measurements adopted two different trucks in three configurations (one with trailer) at different speeds on different surfaces. Summary information on the various vehicles and trailer is shown in Table 2. The measurement locations utilized for the three vehicles are shown in Figure 1.

Both measurement exercises used solid state digital recorders. Whilst the second exercise facilitated the use of continuous recording, the lengthy duration of the first exercise necessitated the use of intermittent recording. The latter were undertaken in both "signal triggered" mode (storing the 500 blocks of 2 048 points containing the largest amplitude measurements) and "time triggered" mode (storing a block of 2 048 points every 3 min). The recorder sample rate was 5 500 sps with a low pass butterworth filter set to 1 000 Hz. Each block of data comprised 2 048 data points and represents an event duration of 0,372 s.

The first measurements adopted a single triaxial transducer located on the bottom of a pallet of packaged, bottled whisky. The vehicle was loaded to full capacity with 16 similar pallets. As the pallets were not stacked (one pallet height only) this payload filled the volume of the vehicle at around 90 % of its maximum weight capacity. The use of measurements made without the knowledge of the vehicle driver, has the advantage that it potentially reflects real world conditions. However, it has the disadvantage that the validity of the data is difficult to verify. The SRETS report specifically addresses this aspect comparing the data with itself (using the 19 separate runs) and with the test track work using several techniques such as comparing group means and by use of "analysis of variance".

The SRETS study adopted a variety of different data analysis procedures including power spectral density (PSD), amplitude probability density (APD) and fatigue damage spectra (FDS). In total, three different methods of establishing vibration and shock test severities were adopted. The resultant test schedules were verified by using them to test four different products and comparing the resultant damage with those experienced in the real world. These exercises demonstrated that the tests induced similar damage to that occurring in practice at a slightly accelerated rate. However, the rate of damage appeared more representative than some existing tests. The SRETS study also addressed a number of practical testing limitations and addressed some novel testing strategies.

The measurements from the SRETS are stored digitally; however, intellectual property rights limit the extent this data can be circulated. Summary information is included here in Figure 2 to Figure 17.

3.2 CEEES 'round robin' 10 tonne truck measurements

Although the CEEES 'round robin' exercise (see [2]) was not a measurement exercise, it did subject the same piece of real world road transportation measurements to analysis by a number of different methods and by a range of agencies. The vibration data used for the CEEES work (Figure 18, Figure 19 and Figure 20) was some 55 min of continuously recorded vibration measurements. These data were supplied to some 20 different agencies in Europe for analysis. These participants made independent analysis of this data (Figure 21, Figure 22 and Figure 23).

The data used in the CEEES exercise measurements were only part of a larger measurement exercise, undertaken by Cranfield University, the major part of which involved continuously recorded vibration measurements (see [3]) on a journey from central UK to central Germany (Figure 24 and Figure 25). The exercise involved 12 channels of measurement (plus vehicle velocity) on two payloads with a single triaxial measurement at the cargo bed. The vehicle used was a 10 tonne vehicle, of early 1970's design, able to operate on and off-road (it had 4 x 4 capability). Though it was a military vehicle it was based upon a commercial chassis and included commercial modifications (an integral hydraulic hoist). In addition to the continuous exercise, some measurements were made over degraded roads and obstacles (Figure 26 and Figure 27) at the maximum speed the driver considered safe. The continuous and degraded road measurements for the basis for environmental information contained in the UK defence standard 00-35 Part 5 (see [17]) as well as contributing to the NATO document STANAG 4370.

The analysis undertaken on the measured data was in the form of PSD and APD, each of a 1 h journey segment and combined for the complete journey. Additionally APD analysis was undertaken of the vehicle velocity measurement to establish a realistic usage profile. Whilst this is of some interest, it has limited application to this work as the upper speed limit of the vehicle was somewhat less than that imposed of commercial vehicles.

Measurements were recorded on an analogue recorder with calibration equipment. The measurement frequency range was up to 500 Hz. The PSD analysis was undertaken with a frequency resolution of 1 Hz and the APD analysis with an amplitude resolution of 0,002 g. In both cases, the analysis duration was typically in 1 h segments with the composite analysis covering a period of over 7 h. As a consequence of the latter duration, the APD from the composite measurement has good statistical accuracy down to very low levels of probability.

3.3 Various vehicle measurements by Hoppe and Gerock

Work by Hoppe and Gerock was under taken in the early 1970's and the resultant data are reproduced in a number of publications (see [4] and [5]). These data appear to be the basis for the severities in a number of national standards and, as far as can be identified, are probably the original basis for the severities in IEC 600721-3-2. Although the vibration data presented is very limited, the scope of the shock data is sufficient to justify its inclusion here.

The work by Hoppe and Gerock involved some nine vehicle and trailers; these are detailed in Table 3. The vehicles are mostly of leaf suspension designs, reflecting the vehicles' ages ranging between 1946 and 1970. All the test drives were made on dry roads on a closed circular route of 25 km consisting of

– 70 % concrete and asphalt,
– 18 % damaged and repaired roads,
– 10 % rough unpaved roads,
– 2 % cobble stones.

In addition to the above, four level crossings were included in the route. Vehicle speeds varied between 35 km/h and 45 km/h within town limits and up to 70 km/h on open roads. On rough parts of the route, speeds were reduced to between 10 km/h and 20 km/h. The test drives were made with the vehicles loaded to different degrees.

Little vibration data are presented in the reference, with information limited to a typical spectra (Figure 28) and an envelope of the measurements (Figure 29) broken into trucks and semi-trailer/pull trailers. However, the reference contains some useful shock data reproduced in Table 4, Table 5 and Figure 30.

Triaxial acceleration measurements were made above the rear axle, vertically in the centre of the load platform, vertically at the side of the platform at the rear and vertically at the front of the platform in the centre. All six measurements were recorded simultaneously and continuously on an analogue FM recorder. The frequency range covered was 1 Hz to 1250 Hz. All PSD analysis was undertaken using a 3 Hz frequency resolution and a record duration of 32 s. The shocks were classified into eight amplitude levels and sixteen time increments.

3.4 Millbrook measurements on Landrover Defender

This 1998 measurement exercise (see [6]) was undertaken at the UK Millbrook test track by Millbrook test engineers for Hunting Engineering Ltd. The measurements were made as part of a proving exercise on electronic equipment installed in Landrover Defender model LR10 (SVIC 34 / C112) registration CD 70 AA. As implied by the registration, it was a military registered vehicle but had only cosmetic modifications from the commercial variant.

The measurement configuration was 4 triaxial accelerometers and a optical tachometer to determine vehicle velocity. All the measurements were recorded on a Millbrook supplied analogue tape recorder using fully calibrated and traceable equipment. Three of the measurement locations were on equipment shelves and on the rear floor of the cargo area. Recordings were made on the following tracks at Millbrook:

- Test 1: high speed circuit at 48 km/h (30 mph) and record duration 130 s;
- Test 2: rough road test at 16 km/h (10 mph) and record duration 46 s;
- Test 3: pave at 40 km/h (25 mph) and record duration 266 s;
- Test 4: hill route at normal speeds and record duration 366 s;
- Test 5: random waves and record duration 56 s;
- Test 6: severe waves at 16 km/hr (10 mph) and record duration 30 s;
- Test 7: cross country at normal speed and record duration 673 s.

All the results are presented in [6]. All analysis was undertaken using the same analysis software presenting data from each channel in a consistent way. Essential for each measurement channel and track, a typical time history is presented along with an APD and PSD. The sample rate was 1 024 sps producing a frequency resolution of approximatly 0,5 Hz. The record durations varied according to track surface and are indicated in the list above. The data is summarized here in terms of variations in vibration r.m.s. with road surface in Figure 31 and the variation in shock amplitude in Figure 32. The spectra for the vertical axis are shown in Figure 33.

3.5 Millbrook measurements on Ford transit van

This 1996 measurement exercise (see [7]) was undertaken at the UK Millbrook test track by Millbrook test engineers for Hunting Engineering Ltd. The measurements were made as part of a proving exercise on a communication installation in a (new) Ford Transit Van registration M639 BTL. The loading on the front axle was 1 248 kg, on the rear axle 969 Kg, giving a total of 2 217 Kg.

The measurement configuration was 3 triaxial accelerometers, 3 uni-axial accelerometers and a vehicle speed transducer. All the measurements were recorded on a Millbrook supplied analogue tape recorder using fully calibrated and traceable equipment. Most of the measurement locations were on equipment shelves but two triaxial measurements were in the cargo area (one over the rear axle and one in the centre of cargo area). Recordings were made on the following tracks at Millbrook:

a) Vibration

   high speed circuit at 85 km/h and record duration 376 s;

   gravel road test at 48 km/h (30 mph) and record duration 157 s;

   B Class road (incl. level crossing) at 64 km/h (40 mph) and record duration 192 s;

b) Shocks

   pot hole “A” and “B” at 16 km/h (10 mph);

Millbrook cat’s eyes at 48 km/h (30 mph);

railway level crossing at 32 km/h (20 mph).

Analysis was undertaken for each measurement channel and surface and a typical time history presented along with an APD and PSD. The sample rate was 1 024 sps, producing a frequency resolution of approximatly 0,5 Hz. The record durations varied according to track surface and are indicated in the list above. The data is summarized here in terms of variations in vibration r.m.s. with road surface in Figure 34, in terms of peak spectral value in Figure 35 and the variation in shock amplitude in Figure 36. The spectra for the vertical axis are shown in Figure 40.

3.6 Millbrook measurements on Renault Magnum

This 1996 measurement exercise (see [8]) was undertaken at the UK Millbrook test track by Millbrook test engineers for Hunting Engineering Ltd. The measurements were made as part of a proving exercise on a communication installation in a (new) Renault AE 385ti Magnum semi trailer with a box trailer equipped as a command and communication centre. The loading on the front axle was 5 764 kg, on the rear axle 8 985 Kg, giving a total of 14 749 Kg.

The measurement configuration was 1 triaxial accelerometer, 4 bi-axial accelerometers, 2 uni-axial accelerometers and a vehicle speed transducer. All the measurements were recorded on a Millbrook supplied analogue tape recorder using fully calibrated and traceable equipment. Most of the measurement locations were on equipment shelves but some (2 bi-axial) were directly mounted on the van sides of the trailer. All of the remainder had a very short transmission path to the van sides of the trailer. Recordings were made on the following tracks at Millbrook:

a) vibration;
b) high speed circuit at 85 km/h and record duration 347 s;
c) gravel road test at 32 and 48 km/h (20 and 30 mph) and record duration 197 s;
d) B class road at 48 and 64 km/h (30 and 40 mph) and record duration 254 s;
e) shocks;
f) Millbrook pot hole “A” and “B” at 16 km/h (10 mph) ;
g) Millbrook cat’s eyes at 48 km/h (30 mph);
h) Railway level crossing at 32 km/h (20 mph).

Analysis was undertaken for each measurement channel and surface, with a typical time history presented along with an APD and PSD. The sample rate was 1 024 sps, producing a frequency resolution of approximately 0,5 Hz. The record durations varied according to track surface and are indicated in the list above. The data is summarized here in terms of variations in vibration r.m.s. with road surface in Figure 37, in terms of peak spectral value in Figure 38 and the variation in shock amplitude in Figure 39. The spectra for the vertical axis are shown in Figure 40.

3.7 Supplementary data

The data collection exercise which preceded this assessment identified several relevant sets of information, which come from reputable sources, but for which the data quality could not be adequately verified. Although, they are included here to facilitate validation of data from other sources, care should be taken when utilizing information in this category.[2]

Renault Trafic (1,9 tonne) and TRM 1000 (20 tonne). Information is contained within the French military specification GAM EG 13 (see [9] from two different vehicles. The 4 x 2 Renault Trafic was loaded to an all up mass of 1 950 Kg and triaxial acceleration measurements made at two locations designated only as “central platform” and less specifically “longeron ArG”. The triaxial acceleration measurements on the TRM 1000 were made on the chassis. The measurements were made on a variety of real road conditions and specific surfaces (whether these are real road surfaces or test tracks is not known). All the data are presented in the form of PSD’s of 1 Hz (or better) frequency resolution. The duration of the records used for the analysis is unknown and hence the analysis random error cannot be determined. A summary of the r.m.s. variations with road surface and vehicle speed are presented in Table 6 and Table 7 for the Renault Trafic and TRM 1000 respectively. Overlaid spectra for the two vehicles are also presented in Figure 41 and Figure 42.

Various US road vehicles circa 1970. As part of an exercise, in the early 1970’s, to authenticate severities for the US military specification Mil Std 810, J.T. Foley (see [10]) at Sandia National Laboratories in the US undertook an extensive exercise to establish transportation requirements on a number of platforms including several road vehicles. As far as can be determined, the vehicles used real US roads and conditions. The vehicles included

a) well used tractor – flatbed trailer with leaf springs suspension,
b) renewed tractor – flatbed trailer with leaf spring suspension,
c) well used tractor van trailer with air ride suspension,
d) new tractor – van trailer with air ride suspension,
e) carefully driven tractor – van trailer with leaf spring suspension,
f) 2,5 tonne flatbed truck of conventional commercial design,
g) 2,5 tonne van truck modified to carry explosives.

The measurements encompassed seven road vehicles but the process adopted does not allow information from individual vehicles to be identified. Moreover, the analysis process Foley used throughout his work is relatively unique and not immediately compatible with other information presented in this assessment. Foley generated test spectra (Figure 43) which can be usefully compared with those from other methods and sources.

Various US road vehicles circa mid 1980’s. As part of an exercise, in the mid 1980’s, to authenticate test severities for the US military specification Mil Std 810, William Connon (see [11]) at the US Army Aberdeen proving ground, undertook an extensive exercise to establish severities on a number of platforms including several road vehicles. The measurements were entirely made on the special test tracks at the Aberdeen proving ground. The (essentially military) vehicles included

(1) M127 12 tonne semi-trailer,
(2) M813 5 tonne truck,
(3) M814 5 tonne truck,
(4) M36 2,5 tonne truck,

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[2] Landrover Defender Model LR10 (SVIC 34 / C112) Registration CD 70 AA, Ford Transit Van Registration M639 BTL, Renault AE 385ti Magnum Semi Trailer, Renault Trafic (1,9 tonne), Renault TRM 1000 (20 tonne), as well as various US Military road vehicles, are the trade names of products supplied by Renault, Ford and the US Military, respectively. This information is given for the convenience of users of this technical report and does not constitute an endorsement by IEC of the products named.

(5) CUCV M1009 1,5 tonne truck,
(6) HMMWV M998 1,25 tonne truck,
(7) HEMTT M985 10 tonne truck,
(8) M416 0,25 tonne 2 wheeled trailer,
(9) M105A2 1,5 tonne 2 wheeled trailer.

The measurements encompassed nine different vehicles but the process adopted does not allow information from individual vehicles to be identified. Moreover, the analysis process used throughout the work is relatively unique and not immediately compatible with other information presented in this assessment. Connon generated test spectra (Figure 44) which can be usefully compared with those from other methods and sources.

Miscellaneous data. During the course of the data search a number of possible data sources were identified for which the data were not traceable to any reasonable extent. These are included here for completeness because they may help support information from more traceable sources. Most of these sources are courtesy of Dr Ulrich Braunmiller and the SRETS work. Vertical responses from several road surfaces presented in ASTM D4728-91 (see [12]) are shown in Figure 45. Multi-axis responses from a trailer originating from ASTM D4728-95 (see [13]) are shown in Figure 46 and for a semi-trailer in Figure 49. The vertical vibrations from a 15 tonne truck originating from EXACT DK 1-237 ([14]) are shown in Figure 47. Information from a trailer with leaf springs ([15]) are shown in Figure 48. Lastly information from an intermodal study ([16]) are shown in Figure 50.

4 Intra data source comparison

4.1 General remark

The purpose of the following paragraphs is to review each data source for self consistency. The process for evaluating the vibration data takes into account the variations arising from vehicle type, road surface, vehicle velocity and vehicle loading. Whilst historical evidence suggests that all of these have some influence on vibration severity, the same evidence also suggests an even bigger influence may be the way the vehicle is driven.

4.2 SRETS road and test track measurements

The SRETS work specifically undertook an intra and inter data source comparison to verify the quality of the data acquired. For the overtly acquired data specific comparisons were made between vehicle type (Figure 8), road types (Figure 9) and vehicle load (not included). These information are also summarized in Figure 5. The entire basis for the covertly acquired data was to maintain practically similar vehicle class, road route and vehicle load conditions. The very purpose was to quantify the variations arising from any other practical influence including the way the vehicle is driven. Shown in Figure 2 and Figure 3 are the variations from 18 journeys of which 16 (journeys 4 to 19) were nominally identical.

Analysis of variance (ANOVA) calculations between the various data sets indicated that the covertly and overtly data sets are not significantly different to a level of confidence of 95 %, provided data acquired in a similar manner are compared. That is provided real road data are compared and the overtly acquired test track data are excluded (Figure 6). This appears reasonable as ANOVA calculations between the overtly acquired road data and overtly acquired test track data are significantly different. The other difference identified was between the covertly acquired “signal triggered” data and “time triggered” data. The difference between these two acquisition strategies are shown in Figure 10, Figure 11, Figure 12 and Figure 13. These figures also illustrate other aspects of covert measured environment. The SRETS workers observed a markedly greater variance in the covertly acquired data from similar overtly acquired data. This would appear to support the use of covert measurements.

The trends indicated by the SRETS assessment are summarized as follows:

Relative severity due to road type. The SRETS assessment indicated that good ordinary roads and motorways were not significantly different. However, test tracks produced vibration some 2 to 3 times greater than ordinary roads.

Relative severity of measurement axes. The SRETS data generally indicated that the horizontal measurements (lateral and fore/aft) to be statistically similar. However, the vertical measurements were marginally greater than the horizontal measurements by between 10 % and 40 %.

Relative severity due to vehicle type. The SRETS assessment suggested that the truck was slightly more severe than its trailer which in turn was slightly worse than the semi-trailer. However, it has to be said difference were relatively modest.

Relative severity due to vehicle load. The SRETS assessment indicated severities increased with reduced payload that is a full vehicle is better than an empty one.

Relative severity of signal triggered and time triggered data. The difference between signal and time triggered data is relevant to modern measurement strategies which frequently adopt signal triggered digital recorders. Essentially signal triggered data result in slightly greater amplitude responses than is the case for time triggered data. However, the characteristics of both the spectra and probability densities are broadly similar.

4.3 CEEES ‘round robin’ 10 tonne truck measurements

This measurement exercise included a measure of vehicle speed allowing the relationship with vibration and shock to be quantified for this vehicle. Additionally, the very lengthy measurement allowed probability densities, to a very low level of probability, to be determined with statistical confidence.

Vibration severity with vehicle speed. The analysis indicated a clear relationship of vehicle speed with vibration severity (Figure 19). The indicated relationship was not linear, with vibration amplitudes increasing at a greater rate at higher speeds. The latter SRETS work also indicated a relationship with vehicle speed but could not quantify it.

Shock severity with vehicle speed. The analysis indicated no clear relationship of vehicle speed with shock severity (Figure 20). Rather the shock amplitudes appeared to occur over a broad range of vehicle speeds.

Relationship between vibration and shock. The extensive APD analysis indicated that the shocks produce a clear amplitude distribution which, with sufficient data, appears to be broadly Gaussian (Figure 25). The APD’s also show that the amplitude distribution of the shocks is an extension of the vibration distribution. In effect the APD suggests that previously assumed distinctions between vibration and shock may be arbitrary. The later SRETS work came to similar conclusions.

4.4 Various vehicle measurements by Hoppe and Gerock

Insufficient data are available to allow an intra measurement comparison of the Hoppe and Gerock vibration data. Indeed, information is lacking to ascertain any basis for the vibration levels. More extensive information on the shocks is available from which it is possible to identify and compare the effects of different vehicles. As a consequence of the lack of traceability of the vibration data the Hoppe and Gerock fails the data verification tests set for uncaveated consideration of information in this assessment. The continued inclusion of the Hoppe and Gerock measurements is only a consequence of the fact it appears to be the source for the existing IEC 60721 severities.

4.5 Millbrook measurements on Landrover Defender, Ford Transit Van and Renault Magnum

Although no published results are available for the intra measurement comparison exercise, the data summaries presented in this report were originally compiled to demonstrate the credible data. The main concern at the time were that the severities appeared a little lower than anticipated particularly for the landrover which is a relatively small vehicle. However, all the vehicles indicated a relatively consistent variation between road surfaces, none of which were particularly bad. Both the Ford Transit van and the Renault Magnum also indicated relatively low vibration amplitudes but both were modern vehicles clearly designed to have good ride characteristics.

4.6 Renault Trafic (1,9 tonne) and TRM 1000 (20 Tonne)

These GAM EG 13 data were presented solely as PSD plots with apparently no further assessment or data verification. The summary information presented here appears to indicate a better degree of consistency than is first apparent from the GAM EG 13 presentation. Although one or two measurements from the TRM 1000 are slightly inconsistent with the remainder, the variations are not particularly greater than observed in other data. Data from surfaces designed as metal strips at 23,5 km/h and small pot holes are 13,5 km/h are greater than the remainder and have a spectra (not included in the data presented) different to the remainder.

4.7 Various US road vehicles circa 1970 and circa mid 1980’s

Although both of these US exercises where intrinsically different, they both adopted an “automated” approach which do not readily allow intra source comparison. It is known that the Foley approach only utilized to the highest 10 % (amplitude) measured data. However, the manner in which the various vehicles contributed to the final values is unclear. Similarly the Connon approach of adopting a mean plus one standard deviation meant that the automatic compilation of data was undertaken. With this said it is understood that the final computation of mean plus one standard deviation (that between vehicle types) was only undertaken when Connon was satisfied that the inclusion of information on that vehicle was not going to disrupt the data ensemble. In neither case is it possible to undertake an intra data comparison here from the information available nor are any comparisons published.

5 Inter data source comparison

For the most part, the data from the various sources indicated a reasonable degree of self consistency at least between the vibration responses. However, it is clear some differences do exist between sources and more significantly within individual measurement exercises. This could be an indicator of the inclusion of inconsistent or invalid data, but, it appears more likely to be a consequence of the variations of arising from real world roads and drivers. However, a number of broad trends can be identified within the various data sources and the broad trends are essentially consistent for all the vehicles addressed.

Generally the highest vibration response amplitudes occur at low frequency (typically 6 Hz to 10 Hz) which appears to be the effect of vehicle suspension. The next highest amplitudes typically occur in the 100 Hz to 300 Hz region and these responses appear to be related to vehicle dynamic characteristics. On vehicles with good suspension on reasonable roads the amplitude of the low and mid frequencies are broadly similar. However, on vehicles with older suspensions and/or poor roads (and particularly test tracks) the responses at the low frequency suspension modes rise markedly in amplitude.

Other than the above, the spectral content of the vibrations from a particular vehicle appear to be remarkably consistent. As such, several workers have postulated that variations in amplitude (due to speed, driver road surface) can be quantified in terms of the variations in overall r.m.s. alone. A few workers have extended this further by assuming spectra of similar shape also occur between different vehicles. However, only limited success is evident in this regard.

The data sources indicate that responses in the vertical axis are greater than the two horizontal axes. Insufficient data are available to identify a definitive trend with regard to location in the vehicle. Work presented in UK defence standard 00-35, (see [17]), but not reproduced here, indicates worst case condition exist over the rear axle and (for semi-trailer) over the fifth wheel. Several of the workers whose data are presented here appear have assumed this in setting up their measurement exercises.

Having established a number of underlying trends, these were used to determine whether any of the vibration databases were inconsistent with others. Generally the vibration databases align reasonably well. However, this is not entirely the case for the measurements by Hoppe and Gerock which seem to be different in both spectra and amplitude. The measurements by Hoppe and Gerock do contain a number of quite old vehicles. Moreover, insufficient data are available to determine whether the Hoppe and Gerock results are dominated by specific vehicles. For these reasons some doubt exists as to the applicability of the Hoppe and Gerock results. It is also observed that US Army Aberdeen proving ground database seems to produce a very strong low frequency response at the suspension mode. This is out of line with the real road running information and seems likely to arise from the exclusive use of severetest tracks.

Some differences exist in the way shock severities were obtained and other differences exist in how the shocks were described and quantified. Essentially, some shock severities were obtained by deliberate encounters with severe obstacles. Others shocks responses were quantified from peak acceleration levels observed during actual during road running (representing the effects of real road obstacles). The information derived from the latter approach has advantage that the shock occurrence rate can be quantified. Also if sufficient information is processed the extreme values of the latter should (in theory at least) approach the levels from the former approach (provided sensible speeds and obstacles are chosen).

Broadly, the shocks from the two acquisition approaches do tend to converge. Most of the exceptions seem to originate from unrealistic obstacles (i.e. head on into a 300 mm height kerbstone) or from severe test track conditions. Again, the measurements by Hoppe and Gerock again seem out of line with the body of the data reviewed here. Specifically, the amplitudes are consistently of much greater than from other data sources. In this case a reasonable breakdown of data exist which seems to suggest the main reason is the inclusion of some quite old vehicles (and also the approach of making measurements on almost empty vehicles). The limited information from “newer” air suspension vehicles are relatively similar to the body of the data reviewed here. However, it should be noted that even these “newer” vehicles are comparatively old.

All the data sources, with one exception, have utilized acceleration power spectral density as the means of analysing the vibration data. This approach appears to be used for the analysis of vibrations as they have a broad band random characteristic, However, some care is needed as the vibrations from real road conditions are clearly non-stationary. Given that power spectral density analysis is essentially an averaging process, the amplitudes could vary due to this aspect alone. To minimize variations in this regard, some workers have adopted “peak” or “mean plus one standard deviation” power spectral density values be observed as well as the usual “average”. Another commonly used strategy appears to be to supplement the power spectral densities with amplitude probability density values. None of the workers whose data are presented in this report indicated the use of a specific stationarity check but on the CEEES ‘round robin’ a few did.

Several different approaches were used to identify shocks. One reason for this appears to be how the shocks conditions were obtained. Shocks occurring during lengthy vibration conditions appear difficult to identify by simple methods (again the CEEES ‘round robin’ found this to be a problem). The most common approaches adopted were based on amplitude probability density methods or simple level crossing approaches (on older data). Exercises which have deliberately induced shocks by including vehicle encounters with specific obstacles in the measurement exercise have commonly used shock response spectra.

6 Identified test severities

In addition to the various descriptions of the road transportation dynamic environment, a number of documents present test vibration spectra. A number of these were compared by Dr Ulrich Braunmiller as part of the SRETS work. His investigation (see [1]) indicated considerable variation in existing test severities.

The SRETS work itself generated four different sets of test spectra along with recommended durations of application. Essentially, the spectra originated from four different strategies for transforming the measured data into test severities. Two of the sets of test severity have been subsequently put forward as more representative of actual conditions.

One set of severities were derived from the PSD analysis alone. The vibration spectra from this approach are presented in Figure 51 and Figure 52 for the vertical and transverse axes. The vibration severities are intended to be augmented by a shock test program set out in Table 8. It will be noted that different vibration amplitudes are recommended for good, poor and very bad road conditions.

The second set of severities were based upon the PSD as well as the observed variations in APD and r.m.s. Essentially they are intended to better represent the variations in vehicle speed, actual road surface conditions and driver. The derived spectra are intended to encompass shock conditions. The derived test spectra are presented in Figure 53 and Figure 54 for the vertical and transverse axes. The severities are intended for all conditions except very poor road surfaces.

As addressed previously both the Foley and Connon work was used to generate two different sets of severity in Mil Std 810. In that specification the severities are referred to as “basic vibration” (from Foley – Figure 43) and “composite vibration” (from Connon – Figure 44). The Foley based severities are similar to a number of other test severities presented here. The Connon severities are markedly different from almost all others. This is partly because the Connon severities are intended for military vehicles used in bad and degraded road conditions. However, it also seems to be a consequence of deliberately including the amplitudes arising from the low frequency suspension modes. These induce quite large displacements requiring so called “long stroke” vibration generators and they cannot be done on more conventional vibration generators.

The test severities from two other military standards (see [17] and [18]) are presented in Figure 55 and Figure 56. Both these are similar to each other and to the Foley based severities of Mil Std 810. Similarity of severity also exists with that of Elektrotechnische Apparate (or Electrotechnical Instruments) specification (see [19]) shown in Figure 58, as well as with ETS 300-019-2-2 (see [20]) shown in Figure 60.

Test spectra from ASTM D4728-95 (see [13]) are presented in Figure 57. Lastly spectra proposed by CEN TC 261 and ISO TC 122 are shown in Figure 59.

7 Environmental description

Ideally an environmental description should quantify all aspects of an environmental condition. Practically it is usually sufficient to quantify the aspects that may induce damage and failure to any equipment that may subject to it. For some environments this is easy to achieve, for others it is quite difficult. The vibration and shock conditions arising from road transport undoubtedly fall into the latter category. Historically, the conditions occurring during road transportation have been defined by a few tests (typically vibration, shock and bounce). These tests appear to have been set based upon limitation on testing facilities (in the 1950’s and 60’s), rather than for their ability to exercise all potential equipment damage and failure modes.

The poor definition of the road transportation environment is exacerbated by the very wide range of strategies adopted for the protection (packaging) of equipment during transportation.

This has become an issue in recent years with considerations of speed and cost of package handling becoming important issues. Failure and damage modes of packaged equipment are diverse, a factor illustrated in the recent SRETS study see [21]).

The road transport environment is made difficult to describe by the many variables that affect it. Not only do conditions such as road surface and vehicle speed have an influence on the environment, these effects are synergistic. In this particular case the extent to which they are related is controlled almost entirely by the actions of a third influence – the vehicle driver.

The most predominant feature of the vibration environment is the low frequency responses that occur at vehicle suspension modes. These responses frequently generate the highest acceleration spectral amplitudes as well as the highest velocities and displacements. As would be expected from a mode arising from vehicle suspension, the response amplitudes are affected by considerations such as vehicle speed and road surface. By design, vehicle suspension systems are intended to limit dynamic magnification (by modestly high levels of damping) and attenuate much of the shock and vibration conditions that are imposed on the vehicle (by setting a low suspension mode frequency and consequently acting as “filter” for the higher frequency excitations). Modern air suspension systems are able to achieve these design aims better than older leaf spring suspension systems as they allow a lower frequency suspension mode to be established almost independent of payload.

The dominance of a single (suspension) frequency in the vibration responses lead some early workers to believe the vibration motions to be predominately sinusoids. However, the use of modern analysis techniques has extensively proven that the vibration motions are random and predominantly Gaussian when a sufficient stretch of “real road” is considered. However, quantifying the Gaussian distribution is complicated by the amplitude variations that occur due to variations in road speed. The effects of the central limit theorem is such that, with sufficient data, the resultant distribution of Gaussian distributions should eventually also become Gaussian. One influence sometimes seen to limit this occurrence is the existence of non-linear characteristics in the (usually) vehicle suspension system.

The acceleration PSD values at the frequency suspension are generally the highest experienced. However, the loading effects on the equipment of this acceleration are not the only potential means of damaging equipment. The velocities and displacements arising from this response also have the potential to produce damage to certain equipment. With that said, high velocities and displacements are of concern for another reason. Specifically, the imposition of such conditions on equipment which are not perfectly constrained to the motions of the vehicle can give rise to an entirely different dynamic environment with its own damage potential. Essentially, in such conditions the equipment lifts off the vehicle and subsequently, under the effects of gravity, impacts with it. The kinetic energy of the equipment just prior to impact should be related to velocity imparted to the equipment by the vehicle. However, it is the characteristics (mainly stiffness) of the impacting faces (typically the vehicle and equipment) that will influence how this kinetic energy is transferred to strain energy. Generally, the more rapid the transfer of kinetic energy to strain energy the greater the acceleration shock amplitudes. This condition is frequently referred to as “bounce” and has its own test procedure in IEC 60068-2-55 [24]. The shocks condition experienced by equipment due to bounce should not be confused with the shocks imparted by the vehicle from the road surface. The two are caused by different mechanisms and the severities are influenced by different factors.

Quantifying the enveloping amplitude of the low frequency suspension mode is not entirely straightforward. The problem is made more difficult by the inadequacy of the frequency resolution of the majority of vibration analysis undertaken. However, it appears that an amplitude of 0,001 g^2/Hz would encompass the vast majority of vibration occurring (at the vehicle suspension mode) from reasonable vehicles on reasonable roads. In those cases, but for brief periods, the amplitude could rise to be encompassed by an envelope of 0,01 g^2/Hz. In less able vehicles on poor roads the enveloping value for the majority of conditions would be 0,01 g^2/Hz rising to an enveloping condition of 0,1 g^2/Hz for short periods. Based entirely upon the unvalidated Mil Std 810 composite wheeled vehicle spectra it is suggested in extremely poor road conditions that the envelope of the vehicle suspension mode response could be up to 0,7 g^2/Hz. All of the above figures relate to the vertical axis only. The typical frequency range for the dominant vehicle suspension mode is 1 Hz (usually air suspension) to a little over 10 Hz (usually a lightly loaded leaf sprung vehicle). The vehicle displacements arising as a consequence of the vehicle suspension mode may exceed 100 mm even for a reasonable vehicle on reasonable roads.

Currently the random vibration severities of IEC 60068 [23] and IEC 60721 [25] have a lower frequency of 5 Hz. This is only slightly below the low suspension mode frequency of vehicles with leaf spring suspension. However, it is commonly above the suspension mode frequency of vehicles with air suspension. The reason for a 5 Hz lower frequency is a consequence of the limitations on displacements and velocity imposed by electro-magnetic vibration exciters. The majority of these are limited to 25 mm stroke with others limited to a stroke of 50 mm. Above that displacement the use of hydraulic excitation generators is generally necessary, this brings further problems as such devices have a limited upper excitation frequency.

The vibration responses occurring above the vehicle suspension mode, mostly occur in the 100 Hz to 200 Hz region. These appear to be a result of the vehicle dynamic characteristics as well as the effects and condition of the engine and transmission system. The amplitudes of these responses seem far less affected by vehicle speed and road condition than the vehicle suspension modes. Moreover, vibration analysis is almost always adequate at these frequencies. Typically these conditions are enveloped by an amplitude of 0,001 g^2/Hz with a (very) few occurrences approaching 0,01 g^2/Hz (which appears to vehicles with poor quality engine and transmission). Typically above around 200 Hz the responses fall at (approximately) 6 db/ octave. A similar roll off can be observed above the vehicle suspension mode up to nearly 100 Hz. The vast majority of r.m.s. values are below 0,2 g, a number occur up to 0,4 g and a very few up to 1,0 g.

Quite a variation exists in the severities of the shocks occurring due to the vehicle traversing real roads. As set out earlier, this is partly a consequence of the different methods used to quantify the shocks and partly due to the different ways used to acquire the information. The ability to undertake analysis for records spanning very long durations of real road running, has indicated that shocks appear to occur with a distinct distribution which logic suggests will probably tends towards Gaussian. The characteristics of the “shocks” seem to be those of transient vibrations rather than of a shock pulse (see Figure 16 and Figure 17). This was demonstrated by some of the SRETS transients arising from impacts with speed bumps. A speed bump essentially imposed a fixed displacement half sine pulse on the vehicle wheels. These appeared, on the cargo bed, as a series of overlapping decaying transients. The timing between the transients arising as a function of the distance between sets of wheels and the speed of the vehicle. The shock response spectra of almost all the shocks were very similar to those from high amplitude random vibration.

The shocks amplitudes from real road conditions acquired overtly and from deliberate encounters with realistic obstacles are enveloped by an amplitude of 2 g. However, some of the SRETS measurements exceed this value. A significant issue here appears to be that these higher amplitudes were from covert measurements. This would support a logical surmise that drivers have a significant effect on shock amplitude, encountering obstacles at higher speeds than would be the case overtly. Another reason the SRETS are high is that the measurements were made immediately below a loose pallet. Under most conditions these stayed in contact with the payload bed. However, under high displacements the pallets “bounced”. If those occurrences are disregarded the vehicle induced shock were enveloped by an amplitude of 8 g.

As indicated previously the amplitude of shocks arising from cargo bounce are influenced by the (mostly stiffness) characteristics of the impacting faces (equipment and cargo bed) rather than any other influence. Whilst the SRETS measurements indicate that bounce can occur during commercial transportation on real roads, it does so at a very low rate (for apparently less than 0,000 1 % of the transport duration). This occurrence rate is almost certainly far exceeded during military transport in combat zones. This is almost certainly why simulating the bounce condition is a common requirement for off-road (military) equipment but rarely adopted for on-road commercial (non-defence) equipment. Quantifying the range of shock amplitudes for bounce would require consideration of a vast range of equipment and vehicles as well as combination. That is well beyond the scope of this assessment and data collection exercise. However, the values already set out previously do quantify the conditions inducing bounce.

8 Comparison with IEC 60721 and IEC 60068

The environmental severities of IEC 60721-3-2:1997, Table 5, environmental category b) (stationary vibration random), Table 5, environmental category a) (stationary vibration sinusoidal)and Table 5, environmental category c) (non-stationary vibration including shock), are illustrated in Figure 61, Figure 63 and Figure 65, respectively. These are intended for "transport" in general and not specifically for road transport. No durations or number of applications are specified.

The test procedures of IEC 60068-2 contain vibration and shock severities related to transport. These are different to those of IEC 60721-3. The severities for stationary vibration random, stationary vibration sinusoidal and shock, are illustrated in Figure 62, Figure 64 and Figure 66 respectively. In these cases the duration of vibration testing and number of shock applications is quoted.

As the amplitudes of IEC 60721-3 differ from those of IEC 60068-2, reconciliation between the two documents is set out in IEC 60721-4-2 [27]. For the two vibration conditions, IEC 60721-4-2 recommends the IEC 60068-2 amplitudes. However, for the shock a third option is recommended those are illustrated in Figure 67.

The three "transport" categories set out in IEC 60721-3-2:1997 are designated 2M1, 2M2 and 2M3. Only a brief explanation is given as to the conditions these represent but seem to be essentially:

- 2M1 – air cushioned trucks and trailer;
- 2M2 – lorries and trailers on well developed road systems;
- 2M3 – road vehicles in areas without well developed road systems.

When the spectra from IEC 60068 [23] and IEC 60721 [25] are reviewed against the information surveyed for this assessment, a number of significant issues arise. These are addressed in the following paragraphs.

Of particular concern is that the IEC 60721 spectra do not have the potential to exercise all potential damage mechanisms. The IEC 60721 recommendations are split into three headings viz. stationary vibration random, stationary vibration sinusoidal and non-stationary vibration including shock; these are in fact the different test procedures of IEC 60068. It is presumed that the two stationary vibration categories (sinusoidal and random) are intended to be alternatives. IEC 60721-3-2 does not mention the IEC 60068 bounce although IEC 60721-4-2 does use the IEC 60068 bump test to undertake shock testing. No information is available to determine the assumptions made in originally dividing the dynamic road transport environment into these testing categories. However, some inferences can be deduced from the Hoppe and Gerock paper. These inferences would suggest that the dissection into the various testing categories was based upon limitations testing facilities available in the late 1960's and early 1970's capabilities rather than attempting to accurately reproduce damage inducing mechanisms. As such, a review is justified of the various testing categories against current understanding of the actual dynamic road transport environment and testing facilities.

Random vibration. The dynamic environment is predominantly Gaussian random and this is the most realistic of the two vibration severities. However, the lowest frequency of the spectra is at the top of the range in which vehicle suspension modes generally occur. The amplitudes at the lowest frequency are such that displacements and velocities are very low compared with those that can actually occur. As such, the test does not have the ability to exercise all potential failure modes associated with either displacement or velocity. When the spectra were originally derived the capability existed to achieve greater displacements and velocities than those adopted. Today even greater displacements are possible and a number of test standards have made use of this increase to better replicate the dynamic road transport environment. It is not clear why the IEC 60721 random vibration spectra extended the excitations up to 2 000 Hz which is not strongly supported by the information presented in this assessment.

Shock. All the IEC 60721 transportation shock definitions are half sine pulses. These are not representative of the transient responses actually occurring. It is appreciated that at the time the severities were originally derived only a limited capability existed to undertake anything other than basic pulse shock testing. However, today facilities commonly exist to undertake transient vibration testing on the same excitation equipment as the vibration test. These are able to more closely replicate actual conditions, require less facilities (no separate shock test machine) and can mean more economic testing (no re-rigging of equipment from vibration to shock test). Some industries have taken the use of a vibration generator to replicate road transportation shocks even further by adopting short durations of high amplitude random vibrations to replicate the distribution of shocks observed in real road conditions. Other industries have included transient vibrations within the stationary vibrations. Unfortunately, IEC 600721 entirely fails to accommodate any of these more accurate, and cost effective, simulations of actual conditions.

Sinusoidal vibration. The sinusoidal severity almost certainly pre-dates the random severity and no attempt appears to have been made to ensure compatibility between the two. It is likely that the sinusoidal sweep severity was only retained to allow continued use of older facilities. Nevertheless, continued inclusion of the sinusoidal sweep severity is difficult to justify when it is so different from the random severity. The frequency ranges of the two severities are entirely different (random 5 Hz to 2000 Hz and sinusoidal 1 Hz to 500 Hz). The lowest frequency of the sinusoidal sweep results in displacements and velocities far more severe than the random severity. If the effects of the two severities are compared using techniques such as maximum response spectra (Figure 68 and Figure 69) and fatigue damage spectra (Figure 70), it is found that the damage potential of the two are remarkably different. The two severities only producing similar damage effects for a very small range of resonator frequencies. Today it seems likely that few test facilities are constrained to a sinusoidal sweep. As such no real justification appears to exists for keeping the sinusoidal severity. However, if the option is kept it should at least match the damage inducing potentials of the random severity.

Bounce (loose cargo). Although not currently required from within IEC 60721-3-2, the bounce or loose cargo environment is relevant and for completeness included here. The bounce test machine currently specified in IEC 60068-2 is a mechanical device intended to give 25 mm sinusoidal motion of a table at approximately 4,5 Hz. By using two cams running at slightly different frequencies, both heave and pitching motion is induced. The equipment is loosely placed upon the table and allowed to bounce. As the motion is fixed the only severity parameter the user is able to adjust is test duration. This machine broadly replicates the vertical vehicle suspension mode. However, it is debatable whether the large amount of pitching motion induced by the bounce machine actually occurs. Some test facilities undertake bounce testing using long stroke hydraulic vibration generators, others on long stroke electro-dynamic vibrators. These generators allow the user to control the amplitudes and frequencies of excitation. A few facilities undertake combined random vibration and bounce testing by not fixing the equipment to the vibrator table. These approaches are not without problems and no specific and appropriate test procedure exists within IEC 60028-2.

To summarize the above, the damage potential of the dynamic road transport environment is inadequately replicated by the current way it is split by IEC 60721 into different test procedures of IEC 60068-2. Moreover, the specification of out of date techniques is preventing the use of more rigorous and potentially more cost effective techniques. Current day techniques would permit the entire dynamic road transport environment to be simulated with a single test.

The environmental and test severities set out in IEC 60721 and IEC 60068 do not appear particularly representative of actual condition nor do they replicate all aspects of the environment exercising potential equipment failure modes. The problem as already explained is encompassing the full range of vehicle suspension modes. Only a moderate number of equipment will have failure modes sensitive to the conditions induced by the vehicle suspension modes. The most commonly encountered mode will arise when the motions are sufficient to cause impacting between parts of the equipment. In such cases the severity of impact will be characterized by the applied velocities. As currently indicated, the velocities arising from the severities of IEC 60721 and IEC 60068 are below those of actual conditions.

It has to be acknowledged that not all equipment will be sensitive to the motions induced by the suspension modes. However, the decision whether equipment is sensitive should be made by the equipment manufacturer and not by IEC 60721 and IEC 60068. The equipment manufacturer should decide on the need for including severities to replicate the motions of the vehicle suspension mode and IEC 60721 should offer advice and assistance.

Even for equipment not sensitive to the motions of the vehicle suspension, the amplitudes of the suspension responses still have an influence. This is because the suspension mode is the dominant influence on responses up to nearly 100 Hz. Essentially above the suspension mode the responses are “rolling off” at around 6 db per octave up to around 100 Hz when vehicle and transmission responses become dominant. Previously set severities are a constant amplitude in this frequency region and appear to have been set based on the amplitude at around 10 Hz. The implications of this are the derived test amplitudes are very sensitive to a significant number of variables.

The mid frequency amplitudes appear to be set by vehicle dynamics and transmission characteristics. Variations appear to be more related to the condition of the vehicle engine and transmission. The amplitudes appear to be 0,001 g^2/Hz with a (very) few occurrences approaching 0,01 g^2/Hz (which appears to arise from vehicles with poor quality engine and transmission). The current IEC 60068 amplitudes fall in the same mid frequency region although the severities are still above those occurring.

It is noticeable that significant variations exist in the upper test frequency adopted by various test specifications. This variation exists even within IEC 60721 and IEC 60068 as the random and sine tests adopt markedly different frequency ranges. The reason for this appears to be that measurements dominated by the suspension mode appear to “roll off” from 10 Hz or so and consequently by 500 Hz are of relatively low amplitude. Conversely, where the suspension mode is not such a significant feature (good vehicles and good roads) the mid frequency vehicle responses become significant features. In that case the responses only start to “roll off” again from around 200 Hz. In those cases it is only above 1 000 Hz or so that the levels become significantly lower. This variation in upper frequency may be further complicated by equipment packaging which will usually offer increasing protection against higher frequencies. The selection of an unnecessarily high upper test frequency may restrict test facilities (such as making the use of hydraulic vibrators impractical) and reduce control resolution at low frequency. With that said some equipment may be sensitive to higher frequencies. Again, it has to be acknowledged that the equipment manufacturer is in the best position to assess equipment damage sensitivity frequencies above 500 Hz. As such, the decision as to whether equipment shalltested to frequencies above 500 Hz should be made by the equipment manufacturer and not by IEC 60721 and IEC 60068. However, IEC 60721 needs to offer advice and assistance to the equipment manufacturer on this matter.

The overall r.m.s. of the IEC 60721 and IEC 60068 random vibration severities is at least 8 to 10 times greater than from corresponding measurements. Some of this is a consequence of the test frequency range extending up to 2 000 Hz. However, even without this the margin between actual and test conditions is greater than the norm of around 2 which can be considered a respectable enveloping of actual conditions. The main reason the overall r.m.s. of the IEC 60721 and IEC 60068 random vibration severities are so much greater than the corresponding measurements is the spectral shape is not particularly representative of the vast majority of actual measurements. A more representative spectrum shape which would produce an r.m.s. more closely matched to actual conditions has been discussed previously in this report.

Significant evidence exists that the actual road transportation dynamic environment exhibits considerable variability. Currently this extensive variability appears to have been accounted for by simply enveloping all conditions. This approach is unlikely to create a test which appears credible to the majority of informed users. Several specifications, generated more recently than IEC 60721, have adopted strategies specifically for dealing with this variability. Currently no single strategy appears to have predominance. The situation is further complicated by the fact that users subject equipment to transportation vibration testing for different reasons. Not all users require a test that will ensure equipment survival in real conditions. This is because such confidence frequently comes at a significant cost in terms of packaging and protection that has to be incorporated. This latter aspect can be overcome by use of an environmental description incorporating amplitude probabilities. This would allowing the user to select a severity level (or levels) at an appropriate degree of confidence for their application and purpose. However, this would require a more accurate environmental description for road transportation to be included in IEC 60721.

The amplitudes of the shocks require further consideration and are addressed in the following paragraphs. As already indicated, equipment may experience shocks originating from the road surface or from vehicle/equipment impacts. As these originate from different sources they are addressed separately in the following paragraphs. Currently IEC 60721 appears to deal with both aspects as a single shock description. This does not appear appropriate as bounce can be intrinsically mitigated by good equipment/package design and the current tests do not acknowledge that in terms of severity.

Road shocks. The currently specified shocks in IEC 60721 and IEC 60068 seem to be based upon the Hoppe and Gerock identified levels. Mostly those levels do not seem compatible with conditions arising in modern vehicles. The SRETS and CEEES exercises suggest a distribution of shock amplitudes actually occur. For that reason an environmental description should preferably include amplitude probabilities allowing the user to select a severity level (or levels) at an appropriate degree of confidence for their application and purpose. For current vehicles, and addressing road shocks only, it is suggested the 2M1 levels should be reduced by a factor of 2 to better encompass actual conditions. The 2M2 levels should be the same as 2M1 to reflect that that air suspension and good ride characteristics are now the norm. Insufficient information is available to propose a value for the 2M3 levels with confidence but no real evidence exists for them exceeding the current 2M2 levels. Even at that level they are well in excess of much of the test track conditions reviewed here. It is suggested that the current 2M3 levels have no firm basis and exceed even the severities specified for off road military conditions.

Bounce. The current bounce test seems to be based mostly to replicate military conditions, for this reason it is not surprising the test is rarely used for commercial transport and cargo’s. Evidence does suggest impacting does occur between the vehicle cargo bed and equipment (or more usually its package). Today many commercial cargos are carried with either no or limited vertical restraints and, because of this, in certain circumstances impacting between the vehicle cargo bed and equipment can occur. Whilst the covert SRETS measurements indicate that such events occur, the measurements also indicate they are relatively infrequent (the occurrence is probably related to driver quality). The amplitude of the shocks will be primarily related to package stiffness and mass. The SRETS measurements were made on a relatively highly loaded and stiff pallet. This would result in relatively high amplitude, short-duration shock pulses, whilst, a lightly loaded soft package would produce much lower amplitude and longer duration shock pulses. Bounce may occur from either the highest amplitude vibrations or the shocks. In either case, an environment including amplitude probabilities would allowing the user to select a severity level (or levels) at an appropriate degree of confidence for their application and purpose. Converting these conditions into a bounce impact severity needs consideration of the package stiffness and mass. As these vary significantly for different packages and equipment, it would be entirely inappropriate to quote a generic value. Practically the best that IEC 60721 can achieve is to specify the conditions that may cause vehicle cargo bed and equipment impacting.

When the SRETS work started, no explanation was apparent as to why so much variation existed between the various test specifications. However, the SRETS work indicated a variation in measurements not that different from the variation in test severities. The data assembled for this report indicates an essential identical finding to the SRETS work. Another consideration not so far addressed is that most test severities include a test conservatism factor to account for measurement variations, etc. Only for a few of the test severities presented here is information available as to the size of the factors included. Moreover, even in those few cases, no real consistency of factor or even strategy exists.

Although no detailed work in this assessment has been undertaken to establish equivalent test durations, a basic review indicates that tests durations should be much shorter than actual conditions. This is a consequence of the variations that exist in the actual conditions rather than any deliberate attempt to accelerate the test duration. The SRETS work suggested that periods of significant vibrations occur for no more than 8 % of the time. Two items of data analysis, used to quantify the road transportation environment, are particularly useful in establishing “equivalent durations”. The first is amplitude probability density analysis which can be used to effectively quantify the number of times the amplitudes are at a particular amplitude. If the APD analysis encompasses a sufficient duration and mix of real conditions, then a good estimate of equivalent duration can be established. The other form of analysis is fatigue damage spectra. This allows an equivalent test duration to be established based upon equivalent fatigue damage. Both the SRETS and CEEES exercises used both methods to derive test durations.

9 Recommendations

Good data have been identified from three sources, for which a considerable amount of information is available and by which data validity can be established. The three sources include seven, largely modern vehicles covering a significant weight range. The information from these sources was acquired on both public roads and test tracks and include overt and covert measurements. Three additional data sources have been identified which come from reputable sources but for which the available information is insufficient for the data quality to be adequately verified. Lastly information has been reviewed from a source which is probably the basis for the existing IEC 60721 severities.

For the most part, the data from the various sources not only indicates a reasonable degree of self consistency but also a fairly good degree of consistency across the various sources. None of the data sources are so obviously significantly different from the remainder to the extent that the validity of this assessment exercise is called into question. It is clear from the information reviewed that the road transportation dynamic environment is complicated and sensitive to a considerable number of variables. However, some broad trends are consistent for the majority of vehicles addressed.

The severities of IEC 60721-3-2:1997, Table 5, environmental category b) (stationary vibration random) encompass a variety of transportation conditions as well a transportation by road vehicles. However, it seems likely that the dynamic environment arising from road transportation will be the main condition setting the IEC 60721-3-2:1997, Table 5, environmental severities. The basis for the severities of IEC 60721-3-2:1997, Table 5, environmental category a) (stationary vibration sinusoidal) is uncertain and are in any case not representative of actual conditions. The shocks of IEC 60721-3-2:1997, Table 5, environmental category c) (non-stationary vibration including shock) also encompass a variety of transportation conditions although it seems likely that the dynamic environment arising from road transportation will be the main condition setting the IEC 60721-3-2:1997, Table 5, severities.

Utilizing the data identified in this assessment has found a significant number of deficiencies in the current IEC 60721 conditions and the IEC 60721 and IEC 60068 severities. The most significant deficiencies are set out below.

a) The current severities in IEC 60721 do not constitute a full description of the dynamic road transport environment. A full dynamic road transport environmental description would be relatively complicated but would allow users to set severities best able to exercise potential damage conditions for their equipment.

b) The current description in IEC 60721 is inadequate as it does not represent the entire damage inducing potential of the dynamic road transport environment. Whilst, it is acknowledged that not all users will need to exercise all potential damage mechanism, IEC 60721 should not be unnecessarily restricting the scope of the test. This is particularly relevant for transportation where a vast range of packaged equipment needs to be encompassed.

c) The division of the dynamic road transportation environment into random and shock tests appears to be based upon the capabilities of old test facilities and are not representative of modern capabilities. Not only is it now possible to more closely replicate actual conditions, they require fewer facilities and can result in more economic testing. However, a fundamental revision of the strategy behind IEC 60721 would be required to implement such advances.

d) The severities in IEC 60721-3-2 and IEC 60721-4-2 appear to be envelopes of absolute worst cases. With the variabilities inherent in the road transportation dynamic environment, many users consider such a high level of confidence to be unnecessary and expensive. A number of recently derived road transportation spectra take better account of such variabilities. This would be possible here also if a full environmental description were included.

With regard to the definition of the categories in IEC 60721-3-2, only category 2M1 applies to air suspension vehicles which today constitute the vast majority of the transport fleet. Today the majority of vehicles are either air cushioned trucks and trailer or comprise vehicles with far better ride characteristics than older vehicles. This has reduced suspension frequencies from typically 7 Hz to 8 Hz,prevalent 30 or 40 years ago, to closer to 2 Hz today.

The random vibration spectra set out in IEC 60721-3-2 and IEC 60721-4-2 are markedly different from the vast majority of actual conditions and the majority of corresponding test spectra developed in recent years. The spectra do not include the predominant vehicle suspension mode (as the frequency range does not go low enough) and consequently does not replicate the full velocities and displacements occurring in real conditions. Conversely, the upper frequency limit is unnecessarily high for most equipment. The overall r.m.s. is much higher than actual conditions and markedly greater than the corresponding values for many recently developed road transportation test spectra. Also, the actual spectral shape and levels do not reflect particularly well actual conditions.

Currently, IEC 60721 appears to deal with shock in terms of a single shock description. However, equipment may experience shocks originating from the road surface or from vehicle/equipment impacts. As these originate from different sources they need to be addressed separately from vehicle/equipment impacts; such shocks can be intrinsically mitigated by good equipment/package design and the current tests do not acknowledge that in terms of severity.

(1) ***Road surface shocks***. The information reviewed would suggest that shocks arising from the road surface alone are around half the current 2M1 levels. It is suggested that the 2M2 levels should be the same as 2M1 to reflect that air suspension and good ride characteristics are now the norm. The 2M3 levels appear excessively high and are well in excess of conditions reviewed here. Indeed they exceed even the severities specified for off road military conditions.

(2) ***Vehicle/equipment impacts***. Whilst the covert measurements indicated that such events occur, the measurements also indicate that they are relatively infrequent (the occurrence is probably related to driver quality). Establishing the severity of these shocks requires consideration of the package stiffness and mass. As these vary significantly for different packages and equipment it would be entirely inappropriate for IEC 60721 to quote a generic value. However, it can properly quantify the conditions causing the events and offer guidance on how to derive a severity.

Table 1 – Summary of SRETS journeys

Journey	Transport method	Approximate total distance	Total number of journeys
UK Dumbarton to Daventry	Road	550 km	19 (6 time triggered)
European			
Dumbarton/Greenock	Road		
Greenock/Bilbao	Sea	1 920 km	1
Bilbao/Madrid	Rail	(400 km by rail)	
Madrid railhead/depot	Road		
Dumbarton/Dover	Road		
Dover/Calais	Sea	1 935 km	1
Calais/Madrid	Road		
Dumbarton/Dover	Road		
Dover/Calais	Sea	2 325 km	1
Calais/Lisbon	Road		

Table 2 – Summary of measurements made by Bosch using a number of vehicles and under different test conditions

Road category		Speed km/h	Vehicle 1 (V1) load factor		Vehicle 2 (V2) load factor	Vehicle 3 (V3) load factor	
			50 %	100 %	30 %	40 %	80 %
Test track (bumpy road)	R1	30	2 [a]	2 [a]	2	3	–
		50	2 [a, b]	2 [a, b]	2	3	3
Test track (road bumps)	R2	30	2 [a]	2 [a]	2	2	5
		50	2 [a]	2 [a]	2	2	2
Ordinary road	R3	50	1 [c]	–	1 [c]	1	–
		60	4 [c]	–	4 [c]	4	–
Motorway	R4	70	5 [c]	–	5[c]	5	–

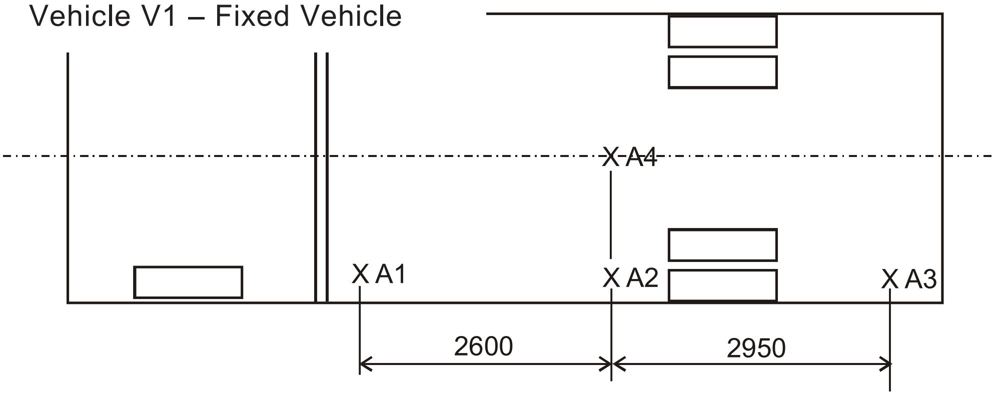
[a] Truck without trailer.

[b] Tri-axial measurement at all points.

[C] Truck with trailer, measurement only at point M3.

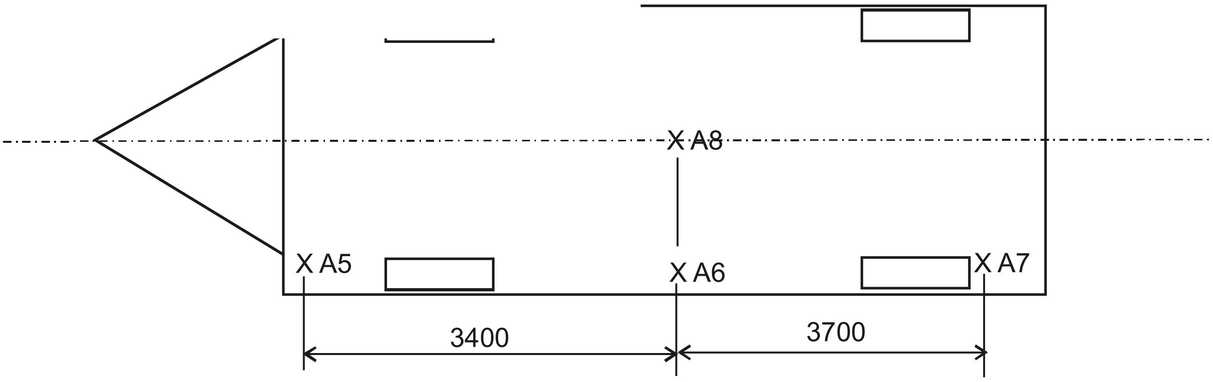
V1

Vehicle V1 – Fixed Vehicle



V2

Vehicle V2 – Semi-Trailer



V3

Vehicle V3 – Articulated Vehicle

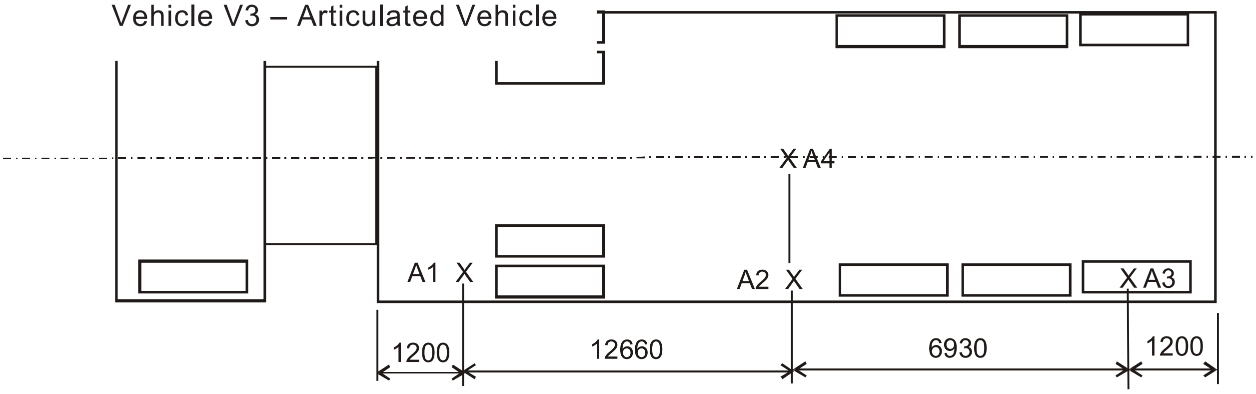


Figure 1 – Schematic of SRETS vehicles

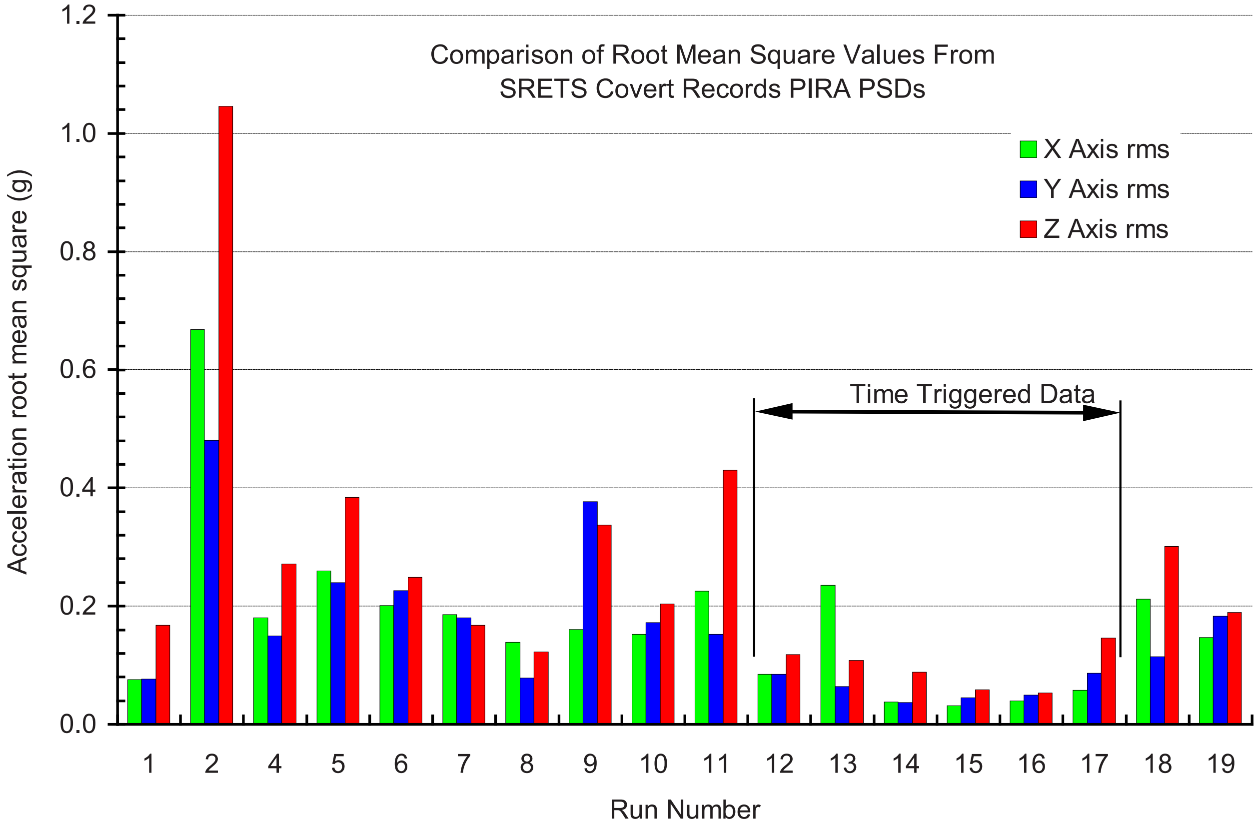


Figure 2 – Effective values of all runs from covert SRETS measurements

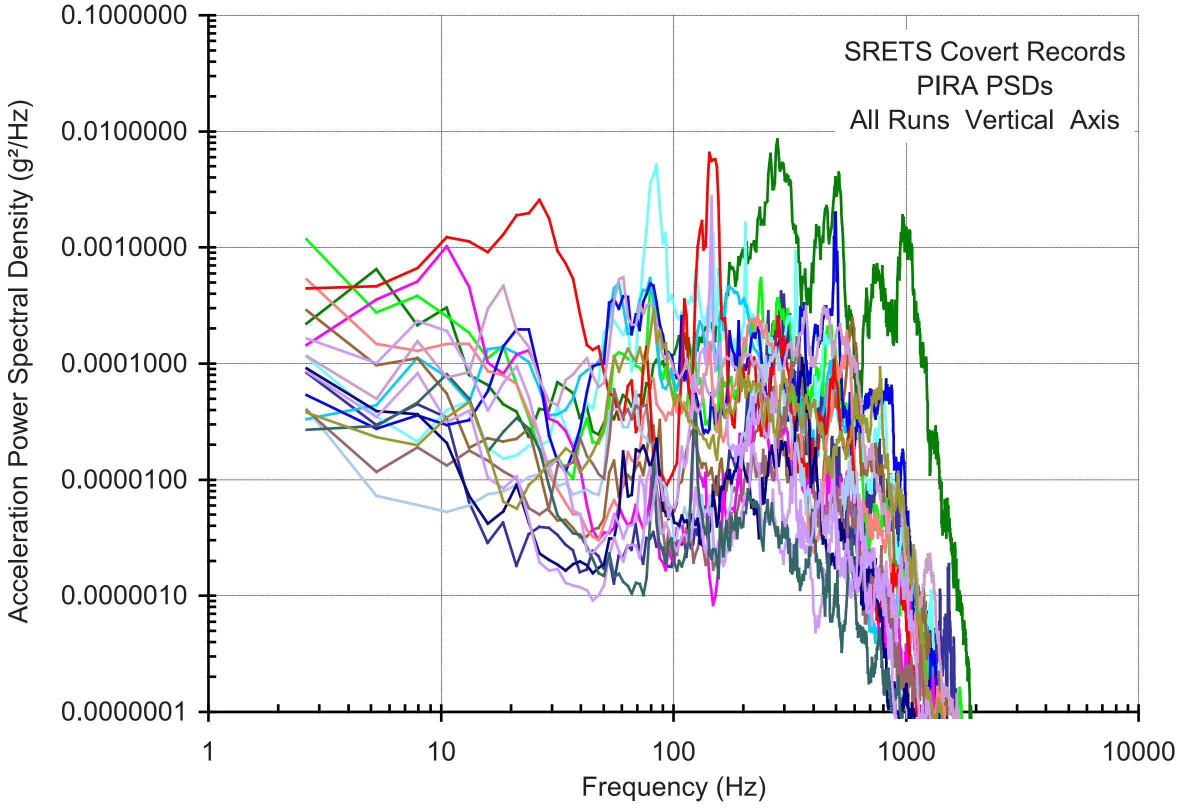


Figure 3 – All PSD form covert SRETS measurements

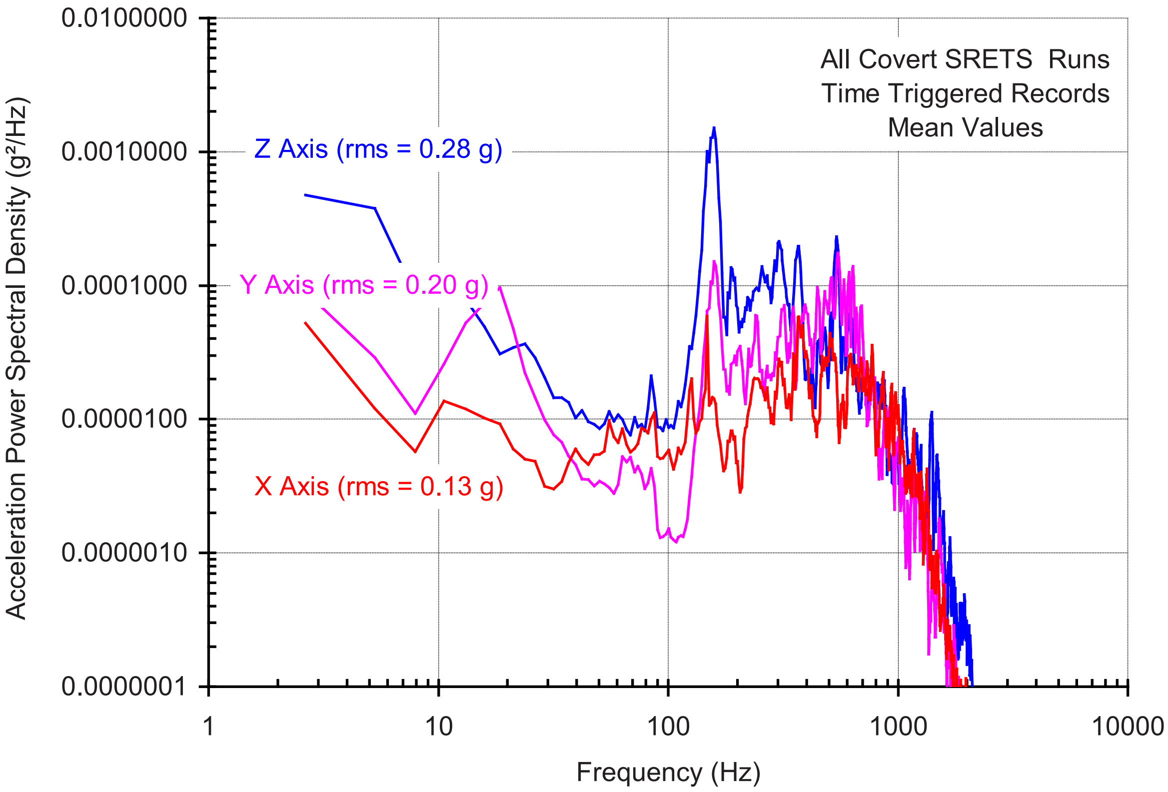


Figure 4 – Comparison of SRETS amplitudes in the 3 axis

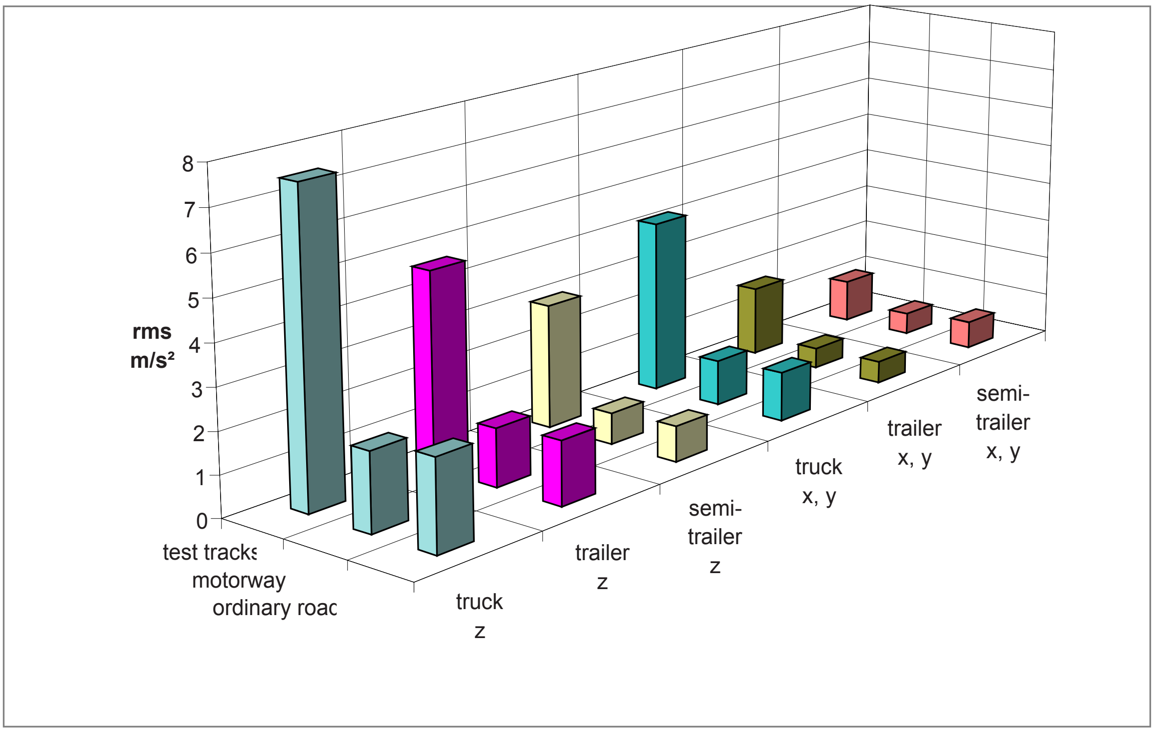


Figure 5 – Comparison of SRETS measurements made with driver’s knowledge

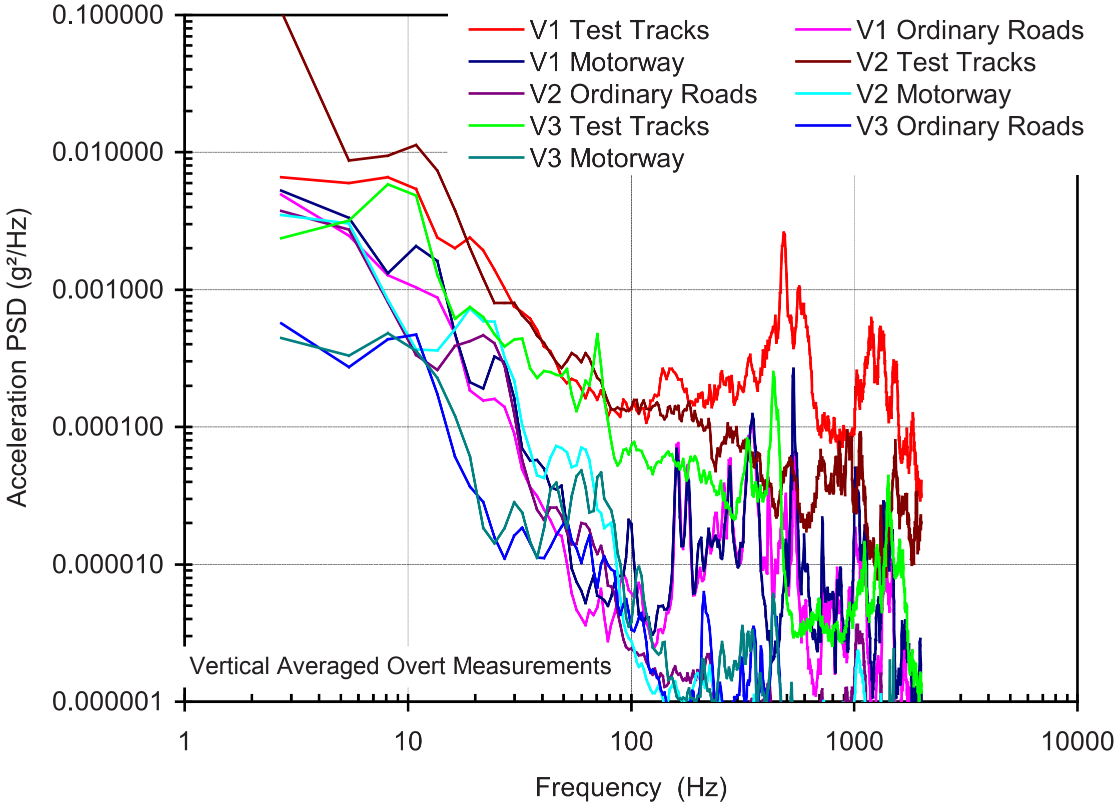


Figure 6 – Comparison of SRETS PSDs of different vehicles (v1, v2,v3) and road categories made with driver's knowledge

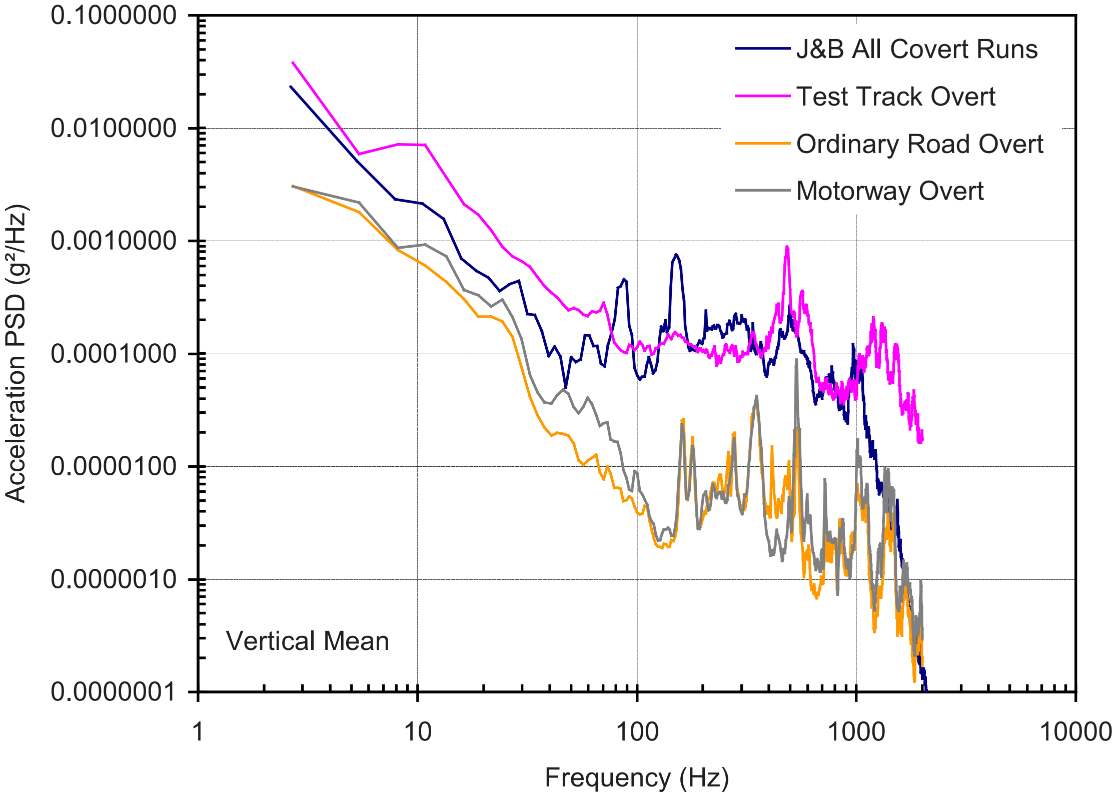


Figure 7 – Comparison of SRETS measurements made without driver's knowledge (covert) and with driver's knowledge (overt) on different roads

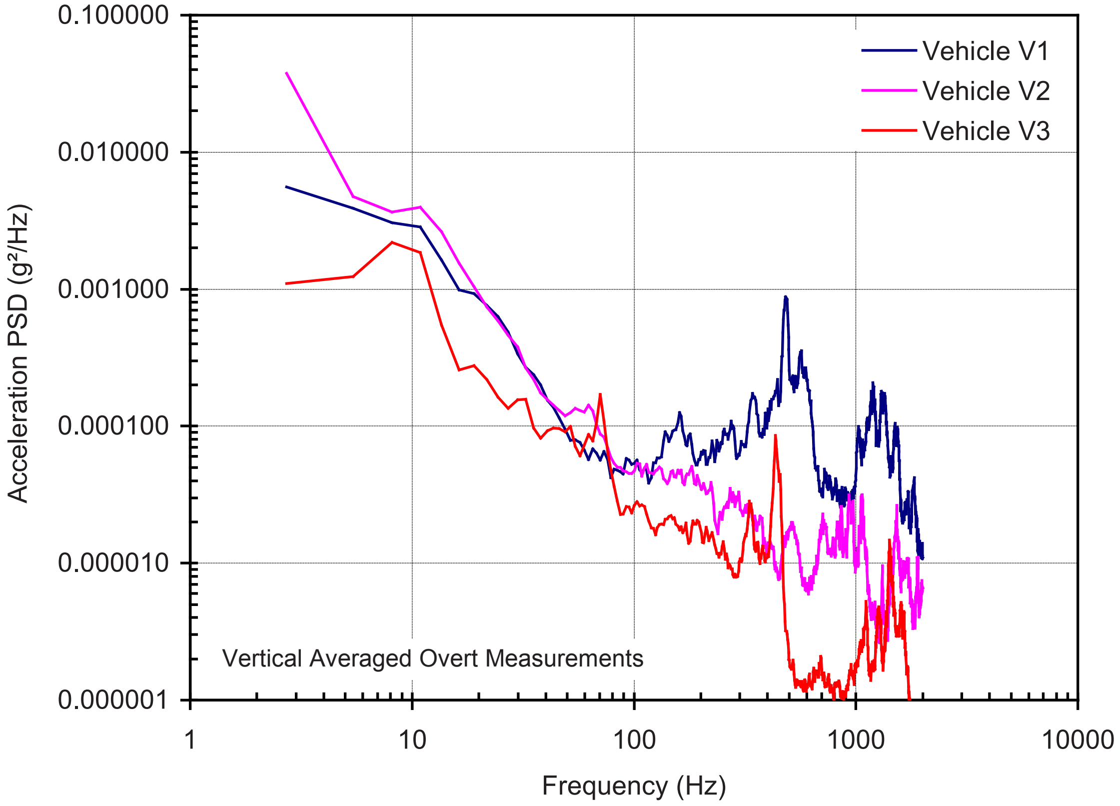


Figure 8 – Comparison of different SRETS vehicles at the load platform – Measurements made with driver's knowledge

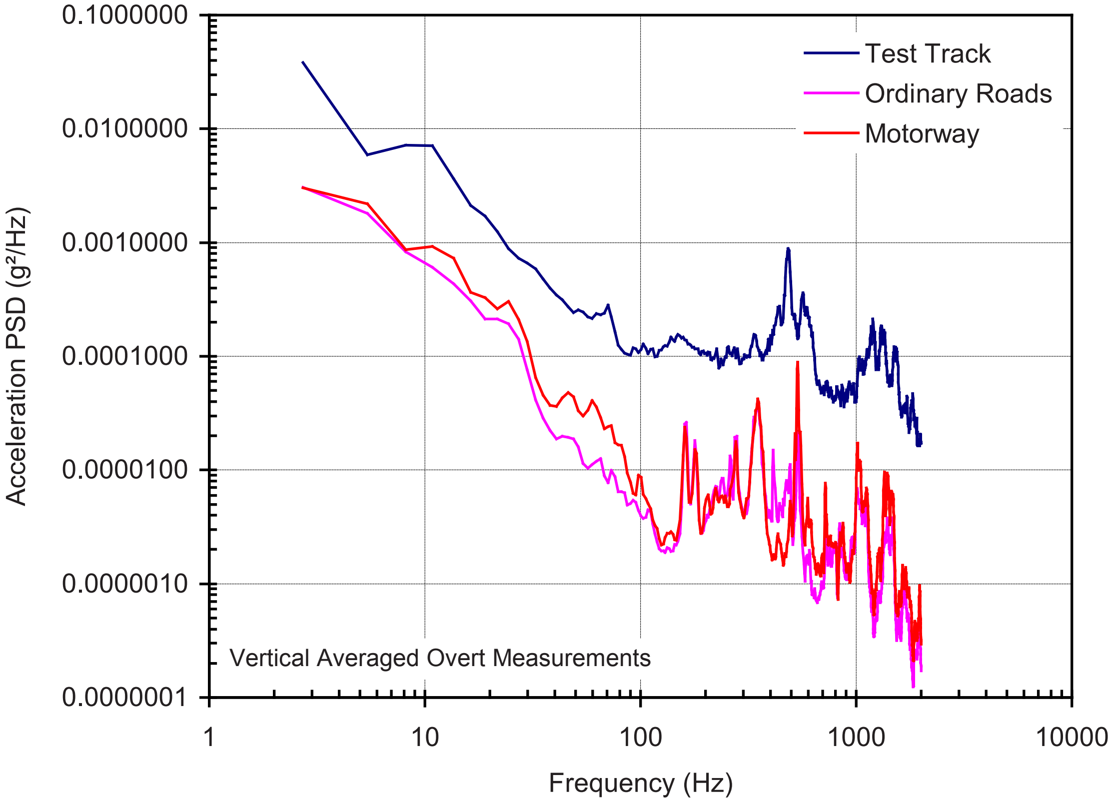


Figure 9 – Comparison of SRETS measurements with different road categories – Made with driver's knowledge

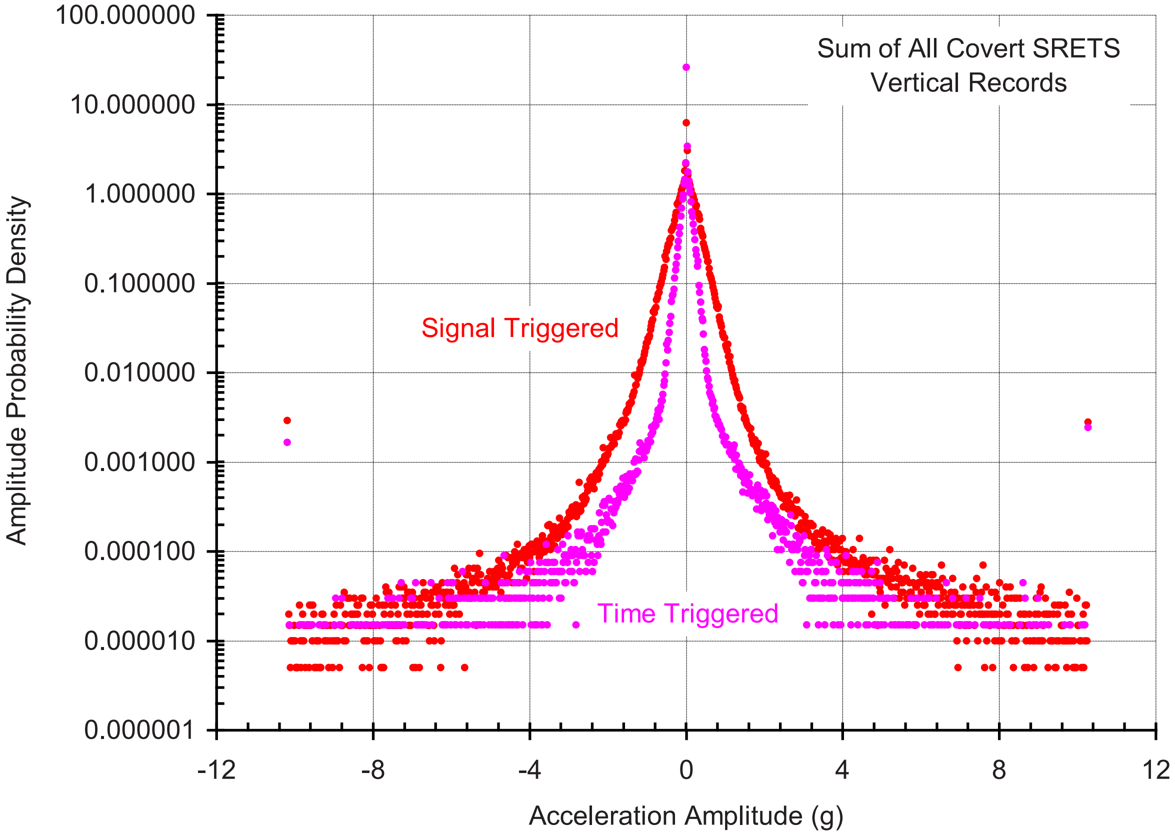


Figure 10 – Comparison of vertical SRETS time and signal triggered data made without driver's knowledge

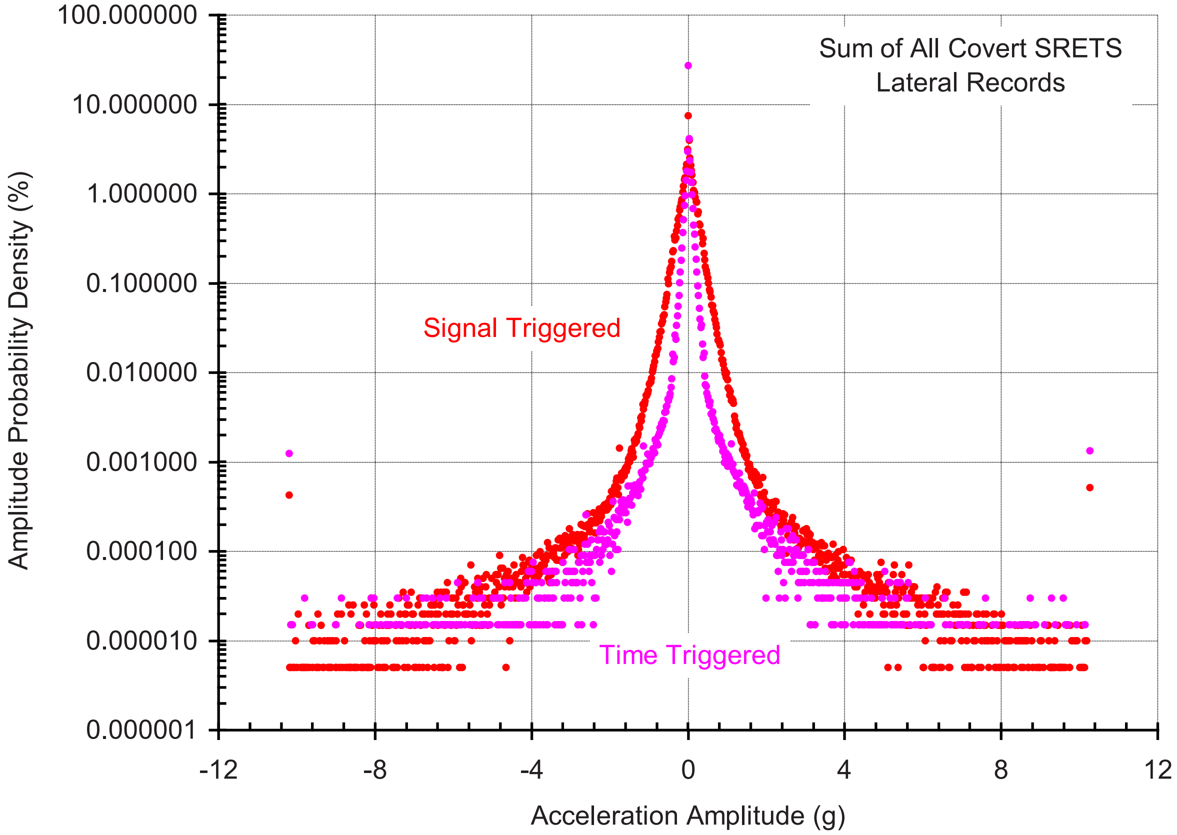


Figure 11 – Comparison of fore/aft SRETS time and signal triggered data made without driver's knowledge

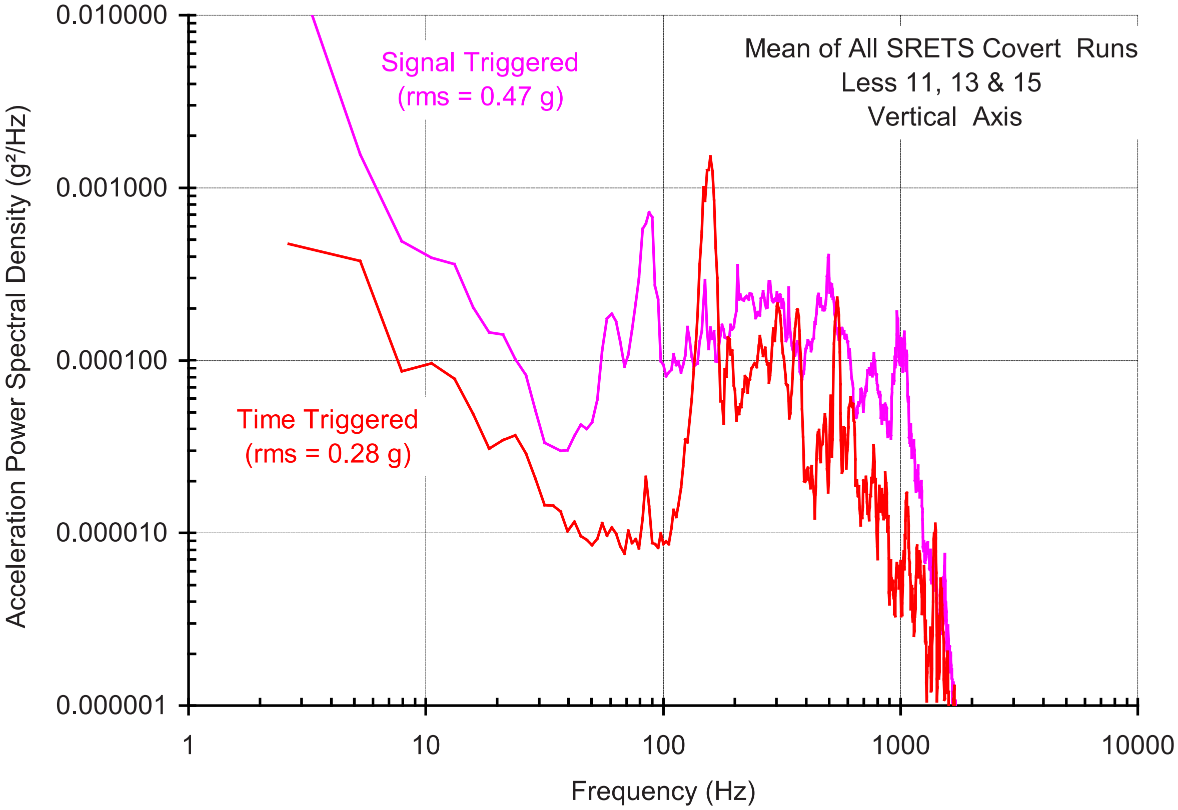


Figure 12 – Power spectral density of SRETS time and signal triggered data made without driver's knowledge

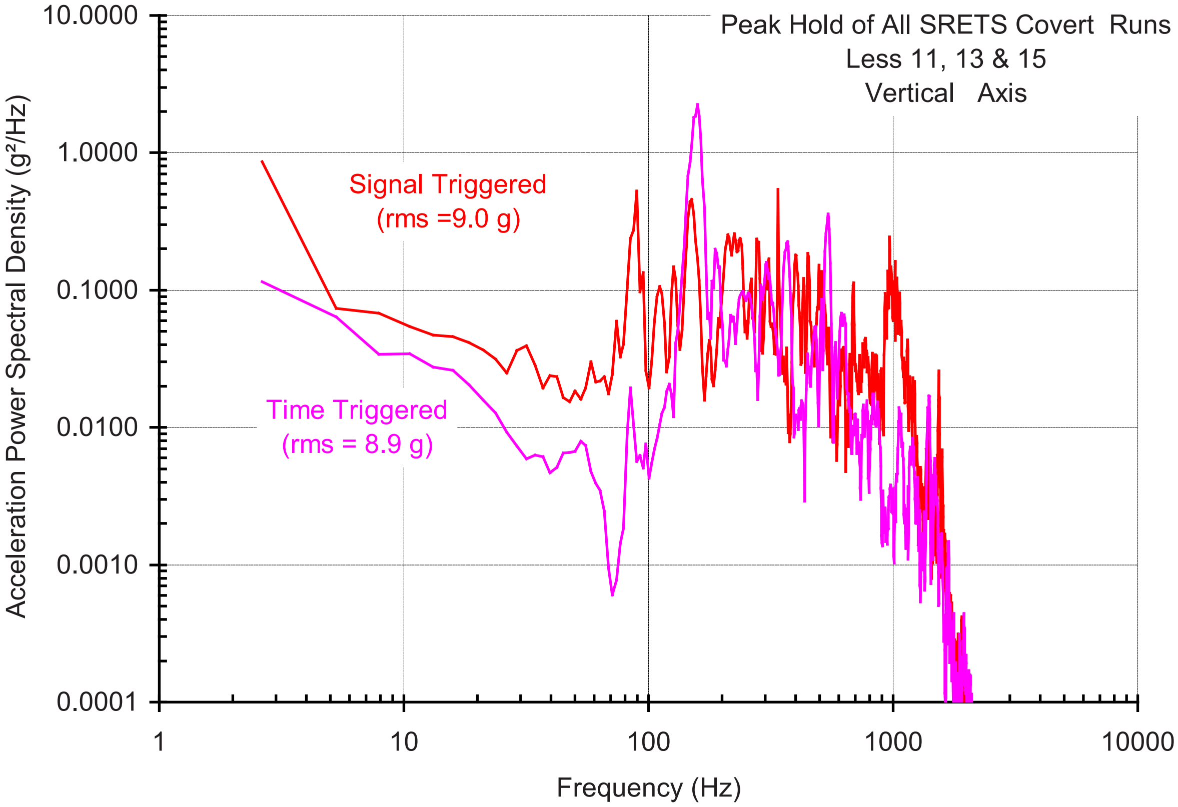


Figure 13 – Peak hold PSD of SRETS time and signal triggered data made without driver's knowledge

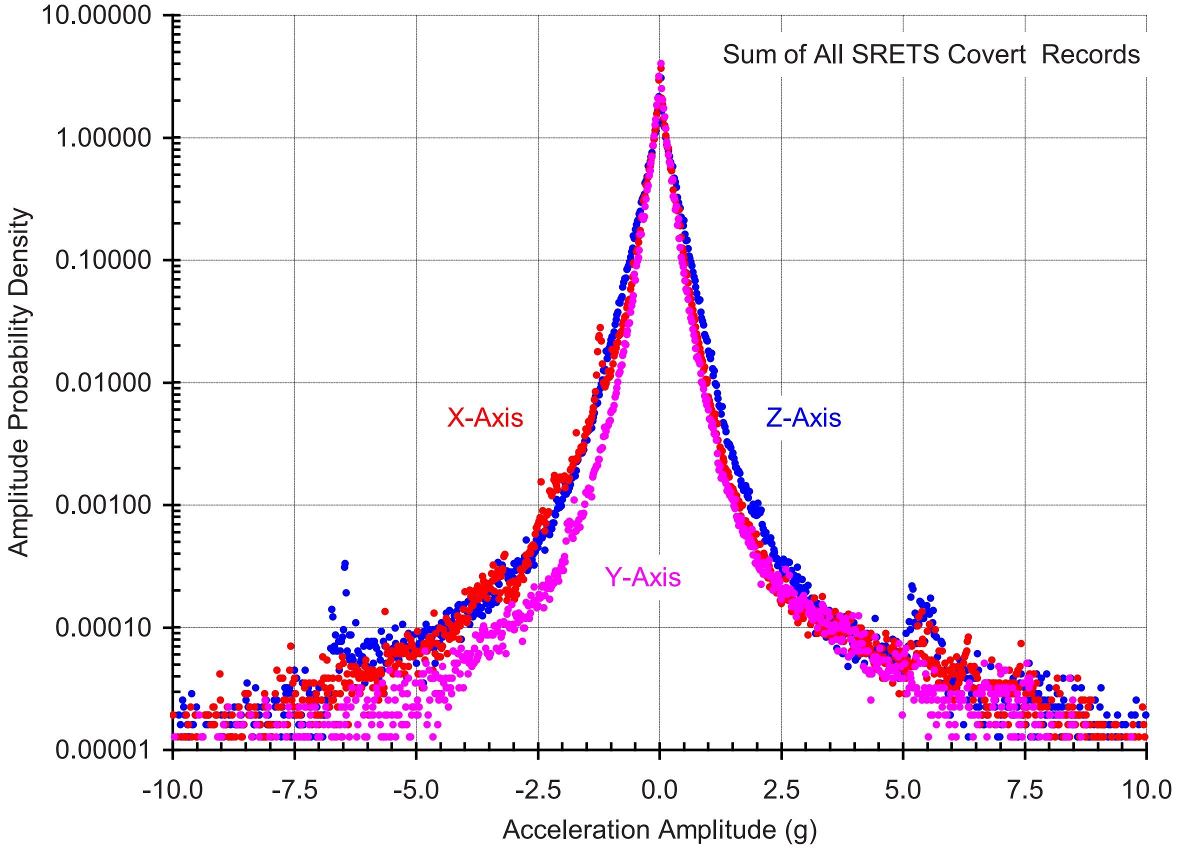


Figure 14 – APD of the SRETS measured data made without driver's knowledge

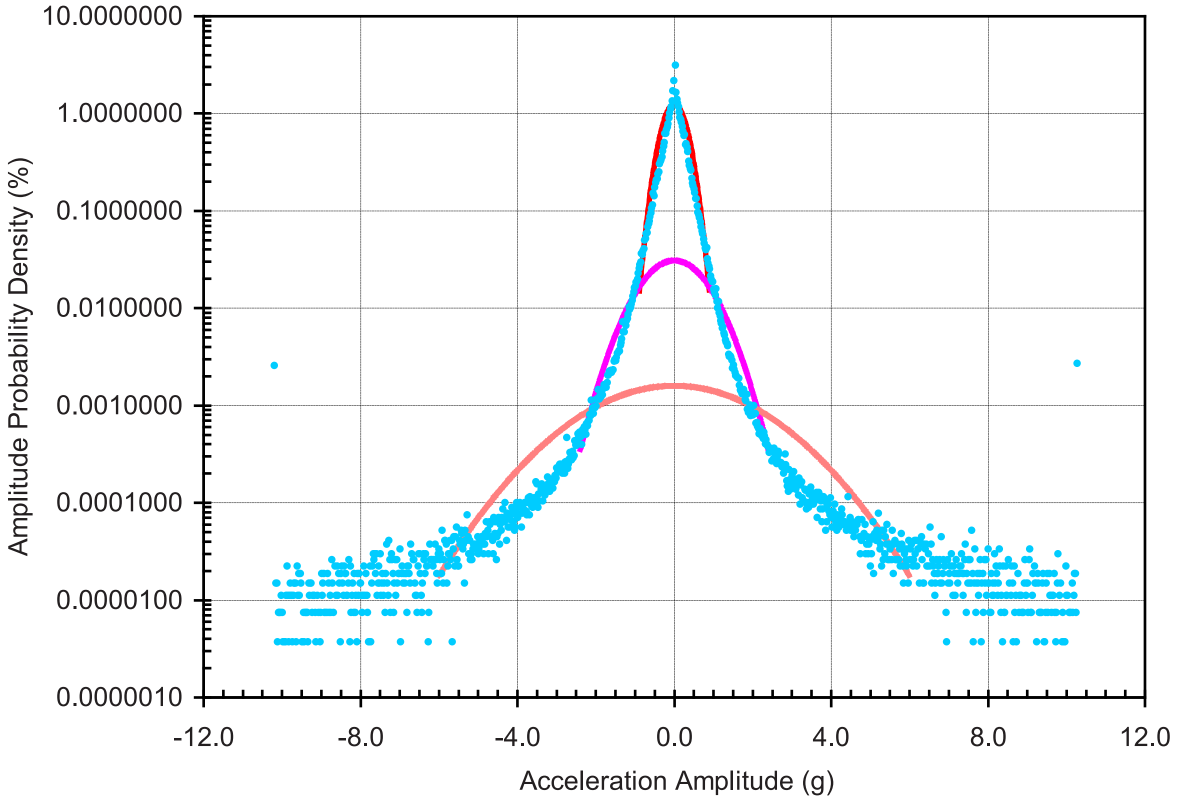


Figure 15 – Fitting of SRETS APD with multiple gaussian distributions

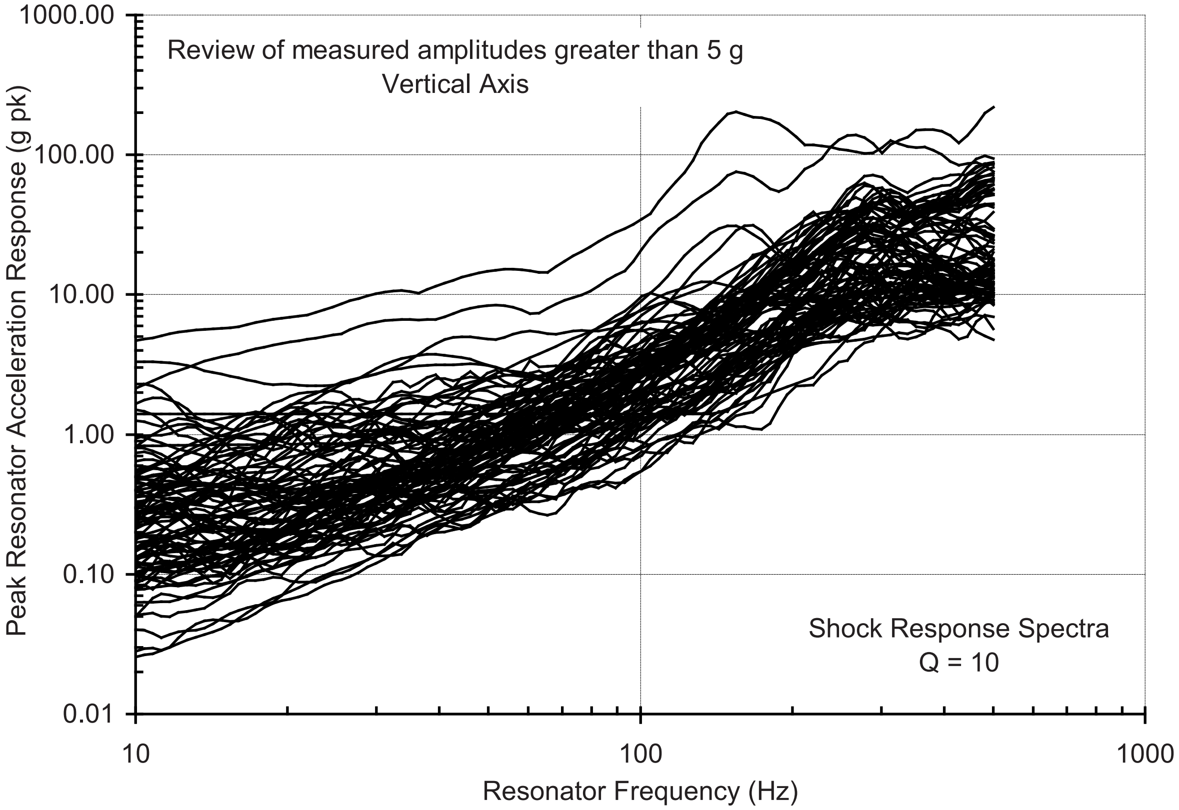


Figure 16 – Vertical SRS of SRETS measured amplitudes greater than 5 g – Made without driver's knowledge

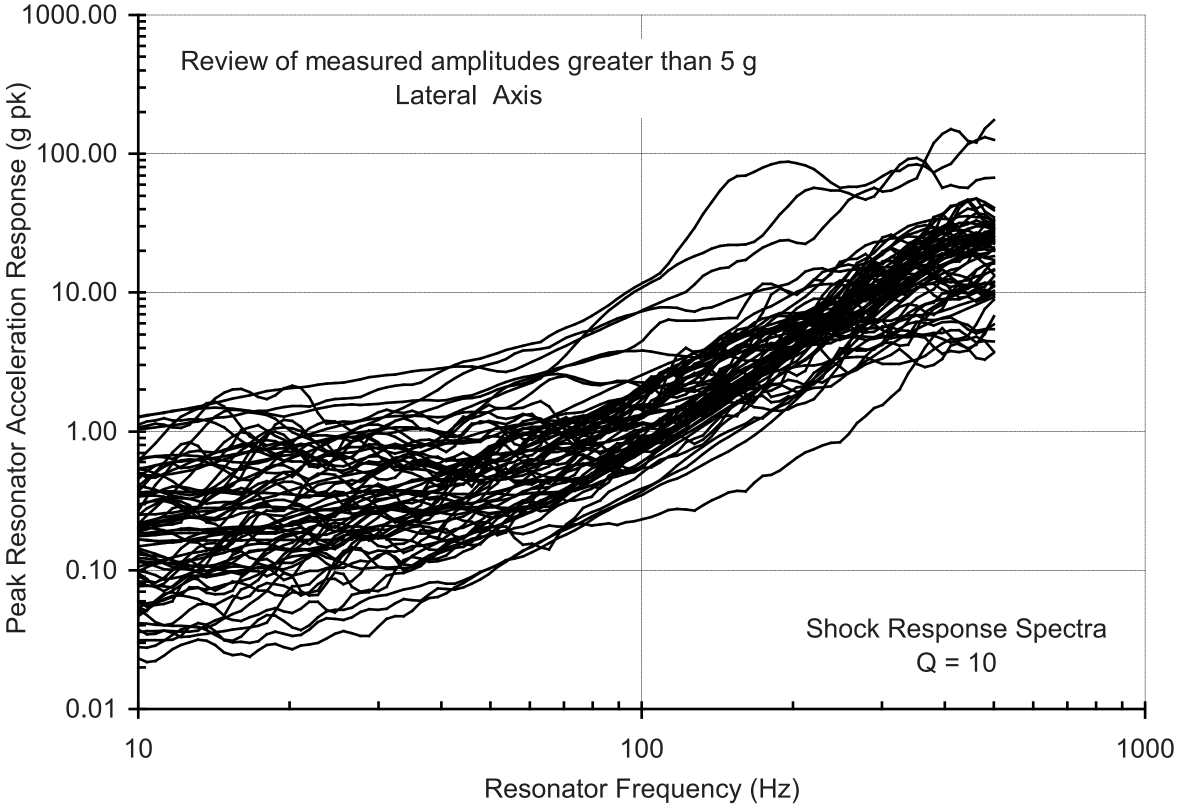


Figure 17 – Lateral SRS of SRETS measured amplitudes greater than 5 g – Made without driver's knowledge

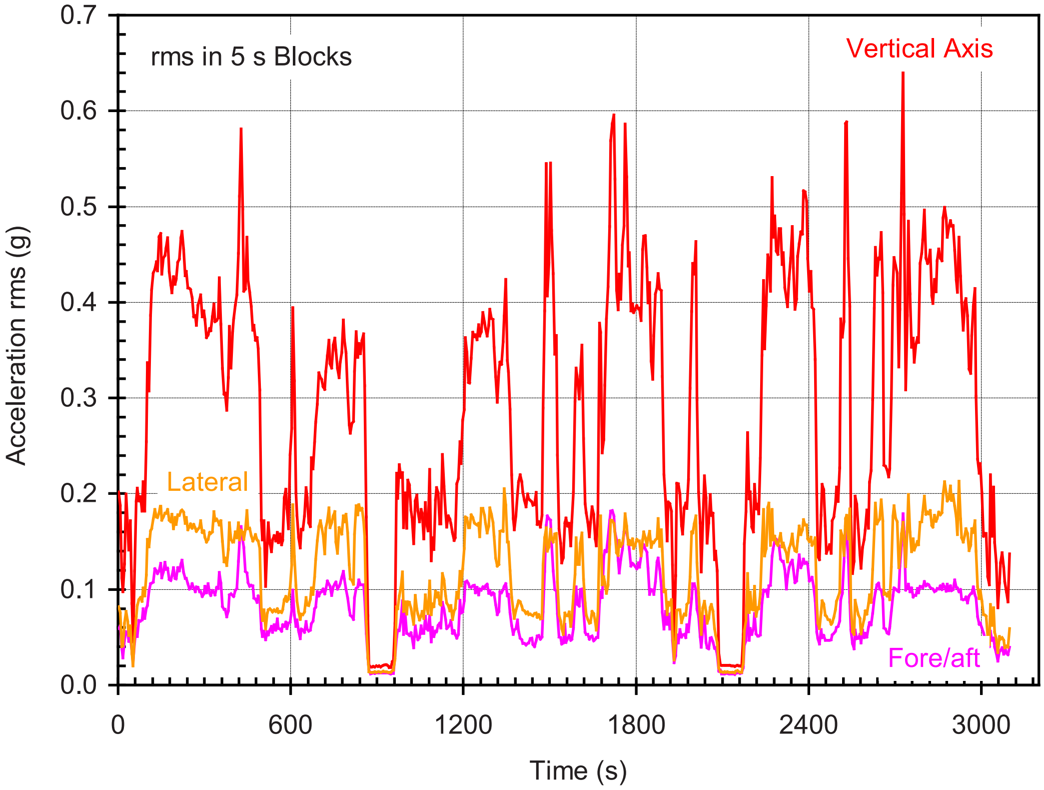


Figure 18 Vibration r.m.s. against time for CEEES analysis

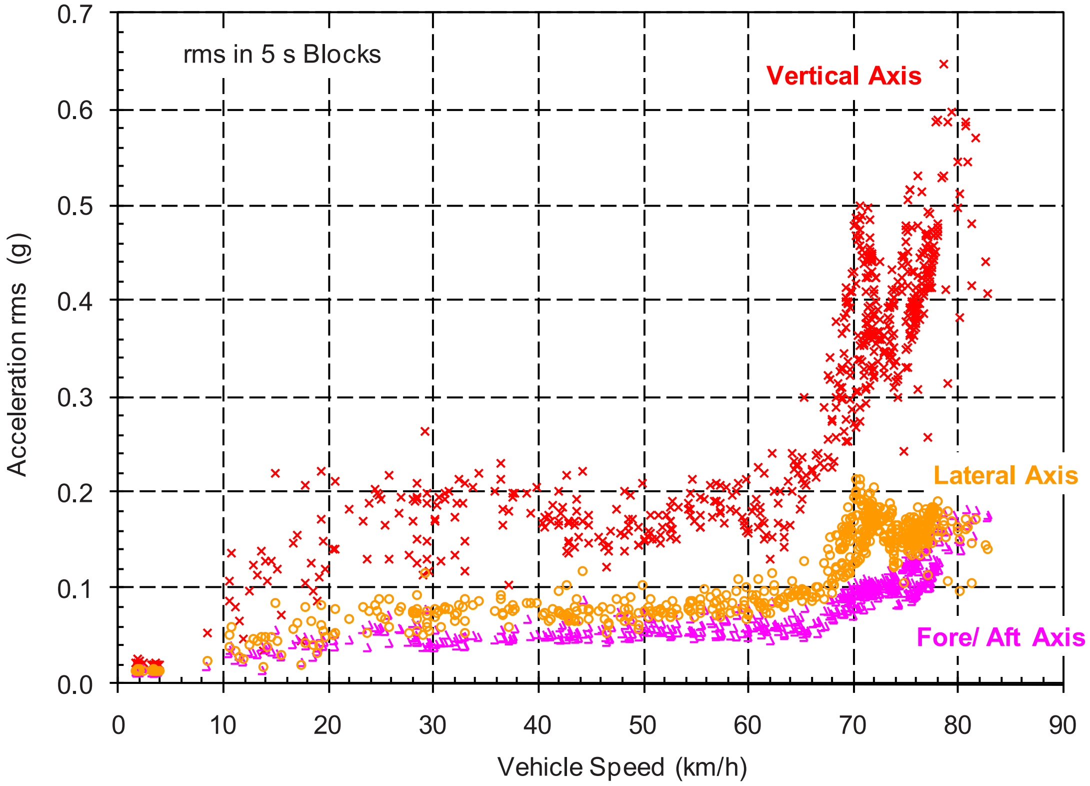


Figure 19 – Vibration r.m.s. against vehicle velocity for CEEES analysis

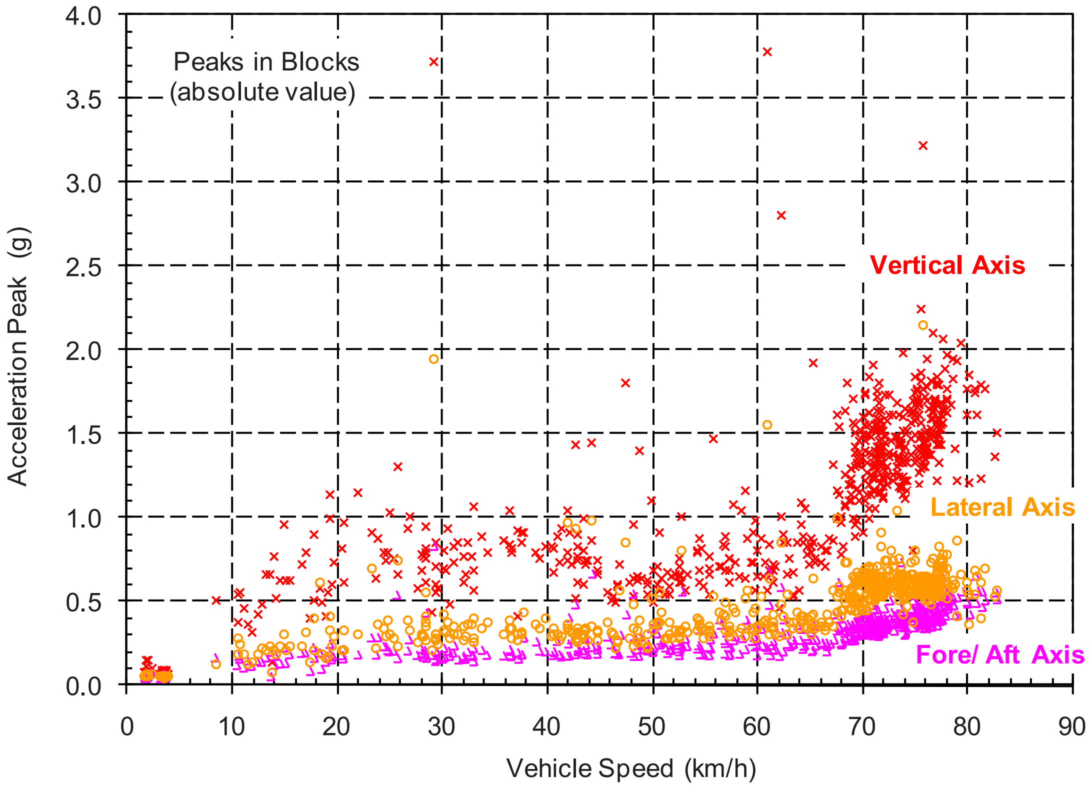


Figure 20 – Acceleration peaks against vehicle velocity for CEEES analysis

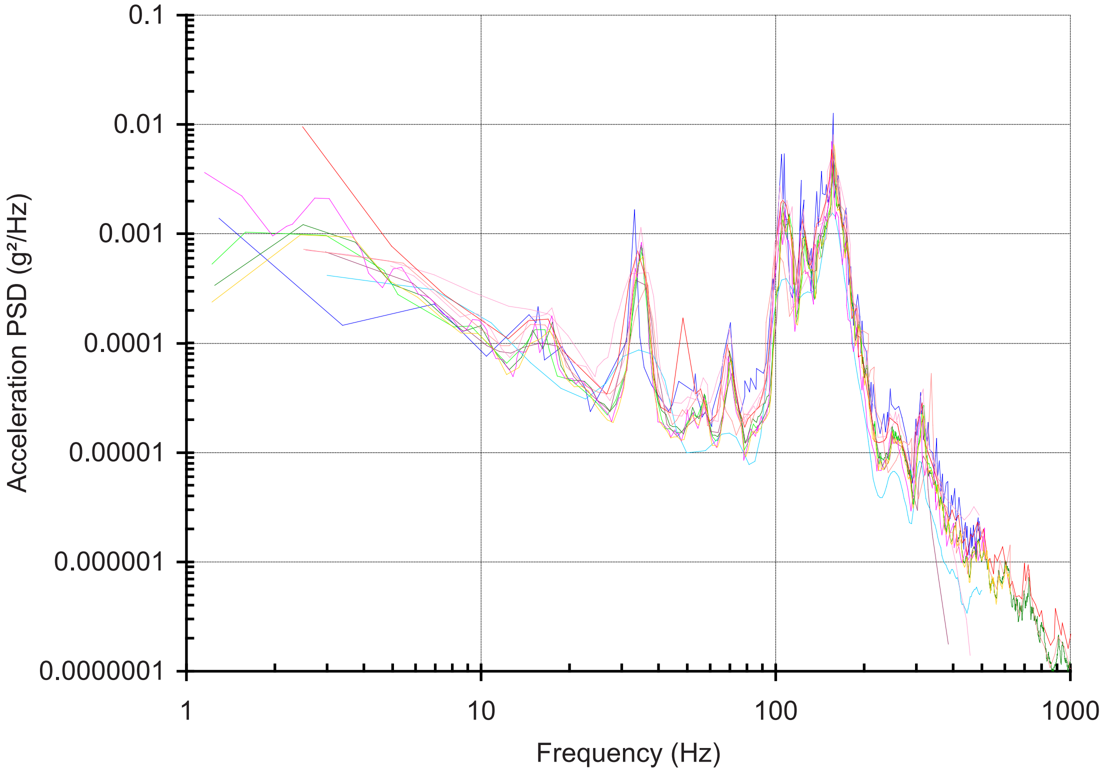


Figure 21 – Vibration PSD analysis from CEEES ‘round robin’ exercise

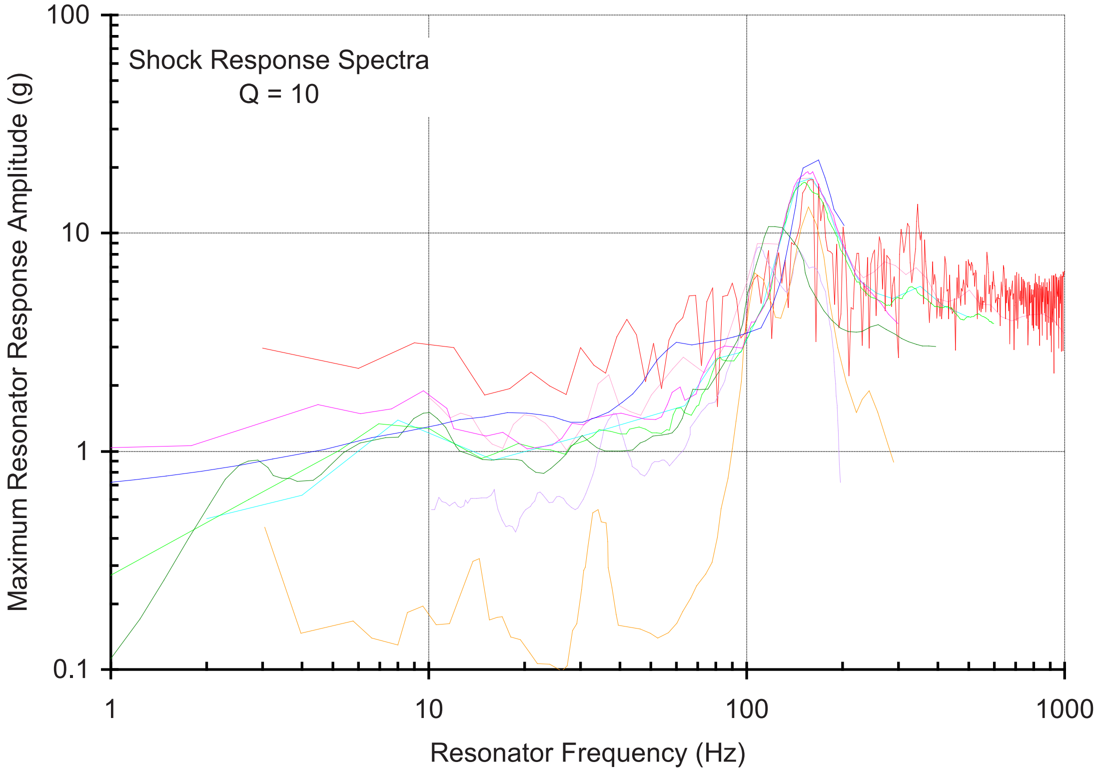


Figure 22 – Shock SRS analysis from CEEES 'round robin' exercise

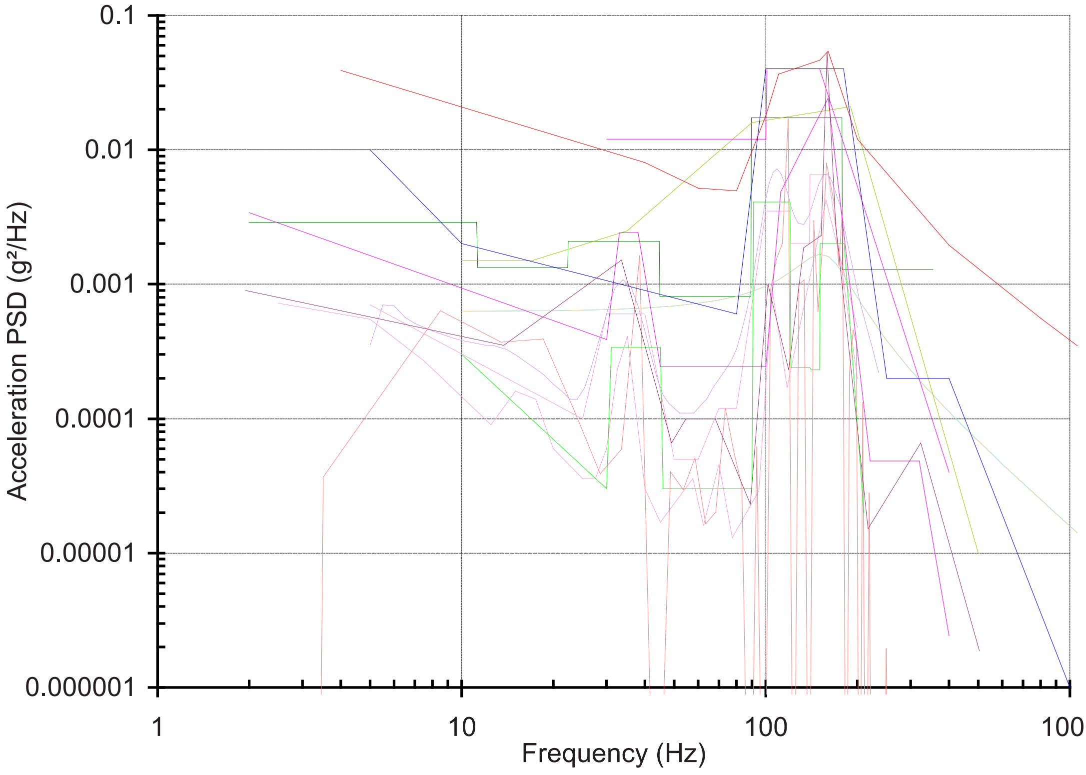


Figure 23 – Vibration test severities from CEEES 'round robin' exercise

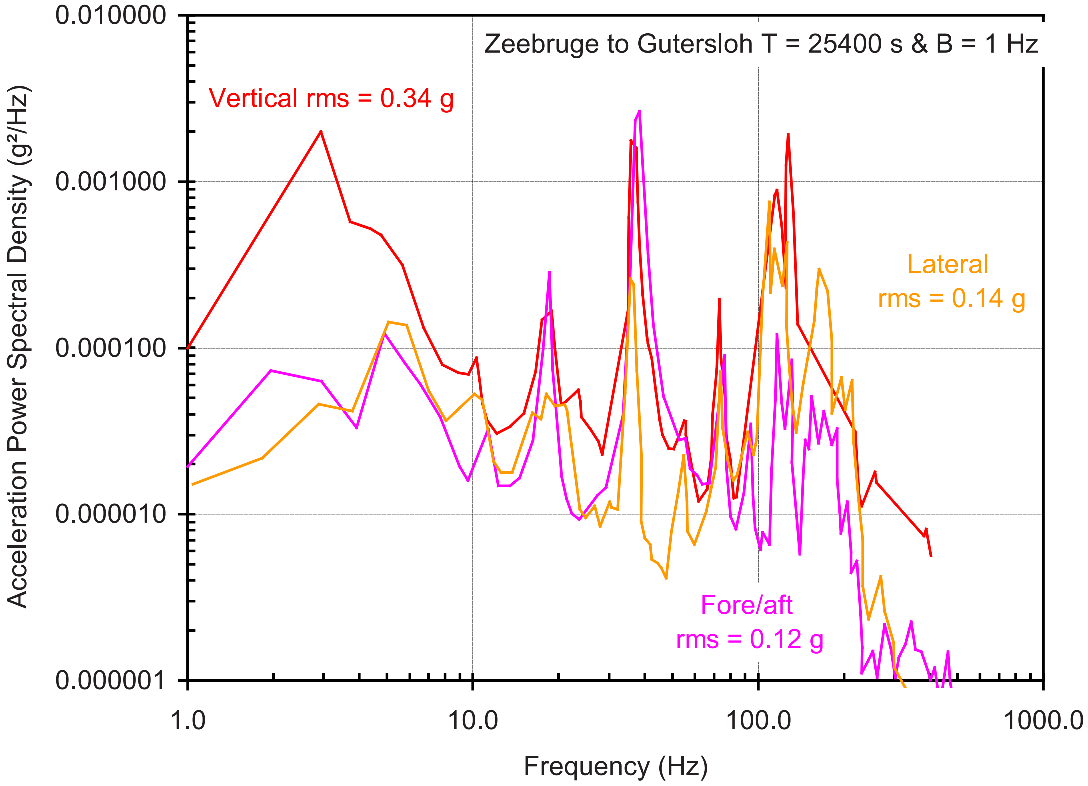


Figure 24 – Composite vibration PSD of CEEES measurements

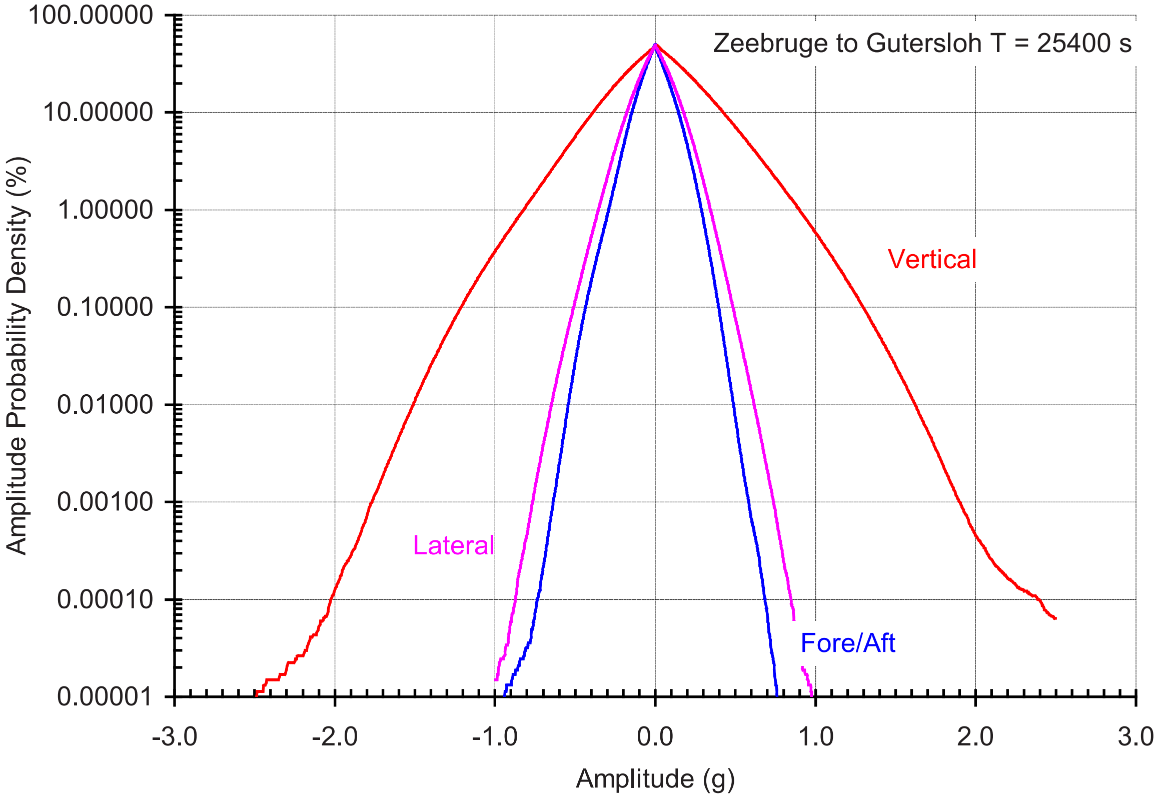


Figure 25 – Composite vibration APD from CEEES measurements

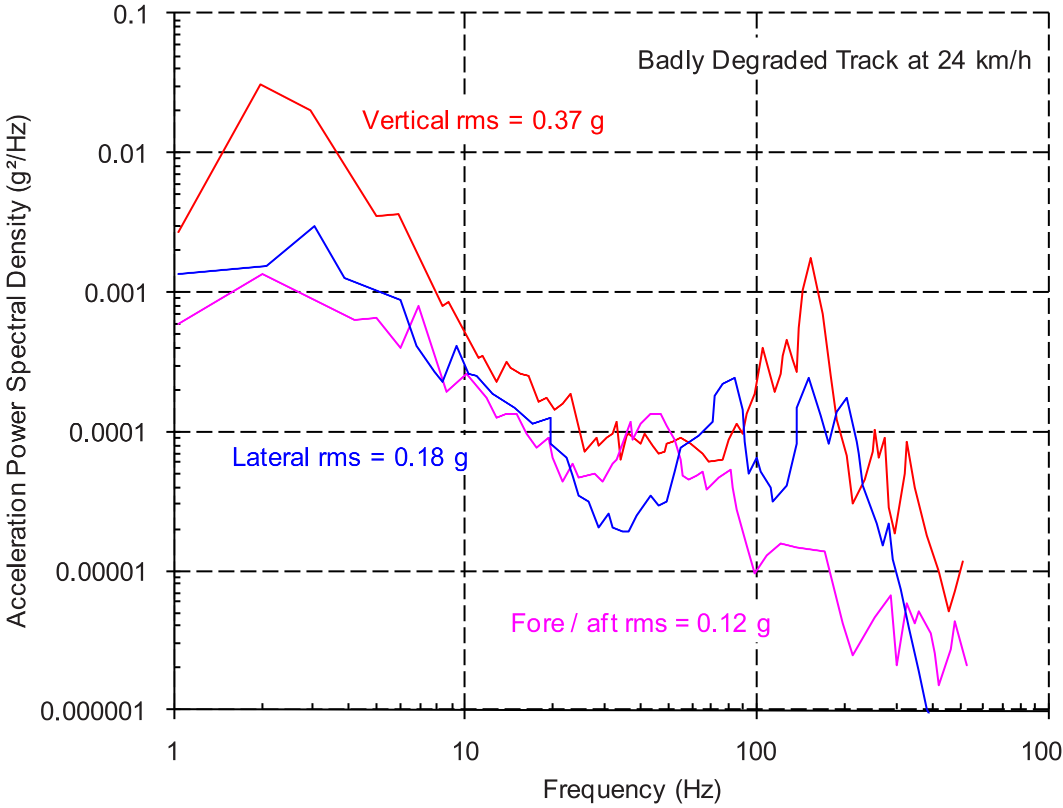


Figure 26 – Vibration PSD from degraded roads on CEEES measurements

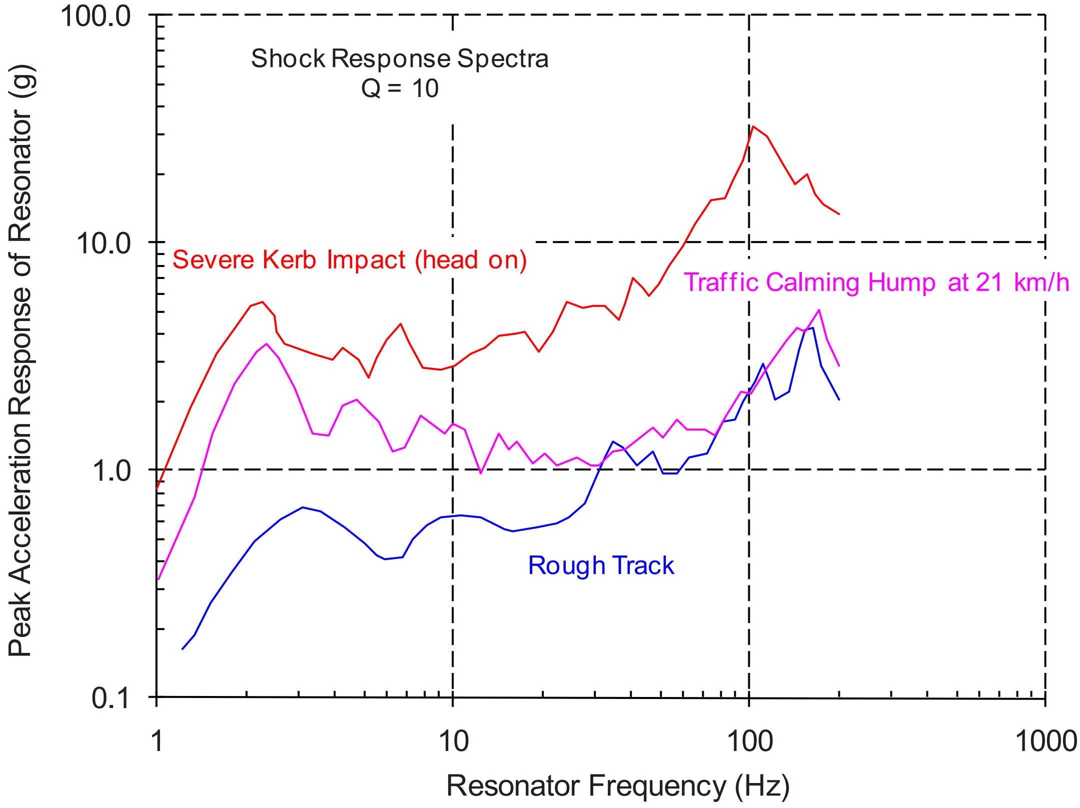


Figure 27 – Shocks from CEEES measurements

Table 3 – Vehicles included in Hoppe and Gerock measurements

Vehicle	Manufacturer	Type	In service since	Max total weight Kg	Empty weight Kg	Platform dimension m x m	Suspension type
Small van	VW		1970	2,2	1,25	1,6 x 1,5	Torsion bar
4 tonne truck	Daimler-Benz	L405	1964	3,9	1,9	3,0 x 2,0	Leaf
10 tonne truck	MAN	520H	1962	10,2	4,5	5,5 x 2,2	Leaf
22 tonne truck	Daimler-Benz	LP2224 /Gr	1970	22	8,4	7,1 x 2,4	Leaf
16 tonne pull trailer	Moessbauer		1961	16	4,4	7,0 x 2,4	Leaf
25 tonne pull trailer	Kaessbohrer		1946	25	6,0	11,0 x 2,4	Leaf
Semi-trailer tractor	Henschel	520F/6 R 1215F	1964	16	6,1		Leaf
22 tonne truck	Buessing	BS22L	1971	22	9,0	7,1 x 2,4	Air
12 tonne pull trailer	Ackermann		1970	16	3,7	7,1 x 2,4	Air

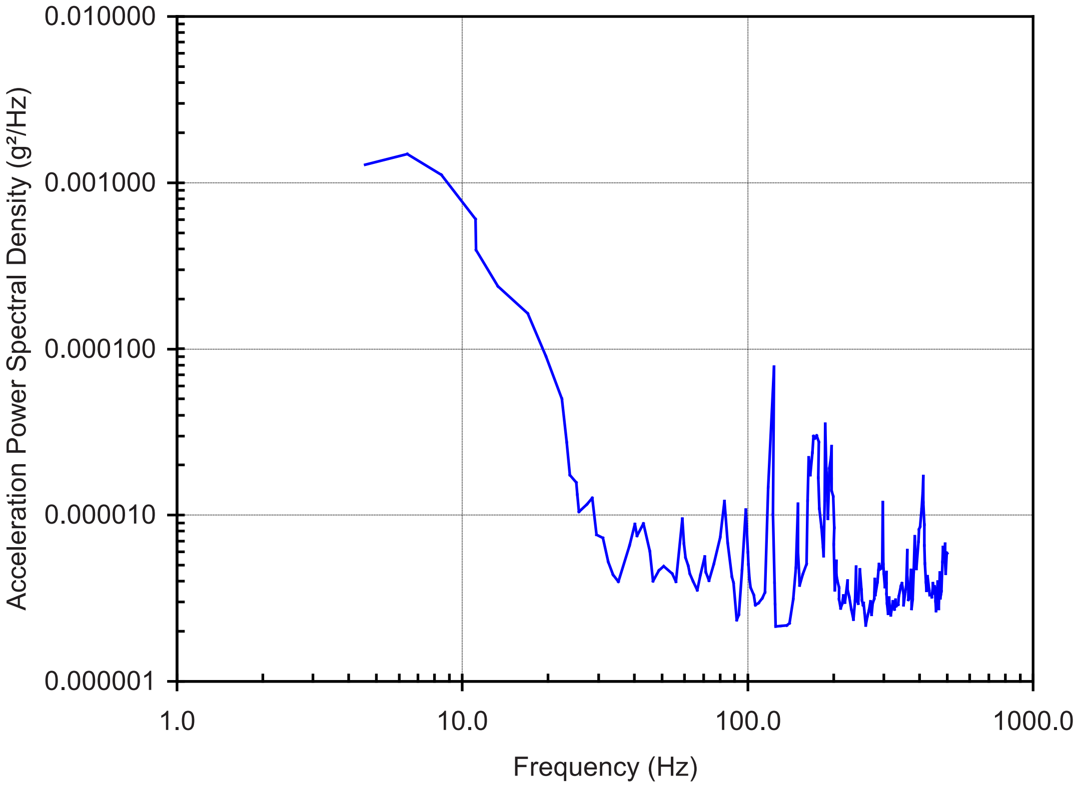


Figure 28 – Typical vibration PSD from Hoppe and Gerock measurements

Table 4 – Shock occurrences from Hoppe and Gerock measurements

Vehicle		Degree of loading %	No of Shocks at Shock Level				
			>3 g	>5 g	>10 g	>12 g	>15 g
Small van	M	80	400	90	4	6	
	E	80	3 000	700	50		
4 tonne truck	M	65	10 000	200	150	40	1
	E	65	40 000	6 000	50	150	6
10 tonne truck	M	20	20 000	2 000	100	40	1
	E	20	50 000	6 000	400	150	5
	M	55	6 000	50			
	E	55	20 000	200	1		
22 tonne truck	M	10	2 000	20	5		
	E	10	6 000	70	15	1	
	M	90	800	40			
	E	90	1 000	100			
Semi trailer	M	6	20 000	2 000	100	30	1
	E	6	70 000	10 000	450	90	2
	M	50	5 000	500	5		
	E	50	20 000	1 500	15	1	
25 tonne pull trailer	M	0	7 000 000	20 000	450	150	30
	E	0	5 000 000	50 000	1500	500	130
	M	70	3 000	3 000	900	500	5
	E	70	10 000	2 500	400	150	20
Truck with air suspension	M	7	800	90	1		
	E	7	1 500	170	3		
	M	89	2				
	E	89	6				
Pull trailer with air suspension	M	0	60 000	7000	270	100	8
	E	0	160 000	22 000	800	100	30
	M	57	2 200	110	15	5	
	E	57	20 000	700	3		
M Mean reading of 6 accelerometers. E Extreme reading of 6 accelerometers.							

Table 5 – Probable" shock durations from Hoppe and Gerock measurements

Percentage distribution of shock durations				
Vehicle	≥ 1 ms	≥ 10 ms	≥ 50 ms	≥ 80 ms
Small van	25	3	0,1	0,03
Truck	57	10	1	0,2
Semi-trailer	64	27	6	4
Pull trailer	33	10	6	2
Vehicle with air suspension	91	4	0,02	

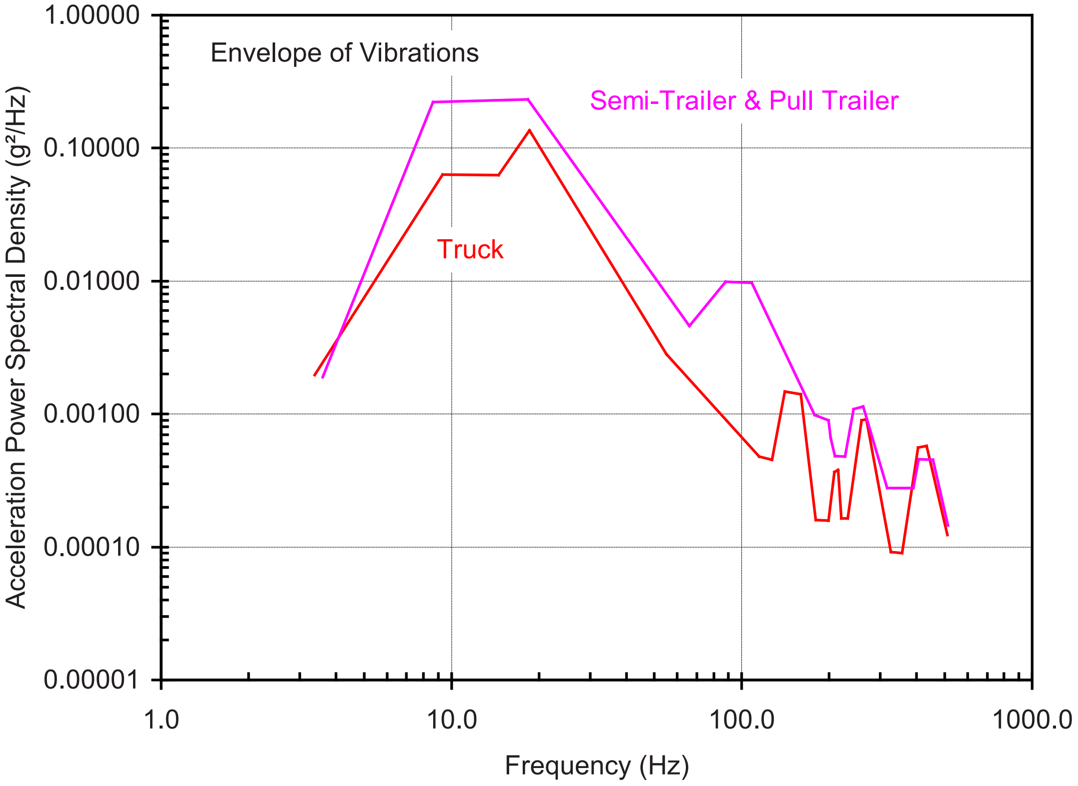


Figure 29 – Envelope of vibration PSD from Hoppe and Gerock measurements

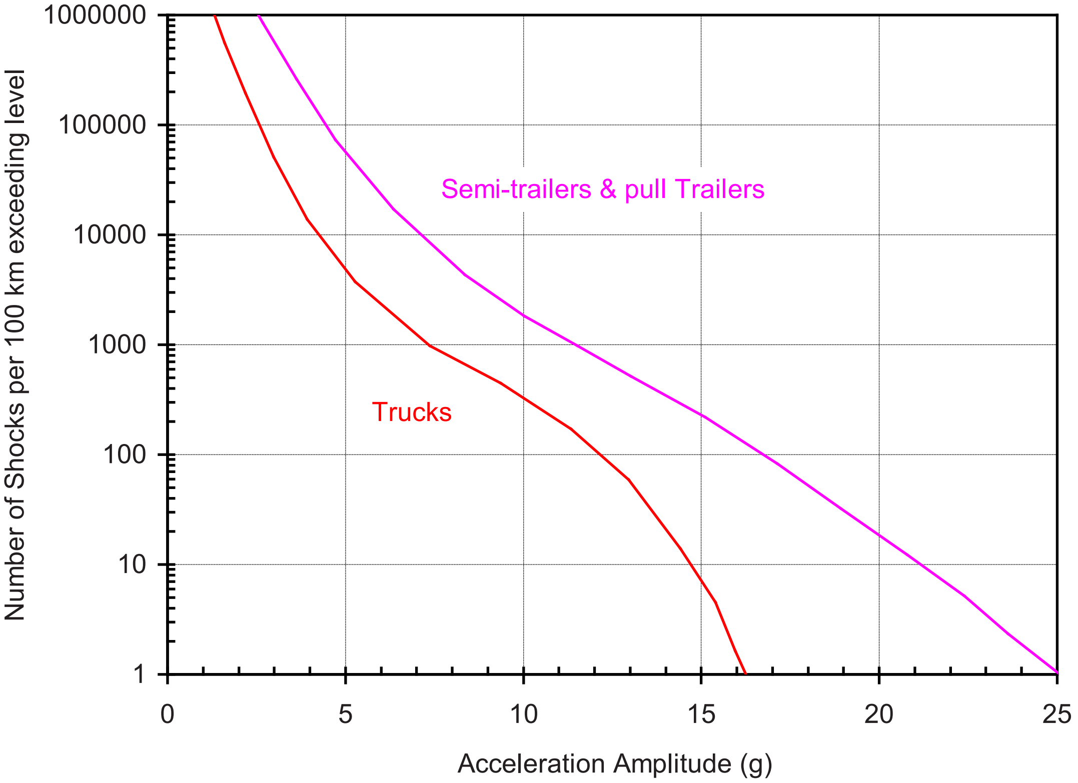


Figure 30 – Number of shocks per 100 km FROM Hoppe and Gerock measurements

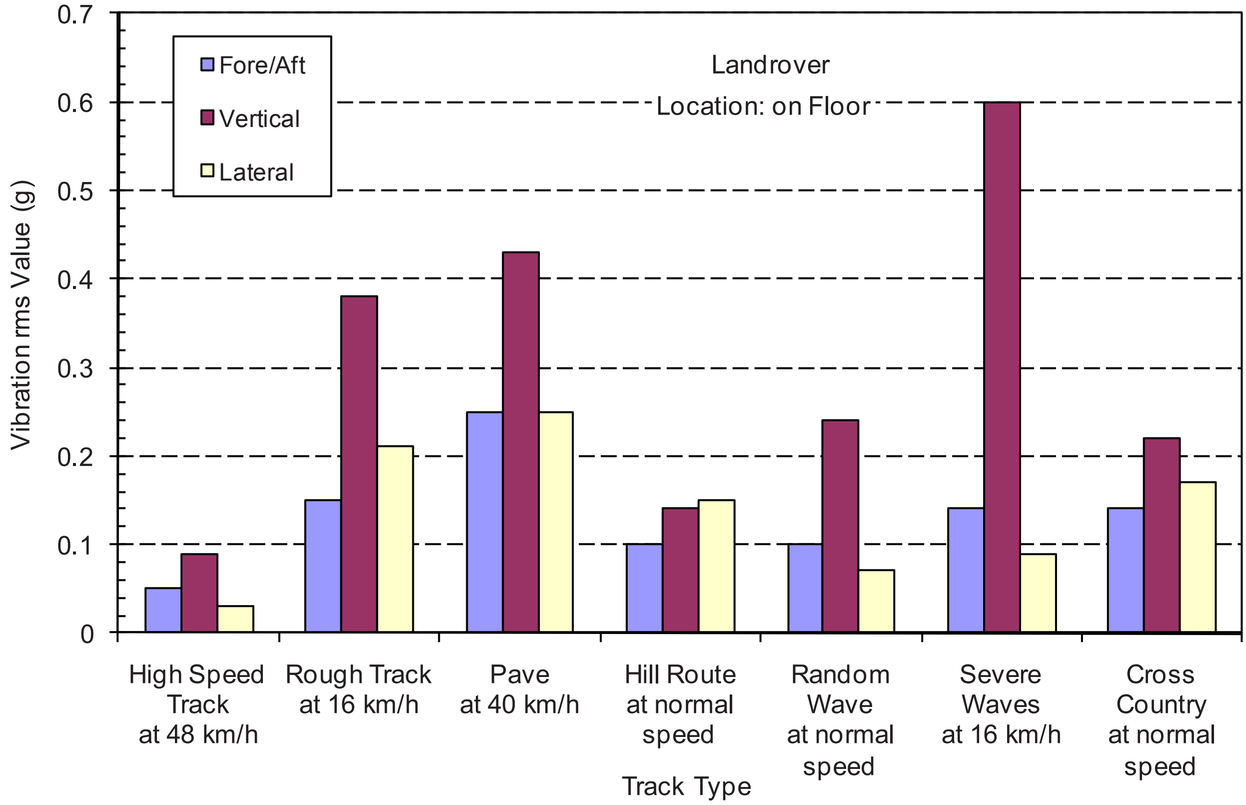


Figure 31 – Vibration r.m.s. from Millbrook measurements on landrover

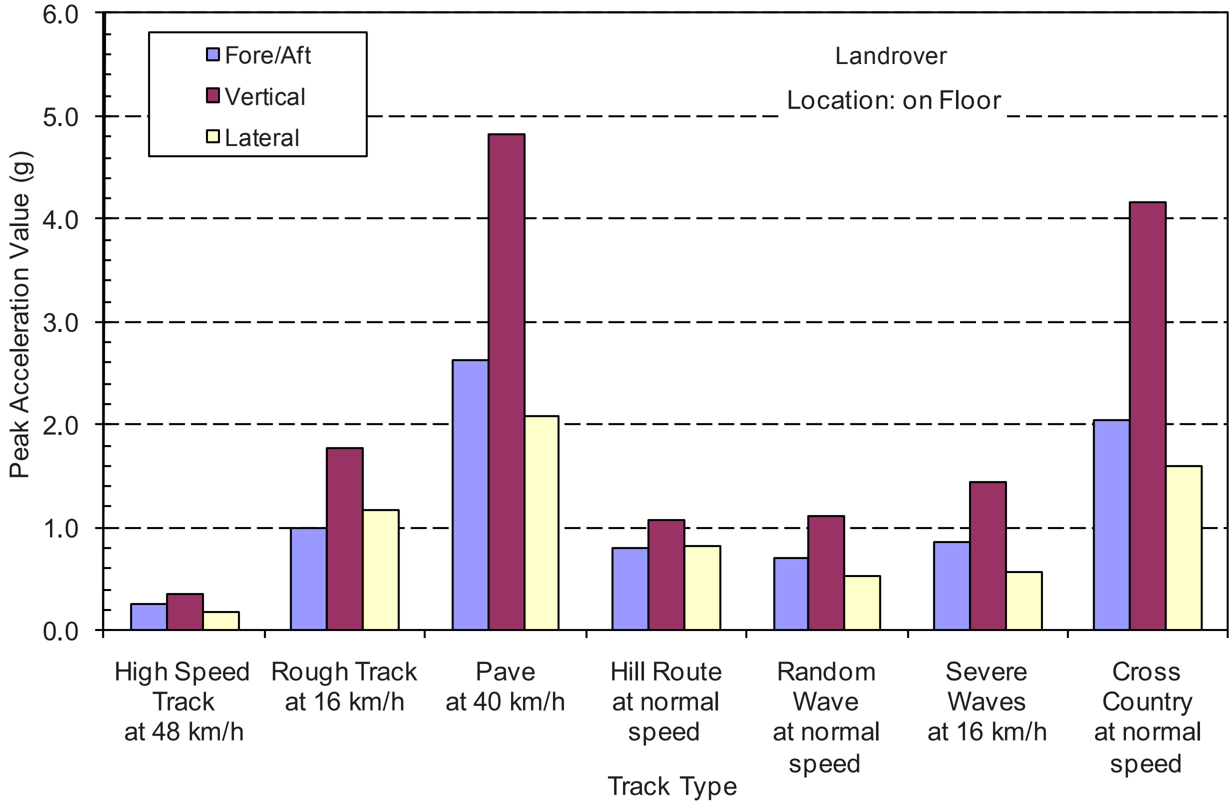


Figure 32 – Shock peaks from Millbrook measurements on landrover

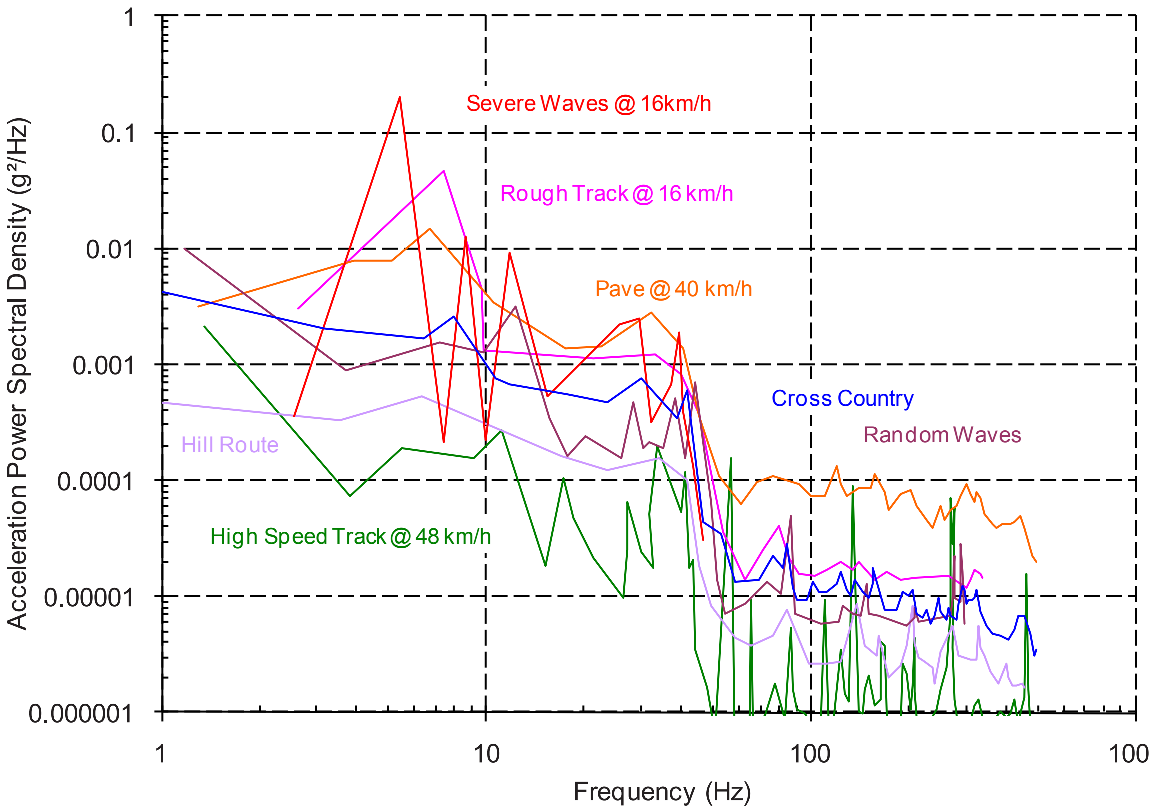


Figure 33 – Vibration PSD from Millbrook measurements on landrover

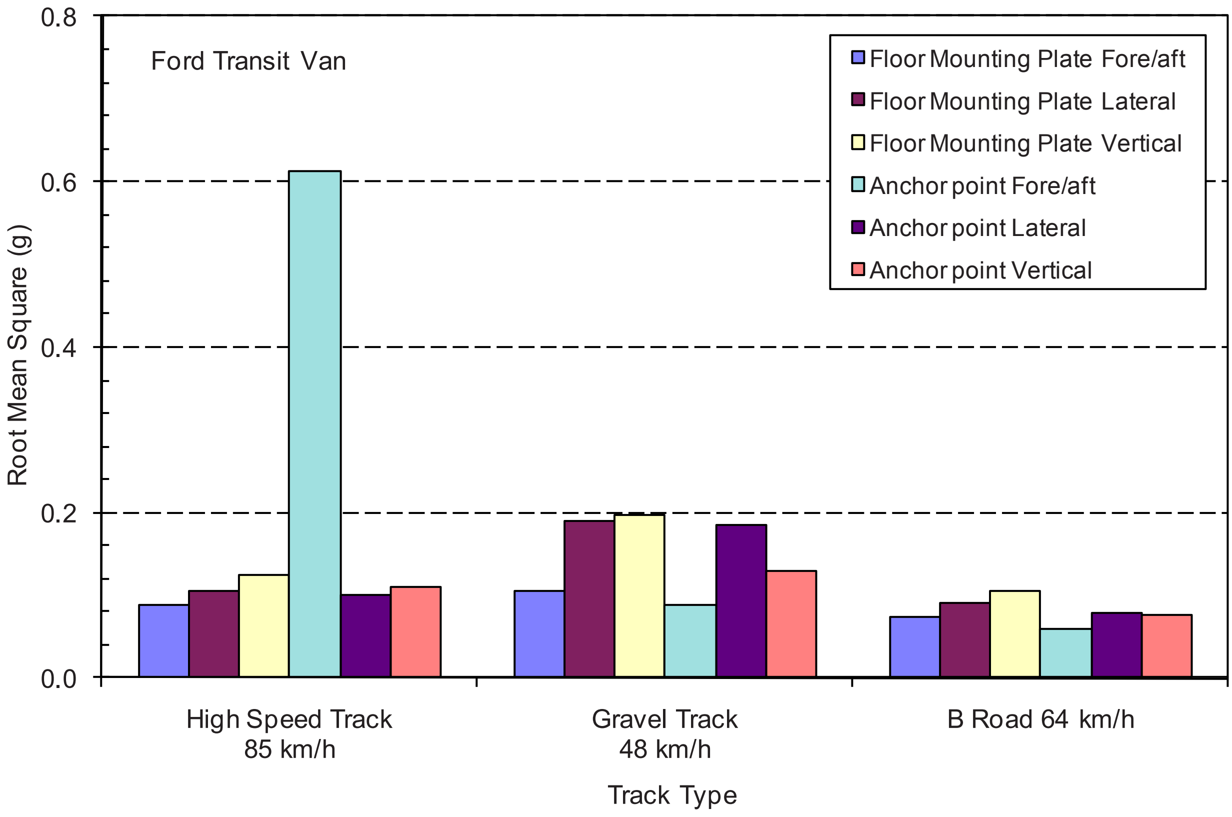


Figure 34 – Vibration r.m.s. from Millbrook measurements on transit van

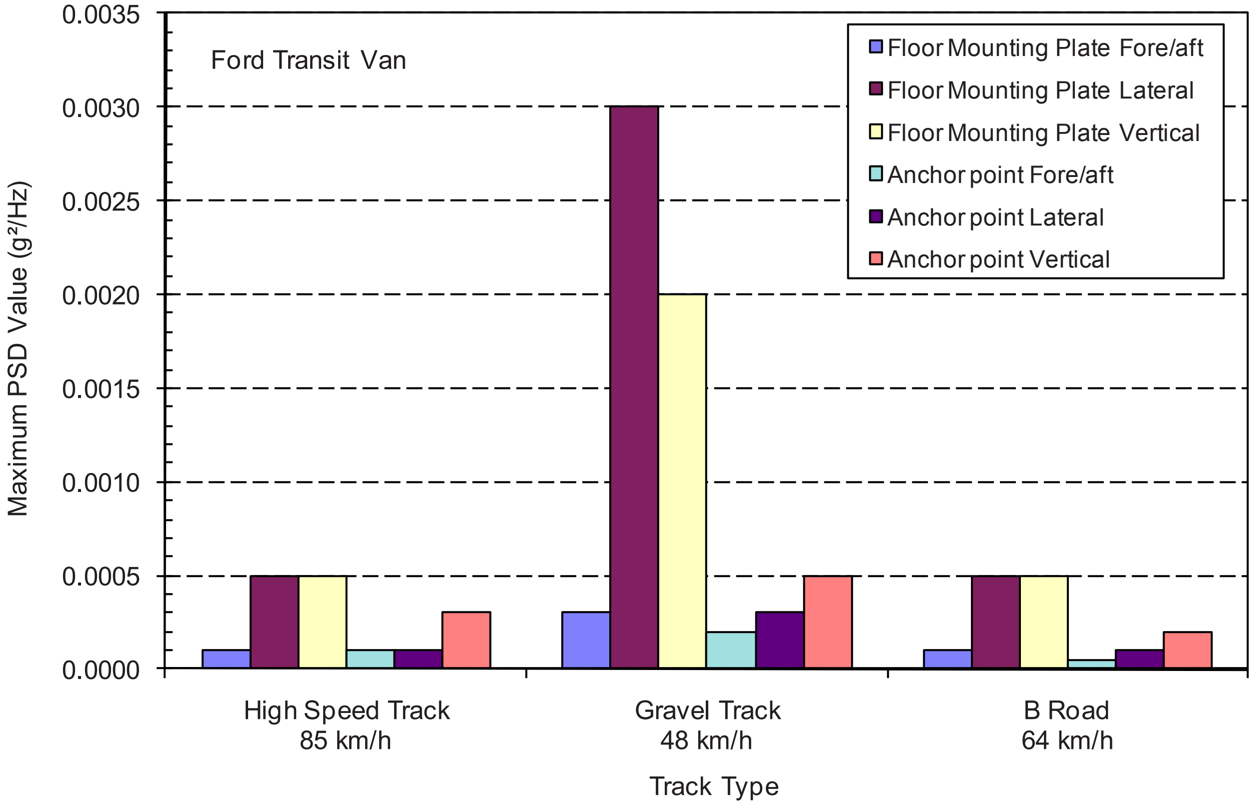


Figure 35 – Maximum PSD values FROM Millbrook measurements on transit van

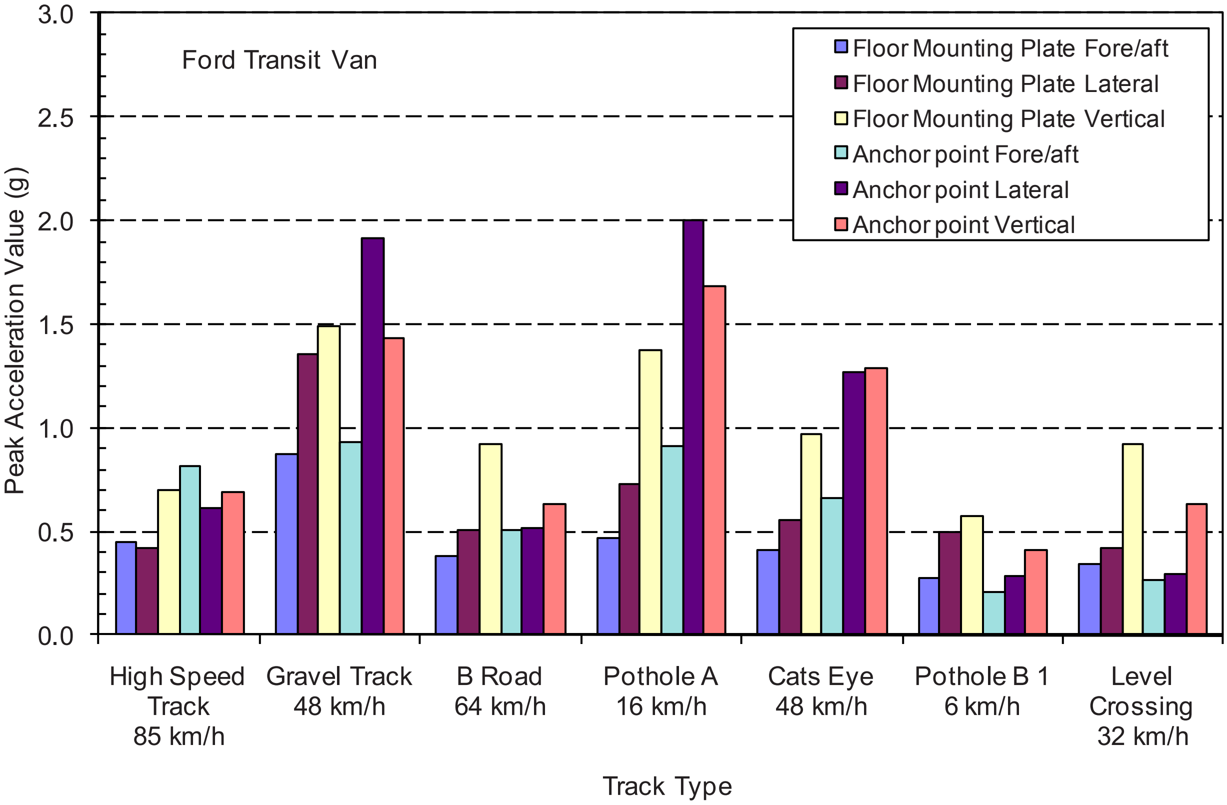


Figure 36 – Shock amplitudes from Millbrook measurements on transit van

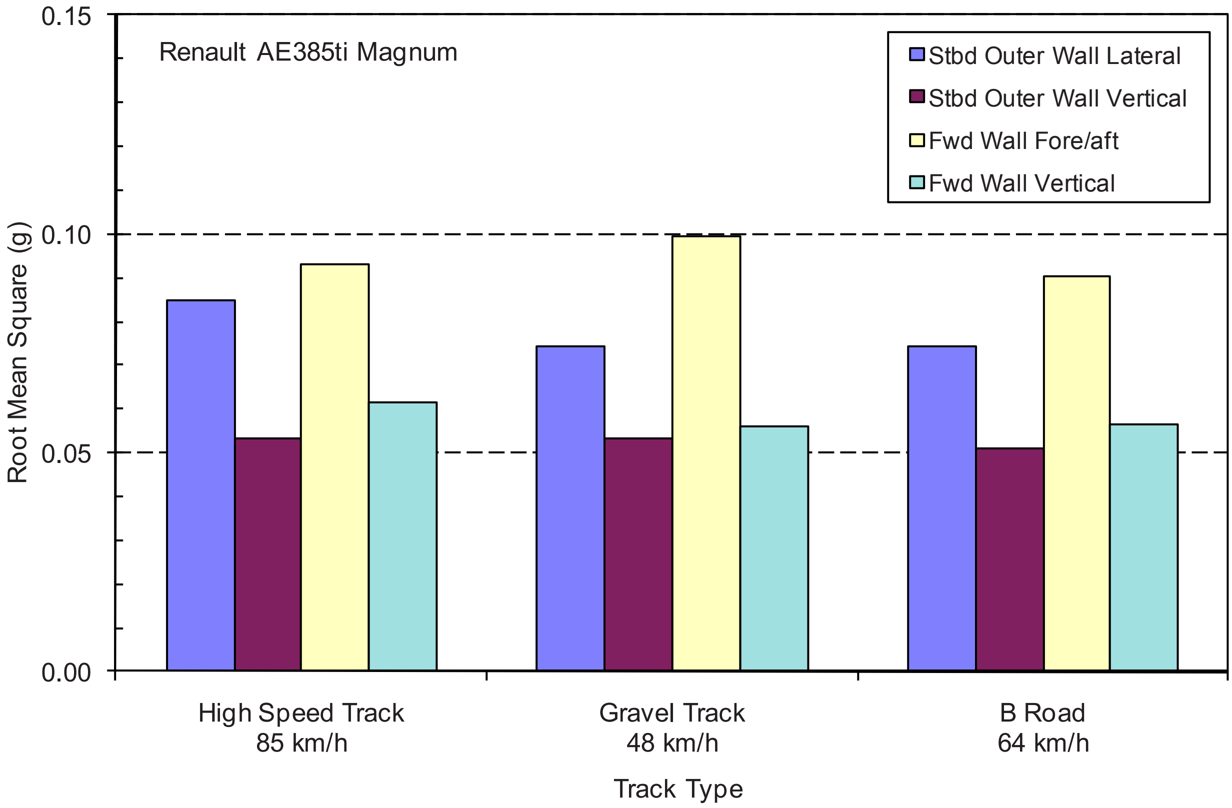


Figure 37 – Vibration r.m.s. from Millbrook measurements on Renault Magnum

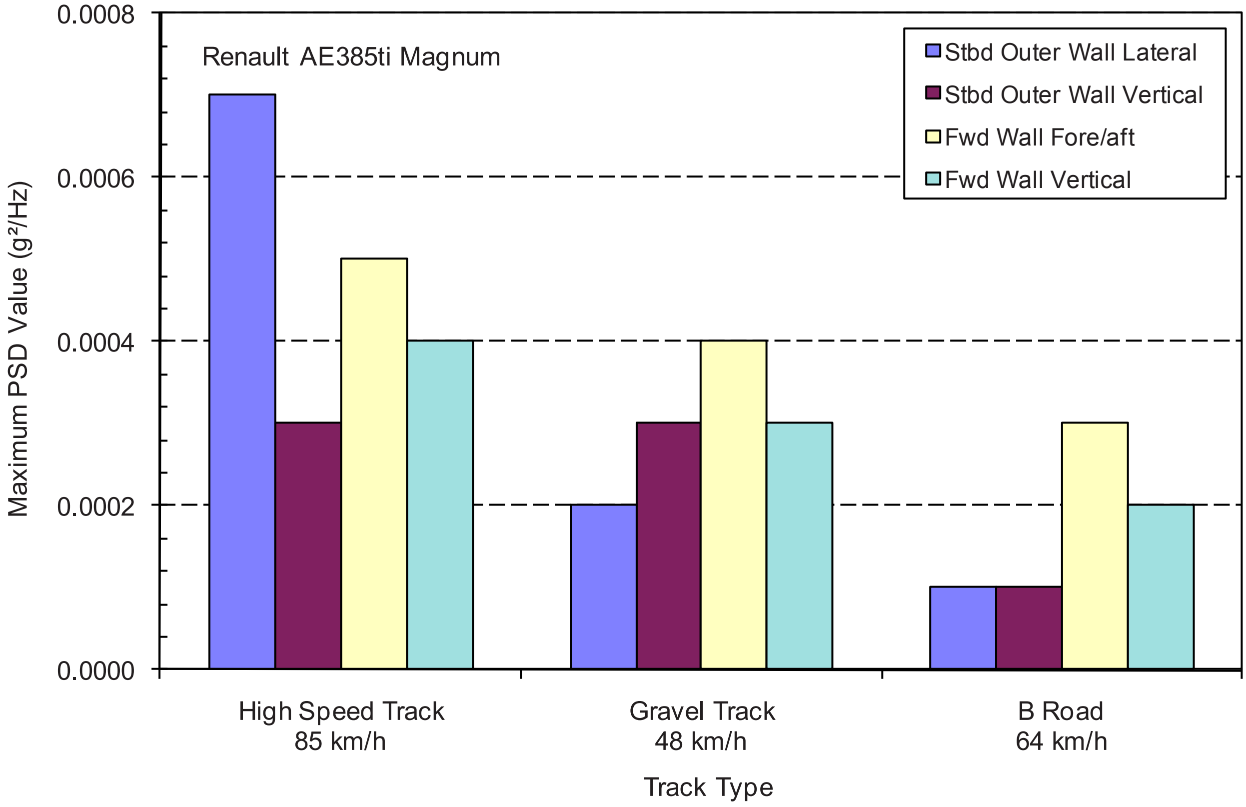


Figure 38 – Maximum PSD values from Millbrook measurements on Renault Magnum

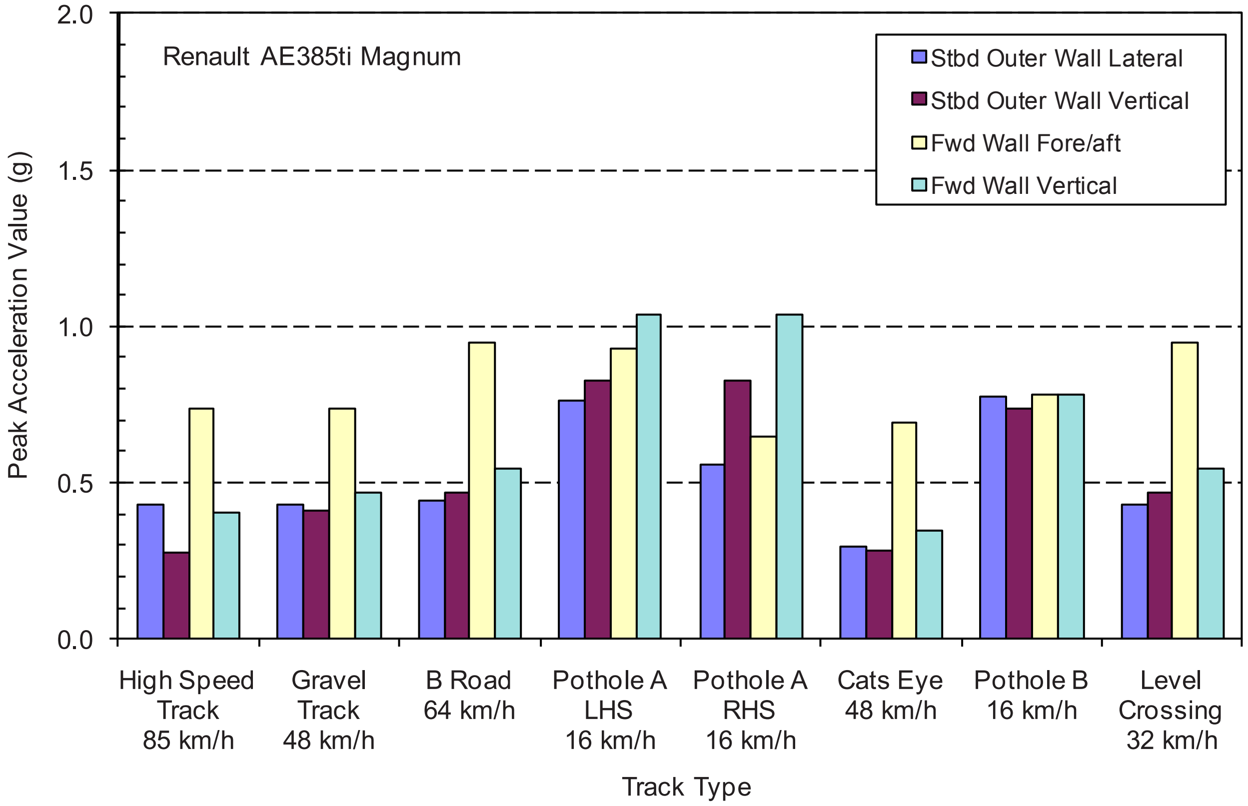


Figure 39 – Shock amplitudes from Millbrook measurements on Renault Magnum

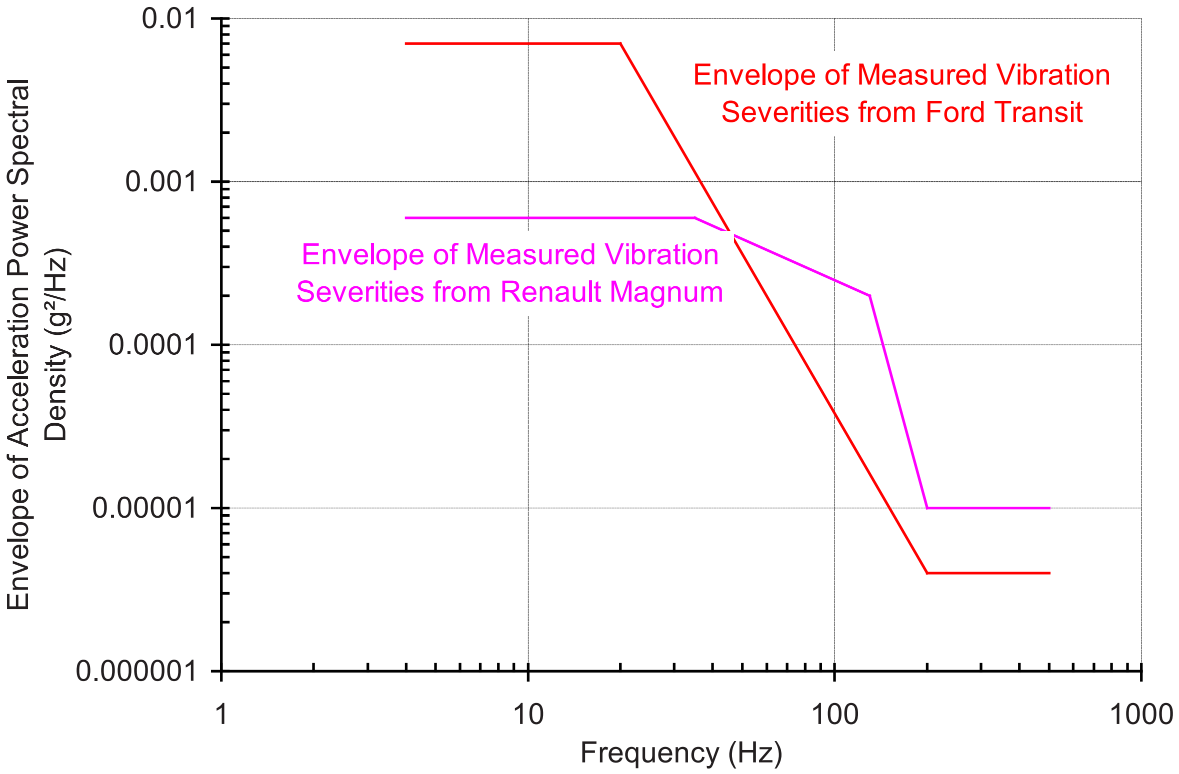


Figure 40 – Maximum PSD values from Millbrook measurements on Renault Magnum

Table 6 – Vibration r.m.s. from GAM EG 13 measurements on Renault Traffic

Road surface	Acceleration r.m.s. g		
	X axis	Y axis	Z axis (vertical)
Autoroute 130 km/h	0,15	0,19	0,23
Secondary route 90 km/h	0,08	0,10	0,11
Secondary route 60 km/h	0,06	0,09	0,08
Good route 90 km/h	0,11	0,12	0,20
Good route 60 km/h	0,09	0,09	0,15
Village	0,05	0,06	0,08
Belgium pave	0,11	0,10	0,14

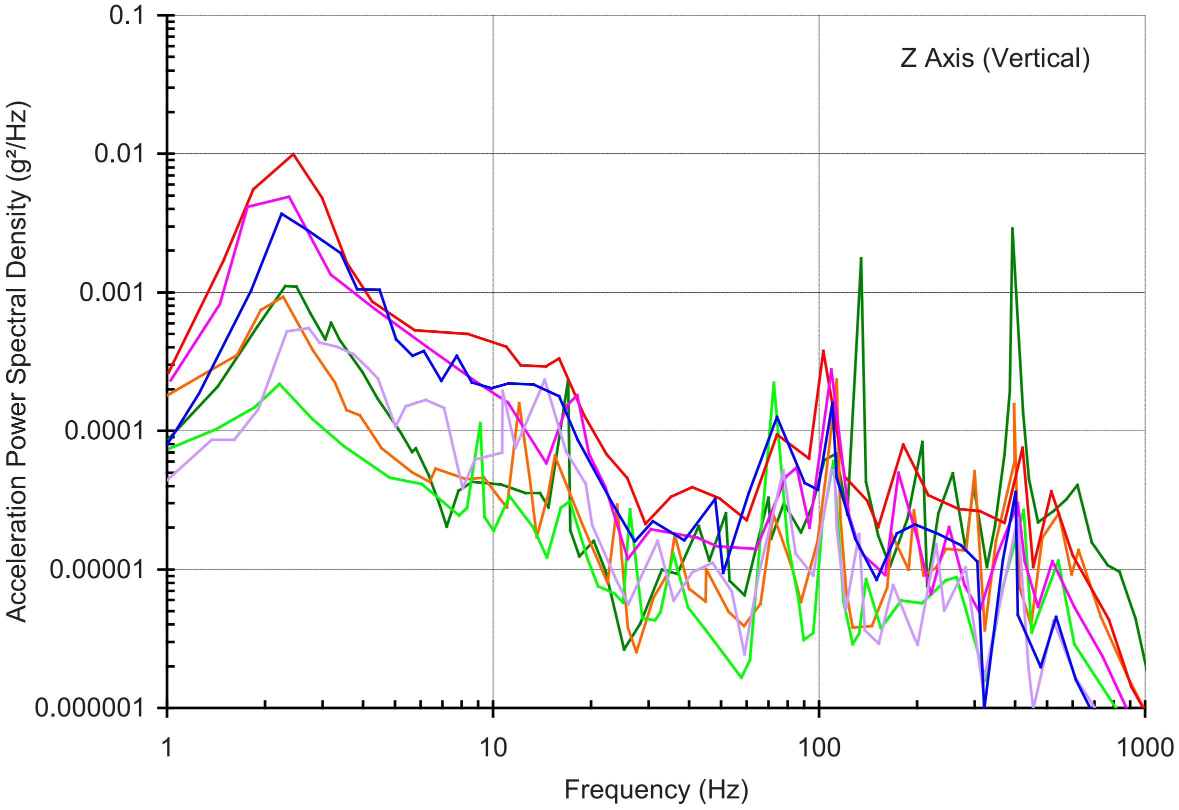


Figure 41 – Vibration PSD from GAM EG 13 measurements on Renault Traffic

Table 7 – Vibration r.m.s. from GAM EG 13 measurements on RVI TRM 1000

Road surface	Acceleration r.m.s. g		
	X axis (fore-aft)	**Y AXIS** (transverse)	**Z Axis** (vertical)
Good road 60 km/h	0,11	0,16	0,17
Good road 75 km/h	0,14	0,21	0,25
Very good road	0,16	0,26	0,26
General road driving full speed	0,08	0,12	0,17
General road driving 80 % full speed	0,13	0,19	0,40
General road driving full speed	0,09	0,14	0,28
General road driving 80 % full speed	0,08	0,13	0,18
General road driving full speed	0,10	0,15	0,26
General road driving 80 % full speed	0,07	0,10	0,15
General road driving full speed	0,11	0,17	0,29
General road driving 80 % full speed	0,08	0,13	0,20
General road driving full speed	0,14	0,22	0,30
General road driving 80 % full speed	0,10	0,16	0,22
General road driving 23,5 km/h	0,41	0,31	0,61
General road driving 13,5 km/h	0,16	0,19	0,44

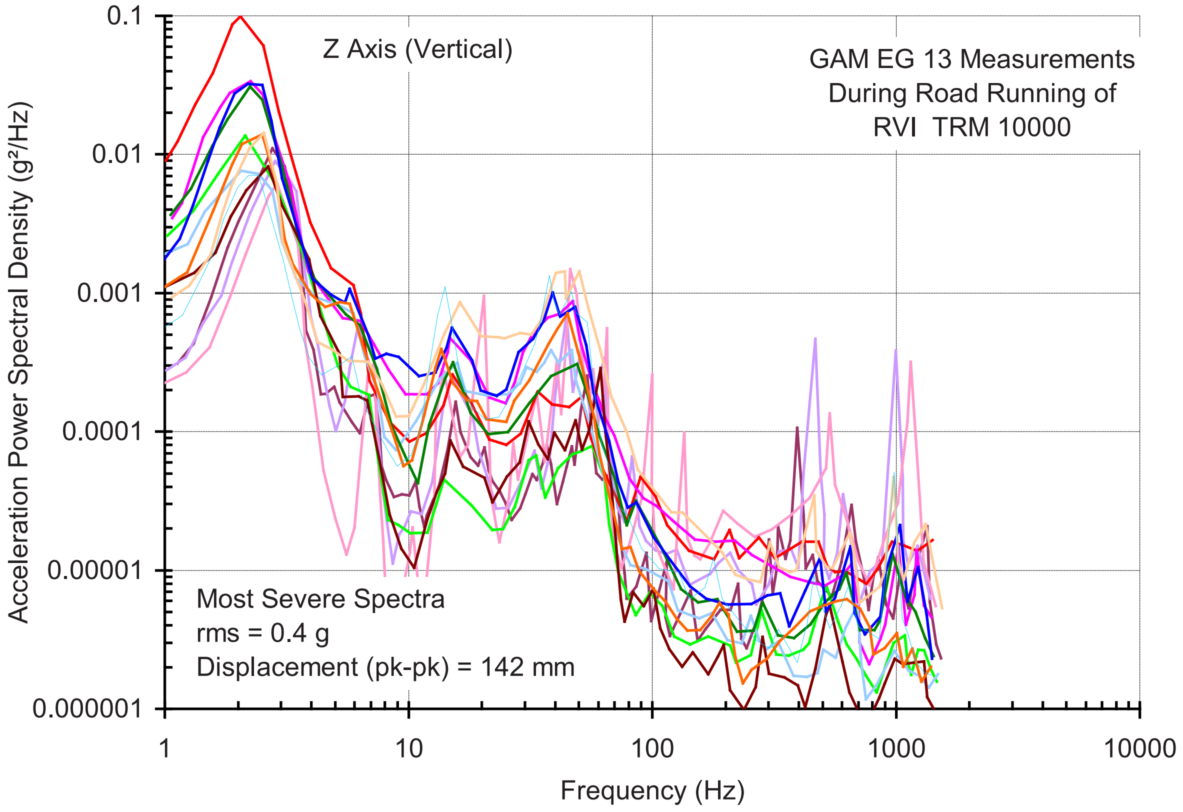


Figure 42 – Vibration PSD from GAM EG 13 measurements on RVI TRM 1000

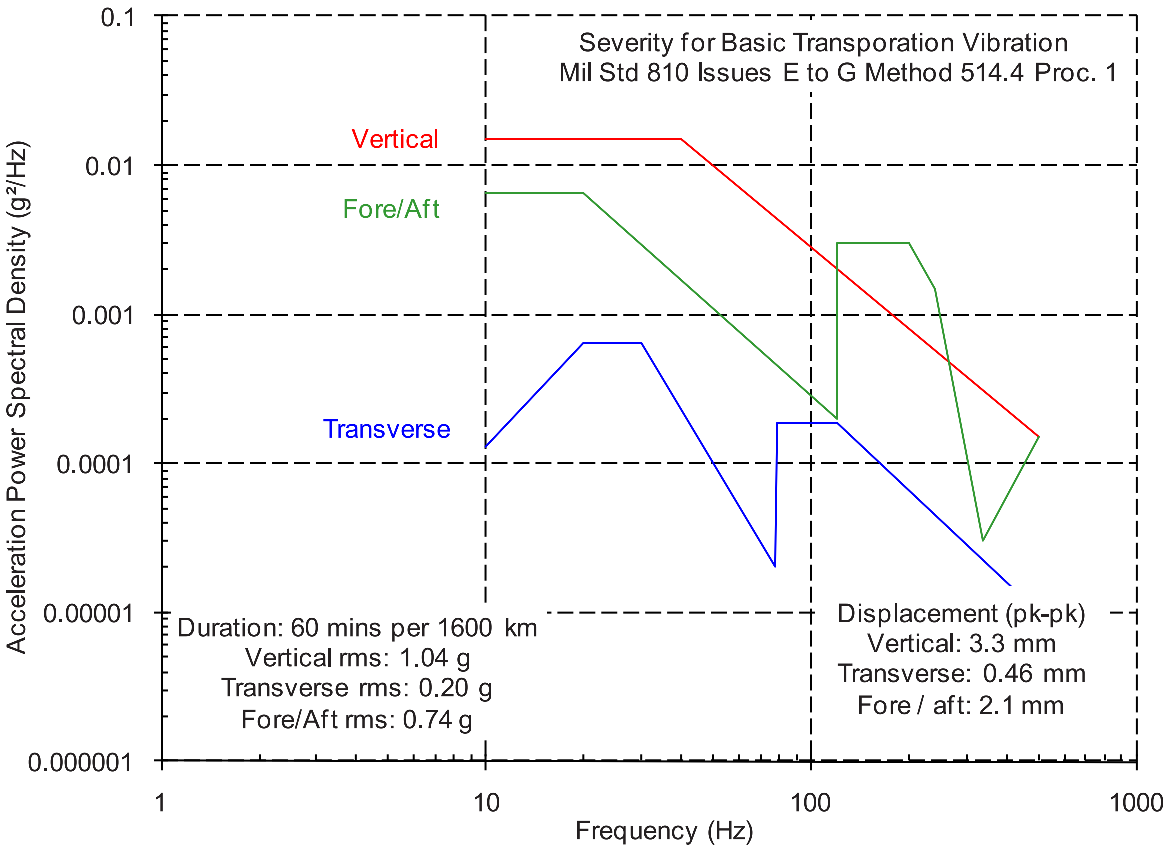


Figure 43 – Vibration severities from Mil Std 810 (Foley)

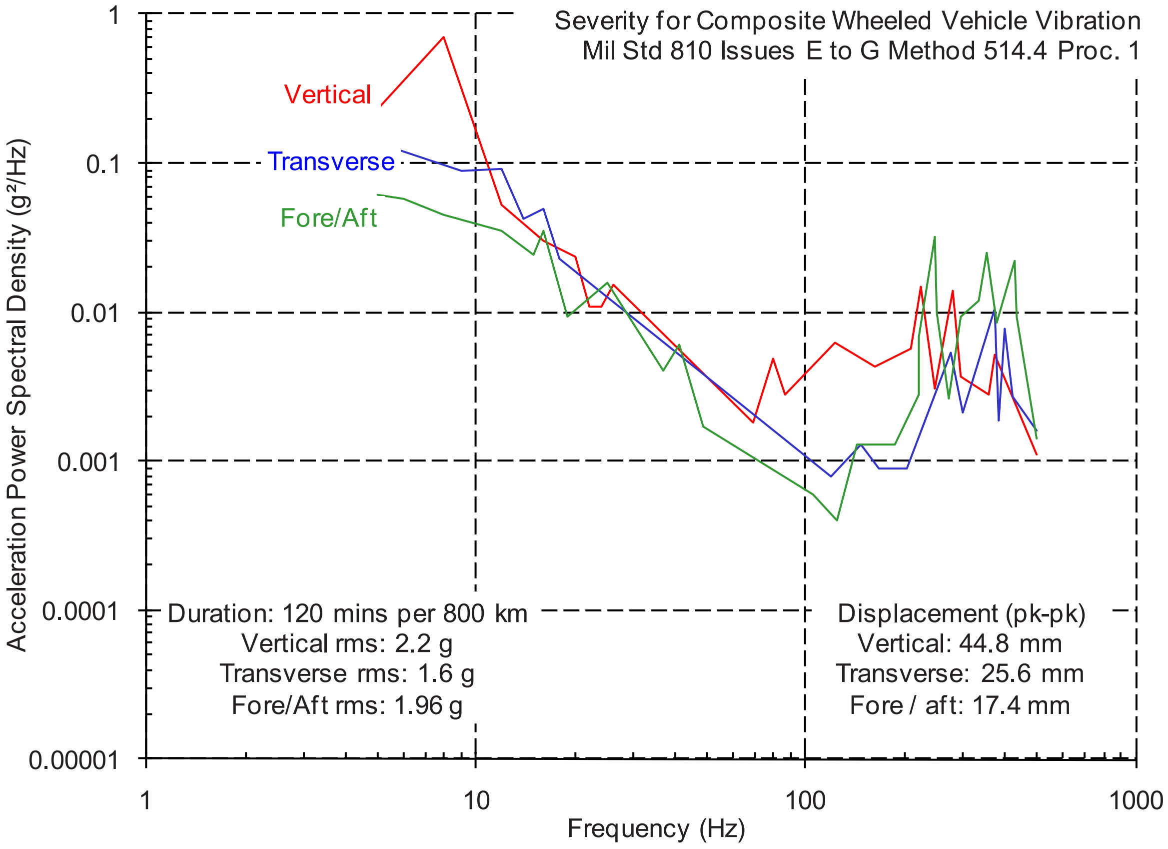


Figure 44 – Vibration severities from Mil Std 810 (Connon)

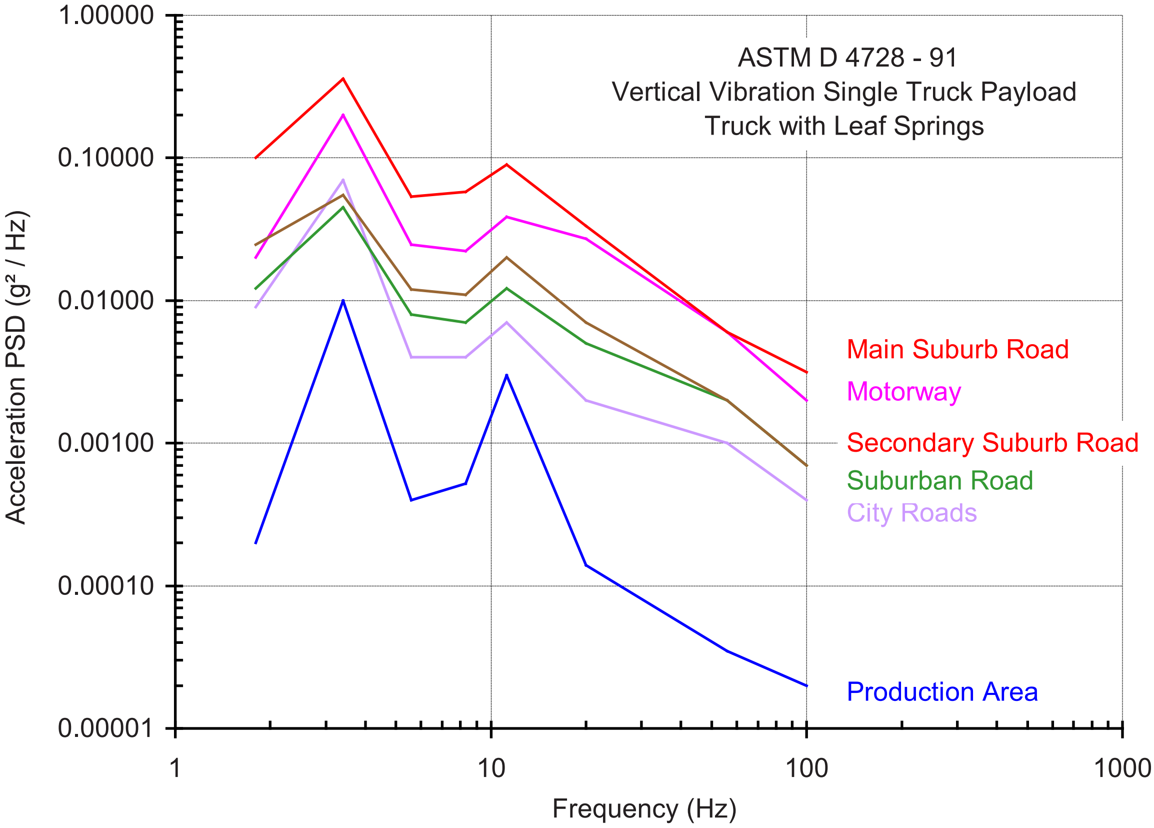


Figure 45 – Data from ASTM 4728-91

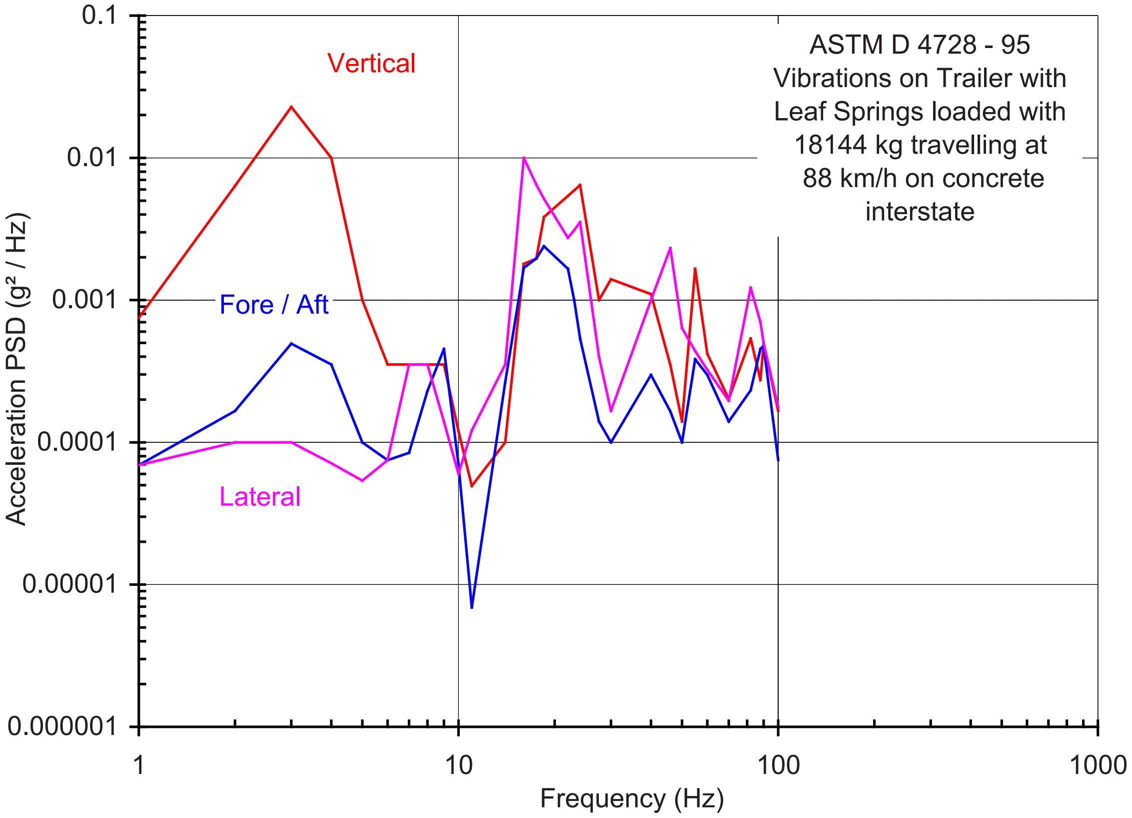


Figure 46 – Data from ASTM D4278-95

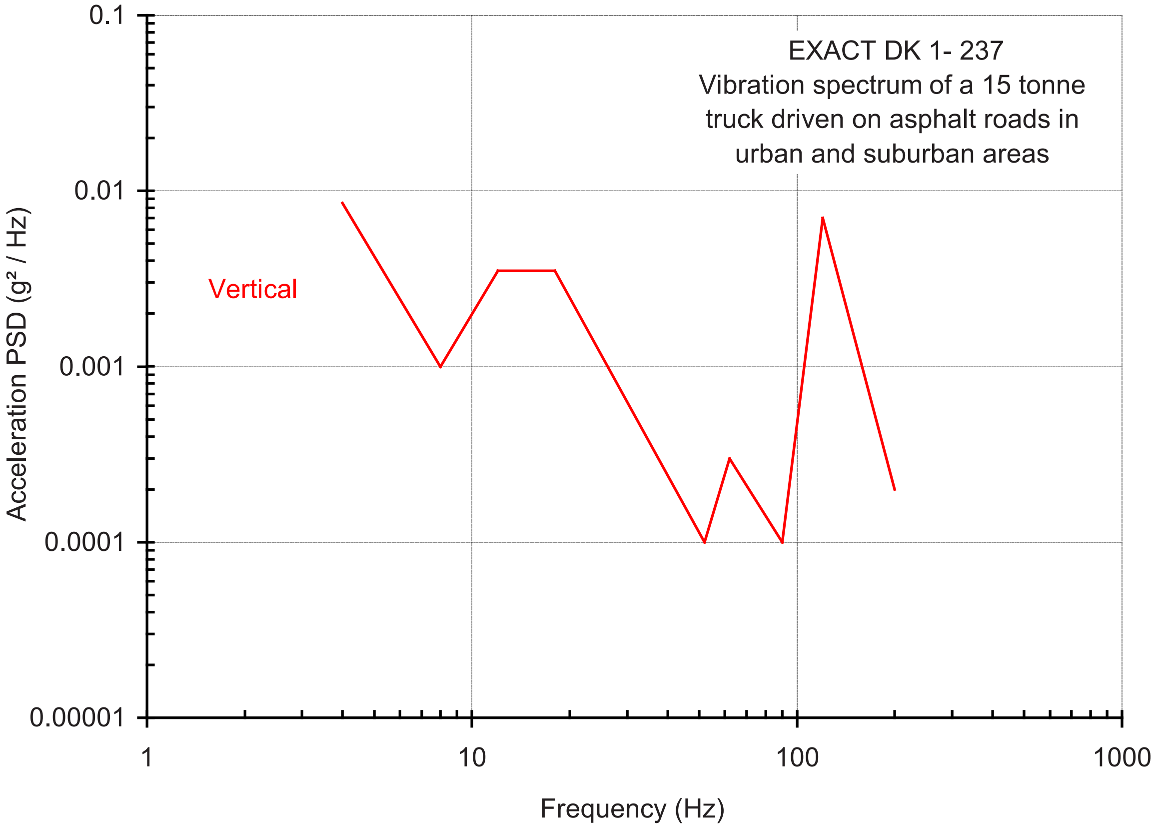


Figure 47 – Data from EXACT DK 1 – 237

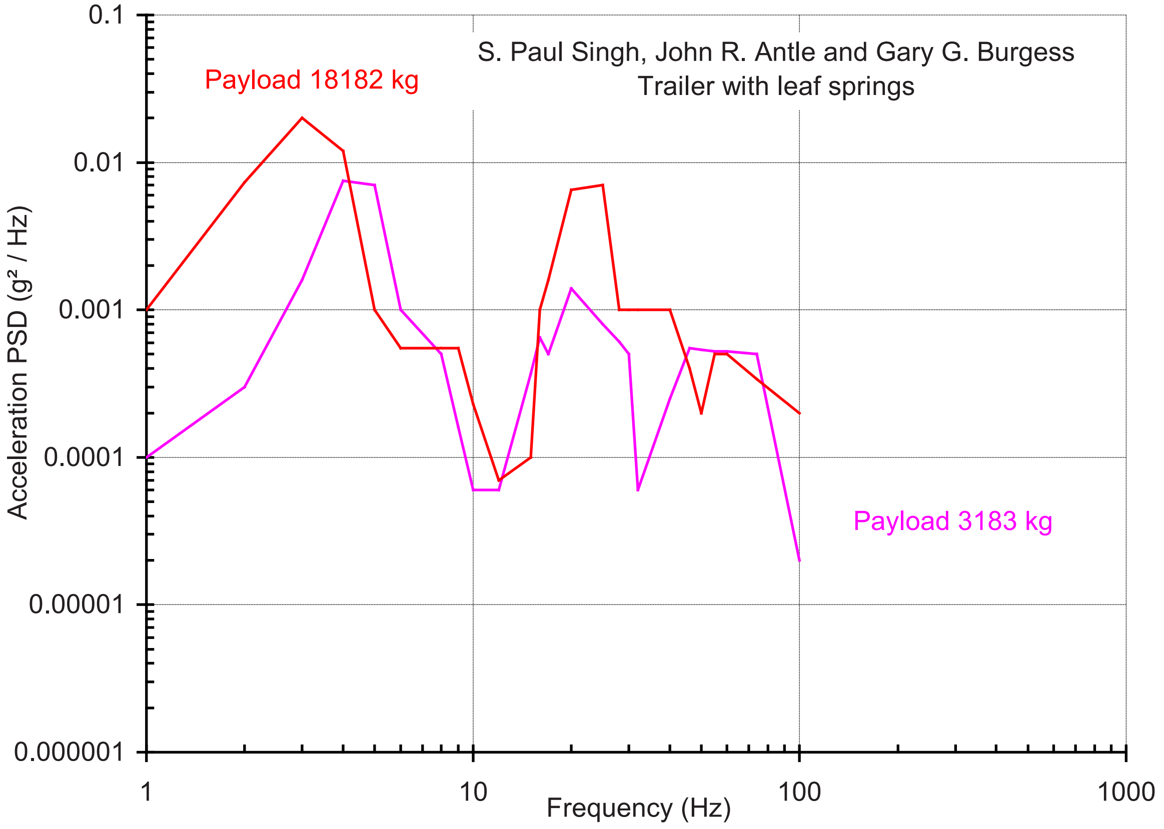


Figure 48 – Data from reference 15

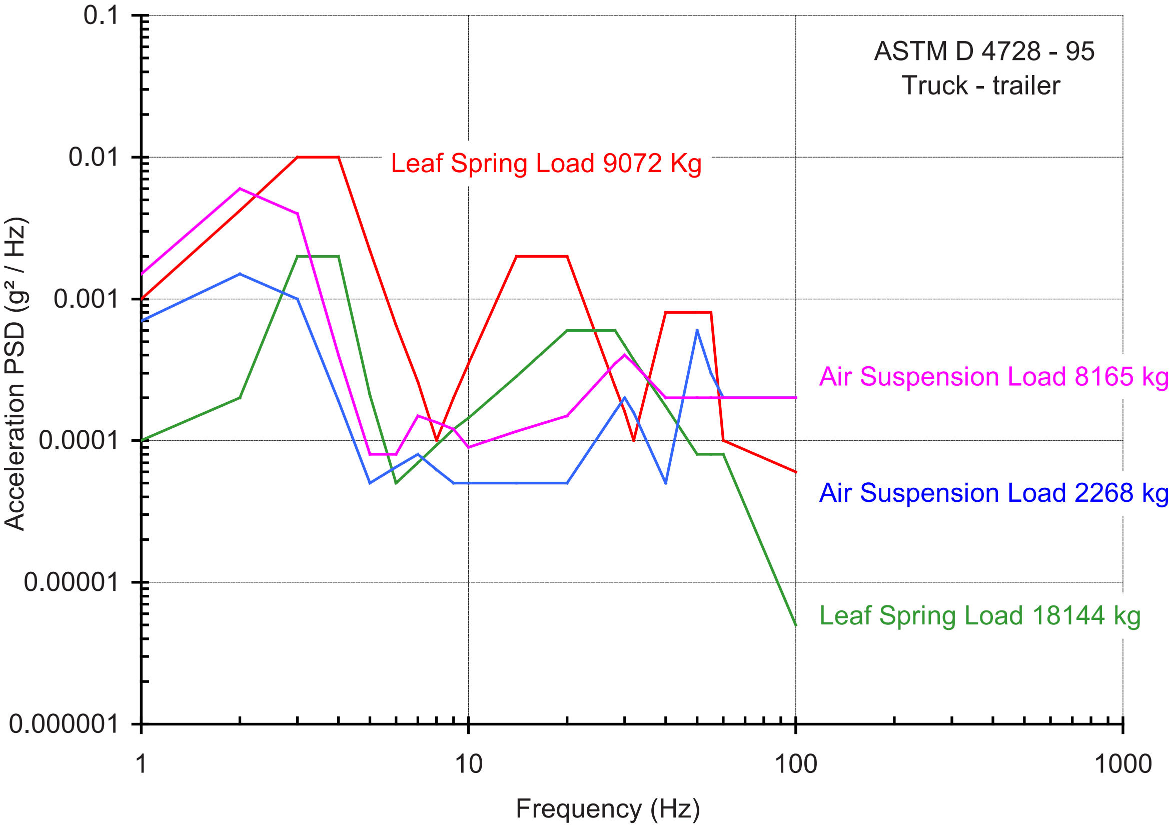


Figure 49 – Data from ASTM D 4728-95

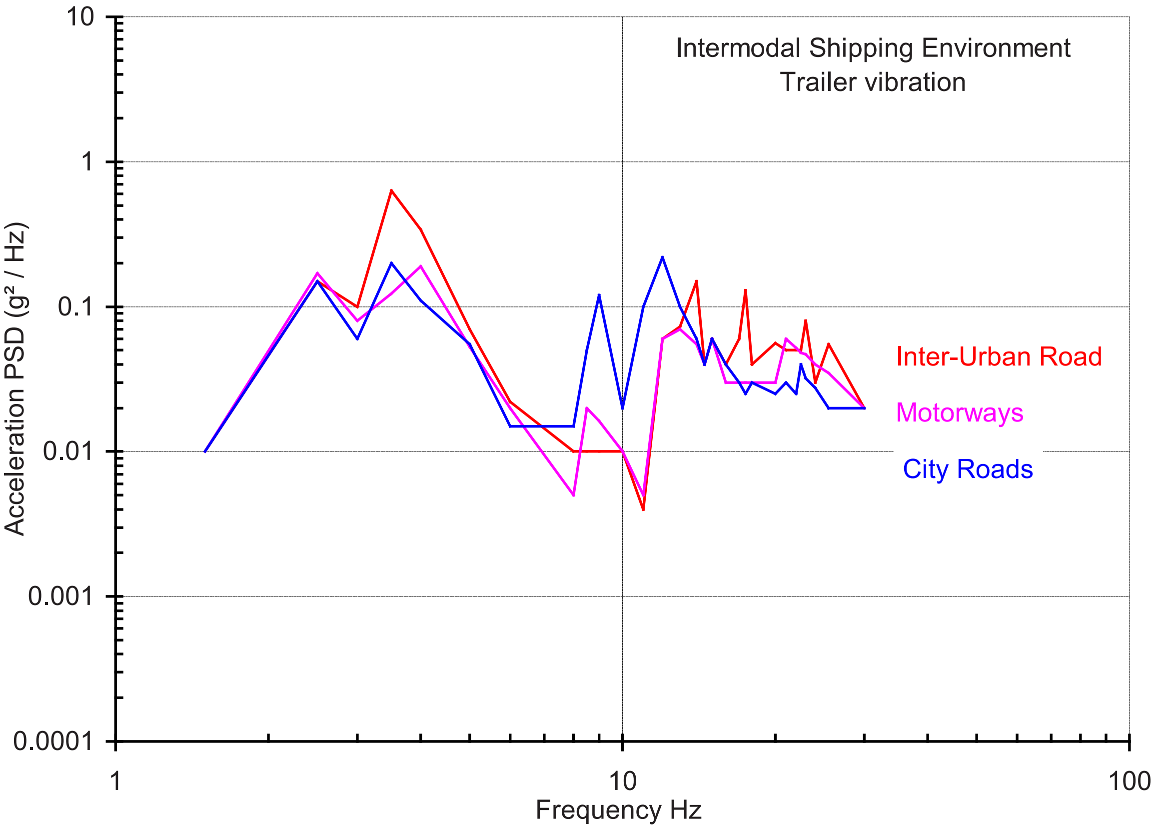


Figure 50 – Data from reference 16

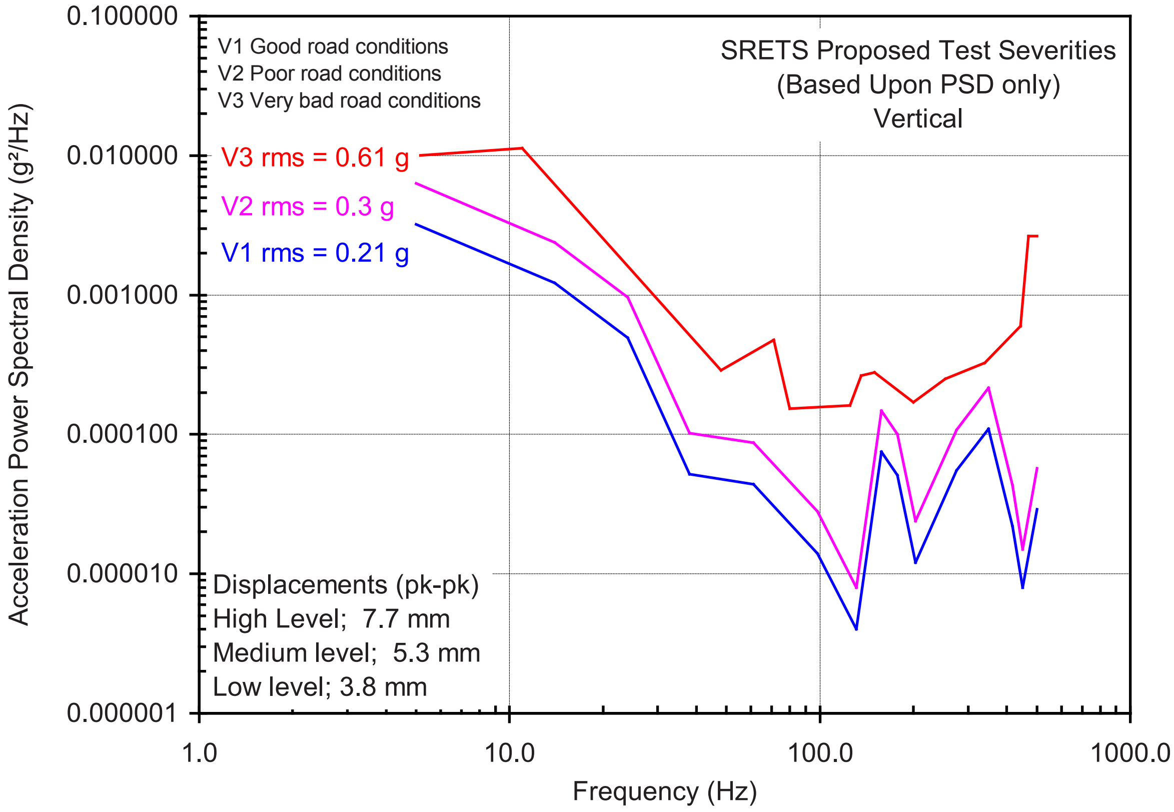


Figure 51 – SRETS test severity from PSD

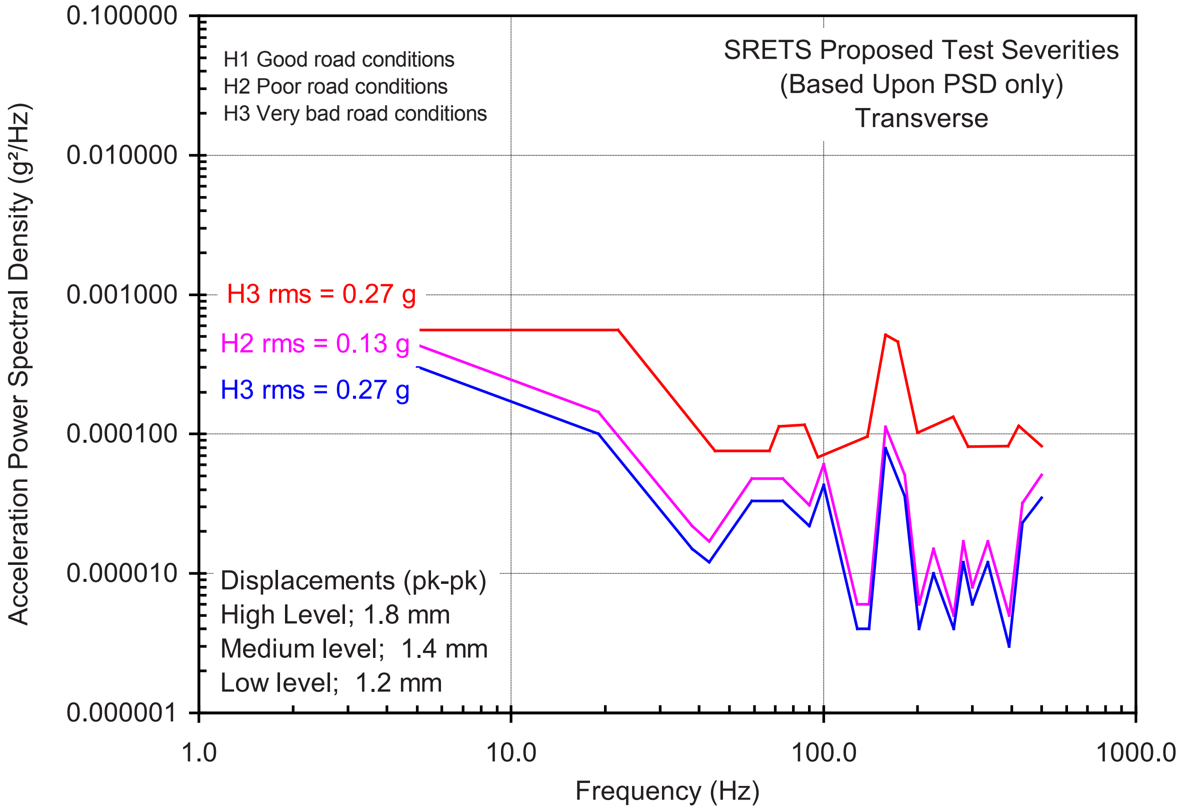


Figure 52 – SRETS test severity from PSD

Table 8 – SRETS shock test definition to augment vibration test from PSD

Horizontal (x-axis)			**Horizontal** (y-axis)			**Vertical** (z-axis)		
Number of shocks per 1 000 km	**Acceleration** g	**Duration** ms	**Number of shocks per 1 000 km**	**Acceleration** g	**Duration** ms	**Number of shocks per 1 000 km**	**Acceleration** g	**Duration** ms
1	2	5	1	2	10	12	2	5
12	2	20	2	2	15	7	2	10
25	2	25	7	2	20	3	2	15
29	2	30	13	2	25	17	2	20
21	2	35	10	2	30	6	2	25
3	2	40	2	2	35	4	2	30
			1	2	40	2	2	35
						1	2	40
2	4	5	1	4	5	16	4	5
						2	4	10
						2	4	20
						1	4	25
1	6	5	1	6	5	3	6	5
						1	6	10
						1	6	20
1	8	5		8	5	1	8	5

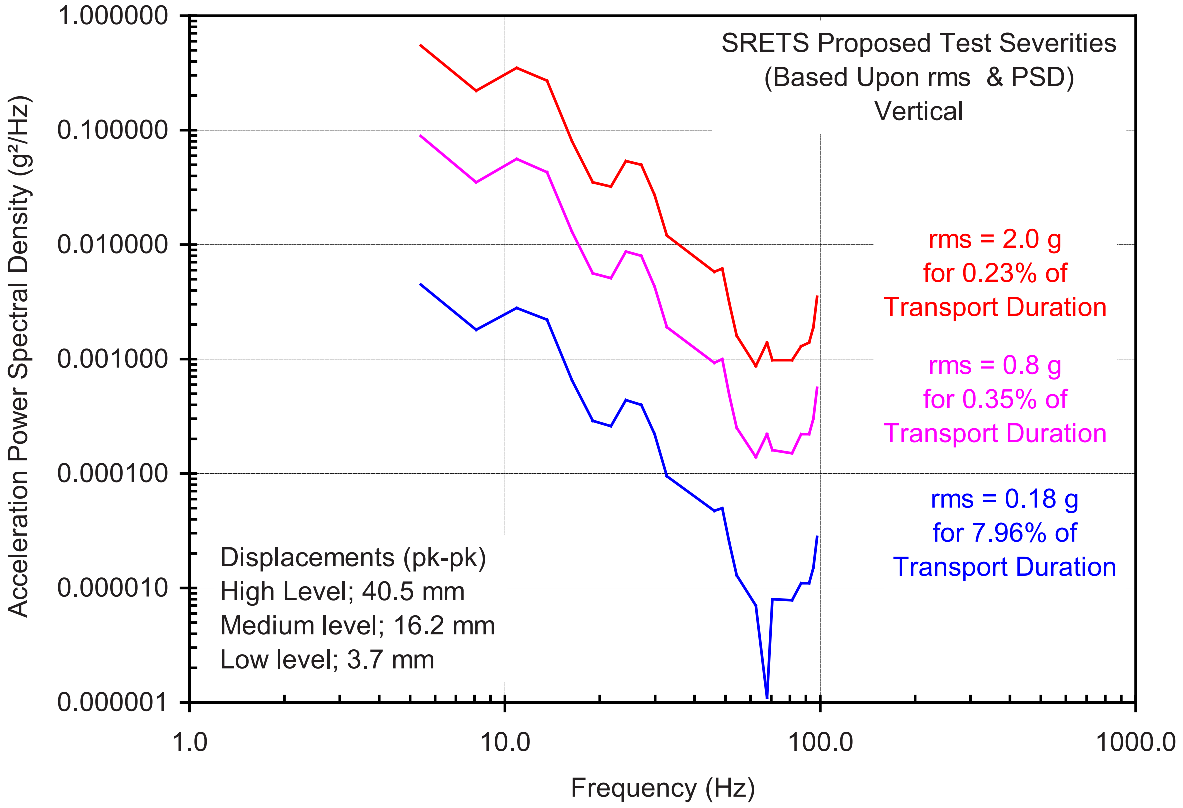


Figure 53 – SRETS test severity from r.m.s. (including shocks)

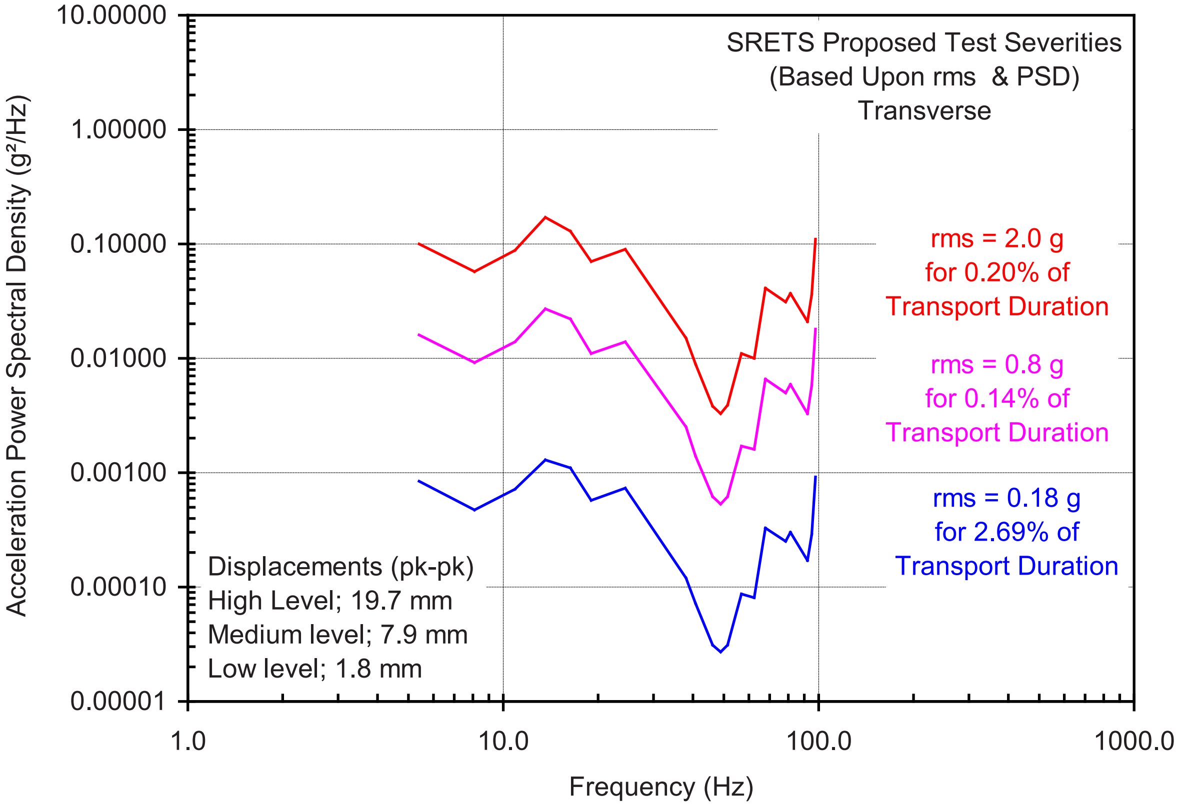


Figure 54 – SRETS test severity from r.m.s. (including shocks)

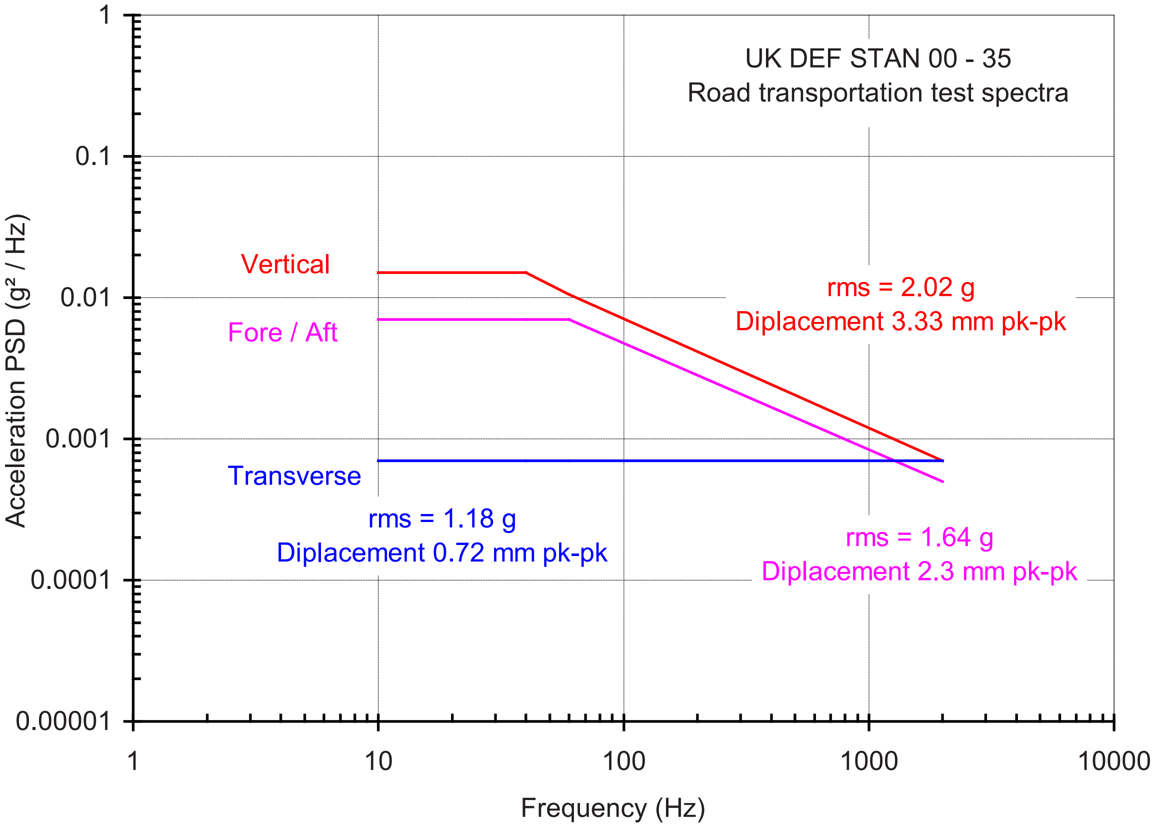


Figure 55 – Test severities from UK defence standard

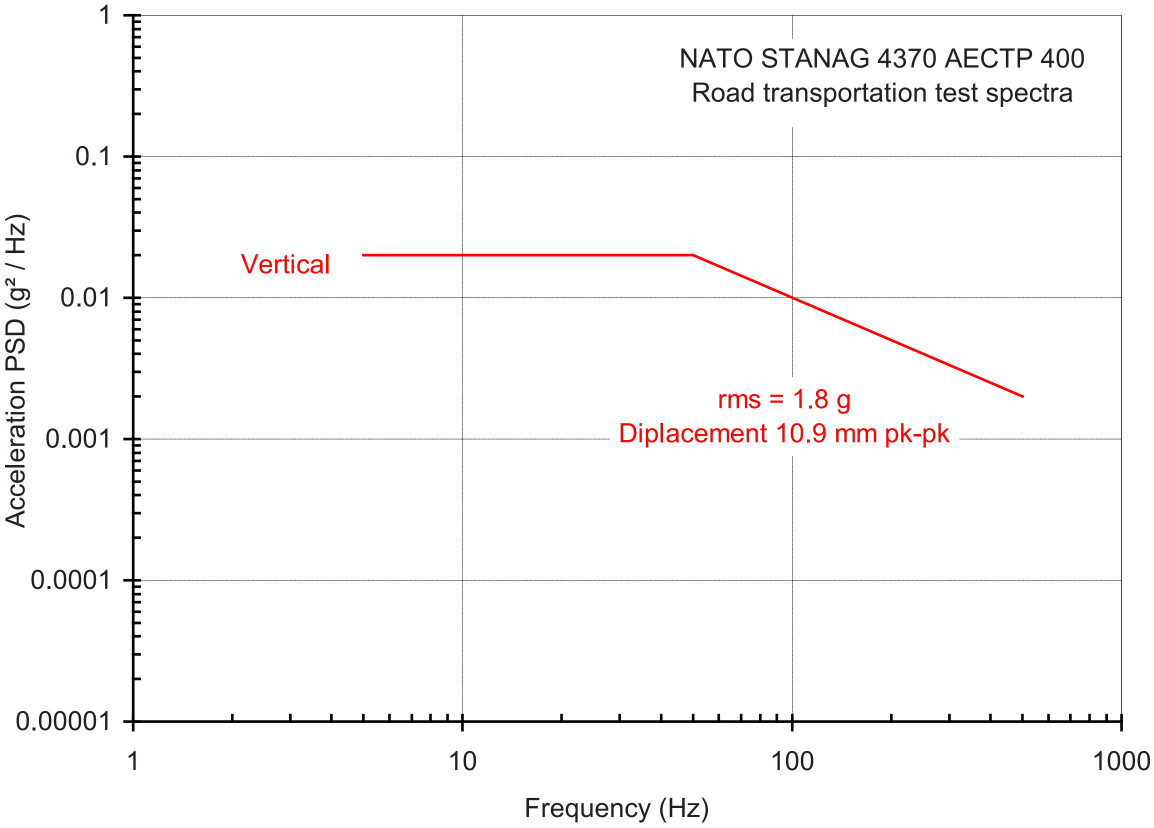


Figure 56 – Test severities from NATO STANAG

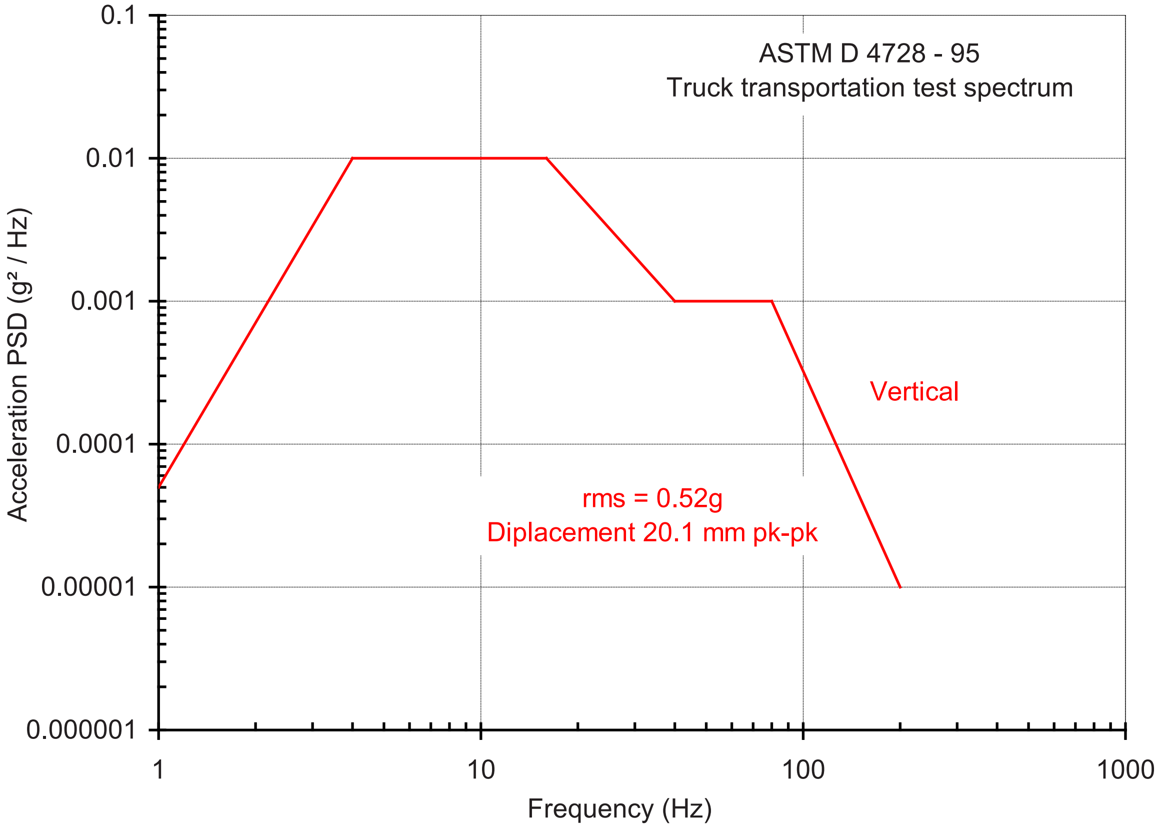


Figure 57 – Test severities from ASTM D 4728-95

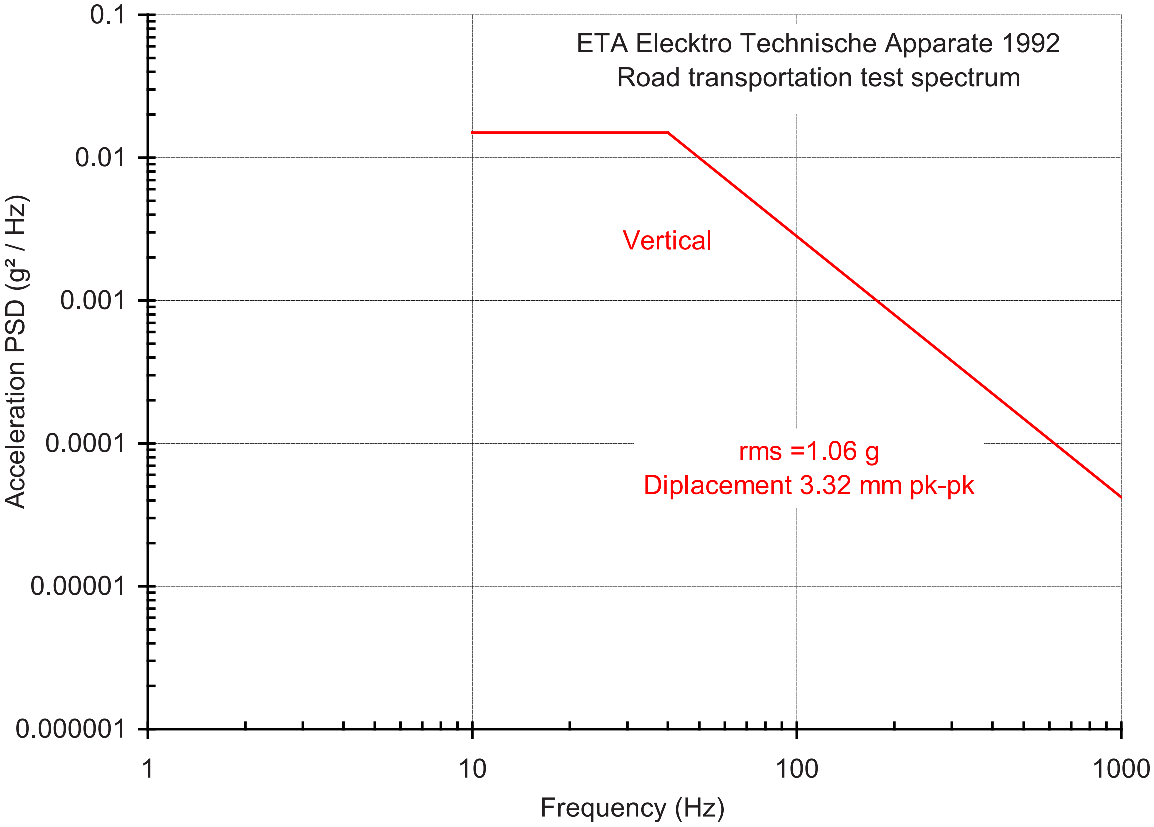


Figure 58 – Test severity from ETA

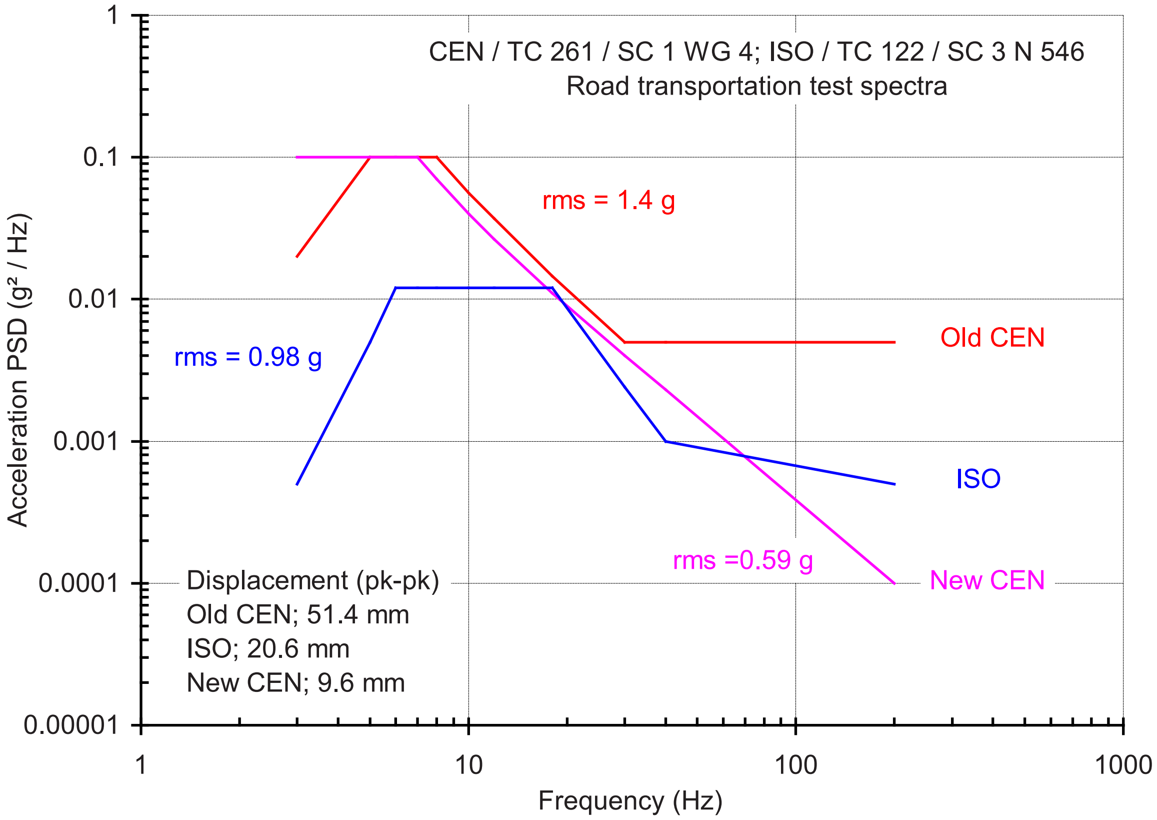


Figure 59 – Test severities from CEN and ISO

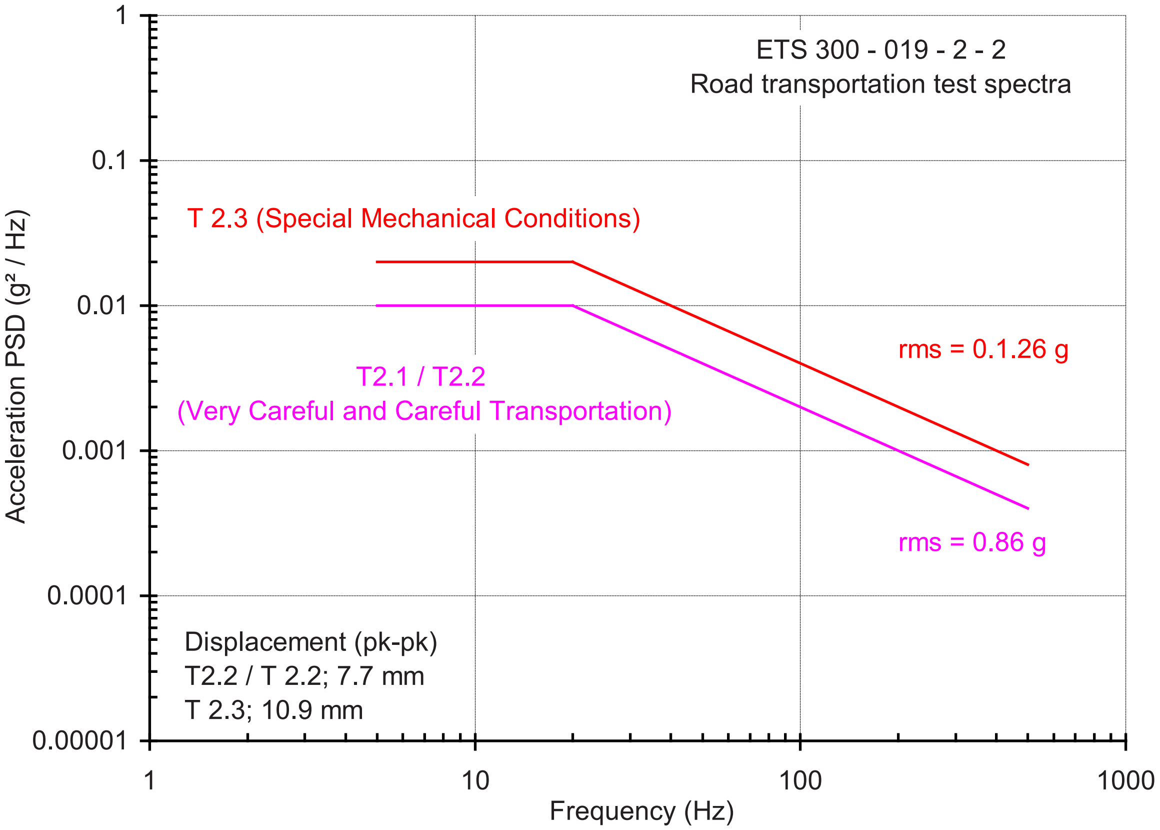


Figure 60 – Test severities from ETS

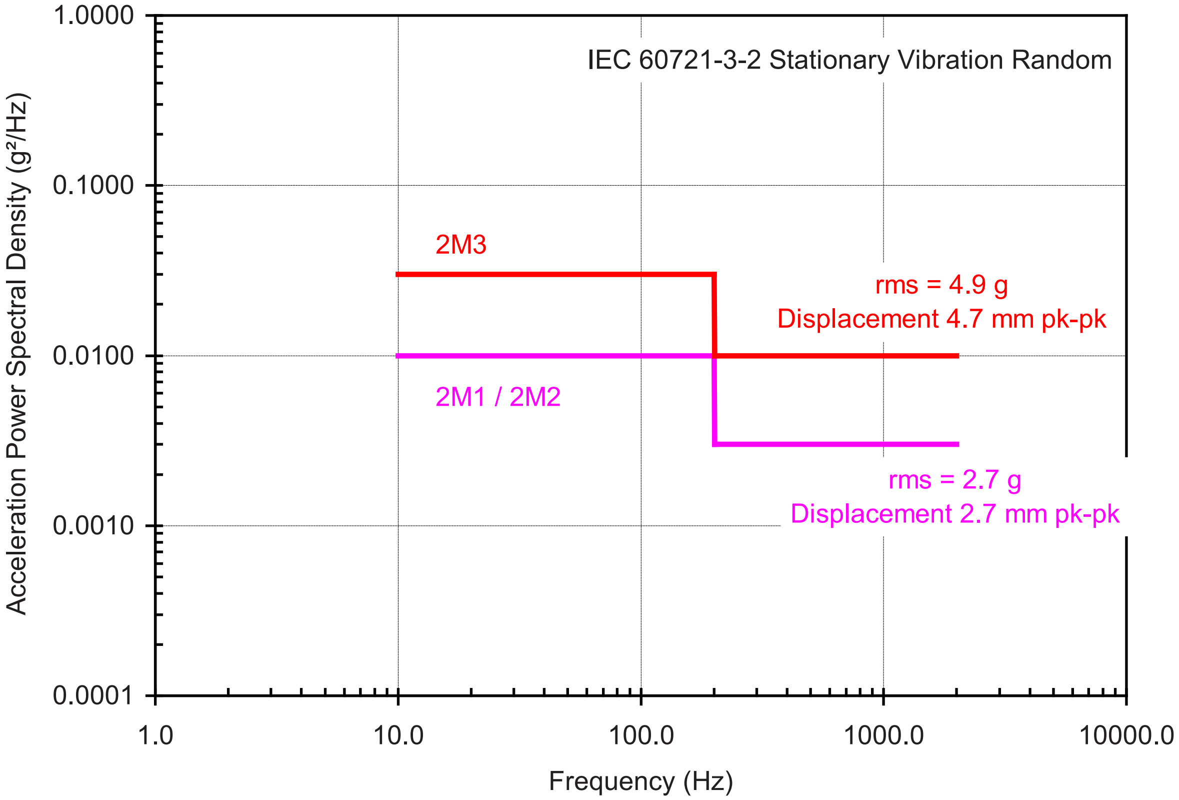


Figure 61 – IEC 60721-2-2:1997 [26] – Random vibration severity

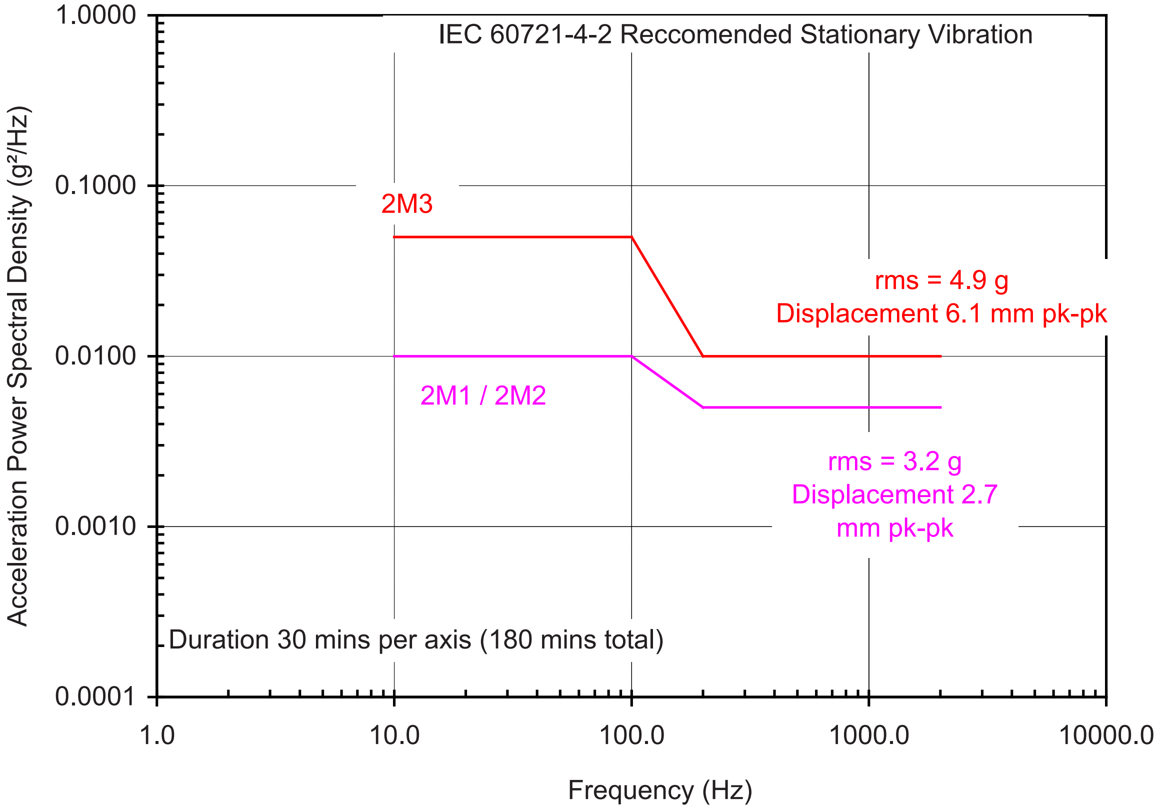


Figure 62 – IEC 60721-4-2:1997 – Random vibration severity

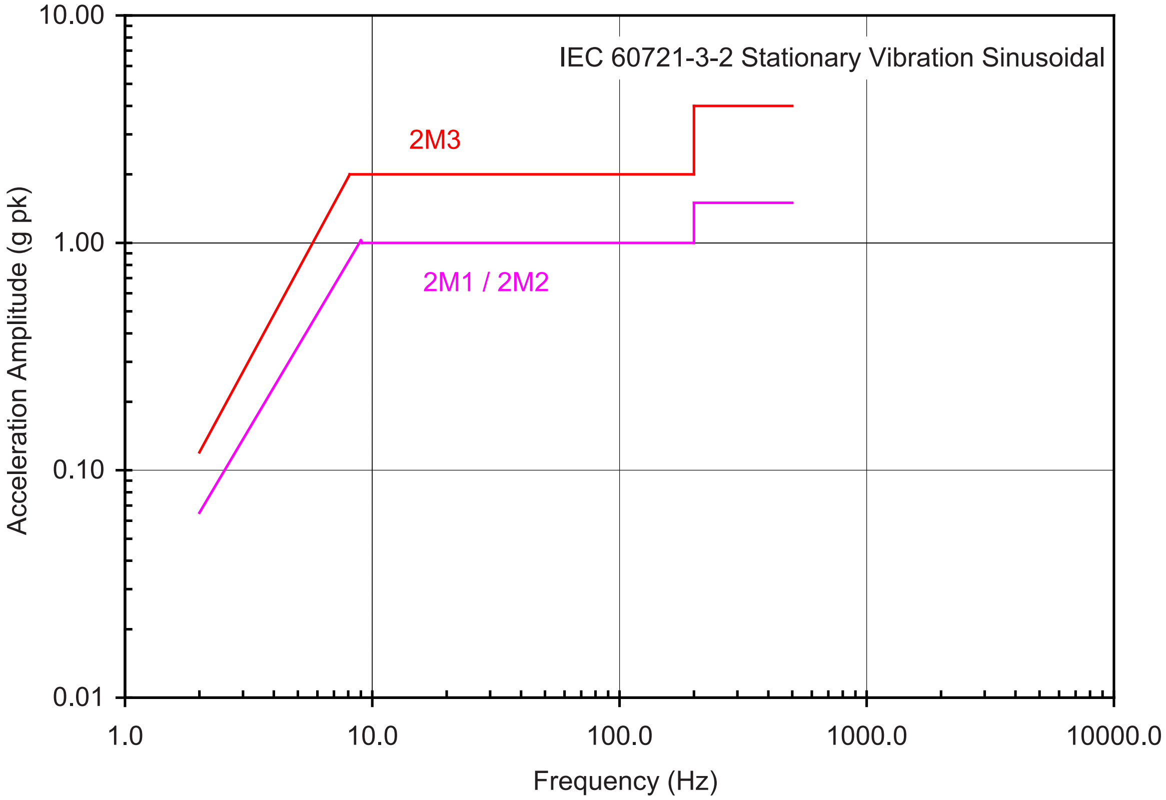


Figure 63 – IEC 60721-3-2:1997 – Sinusoidal vibration severity

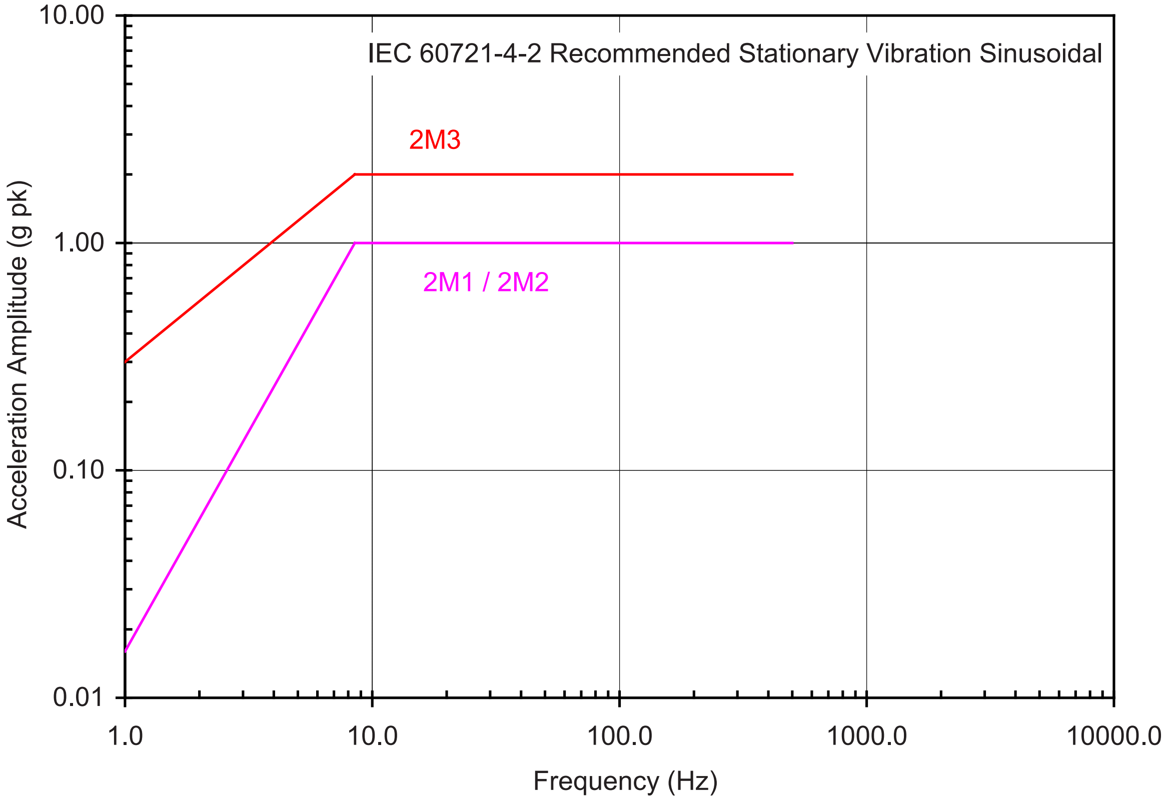


Figure 64 – IEC 60721-4-2:1997 – Sinusoidal vibration severity

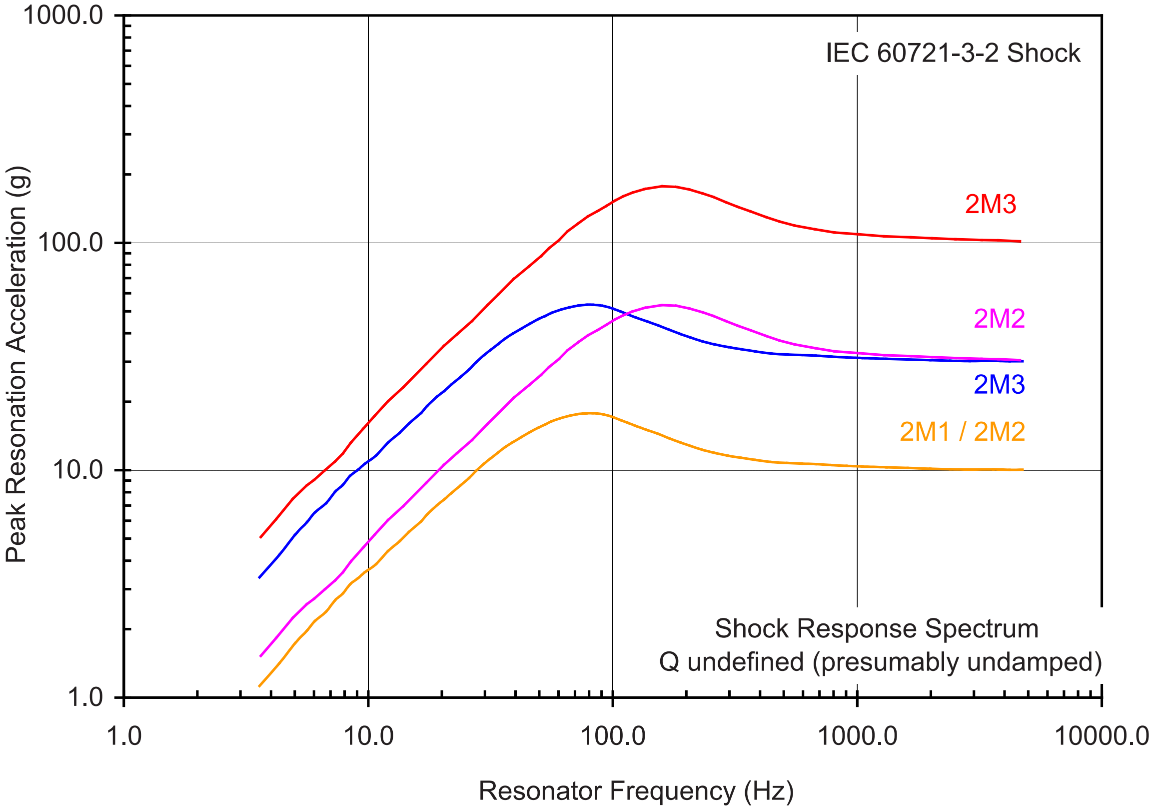


Figure 65 – IEC 60721-3-2:1997 – Shock severity

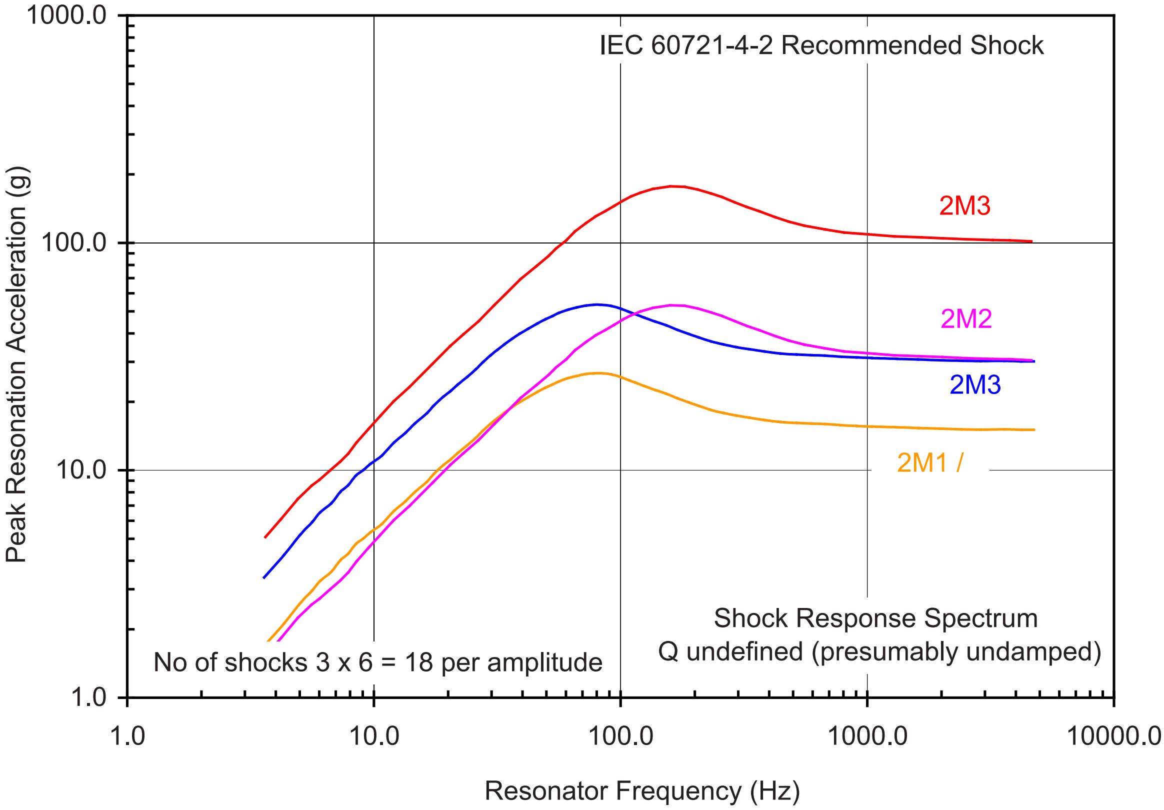


Figure 66 – IEC 60721-4-2:1997 – Shock severity

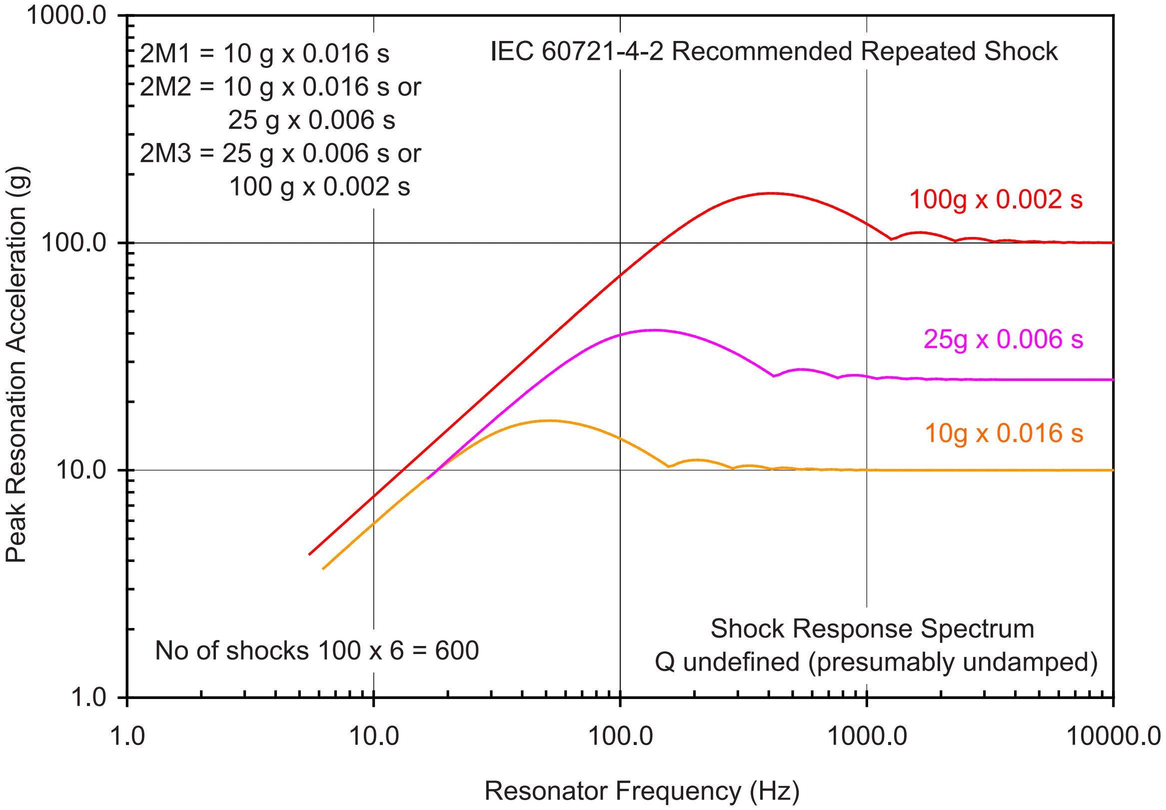


Figure 67 – IEC 60721-4-2:1997 – Recommended repeated shock severity

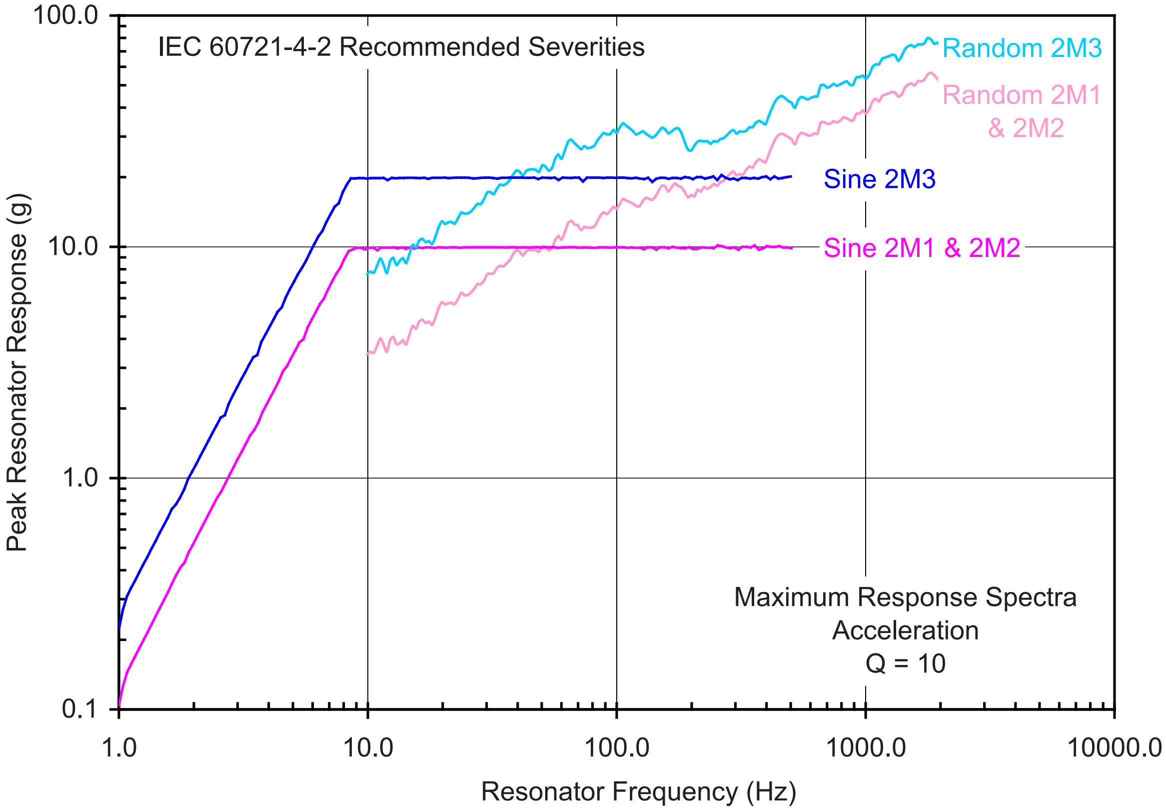


Figure 68 – Comparison of the effects of IEC 60721-4-2:1997 –
Random and sinusoidal vibration severities

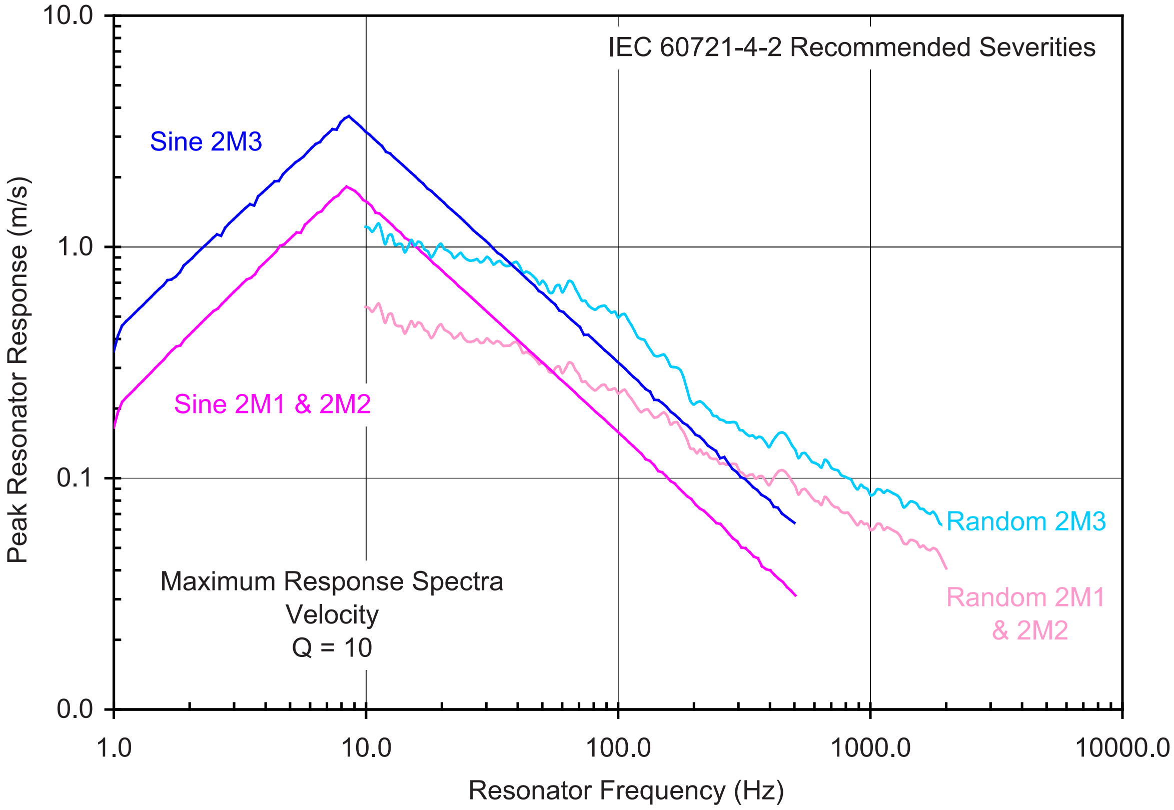


Figure 69 – Comparison of the effects of IEC 60721-4-2:1997 – Random and sinusoidal vibration severities

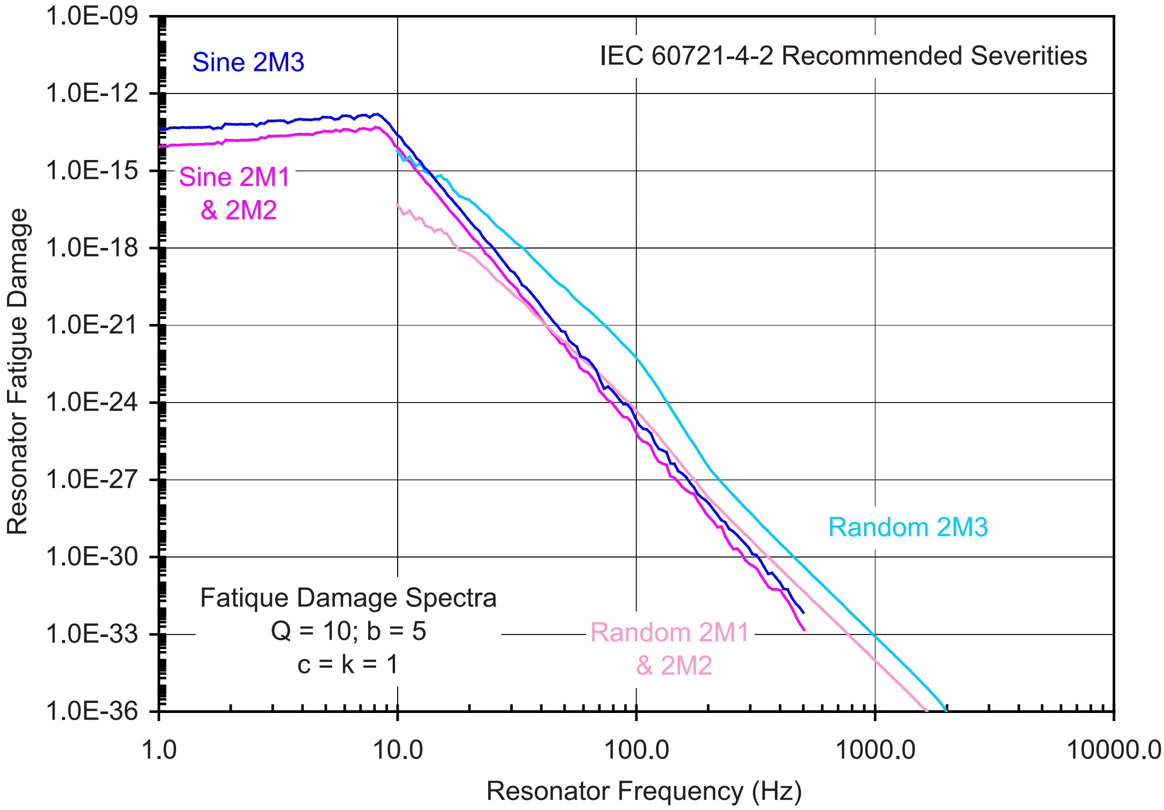


Figure 70 – Comparison of the effects of IEC 60721-4-2:1997 – Random and sinusoidal vibration severities

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