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14. ABSTRACT
This TOP describes methods for evaluating the ride dynamics or ride quality and whole body vibration (WBV) of ground vehicles. Ride dynamics and WBV pertain to the sensation or feel of the passengers in the environment of a moving vehicle. The technique for evaluating the ride dynamics and WBV involves the use of instrumented seats or ride quality pads which contain accelerometers molded in a rubber disk to provide measurements in three mutually perpendicular axes. The instrumented seats are occupied by the normal vehicle crew. Ride dynamics data are acquired while the vehicle traverses various test courses at pre-determined speeds. The data are then processed by performing Fourier transformations and creating Power Spectral Density (PSD) files for the individual test runs.

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U.S. ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

*Test Operations Procedure 01-1-014B 16 November 2020
DTIC AD No.

RIDE DYNAMICS AND EVALUATION OF HUMAN EXPOSURE TO WHOLE-BODY VIBRATION

*This TOP supersedes TOP 01-1-014A, Change 1, 3 April 2012

Approved for public release; distribution unlimited.

1. SCOPE.

This Test Operations Procedure (TOP) describes methods for evaluating the ride dynamics or ride quality of ground vehicles as well as the vehicle occupants' exposure to Whole-Body Vibration (WBV). Ride dynamics pertains to the sensation or feel of the passengers in the environment of a moving vehicle. Ride quality is a measure of vehicle mobility (linking vehicle speed and terrain roughness) while WBV exposure is concerned with the adverse health effects or serious injuries that may occur as a result of vibration exposure. The technique for collecting data to be used for either ride dynamics or WBV exposure assessments is similar. The vehicle seats are instrumented with ride quality pads which contain accelerometers molded in a rubber disk to provide measurements in three mutually perpendicular axes. The instrumented seats are occupied by a vehicle crew. Data are acquired while the vehicle traverses various test courses at pre-determined speeds. The collected raw data are processed according to three analysis techniques. For the ride dynamics analysis, the data are processed by performing Fourier transformations and creating frequency weighted Power Spectral Density (PSD) files for the individual test runs. The ride dynamics analysis techniques are described in Paragraph 4. For WBV exposure analysis, the data are processed via specifications called out in International Organization for Standardization (ISO) 2631-1[1**] and ISO 2631-5[2]. The analysis technique for ISO 2631-1 is described in Paragraph 4.2 and the analysis technique for ISO 2631-5 is described in Paragraph 4.3.

2. INSTRUMENTATION.

2.1 Ride Quality Pads.

Vibration will be sensed by accelerometers mounted in ride quality pads, which will be placed in designated vehicle seats. The ride quality pads are typically fabricated in-house and contain three uniaxial piezoresistive accelerometers (vertical, transverse, and longitudinal) mounted in a rubber disk. The primary requirements of these pads are that they should not adversely affect occupant comfort and shall not significantly distort the buttock-cushion load distribution. These pads generally conform to the suggested design of Society of Automotive Engineers (SAE) J1013[3], as shown in Figure 1. The semi-rigid disk is fabricated of molded rubber of approximately 80 to 90 durometer (A Scale).

2.2 Other Measurement Locations.

Additional vibration (acceleration) measurements should be made to provide a "dynamic map" from the terrain surface to the seat (frame and floor of the vehicle are also used) for correlation with future testing that may not have seat pad instrumentation (e.g., endurance test vehicles). As a minimum, acceleration measurements should be made in the vertical axis at one unsprung mass (suspension) location near the tire or roadwheel, the sprung mass corresponding to the previous location (frame), and the base of any instrumented seat. All additional accelerometers should be direct current coupled devices.

** Superscript numbers correspond to Appendix G, References.

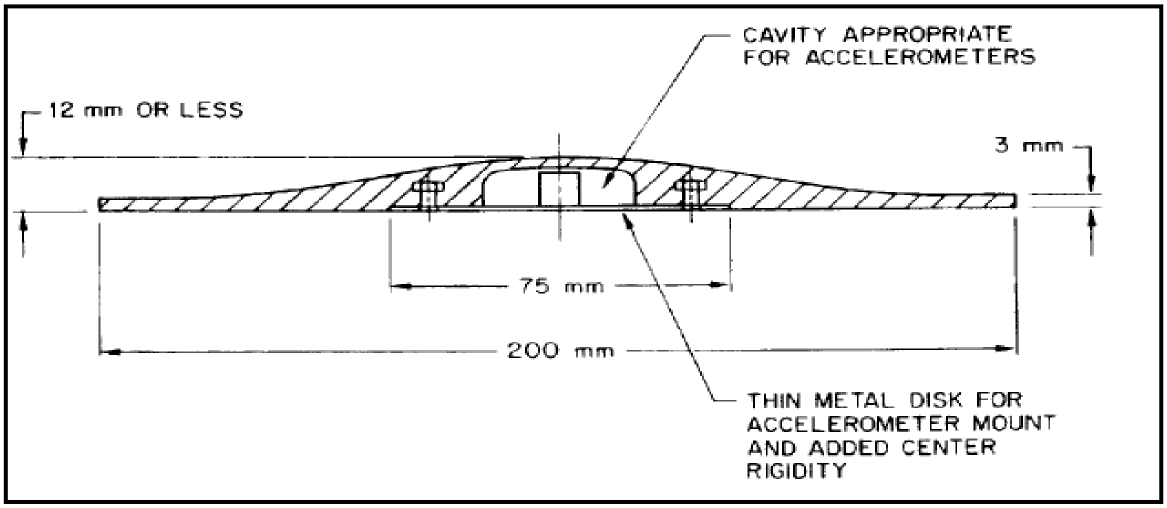

Figure 1. Suggested design for ride quality pad.

2.3 Vibration Measurement Axes.

Vibrations are to be measured utilizing the seat pad mounted accelerometers in the vertical (z axis), fore/aft (x axis), and lateral (y axis) directions. The vibration measured along these three mutually perpendicular axes pass through a point on the interface between the seated crew member and the seat. This orientation is shown in Figure 2.

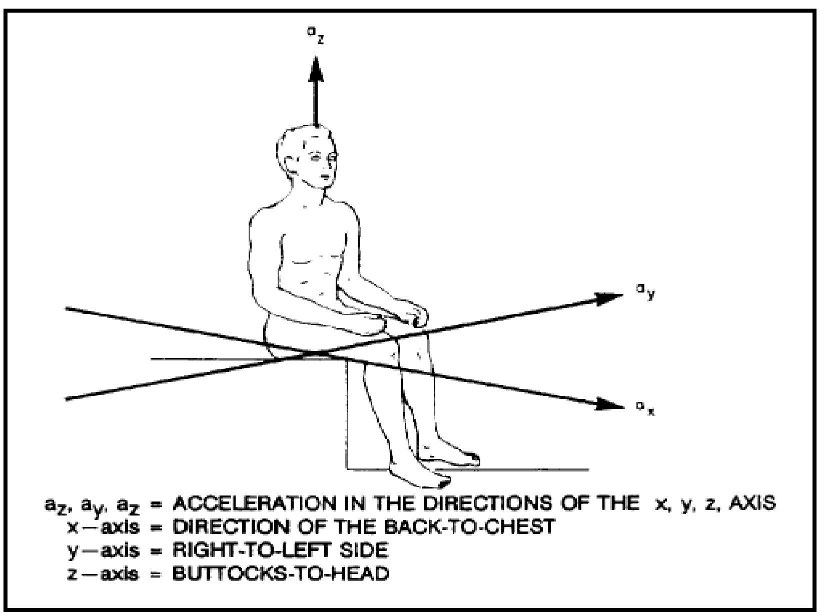

Figure 2. Measurement axes.

2.4 Test Subject Anthropometry and Seat Adjustment.

Measurements will be made at the driver's seat and at other crew positions as required by the vehicle specification and/or the detailed test plan. The gender, height, and weight of each occupant of the instrumented seats, as well as the seat location within the vehicle, will be recorded. Test subjects should preferably have a height and weight between the Army 5th percentile female and 95th percentile male, and should not be outside the height and weight range allowable within the Department of Defense (DOD) Handbook (HDBK)-743A[4], except for unique circumstances (e.g., limited personnel resources with required skill). The U.S. Army Anthropometry measurements are provided in Table 1. The seat, if adjustable, will be properly adjusted per manufacturer's specification. To date no known anthropometric manikin is known to replicate the responses produced by a human occupant. Occupants will maintain contact between the seat pad and buttocks at all times. Significant loss of contact during the test will require a retest for that condition. When loss of contact is observed during a run it should be noted in field notes and reporting. Other (non-instrumented) seats will be filled with a dummy load to simulate the weight of a crew member.

TABLE 1. U.S. ARMY ANTHROPOMETRY

CATEGORY	HEIGHT		WEIGHT	
	centimeter (cm)	inches (in.)	kilogram (kg)	pound (lb)
Male - Max	203	80	113[a]	250[a]
Female - Min	147	58	41	91
Male – 95%	187	73.5	98	216
Female – 5%	153	60.2	49	109

[a] Age dependent - max age (40+) shown

2.5 Accelerometers and Signal Conditioning.

The pad and ancillary accelerometers together with their associated signal conditioning shall be capable of measuring signals in the 0.1 to 100 Hertz (Hz) bandwidth. An on-board or telemetry data acquisition system will be used to acquire data while the vehicle is operated on the test courses. All data will be digitized at a minimum of 400 samples per second per channel after having been low-pass filtered at a minimum of 100 Hz. Ensure anti-aliasing low pass filters are adequate to prevent aliasing of the data. If a half-round obstacle requirement must be met, a vertical accelerometer will be installed at the base of the driver's seat to comply with historical data. Other locations (e.g., on the seat) may be instrumented as required by the vehicle specification and/or the detailed test plan. This (half-round obstacle) accelerometer will be low-pass filtered (posttest) at 30 Hz (Paragraph 4.4). Amplifiers should be adjusted to provide an acceleration resolution better than 0.01 g. Analysis parameters should be chosen so that frequency domain resolution is 0.25 Hz or less.

2.6 Acceleration Units.

Acceleration units for analysis will be meters/sec^2 for ISO-2631-1/ISO 2631-5 computations, ft/sec^2 for absorbed power computations and "g" for other acceleration computations.

2.7 Data Validation.

Prior to analysis, data from each transducer and each data run will be checked for stationarity and for errors such as noise, amplifier drift, clipped data, etc. Procedures used for data validation will be presented in the test report.

2.8 Length of Data Run.

The precision of acceleration spectral estimates is related to the length of the data run. Data should generally be recorded for a period of at least one minute unless restricted by test course length and vehicle speed.

2.9 Vehicle.

The test vehicle will be described by recording the information in Appendix A.

2.10 Vehicle Speed.

Vehicle speed will be recorded by an auxiliary, calibrated speed sensing system to an accuracy of ± 0.2 kilometers per hour (km/hr) (0.1 miles per hour (mph)). The test speed will be held constant (to the extent possible) at the target speed for the duration of the data run. The speed Coefficient of Variation (COV (standard deviation/mean)) for each data run used in the analysis should be equal to or less than 0.10.

2.11 Test Courses for Ride Quality.

Test courses used for ride quality should be characterized in terms of wave number spectrum (power spectral density function of the instantaneous terrain vertical profile in the spatial domain). In the past ride quality courses were considered to have a slope of approximately -2 in the log-log domain, though this was an anecdotal reference and not a requirement. Historically slopes have tended to be between -2 and -4, with broadband content deviating from an ideal representation. The rms roughness value will be computed as the square root of the integral of the wave number spectrum and will be computed between wave numbers that cover the frequency range of interest (typically 0.5 to 80 Hz). The bounds of integration should be reported with the results data (typically wavelengths of 0.5 feet to 36.6 feet or 64 feet). Refer to Appendix E for more detailed information on ride quality course characterization. Efforts should be made to characterize the content of the courses used in the test, relating actual responses to responses from a course with an idealized wave number spectrum.

2.12 Test Courses, Speeds, and Accelerometer Locations for WBV Analysis.

Data must be collected in a manner that is representative of the mission profile of the vehicle and is typical of the expected exposures. Duration of measurements shall be sufficient to ensure statistical precision. Whole-body vibration data must be collected in accordance with ISO 2631-1 and ISO 2631-5. Refer to ISO 2631-1 and ISO 2631-5 for complete data collection guideline details. In order to properly assess health effects from exposure to WBV, the vehicle should be tested under its normal operating conditions. Vibration data will be recorded on test courses with vehicle speeds and vehicle maneuvering scenarios analogous to the Operational Mode Summary/Mission Profile (OMS/MP). For example, if the vehicle's OMS/MP states the vehicle will operate on primary, secondary, and cross country terrain, then vibration data must be collected on test courses that represent each of the three terrains. If the vehicle's mission profile calls for speeds on primary terrain up to 50 mph, then the vehicle should be tested at increments of 10 mph up to 50 mph on primary terrain. Coordination with the vehicle's program office to determine test courses and speeds that best represent the vehicles normal operating conditions is recommended. If program office guidance is not forthcoming, Table B-1 in Appendix B contains the minimum requirements for speed and course terrains the vehicle needs to traverse to complete the WBV data set. Seat pad accelerometers are to be located at seats that will represent all troops' WBV exposure. Seat design, location of the seat within the vehicle, and how the seat is mounted should be considered when determining accelerometer placement.

2.13 WBV Analysis of Operational Mode.

Vehicles that produce WBV in environments other than traversing terrain are to be tested under conditions that replicate the operational environment in which the WBV is produced. For example, backhoes with breaker attachments generate large amounts of vibration while the vehicle is stationary. A proper assessment will include WBV data collected while the backhoe's breaker is in operation. Table B-2 in Appendix B provides general examples of Operational Mode Analysis.

2.14 Test Conduct.

a. Acceleration and speed data will be acquired as the vehicle is driven over each test course at multiple constant speeds as described in the test plan for a period of at least 1 minute (when not limited by test course length) for the ride dynamics courses, and for a sufficient period of time to capture the shock event when negotiating the half-round obstacles. A speed increment of approximately 3 km/hr (2 mph) should be used because vertical absorbed power generally increases as a power law function of speed for a given rms roughness (e.g., Absorbed Power ~ $k*Speed^b$). Following each data run, the crew will be polled to ensure that it is safe to proceed to the next speed. Each instrumented crew member's seat vertical acceleration data will be processed at the test site after each data run to provide an absorbed power value. The test on each course will be considered as completed when the driver's vertical absorbed power equals or exceeds 15 watts, when any crew member believes that an increase in speed would create a hazardous condition, or when the course speed limit is reached (applicable only to relatively smooth courses). The limit value of 15 watts was chosen to satisfy the requirements of at least one Army vehicle (a ride specification based on "9 to 12 watts") and to enhance the ride-speed distribution for the health hazard assessment (Paragraph 5). Data runs that produced absorbed power values from above 1 watt to the maximum speed run will be repeated to enhance data confidence.

b. To evaluate the shock input test criteria, the half-round obstacles should be traversed with either wheel or track paths crossing the obstacle simultaneously. To evaluate vehicle roll dynamics and suspension characteristics, additional data runs can be performed with a single wheel or track path crossing the obstacle while the other wheel or track path remains on level ground.

3. VIBRATION EVALUATION.

a. Vibration evaluation will be performed using two techniques; an ISO technique which addresses health effects of exposure to vibration, and an absorbed power technique which is used to describe speed limiting effects over rough terrain.

b. The principal factors that combine to determine the degree to which human exposure to whole body vibration will be acceptable is described in ISO 2631-1. Four possible effects of vibration include Degraded Health, Comfort, Perception and Motion Sickness. The frequency ranges of these effects are:

(1) 0.5 Hz to 80 Hz for Degraded Health, Comfort and Perception.

(2) 0.1 Hz to 0.5 Hz for Motion Sickness.

c. Unless required by the test plan, only the issue of degraded health will be evaluated. This type of vibration is transmitted to the human body as a whole through the supporting surfaces of the buttocks, back, and feet of a seated person in a moving wheeled or tracked vehicle. Vibration is measured according to the coordinate system originating at a point from which vibration enters the human body. The coordinate system for the alignment of the vibration transducers is shown in Figure 2. The three principal areas of contact for seated persons are: (1) the supporting seat pan, (2) the seat back, and (3) the feet, but only the seat pan data are of interest for degraded health analysis.. Seat data are also the basis for the absorbed power analysis. Vibration transmitted to the body through a non-rigid material, like a seat cushion, is measured with the transducer interposed between the person and the principal contact areas of the surface. This is achieved by mounting the transducers within a ride quality pad as described in Figure 1.

4. ANALYSIS TECHNIQUES.

4.1 Absorbed Power Technique.

a. Absorbed power is a measure of the rate at which energy is absorbed by a human subjected to ride vibration developed by Pradko and Lee[5,6] in the 1960's. It is accepted as a measure of human tolerance to vibration for military vehicles negotiating rough terrain. The absorbed power for a given location and axis is computed by multiplying the acceleration power spectral density spectrum by the appropriate transfer function and integrating the resultant spectrum. An advantage of this approach is that average absorbed power is a scalar quantity and can be summed in complex multi-degree of freedom systems to yield a single value describing the total average absorbed power. Typically a standard ride quality test procedure involves determining the speed at which the vertical average absorbed power reaches an upper limit of 6 watts for different types of terrain at selected crew location seats. The terrain is usually characterized by the surface roughness reported as inches or centimeters rms. The vehicle speed as a function of terrain roughness obtained from this process is used as one of the mobility limiting factors in the North Atlantic Treaty Organization (NATO) Reference Mobility Model. Military vehicle specifications frequently include ride quality requirements based on absorbed power (e.g., the vehicle must be capable of producing a ride of 6 watts or less at the driver's seat in the vertical axis for a given speed and surface roughness).

b. Pradko and Lee[5,6] developed the constants and equations below by exposing seated subjects to different magnitudes of input at different frequencies and assessing their levels of tolerability. The absorbed power in each axis is calculated from:

$$P = \sum_{i=1}^{n} (C_i) A_i^2 \qquad \textit{(Equation 1)}$$

where:

P = Absorbed power, watts.

A_i = rms acceleration in ft/sec^2 within the ith spectral band.

$C_i = K_1 K_0 (F_1 F_4 - F_2 F_3) / (F_3^2 + W_i^2 F_4^2)$.

Wi = Frequency, radians/second.

F and K values = Calculated from Appendix C.

c. The result is a frequency weighting, scaling and integration of the acceleration power spectral density. The weighting functions are shown (by axis) in Figure 3. The factors have been normalized to a value of 1.0 to show frequency without the appropriate scaling.

d. For each test course, the absorbed power will be plotted as a function of speed. Specification requirements are generally written in terms of the driver's vertical absorbed power (only), but the following technique will be applied to other locations and axes, if applicable. A non-linear interpolation or a power law ($y = ax^b$, linear fit in a log-log domain,) or nth degree polynomial curve fit will be performed and the speed at which an absorbed power of 6 watts is achieved, will be interpolated from the data set. Absorbed power values of less than 1 watt or greater than 10 watts will not be used in the curve fit process, if possible. The 6-watt speed will then be plotted as a function of terrain roughness rms (a specific value for each test course) to determine a ride quality curve for the vehicle.

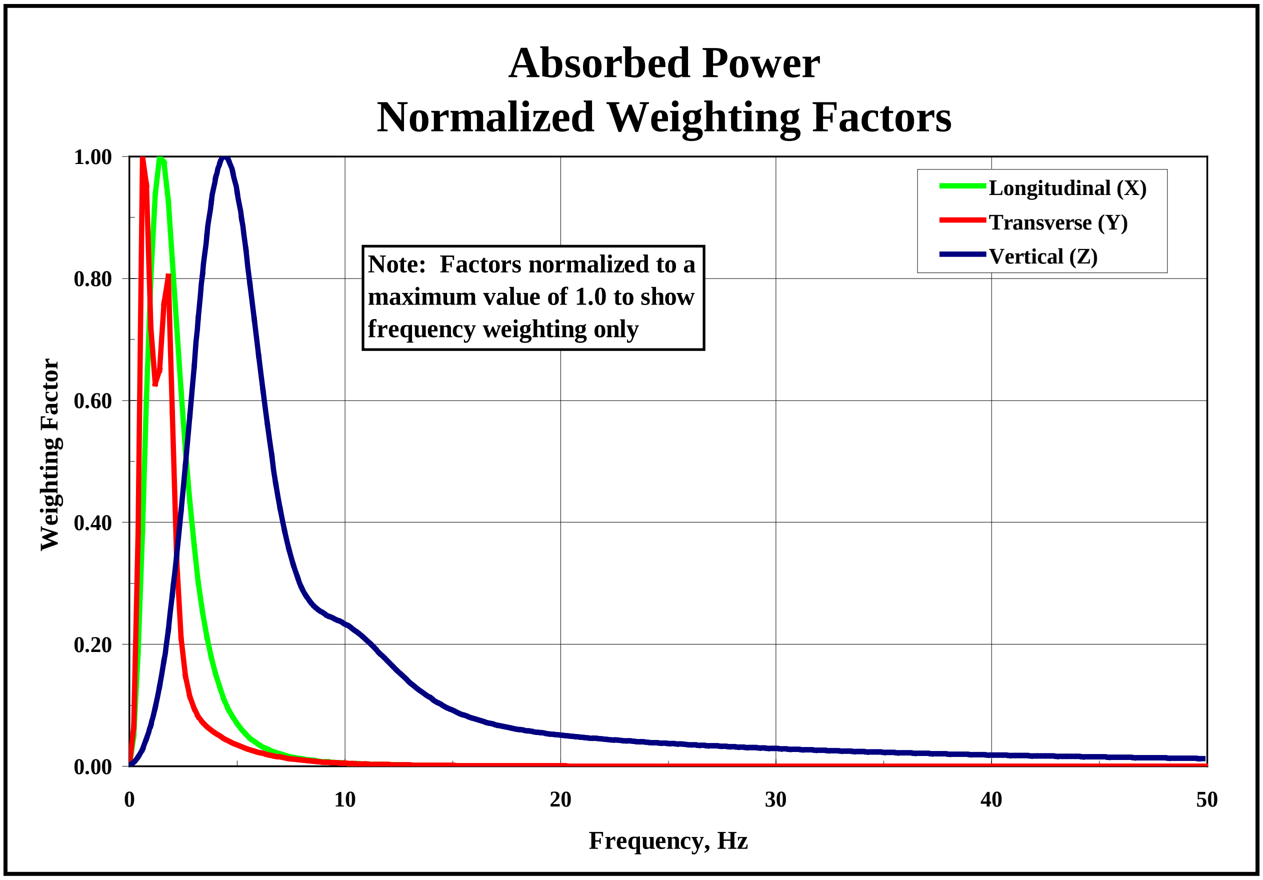

Figure 3. Absorbed power normalized frequency weighting factors.

4.2 <u>ISO 2631-1 Technique</u>.

a. The basic evaluation method described in ISO 2631-1 utilizes the weighted rms acceleration. The weighted rms acceleration is expressed in meters per second squared (m/s^2) for translational vibration and radians per second squared (rad/s^2) for rotational vibration. The weighted rms acceleration is calculated in accordance with the following equation or its equivalent in the frequency domain:

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)\,dt \right]^{1/2} \quad \textit{(Equation 2)}$$

where:

$a_w(t)$ is the weighted acceleration (translational or rotational) as a function of time (time history), in m/s^2 or rad/s^2, respectively.

T is the duration of the measurement, in seconds.

b. The crest factor may be used to investigate whether or not the basic evaluation method is suitable for describing the severity of the vibration in relation to its effects on human beings. The peak value is determined over the duration of the measurement, i.e. the time period *T* used for integration of the rms value. The crest factor does not necessarily indicate the severity of vibration. The basic evaluation method outlined above is normally sufficient for crest factors below or equal to 9. In cases where the basic evaluation method may underestimate the effects of vibration (high crest factors, occasional shocks, and transient vibration) an alternative technique should be utilized such as the running rms method or the fourth power vibration dose method.

c. The running rms method evaluation method takes into account occasional shocks and transient vibration by use of a short integration time constant, for example 1 second. The vibration magnitude is defined as a Maximum Transient Vibration Value (MTVV), given as the maximum in time of $a_w(t_o)$, defined by:

$$a_w(t_0) = \left\{ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} [a_w(t)]^2 \, dt \right\}^{1/2} \qquad \textit{(Equation 3)}$$

where:

$a_w(t)$ is the instantaneous frequency-weighted acceleration.

τ is the integration time for running averaging.

t is the time (integration variable).

t_o is the time observation (instantaneous time).

d. The fourth power vibration dose method is more sensitive than the basic evaluation method by using the fourth power instead of the second power of the acceleration time history as the basis for averaging. The fourth power Vibration Dose Value (VDV) in meters per second to the power 1.75 ($m/s^{1.75}$), or in radians per second to the power 1.75 ($rad/s^{1.75}$), is defined as:

$$VDV = \left\{ \int_0^T [a_w(t)]^4 \, dt \right\}^{1/4} \qquad \textit{(Equation 4)}$$

where:

$a_w(t)$ is the instantaneous frequency-weighted acceleration.

T is the duration of measurement.

(1) The total VDV (VDV_{total}) from separate events can be calculated with the 4-th root of the sum of the VDV_i of the individual events taken to the fourth power, or expressed as:

$$VDV_{total} = \left\{ \sum_i VDV_i^4 \right\}^{1/4} \qquad \textit{(Equation 5)}$$

(2) The total VDV from a repeating specific condition can be estimated by using an individual VDV_i value multiple times in the above expression. For example, the total VDV value from N impacts on a half round at a specific speed can be estimated with the following expression:

$$VDV_{total} = \left\{ N \cdot VDV_i^4 \right\}^{1/4} \qquad \textit{(Equation 6)}$$

where:

VDV_i is the VDV from a single impact at a particular speed.

VDV_{total} is the total VDV which is being calculated.

N is the number of impacts for which the total VDV is being calculated.

e. The frequency weighting curves used for various directions of measurement in the calculation of frequency-weighted acceleration for the seat surface as outlined in ISO 2631-1 are provided in Appendix D and Figure 4.

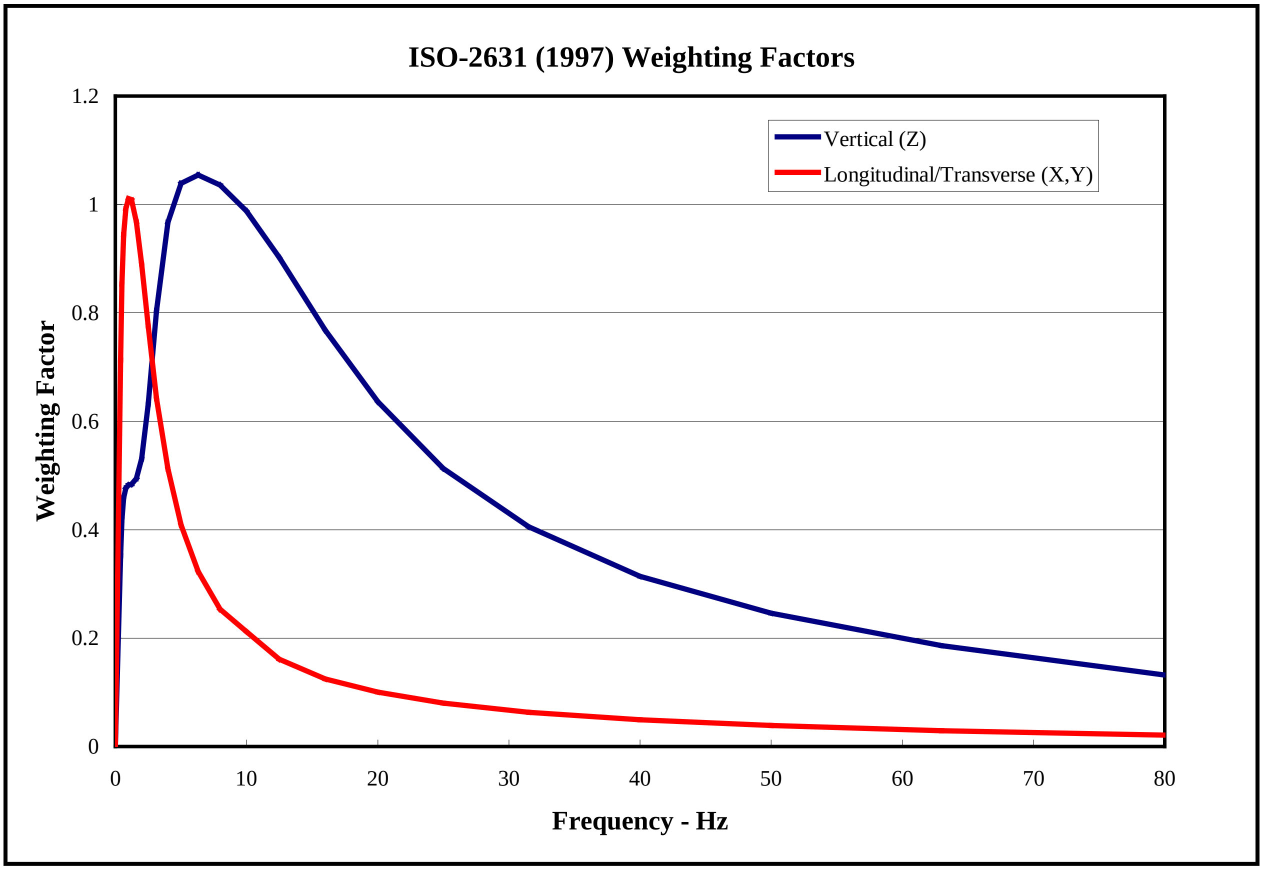

Figure 4. ISO 2631-1 frequency weighting factors.

f. Daily vibration exposure limits are determined from the weighted acceleration, a_w, in each axis. The assessment is made independently for each axis, but the vector sum is used if the weighted accelerations from two or more axes are comparable. The evaluation is made using the frequency weighting factors shown in Appendix D with the multiplying factors as shown in Table 2.

TABLE 2. MULTIPLYING FACTORS

AXIS	FACTOR
X,Y	1.4
Z	1.0

g. Exposure times for three conditions – no documented health risks, caution zone for health risks, and health risks likely are calculated from the weighted acceleration as follows:

(1) No documented health risks: Exposure time = $1.5/a_w^2$.

(2) Caution zone for health risks: Exposure time > $1.5/a_w^2$ and < $6.0/a_w^2$.

(3) Health risks likely: Exposure time = $6.0/a_w^2$.

(4) For example: let $a_w = 2.0$ m/s^2.

(a) Exposure time = 0.4 hours for no documented health risks.

(b) Exposure time = 0.4 to 1.5 hours for a health risk caution.

(c) Exposure time = 1.5 hours for a likely health risk.

(d) Thus, an exposure (per 24 hours) to this level of vibration for less than 0.4 hours should produce no health risks, an exposure between 0.4 hours and 1.5 hours will result in a health risk caution, while an exposure of 1.5 hours or greater will create a likely health risk.

h. The health guidance caution zone is shown in Figure 5.

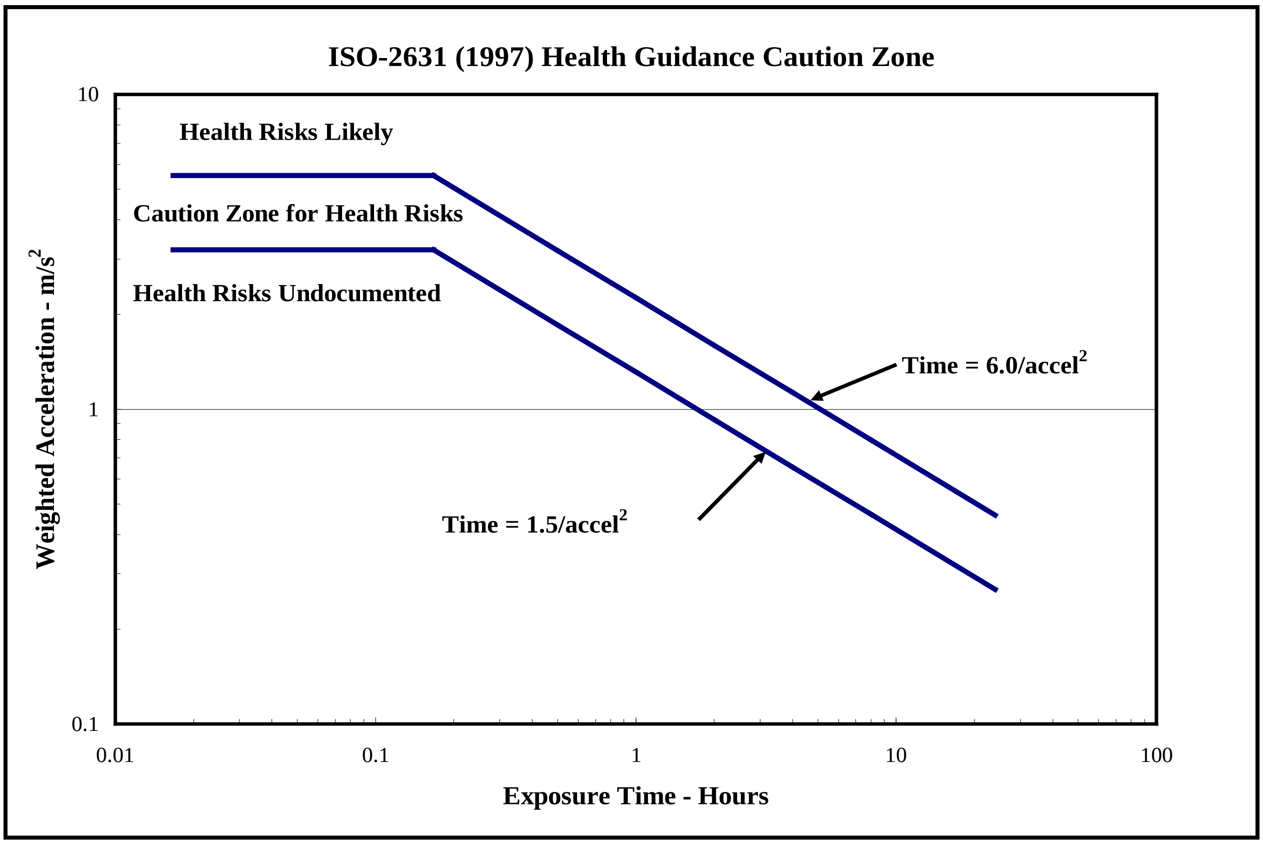

Figure 5. Health guidance caution zone.

4.3 ISO 2631-5 Multiple Shock Method.

a. The methods conveyed in ISO 2631-5 are an attempt to quantify whole-body vibration containing multiple shocks in relation to human health. The assessment methods described in ISO 2631-5 presume an individual is in good physical condition and is maintaining a seated posture. Specifically these methods are meant to focus on the lumbar spine. Different postures will result in different responses in the spine. The methods attempt to create predictions about the number of years for which an individual can be subjected to a sample time history prior to the onset of adverse health effects. However it must be recognized that these assessment methods and related models have not been epidemiologically validated.

b. Two separate approaches are presented in ISO 2631-5, with the method for more severe conditions described below. The approach for the more severe conditions is more appropriate for military vehicle environments, allowing for possible moments of "free fall" of the seat. This method involves the calculation of a spinal dose through the following steps: using seat pad accelerations to estimate the response in the spine, $Az(t)$, identifying the peaks in the spinal response, applying a dose model and assessing severity with a biomechanical model related to experimental data related to the Palmgren-Miner fatigue theory. The spinal response in the vertical axis is approximated with the filter described in Appendix D, Equation D-1 and Table D-2. The data collected for this analysis should be re-sampled to 256 Hz because the coefficients used for the vertical model are specific to that sample rate

c. The acceleration dose, D_z, in meters per second squared in the z-direction is defined as:

$$D_z = 1.07\left(\sum_i A_{z,i}^6\right)^{1/6} \qquad \textit{(Equation 7)}$$

where:

$A_{z,i}$ is the i^{th} peak of the response acceleration $A_z(t)$.

d. The average daily dose from one or more conditions, D_{zd}, in meters per second squared, can be computed with the following:

$$D_{zd} = \left(\sum_j D_{z,j}^6 \frac{t_{d,j}}{t_{m,j}}\right)^{1/6} \qquad \textit{(Equation 8)}$$

where:

$D_{z,j}$ is the acceleration dose for condition j.

$t_{d,j}$ is the duration of the daily exposure to condition j.

$t_{m,j}$ is the period over which $D_{z,j}$ was measured.

e. As stated, the ISO 2631-5 method is partly based on experimental data which shows a linear relationship between compressive stress due to input shocks and peak acceleration response in the spine. A different conversion factor is provided for men and women related to anticipated endplate area of the vertebral body. The daily equivalent static compression dose, S_d, in megapascals is obtained from D_{zd}:

$$S_d = m_z D_{zd} \qquad \textit{(Equation 9)}$$

where:

m_z = 0.029 MPa/(m/s^2) for a young man weighing 82 kg with 49% of his weight above the pelvis and an endplate area of 14 cm^2.

m_z = 0.025 MPa/(m/s^2) for a young woman weighing 64 kg with 45% of her weight above the pelvis and an endplate area of 11.6 cm^2.

f. A factor R is defined to account for the repeated exposure to the same environment for a number of years. The method attempts to take into account the differences in initial tissue strength related to the age of the seat occupant. As the exposure time increases the muscle tissue reduces in strength. For this reason R must be calculated sequentially:

$$R = \left[\sum_{i=0}^{n-1} \left(\frac{S_{d,i} N_i^{1/6}}{S_{u,i} - S_{stat,i}}\right)^6\right]^{1/6} \qquad \textit{(Equation 10)}$$

where:

N is the number of exposure days per year.

i is the incremented year count from the beginning of exposure.

n is the number of years of exposure.

$S_{d,i}$ is the daily compression dose related to year i.

$S_{stat,i}$ is a constant representing the static stress due to gravitational force which depends on the body mass and cross sectional area in the vertebrae in year i. $S_{stat} = 9.81 m_z$

$S_{u,i}$ is the ultimate strength of the lumbar spine for a person of age ($b+i$) years.

g. The value $S_{u,i}$ is intended to account for the variation in vertebrae bone density, which normally reduces with age. In-vitro studies were used to derive the relationship between $S_{u,i}$ (in megapascals) and $b+i$ (years):

$$S_{u,i} = 6.75 - S_{age}(b+i) \qquad \textit{(Equation 11)}$$

where:

b is the age at which the exposure starts.

S_{age} accounts for reductions in vertebrae strength with age, with S_{age} = 0.052 MPa for men and S_{age} = 0.039 MPa for women.

h. The method then details how to calculate the probability of injury for a given exposure, R, over n years by presuming a Weibull survival model:

$$\Pi = 1 - exp\left[-\left(\frac{R}{\alpha}\right)^{\beta}\right] \qquad \textit{(Equation 12)}$$

where α and β are gender dependent coefficients given in Table 3, and Π ranges from 0 to 1 (0% to 100% risk of injury).

TABLE 3. PARAMETERS FOR CALCULATING RISK OF INJURY

GENDER	PARAMETERS (lower 95%, upper 95% confidence intervals)	
	α	β
Male	1.613 (1.460, 1.809)	2.799 (2.168, 3.511)
Female	0.959 (0.854, 1.093)	3.709 (2.509, 5.207)

i. The example given in the standard is of an occupant exposed to a high-impact environment for 120 days/year for 20 years, starting at age b = 20 to age 40 (b + n), during which there are 40 m/s^2 accelerations each day, producing a compressive stress S_d of 1.623 MPa. For an 82 kg male, this leads to a value R = 1.22. Therefore the probability of injury, from Equation 12, is 37%, which the standard describes as “moderate”. The same exposure for a 64 kg female gives an S_d value 1.40 MPa and R = 0.97, resulting in a probability of injury of 91%, which the standard describes as “high”.

j. Often the number years of anticipated exposure is not known. Exposure will change for an individual when that person is transferred or promoted away from an environment. Therefore it may be more informative to use software to iteratively back calculate the acceptable number of years of exposure to a given environment to achieve different probabilities of injury. The ISO 2631-5 standard identifies the 10%, 50%, and 90% probabilities of injury for a given R value for both males and females, given in Table 4. For an enlisted soldier, an average starting age of 20 years can be a good presumption.

TABLE 4. *R* VALUES FOR DIFFERENT RISKS OF INJURY

GENDER	R VALUE (lower 95%, upper 95% of confidence intervals)		
	RISK OF INJURY		
	10%	50%	90%
Male	0.72 (0.58, 0.89)	1.42 (1.27, 1.57)	2.17 (1.91, 2.48)
Female	0.52 (0.41, 0.67)	0.87 (0.77, 0.98)	1.20 (1.04, 1.38)

4.4 Half-Round Obstacle Technique.

The peak acceleration from the vertical accelerometer at the base of the driver's seat will be low-pass filtered at 30 Hz (4-pole Butterworth filter forward and backward to preserve phase) and the resulting peak acceleration will be plotted as a function of speed for each half-round obstacle. The speed at which a peak value of 2.5 g's is reached will be determined by a non-linear interpolation or curve fitting technique as described above.

5. HEALTH HAZARD ASSESSMENT.

a. Often health hazard assessments are performed by organizations such as the U.S. Army Public Health Center, which will require transferring of files for their analysis. It is recommended that vibration data files be transferred in a commonly readable format.

b. The health hazard assessment is based on the vehicle's mission profile, which is reflected in the test course mileage breakdown of the endurance test. The same ride data previously described will be collected on the endurance test courses following the guidelines of Paragraph 2.11. To improve test efficiency, data from remote test courses need not be acquired if the ride is judged to be similar to that of convenient test courses (e.g., data from Aberdeen Test Center Munson Gravel course can be used as a replacement for the Churchville "C" course).

c. Because health hazard is dependent on both exposure magnitudes and duration, and the magnitudes are dependent on speeds, the distribution of speeds on a terrain type must be taken into account. An exposure time for each test speed (by test course) will be determined from a measured probability distribution function of a recent endurance test of a similar vehicle or will be computed using the assumption of a beta distribution. The beta distribution is defined as:

Probability Density Function

$$f(X) = \frac{X^{\alpha-1}(1-X)^{\beta-1}}{B[\alpha,\beta]}$$

where $B[\alpha,\beta]$ is the beta function with parameters α and β, given by *(Equation 13)*

$$B[\alpha,\beta] = \int_0^1 X^{\alpha-1}(1-X)^{\beta-1}\,dX$$

d. The parameter alpha is based on the ratio of the average speed to the maximum speed and is selected from Table 5. The parameter beta is calculated using an optimization routine such that the resultant average speed equals the desired average speed. An example using a minimum speed of 10 km/hr (6 mph), an average speed of 23 km/hr (14 mph), and a maximum speed of 32 km/hr (20 mph) is shown in Figure 6.

TABLE 5. VALUES OF ALPHA

RATIO OF AVERAGE TO MAXIMUM SPEED	ALPHA
10%	0.2
20%	0.5
30%	0.75
40%	1.25
50%	2
60%	3
70%	4
80%	6
90%	13

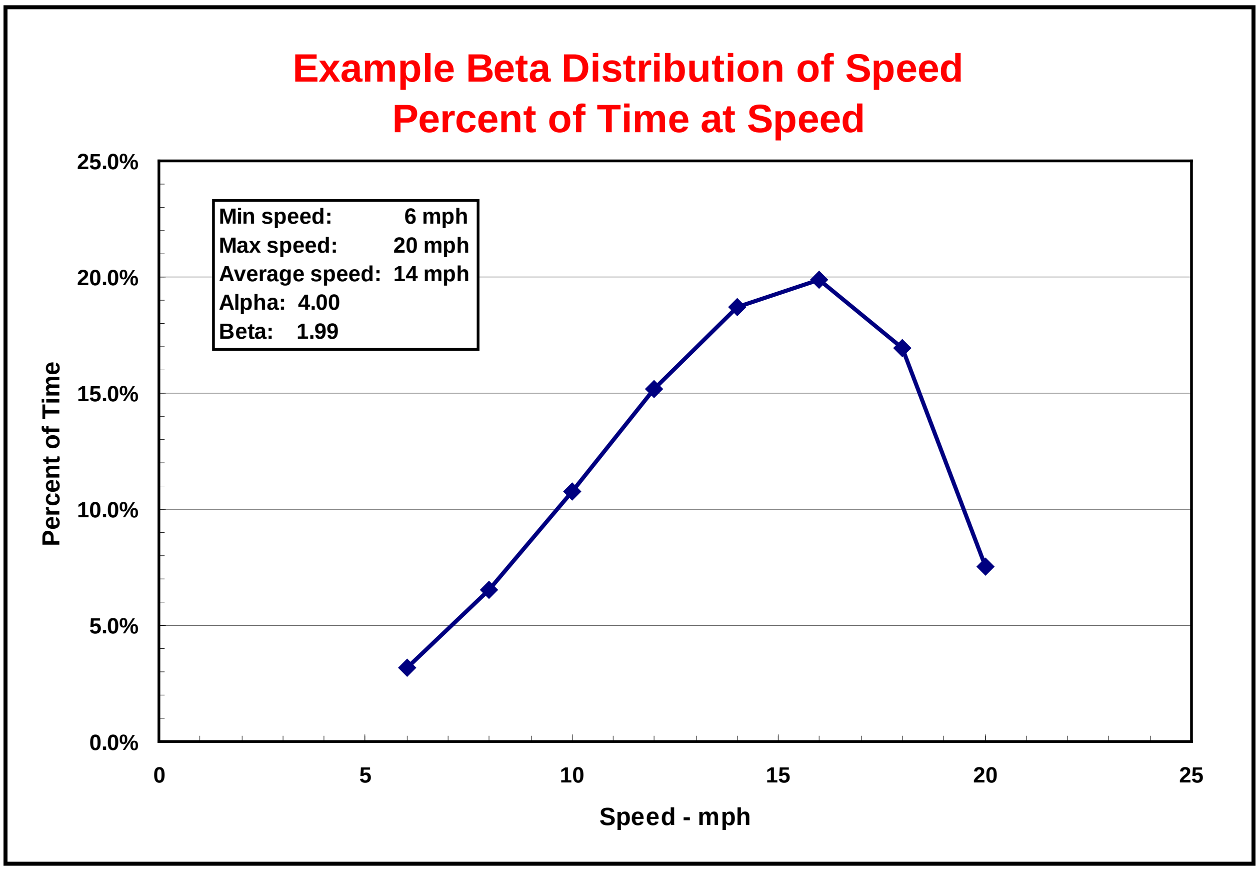

Figure 6. Example beta distribution.

e. The exposure times for each test speed are combined with the corresponding ride level to compute an overall weighted acceleration using (Equation B3 from ISO 2631-1):

$$a_{ws} = \left[\frac{\sum a_{wi}^{\ 2} * T_i}{\sum T_i} \right]^{1/2} \qquad \textit{(Equation 14)}$$

where:

a_{ws} = equivalent vibration magnitude (rms acceleration in m/s^2).

a_{wi} = vibration magnitude (rms acceleration in m/s^2) for exposure duration T_i.

T_i = exposure duration, minutes.

f. The overall weighted acceleration can be used to provide a health hazard assessment by terrain type (primary, secondary, off-road).

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APPENDIX A. VEHICLE INFORMATION.

Vehicle Model: ______________________

Year of Manufacture/Delivery: ______________________

Serial Number: ______________________

Odometer Reading: ______________________

Engine Hours: ______________________

Type Test Load: ______________________

Vehicle Weight as Tested:
  Total: ______________________
  Front Axle: ______________________
  Intermediate Axle: ______________________
  Rear Axle: ______________________

Tire Information:
  Front:
    Manufacturer: ______________________
    Size: ______________________
    Type: ______________________
    Pressure: ______________________
  Rear:
    Manufacturer: ______________________
    Size: ______________________
    Type: ______________________
    Pressure: ______________________

Seat Description:
  Driver: ______________________
  Passenger: ______________________

Seat Setting:
  Driver: ______________________
  Passenger: ______________________

Condition of the Vehicle:
  General Comments:

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APPENDIX B. WBV TEST COURSES AND OPERATIONAL MODE EXAMPLES.

TABLE B-1. TEST COURSES AND SPEEDS FOR WBV ANALYSIS.

TERRAIN TYPE	COURSE	APPROXIMATE ROUGHNESS (in rms)	TOP SPEED (mph)	SPEED INCREMENT[a] (mph)
Primary	Perryman Paved	0.07	50	10
Secondary	Perryman 1	0.3	35	5
Secondary	Perryman A	0.3	35	5
Cross Country	Perryman 2	0.8	25	5
Cross Country	Perryman 3	2.75	20	5

[a] Test Engineer's discretion.

TABLE B-2. EXAMPLES OF WBV ANALYSIS FOR OPERATIONAL MODE.

VEHICLE TYPE	VEHICLE CAPABILITIES	DATA NEEDS	REASONING
High Mobility Engineer Excavator	Earthmoving machine. Performs backhoe, loader, and bull dozing operations.	Collect data while vehicle is performing bull dozing and backhoe operations.	Multiple shock forces from buckets engaging in operations can transfer to seat.
XM1157 10-ton Dump Truck	Transport and spread up to 20,000 pounds of aggregate.	Collect test course and speed data while vehicle is loaded and unloaded.	Weight of aggregate will affect WBV exposure due to added weight on suspension system of vehicle.
Airborne Scraper and Water Distribution System (ASWDS)	ASWDS performs earthmoving road construction and water distribution functions.	Collect movement data while simulating scraping operations, unloaded and loaded water operations.	Scraping operations will impart significantly more WBV into vehicle cab than the water distribution.
Bituminous Material Paving Machine	Performs paving operations.	Simulating paving operations by loading hopper and activating extended screed.	Added load and extended screed may shift center of gravity, resulting in different WBV exposure.

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APPENDIX C. ABSORBED POWER CONSTANTS.

$$P = \sum_{i=1}^{n} (C_i) A_i^2 \qquad \textit{(Equation C-1)}$$

where:

P = Absorbed power, watts.

A_i = rms acceleration in ft/sec^2 within the ith spectral band.

$C_i = K_1K_0(F_1F_4 - F_2F_3) / (F_3^2 + W_i^2F_4^2)$.

Wi = Frequency, radians/second.

<u>Longitudinal (X)</u>

K_0	4.3532
K_1	1.356
W_i	$2\pi f_i$
F_1	1.0
F_2	0.219106
F_3	$-0.0185309W_i^2 + 1$
F_4	$-0.00061893W_i^2 + 0.219106$

Note: f_i = Center frequency (Hz) of ith spectral band.

APPENDIX C. ABSORBED POWER CONSTANTS.

Transverse (Y)

K_0	4.353
K_1	1.356
W_i	$2\pi f_i$
F_1	$0.24052124 \times 10^{-3} W_i^4 - 0.066974483 W_i^2 + 1$
F_2	$0.57384538 \times 10^{-5} W_i^4 - 0.50170413 \times 10^{-2} W_i^2 + 0.33092592$
F_3	$-0.14979958 \times 10^{-5} Wi^6 + 0.0010088882 W_i^4 - 0.10108617 W_i^2 + 1$
F_4	$-0.1713749 \times 10^{-7} W_i^6 + 0.53137351 \times 10^{-4} W_i^4 - 0.011096507 W_i^2 + 0.33092592$

Note: f_i = Center frequency (Hz) of i^{th} spectral band.

Vertical (Z)

K_0	4.3537
K_1	1.356
W_i	$2\pi f_i$
F_1	$-0.10245 \times 10^{-9} W_i^6 + 0.17583 \times 10^{-5} W_i^4 - 0.44601 \times 10^{-2} W_i^2 + 1$
F_2	$0.12882 \times 10^{-7} W_i^4 - 0.93394 \times 10^{-4} W_i^2 + 0.10543$
F_3	$-0.45416 \times 10^{-9} Wi^6 + 0.37667 \times 10^{-5} W_i^4 - 0.56104 \times 10^{-2} W_i^2 + 1$
F_4	$-0.21179 \times 10^{-11} W_i^6 + 0.51728 \times 10^{-7} W_i^4 - 0.17947 \times 10^{-3} W_i^2 + 0.10543$

Note: f_i = Center frequency (Hz) of i^{th} spectral band

APPENDIX D. ISO 2631-1:1997 AND ISO 2631-5 FILTERS

TABLE D-1. ISO 2631-1 WEIGHTING FACTORS.

CENTER FREQUENCY (Hz)	WEIGHTING FACTORS	
	LONGITUDINAL/TRANSVERSE (X,Y)	VERTICAL (Z)
0.2	0.243	0.121
0.25	0.365	0.182
0.315	0.530	0.263
0.4	0.713	0.352
0.5	0.853	0.418
0.63	0.944	0.459
0.8	0.992	0.477
1.0	1.011	0.482
1.25	1.008	0.484
1.6	0.968	0.494
2.0	0.890	0.531
2.5	0.776	0.631
3.15	0.642	0.804
4.0	0.512	0.967
5.0	0.409	1.039
6.3	0.323	1.054
8.0	0.253	1.036
10.0	0.212	0.988
12.5	0.161	0.902
16.0	0.125	0.768
20.0	0.100	0.636
25.0	0.080	0.513
31.5	0.0632	0.405
40.0	0.0494	0.314
50.0	0.0388	0.246
63.0	0.0295	0.186
80.0	0.0211	0.132
100.0	0.0141	0.0887

APPENDIX D. ISO 2631-1:1997 AND ISO 2631-5 FILTERS

$$a(1)y(n) = b(1)x(n) + b(2)x(n-1) + \cdots + b(nb-1)x(n-nb) - a(2)y(n-1) - \cdots - a(na+1)y(n-na) \qquad \textit{(Equation D-1)}$$

TABLE D-2. ISO 2631-5 FILTER COEFFICIENTS.

COEFFICIENT NUMBER	COEFFICIENT b	COEFFICIENT a
1	-5.71e-06	1.00000000
2	2.001e-05	-3.3232176
3	0.0013739	4.25612615
4	0.01454192	-1.98041727
5	0.02515231	-1.48873547
6	-0.01424205	3.32951129
7	-0.04426284	-2.94907214
8	-0.00888851	1.65340341
9	0.01771572	-0.6356778
10	0.01021642	0.16751942
11	0.00203074	-0.02807698
12	5.598e-05	0.00234873

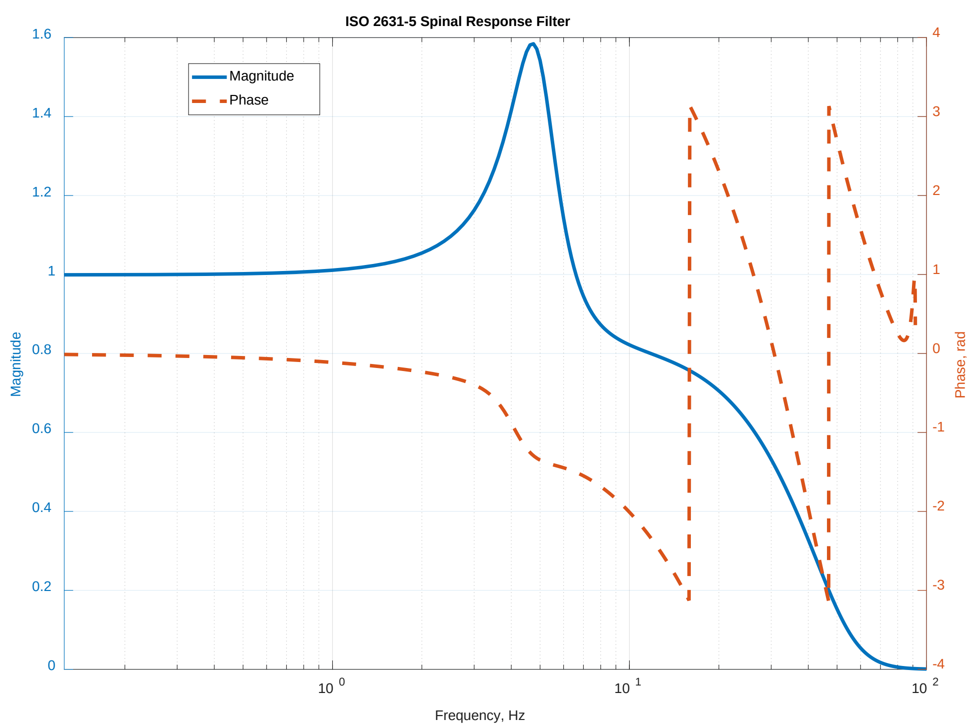

Figure D-1. Spinal Response Filter

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

E.1. OVERVIEW.

E.1.1 Purpose.

A ride quality course is intended to represent a plausible off-road terrain with a random pattern of random heights that is statistically consistent along the length of the test course. Different courses are used to represent different severity levels, just as there are different degrees of severity in off-road terrain. It is generally expected that as a vehicle travels faster on a given course the severity of the responses increases.

E.1.2 Historical Background.

a. A brief review of ride quality testing practices is useful to understand the degree of precision and accuracy implied by ride quality course characteristics. Specifically, testing in the past expected less precision than contemporary activities. In the past, a ride quality test was performed on virgin terrain identified by a field test team. The field team would survey a course laid out on the virgin terrain and make an assessment of its suitability and characteristics. Rod and level measurements would be performed at a spacing of approximately 1-ft (which means the shortest wavelength estimate would be at 0.5 cycles/ft). Repeated passes from a vehicle would result in surface wear, changing those characteristics. The field team would cease testing when they deemed the course no longer suitable, possibly resuming testing at a new location.

b. Eventually the practice was adopted to construct ride quality courses, built with different severity levels. These courses are made from compacted gravel using standard construction equipment, with the intention that the left and right tracks have the same elevation profile. The constructed courses were much more durable compared to the courses laid out on virgin terrain. This allowed consistency in testing which enabled comparisons of results between different vehicles (vendors, modifications, etc.). Ride quality testing was not too frequent an activity so field testers could avoid testing on days with inclement weather that would accelerate wear and tear. Occasionally maintenance activities would need to be performed by adding and compacting new material. General recollection is that these initial courses had an undulating quality, which is an important consideration when contrasting idealized representations against the courses built under practical and budgetary constraints of the time.

c. Four test courses were constructed with lengths on the order of 350 ft . As test speeds increased these lengths become inadequate. A vehicle moving at 10 mph travels 350 ft in less than 24 seconds. A vehicle moving 20 mph travels 350 ft in less than 12 seconds. A 12 second run only produces six overlapping spectral blocks (with 0.25 Hz resolution). This should be considered insufficient for Absorbed Power (ABP) analysis. Repeated runs could be performed for increased confidence, however at higher speeds a greater portion of the course length is

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

traversed while the vehicle is transitioning into its steady state response. The need for longer test courses was apparent, especially as improvements in mobility lead to faster speeds. For this reason, new courses were built with lengths on the order of 1000 ft.

E.1.3 Practical Limitations.

There are several practical limitations when it comes to constructing ride quality courses:

a. There is a limited amount of space available, creating a limited number of courses.

b. There is limited material for building up longer wavelengths.

c. Short wavelength content in gravel will wear away quickly, especially on frequently used courses in high moisture environments.

d. Shorter wavelength details are difficult to construct. Heavy equipment used for earthwork construction have buckets and blades with dimensions on the order of tire sizes.

e. More detail and precision requires more time and manpower.

E.2. RMS and Wave Number Spectrum (WNS).

E.2.1 General Information.

a. Ride quality requirements for military vehicles specify the terrain severity in terms of rms. As described in TOP 1-1-010A “Vehicle Test Course Severity (Surface Roughness)”[7], the standard practice is to calculate rms from a test course profile by first estimating its frequency domain content as a WNS. The rms is determined as the square root of the area between two wavelengths of the WNS, typically from 0.5 ft to either 64 ft or 36.57 ft. A representative WNS is presented in Figure E-1. The typical ride quality course WNS is generated from overlapping 256 ft blocks. For a 1024 ft long test course the WNS is made from 7 overlapping blocks. A WNS is generated for both the left and right tracks. Often the ride quality course is profiled in both directions, with the reported rms being the average of all individual wheel path rms values. Keeping with historical precedent, the constructed courses were built so that the left and right tracks have the same basic elevation profile.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

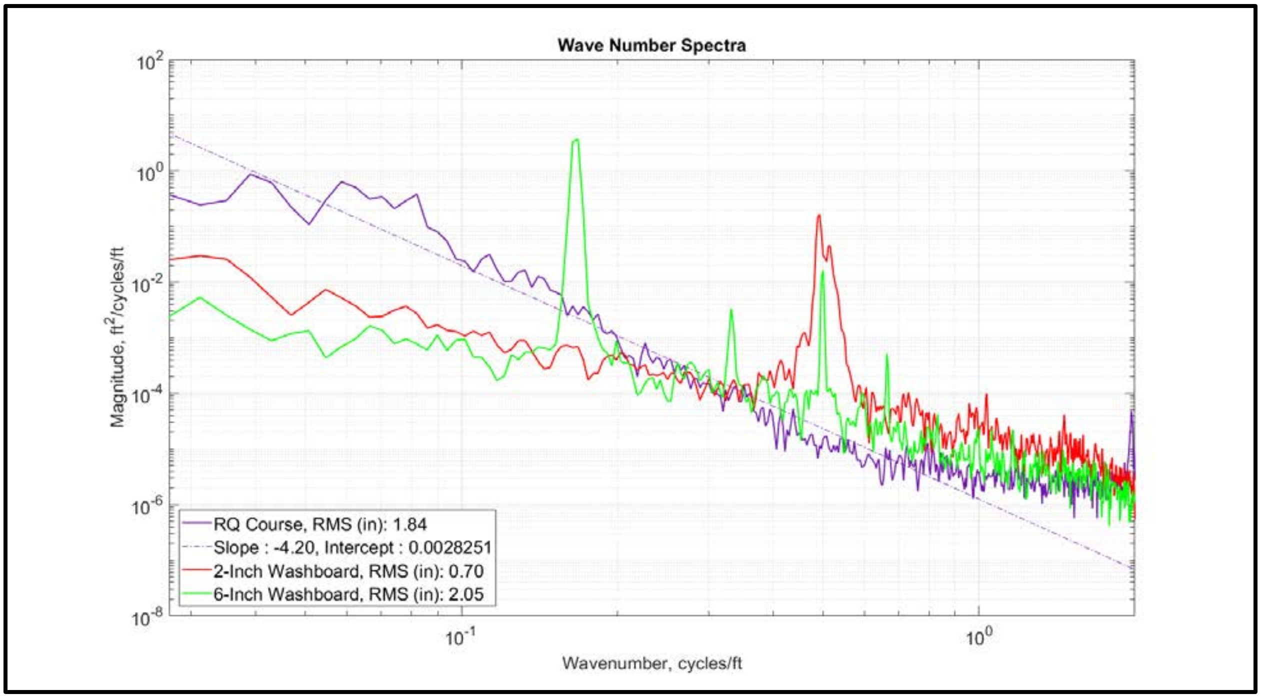

Figure E-1. WNS from Ride Quality course and Washboarding course.

b. Any number of WNS curves can produce the same rms values. However the activity of evaluating ride response (ex: Absorbed Power) versus rms requires using courses that contains broadband content, ideally with increasing amplitudes at longer wavelengths. This is in contrast with non-broadband content, such as washboarding, sparsely spaced events such as potholes, or hill-crest-type features (such as from ATC Perryman 3 Course). Washboarding courses (example: 2-Inch Washboard, 0.7 in rms) produce a strong frequency that is proportional to the vehicle speed, with the excitation frequency shifting through significant resonances as the vehicle speed increases. Sparsely spaced potholes are non-stationary inputs, which are important, but should not be used as inputs for analysis which presume stationary inputs (such as the PSD from which absorbed power is calculated). And hill-crest-type features can produce large rms values due to long wavelength content, but essentially provide the significant ride inputs only at hill cresting points. Representative WNS curves from a ride quality course and Washboard courses are provided in Figure E-1.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

E.2.2 Idealized vs Realistic Representations, with Speed Influences.

a. Conventionally the idealized representation of terrain presumes the WNS has a slope of -2 in the log-log domain[8,9], with the terrain severity then being defined by the intercept. This representation follows the form in Equation E-1:

$$G(\mathrm{F}) = C(2\pi\mathrm{F})^{-w} \qquad \textit{(Equation E-1)}$$

with *F* being the frequency (cycles/distance) and a *w* value of 2 representing the idealized presumption. Some researchers use the terms "waviness" to describe the *w* parameter and "unevenness index" to describe the intercept *C*[9,10]. This idealized representation has long been recognized as an imperfect representation when compared against real-world profiles. The idealized representation, especially with a waviness value of 2, is an easy tool for terrain simulation and mathematical analysis. Such a representation corresponds to a profile with a simple "random walk", whereby the height changes are purely random with a Gaussian distribution for all distance scales. It is rare to find such self-affinity in a real world terrain; it is even more unlikely to build one.

b. Some research has proposed using three separate subdomains of the WNS ("short", "medium" and "long"), with a different waviness and unevenness index for each subdomain[8]. A review of "short" and "long" waviness values for a variety of terrains around the world showed a range from 1.5 to more than 3. Though the researcher's motivation for using three subdomains was still for abstract analysis, important considerations can be identified from their work. For instance, the breakpoint wavelengths for the subdomains are determined by resonant frequencies of subsystems of the vehicle and typical vehicle speeds over the terrain (road). As an example, a vehicle with sprung mass natural frequencies in the range of 1 to 2 Hz traveling at 25 mph will have those frequencies excited by wavelengths of 18.4 ft to 36.7 ft. Likewise un-sprung natural frequencies in the range of 8 to 15 Hz are excited by wavelengths of 4.6 ft to 2.5 ft, when traversed at 25 mph. This relationship follows the form in Equation E-2,

$$f_o = vF \quad or \quad L = v/f_o \qquad \textit{(Equation E-2)}$$

with wavelength *L* being the inverse of the distance domain frequency, *v* the vehicle speed, and f_o the time domain frequency excited by the terrain. The research considered "short" wavelengths in the range of 2.6 ft to 10.25 ft, "medium" wavelengths from 10.25 ft to 41 ft, and "long" wavelengths greater than 41 ft. Obviously the definition of "long", "medium" and "short" wavelengths is dependent on the speed and frequency response characteristics of the system traversing the terrain. Most values presented in research deals with commercial roads traveled at speeds appropriate for those roads (i.e., greater than 50 mph).

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

c. Typical ride quality test speeds are in the range of 5 to 40 mph. The most important systems for consideration are the sprung mass and human occupant sensitivities. The occupant sensitivities are described in the main body of this TOP, with vertical absorbed power sensitivities receiving most attention. The peak of the absorbed power weighting curve is between 4 and 6 Hz. Content between 1.65 Hz and 84 Hz represents approximately 98 percent the total weighting. At 5 mph the 1.65 Hz to 84 Hz content is excited by the 0.1 ft to 4.4 ft wavelength subdomain. At 40 mph the 1.65 Hz to 84 Hz content is excited by the 0.7 ft to 35.6 ft wavelengths subdomain. These are partially overlapping but are two different subdomains of the WNS, as shown in Figure E-2. The lower speed subdomain actually extends past the shortest measurement wavelength. A similar analysis could be performed for the sprung mass.

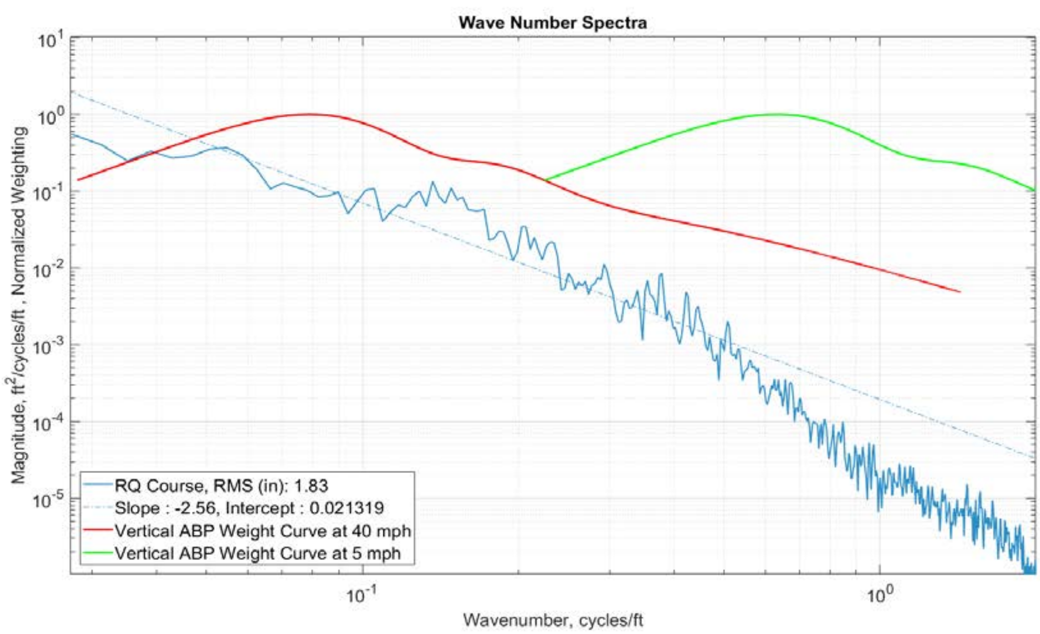

Figure E-2. WNS with ABP Weighting Curve positions for different speeds.

d. The ride quality test procedure involves running the same course at incrementally greater speeds. This creates a shifting window of subdomains for each speed (both for the sprung mass and occupant sensitivities). How to characterize the input from these shifting subdomains has yet to be defined and incorporated into vehicle specifications. Vehicle specifications still use rms, which is heavily influenced by the longer wavelength content. As stated above, the rms is determined as the square root of the area under the WNS from 1 cycle/36.57 ft (or 1 cycle/64 ft) to 1 cycle/0.5 ft. The 0.5 ft wavelength is basically an arbitrary artifact of the practice of sampling profiles every 3 inches.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

e. There may be motivation to characterize the ride quality course with waviness and unevenness index of Equation 1. ISO 8608:2016[8] suggests first "smoothing" the WNS by using the mean within proscribed frequency bands. The smoothed data are then used with a least-mean-square method in the wavelength range of 90.91 m (298 ft) to 0.35 m (1.16 ft), wavelengths that are probably more appropriate for higher speeds. However a problem arises because the WNS has more data points in the shorter wavelength content. If a simple first order regression were performed through all the data points, with or without smoothing, then the greater density of points in the short wavelength content would dominate the fit. Therefore the longer wavelength content should be weighted more because the rms is dominated by the longer wavelength. A reasonable fit can be generated using a weighted first order regression, with the weighting from Equation E-3,

$$W(F) = 10^{-F} \qquad \textit{(Equation E-3)}$$

where W is the weight to be applied to the WNS values at frequency F. A weighted first order regression is provided as the dashed lines in Figures E-1 and E-2. As shown in these plots, the actual content of the course never fits the Equation 1 form for any subdomain. The excitation from the course will always depend on the course content and the speed of the test item.

E.2.3 Undulating vs. Random Content and WNS Slope Influence on Ride.

a. As stated before, early ride quality course construction practices produced undulating profiles. This was not because off-road content was believed to have an undulating nature. Instead those courses were best effort products using techniques and resources available at the time. In the autumn of 2019 a novel course shaping technique was introduced during repair and maintenance work which resulted in more random content. The change in the nature of the content provided an opportunity to assess how content influenced vehicle responses.

b. Previously courses were constructed by adding localized mounds on top of a relatively level gravel road. The added mounds created positive height content, with the bases of the mounds merging together. The 2019 course construction method involved adding material but also involved digging down to create negative height content. Two representative elevation profiles, one from the new course construction method from 2019 and one from a previous constructed course having an "undulating" nature, are shown in Figure E-3 with their corresponding probability distributions and WNS curves in Figures E-4 and E-5.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

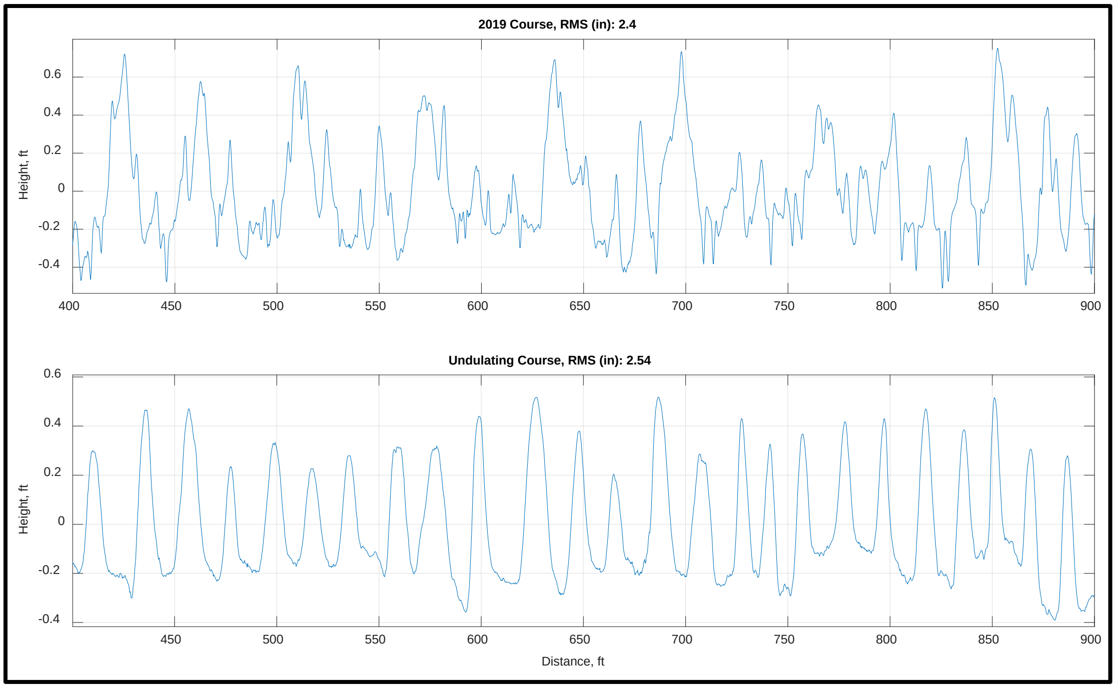

Figure E-3. Profiles from two courses with comparable rms, built with different methods.

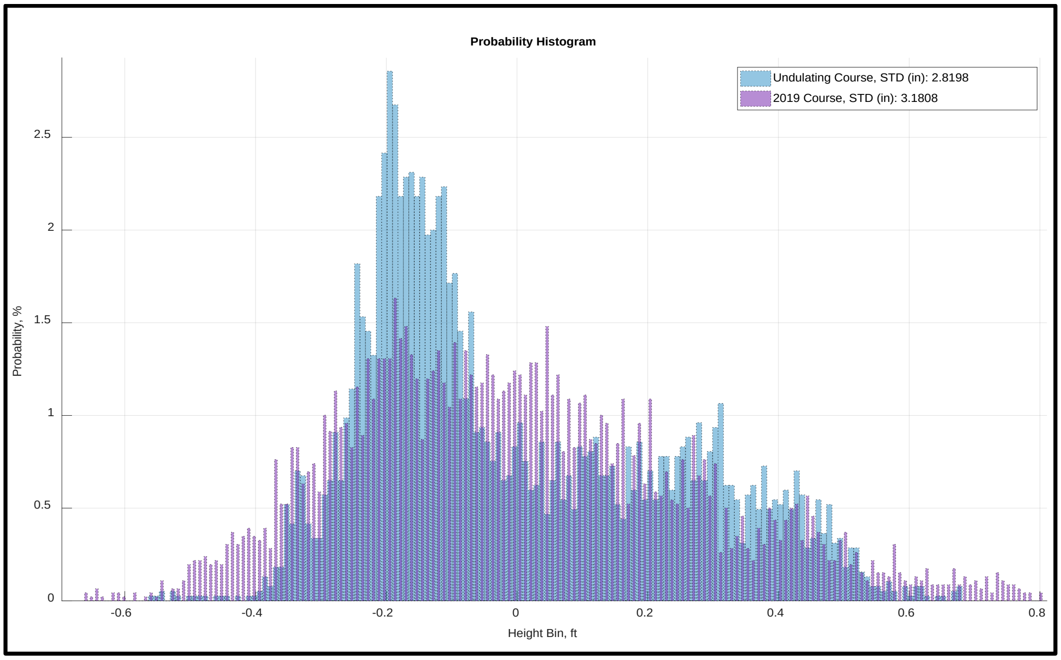

Figure E-4. Histograms from two courses with comparable rms, built with different methods.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

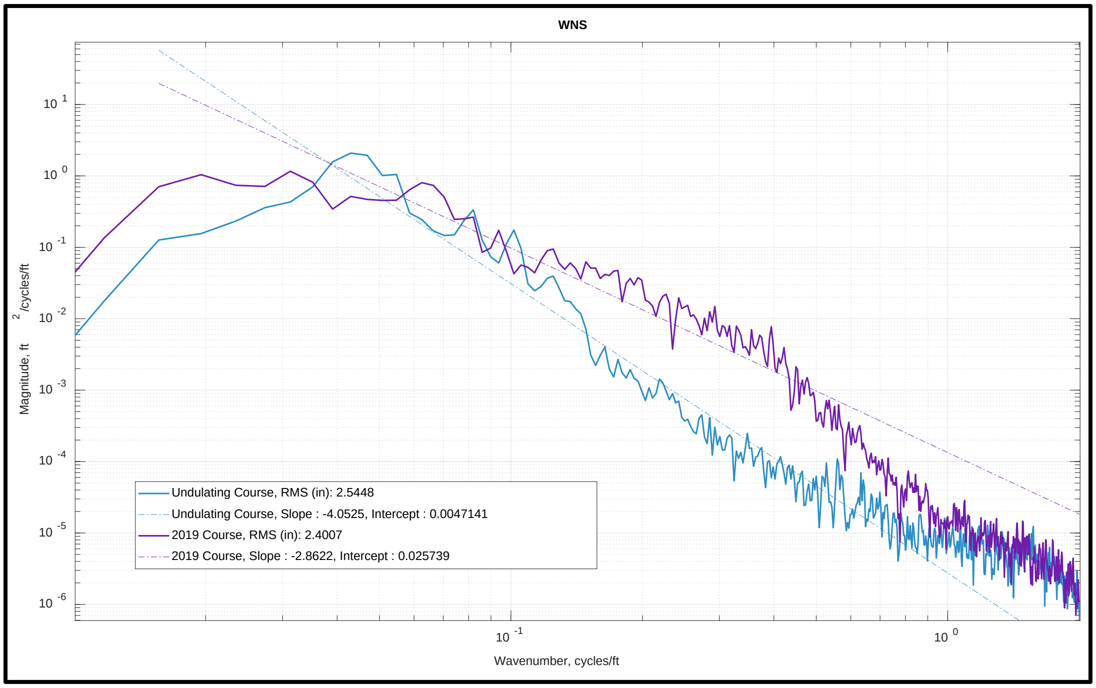

Figure E-5. WNS from two courses with comparable rms, built with different methods.

c. The histogram of the profile shows the 2019 course has a more Gaussian distribution, while the 2016 course is skewed with tails towards a positive elevation. The mode of the 2016 undulating course is slightly below the average, being influenced by the flat base to which the mounds were added. The WNS curves show the 2019 course has a slope closer to the idealized "waviness" value of 2, while the prior construction method tended to result in waviness values between 3 and 4. The 2019 method enables more randomness in the elevation changes by having changes be either positive or negative. Having a Gaussian input is a typical assumption for almost all analysis and testing. In this sense the 2019 construction method is an improvement. It is also assumed that virgin cross-country terrain is nominally Gaussian.

d. Vehicles that have been tested on courses constructed in both styles show harsher responses when tested on the newer courses, even when the rms values are comparable. This is further evidence that rms alone is insufficient to describe terrain input. This creates a problem when considering a legacy vehicle which has met the criteria on undulating courses with a waviness value between 3 and 4, but fails to meet the criteria on newer courses with waviness values closer to 2. This indicates most legacy vehicles were tested on courses with waviness values between 3 and 4. This is important to note because later vehicle generations have their

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

criteria set in relation to the performance of the legacy vehicle they are replacing. This means a detailed comparison against the criteria or prior results requires taking the WNS slope into account.

e. The concept of a speed dependent weighted rms (wrms) is introduced to evaluate the influence of local-WNS slope, whereby a normalized weighting curve (the vertical absorbed power curve shown in Figure E-2) is applied to the WNS curve at speed dependent wavelengths according to Equation E-2. As speed increases the weighting curve is shifted to the left, applying the weighing curve to different wavelengths of the WNS. The wrms presented here is the square root of the area under the weighted WNS curve from wavelengths 36.57 ft to 0.5 ft, with wrms values increasing as speed increases on courses with negatively sloped WNS curves. Theoretically, if a vehicle is subjected to the same wrms it should produce the same response, particularly for the occupant. What the speed dependent wrms enables is a mapping from one speed on a given test course WNS to another speed on an alternative test course WNS.

f. A computer search algorithm can be performed to determine what speed is needed on one course to achieve the same wrms caused by a given speed on another course. Generally, as the w value increases the necessary speed also increases. Figure E-6 presents the speed mapping from an idealized course (Equation E-1) with a waviness value, w, of 2.5 to other idealized courses with the same traditional rms value. In this graphic, the “From Speed” is the speed at which the w = 2.5 course was traversed, giving the same wrms value as the “To Speed” on the alternative course. For example, traveling at 15 mph on the $w = 2.5$ course gives the same wrms as traveling 12.3 mph on the $w = 2$ course, and 19.3 mph on the $w = 3.5$ course.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

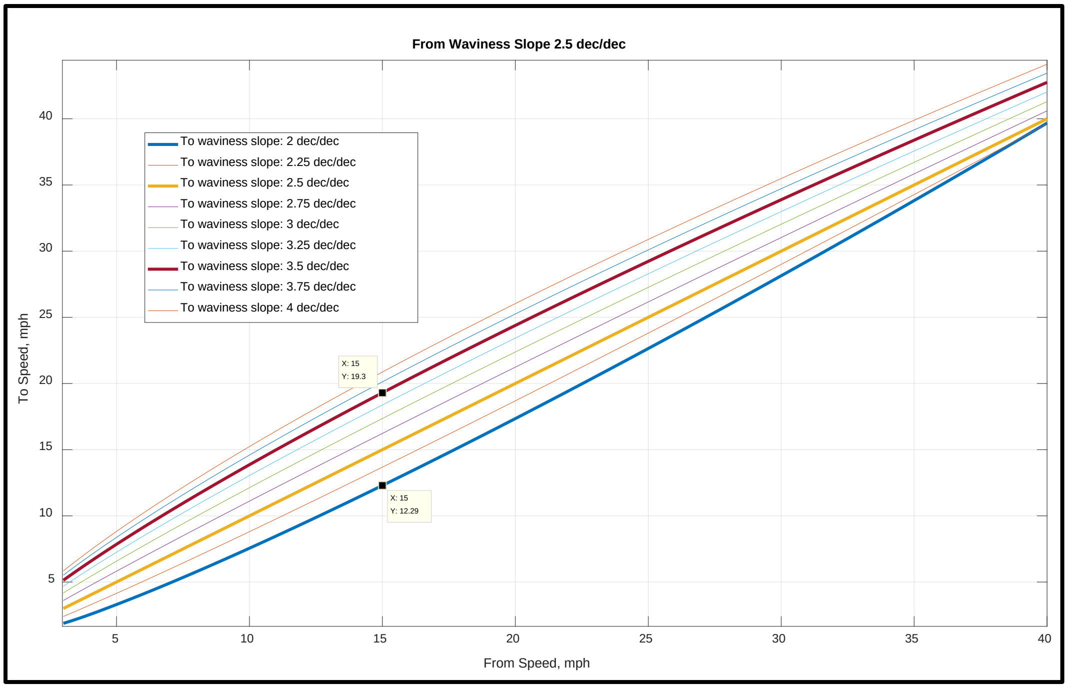

Figure E-6. WRMS Mapping from an idealized course with waviness of 2.5 to other idealized courses for the same traditional rms value.

g. The same algorithm was applied to the WNS curve shown in Figure E-5 to map to an idealized course having the same traditional rms value with alternative waviness values, producing the graphic in Figure E-7. Overall the pattern is similar to Figure E-6, with greater speeds being needed to map to greater *w* values. For example, traveling at 10 mph on the actual courses would produce the same wrms value as 19 mph on an idealized course with w = 3.5. However the influence of the changing localized slope in Figure E-5 is also apparent, with 5 mph on the actual course mapping to 5 mph on the w = 2.5 idealized course, but 10 mph on the actual course mapping to 10 mph on the w = 2.25. At 17 mph the actual course would behave as an idealized course with a WNS slope of w = 2 in the log-log domain.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

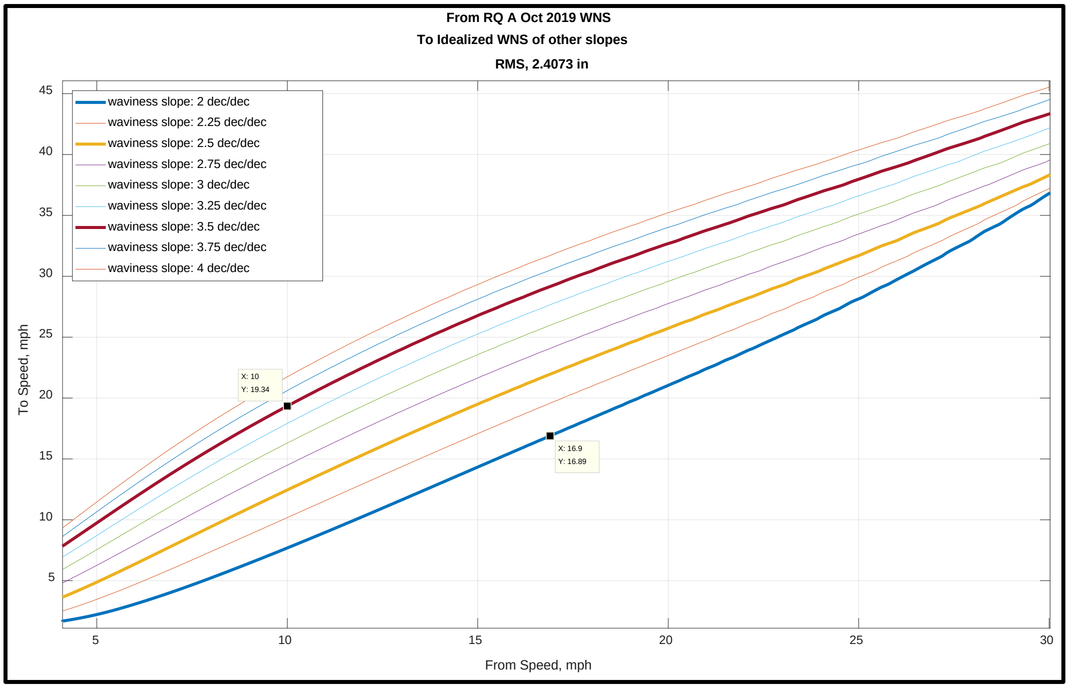

Figure E-7. WRMS Mapping from an actual course to other idealized courses for the same traditional rms value.

h. The speed-mapping approach laid out above demonstrates that vehicle and occupant inputs are not only dependent on overall rms values but also on the local WNS waviness parameters. The harsher responses of legacy vehicles tested on courses with lower waviness values (w = 2 to 2.5) supports the supposition that historically vehicles have been tested on courses with higher waviness values (w = 3 to 4). This implies the "log-log slope of -2" referenced in past documentation and literature was treated as a "rule of thumb" for guidance.

i. The "6-Watt Speed" is an example of a speed that could be mapped with this method. A vehicle which failed to meet a "6-Watt Speed" criteria on a course with a lower waviness value could be mapped to a passing speed for an idealized course with a higher waviness value. It is suggested that a range of waviness values be evaluated when comparing recent results against past results. Similarly a speed mapping could be performed from one actual course WNS to another WNS from an actual course.

j. When doing speed mappings from actual courses to another WNS (actual or idealized) there is a difficulty in matching rms values. The real-world courses will never have the exact rms values required in performance criteria (ex: 2.0 in. rms), but instead may have values which are above and below the criteria (ex: 1.7 in rms and 2.3 in rms). A similar point could be made

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

when mapping to past courses which will also have different rms values. This creates uncertainty about which courses should be used (1.7 in rms or 2.3 in rms) when mapping to a different rms (ex: 2.0 in rms). This uncertainty can be resolved with a weighting of mappings from many actual courses to one desired rms, as described in Equation E-4,

$$s_i = \frac{1}{(RMS_{TO} - RMS_i)} \quad , \quad w_i = \frac{|s_i|}{\sum_{i=1}^{N} |s_i|}, \quad v_{To} = \sum_{i=1}^{N} v_i w_i \qquad \textit{(Equation E-4)}$$

where RMS_{TO} is the rms value to which values are being mapped, while RMS_i is the i^{th} rms value of the N actual courses from which speeds are being mapped. The intermediary value s_i is the inverse of the difference between rms values (creating a strong weighting when RMS_i is close to RMS_{TO}; a weak weighting when RMS_i is far from RMS_{TO}). The speed v_i is from the i^{th} actual course, to which weighting w_i is applied in the summation to give the weighted average speed mapping, v_{TO}.

E.3. ROLL INDUCING COURSES, WITH LEFT AND RIGHT TRACKS NOT IN PHASE.

E.3.1 General Information.

a. As stated before, the ride quality courses were built with the intention that the left and right tracks have the same elevation profile, in phase with each other. One reason for this is so that the same input characteristic (rms or alternative) could be used regardless of the test item's track width and path down the course. However, there is increasing motivation for testing on ride quality courses that induce Roll. Some attempts have been made to induce roll with courses which continuously vary amplitude across the course width. But on such courses the actual input is unknown because the exact path down the course is too onerous to measure. Additionally, repeating that same path for runs of increasing speed is impossible. Simply taking the average of more runs that cover the entire width of the course is inappropriate.

b. The only way to ensure run-to-run repeatability with the same input characteristics is to construct a test course which consists of two adjacent tracks, with the test vehicle straddling the two tracks. The "left" track would have the same profile across its width, as would the "right" track. The course would need to be constructed such that the left and right tracks are uniquely random and not in phase with each other, essentially being their own in-phase courses. The left and right tracks would be wide enough (example: 7 ft each) to permit variations in vehicle positioning from left to right so that the same roll input is induced with each run.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

c. Unfortunately such a course design still has the problem that vehicles with different wheel base track widths would have different magnitudes of roll input. Having the same elevation difference between left and right tracks for all vehicle widths means wider tracked vehicles would be given lesser roll inputs. This simply means that knowing a vehicles wheel base dimensions is required to characterize the amount of roll input from a test course.

E.3.2 Wheelbase Projection for Course Characterization.

a. An analytical method has been developed[11] which uses wheel base dimensions to project left and right track profiles into resultant profiles (Heave, Roll, and Pitch, as well as non-rigid body profiles), for vehicles with any number of axles. The projected Heave, Roll, and Pitch profiles can then be analyzed to characterize those modes of input (example: WNS, rms). The projected profiles and metrics will depend on the axle spacings and track widths. But if the course is constructed so that the left and right tracks are not continuously varying across their respective widths, then the projected profiles will not depend on how the vehicle is driven on the course.

b. In this method, profiler data are used with the axle spacings and track width measurements to create synchronized profiles underneath each wheel. These wheel profiles are combined to form an array with each column representing the profile under a wheel. The wheel locations are also used to create normalized orthogonal basis vectors, with each vector corresponding to the resultant profile to be extracted (Heave, Roll, Pitch, etc.). The wheel profile matrix is multiplied against the basis vectors to produce the resultant profile. Table E-1 presents the normalized basis vectors for a hypothetical three-axle vehicle with a track width of 80 in. and an axle spacing of 130 in. from axle 1 to axle 2, and 210 in. from axle 1 to axle 3. See reference 9 for details in its development.

TABLE E-1. BASIS VECTORS FOR EXAMPLE WHEEL BASE

TRACK / AXLE	HEAVE	ROLL	PITCH	TWIST	CREST	DOUBLE TWIST
Left Axle 1	0.408	0.408	-0.535	-0.535	-0.218	-0.218
Right Axle 1	0.408	-0.408	-0.535	0.535	-0.218	0.218
Left Axle 2	0.408	0.408	0.079	0.079	0.572	0.572
Right Axle 2	0.408	-0.408	0.079	-0.079	0.572	-0.572
Left Axle 3	0.408	0.408	0.456	0.456	-0.354	-0.354
Right Axle 3	0.408	-0.408	0.456	-0.456	-0.354	0.354

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

c. The simple equation to create the projected profiles is presented in Equation E-5,

$$M = PB \qquad \textit{(Equation E-5)}$$

where each column of *M* contains the unscaled projection profiles corresponding to the columns of the basis vectors in matrix *B*, which are applied against each row of the wheel profiles in matrix *P*.

d. Now consider two randomly generated profiles, as presented in Figure E-8, with Gaussian distributions and log-log slopes of -3.5. The “Right” track is uncorrelated with the “Left” track, as demonstrated by the low coherence values presented in Figure E-8. From these tracks, a six column profile matrix, *P*, was made for the elevation under each wheel for the hypothetical vehicle which produced Table E-1. It is important to note that the profiles for a given side are basically the same but with a simple phase lag determined by the axle spacing. Using Table E-1 for matrix *B*, the projected profiles for matrix *M* can be calculated with Equation E-5, with Heave, Roll and Pitch presented in Figure E-9. Because the basis vectors are normalized the Roll and Pitch profiles are not presented in terms of angles. Converting those profiles to angular displacement is simply a matter of scaling based on the track width or overall wheelbase. The unscaled profiles are useful for presentation purposes.

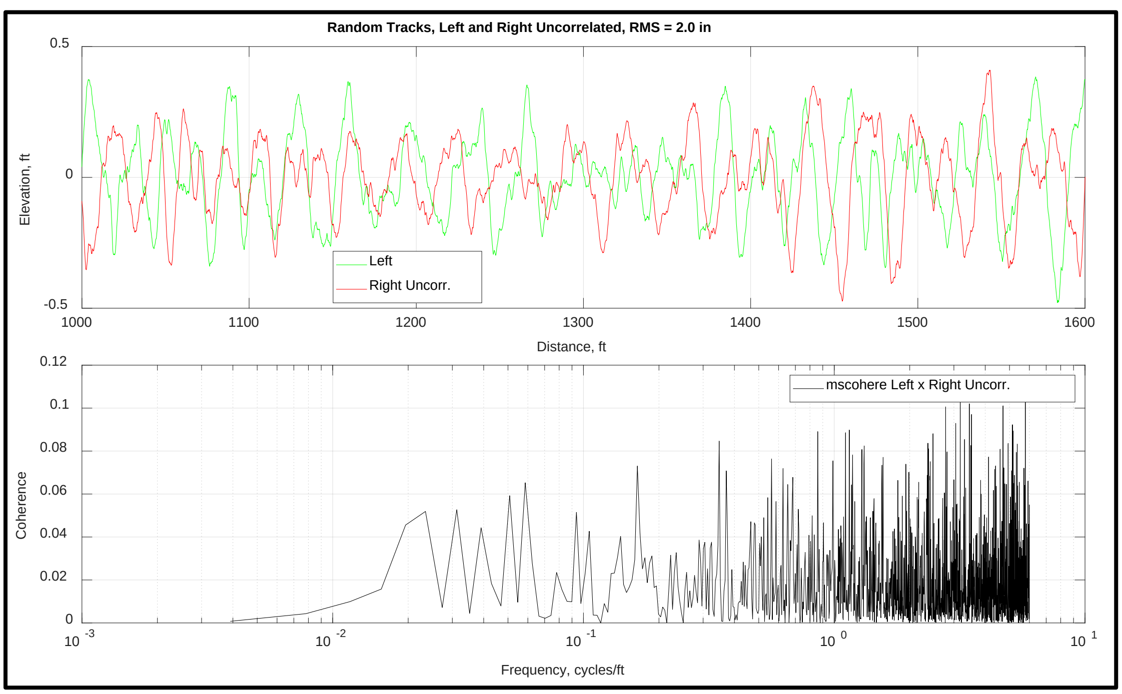

Figure E-8. Randomly generated Left and Right Tracks profiles and low Coherence Values.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

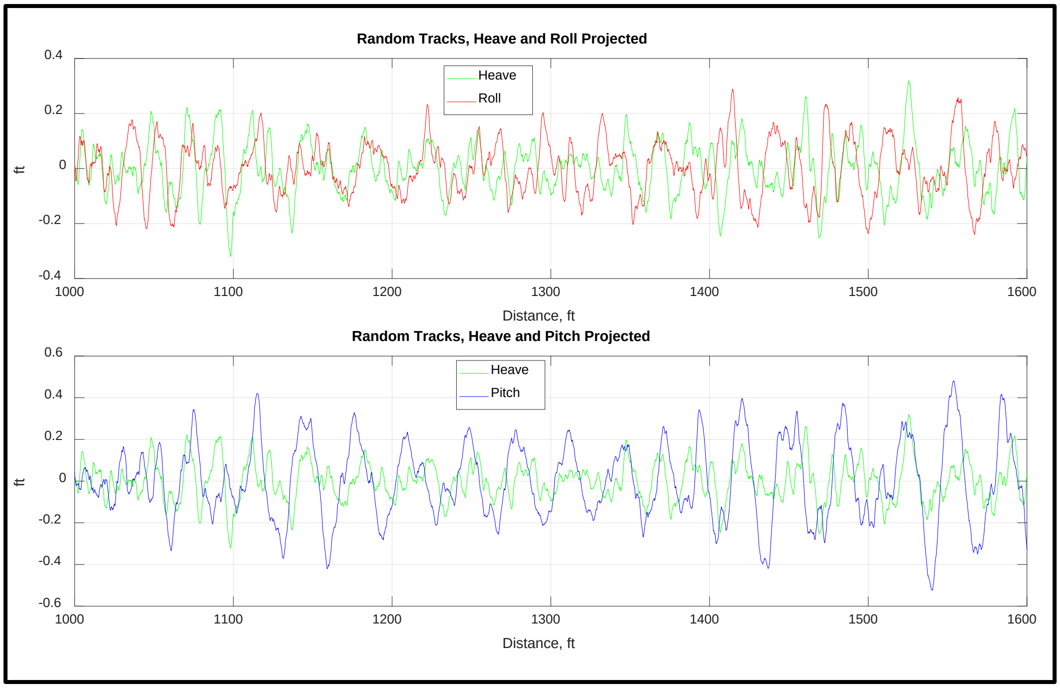

Figure E-9. Heave Pitch and Roll projected profiles.

e. The spectral content for the projected profiles is presented in Figure E-10. These plots show a few interesting characteristics. One characteristic is the notching that occurs in the Pitch WNS at harmonics of 1/210 inches, with the strongest appearance in the coherence curve between Heave and Pitch. This is due to a known phenomenon where the vehicle wheelbase acts as a filter attenuating pitching inputs at wavelengths equal to a harmonic of the wheelbase. For this vehicle the distance from the first to last axle is 210 inches. At harmonics of 210 inches the front and rear axles are being lifted at the same time, which means there is no pitching input from these wavelengths. Another spectral characteristic is the high coherence value between Heave and Pitch, which is due to the wheel profiles for a given track being the same but simply out of phase with each other. Also, it should be noted there are low coherence values between Roll and Heave, and between Roll and Pitch, which is not surprising given the left and right tracks are uncorrelated.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

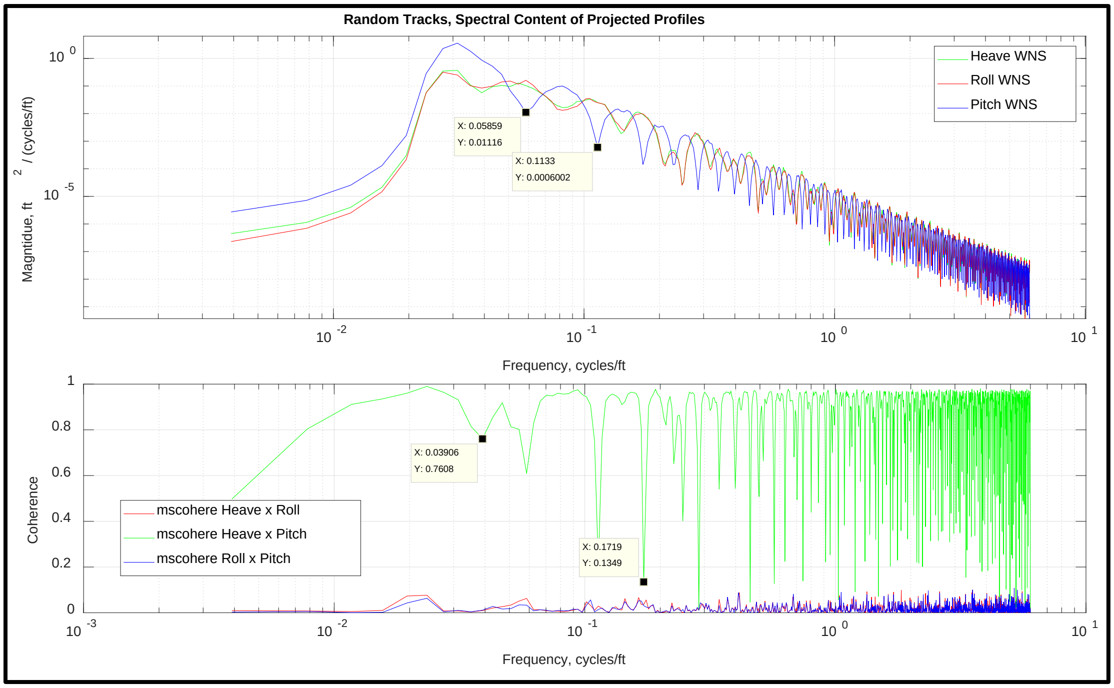

Figure E-10. Spectral Content for Heave Pitch and Roll Projected Profiles.

f. Further work needs to be done with the above method to enable designing a course with specific Heave, Pitch and Roll properties. Mathematically it is possible to start with a projection profile matrix M having the desired properties (example: uncorrelated Heave and Roll, or attenuated Roll) and determine the necessary wheel profiles, P, by multiplying M by the inverse of B. However a closer inspection of the resultant profile elevations shows the forward and rearward profile elevations from the same track will be different, which is physically impossible.

E.3.3 <u>Other Considerations</u>.

Other ideas need to be considered when thinking about roll inducing courses:

a. The influence of important suspension components such as anti-roll bars are not evaluated for non-roll inducing courses.

b. Criteria and vehicle specifications do not currently exist for roll inducing terrain.

APPENDIX E. RIDE QUALITY COURSE CHARACTERIZATIONS.

c. Roll inducing courses may need to be longer. A non-roll inducing test course has two degrees of freedom (Heave and Pitch); a roll inducing test course has a third (Roll). A course may need to be longer to ensure the Pitch dimension is not too strongly correlated with either Heave or Roll.

d. Test courses will be used for a variety of vehicle types, with unique wheel base dimensions and axle counts. That means each unique vehicle will have different amounts of Roll (and Heave and Pitch) input.

e. A seat's distance from a vehicle's pitch and roll axes influences how much the vertical inputs to a seat are due to pitching and rolling dynamics.

f. The pitch and roll axes for a vehicle body are often below the seating areas, which means pitching and rolling dynamics will contribute to longitudinal and lateral excitations.

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APPENDIX F. ABBREVIATIONS.

ABP	Absorbed Power
ASWDS	Airborne Scraper and Water Distribution System
cm	centimeter
COV	Coefficient of Variation
DOD	Department of Defense
ft	feet
HDBK	Handbook
Hz	Hertz
in.	inch
ISO	International Standards Organization
kg	kilogram
km/hr	kilometers per hour
lb	pound
m/s^2	meters per second squared
MPa	megapascal
mph	miles per hour
MTVV	Maximum Transient Vibration Value
NATO	North Atlantic Treaty Organization
OMS/MP	Operational Mode Summary/Mission Profile
PSD	Power Spectral Density
rad/s^2	radians per second squared
rms	root mean square
SAE	Society of Automotive Engineers
sec	second
TOP	Test Operations Procedure
VDV	Vibration Dose Value

APPENDIX F. ABBREVIATIONS.

WBV	Whole-Body Vibration
WNS	Wave Number Spectrum
wrms	weighted root mean square

APPENDIX G. REFERENCES.

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APPENDIX G. REFERENCES.

c. Bekker, M.G., Introduction to Terrain Vehicle Systems, the University of Michigan Press, 1969.

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APPENDIX H. APPROVAL AUTHORITY.

CSTE-CI 16 November 2020

MEMORANDUM FOR

Commander, U.S. Army Operational Test Command
Director, U.S. Army Evaluation Center
Commanders, ATEC Test Centers
Technical Directors, ATEC Test Centers

SUBJECT: Test Operations Procedure 01-1-014B, Ride Dynamics and Evaluation of Human Exposure to Whole Body Vibration, Approved for Publication

1. Test Operations Procedure (TOP) 01-1-014B, Ride Dynamics and Evaluation of Human Exposure to Whole Body Vibration, has been reviewed by the U.S. Army Test and Evaluation Command (ATEC) Test Centers, the U.S. Army Operational Test Command, and the U.S. Army Evaluation Center. All comments received during the formal coordination period have been adjudicated by the preparing agency.

2. Scope of the document. This TOP describes methods for analyzing the ride dynamics or ride quality and whole body vibration (WBV) of ground vehicles. Ride dynamics and WBV pertain to the sensation or feel of the passengers in the environment of a moving vehicle. The technique for evaluating the ride dynamics and WBV involves the use of instrumented seats or ride quality pads which contain accelerometers molded in a rubber disk to provide measurements in three mutually perpendicular axes. The instrumented seats are occupied by the normal vehicle crew. Ride dynamics data are acquired while the vehicle traverses various test courses at pre-determined speeds.

3. This document is approved for publication and has been posted to the Reference Library of the ATEC Vision Digital Library System (VDLS). The VDLS website can be accessed at https://vdls.atc.army.mil/.

4. Comments, suggestions, or questions on this document should be addressed to U.S. Army Test and Evaluation Command (CSTE-CI), 6617 Aberdeen Boulevard-Third Floor, Aberdeen Proving Ground, MD 21005-5001; or e-mailed to usarmy.apg.atec.mbx.atec-standards@mail.mil.

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Forward comments, recommended changes, or any pertinent data which may be of use in improving this publication to the following address: Policy and Standardization Division (CSTE-CI-P), U.S. Army Test and Evaluation Command, 6617 Aberdeen Boulevard, Aberdeen Proving Ground, Maryland 21005-5001. Technical information may be obtained from the preparing activity: Commander, U.S. Army Aberdeen Test Center (ATTN: TEDT-AT-AD), Aberdeen Proving Ground, MD 21005-5059 Additional copies can be requested through the following website: https://www.atec.army.mil/publications/documents.html, or through the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Fort Belvoir, VA 22060-6218. This document is identified by the accession number (AD No.) printed on the first page.