VIBRATION TESTING EQUIVALENCE

HOW MANY HOURS OF TESTING EQUALS HOW MANY MILES OF TRANSPORT?

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ABSTRACT

The question is often asked – how many hours equals how many miles? But there are numerous kinds of vibration tests, and numerous kinds of transport – so first we need to be *much* more specific. What *type* of test are we trying to relate to what *type* of transport? Even with proper definitions, the answer still isn't easy. This paper examines several existing recommendations, discusses the various factors, explores different approaches involving frequency-domain and time-history testing, then proposes a methodology which might lead to improved simulations.

ONE HOUR EQUALS 1000 MILES – AND OTHER CONJECTURES

Unfortunately, there *are* some simplified recommendations to be found in the literature. We use the word "unfortunately", because if people believe there really *should* be an easy answer, they're less likely to listen to the correct, thorough explanation. Below are some recommendations and conjectures to which the author of this paper *does not* subscribe.

Mil-Std-810E

This standard, "Environmental Test Methods and Engineering Guidelines"[1], is one of the mainstays of the environmental testing community. Among its 500+ pages, it contains random vibration profiles (spectra) purportedly representing "common carrier" transport. A legend says "Test Duration: 60 minutes per 1000 miles" (Figure 1).

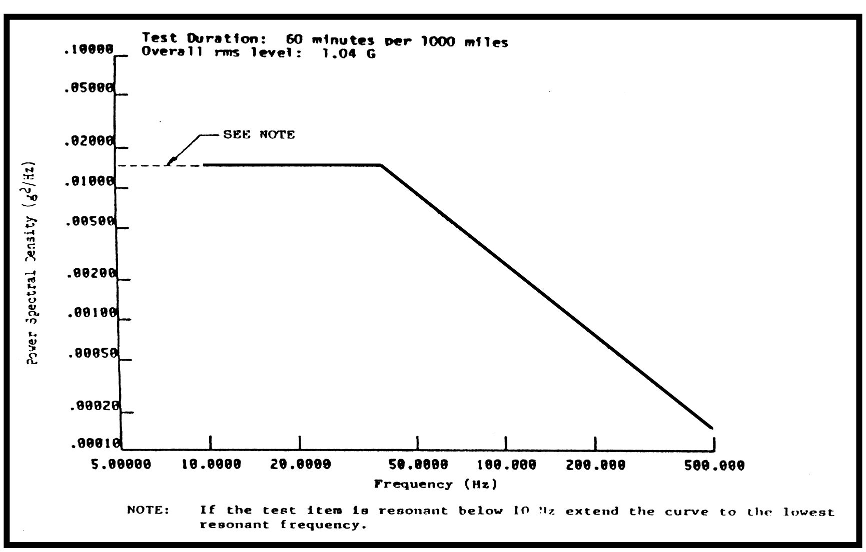

FIGURE 1: MIL-STD-810E "BASIC TRANSPORTATION, COMMON CARRIER ENVIRONMENT, VERTICAL AXIS"

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At first glance, this looks great – at least for this specific test and this specific(?) mode, a direct equivalence is given. But if one looks more closely, the random vibration profile appears suspect; the low-frequency limit is 10 Hz. (with a note "if the test item is resonant below 10 Hz. extend the curve to the lowest resonant frequency", but even then the graph only goes to 5 Hz.), the shape seems overly simplified, and the 500 Hz. maximum frequency seems too high. We know that truck and rail spectra have *significant* content below 10 Hz., with usually a large peak at the natural frequency of the suspension system (typically 2.5 -10 Hz.). For trucks, there is often a secondary peak at the tire frequencies (perhaps 12-25 Hz.). Further, we believe that these spectra have no significant frequency content above 100-300 Hz. Finally, are we to suppose that the "1 hour = 1000 miles" equivalence holds for *worldwide* transport? Aren't road conditions generally quite different in undeveloped than in developed countries?

Few, if any, people involved in transport package testing use this Mil-Std-810E test.

11,800 and 14,200 Impacts

Several of the ISTA[2] Procedures and Projects[3] call out a "vibration" test in accordance with ASTM[4] D999 Method A1 or A2[5]. Technically this is not vibration, but a repetitive shock ("bounce") test where the specimen repeatedly leaves the test surface – as evidenced by the ability to insert a thin shim under it. The ISTA test durations are specified in terms of the total number of impacts ("bounces"), either 11,800 or 14,200. The test time varies depending on the actual frequency used, but usually is in the neighborhood of 40 to 60 minutes.

Where do these impact numbers come from, and what do they mean? Several years ago, we asked Chester Gaynes[6] this question – he thought the origin might have been an attempt to relate the test to rail transport. Rail joints are 39 feet apart, and if one assumes that every rail joint causes a "bounce", it should be possible to calculate an equivalent distance. If we make these assumptions and calculations, the answers are 87 and 105 miles.

The numbers seem too low, don't they? Especially if you've seen the damage that can be produced by these types of tests. Don't misunderstand: ISTA (and Chester) do *not* claim that these tests are equivalent to any distances – on the contrary, the "Guidelines for Using ISTA Projects and Procedures" clearly state that certain tests are "not designed to simulate environmental occurrences".

ISO 4180/2

International Standard ISO 4180/2[7], "Complete, Filled Transport Packages – General Rules for the Compilation of Performance Test Schedules" includes a version of the "vibration" (repetitive shock) test in accordance with ISO 2247. Table 2 of 4180/2, "Basic Test Intensities", recommends a basic test duration of 20 minutes, with a range of from 10 to 60 minutes. The times of 10-20 minutes seem short by ISTA standards, but 60 minutes corresponds well.

Table 4 of 4180/2, "Test Intensity Modifying Factors", for situations of "known features of the distribution system", contains the following recommendations for "vibration duration":

Road	a) Journey Length: For road journeys between 1000 and 1500 km. in length, the vibration duration should be 40 min., and for journeys longer than 1500 km the duration should be 60 min. For journeys of less than 1 h, a duration of 10 min. should be used. b) Rough Journeys: For known journeys over bad roads, where poor vehicles are used, or where the journey is known to be severe in some other way, the distances quoted in a) should be halved before a decision is made concerning the duration of vibration.
Rail	a) Journey Length: For rail journeys between 3000 and 4500 km. in length, the vibration duration should be 40 min., and for journeys longer than 4500 km the duration should be 60 min. For journeys of less than 3 h, a duration of 10 min. should be used. b) Rough Journeys: For known journeys over poor track, or where poor vehicles are used, the distances quoted in a) should be halved before deciding whether the basic duration of vibration should be modified.

EXCERPTS FROM TABLE 4 OF ISO 4180/2

The distance divisions seem rather course, and there's a gap between the 1 hour (about 100 km?) and the 1000 km distances for Road [3 hours (about 300 km?) and 3000 km for Rail]. No rationale is given for the numbers, and no significant attempt is made to reconcile the recommendations within Table 4 or between Tables 2 and 4.

Since the fundamental test is basically the same "bounce" test as described previously, the author feels that the ISTA "Guidelines" statement of "not designed to simulate environmental occurrences" is applicable here as well.

LET'S GET SPECIFIC

In order to begin adequately addressing the question of vibration testing equivalence, we need to be specific about the <u>*type*</u> of test and the <u>*types*</u> and <u>*conditions*</u> of transport.

Vibration Tests

There are three categories of commonly-used tests in the transport packaging field, and sub-categories of each. First is the "bounce" test (not really vibration) discussed above. This test is usually conducted at the frequency where bouncing just begins (nominally 4.6 Hz. or so), but is sometimes conducted at other frequencies (ISTA 1F requires 3.3 Hz., ISO 2247 mentions frequencies between 3 and 4.6 Hz., we've seen corporate specifications of 7 and 10 Hz., etc.).

The second category is a sinusoidal (sine) test, with specified accelerations and frequencies. The sub-categories are sweep tests and dwell tests. As used for transport packaging, sweep tests keep the acceleration constant and slowly change the operating frequency over a specified range. For example, ASTM D4169 recommends 0.25 or 0.5 G sweeps between 3 and 100 Hz. In some specifications, the entire vibration requirement is met by one or several sine sweeps. In many cases, however (such as ASTM D4169, D999, D3580, and D5112), the sweep is used to search for resonances (natural frequencies) in the product or product/package system. Once these resonant frequencies are identified, dwell tests are conducted at each, at the lowest few, or at the most severe. A dwell test is a single-frequency, constant amplitude sine test. ASTM recommends specific dwell times, and suggests that the test frequency be shifted slightly, if necessary (to track any shift in the test item's resonant frequency due to fatigue or other effects), so that testing is always conducted "at the frequency of maximum response".

The third vibration test category is random vibration. These tests can most nearly simulate actual field and transport conditions, and are typically described by power spectral density (PSD) plots – graphs of "average" acceleration intensity in the frequency domain (PSD as a function of frequency).[8,9] Sub-categories are numerous, with many different profiles intended to simulate many different modes and conditions of transport. Figure 2 shows typical random spectra presentations.

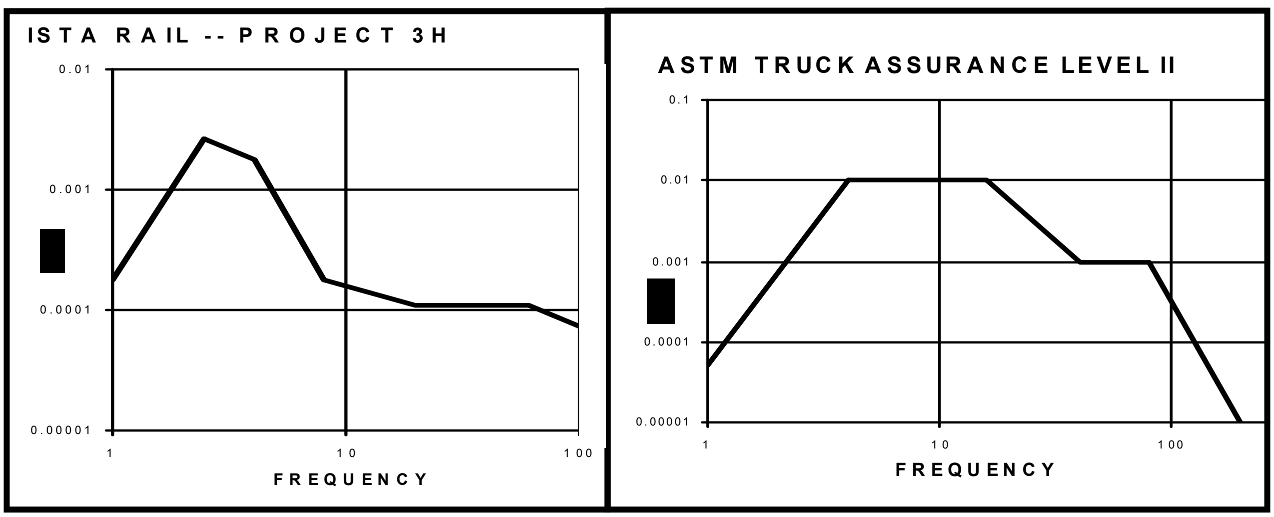

FIGURE 2: TYPICAL RANDOM SPECTRA (PSD PLOTS)

Types and Conditions of Transport

There are four basic modes of long-distance transport: road, rail, air, and ocean. But within each mode can be a number of variables – types and sub-types of vehicles; lading amount and configuration, transit conditions (highway, track, turbulence, sea state); etc. The result is an almost infinite number of possible combinations. In an attempt to condense the variables into a usable format, an ISTA technical committee has suggested (unofficially at this point) the vibration categories and sub-categories shown in Figure 3 – the idea is that there could potentially be a random vibration spectrum (PSD plot) for each bulleted item:

<table>
<tr><th>ROAD</th><th>RAIL</th></tr>
<tr><td rowspan="3">• Package Delivery Truck
Straight Truck
• Steel Springs – Light/Moderate Loading
• Steel Springs – Heavy Loading
• Air Springs – Light/Moderate Loading
• Air Springs – Heavy Loading
Trailers and Semi-Trailers
• Steel Springs – Light/Moderate Loading
• Steel Springs – Heavy Loading
• Air Springs – Light/Moderate Loading
• Air Springs – Heavy Loading</td><td>• Standard Car – Light/Moderate Loading
• Standard Car – Heavy Loading
• Hy-Cube Car – Light/Moderate Loading
• Hy-Cube Car – Heavy Loading
• TOFC – Flat Car
• TOFC – Spine Car
• COFC – Well Car
• COFC – Spine Car</td></tr>
<tr><th>OCEAN</th></tr>
<tr><td rowspan="2">• Containerized
• Non-containerized</td></tr>
<tr><th>AIR</th></tr>
<tr><td rowspan="2">• Propeller
• Jet</td><th>OTHER</th></tr>
<tr><td>• Lmtd-use vehicles– Helicopters, Oxcarts, etc.
• Lift Trucks
• Conveyors, AGV's, etc.</td></tr>
<tr><td colspan="2">Test Times, Intensities (To Account for Transit Conditions), Top Loads, etc.
Would Be Superimposed Test Conditions</td></tr>
</table>

FIGURE 3: POSSIBLE VIBRATION CATEGORIES AND SUB-CATEGORIES

That's potentially over 25 different PSD profiles, plus various test conditions! Perhaps the number will be reduced as the committee's work proceeds and more data becomes available, but this serves to illustrate the complexity of the situation.

EQUIVALENCE BETWEEN TEST "X" AND TRANSPORT "Y"

Once we are able to adequately specify the test to be conducted and the type of transport vibration to be simulated, then we can begin to address the issue of equivalence.

The Repetitive Shock ("Bounce") Test

Although in the past claims have been made about the equivalence of this test to actual transport, and in spite of the recommendations in ISO 4180/2, current wisdom holds that it does not "simulate environmental occurrences" – i.e., cannot and should not be related to specific modes of transport or transport distances. This is not to say that the tests aren't useful, only that they're intended as "Integrity" tests, not simulations.

A possible exception would be in the case of a specific product/package system and specific modes/conditions of transport where actual field performance is known. Assume that "x" minutes of a repetitive shock test were shown to consistently create the same damage or performance as "y" miles of the specific transport. This narrow equivalence could then be defended on the basis of that particular empirical evidence. But the user should be *very* cautious about extending the conclusion to any other product/package and transport situation.

Sine Tests

Sine tests are also not environmental simulations, therefore it follows that they also cannot and should not be related to specific modes of transport or transport distances. While a different conclusion could be supported, it is the author's opinion that the recommended dwell times of ASTM D4169 and ASTM D999 (5-15 minutes) are not generally intended to be related to actual transport, only to determine if an identified resonance is *critical* (could result in damage).

As with the repetitive shock test, a possible exception would be in the case of a specific product/package system and specific modes/conditions of transport where actual field performance is known. If "x" minutes of a sine dwell test were shown to consistently create the same damage or performance as "y" miles of the specific transport, the two could be deemed equivalent. But, as before, the user should be *very* cautious about extending this conclusion to any other product/package and transport situation.

Random Vibration

Random vibration tests *are* intended as environmental simulations. This is the *only* commonly-used vibration test category in the transport packaging field that can be realistically related to actual transport. Assuming that the PSD profile and intensity used is a reasonable and accurate representation of the mode and condition of transport, then one hour of the test would equal one hour of the represented transport motion. Notice that this is not a "time vs. miles" relationship, it's "time vs. time". But since transport time is the actual "in motion" duration (not the total elapsed trip time), a relationship to distance could be established. If, for example, the vehicle moved constantly at 60 miles/hour and while doing so produced the PSD profile and intensity to be used in the laboratory, then one hour of the test would be equivalent to 60 miles.

ACCELERATED VIBRATION TESTING

We're making progress: as outlined above, a properly-configured laboratory random vibration test *can* be related to actual transport. But the idea of testing for an hour to simulate only 60 miles or so isn't very appealing. This is where the concept of *accelerated* vibration testing comes in.

In a 1971 Shock & Vibration monograph, Curtis, Tinling, and Abstein of the Hughes Aircraft Company postulated a methodology for the time-compression of vibration tests[10]. In 1993, Dennis Young (now ISTA's Technical Director) referenced that in his paper "Focused

Simulation"[11], where he presented a formula for calculating the amount of acceleration increase corresponding to a test time decrease. Restated, the formula is

$$I_T = I_0 \sqrt{T_0 / T_T}$$

Where I_T = the test intensity in Grms (the overall intensity of the PSD profile)

I_0 = the original intensity (overall Grms of the original profile)

T_0 = time duration of the original profile

T_T = the test time

A time-compression ratio of not greater than 5:1 is recommended to preserve validity.[12] Based on the T_0 / T_T ratio chosen, a new test intensity is calculated from the formula. The _shape_ of the profile remains unchanged; it simply gets translated _up_ on the PSD plot to increase its intensity.

So in our "1 hour = 60 miles" example above, if we multiplied the test intensity (overall Grms) by a factor of $\sqrt{5}$, we could accelerate the test (compress the time) by a factor of 5, making it "1 hour = 300 miles".

ASTM D4169 TRUCK, ASSURANCE LEVEL II

The ASTM D4169 Truck, Assurance Level II random profile (right side of Figure 2) may be the most widely used general simulation vibration test in the world. It has been on the books for many years, has been used by hundreds of organizations to run tens of thousands of tests, and has been instrumental in solving or avoiding countless transport problems. It _works_, in many, many cases. It has an overall intensity of 0.52 Grms, and is specified to be run for a total of 180 minutes (3 hours). Can it be equated to some number of miles with a rationale that makes sense and explains its effectiveness? ASTM does not mention any sort of equivalence, and what follows is _strictly the author's experience and opinion_. But it seems to have reasonable merit, based on two key pieces of information:

1. In the last 6 years, we have participated in and been aware of the data from a considerable number of actual over-the-road truck vibration measurements. Of course there are variances in both the profile shapes and intensities, but for trailers with leaf/coil spring suspensions, the overall Grms usually falls in the range of 0.2 to 0.3 Grms, and seems to "average" around 0.25 Grms.
2. At ISTA Con 96, the keynote speaker was Donald Bowman of the American Trucking Associations.[13] During his address, he mentioned that the "average" length of long-haul truck transport in the U.S. was 750 miles. He didn't mention an "average" speed, but if it was 60 miles/hour the "average" trip length would be 12.5 hours.

If we take this information into the "accelerated vibration testing" formula from the section above, using 0.25 Grms for I_0, 12.5 hours for T_0, and 3 hours for T_T (from D4169), we get

$$I_T = 0.25\sqrt{12.5\ /\ 3} \qquad \text{or} \quad I_T = 0.51 \text{ Grms.}$$

Almost exactly the Grms of ASTM D4169 Truck, Assurance Level II! This could lead us to the conclusion that the test simulates an "average" truck trip of 12.5 hours, or about 750 miles. While this is certainly based on a number of arguable assumptions, the numbers seem reasonable and the method of arriving at them seems sound.

Some caveats: First, if this is valid at all, it likely only applies for U.S. roads and trucks. After all, "American" is in the names of both the American Trucking Associations and the American Society for Testing and Materials. Second, it focuses only on the Grms levels, and ignores the spectra shapes, which can have a great effect on test results. Although the spectrum in D4169 is roughly based on data from Forest Products Lab Report FPL-22[14], individual truck measurements never yield spectra which exactly match.

We feel comfortable in believing that ASTM D4169 Truck, Assurance Level II is a reasonable simulation of a 750 mile leaf/coil spring truck trip in the U.S. At this point we have no similar supporting rationale, however, to form opinions about the other D4169 profiles or levels.

HOW TO ACHIEVE VIBRATION TESTING EQUIVALENCE

The above discussion illustrated a "reverse" method of calculation: we started with a test, and calculated its equivalence to a transport distance. Generally one wants to create, from estimated or known transport conditions and distance, a realistic laboratory test. In this case, the steps would be as follows:

1. Select or determine PSD profile(s) and intensities which are accurate and reasonable representations of the mode(s) and condition(s) of transport to be simulated. This is not a trivial matter. Industry-standard recommendations usually represent accelerated tests, but don't give the acceleration factors. Even when working with baseline data, they should be closely examined regarding their origins and applicabilities to any given testing/simulation situation. Often the best approach is to measure (suitable transport environment measuring recorders are available[15]) a number of shipments that are directly applicable to your particular situation, then compile that data into customized PSD profiles. Also, be aware that shipments may include different road conditions or other parameters; if so, the PSDs and tests should change, to maintain the proper relationship. It's obvious that, for maximum accuracy and equivalence, the overall test must correspond to actual field conditions. If this correspondence is degraded, so will be the equivalence.

2. Estimate or determine the time of the trip (or the times of the trip segments/-conditions) to be simulated. If actual measurements have been made, this information can come directly from the data, as the total "in-motion" times. Estimate or equate these times to distances.
3. Use the "accelerated vibration testing formula" to compress the time (and distance), and calculate the increased test intensity. A time compression of not greater than 5:1 is recommended. If multiple trip segments/conditions with different parameters are to be simulated, a separate test must be configured for each.
4. The resulting test(s), at the increased test intensities and the compressed times, will be equivalent to the distances of step 2.

Example: Assume we had a PSD profile, with an overall Grms of 0.15, which was an accurate representation of a segment of a particular trip. We'd like to simulate 5 hours of that condition (which we feel would represent a distance of 250 miles) in the laboratory. Using the maximum recommended time compression of 5:1, $\sqrt{T_0 / T_T} = \sqrt{5/1} = 2.24$. Multiplying 0.15 Grms by 2.24 gives a test intensity (using the same profile shape) of 0.336 Grms. So one hour of this 0.336 Grms test would be equivalent to 250 miles of the given transport condition.

THE BEST DEMONSTRATION OF EQUIVALENCE

This was mentioned previously, but warrants a further clear explanation: the best demonstration that a laboratory test or test series is equivalent to some transport condition is *correlation of damage or performance*. If a reasonable test consistently reproduces damage or results that are similar to actual field experience, it's probably a good test – at least for those particular situations. Too many times we hear, "I don't understand it – we passed all the lab tests, but we're still having problems in the field". Then the tests are wrong! The opposite can also happen, "We don't have any damage in shipment, but we can't pass the laboratory tests". Then the tests are wrong!

The transport packaging engineers' work is not done just because the product and package have been designed and the lab testing has been completed. Field performance data should be gathered and carefully studied for proper correlation, and adjustments should be made if necessary.

FREQUENCY-DOMAIN, PSD-BASED TESTING

The random vibration approaches we've been discussing above are based on frequency-domain data analysis and test control. In other words, we analyze vibration in terms of PSD plots and use those to control our vibration test systems. This is the most widely-used approach for environmental testing of all kinds, and is almost universally employed for transport product/-package testing. It's advantages are as follows:

1. Multiple PSDs can be easily compiled to increase statistical significance. For example, a measurement from only one trip may not be representative of other trips of the same type. By making multiple measurements and compiling the results, statistical significance is increased.
2. The "accelerated test formula" may be applied to reduce test times while still maintaining validity.
3. All modern vibration controllers will accept PSD data in terms of PSD value vs. frequency "breakpoints", and will control a valid test accordingly.

There is one characteristic of PSD-based simulations which is a potential disadvantage, however. That is, since the PSD values are "average intensities" of the vibrations at each of the frequencies across the spectrum, rarely-occurring but large peak g-levels tend to be "averaged out". For example, if the measurement of a truck trip included one large "pot hole" in a long, otherwise smooth ride, the pot hole data would be averaged in with so much low-level data that it would essentially disappear. This is illustrated in Figure 4: PSDs calculated from the two time-domain waveforms might be indistinguishable, yet the bottom signal contains a huge transient.

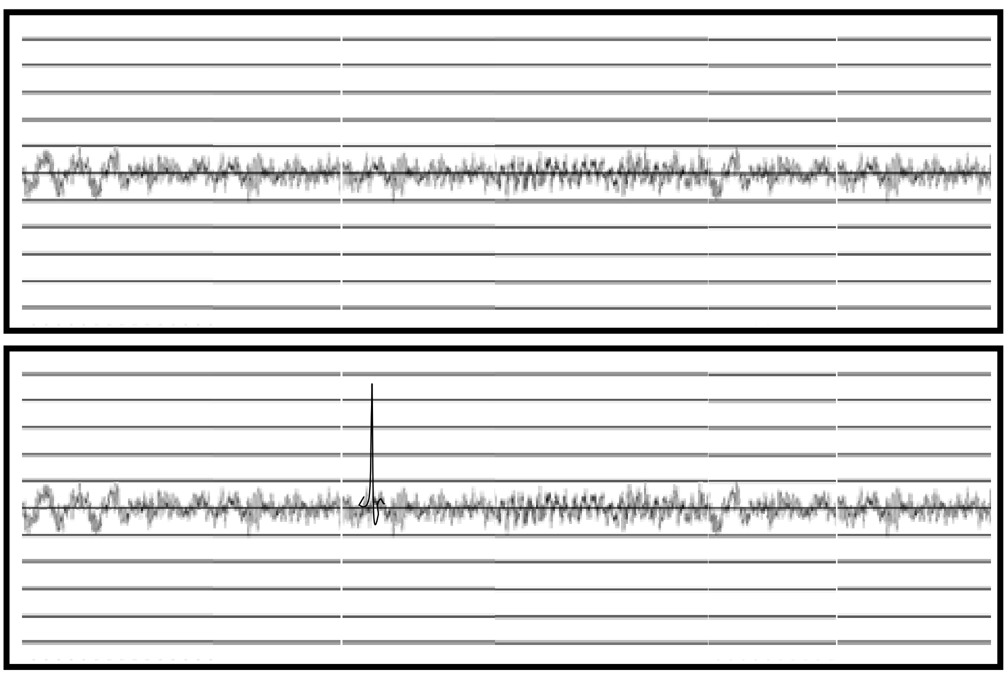

FIGURE 4: CALCULATED PSDs FROM THESE TWO WAVEFORMS WOULD BE ESSENTIALLY THE SAME

That one "pot hole" could be damaging to the lading, or set up a condition (such as mis-alignment of a pallet load) that would lead to later damage from the low-level motions. This doesn't invalidate the frequency-domain approach – PSDs represent ***vibration***, and the huge transient is a *shock*. It could be simulated with a separate drop or impact test. Still, it occurred in the vehicle and during the trip, and seemingly should be a part of the vibration test.

Sometimes there's a temptation to increase the intensity (Grms) of the controlled PSD to the point where such large g-levels occur. In some instances this can replicate the instantaneous damage or damage-potential effects, but the average vibration levels are then so high that the test becomes unrealistic.

TIME-HISTORY TESTING

There is a technique called "real-time" or "time-history reproduction" which is almost never used for transport product/package vibration testing, but which is employed extensively in the automotive (and perhaps other) industries. It's a technique which is promoted as "bringing the test track into the laboratory". Here the recorded acceleration-vs.-time data is *kept* in the time-domain and directly translated into a format which is then used to drive the vibration system. Within controller and system accuracies, every pot hole, bump, bounce, and vibration in the recorded data is reproduced exactly. While potentially a very accurate simulation of that particular trip or segment, this technique has the following drawbacks:

1. There is essentially no valid way to compile time-history data to increase statistical significance. Tests can be run *in series* (one after the other) to simulate more and more actual transit time, but this leads to extremely lengthy tests and still isn't statistically effective.
2. Tests cannot be significantly "accelerated" to compress the testing time. Of course all zero-data ("dead time") is removed, and sometimes even the lower-level data is edited out, but to our knowledge there is no consistent or meaningful rationale for doing this. The intensity of the recorded information cannot viably be increased for testing: there is no accepted protocol; if one attempts to time-compress the vibration by increasing intensity, the large transient (shock) peaks quickly become unrealistic.
3. Until recently, special vibration control hardware and software was required to accomplish time-history testing. Automotive test labs with extremely powerful and specialized computer systems would spend literally hours of computational time to derive a "drive file" representing perhaps only 20-30 minutes of a specific trip or segment. Fortunately, current vibration controller developments have removed most of these practical impediments.

A PROPOSAL

If the frequency-domain (PSD) approach is good for obtaining statistical significance and allows valid time-compression but does not adequately reproduce large transient motions, and if the time-history approach falls short in the first two categories but is good for transients, why not combine the two? We could imagine a test consisting of accelerated PSDs as described in this paper, interspersed with actual time-history reproductions of field-recorded data (rail crossings, pot holes, construction zones, curb hops, switches, bad track, rough landings, etc.). While there would still be issues to address (what *kinds* of transients, how many, what time intervals between them, etc.) , this combination approach would seem to hold promise as a realistic and equivalent, yet efficient and (with today's vibration systems and controllers) practical and attainable testing methodology.

SUMMARY, CONCLUSION

How many hours equals how many miles? The short answer is that "bounce" tests and sine sweep/dwell tests, although widely used and useful for other purposes, are not simulations of the transport environment; therefore they cannot be thought of as "equivalent" to actual shipment times or distances. Only a truly "representative" random vibration test, properly configured, can be considered in any way "equivalent". An established methodology for accelerating a random vibration test may be used to compress the test time by properly increasing the test intensity. However, even a an accelerated random vibration test may not adequately address the issue of transient shocks which occur along with the vibration. Perhaps a combination test consisting of accelerated random vibration interspersed with time-history reproductions of realistic transport shocks will provide the most complete answer.

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